WAVEGUIDE II USER'S MANUAL

(This manual works "pretty good" for WAVEGUIDE III)

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Waveguide II User's Manual

WAVEGUIDE II is a photonics software package that calculates the complex propagating modes in plane-layered optical waveguides composed of homogeneous, isotropic materials having arbitrary complex indices of refraction. Based on a 1977 University of Washington Ph.D. thesis by Robert Smith [1], WAVEGUIDE II has been modified extensively over more than three decades and has been used extensively to model photonic components including semiconductor lasers, grating assisted directional couplers and isolators. WAVEGUIDE II, available for free on the SMU photonics website, has been downloaded all over the world to researchers in (in descending order): Korea, Germany Taiwan, Canada, Great Britain, China, Japan, France, the United Arab Emirates, and 30 other countries. This thesis, a user's manual for the latest version of WAVEGUIDE II, outlines the theoretical basis and capabilities of the software. The user is guided through numerous examples (infrared, red and blue lasers; and directional couplers) that illustrate the optimization of photonic devices by using the capabilities of WAVEGUIDE II to calculate near-fields, far-fields, and layer confinement factors. WAVEGUIDE II includes built-in subroutines to calculate the index of refraction of AlGaAs, InGaAsP, AlGaInAs, AlGaAsSb, AlInAsSb, GaInPSb, AlAsSb, AlGaInP, InGaAs, and GaInP alloys.

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Chapter 1

INTRODUCTION

WAVEGUIDE II is a photonics software package that calculates the complex propagating modes in plane-layered optical waveguides composed of homogeneous, isotropic materials having arbitrary complex indices of refraction. Based on a 1977 University of Washington Ph.D. thesis by Robert Smith [1], WAVEGUIDE II has been modified extensively over more than three decades by Gary Evans and his colleagues at Aerospace Corporation (1979 - 81), TRW (1981 - 1984) (now Northrop Grumman), RCA Laboratories (1984 – 1992) (now Sarnoff), and his students at Southern Methodist University (1992 – present).

WAVEGUIDE II (and early versions) has been used extensively to model photonic components including semiconductor lasers, grating assisted directional couplers and isolators. Available for free on the SMU photonics website, WAVEGUIDE II has been downloaded all over the world to researchers in (in descending order): Korea, Germany Taiwan, Canada, Great Britain, China, Japan, France, the United Arab Emirates, and 30 other countries. This thesis, a user's manual for the latest version of WAVEGUIDE II, outlines the theoretical basis and capabilities of the software. The user is guided through numerous examples (infrared, red and blue lasers; and directional couplers) that illustrate the optimization of photonic devices by using the capabilities of WAVEGUIDE II to calculate near-fields, far-fields, and layer confinement factors. WAVEGUIDE II includes built-in subroutines to calculate the index of refraction of AlGaAs, InGaAsP, AlGaInAs, AlGaAsSb, AlInAsSb, GaInPSb, AlAsSb, AlGaInP, InGaAs, and GaInP alloys.

The Transfer Matrix Method (TMM) is used to find Eigen modes in a multi-layer slab waveguide structure. Transfer matrices of each layer are calculated and Eigen values are found by solving the characteristic Eigen function.

This thesis is organized as follows: Chapter 2 discusses the fundamental principles and general procedures for analyzing a 3-layer optical waveguide, followed by a description of the input and output parameters. Use of the built-in subroutines to calculate the refractive index for numerous semiconductor alloys as a function of composition and wavelength is described in chapter 3. Chapter 4 demonstrates basic concepts and the design of a directional coupler. Multiple quantum well (MQW) semiconductor lasers emitting at 980 nm and 820 nm in the InGaAs/AlGaAs/GaAs material system are analyzed chapter5. InGaAsP/InP lasers emitting at 1310nm and 1550nm are analyzed in Chapter 6. InGaAlAs/InP lasers emitting at 1310nm and 1550nm are analyzed in Chapter 7. AlInGaP/GaAs lasers emitting at 635nm are analyzed in Chapter 8. InGaN lasers emitting at 415nm) are analyzed in Chapter 9. The complete design and optimization of a 1310 nm ridge-guide laser is presented in Chapter 10. The final chapter illustrates the effect of metal contacts on InP lasers.

Chapter 2

THEORY BACKGROUND

2.1 Introduction

This chapter includes the theoretical overview of optical waveguides and a description of how to run the WAVEGUIDE II program for a simple three-layer slab waveguide.

Section 2.1 briefly introduces the field notations and the formulas utilized in the WAVEGUIDE II software for calculating those parameters. Section 2.2 provides a general idea on how the WAVEGUIDE II software solves the complex mode. Numerical methods that are used by the WAVEGUIDE II software to solve the propagation constant are also covered in this part. Section 2.3 provides a step-by-step explanation on how to construct and evaluate an input file with the WAVEGUIDE II software, followed by the illustration of how to analyze the generated data and plots to obtain useful information of waveguide structure.

2.2 A Three-Layer Waveguide Example

This section gives a basic introduction of how the WAVEGUIDE II solves complex modes for a three-layer slab waveguide. The first part of this section introduces the 2×2 matrix which is used by WAVEGUIDE II for solving the propagation constant of a three-layer waveguide. Numerical methods are mentioned in the second part to give readers a general idea of how those numerical answers are found.

2.2.1 Transfer Matrix Method (TMM)

Figure 1 shows the geometry and field variables for a multi-layered optical waveguide. Mode propagation is in the z direction. The x direction is perpendicular to the layers that make up the waveguide. The layers are parallel to the y and z directions. Such a layered structure only supports TE and TM modes. F_x, F_y, and F_z are normalized field variables that correspond to H_x, E_y and H_z for TE modes and E_x, H_y and E_z for TM modes. The output files for F_x, F_y and F_z are variable.fx, variable.fy and variable.fz.

The complex Poynting vector in the z direction is P_z, where $P_z = (F_x \times F_y^*)$. $P_z/2$is the time-averaged power flowing in the z direction. The complex Poynting vector in the x direction is P_x, where $P_x = (F_y \times F_z^*)$. $P_x/2$ is the time-averaged power flowing in the x direction. The output files for P_z and P_x are variable.pz and variable.px.

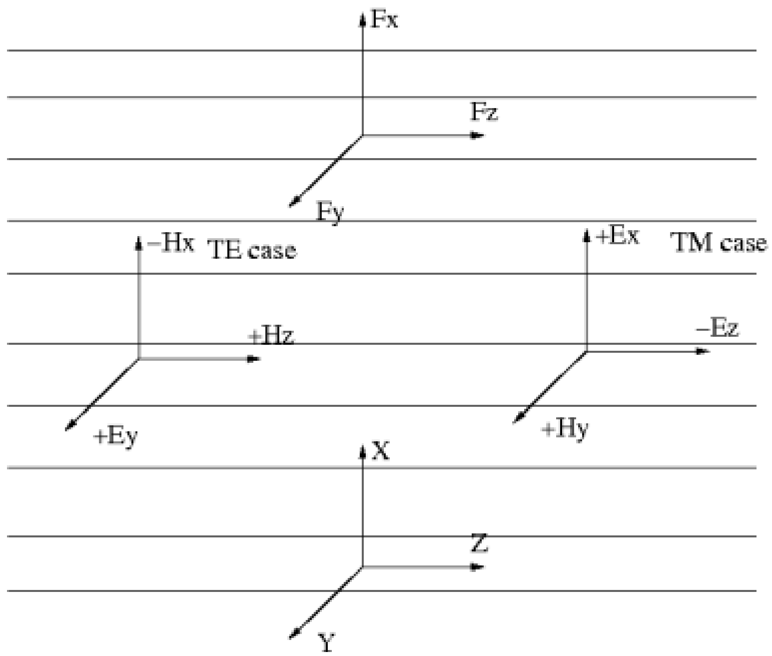


Figure 1. Normalized field variables (F_x, F_y, and F_z) correspond to TE and TM polarizations for a layered structure.

Maxwell's equations provides a scalar wave equation for the i^{th} layer:

$$\frac{\partial^2}{\partial x^2} F_{yi} + (k_0^2 \varepsilon_i + \gamma^2) F_{yi} = 0 \qquad (2.1)$$

where F_{yi} is E_y for TE modes and H_y for TM modes,

γ is the modal propagation constant (= $\alpha + j\beta$), and

$k_0^2 = \omega^2 \mu_0 \varepsilon_0$.

For TE modes the boundary conditions require F_{yi} and $\partial F_{yi} / \partial x$ be continuous at each interface. We can get a coupled equation in matrix form for each layer:

$$\begin{bmatrix} F_{yi} \\ \dfrac{\partial F_{yi}}{\partial x} \end{bmatrix} = \begin{bmatrix} \cos(h_i x) & \sin(h_i x) \\ -h_i \sin(h_i x) & h_i \cos(h_i x) \end{bmatrix} \begin{bmatrix} A_i \\ B_i \end{bmatrix} \quad (2.2)$$

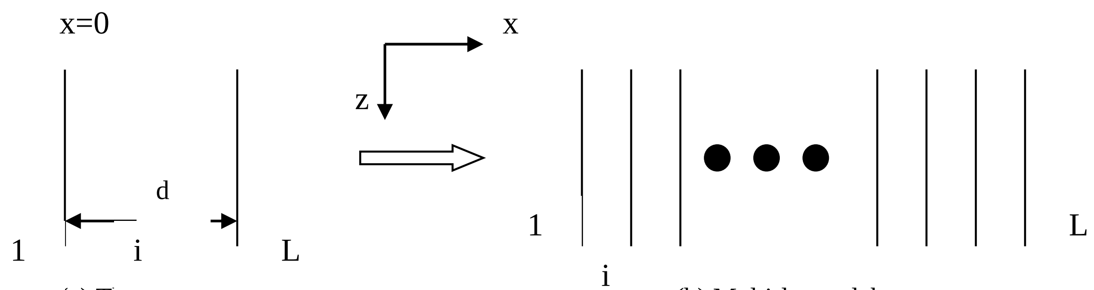
where h_i , the lateral propagation constant for the ith layer, is $\sqrt{| k_0^2 \varepsilon_i + \gamma^2 |}$ and $|\gamma^2| > |k_0^2 \varepsilon_i|$.

The outer layers have the matrix form:

$$\begin{bmatrix} F_{yi} \\ \dfrac{\partial F_{yi}}{\partial x} \end{bmatrix} = \begin{bmatrix} 1 & h_{1orL} \end{bmatrix} \begin{bmatrix} A_o \\ A_o \end{bmatrix} \quad (2.3)$$

where h_{1orL} is $\sqrt{\gamma^2 - k_0^2 \varepsilon_{1orL}}$, h_1 is the propagation constant for the 1st layer and h_L is the propagation constant for the L^{th} layer,

A_0 is A_1 for 1st layer and A_L for the last layer.



(a) Three layer slab

(b) Multi-layer slab WAVEGUIDE

Figure 2.2.1 Slab waveguide

After we match the boundary conditions at each layer, we can get the following matrix form for the whole waveguide structure:

$$\begin{bmatrix} A_L \\ -h_L A_L \end{bmatrix} = T \begin{bmatrix} A_1 \\ h_1 A_1 \end{bmatrix} \tag{2.4}$$

where $T=\begin{bmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{bmatrix} = \begin{bmatrix} \cos(h_i d) & \frac{\sin(h_i d)}{h_i} \\ -h_i \sin(h_i d) & \cos(h_i d) \end{bmatrix}$.

From equation (2.4), the characteristic equation becomes

$$T_{21}+T_{22}h_1+h_L(T_{11}+T_{12}h_1)=0 \tag{2.5}$$

For multi-layer waveguides, as shown in Figure 2.2.1 (b), the overall T will become a multiplication of matrices T with different h and d in the matrix entries. However, the final characteristic equation is the same as (2.5). The only difference is the final T, which is a 2×2 matrix. The whole idea of TMM is to get the characteristic equation in 2×2 matrix operation. This simple example gives readers a basic idea of how TMM works. In general, WAVEGUIDE II uses complex representations for the matrix elements in T. For other complex cases, like TM-mode case and gain or loss consideration, readers can refer to [1] and [2] for more details.

2.2.2 Numerical Method Consideration

WAVEGUIDE II can handle complex modes in the presence of loss and gain in different layers. Therefore, the boundary condition is different for complex modes. The field solutions are restricted to the solution in the semi-infinite layers. The choice of branch specification for transverse constant in the inner layer does not affect the complex root search because of no singularity in the finite plane. On the other hand, the principle branch specification for transverse propagation constants in the outer layers is important in WAVEGUIDE II for Eigen mode problem.

The mode characteristics in the semi-infinite layers determine whether it is a proper or an improper mode. The mode characteristics, the phase propagation and exponential behavior can be determined from transverse propagation constant plane. For bounded modes, the Eigen value problem is well defined and all the roots are physically acceptable. When searching the complex root for a complex mode, the branch specification is helpful to lead the problem to a well-defined and single-valued characteristic function. For complex mode search, WAVEGUIDE II use an arbitrary branch cut in the square of modal propagation constant plane instead of real axis line for proper mode search. In this way, the bound and leaky mode can appear on the same branch.

The Muller-Traub method for complex plane is used in WAVEGUIDE II to find a complex root. Readers can refer to [1] for the details. The program uses three kinds of convergence tests. If any one test is satisfied, the last iteration is accepted. Users can set up the maximum iteration number. WAVEGUIDE II can generate initial guess, but this can only work well with simple structure and for lower order modes. For a large imaginary part in modal propagation constant, it is better for users to input an initial guess value.

2.3 Theory Introduction

This section gives simple introduction of the most basic theory. Far field, near field and confinement factor are briefly introduced in the section 2.3.1 and 2.3.2 respectively.

2.3.1 Far field and near field

Near field and far field are two of the important characteristics of an emitted optical field. Near field refers to the spatial amplitude or intensity distribution of the guided mode in the waveguide. The angular intensity distribution of the light emitted from the end of the waveguide far from the waveguide end face is known as the far field. Detailed discussion about near fields and far fields can be found in textbooks [3], [4], [5].

Mathematically, the far-field pattern can be approximated by taking the Fourier transform of the near field intensity distribution. WAVEGUIDE II uses the "obliquity factor" during the calculation of far field [6]. Here, we use a 3-layer waveguide to demonstrate the calculation process. We assume the fields to be independent of y direction (lateral direction) if the width of the waveguide is large compared to the thickness of the waveguide. Then the spatial distribution of the optical field is just associated with the transverse mode $\psi(x)$ that can be solved from the wave equation and boundary condition. For TE mode, the electric field can be written in the following form:

$$E_y = F\psi(x)e^{j(\omega t-\beta z)} \tag{2.6}$$

And the modal distribution $\psi(x)$ that propagates along z direction has different form at each of the 3 layers:

$$\psi(x) = \begin{cases} Ce^{-px} & (x \geq d) \\ A\cos(qx) + B\sin(qx) & (d \geq x \geq 0) \\ De^{r(x+d)} & (x \leq d) \end{cases} \tag{2.7}$$

Where, p, q and r are wavenumbers at each layer and they satisfy the following conditions that relate with propagation constant at z direction:

$$\begin{cases} p^2 + \varepsilon_1 k_0^2 = \beta^2 \\ -q^2 + \varepsilon_2 k_0^2 = \beta^2 \\ r^2 + \varepsilon_3 k_0^2 = \beta^2 \end{cases} \tag{2.8}$$

When combining with boundary condition, (i.e. tangential fields and their derivatives are continuous at the interface) and normalizing them, we can solve out the values of p, q, r and coefficients A, B, C and D, thus $\psi(x)$ can be known.

Write $\psi(x)$ in terms of plane waves by Fourier Transform theory,

$$\overline{\psi}(s) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\psi(x)e^{jsx}dx \tag{2.9}$$

where s is the propagation constant at x direction.

The electric field is in the following form:

$$E_y(x) = \frac{1}{\sqrt{2\pi}} F \int_{-\infty}^{\infty} \overline{\psi}(s) e^{j(\omega t - sx - \beta z)} ds \tag{2.10}$$

When the light radiates from the end face of the waveguide, both reflection and transmission happen and the transmitted field is:

$$E_y(x)^{trans} = \tau F' \int_{-\infty}^{\infty} \overline{\psi}(s) e^{j(\omega t - sx - \beta z)} ds \tag{2.11}$$

Where τ is the transmission coefficient

$$\tau = \frac{2\eta_{air}}{\eta_{air} + \eta_{waveguide}} = \frac{2\beta}{(k_0{}^2 - s^2)^{1/2} + \beta} \tag{2.12}$$

Consider the coordinate system shown in Fig 2.3.1, where the electromagnetic field is radiated into the air. We have the following relationships:

$$\begin{aligned} x &= r\sin\theta \qquad & z &= r\cos\theta \\ s &= k_0 \sin\phi \qquad & ds &= k_0 \cos\phi d\phi \end{aligned} \tag{2.13}$$

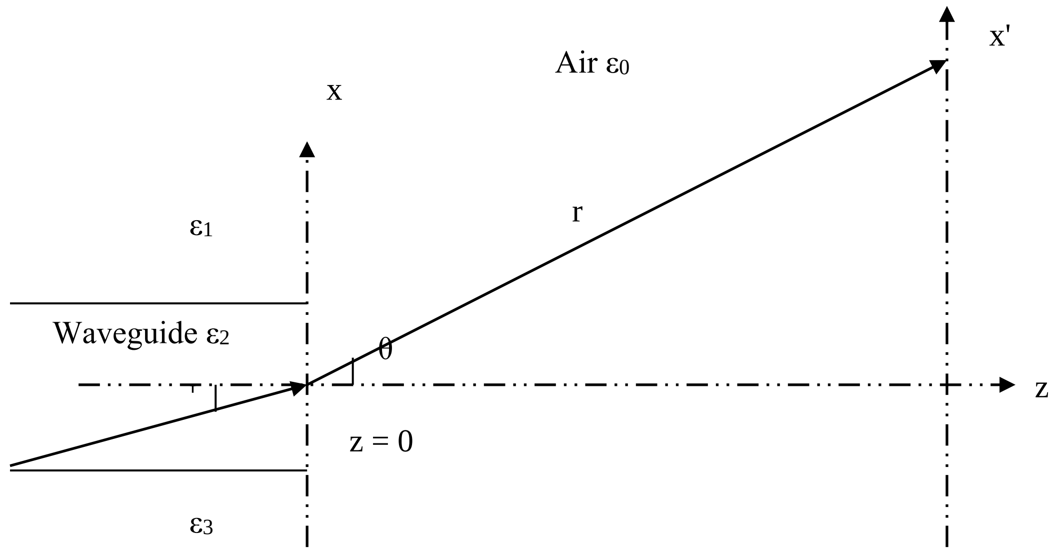


Figure 2.3.1 Schematic coordinate system of the far field of 3-layer waveguide

Then the total field intensity at (r,θ) changes to: (ignore the time term $e^{j\omega t}$)

$$E(r,\theta)=F'\int_{-\infty}^{\infty}\frac{2\beta}{k_0\cos\phi+\beta}\overline{\psi}(k_0\sin\phi)e^{-jk_0r\cos(\theta-\phi)}k_0\cos\phi d\phi \tag{2.14}$$

And then the "saddle point method"[7] is used to approximate the value of $E(r,\theta)$ for large distance. The "saddle point method" is shown below:

$$\int_{-\infty}^{\infty}g(x)e^{kh(x)}dx\approx g(a)e^{kh(a)}\sqrt{\frac{-2\pi}{kh''(a)}} \tag{2.15}$$

where a is from, in our case:

$$h'(x)=0\ ,$$

$$\sin(\theta-\varphi)=0\Rightarrow\theta=\varphi\ \text{ and }\sqrt{\frac{-2\pi}{kh''(a)}}=\sqrt{\frac{-2\pi}{-jk_0r(-\cos(\theta-\varphi))}}=\sqrt{\frac{2\pi}{k_0r}} \tag{2.16}$$

Therefore the calculation equation for far field distribution is:

$$E(r,\theta) = F'\sqrt{\frac{2\pi}{k_0 r}}\,\frac{2\beta}{k_0\cos\theta+\beta}\,k_0\cos\theta\,\overline{\psi}(k_0\sin\theta)e^{-jk_0 r} \tag{2.17}$$

and the intensity of the far field is

$$I(\theta) = \left|E(r,\theta)\right|^2 = I_0\,\frac{\cos^2\theta}{\left|k_0\cos\theta+\beta\right|^2}\left|\overline{\psi}(k_0\sin\theta)\right|^2 \tag{2.18}$$

We call $\cos\theta$ the "Huygens obliquity factor" and $\cos^2\theta$ the "intensity obliquity factor".

In WAVEGUIDE II, a coefficient *g(θ)* [6] is used to combine all Huygens obliquity factor terms and the effective index of refraction calculated from previous steps contributes here to find the value of *g(θ)*.

$$g(\theta) = 2\cos\theta\,\frac{\beta/k_0 + \sqrt{{n_{eff}}^2-\sin^2\theta}}{\cos\theta+\sqrt{{n_{eff}}^2-\sin^2\theta}} \tag{2.19}$$

Then the far field intensity in WAVEGUIDE II is calculated as following:

$$I(\theta) = I_0\left|\overline{\psi}(k_0\sin\theta)\right|^2 \mathrm{g}(\theta)^2 \tag{2.20}$$

In addition, WAVEGUIDE II normalized the entire far field so that the maximum value is 1 for $\theta = 0°$.

2.3.2 Normalizations, Confinement Factor Calculations, and Overlap Integral Calculations in WAVEGUIDE II

2.3.2.1 Normalizations

The transverse fields (F_x and F_y) are normalized to contain unity power so that the modes form an othornormal basis set [1]. The normalization constant A, which in the most general case is real, is

$$A = \sqrt{\int_{-\infty}^{\infty} \mathrm{Re}(P_z^{'})dx}$$

The normalized fields are

$$F_x = F_x^{'} / A$$
$$F_y = F_y^{'} / A$$
$$F_z = F_z^{'} / A$$

where $F_x^{'}$, $F_y^{'}$, and $F_z^{'}$ are the fields calculated by WAVEGUIDE II before normalization.

The normalized Poynting vectors P_z and P_x are given by:

$$P_z = P_z^{'} / A^2$$
$$P_x = P_x^{'} / B^2$$
$$\text{where } B^2 = \int_{-\infty}^{\infty} \mathrm{Re}(P_x^{'})dx$$

where $P_z^{'}$ and $P_x^{'}$ are the Poynting vectors calculated by WAVEGUIDE II before normalization.

Note that in a simple three-layer waveguide with real indices of refraction and with the middle layer having the highest index of refraction, all of the bound modes have purely real or purely imaginary fields. In such cases, the total integrated power (P_x) in the x direction is zero and P_z is real and the normalization procedure described above is exact. However, if the layers have complex indices of refraction, F_x, F_y, F_z, P_z and P_x are complex. Further, if the superstrate and/or substrate (which correspond to the first or last layer) has a real part of the refractive index that is equal to or greater than the value of the real part of the effective refractive index of the mode, energy can be radiated in the x-direction and P_x will be nonzero [2].

For most cases, P_x will be $<<$ P_z. In such cases, the field normalization discussed above gives accurate results for calculating confinement factors.

2.3.2.2 Confinement Factor

Often the fraction of the mode power in specific layers is of interest. For example, the fraction of power in the cladding layers or the fraction of power in the quantum wells of a semiconductor laser structure is often calculated. Such power fractions are called confinement factors and are given by

$$\Gamma_i = \frac{\int_{w_1}^{w_2} \mathrm{Re}(P_z)\,dx}{\int_{-\infty}^{\infty} \mathrm{Re}(P_z)\,dx}$$

Here, w_1 and w_2 are the boundaries of the layer of interest and $|w_1 - w_2|$ is the thickness of the layer.

2.3.2.3 Overlap integrals

The fraction of the field amplitude coupled between mode p of an optical waveguide butt-coupled to another optical waveguide supporting mode q is

$$AO_{pq} = \frac{\int_{-\infty}^{\infty} (F_y^p)^* \times F_y^q\,dx}{\left(\int_{-\infty}^{\infty} F_y^p (F_y^p)^*\,dx \int_{-\infty}^{\infty} F_y^q (F_y^q)^*\,dx\right)^{1/2}}$$

AO_{pq} is the normalized amplitude overlap._F_y^p is the field in the y direction of the p^{th} mode and F_y^q is the field in the y direction of the q^{th} mode.

The file variable.ovin is used for the overlap integral calculation.

The fraction of power coupled between mode p of an optical waveguide butt-coupled to another optical waveguide supporting mode q can be estimated by

$$PO_{pq} = \frac{\left| \int_{-\infty}^{\infty} (F_y^p)^* \times F_y^q dx \right|^2}{(\int_{-\infty}^{\infty} F_y^p (F_y^p)^* dx \int_{-\infty}^{\infty} F_y^q (F_y^q)^* dx)}$$

where PO_{pq} is the normalized intensity overlap and is related to AO_{pq} by

$$PO_{pq} = \left| AO_{pq} \right|^2$$

2.3 Running the program

This section gives users a brief overview of how to run WAVEGUIDE II program to obtain the useful information about waveguide structures such as the propagation constant of the fundamental mode and far-field profile. A detailed explanation of input and output parameters and files will be provided in Chapter 6 and the simulations of complicated waveguide structures will be discussed in later chapters

The first step in running WAVEGUIDE II program is to create an input file with information of the layer structures, input and output commands, looping parameters, free space wavelength, and other program variables such as maximum iteration times and tolerances. Next, the input file is evaluated and output files are generated according to the output commands specified in the input file. Third, data in the output files are analyzed by either the plot command of WAVEGUIDE II program or spreadsheet editors.

In the following subsections, the above-motioned steps of running the WAVEGUIDE II program will be demonstrated using a three-layer waveguide example in an ordered and straight-forward way.

2.4.1 Description of layer structure

As shown in Figure 2.4.1, the three-layer waveguide is a symmetric waveguide with a 2-um thick dielectric layer of refractive index 3.60 sandwiched by two dielectric layers of refractive index 3.55. The thicknesses of the two outermost layers are deemed infinity in WAVEGUIDE II program. In the example, the waveguide is assumed to be lossless for simplicity.

As discussed in the previous sections of this chapter, the WAVEGUIDE II program will solve the wave equations and match the boundary conditions, obtain the wave function of interested mode, calculate the confinement factors, near field and far field of the mode, and loop particular parameters such as layer thicknesses and wavelengths.

WAVEGUIDE II also has powerful plot features, and its user-interface allows users to easily select the x-axis variables and y-axis variables and modify graph properties such as color, line type, and graph title.

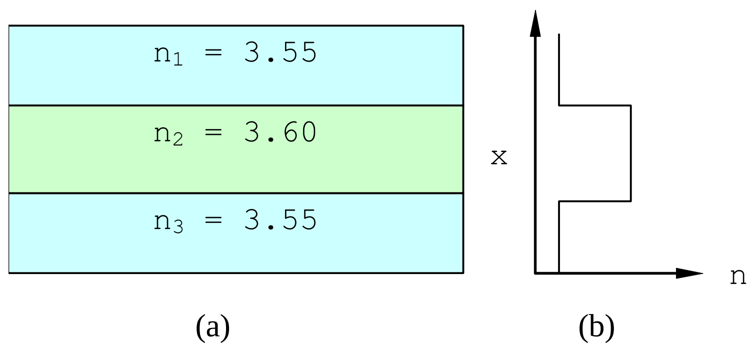


Figure 2.4.1 (a) diagram and (b) index profile of the three-layer waveguide

2.4.2 Construction of an input file

An input file contains all the information of a waveguide structure and input output commands. It can be generated in the "WAVEGUIDE II Input File Editor" (WIFE) or word editors including notepad. A new user is advised to use WIFE to create input files before getting familiar with WAVEGUIDE II commands.

After the installation of the WAVEGUIDE II program, start the program by selecting WAVEGUIDE II in the start menu. When WAVEGUIDE II is running, the main screen shown in Figure 2.4.2 pops up.

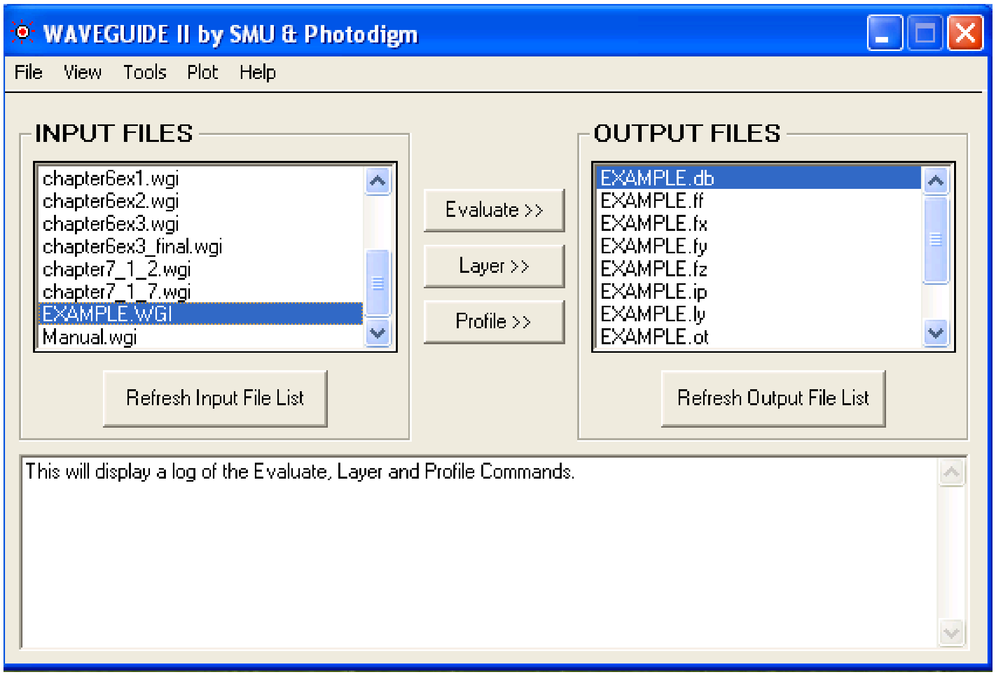


Figure 2.4.2 WAVEGUIDE II main screen

Next, activate the WIFE by selecting "Create New Input File" in the pull down menu "File". As shown in Figure 2.4.3, all the parameters and commands are divided into categories and listed in the tabs; an input file is created by completing all the tabs. Although all the options have default values, it is suggested that users review and fill all the tabs carefully according to structures to be simulated. The construction of an input file for the three-layer waveguide using WIFE is explained by completing the tabs in an order from left to right in the rest of the section.

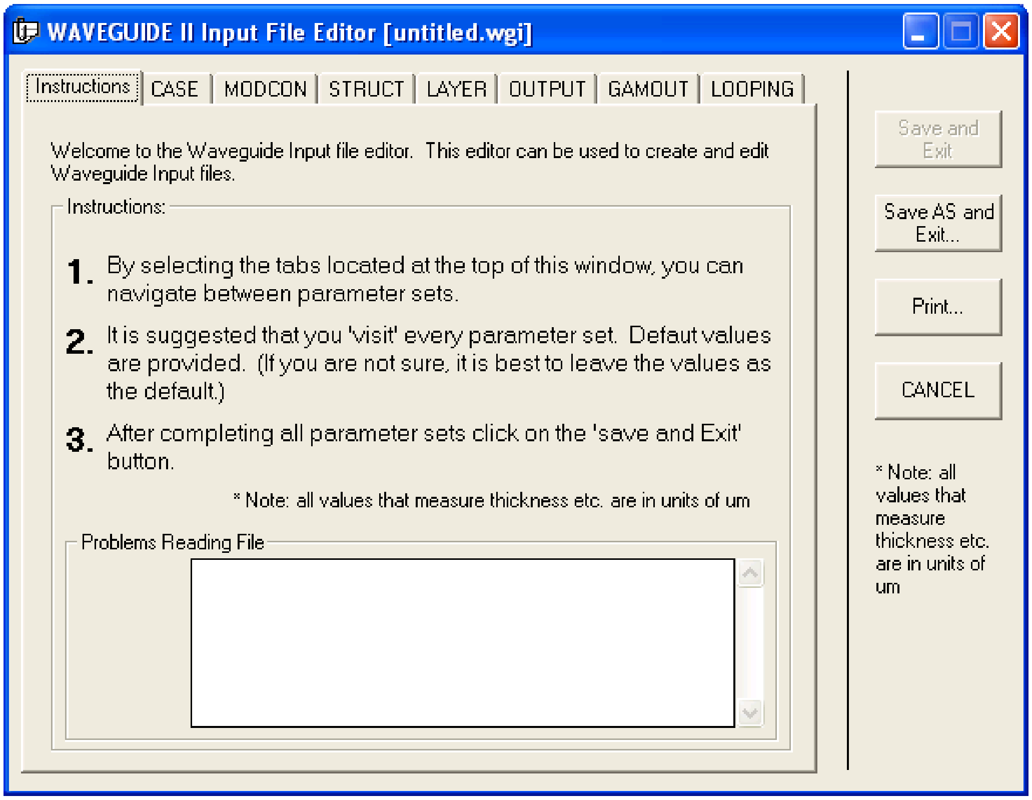


Figure 2.4.3 WAVEGUIDE II Input File Editor

2.4.2.1 Tab "Instructions" and "Case"

The first tab "Instructions" contains basic operation instructions and can be taken as a general guide. The second tab "Case" sets general program variables and flags. The detailed explanation of the program variables and flags will be discussed in Chapter 6. For the three-layer waveguide example, as illustrated in Figure 2.4.4, first click the "Case" tab and type "WAVEGUIDE II Example File" into the "Description" blank as a brief description of the purpose of the file. Then enter "12.6" in "QZMR" which is the initial guess of effective refractive indices of modes in the waveguide. As it can be seen from Figure 2.4.4, all the default values of the other program variables and flags are already filled in the blanks automatically. The default values are used in our example, so leave the blanks as they are.

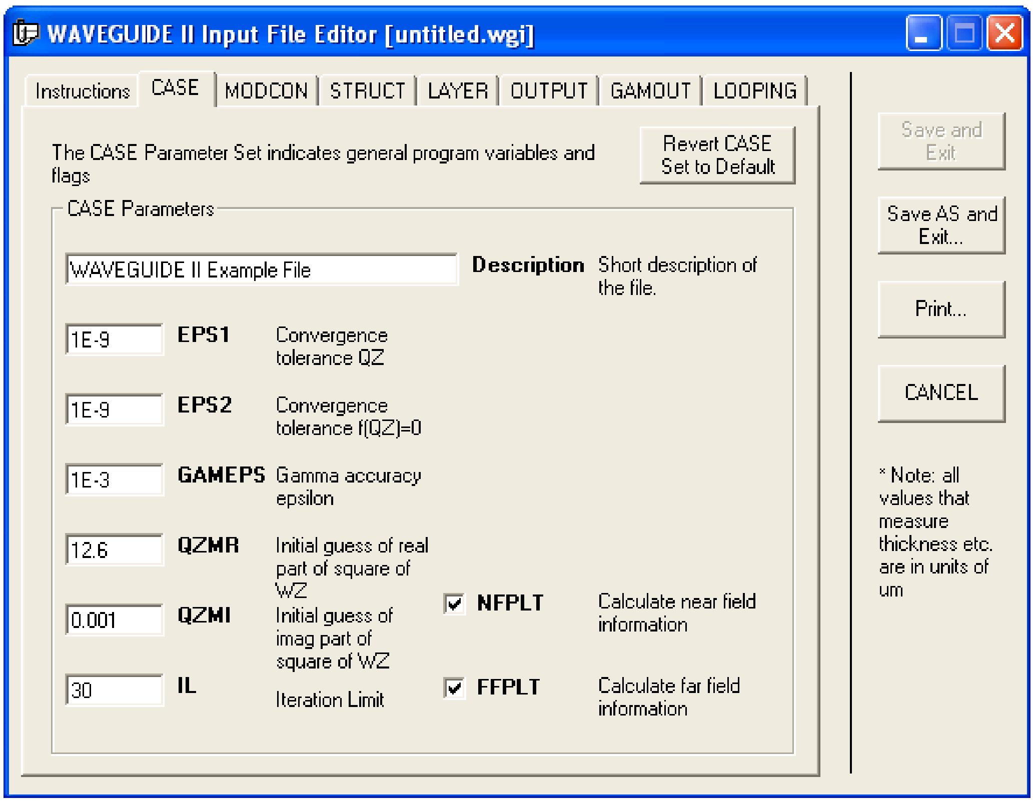
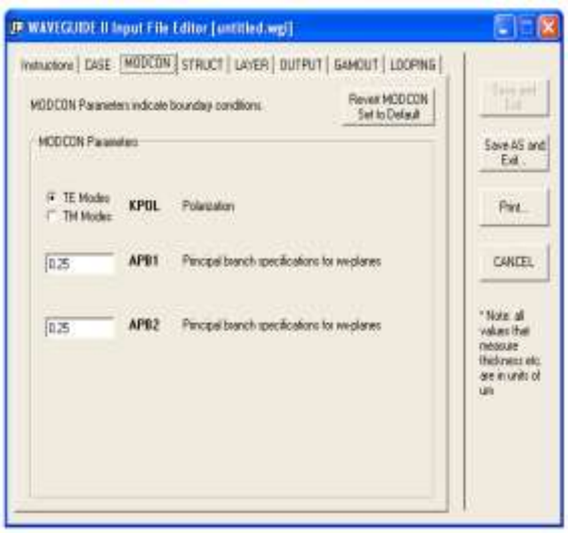


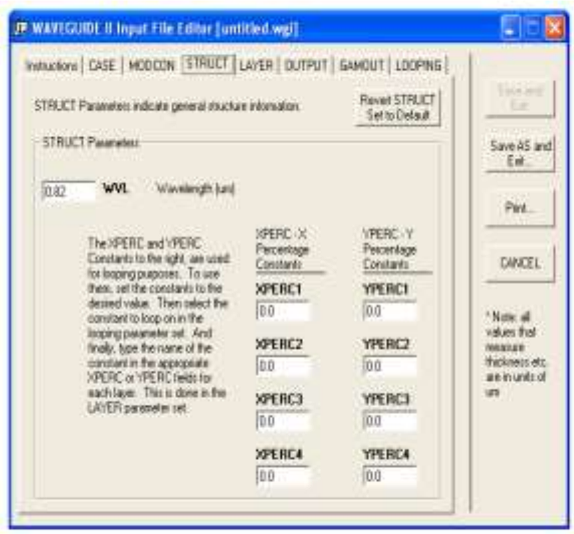
Figure 2.4.4 Illustration of tab “CASE” in WAVEGUIDE II Input File Editor

2.4.2.2 Tab "MODCON" and "STRUCT"

Next, click "MODCON" tab, review and use all the default values as revealed in Figure 2.4.5 (a). After that, click "STRUCT" tab to specify the free space wavelength of the modes in the waveguide, which is 0.82 um in our three-layer waveguide example. At the same time, as shown in Figure 2.4.5 (b), leave the default values as they are.



(a)

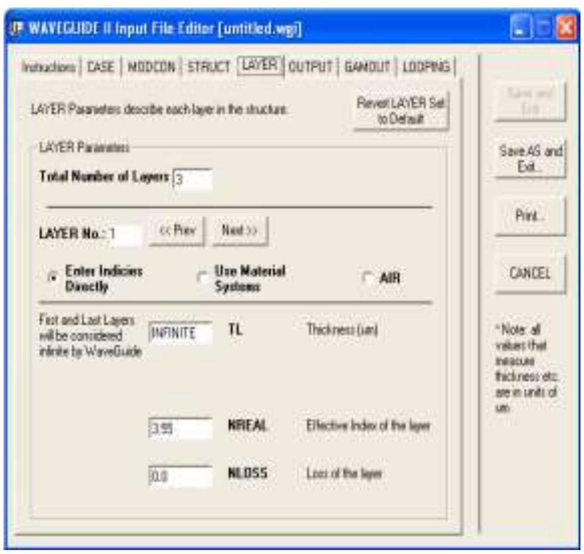


(b)

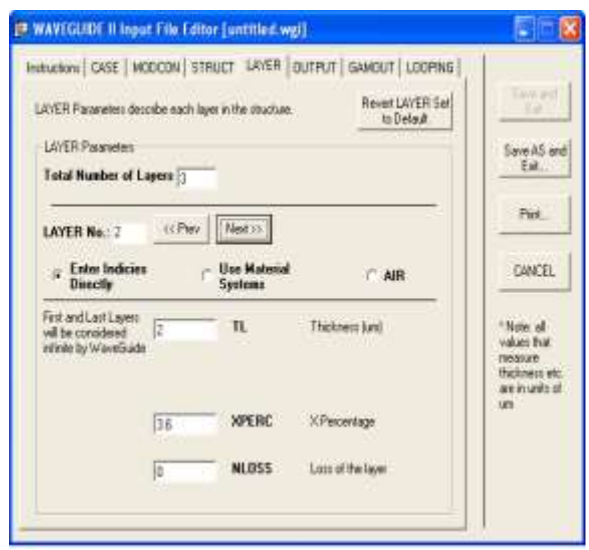
Figure 2.4.5 Tab a) "MODCON" and b)"STRUCT" in WAVEGUIDE II Input File Editor

2.4.2.3 Tab "LAYER"

Click the "LAYER" tab as displayed in Figure 2.4.6, specify the total number of layers to be 3 and input characteristic parameters of each layer. When entering the parameters of the layers, users are allowed to choose either entering the refractive indices and loss of the layers or entering material compositions of select material systems for the layers. In this example, we choose the former method. The first and third layers have refractive indices of 3.55 and infinite thickness, while the middle layer has a refractive index of 3.60 and a thickness of 2 um. You may realize that the default values have been set to the three-layer waveguide example, so just scroll down and review the choices and leave the inputs as they are.



(a)



(b)

Figure 2.4.6 Layer structure inputs for a) layer 1 and b) layer 2 in tab “LAYER”

2.4.2.4 Tab “OUTPUT” and “GAMOUT”

The next step is to select output of the WAVEGUIDE II program, and in this example, check all output as illustrated in Figure 2.4.7. Then in “GAMOUT” tab shown in Figure 2.4.8, enter “2” in the “LAYGAM” blank indicating the program will calculate and output the confinement factor of the layer 2 and leave the “COMGAM” and “GAMALL” unchecked.

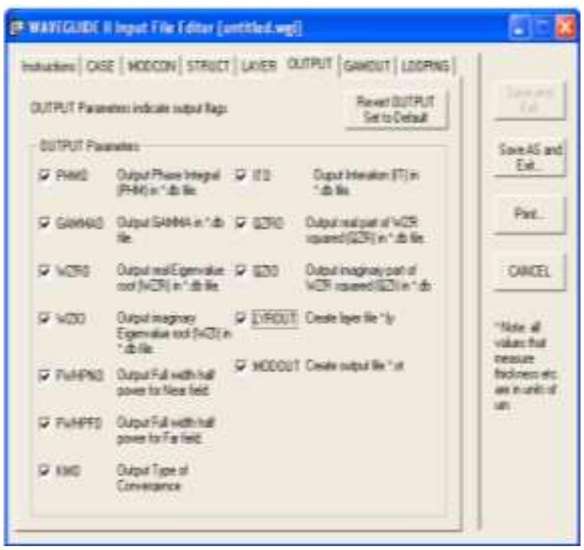


Figure 2.4.7 Tab “OUTPUT” in WIFE

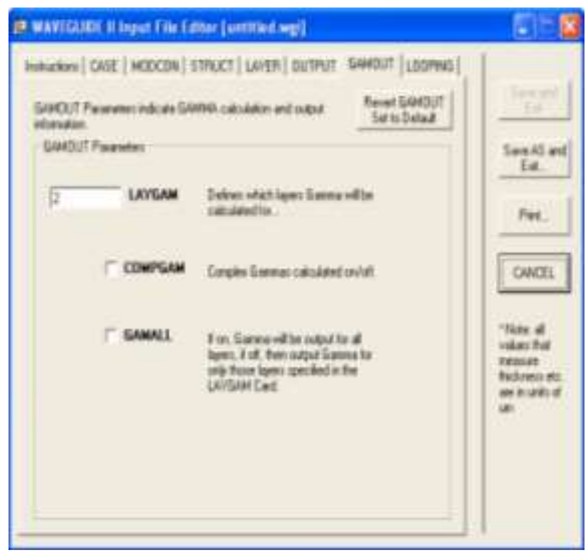


Figure 2.4.8 Tab “GAMOUT” in WIFE

2.4.2.5 Tab “LOOPING”

Finally, click the “LOOPING” tab shown in Figure 2.4.9. WAVEGUIDE II program can vary different variables of the waveguide through LOOPX and LOOPZ commands. Usually LOOPX is used to varying the layer thickness and LOOPZ is used to varying effective refractive index guess (square root of “QZMR”) and free space wavelength “WVL”. In the three-layer waveguide, we first need find the effective refractive index, so we check “LOOPZ” to loop “QZMR”.

As discussed in the previous sections in Chapter 2, the values of effective indices of modes in three-layer waveguide are between the highest and lowest refractive indices of all the layers. Therefore, enter the final value of “QZMR” to be the square of the refractive index of layer 2, which is 12.96 in this example, and then enter the increment 0.01. The initial value of “QZMR” was already set to be the square of the lowest refractive index 12.6 in tab “CASE” described in step 1). The WAVEGUIDE II program will loop the QZMR from 12.6 to 12.96 with an increment 0.01 until it finds the QZMR’s that satisfy the wave equations and boundary conditions.

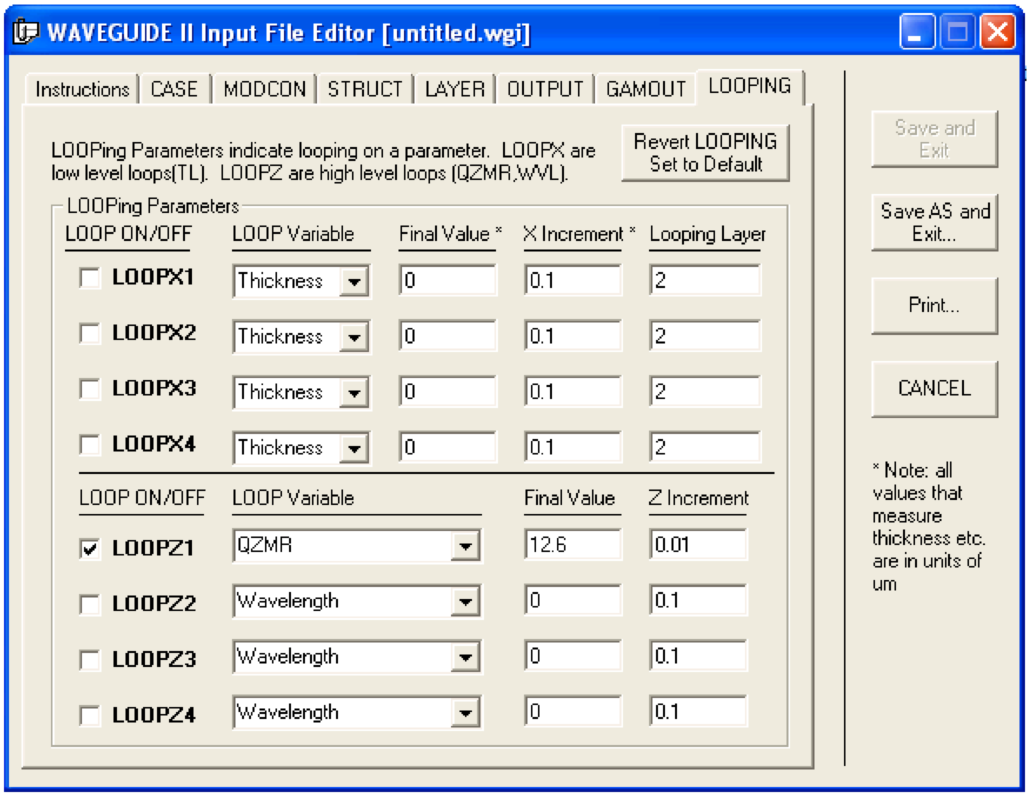


Figure 2.4.9 Tab “LOOPING” in WAVEGUIDE II Input File Editor

2.4.2.6 Save and Edit Input File

After going through all the tabs, we complete the input file by clicking the button “Save As and Exit” and saving the input file in the default directory “C:\waveguideii\work\input\” as “example.wgi”. WAVEGUIDE II can only work under this directory, so make sure the input files are saved in this directory. Table 2.4.1 shows the text form of the input file created by WIFE through step 1) to 5). Users may have noticed that in WAVEGUIDE II input file, texts starting with “!” are word description rather than commands.

Table 2.4.1 Input file of three-layer waveguide generated through WIFE.

```
!WIF generated by WIFE (Waveguide Input File Editor)
!---------------------------------------------------------------
!FILENAME:    C:\waveguideii\work\input\EXAMPLE.WGI
!DESCRIPTION: Waveguide II Example File
!Last Modified: 7/2/2009 10:42:59 PM
!---------------------------------------------------------------

!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=12.96 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=1 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=0.82
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set
LAYER NREAL=3.55 NLOSS=0.0 TL=1.0
```

```
LAYER NREAL=3.6 NLOSS=0 TL=2

LAYER NREAL=3.55 NLOSS=0 TL=1


!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set

GAMOUT LAYGAM=2 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set

LOOPX1 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX2 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2


!LOOPZ Parameter Set

LOOPZ1 ILZ='QZMR' FINV=12.6 ZINC=0.01

LOOPZ2 ILZ=0 FINV=0 ZINC=0.1

LOOPZ3 ILZ=0 FINV=0 ZINC=0.1

LOOPZ4 ILZ=0 FINV=0 ZINC=0.1


END
```

2.4.3 Description of output parameters and output files

An input file can be evaluated by first selecting the input file, “example.wgi” in our example, and click the button “Evaluate >>”. In our example, an error message window pops up as shown in Figure 2.4.10 when evaluating “example.wgi”, indicating that some guess values of QZMR didn’t converge within 30 iterations. But by checking the output file “example.db”, users can find that not all guess values didn’t converge. Usually in spite of the warning message, roots are still able to be found in the output file.

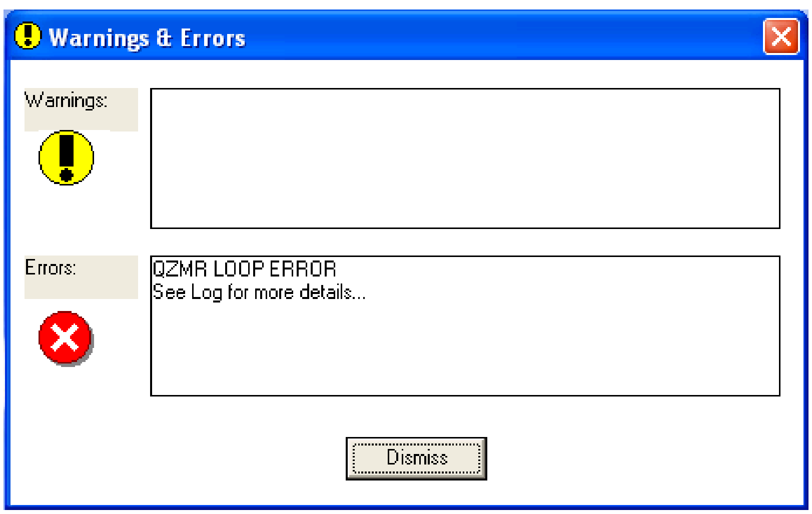


Figure 2.4.10 Error message box appears in evaluation of input file “example.wgi”

2.4.3.1 Effective refractive index of the fundamental mode

As displayed in Figure 2.4.11, after evaluation of the input file, all the output files are listed in the right window of WAVEGUIDE II main screen with the same file name but different extensions such as “example.db” and “example.ff”. The detailed explanation of the output files are offered in Chapter 6, and in this section, a brief overview of the output files will be introduced.

In order to find QZMR of fundamental mode, open the “example.db” by right clicking and selecting “View SELECTED file”. The file “example.db” is opened in Notepad as listed in Table 2.4.2, containing columns of data. The detailed explanation of the parameters in “example.db” will be provided in Chapter 6. In this section, general definitions and criteria to find fundamental mode are introduced. The key parameters to find QZMR of a fundamental mode are PHM, KM, and IT. PHM is phase integral; KM is a computation flag showing QZM quality or type; IT is iteration times. For a fundamental mode, PHM is smaller than 1; KM is 6 or 7, indicating roots of good quality; IT is smaller than 30, which was set in the “CASE” tab of WIFE as discussed before.

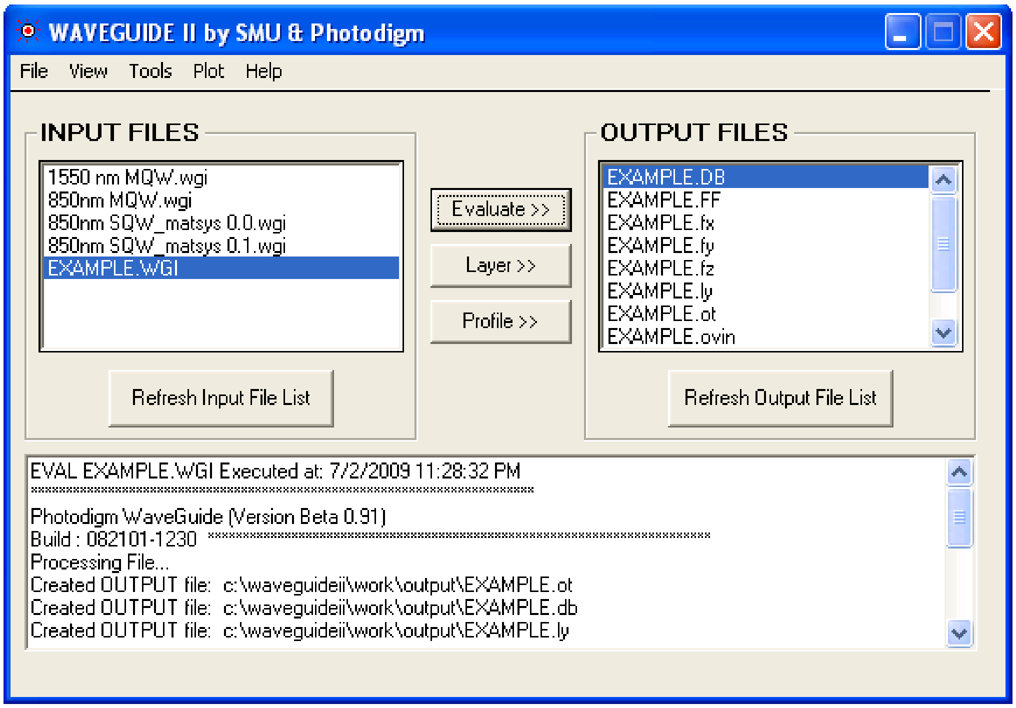


Figure 2.4.11 WAVEGUIDE II main screen showing all the output files after evaluation of the input file “example.wgi”.

Therefore, in the output file “example.db” listed in Table 2.4.2, we look for the QZMR’s that meet the criteria for a fundamental mode, which are highlighted to be bold and italic. You will notice that those QZMR’s have the same values of WZR and QZR, which are effective refractive index and the square of WZR respectively. Therefore, we found the effective refractive index of the fundamental mode in the three-layer waveguide to be 3.596.

Table 2.4.2 The output file "example.db" containing QZMR

QZMR	PHM	GAMMA(2)	WZR	WZI	QZR	QZI	FWHPN	FWHPF	KM	IT
1.260000E+01	2.870376E+00	0.000000E+00	3.551592E+00	1.201351E-03	1.261381E+01	8.533418E-03	0.000000E+00	0.000000E+00	3	30
1.261000E+01	2.914060E+00	0.000000E+00	3.550111E+00	2.056171E-03	1.260328E+01	1.459927E-02	0.000000E+00	0.000000E+00	3	30
1.262000E+01	2.916458E+00	0.000000E+00	3.550031E+00	2.205307E-03	1.260272E+01	1.565782E-02	0.000000E+00	0.000000E+00	3	30
1.263000E+01	2.917461E+00	0.000000E+00	3.550001E+00	2.378989E-03	1.260250E+01	1.689082E-02	0.000000E+00	0.000000E+00	3	30
1.264000E+01	2.916111E+00	0.000000E+00	3.550052E+00	2.568497E-03	1.260286E+01	1.823660E-02	0.000000E+00	0.000000E+00	3	30
1.265000E+01	2.388969E+00	8.149874E-01	3.566533E+00	8.531513E-17	1.272016E+01	6.085584E-16	4.317830E-01	1.687586E+01	5	5
1.266000E+01	2.388969E+00	8.149874E-01	3.566533E+00	5.155953E-18	1.272016E+01	3.677775E-17	4.317830E-01	1.687586E+01	5	5
1.267000E+01	2.388969E+00	8.149874E-01	3.566533E+00	3.047152E-19	1.272016E+01	2.173553E-18	4.317830E-01			

1.687586E+01	6	5						
	1.268000E+01	2.388969E+00	8.149874E-01	3.566533E+00	4.758875E-13	1.272016E+01	3.394537E-12	4.317830E-01
1.687586E+01	5	4						
	1.269000E+01	2.388969E+00	8.149874E-01	3.566533E+00	1.862216E-14	1.272016E+01	1.328331E-13	4.317830E-01
1.687586E+01	5	4						
	1.270000E+01	2.388969E+00	8.149874E-01	3.566533E+00	9.581314E-17	1.272016E+01	6.834414E-16	4.317830E-01
1.687586E+01	5	4						
	1.271000E+01	2.388969E+00	8.149874E-01	3.566533E+00	1.605356E-12	1.272016E+01	1.145111E-11	4.317830E-01
1.687586E+01	5	3						
	1.272000E+01	2.388969E+00	8.149874E-01	3.566533E+00	4.144338E-13	1.272016E+01	2.956183E-12	4.317830E-01
1.687586E+01	5	2						
	1.273000E+01	2.388969E+00	8.149874E-01	3.566533E+00	2.510751E-12	1.272016E+01	1.790935E-11	4.317830E-01
1.687586E+01	5	3						
	1.274000E+01	2.388969E+00	8.149874E-01	3.566533E+00	8.819416E-16	1.272016E+01	6.290947E-15	4.317830E-01
1.687586E+01	5	4						
	1.275000E+01	2.388969E+00	8.149874E-01	3.566533E+00	5.547851E-13	1.272016E+01	3.957319E-12	4.317830E-01
1.687586E+01	5	4						
	1.276000E+01	2.388969E+00	8.149874E-01	3.566533E+00	1.159238E-17	1.272016E+01	8.268922E-17	4.317830E-01
1.687586E+01	5	5						

1.277000E+01	2.388969E+00	8.149874E-01	3.566533E+00	3.427408E-15	1.272016E+01	2.444793E-14	4.317830E-01
1.687586E+01	5	5					
1.278000E+01	2.388969E+00	8.149874E-01	3.566533E+00	2.160358E-13	1.272016E+01	1.540998E-12	4.317830E-01
1.687586E+01	5	5					
1.279000E+01	***2.388969E+00***	***8.149874E-01***	***3.566533E+00***	***2.182583E-19***	***1.272016E+01***	***1.556851E-18***	***4.317830E-01***
1.687586E+01	***6***	***6***					
1.280000E+01	1.624044E+00	9.346155E-01	3.584572E+00	1.199020E-13	1.284916E+01	8.595949E-13	6.180778E-01
1.616682E+01	5	4					
1.281000E+01	1.624044E+00	9.346155E-01	3.584572E+00	1.580543E-18	1.284916E+01	1.133114E-17	6.180778E-01
1.616682E+01	5	4					
1.282000E+01	1.624044E+00	9.346155E-01	3.584572E+00	3.056372E-17	1.284916E+01	2.191157E-16	6.180778E-01
1.616682E+01	5	4					
1.283000E+01	1.624044E+00	9.346155E-01	3.584572E+00	1.411470E-17	1.284916E+01	1.011903E-16	6.180778E-01
1.616682E+01	5	4					
1.284000E+01	1.624044E+00	9.346155E-01	3.584572E+00	1.095169E-12	1.284916E+01	7.851422E-12	6.180778E-01
1.616682E+01	5	3					
1.285000E+01	1.624044E+00	9.346155E-01	3.584572E+00	-4.088430E-12	1.284916E+01	-2.931055E-11	6.180778E-01
1.616682E+01	5	2					
1.286000E+01	1.624044E+00	9.346155E-01	3.584572E+00	1.760407E-18	1.284916E+01	1.262061E-17	6.180778E-01

1.616682E+01	5	4						
	1.287000E+01	1.624044E+00	9.346155E-01	3.584572E+00	2.511560E-13	1.284916E+01	1.800573E-12	6.180778E-01
1.616682E+01	5	4						
	1.288000E+01	1.624044E+00	9.346155E-01	3.584572E+00	1.930753E-16	1.284916E+01	1.384185E-15	6.180778E-01
1.616682E+01	5	5						
	1.289000E+01	1.624044E+00	9.346155E-01	3.584572E+00	7.334633E-13	1.284916E+01	5.258304E-12	6.180778E-01
1.616682E+01	5	5						
	1.290000E+01	1.624044E+00	9.346155E-01	3.584572E+00	1.825410E-16	1.284916E+01	1.308663E-15	6.180778E-01
1.616682E+01	5	6						
	1.291000E+01	***8.188365E-01***	***9.853043E-01***	***3.596084E+00***	***-2.207374E-17***	***1.293182E+01***	***-1.587581E-16***	***1.224312E+00***
2.090706E+01	***6***	***5***						
	1.292000E+01	***8.188365E-01***	***9.853043E-01***	***3.596084E+00***	***2.817344E-15***	***1.293182E+01***	***2.026281E-14***	***1.224312E+00***
2.090706E+01	***6***	***4***						
	1.293000E+01	***8.188365E-01***	***9.853043E-01***	***3.596084E+00***	***-4.097716E-16***	***1.293182E+01***	***-2.947147E-15***	***1.224312E+00***
2.090706E+01	***6***	***3***						
	1.294000E+01	***8.188365E-01***	***9.853043E-01***	***3.596084E+00***	***2.286669E-17***	***1.293182E+01***	***1.644611E-16***	***1.224312E+00***
2.090706E+01	***6***	***4***						
	1.295000E+01	***8.188365E-01***	***9.853043E-01***	***3.596084E+00***	***1.958452E-17***	***1.293182E+01***	***1.408552E-16***	***1.224312E+00***
2.090706E+01	***6***	***5***						

	1.296000E+01	*8.188365E-01*	*9.853043E-01*	*3.596084E+00*	*-9.814521E-17*	*1.293182E+01*	*-7.058769E-16*	*1.224312E+00*
2.090706E+01	*6*	*6*						

2.4.3.2 Far field, near field, and confinement factor of the fundamental mode

The far field, near field, and confinement factor of the modes allowed in waveguides can be simulated in WAVEGUIDE II program. In this section, the fundamental mode propagating in the three-layer waveguide will be simulated to demonstrate how to obtain the information using WAVEGUIDE II program.

To simulate the fundamental mode, first, we need to modify the input file "example.wgi" by WIFE or word editor. By selecting the input file "example.wgi" and right clicking on it, the pull-down menu is displayed, in which "Edit SELECTED file" is used to activate WIFE and "View SELECTED file" views the selected file in Notepad. In this example, "View SELECTED file" is clicked to illustrate how to modify an input file using word editor.

We have simulated that the effective refractive index of the fundamental mode is 3.596, and QZR, which is the square of WZR, is 12.932. So we need to first modify the input file by setting QZMR to 12.932, and then put exclamation mark "!" in front of the "LOOPZ" command which was used to find QZMR. The new input file is listed in Table 2.4.3, and the modified parts are bold and italic.

Table 2.4.3 Input file for simulation of the fundamental mode

```
!WIF generated by WIFE (Waveguide Input File Editor)
!-------------------------------------------------------------------
!FILENAME:    C:\waveguideii\work\input\EXAMPLE.WGI
!DESCRIPTION: Waveguide II Example File
!Last Modified: 7/2/2009 10:42:59 PM
!-------------------------------------------------------------------

!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=12.932 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=1 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=0.82
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set
LAYER NREAL=3.55 NLOSS=0.0 TL=1.0
LAYER NREAL=3.6 NLOSS=0 TL=2
LAYER NREAL=3.55 NLOSS=0 TL=1
```

```
!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1
OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1

!GAMOUT Parameter Set
GAMOUT LAYGAM=2 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
LOOPX1 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX2 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2

!LOOPZ Parameter Set
!LOOPZ1 ILZ='QZMR' FINV=12.96 ZINC=0.01
LOOPZ2 ILZ=0 FINV=0 ZINC=0.1
LOOPZ3 ILZ=0 FINV=0 ZINC=0.1
LOOPZ4 ILZ=0 FINV=0 ZINC=0.1

END
```

The next step is to select the input file and click the “Evaluate” button to evaluate it. Among the output files, “example.db” contains simulation results as shown in Table 2.4.4. GAMMA (2) in the output file is the confinement factor of the layer 2 of the waveguide, 0.9853; WZR is the real part of the effective refractive index of the mode; WZI is the imaginary of the effective refractive index of the mode; QZR is the square of WZR; QZI is the square of WZI; FWHPN is the near field divergence full width half power, 1.22˚; FWHPF is far field divergence full width half power, 20.91˚.

Table 2.4.4 Output file “example.db”

PHM	GAMMA(2)	WZR	WZI	QZR	QZI	FWHPN	FWHPF	KM	IT
8.188365E-01	9.853043E-01	3.596084E+00	-2.244844E-20	1.293182E+01	-1.614529E-19	1.224312E+00	2.090706E+01	7	3

The far field and near field information is contained in output files “example.ff” and “example.pz” respectively. To plot the far field intensity, click “Plot” of the pull-down menu and select “Plot Far Field (*.ff)”, and then in the window that pops up, check “FFIELD” and click “Plot” as illustrated in Figure 2.4.12. Figure 2.4.13 shows the far field intensity graph. Similarly, the near field intensity is plotting by clicking “Plot PZ Field (*.pz)” in the pull-down menu, which is shown in Figure 2.4.14. The graph properties such as chart types and color can be modified in the plot window.

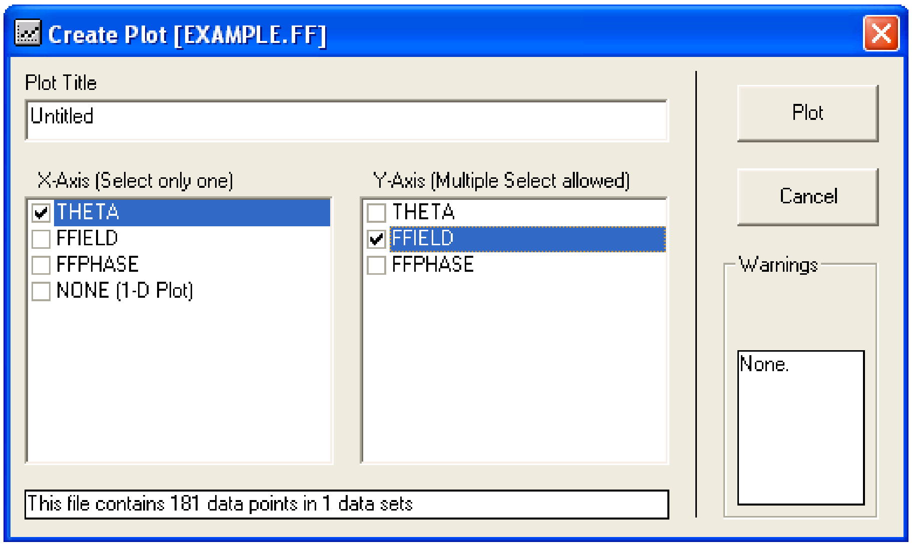
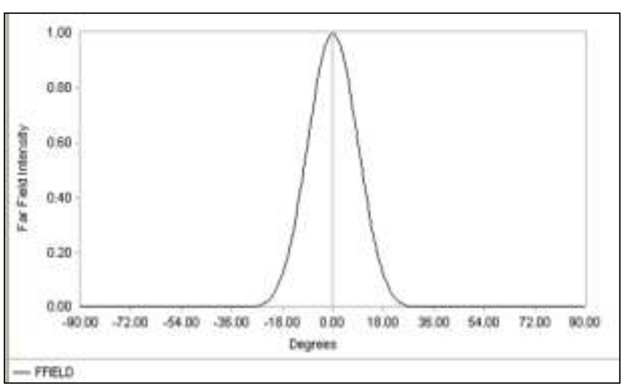


Figure 2.4.12 Plot window allows users to choose X and Y-Axis data.



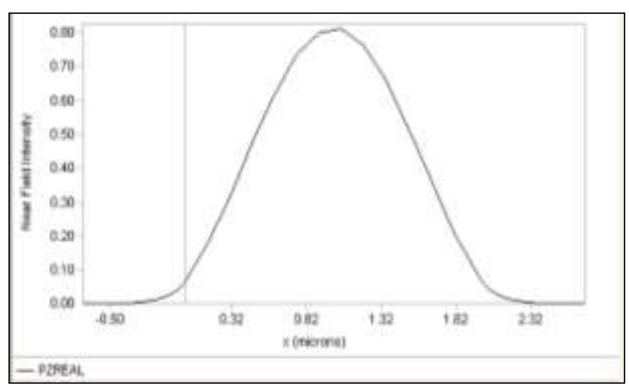


Figure 2.4.13 Far field intensity plot

Figure 2.4.14 Near field intensity plot

In summary, a three-layer waveguide example is used to demonstrate how to use WAVEGUIDE II program for simulations of waveguide structures. A brief introduction of input file is provided and discussed in this section. Output files are explained or/and plotted including Effective refractive indices of modes, confinement factors of the layers, far field, and near field. The detailed explanation of the input and output files are provided in Chapter 6, and the simulations of complicated waveguide structures are discussed in later chapters.

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Chapter 3

MATSYS AND WAVEGUIDE II INPUT/OUTPUT PARAMETERS

3.1 Introduction

This chapter serves as a reference to the program parameters available in WAVEGUIDE II. These parameters include a material system feature called MATSYS and program input and output variables. Examples of using MATSYS and changing the program input and output variables are shown in the other chapters of this user guide.

3.2 Material System MATSYS

Typical III-V structures can be entered in WAVEGUIDE II layer by layer using menu selections: File, Create new input file, and LAYER tab. After filling in the total number of layers, enter the layer number being defined in the box marked LAYER.

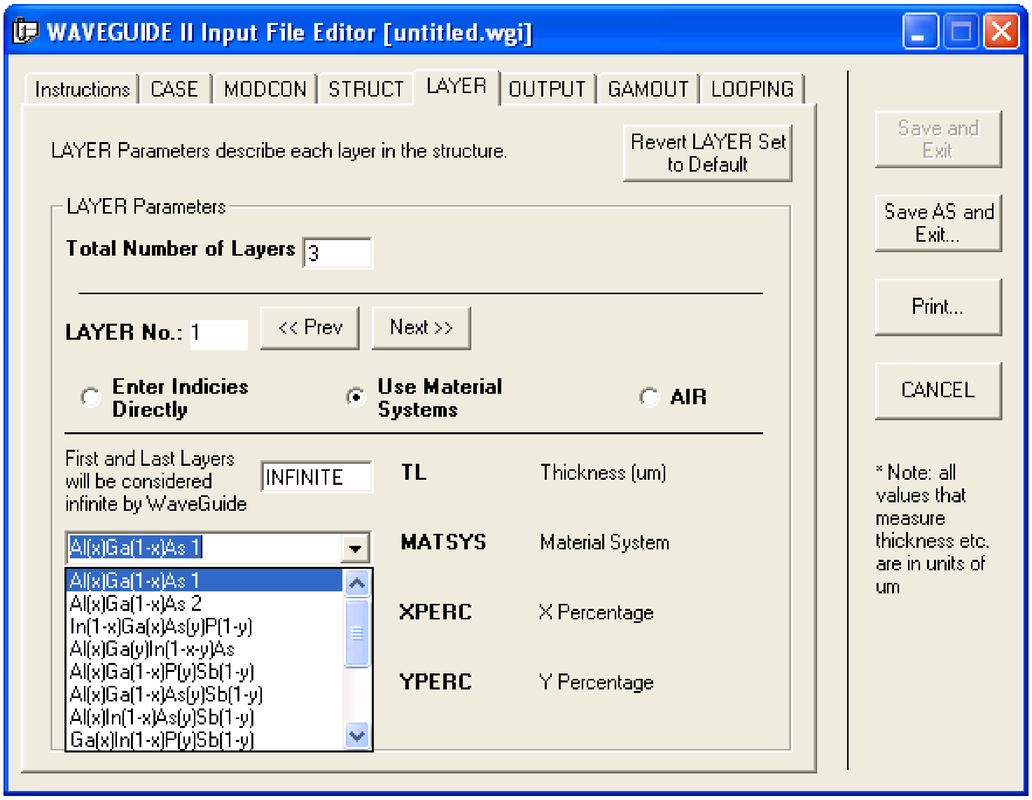

Figure 3.2.1 This is the layer input screen

There are two ways to input the refractive index. You can enter the refractive index directly by selecting the “Indices” button or you can have the MATSYS feature calculate the refractive index by selecting the “Material” button. In both cases, the refractive index value is assigned to the input parameter NREAL corresponding to that layer.

If you use the MATSYS feature, you will see a drop down list of available material compositions to choose from (Figure 3.2.1). Once a specific composition is selected, parameters XPERC and YPERC become available to enter the percent of the element with index "x" and the percent of element with index "y." For example, in Figure 3.2.2 we have selected the second layer composition to be Al(x)Ga(1-x)As. The percent of Al in this layer is 35%. (The software automatically calculates the percent of Ga as 65%.) You can enter 0 for YPERC since this composition does not have this variable. If you want to enter GaAs with 0% Al, you can enter 0 for XPERC.

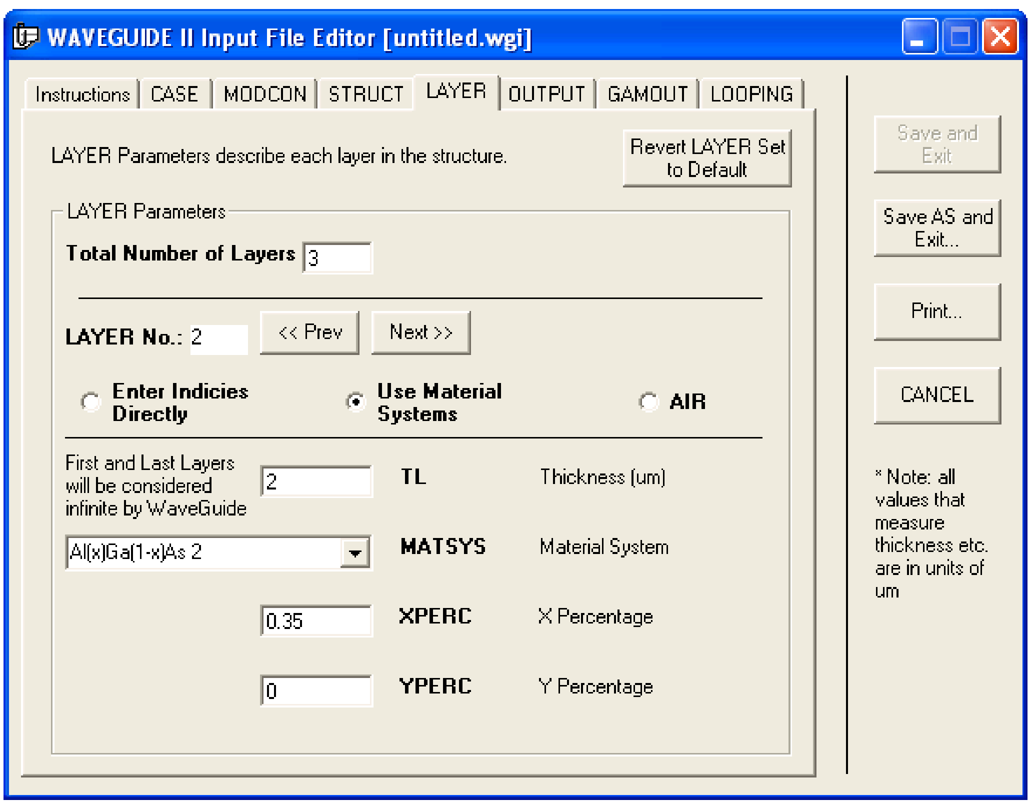

Figure 3.2.2 Layer 2 composition is entered with 35% Al

The LAYER portion of the input file corresponding to 3 layers (GaAs, Al(0.35)GaAs, GaAs) entered using MATSYS are listed below. The middle layer shows XPERC is set to 35%. The parameter MATSYS corresponds to a code assigned to the Al(x)Ga(1-x)As2 material composition we selected.

```
!LAYER Parameter Set
LAYER MATSYS=0.1 XPERC=0 YPERC=0.0 TL=1.0
LAYER MATSYS=0.1 XPERC=0.35 YPERC=0 TL=2
LAYER MATSYS=0.1 XPERC=0 YPERC=0 TL=1.0
```

The layer output file shows the program's calculated refractive indices (NREAL) based on the input layers:

```
# of layers =        3
LAYER01  NLOSS= 0.00000    NREAL= 3.52903    TL=   1.00000
LAYER02  NLOSS= 0.00000    NREAL= 3.32472    TL=   2.00000
LAYER03  NLOSS= 0.00000    NREAL= 3.52903    TL=   1.00000
```

Note that the structure's wavelength must be entered prior to running the program in order for MATSYS to properly calculate the refractive indices. You can enter the structure wavelength on the STRUCT tab (Figure 3.2.3) or you can modify the input file parameter WVL directly in the input file. For example, if we enter 0.98 μm for the structure wavelength the input file parameter WVL will look like this:

!STRUCT Parameter Set

STRUCT WVL=0.98

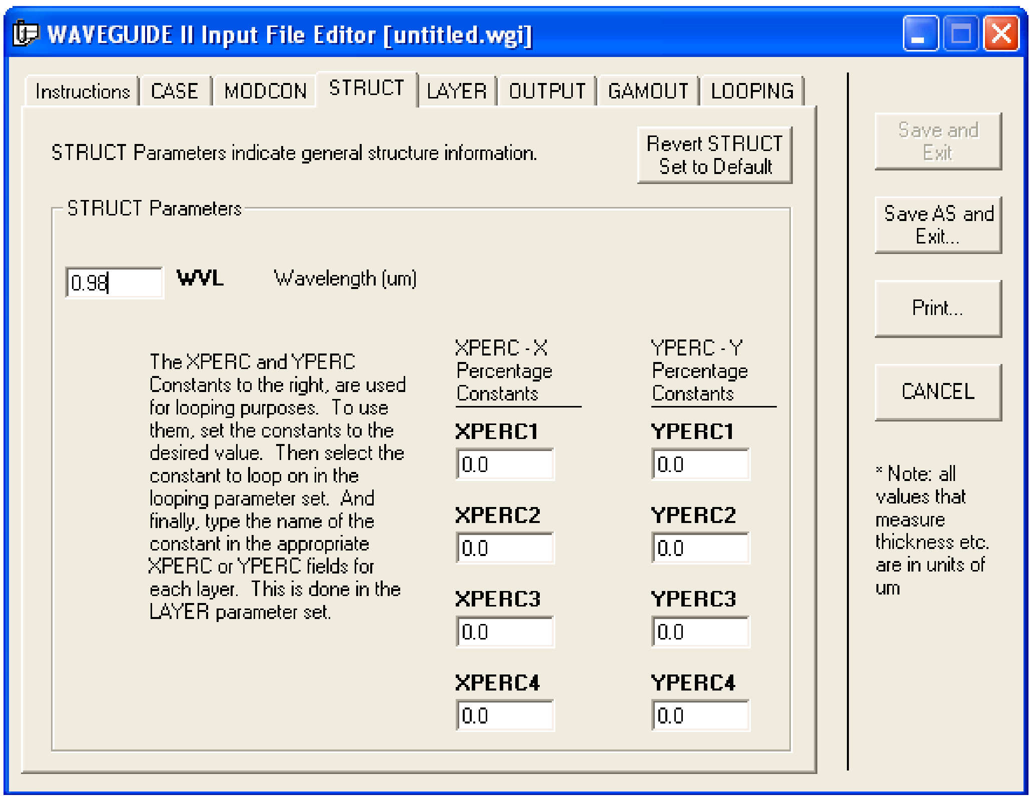

Figure 3.2.3 The wavelength of the light propagating in the structure must be entered before using MATSYS

The available compositions in MATSYS, the MATSYS code, and whether XPERC and YPERC are required are listed in Table 3.2.1. For the InGaAsP [matched to InP] composition instead of entering the composition percentages, MATSYS uses the photoluminescence (PL) to calculate the refractive index. The PL corresponds to the bandgap and assumes the material is lattice matched.

Table 3.2.1 MATSYS Compositions

Material System	**Reference**	**MATSYS Code**	**XPERC Required?**	**YPERC Required?**
Al(X)Ga(1-X)As 1	[1]	0.0	YES	Not Used
Al(X)Ga(1-X)As 2	[2]	0.1	YES	Not Used
In(1-X)Ga(X)As(Y)P(1-Y)		1.0	YES	YES
Al(X)Ga(Y)In(1-X-Y)As		2.0	YES	YES
Al(X)Ga(1-X)P(Y)Sb(1-Y)		3.0	YES	YES
Al(X)Ga(1-X)As(Y)Sb(1-Y)		4.0	YES	YES
Al(X)In(1-X)As(Y)Sb(1-Y)		5.0	YES	YES
Ga(X)In(1-X)P(Y)Sb(1-Y)		6.0	YES	YES
AlAs(X)Sb(1-X)		7.0	YES	Not Used
Al(x)Ga(1-x))0.5In(0.5)P		8.0	YES	Not Used
In(1-x)Ga(x)As [matched to InP]		9.0	YES	Not Used
In(1-x)Ga(x)As [matched to GaAs]		10.0	YES	Not Used
Ga(x)In(1-x)P [matched to GaAs]		11.0	YES	Not Used
InGaAsP [matched to InP]	[8]	12.0	Not Used – Enter PL λ	Not Used
AlGaInAs		13.0	YES	YES

MATSYS computations for each composition are based on Adachi's work and the equations are listed below. (Note: The equations are in the process of being added and some or all of the sections may not yet have the equations listed.) We have included the source code in the appendix for completeness. If you find an error, please let us know so we may update the code!

3.2.1 Al(x)Ga(1-x)As 1

3.2.1 Al(x)Ga(1-x)As 2

3.2.2 In(1-X)Ga(X)As(Y)P(1-Y)

3.2.3 Al(X)Ga(Y)In(1-X-Y)As

3.2.4 Al(X)Ga(1-X)In(Y)As(1-Y) 2

3.2.5 Al(X)Ga(1-X)P(Y)Sb(1-Y)

3.2.6 Al(X)Ga(1-X)As(Y)Sb(1-Y)

3.2.7 Al(X)In(1-X)As(Y)Sb(1-Y)

3.2.8 Ga(X)In(1-X)P(Y)Sb(1-Y)

3.2.9 AlAs(X)Sb(1-X)

3.2.10 Al(x)Ga(1-x))0.5In(0.5)P

3.2.11 In(1-x)Ga(x)As [matched to InP]

3.2.12 In(1-x)Ga(x)As [matched to GaAs]

3.2.13 Ga(x)In(1-x)P [matched to GaAs]

3.2.14 InGaAsP using PL [matched to InP]

3.2.15 InGaAsP [matched to InP]

3.3 Program Parameters

WAVEGUIDE II has input and output parameters that can be defined when creating a new file or by manually modifying the input file. The following sections provide a list of all possible parameters and their function.

3.3.1 Input Parameters

- CASE - General program variables and flags
- MODCON - Boundary conditions
- STRUCT - General structure information
- LAYER - Specific structure (layer) information
- GAMOUT - Confinement factor (Gamma) calculation/output info
- LOOPXn - Low-level looping (Nreal, Nloss, Tl) [n=loop #]
- LOOPZn - High-level looping (Wvl, Grw, Qw) [n=loop #]
- OUTPUT - Output flags

3.3.1.1 CASE Parameters

- DTHETA - Increment for the far field angle theta (1.0)
- DXIN - Dx used for fine detail in near field (0.1)
- EPS1 - Epsilon for convergence test on delta QZ root search (1E-8)

• EPS2 - Epsilon for convergence test on magnitude of eigen equation function (1E-8)

• FFPLT - Far field calculation flag (0)

• GAMEPS - Confinement factor (Gamma) accuracy epsilon (1E-3)

• IDEN - Density of points in X for field calculations per rad or 1/E (10)

• IL - Iteration limit maximum number for each root search (30)

• IMAX - Maximum number of points in each layer for field calculations (not applicable if DXIN is used) (15)

• INFX - number of rad or 1/e dist into semi-infinite layers for field calculations (3)

• INITGS - Initial guess generation routine flag (0)

• INTHM - Half maximum intensity level (0)

• KASE – WAVEGUIDE II case number (yy/mm/dd)

• KCI - Complex frequency factor for normalized KO (imag part) (0.0)

• KCR - Complex frequency factor for normalized KO (real part) (1.0)

• KDOF - Subroutine Fields flag: (1)

0 = No field calculations made

1 = Tangential fields at boundaries only calculated

2 = Fields as a function of X calculated if and only if (iff) KOUT=4

• KEIF - control type of eigen equation used for root searching:

1 = unmodified eigen equation from SM matrix

2 = eigeqf renormalized to R.M.S. magnitude of the 4 possible eigeqf

3 = Eigeqf multiplied by WT function to bias search toward intended MM.

Weight function is WFMP times squared the difference between phase integral index and intended mode index.

Warning: 2&3 are non-analytic functions and can greatly slow root search

- KFI - Explicit complex frequency factor (imaginary (imag) part)
- KFR - Explicit complex frequency factor (real part)
- KGCZ - Control use of guesses in complex root search for all QZ. Used to set

KM= KGCZ for all guesses. (KGSS >2)

=0 guesses not used, initial iterates about point (1.0, 0.0)

=1, 2, 3 initial iterates at radius of 0.1**KGCZ about each guess.

Only converged and iteration limited roots divided out.

=4, 5, 6, 7 radius of 0.1**KGCZ, all other guesses and roots divided out

Warning: Use KGCZ.ge.4 iff guesses are good approximate and distinct.

Do not use if all guesses the same (KGSS=2) or poor input guess.

If good guesses, KGCZ.ge.4 greatly speeds root search convergence.

- KGCZY - Option to control use of estimates for y-modes (3)

(similar in use to KGCZ)

- KGSS - Control type of initial guesses for QZ root search. (3)

=1 QZM (M) and KM (M) from input or previous case used for guesses, =2 all guesses the same (QR max of inner layers),

=3 individual guesses from simple quadratic approximation for real (QZ) vs. phase integral. intended mode indices MM= MO+M.

- KGSSY - Option for obtaining estimates for y-roots (see KGSS)
- KM(M) - Index showing QZM quality or type. (5)

input value used only if KGSS=1.

=0 to 7, see KGCZ

=8 QZM used as fixed known root, no search, divided out for others

(for output and previous case KM= 5,6,7, shows type of convergence).

- KMDO - Modes are output and fields calculated only for KM >KMDO (5)
- KO - Free-space propagation constant for normalization purposes.

(calculated quantity rather than input)

KO = 2PI/WVL used to normalize all propagation constants. See KC below.

Effective values of WVL and KO altered by use of non-unity KC.

- KOUE - Flag to control output from subroutine Eigeqf 1-4 (0)
- KOUF - Flag to control output from subroutine Fields 1-4 (3)
- KOUFY - Option for outputting fields as function of y (3)
- KOUI - Flag to control output from subroutine Putsin 1-4 (1)
- KOUS - Flag to control output from subroutine Search 1-4 (3)

- KOUZ - Flag to control output from subroutine Czerom 1-4 (3)
- KXTL - Control to specify that XL or TL are expected as input (0).

<= 0 if XL expected as input, TL calculated. (default)

>= 1 if TL expected as input, XL calculated. XL(1)= 0.

- LAYER - Finite layer over which numerate integral is performed (2)

in fldint (active layer). Modified 9/85.

Numerator integral is now performed for all finite layers.

Layer now just represents the active layer used in cxmode.

- LCUTOF(M)- Field cutoff criterion for left margin for mode M (-1.0e10).

fy(x) = 0 for x .lt. LCUTOF(M) or for x .get XCUTOF(M).

- MN - Number of x-modes to be searched for or calculations made (1) maximum

number of modes presently dimensioned for is 10.

- MO - Bias for mode indexing of intended modes. MM=MO+M (-1).
- NBARFF - N bar used in the far field calculations (3.45).
- NFPLT - = 1 to plot near field, = 0 otherwise. (0).
- PEROPT - Option for specifying PER(l) and PEI(l): (0)

if = 0, then PER(l) and PEI(l) are input directly

if = 1, then PER(l) and PEI(l) are computed from the input quantities NREAL(l),

NLOSS(l), and GAIN0.

- PFIELD - Field power used to normalize the field fy(x) (1.0)

- PMFR - Fractional part for phase integral (phase shift at outer body) assumed in generating guesses. Units of pi. (0.3).
- PMI(1) - Relative permeability, imaginary part, all layers (0.0).
- PMR(1) - Relative permeability, real part, all layers (1.0).
- PRINTF - Control for printing table of fields, intensities, and phases (0).
- QCNT - Mode index used for the input of multiple mode initial guesses (QZMR(QCNT)= ...) (1).
- QZMR - Input set of complex QZ values (x-modes) M= 1,MN QZMI see KGSS=1.0 used for guesses for root search, or for field calc, no search. Preset to special real values from default case solutions.

(use QCNT for multiple input)

- QZNI - Imaginary part of QZ for generation of initial guesses (-1.0e-4).
- QZNR - Real part of QZ for generation of initial guesses (0.9).
- XAXLEN - X-axis length (inches) (10.0).
- XCUTOF(M) - Field cutoff criterion for right margin for mode M (1.0e10).
- XU - Unit of length implied for all dimensions (meters) (1E-6).
- YAXLEN - Y-axis length (inches) (5.0).

3.3.1.2 MODCON Parameters

- APB1 - Principal branch specification for wx-planes.
- APB2 – Angle into WX half plane for outer layers L1 and L2+1. units of pi.

(0.25) (direction angle of branch cuts in QZ plane is twice APB.). +0.0.le.APB.le.+1.0 branch includes pos imaginary axis of wx- plane. -0.5.le.APB.le.+0.5 branch includes pos real axis of wx- plane. Default APB1=0.25, APB2=0.25, not conventional specification. Rather, imag(wx).get real(wx). bound and leaky mode roots for lossless dielectric structures are all on same principal branch. Branch cuts in QZ plane are in positive imaginary direction. (conventional choice of branches, APB=0.5, KBD=2. bound proper mode roots on principal branch and Riemann sheet of QZ. leaky improper mode roots on second branch and Riemann sheet. Branch cuts in QZ plane in negative real direction.)

- F1 - Determines how far the integration range will extend into layer 1 or layer

LN, respectively (see subroutine fldint)

- KBC1 - Control type of boundary conditions at 1-st and last body L1,L2.KBC2

open-body semi-infinite wave admit/impede, or fixed surf admit/impede, also eigen, non-eigen, conditions, and acceptable solutions.

le.0 open boundary condition, non-eigen condition, no search made. Inward and outward solution both acceptable see KBD1,KBD2 field solution exits for each of KBC1=0, or

KBC2=0, or both. If both, two independent field solutions exist. Calculation independent from two body condition same as for KBC=1, and direction implied by KBD1,KBD2.

=1 open boundary, eigen condition. only a single exponential wave solution acceptable in outer semi-infinite layer. (default).

=0,1 wave admit/impede for semi-infinite layer is function of wx(qz), always defined from wx on principal branch. see KBD1,2 and APB1,2. =2 closed body, a fixed surf admit/impede YB1,YB2. ZB1,ZB2 ignored.

=3 closed body, a fixed surf impede/admit ZB1,ZB2. YB1,YB2 ignored

=2,3 a closed bdy eigen condition. outer semi-infinite layers ignored.

- KBD1 - Controls implied direction of single solution in semi-infinite KBD2

layers inward/outward direction interpretation depends on branch def.

KBD1=1 pos. exponent (inward) complex wave solution in layer L1

KBD1=2 neg. exponent (outward) complex wave solution in layer L1

- KBD2=1 neg. exponent (inward) complex wave solution in layer L2+1

KBD2=2 pos. exponent (outward) complex wave solution in layer L2+1

Default values KBD1=2,KBD2=2. outward solution in semi-infinite layers.

Iff APB= 0.5, then imag(wx) is positive, and direction sense in/out is that of exp decay regardless of phase propagation. inward= leaky, improper or incoming lossy wave. outward= bound, proper or outgoing lossy wave. iff APB= 0.0, real(wx) is pos. and direction is that of phase propagation regardless of exp decay or growth. Direction sense also used for non-eigen case (KBC1,KBC2=0) in generating solutions based on each body condition independently. KBD. also used for direction sense for YB,ZB surf admit/impede.

- KPOL - Polarization. transverse to z-propagation, and to x-norm direct. (1)

.le.1 te, transverse electric case. fy= ey. (default)

> .ge.2 tm, transverse magnetic case. fy= hy

- L1 - First and last boundary for outer boundary conditions.
- L2 preset to L1=1, L2=LN-1 for each case.

For other values (partial structures), L1,L2 must be input for each successive case.

Note. adjacent layers (l= L1 and L2+1) are taken to be >semi-infinite for closed body condition. (KBC=2,3). all outer layers ignored.

- YB1R, YB1I - Fixed body surface admit(te)/impede(tm) looking.
- YB2R, YB2I outward at L1,L2. Used only if respective KBC1,KBC2 are equal to 2 (1.0,0.0).
- ZB1R, ZB1I - Fixed body surface impede(te)/admit(tm) looking outward ZB2R, •

  ZB2I at L1,L2. Used only respective if KBC1,KBC2 are equal to 3. (1.0,0.0).

looking outward iff KBD1,2 equal 2 (default).

3.3.1.3 STRUCT Parameters

- BW - Barrier width
- GRW - Graded layer width

3.3.1.4 LAYER Parameters

- AIR - Air layer effective index
- GRW - Graded layer width
- NLOSS – Field Amplitude Loss of the specified layer in inverse microns
- NREAL – Index of the specified layer
- NSLC - Number of slices for the graded layer

3.3.1.5 GAMOUT Parameters

- COMPGAM - Complex confinement factor (gamma) flag
- GAMALL - Gamma layers to output to output file
- LAYGAM - Gamma layers to output to .db file

The confinement factors (GAMMA) are discussed in chapter 2.

3.3.1.6 LOOPX Parameters

- FINV - Final value of the of the loop variable when looping
- ILX - Loop variable selection flag

0 or 'OFF' = no looping

1 or 'TL' = loop on thickness (TL)

2 or 'NREAL' = loop on effective index (NREAL)

3 or 'NLOSS' = loop on the loss (NLOSS)

- LAYCH - Layer number to loop on
- XINC - Loop increment value

3.3.1.7 LOOPZ Parameters

- FINV - Final value of the of the loop variable when looping
- ILZ - Loop variable selection flag

0 or 'OFF' = no looping

1 or 'WVL' = loop on wavelength (WVL)

2 or 'GRW' =loop on graded width (GRW)

3 or 'QW' = loop on quantum well width (QW)

4 or 'NQW' =loop on quantum well index(NQW)

9 or 'GRW2' = loop on graded width 2

10 or 'GRW3' = loop on graded width 3

11 or 'GRW4' = loop on graded width 4

12 or 'NSLC1' = loop on number of slices 1

13 or 'NSLC2' = loop on number of slices 2

14 or 'BW' = loop on barrier width

15 or 'NBAR' = loop on barrier index

16 or 'NUMQWS' = loop on number of quantum wells

17 or 'QZMR' = loop on initial guess (real part)

18 or 'QZMI' = loop on initial guess (imag part)

- ZINC - Loop increment value

3.3.1.8 OUTPUT Flag Parameters

- DBOUT - .db file output flag (1-enabled)
- DPRINT - .db file auto print flag (0-disabled)
- FFOUT - Far field file output flag (1-enabled)
- FPRINT - Far field file auto print flag (0-disabled)
- FWHPNO - Near field full width half power .db output flag

- FWHPFO - Far field full width half power .db output flag
- GAMMAO - Confinement factor (GAMMA) .db output flag
- LPRINT - Layer file auto print flag (0-disabled)
- MODOUT - Output file output flag (1-enabled)
- NFOUT - Near field file output flag (0-disabled)
- NPRINT - Near field file auto print flag (0-disabled)
- OPRINT - Output file auto print flag (0-disabled)
- PHMO - PHM (phase integral) .db output flag (1-enabled)
- QZIO - QZ root search (imag part) .db output flag
- QZRO - QZ root search (real part) .db output flag
- QZMIO - Initial guess (imag part) .db output flag
- QZMRO - Initial guess (real part) .db output flag
- SCROUT - Screen output flag (1-enabled)
- WZIO - WZ (imag part) .db output flag
- WZRO - WZ (real part) .db output flag

3.3.2 Output Parameters

- PHM - Phase integral
- GAMMA - Confinement factor

- WZR - Eigenvalue root (real part)
- WZI - Eigenvalue root (imaginary part)
- QZR - WZR squared
- QZI - WZI squared
- FWHPN - Near field intensity full width half power
- FWHPF - Far field intensity full width half power

3.4 Summary

Examples of using MATSYS and the various input and output parameters are shown throughout this manual. The earlier chapters of this manual are designed to step you through simple examples so you get familiar with using WAVEGUIDE II. For many cases, the input parameters can be used with their default values.

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Chapter 4

SYMMETRIC – WAVEGUIDE DIRECTIONAL COUPLER

A directional coupler is a passive device consisting of two or more close waveguides that are parallel to each other. If two waveguides are set up close to each other, the energy passing through one is coupled to the other, so we can see the energy switch back and forth from one waveguide to the other during the light propagation. The power ratio at output ports depends on the waveguides thicknesses, the distance between the two waveguides, the length of the interaction area, and the indices difference between the waveguide's core and cladding layers.

In this chapter, we would like to show readers how to simulate the directional coupler with WAVEGUIDE II. For the purpose of simplicity, we take a simple coupler with two identical waveguides as an example.

4.1 Structure of Symmetric-Waveguide Directional Coupler

The symmetric-waveguide directional coupler is shown in Figure 4.1.1. The two core layers are identical and the directional coupler is symmetric about the z-axis. Either waveguide in the directional coupler only supports one mode and for the whole coupler structure, there are two modes - TE0 mode and TE1 mode. If initially light is only in

SW_1 (see figure 4.2.1), then both TE0 and TE1 modes of the waveguide are excited. Figure 4.1.1 shows that with the wave initially set up at sub-waveguide 1 (SW_1), the energy in SW_1 will transmit to sub-waveguide 2 (SW_2) gradually along the wave propagating direction (z direction), and then switch back from SW_2 to SW_1. The distance for one complete energy transfer from one waveguide to the other is called "coupling length". The coupling length Lc can be expressed in terms of the propagation constant of TE0 mode β_0 and that of TE1 mode β_1 as

$$Lc = \pi/(\beta_1-\beta_0) \qquad (4.1)$$

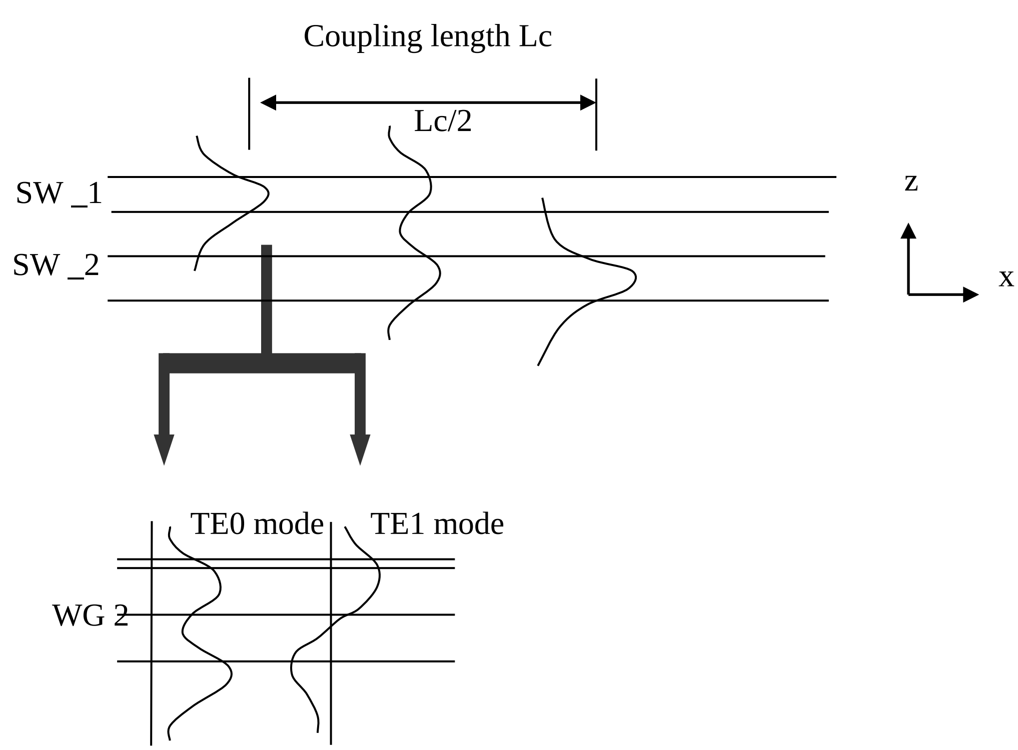
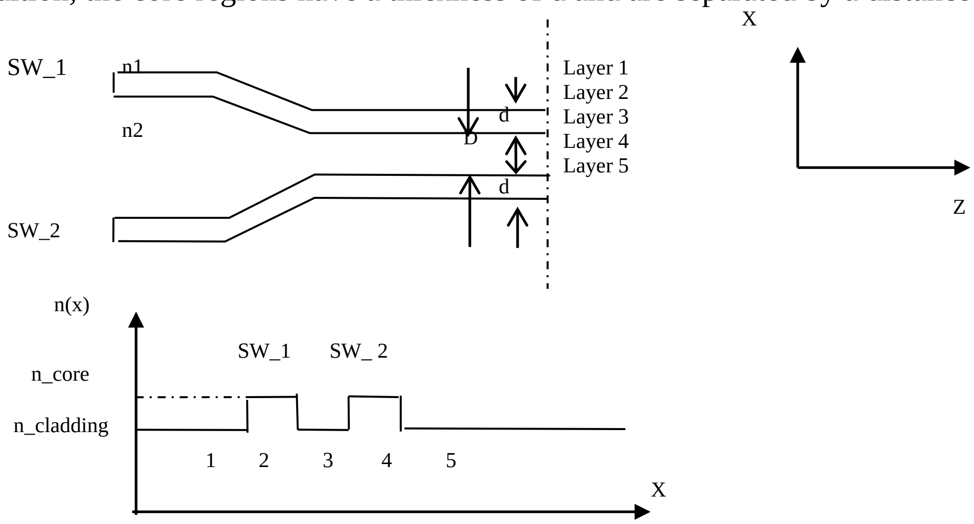


Figure 4.1.1 Structure of symmetric-waveguide directional coupler.

4.2 WAVEGUIDE II Simulation of Symmetric-Waveguide Directional Coupler Structure

A 5-layer waveguide structure can be used to simulate the two-guide directional coupler in WAVEGUIDE II. The 5-layer waveguide structure is illustrated as in Figure 4.2.1. The “directional coupler” has two “core” regions (SW_1 & SW_2) with an index of refraction of n1 and three “cladding” regions with an index of refraction of n2. In addition, the core regions have a thickness of d and are separated by a distance of D.



(a)

(b)

Figure 4.2.1 (a) 5-layer, symmetric-waveguide structure. (b) Layer index profile.

In the subsection below, we are going to show that by using the WAVEGUIDE II program and its looping feature, we are able to (1) find the specific mode of a desired directional coupler structure, and calculate the corresponding propagation constants and coupling length; (2) inspect how the field distribution varies along with the sub-waveguide thickness, sub-waveguide separation and the difference of refractive indices of the core and cladding layer; (3) inspect how the propagation constants and coupling length of the directional coupler varies along with the sub-waveguide thickness and sub-waveguide separation.

4.2.1 Mode Finding and Propagation Constant Calculation of Single Mode, Two-guide Directional Coupler

To simulate the two-guide directional coupler, we create a 5-layer waveguide structure with 1 μm of wavelength in free space. Layer parameters are listed in table 4.2.1.1. The 2nd layer and the 4th layer are two core regions of the coupler (SW_1 & SW_2) with the same refractive index of 3.55 and thickness of 0.2 μm. The 1st, 3rd and 5th layers are the "cladding" regions and have the refractive index of 3.4. The 3rd layer has thickness of 0.5 μm. The thickness of this layer determines how far two sub-waveguides are from each other. We arbitrarily choose the thickness of two outmost layers to be 0.2 μm. However, these two layers are always treated to be infinitely thick by WAVEGUIDE II. The input and output files are shown in table 4.2.1.2 and 4.2.1.3 respectively.

Table 4.2.1.1 Layer parameters of the directional coupler

LAYER01	NLOSS= 0.00000	NREAL= 3.40000	TL= 0.20000
LAYER02	NLOSS= 0.00000	NREAL= 3.55000	TL= 0.20000
LAYER03	NLOSS= 0.00000	NREAL= 3.40000	TL= 0.50000
LAYER04	NLOSS= 0.00000	NREAL= 3.55000	TL= 0.20000
LAYER05	NLOSS= 0.00000	NREAL= 3.40000	TL= 0.20000

Table 4.2.1.2 WAVEGUIDE II input file for directional coupler mode searching

```
!CASE Parameter Set
CASE KASE=Directional coupler (5 layers)
CASE    EPS1=1E-10  EPS2=1E-10  GAMEPS=1E-6
CASE    QZMR=12.60  QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1    FFPLT=1
!MODCON Parameter Set
MODCON  KPOL=1   APB1=0.25   APB2=0.25
!STRUCT Parameter Set
STRUCT  WVL=1
!LAYER Parameter Set
LAYER  NREAL=3.4   NLOSS=0.0    TL=0.2    !n-cladding
LAYER  NREAL=3.55  NLOSS=0.0    TL=0.2    !n-core      SW_1
LAYER  NREAL=3.4   NLOSS=0.00   TL=0.5    !n-cladding
LAYER  NREAL=3.55  NLOSS=0.0    TL=0.2    !n-core      SW_2
LAYER  NREAL=3.4   NLOSS=0.0    TL=0.2    !n-cladding
!OUTPUT Parameter Set
OUTPUT  PHMO=1   GAMMAO=0  WZRO=1  WZIO=0   QZRO=0    QZIO=0
OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1  ITO=1
 OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0
GAMOUT  LAYGAM=2    COMPGAM=0    GAMALL=0
!LOOPX Parameter Set
LOOPZ1 ILZ='QZMR' FINV=11.56 ZINC=-0.01
END
```

Table 4.2.1.3 QZMR looping results

QZMR	PHM	WZR	FWHPF	KM	IT
		.			
		.			
		.			
1.203000E+01	7.303264E-01	3.430612E+00	2.630991E+01	6	8
1.202000E+01	7.303264E-01	3.430612E+00	2.630991E+01	7	8
1.201000E+01	7.303264E-01	3.430612E+00	2.630991E+01	6	7
1.200000E+01	6.738678E-01	3.448619E+00	3.015387E+01	6	6
		.			
		.			
1.192000E+01	6.738678E-01	3.448619E+00	3.015387E+01	6	4
1.191000E+01	6.738678E-01	3.448619E+00	3.015387E+01	7	4
1.190000E+01	**6.738678E-01**	**3.448619E+00**	**3.015387E+01**	**6**	**3**
1.189000E+01	6.738678E-01	3.448619E+00	3.015387E+01	7	3
1.188000E+01	6.738678E-01	3.448619E+00	3.015387E+01	6	3
1.187000E+01	6.738678E-01	3.448619E+00	3.015387E+01	6	4
		.			
		.			
		.			
1.184000E+01	6.738678E-01	3.448619E+00	3.015387E+01	6	4
1.183000E+01	7.303264E-01	3.430612E+00	2.630991E+01	6	4
1.182000E+01	7.303264E-01	3.430612E+00	2.630991E+01	6	4
		.			
		.			
		.			
1.178000E+01	7.303264E-01	3.430612E+00	2.630991E+01	6	3
1.177000E+01	**7.303264E-01**	**3.430612E+00**	**2.630991E+01**	**6**	**2**
1.176000E+01	7.303264E-01	3.430612E+00	2.630991E+01	6	3
1.175000E+01	7.303264E-01	3.430612E+00	2.630991E+01	6	3
		.			

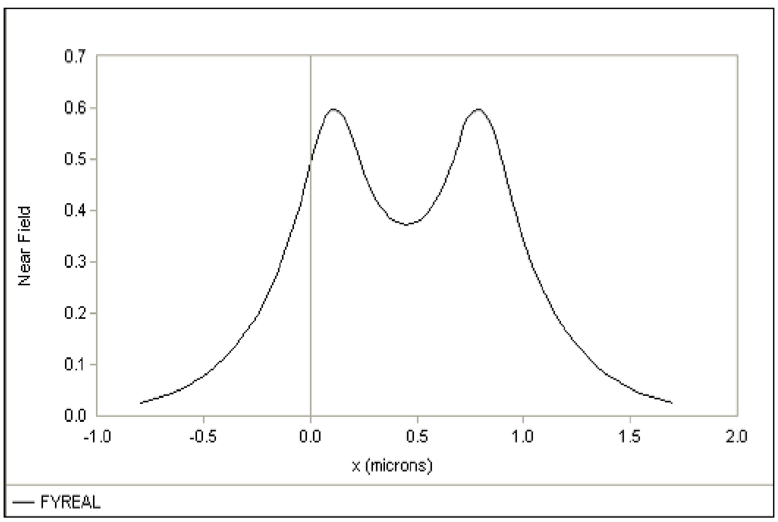
We search for TE0 mode and TE1 mode by looping for parameter QZMR. The upper bound of QZMR is usually approximated by the square of the maximum NREAL – WAVEGUIDE parameter that represents the real part of the effective index of the structure, and the lower bound of QZMR is approximated by the square of the minimum NREAL. From the layer information above, we have

QZMR_upper = (3.55)^2 = 12.60

QZMR_lower = (3.4)^2 = 11.56.

The general criteria to look for a proper QZMR value for the fundamental mode of the waveguide are: (1) PHM < 1.0, (2) KM = 6 or 7. The two-guide directional couplers support at least two modes- TE0 and TE1, and it happens when either of the two guides only support fundamental modes. So we can think of both TE0 and TE1 modes as the fundamental modes of the directional coupler. However, in WAVEGUIDE II, the TE1 mode may or may not meet the first criterion. If we look at the PHM (or WZR) values in table 4.2.1.3, we should see that some QZMR values have the exact same PHM of 7.303264E-01 (or WZR of 3.430612), and the others have the exact same PHM of 6.738678E-01(or WZR of 3.448619). This suggests that these two groups of QZMR values correspond to two different modes of the directional coupler. The TE0 mode should have smallest PHM (or largest WZR) value, and the TE1 mode corresponds to the next PHM (WZR) value. For each group, we should pick the QZMR that has the minimum iteration number (IT), which are QZMR = 11.90 for TE0 mode and QZMR =

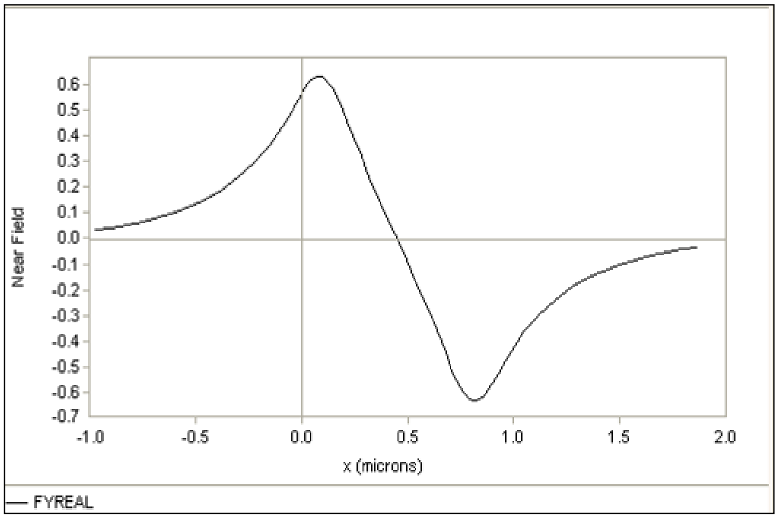
11.77 for TE1 mode in this case. Then we close the loop and do the waveguide evaluation with one QZMR value at a time. For each evaluation, we plot the near field as a function of position along x direction. It will then be very easy to recognize the TE0 mode and TE1 mode from the field profile. The near field plots and the corresponding output parameters are listed in Figure 4.2.1.1.



QZMR = 1.190000E+01
PHM = 6.738678E-01
WZR = 3.448619E+00
FWHPF = 3.015387E+01
KM = 6
IT = 3

(a)

Figure 4.2.1.1 (a) Near field of TE0 mode of the directional coupler.



QZMR = 1.177000E+01
PHM = 7.303264E-01
WZR = 3.430612E+00
FWHPF = 2.630991E+01
KM = 6
IT = 2

(b)

Figure 4.2.1.1 (b) Near field of TE1 mode of the directional coupler

In WAVEGUIDE II, the zero position of x direction, which is indicated by the vertical line in the near field plot, is set at the interface of the 1st layer and 2nd layer (see Figure 4.2.1). From Figure 4.2.1.1, we can see that the peak of the near field occurs at the center of each sub-waveguide (layer 2 & 4) in the directional coupler, and the electric field extends from the "core" layers into the "cladding" layers for both sub-waveguides. The calculation of the propagation constant and coupling length of the directional coupler is straight forward once we find the effective index of the structure for the specific mode. The formula to calculate the propagation constant is

$$\beta = k_0 * n_{eff} = (2\pi/\lambda_0) * n_{eff} \qquad (4.2)$$

where β is the real part of the propagation constant, k_0 is the wave number, λ_0 is the wavelength in free space and n_{eff} is the real part of the effective index of the mode which is equivalent to WZR. The effective indices and propagation constants for TE0 mode and TE1 mode and the coupling length of the structure are shown in table 4.2.1.4.

Table 4.2.1.4 Effective indices and propagation constants for TE0 mode and TE1 mode of the directional coupler.

	Wavelength (μm)	Effective index	Propagation constant (cm^{-1})	Coupling length (cm)
TE0 mode	1	3.448619	21.67E04	0.01
TE1 mode	1	3.430612	21.56E04	

4.2.2 Field Distribution of Single Mode, Two-guide Directional Coupler

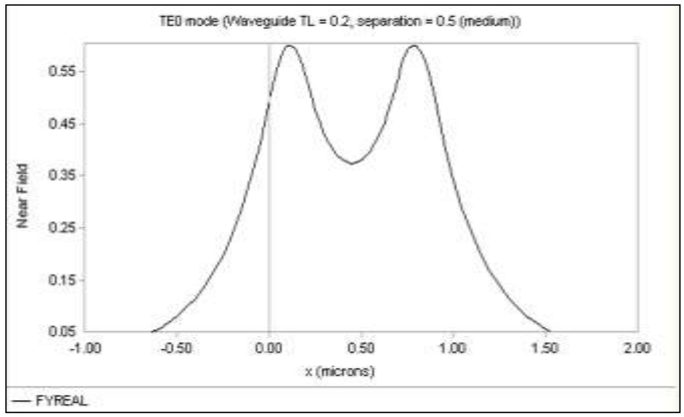
In the last section, we introduced how to find the field distribution for specific mode of fixed directional coupler structure. In this section, we want to show readers that by varying the layer parameters of the directional coupler, and comparing the near field plots of those varied structures, we can find out how the sub-waveguide thickness (d), sub-waveguides separation (D) and the difference of refractive indices of the core and cladding layer (Δn) affect the field distribution of symmetric-waveguide directional coupler.

As shown in the table 4.2.2.1, in the first group, we fix D to be 0.5 μm, Δn to be 0.15, and choose the sub-waveguide thickness d to be 0.2 μm, 0.4 μm and 0.8 μm, respectively. For each value of the sub-waveguide thickness, we loop the QZMR from its upper bound to the lower bound, and find the proper QZMR value for each mode by using the same procedure described in section 4.2.1. With the proper QZMR, the WAVEGUIDE II software can generate the near field distribution as a function of position along x direction. Similarly, in the second group, we fix d and Δn to be 0.4 μm and 0.15 respectively, we vary the sub-waveguides separation D to be 0.05 μm, 0.5 μm and 4 μm, and repeat the same steps as those described above. Finally, in the last group, we fix d and D to be 0.4 μm and 0.5 μm respectively, vary the difference of refractive indices of the core and cladding layer Δn from 0.15 to 0.05 by increasing the cladding layer index from 3.4 to 3.5 at a 0.05 space.

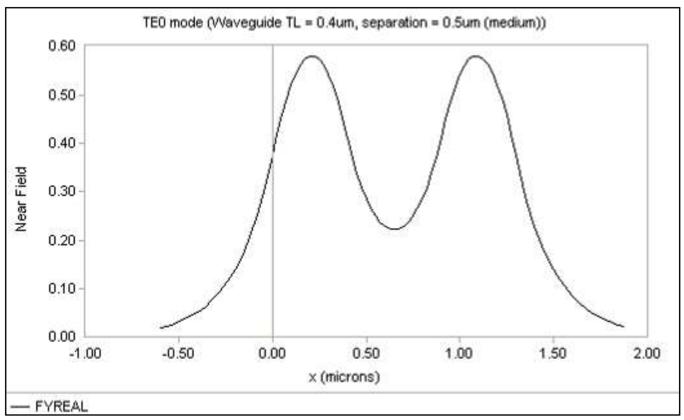
Table 4.2.2.1 Layer parameters of directional coupler structures

Directional coupler	Sub-waveguide thickness - d (μm)	Sub-waveguide separation - D (μm)	Refractive indices difference of core and cladding - Δn
Group 1	0.2	0.5	0.15
	0.4		
	0.8		
Group 2	0.4	0.05	0.15
		0.5	
		4	
Group 3	0.4	0.5	0.15
			0.10
			0.05

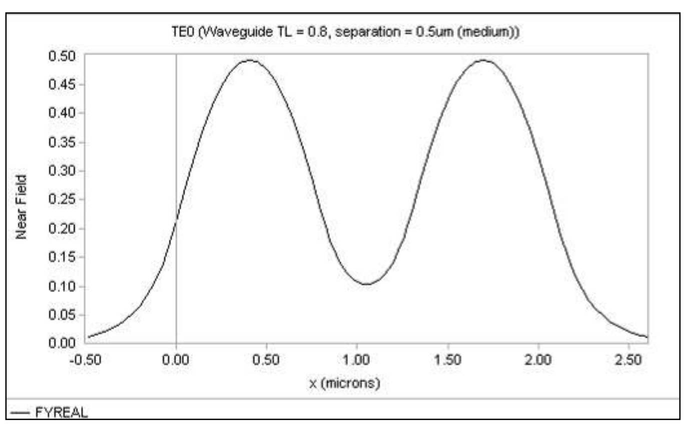
The plots of the near field amplitude for TE0 mode of directional coupler group 1 are presented in Figure 4.2.2.1 below. It is obvious that with the other layer parameters fixed, the larger the sub-waveguides thickness d is, the less the fields of two sub-waveguides overlap at the center layer and the weaker the coupling of two sub-waveguides is.


TE0 mode (Waveguide TL = 0.2, separation = 0.5 (medium))
Near Field
0.55
0.45
0.35
0.25
0.15
0.05
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
x (microns)
FYREAL

(a)


TE0 mode (Waveguide TL = 0.4um, separation = 0.5um (medium))
Near Field
0.60
0.50
0.40
0.30
0.20
0.10
0.00
-1.00
-0.50
0.00
0.50
1.00
1.50
2.00
x (microns)
FYREAL

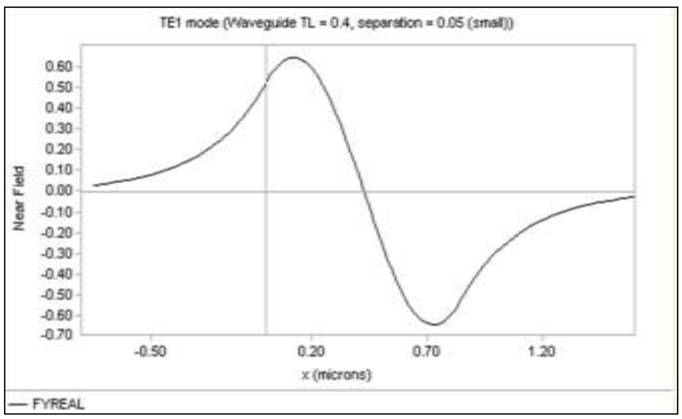
(b)


TE0 (Waveguide TL = 0.8, separation = 0.5um (medium))
Near Field
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.50
0.00
0.50
1.00
1.50
2.00
2.50
x (microns)
FYREAL

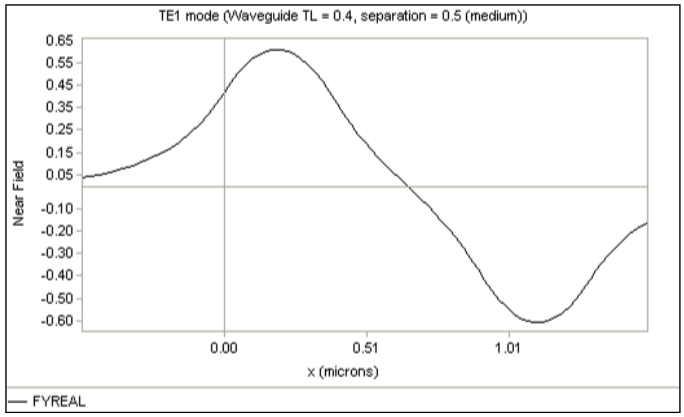
(c)

Figure 4.2.2.1 TE0 field distribution of a two-guide directional coupler for (a) sub-waveguide thickness = 0.2 µm and separation = 0.5 µm, (b) sub-waveguide thickness = 0.4 µm and separation = 0.5 µm, (c) sub-waveguide thickness = 0.8 µm and separation = 0.5 µm.

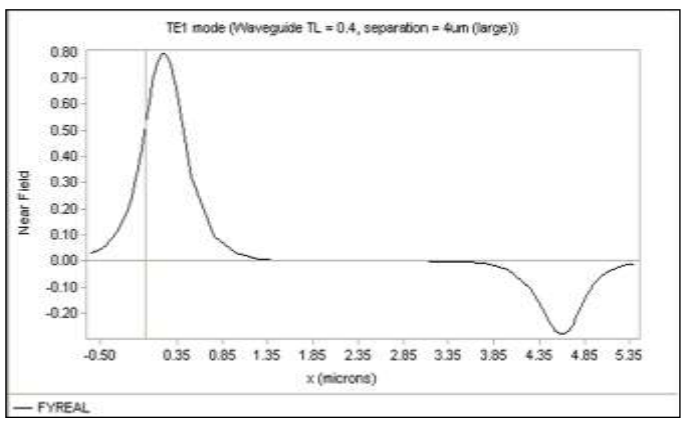
Similarly, the plots of near field for TE1 mode of directional coupler group 2, which are depicted in Figure 4.2.2.1 below, imply that the larger the separation of two sub-waveguides is, the less the electrical fields of two sub-waveguides overlap at the coupler center layer; and therefore the weaker the coupling of two sub-waveguides is.



(a)



(b)



(c)

Figure 4.2.2.2 TE1 field distribution of a two-guide directional coupler for (a) sub-waveguide thickness = 0.4 µm and separation = 0.05 µm, (b) sub-waveguide thickness = 0.4 µm and separation = 0.5 µm, (c) sub-waveguide thickness = 0.4 µm and separation = 4 µm.

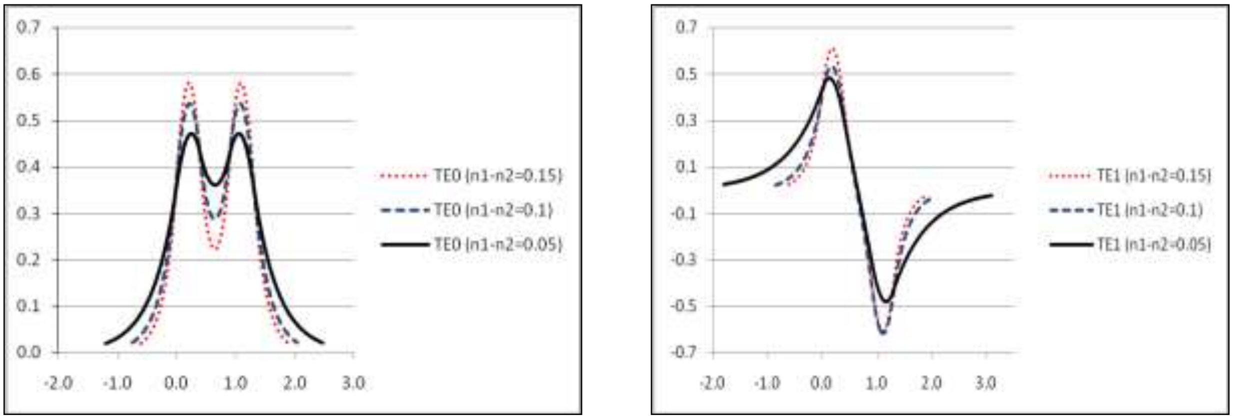


Figure 4.2.2.3 (a) TE0 field distributions of a symmetric-waveguide directional coupler with Δn =0.05, 0.1 and 0.15. (b) TE1 field distributions of a symmetric-waveguide directional coupler with Δn =0.05, 0.1 and 0.15.

Figure 4.2.2.3 plot the near fields for both TE0 mode and TE1 mode of directional coupler group 3. The figures indicate that the smaller the index difference Δn, the larger the electric fields overlap, the stronger the coupling of the two sub-waveguides is.

4.2.3 Coupling length of Symmetric-waveguide Directional Coupler

In this section, we would like to show readers how to use the looping feature of the WAVEGUIDE II program to calculate propagation constants and coupling length as a function of sub-waveguide separation for 5-layer directional coupler.

Table 4.2.3.1 Input parameters for 5-layer waveguide structures.

Directional coupler	Core index (layer 2 & 4)	Cladding index (layer 1, 3 & 5)	SW.1 & SW.2 thickness (layer 2 & 4) (μm)	Looping waveguide separation (layer 3) (μm)	
				Start value	End value
#1	3.55	3.40	0.2	0.2	3
#2	3.55	3.40	0.4	0.2	3

#3	3.55	3.40	0.8	0.2	3

As shown in table 4.2.3.1, we fix the core index of 3.55, cladding index of 3.40 and choose the sub-waveguides separation to be 0.2 μm, 0.4 μm and 0.8 μm for 5-layer directional coupler structure #1, #2 and #3 respectively. Then we evaluate each structure by looping the sub-waveguides separation from 0.2 μm to 3 μm and calculate the corresponding propagation constants and coupling length.

Using structure #1 as an example, the general steps are:

1. Loop the QZMR values, check the ".db" file and find the proper QZMR values for TE0 mode and TE1 mode by using the criteria given in 4.1.1 (See table. 4.2.3.2 and table. 4.2.3.3 for the input and output files).
2. For each mode, plug the selected QZMR into the input file and set the looping parameter –LOOPX1 to be "TL" and layer parameter – LAYCH to be "3" to represent looping for layer 3, which is the sub-waveguides separation layer in 5-layer waveguide. Evaluate the input file (see table 4.2.3.4 for the input file for TE0 mode).
3. The series values of sub-waveguides separations and corresponding refractive indices for TE0 and TE1 modes are given in "TL (3)" column and "WZR" column in the output ".db" file. Copy the two columns into the Excel, calculate

and plot the propagation constants and coupling length by using the equation 4.2 and 4.1.

Table 4.2.3.2WAVEGUIDE II input file of mode searching for directional coupler structure #1.

```
!CASE Parameter Set
CASE KASE=Directional coupler (5 layers)
CASE    EPS1=1E-6  EPS2=1E-6  GAMEPS=1E-6
CASE    QZMR=12.60  QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1

!MODCON Parameter Set
MODCON  KPOL=1   APB1=0.25   APB2=0.25

!STRUCT Parameter Set
STRUCT  WVL=1

!LAYER Parameter Set
LAYER  NREAL=3.4   NLOSS=0.0   TL=0.2    ! cladding
LAYER  NREAL=3.55  NLOSS=0.0   TL=0.4    ! core
LAYER  NREAL=3.4  NLOSS=0.0    TL=0.2    ! cladding
LAYER  NREAL=3.55  NLOSS=0.0   TL=0.4    ! core
LAYER  NREAL=3.4  NLOSS=0.0    TL=0.2    ! cladding

!OUTPUT Parameter Set
```

```
OUTPUT  PHMO=1   GAMMAO=0  WZRO=1  WZIO=0   QZRO=0    QZIO=0

OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1  ITO=1

OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0

GAMOUT  LAYGAM=2    COMPGAM=0     GAMALL=0

!LOOPZ Parameter Set

LOOPZ1 ILZ='QZMR' FINV=11.56 ZINC=-0.01


END
```

Table 4.2.3.3 QZMR looping result for directional coupler structure #1.

QZMR	PHM	WZR	FWHPF	KM	IT
		.			
		.			
		.			
1.226000E+01	9.648328E-01	3.498409E+00	3.635308E+01	6	3
1.225000E+01	9.648327E-01	3.498409E+00	3.635303E+01	6	2
1.224000E+01	**9.648328E-01**	**3.498409E+00**	**3.635311E+01**	**6**	**1**
1.223000E+01	9.648328E-01	3.498409E+00	3.635310E+01	6	2
1.222000E+01	9.648328E-01	3.498409E+00	3.635308E+01	6	3
	.				
		.			
		.			
1.207000E+01	1.205002E+00	3.469193E+00	3.161936E+01	6	3
1.206000E+01	1.205002E+00	3.469193E+00	3.161936E+01	6	3
1.205000E+01	**1.205002E+00**	**3.469193E+00**	**3.161930E+01**	**6**	**2**
1.204000E+01	1.205002E+00	3.469193E+00	3.161936E+01	6	2
1.203000E+01	1.205002E+00	3.469193E+00	3.161936E+01	6	2
1.202000E+01	1.205002E+00	3.469193E+00	3.161942E+01	6	2
1.201000E+01	1.205002E+00	3.469193E+00	3.161936E+01	6	3
		.			
		.			
		.			

Table 4.2.3.4 Input file to loop the sub-waveguide separation for directional coupler structure #1 with TE0 mode.

```
!CASE Parameter Set
CASE KASE=Directional coupler (5 layers)
CASE    EPS1=1E-6  EPS2=1E-6  GAMEPS=1E-6
CASE    QZMR= 12.24  QZMI=0.0   ! TE0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1
!MODCON Parameter Set
MODCON  KPOL=1   APB1=0.25   APB2=0.25
!STRUCT Parameter Set
STRUCT  WVL=1
!LAYER Parameter Set
LAYER  NREAL=3.4   NLOSS=0.0   TL=0.2    ! cladding
LAYER  NREAL=3.55  NLOSS=0.0   TL=0.4    ! core
LAYER  NREAL=3.4  NLOSS=0.0    TL=0.2    ! cladding
LAYER  NREAL=3.55  NLOSS=0.0   TL=0.4    ! core
LAYER  NREAL=3.4  NLOSS=0.0    TL=0.2    ! cladding
!OUTPUT Parameter Set
OUTPUT  PHMO=1   GAMMAO=0  WZRO=1  WZIO=0   QZRO=0    QZIO=0
OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1  ITO=1
OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0
GAMOUT  LAYGAM=2    COMPGAM=0    GAMALL=0
!LOOPX Parameter Set
LOOPX1 ILX='TL' FINV=3  XINC=0.05  LAYCH=3
END
```

Table 4.2.3.4 WAVEGUIDE II separation looping result for directional coupler structure #1 with TE0 mode.

TL(3)	PHM	**WZR**	FWHPF	KM	IT
2.000000E-01	9.648328E-01	**3.498409E+00**	3.635311E+01	6	1
2.500000E-01	9.904514E-01	**3.495611E+00**	3.459116E+01	6	3
3.000000E-01	1.009986E+00	**3.493427E+00**	3.289045E+01	6	3
3.500000E-01	1.025066E+00	**3.491711E+00**	3.133612E+01	6	3
.					
.					
.					
1.200000E+00	1.079220E+00	**3.485331E+00**	1.710198E+01	6	1
1.250000E+00	1.079425E+00	**3.485306E+00**	1.664205E+01	6	1
1.300000E+00	1.079586E+00	**3.485287E+00**	1.618088E+01	6	1
1.350000E+00	1.079712E+00	**3.485272E+00**	1.576260E+01	6	1
1.400000E+00	1.079812E+00	**3.485260E+00**	1.536916E+01	6	1
.					
.					
.					
2.800000E+00	1.080178E+00	**3.485215E+00**	6.235332E+00	6	1
2.850000E+00	1.080178E+00	**3.485215E+00**	6.245429E+00	6	1
2.900000E+00	1.080178E+00	**3.485215E+00**	6.261909E+00	6	1
2.950000E+00	1.080178E+00	**3.485215E+00**	6.260620E+00	6	1
3.000000E+00	1.080178E+00	**3.485215E+00**	6.237595E+00	6	1

Figure 4.2.3.1 and Figure 4.2.3.2 exhibit the propagation constant in logarithm as a function of sub-waveguides separation and the coupling length in logarithm as a function of sub-waveguides separation for the structures listed in table 4.2.3.1. It is clear that at fixed sub-waveguides thickness, for both TE0 mode and TE1 mode, when the distance between two sub-waveguides of the coupler increases, the difference of $\beta 0$ and $\beta 1$ decreases; therefore the coupling length of the directional coupler increases. These simulation results match the theoretical prediction and the conclusion drawn in section 4.2.2. When increasing the separation of two sub-waveguides, their coupling strength decreases, so the energy transmitting from one sub-waveguide to the other becomes slower; therefore we should expect that it will take a longer distance to transmit all the energy from one sub-waveguide to the other. Figure 4.2.3.1 also predicts that if the two sub-waveguides are separated far enough, they will become two independent (uncoupled) waveguides with same propagation constant.

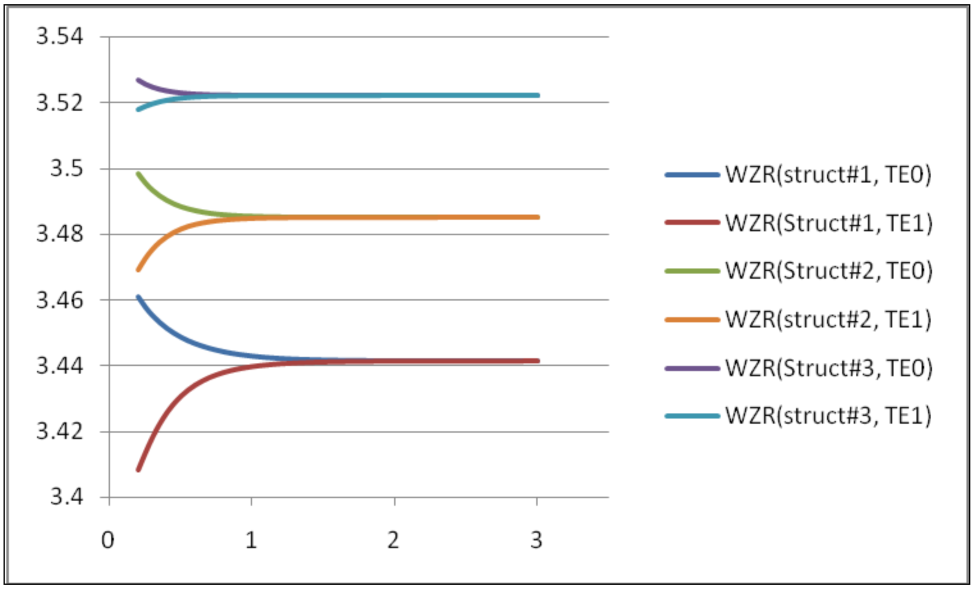


Figure. 4.2.3.1 Effective index WZR vs. separation of sub-waveguides for sub-waveguide thickness =0.2 µm, 0.4 µm and 0.8 µm.

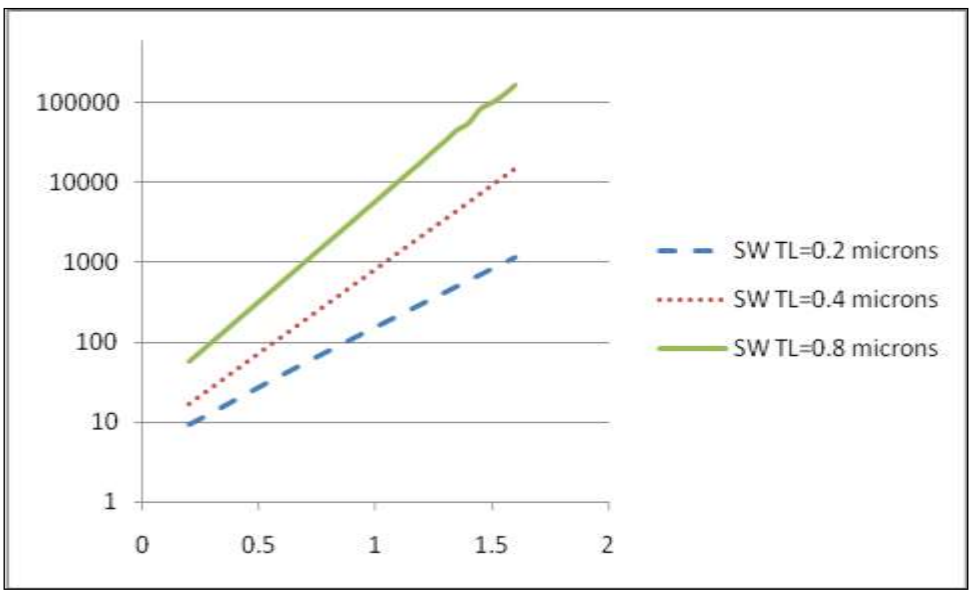


Figure. 4.2.3.2 Coupling length (Lc) vs. separation of sub-waveguides for sub-waveguide thickness =0.2 µm, 0.4 µm and 0.8 µm (coupling length has the unit of μm^{-1}).

Chapter 5

INGAAS/ALGAAS/GAAS STRUCTURE WITH GRINSCH AND ALGAAS/ALGAAS/GAAS STRUCTURE WITH MULTIPLE QW EXAMPLES

5.1 Introduction

This chapter uses material system InGaAs/AlGaAs/GaAs for an example of a semiconductor laser structure at 975 nm and material system AlGaAs/AlGaAs/GaAs for an example of a laser at 820 nm. For the 975 nm structure, the quantum well will be InGaAs, the cladding and SCH layers will be AlGaAs, and the substrate and cap will be GaAs. The 820 nm structure also has a GaAs substrate and cap, but the quantum well, SCH, and cladding layers are all AlGaAs.

We will highlight two WAVEGUIDE II features including a graded index separate confinement heterostructure (GRINSCH) and a multiple quantum well structure (MQW). We will start with a generic single quantum well structure using InGaAs/AlGaAs/GaAs as the first example and change the structure by making the SCH layer graded for the second example. Then we will move more quickly through a generic single quantum well AlGaAs/AlGaAs/GaAs structure and then change the number of quantum wells for the third example. By the end of this chapter, you should feel more comfortable with modifying the WAVEGUIDE II input file to describe a customized laser structure.

5.2 MATSYS Options for AlGaAs/GaAs

There are three possible ways to enter the refractive index for each AlGaAs/GaAs layer in WAVEGUIDE II. You can directly assign the refractive index value to NREAL parameter in the LAYER definition or you can use one of the two MATSYS options; MATSYS will calculate the refractive index for you based on the composition you input and has option AlGaAs 1 which is based on a paper by Adachi (see reference 1 in chapter section 3.3) or you can use AlGaAs 2 which is based on a paper by Jenkins (see reference 2 in chapter section 3.3). The examples in this section use the Jenkins model which has MATSYS code 0.1.

5.3 Single Quantum Well Structure with GRINSCH at 980 nm

In this first example, the initial WAVEGUIDE II input file (Example 5-1) is based on a structure (Table 5.3.1) analyzed in the GAIN program manual for material system 6. To get started in WAVEGUIDE II, the SCH and cladding layer thicknesses are arbitrarily selected. MATSYS is used for all the layers except the quantum well where the refractive index is entered directly.

Table 5.3.1

Layer	λ (μm)	Strain	Thickness (Å)
QW ($In_xGa_{1-x}As$)	1.06	-0.0119285	90
SCH ($Al_xGa_{1-x}As$)	0.871	-	100
Cladding($Al_xGa_{1-x}As$)	0.6665	-	100

Example 5-1 Input File

```
!WIF generated by WIFE (Waveguide Input File Editor)
!CASE Parameter Set - 975 nm Structure
CASE KASE=WIFE
CASE EPS1=1E-8 EPS2=1E-8 GAMEPS=1E-6 QZMR=11.60 QZMI=0
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=0 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=0.975

!LAYER Parameter Set
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.0   !L1 Substrate and Buffer
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=1.5  !L2 AlGaAs n-Cladding at 35% Al
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.3  !L3 AlGaAs n-SCH at 15% Al
LAYER MATSYS=0.1 XPERC=0.0 TL=0.005  !L4 GaAs Shoulder
LAYER NREAL=3.635219 NLOSS=0.00 TL=0.009  !L5 InGaAs QW at 15% In
```

```
LAYER MATSYS=0.1 XPERC=0.0 TL=0.005 !L6 GaAs Shoulder

LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.3  !L7 AlGaAs p-SCH at 15% Al

LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=1.5  !L8 AlGaAs p-Cladding at 35%

LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.2  !L9 GaAs cap


!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set

GAMOUT LAYGAM=5 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set

!LOOPX1 ILX='TL' FINV=0.25 XINC=0.0001 LAYCH=30


!LOOPZ Parameter Set

!LOOPZ1 ILZ="QZMR" FINV=11.0 ZINC=-0.01

!LOOPZ1 ILZ="WVL" FINV=1.1 ZINC=.005

END
```

A layer file with the calculated refractive indices listed for each layer can be generated by clicking on “Layer” (the center button) on the main screen in WAVEGUIDE II. It is recommended that you check the layer file (*.ly file) and verify that the structure is what you expected. The layer file, which includes the refractive indices and the layer thicknesses, is shown below. The layer file is also useful for finding the layer number of the quantum well which I will assign to the LAYGAM parameter so calculations of confinement in the quantum well will be performed. In this case, the quantum well is layer 5.

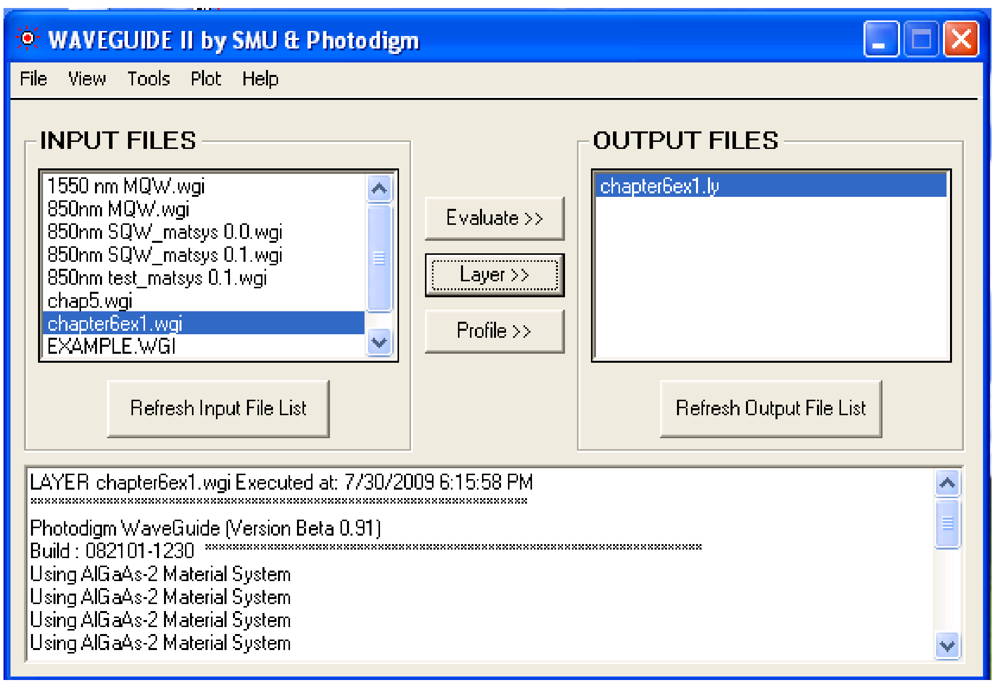


Figure 5.3.1 A layer description file can be generated using the “Layer>>” button.

Example 5-1 Layer File

# of layers = 9

LAYER01	NLOSS= 0.00000	NREAL= 3.53212	TL= 0.00000
LAYER02	NLOSS= 0.00000	NREAL= 3.32663	TL= 1.50000
LAYER03	NLOSS= 0.00000	NREAL= 3.43305	TL= 0.30000
LAYER04	NLOSS= 0.00000	NREAL= 3.53212	TL= 0.00500
LAYER05	NLOSS= 0.00000	NREAL= 3.63522	TL= 0.00900
LAYER06	NLOSS= 0.00000	NREAL= 3.53212	TL= 0.00500
LAYER07	NLOSS= 0.00000	NREAL= 3.43305	TL= 0.30000
LAYER08	NLOSS= 0.00000	NREAL= 3.32663	TL= 1.50000
LAYER09	NLOSS= 0.00000	NREAL= 3.53212	TL= 0.00000

After verifying the structure is entered properly, the QZMR parameter is found by looping (LOOPZ1) from 12.0 to 11.0. One of the values (11.60) with the convergence parameter (KM) equal to 7 was selected. The db output file below shows the looping.

Example 5-1 dB File

QZMR	PHM	GAMMA(5)	KM
1.200000E+01	5.405490E+00	0.000000E+00	3
1.199000E+01	6.449031E+00	0.000000E+00	3
1.198000E+01	6.450929E+00	0.000000E+00	3
1.197000E+01	6.452955E+00	0.000000E+00	3
1.196000E+01	6.455115E+00	0.000000E+00	3
1.195000E+01	6.457413E+00	0.000000E+00	3

.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
1.163000E+01	5.861396E-01	1.852656E-02	7	
1.162000E+01	5.861396E-01	1.852656E-02	7	
1.161000E+01	5.861396E-01	1.852656E-02	7	
1.160000E+01	**5.861396E-01**	**1.852656E-02**	**7**	
1.159000E+01	5.861396E-01	1.852656E-02	7	
1.158000E+01	5.861396E-01	1.852656E-02	6	
1.157000E+01	5.861396E-01	1.852656E-02	7	
1.156000E+01	5.861396E-01	1.852656E-02	7	
1.155000E+01	5.861396E-01	1.852656E-02	7	
1.154000E+01	5.861396E-01	1.852656E-02	7	
1.153000E+01	5.861396E-01	1.852656E-02	6	
1.152000E+01	5.091807E+00	1.591408E-03	5	
1.151000E+01	5.091807E+00	1.591408E-03	5	
.	.	.	.	.
.	.	.	.	.
.	.	.	.	.
1.113000E+01	3.083710E+00	6.530596E-04	5	
1.112000E+01	3.083710E+00	6.530596E-04	5	
1.111000E+01	3.083710E+00	6.530596E-04	5	
1.110000E+01	1.283672E+00	1.354180E-06	6	
1.109000E+01	1.283672E+00	1.354180E-06	7	
1.108000E+01	1.283672E+00	1.354180E-06	7	
1.107000E+01	1.283672E+00	1.354180E-06	6	

1.106000E+01	1.283672E+00	1.354180E-06	6
1.105000E+01	1.283672E+00	1.354180E-06	7
1.104000E+01	1.283672E+00	1.354180E-06	6
1.103000E+01	3.083710E+00	6.530596E-04	5
1.102000E+01	3.083710E+00	6.530596E-04	5
1.101000E+01	3.083710E+00	6.530596E-04	5
1.100000E+01	3.083710E+00	6.530596E-04	5

The near field intensity and magnitude are plotted in Figure 5.1 to verify that the QZMR value of 11.60 results in a single mode. Note that this plot was made using the plotting feature in WAVEGUIDE II.

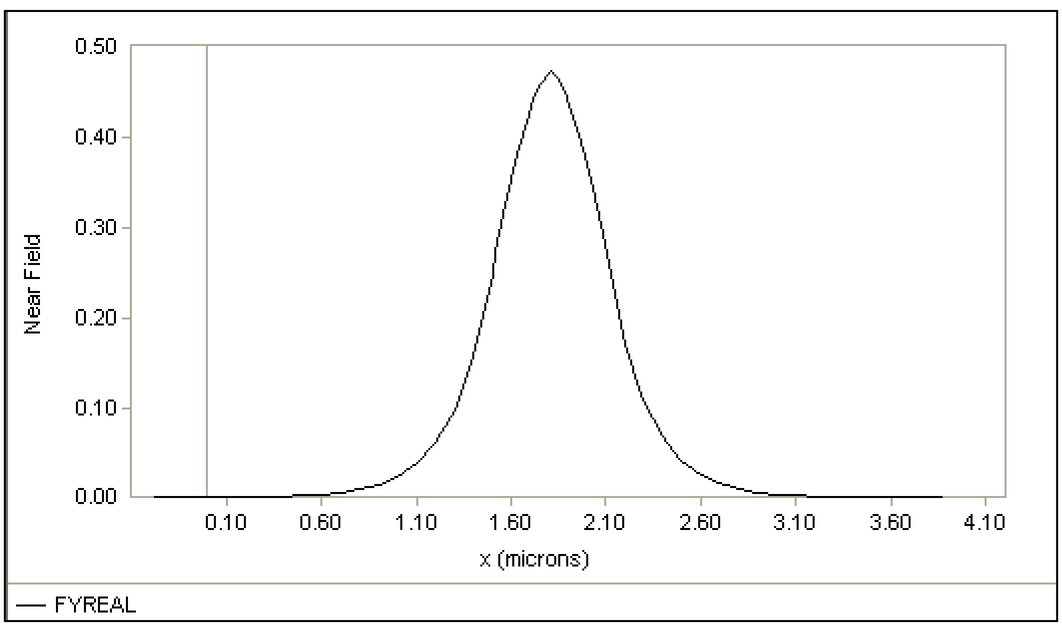


Figure 5.3.2 Near field amplitude plot verifies single mode.

Now that we have a generic laser structure defined, we will modify the structure to have a graded separate confinement heterostructure (GRINSCH) and then optimize the structure.

We can change the SCH layers to GRINSCH layers by modifying the input file. The n-side SCH layer is replaced with 3 lines. The first line indicates the composition we are starting with and the total thickness of the GRINSCH. The second line indicates the ending composition, the total GRINSCH thickness, and the number of graded layers (NSLC). For this example, we will have ten graded layers. The third line indicates again the final composition for the GRINSCH and the total thickness. We do the same process for the p side SCH layer.

Original n-SCH:

```
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.3  !L3 AlGaAs n-SCH at 15% Al
```

is replaced with:

```
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.30           !L3 Base starts at 35% Al
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.30 NSLC=10  !n-Graded
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.30           !L13 Top ends at 15% Al
```

Original p-SCH:

```
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.3  !L7 AlGaAs p-SCH at 15% Al
```

is replaced with:

```
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.30            !L17 Base starts at 15% Al
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.30 NSLC=10  !p-Graded
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.30            !L27 Top ends at 35% Al
```

The modified input file is shown in Example 5-2 below. Note this input file also includes LOOPX1 parameters for each layer in the n and p side GRINSCH. This will enable looping on the GRINSCH layers to optimize the structure.

Example 5-2 Input File

```
!WIF generated by WIFE (Waveguide Input File Editor)
!CASE Parameter Set - 975 nm Structure with GRINSCH
CASE KASE=WIFE
CASE EPS1=1E-8 EPS2=1E-8 GAMEPS=1E-6 QZMR=11.36 QZMI=0
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=0 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=0.975

!LAYER Parameter Set
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.0   !L1 Substrate and Buffer
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=1.5 !L2 AlGaAs at 35% Al
```

```
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.30            !L3 Base starts at 35% Al
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.30 NSLC=10  !n-Graded
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.30            !L13 Top ends at 15% Al
LAYER MATSYS=0.1 XPERC=0.0 TL=0.005                      !L14 GaAs Shoulder
LAYER NREAL=3.635219 NLOSS=0.00 TL=0.009                 !L15 InGaAs QW at 15% In
LAYER MATSYS=0.1 XPERC=0.0 TL=0.005                      !L16 GaAs Shoulder
LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.30            !L17 Base starts at 15% Al
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.30 NSLC=10  !p-Graded
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.30            !L27 Top ends at 35% Al
LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=1.5 !L28 AlGaAs at 35%
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.2   !L29 GaAs contact


!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0
OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set
GAMOUT LAYGAM=15 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set
!LOOPX1 ILX='TL' FINV=0.25 XINC=0.0001 LAYCH=30
!LOOPX1 ILX='TL' FINV=0.0 XINC=0.005 LAYCH=32
!LOOPX1 ILX='TL' FINV=0.1 XINC=0.001 LAYCH=5
!GRINSCH 1
!LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=3
```

```
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=4
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=5
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=6
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=7
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=8
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=9
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=10
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=11
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=12
!LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=13
!GRINSCH 2
LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=17
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=18
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=19
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=20
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=21
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=22
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=23
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=24
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=25
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=26
!LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=27
!LOOPZ Parameter Set
!LOOPZ1 ILZ="QZMR" FINV=11.0 ZINC=-0.01
!LOOPZ1 ILZ="WVL" FINV=1.1 ZINC=.005
END
```

The layer output file shows the GRINSCH layers are evenly divided into 9 layers with thickness 0.03 μm and the first and last layers are 0.015 μm thick. The total thickness of the n or p side GRINSCH is 0.3 μm and each has eleven layers. The composition is linearly graded in steps over the total layer.

Example 5-2 Layer File

# of layers = 29

```
LAYER01  NLOSS= 0.00000    NREAL= 3.53212    TL=   0.00000
LAYER02  NLOSS= 0.00000    NREAL= 3.32663    TL=   1.50000
LAYER03  NLOSS= 0.00000    NREAL= 3.32663    TL=   0.01500
LAYER04  NLOSS= 0.00000    NREAL= 3.33727    TL=   0.03000
LAYER05  NLOSS= 0.00000    NREAL= 3.34791    TL=   0.03000
LAYER06  NLOSS= 0.00000    NREAL= 3.35855    TL=   0.03000
LAYER07  NLOSS= 0.00000    NREAL= 3.36920    TL=   0.03000
LAYER08  NLOSS= 0.00000    NREAL= 3.37984    TL=   0.03000
LAYER09  NLOSS= 0.00000    NREAL= 3.39048    TL=   0.03000
LAYER10  NLOSS= 0.00000    NREAL= 3.40112    TL=   0.03000
LAYER11  NLOSS= 0.00000    NREAL= 3.41176    TL=   0.03000
LAYER12  NLOSS= 0.00000    NREAL= 3.42241    TL=   0.03000
LAYER13  NLOSS= 0.00000    NREAL= 3.43305    TL=   0.01500
LAYER14  NLOSS= 0.00000    NREAL= 3.53212    TL=   0.00500
LAYER15  NLOSS= 0.00000    NREAL= 3.63522    TL=   0.00900
LAYER16  NLOSS= 0.00000    NREAL= 3.53212    TL=   0.00500
LAYER17  NLOSS= 0.00000    NREAL= 3.43305    TL=   0.01500
```

LAYER18 NLOSS= 0.00000 NREAL= 3.42241 TL= 0.03000

LAYER19 NLOSS= 0.00000 NREAL= 3.41176 TL= 0.03000

LAYER20 NLOSS= 0.00000 NREAL= 3.40112 TL= 0.03000

LAYER21 NLOSS= 0.00000 NREAL= 3.39048 TL= 0.03000

LAYER22 NLOSS= 0.00000 NREAL= 3.37984 TL= 0.03000

LAYER23 NLOSS= 0.00000 NREAL= 3.36920 TL= 0.03000

LAYER24 NLOSS= 0.00000 NREAL= 3.35855 TL= 0.03000

LAYER25 NLOSS= 0.00000 NREAL= 3.34791 TL= 0.03000

LAYER26 NLOSS= 0.00000 NREAL= 3.33727 TL= 0.03000

LAYER27 NLOSS= 0.00000 NREAL= 3.32663 TL= 0.01500

LAYER28 NLOSS= 0.00000 NREAL= 3.32663 TL= 1.50000

LAYER29 NLOSS= 0.00000 NREAL= 3.53212 TL= 0.00000

The refractive index profile of this structure is shown in Figure 5.3.3.

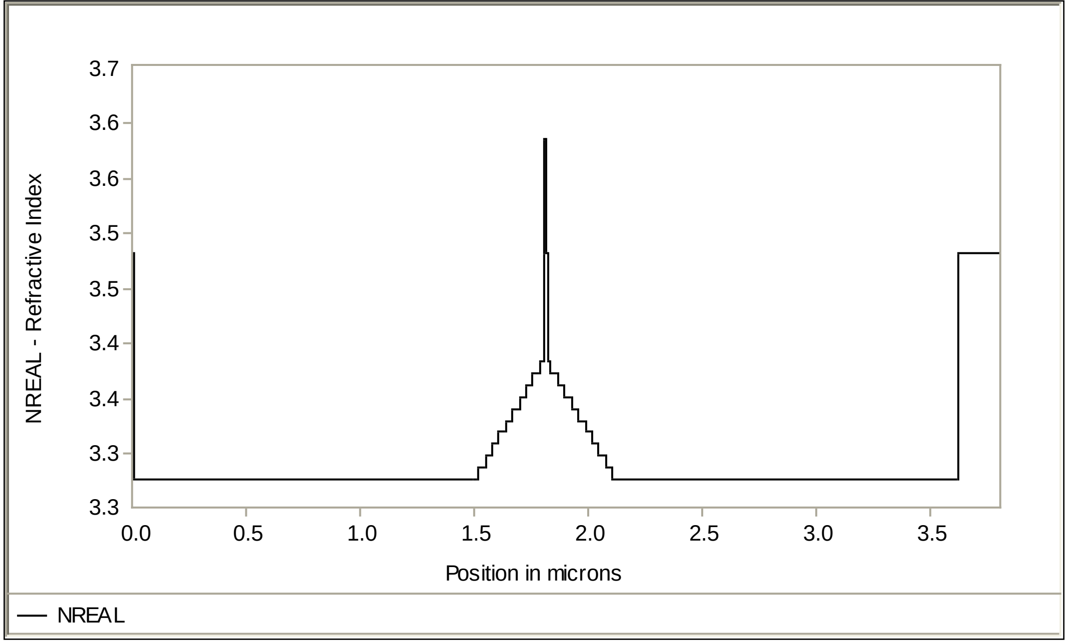


Figure 5.3.3 Refractive index profile for the GRINSCH is plotted with the zero point at the interface of the substrate and first layer of growth.

We can optimize the cladding thickness by looping and selecting the thickness which gives a negligible loss term. For wavelength 0.975 μm, I have selected the cladding thickness of 2.1 μm (Figure 5.3.4) which corresponds to loss ~ 0.00130 cm^{-1}. The loss is calculated using the following formula with WZI taken from the db output file:

$$\alpha = WZI \cdot (4\pi/\lambda) \cdot 10^4 \text{ /cm}$$

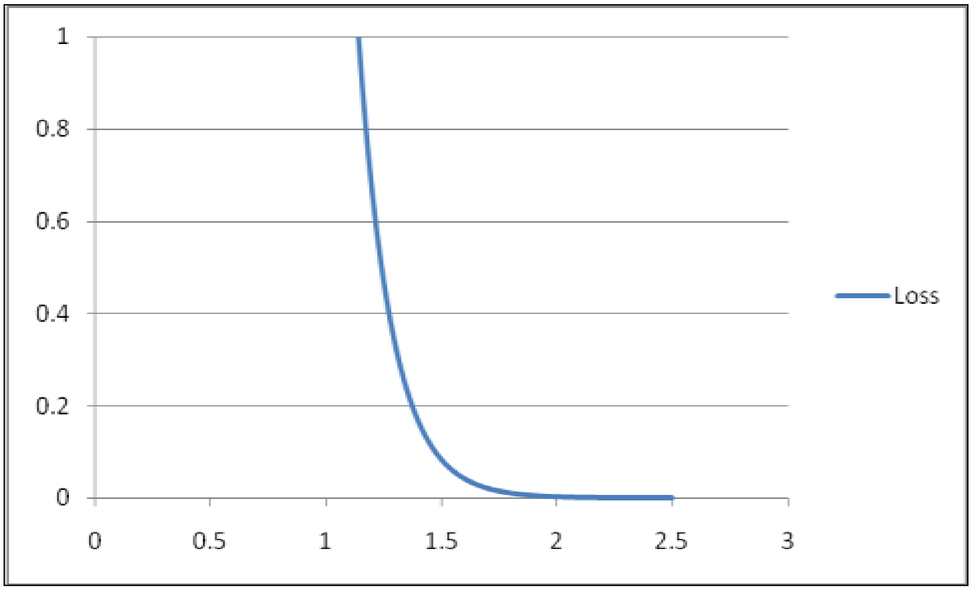


Figure 5.3.4 Loss is negligible for cladding thickness of 2.1 μm.

Next, we can optimize the confinement factor in the quantum well by varying the thickness of the GRINCH layers. In general, we will start with a maximum thickness and loop to a minimum thickness to optimize parameters (this method is used to minimize the numerical error in the code). For the GRINSCH thicknesses, we will start at 0.5 μm thick and loop for QZMR. The new QZMR is 11.46. Then we loop the GRINSCH layers. A plot of the quantum well confinement factor vs. the GRINSCH layer thicknesses is shown in Figure 5.3.5. A maximum confinement factor of 0.02010344 is achieved at GRINSCH thickness 0.27 μm. The effective index of the structure at this maximum confinement factor is 3.366145 (Figure 5.3.6).

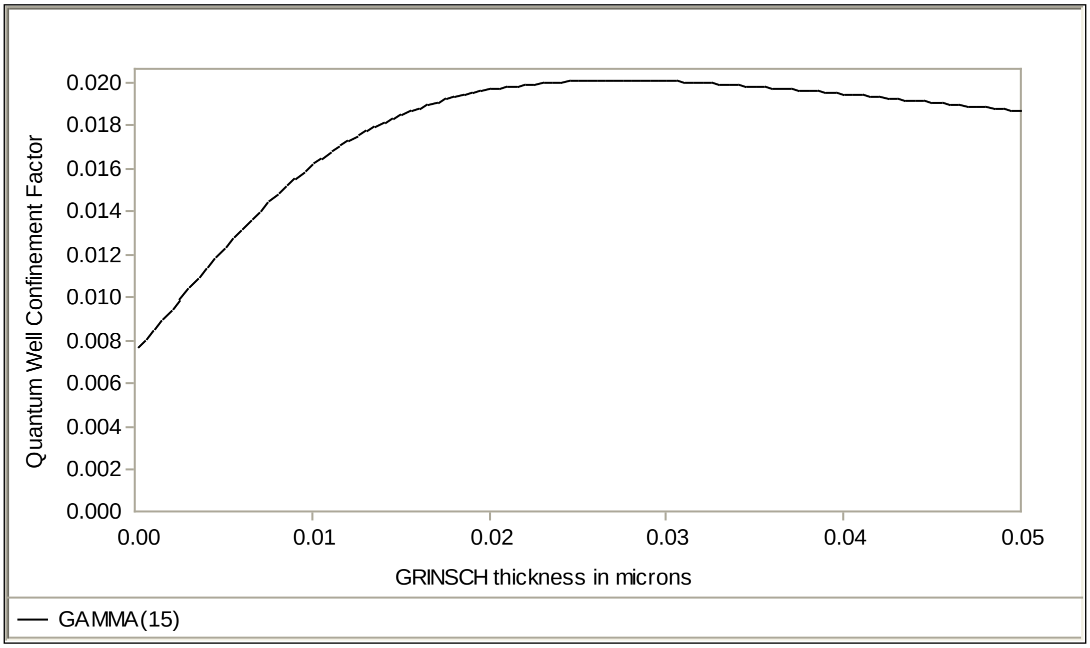


Figure 6.3.5 The maximum confinement in the quantum well (GAMMA) occurs at GRINSCH thickness 0.27 μm.

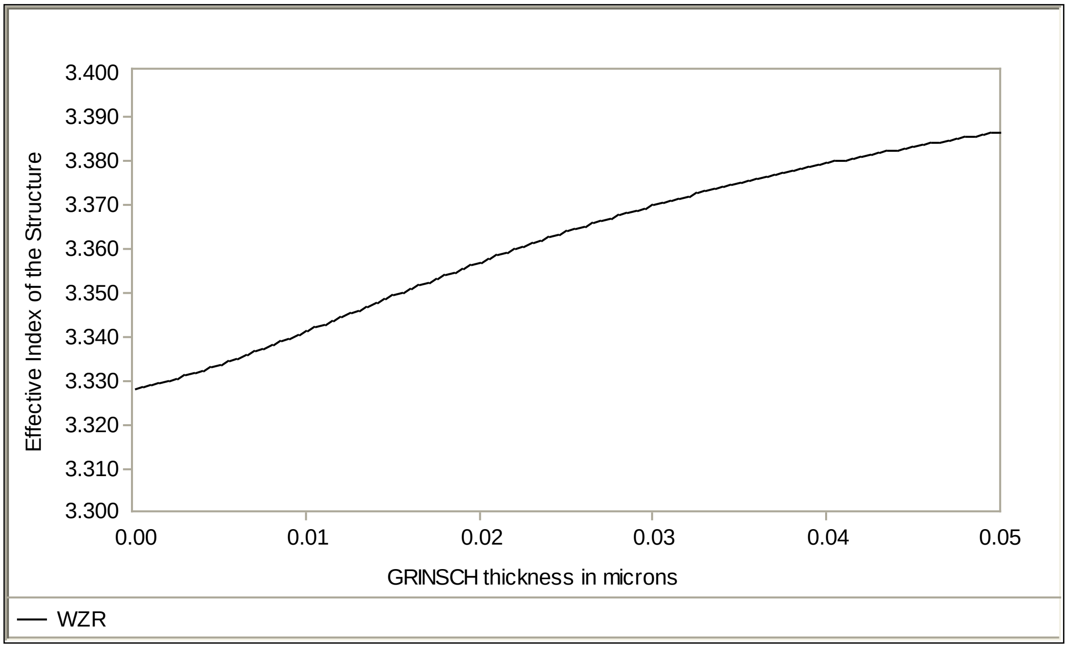


Figure 5.3.6 The effective index of the structure (WZR) varies as the thickness of the GRINSCH layers varies.

With our final structure parameters of cladding layer thickness 2.1 μm and GRINSCH layer thickness 0.27 μm, our new QZMR value is 11.33. It is critical to find a new QZMR value each time you modify the input file – otherwise you will get garbage out and waste time trying to interpret results that are unexpected!

Our final input file for example 2 is shown below.

Example 2 – Final Input File

```
!WIF generated by WIFE (Waveguide Input File Editor)

!CASE Parameter Set - 975 nm Structure with GRINSCH

CASE KASE=WIFE

CASE EPS1=1E-8 EPS2=1E-8 GAMEPS=1E-6 QZMR=11.33 QZMI=0

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30


!MODCON Parameter Set

MODCON KPOL=0 APB1=0.25 APB2=0.25


!STRUCT Parameter Set

STRUCT WVL=0.975


!LAYER Parameter Set

LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.0   !L1 Substrate and Buffer

LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=2.1 !L2 AlGaAs at 35% Al

LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.27           !L3 Base starts at 35% Al

LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.27 NSLC=10  !Graded

LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.27           !L13 Top ends at 15% Al

LAYER MATSYS=0.1 XPERC=0.0 TL=0.005 !L14 GaAs Shoulder

LAYER NREAL=3.635219 NLOSS=0.00 TL=0.009          !L15 InGaAs QW at 15% In

LAYER MATSYS=0.1 XPERC=0.0 TL=0.005 !L16 GaAs Shoulder

LAYER MATSYS=0.1 XPERC=0.15 NLOSS=0.0 TL=0.27           !L17 Base starts at 15% Al

LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.27 NSLC=10  !Graded

LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=0.27           !L27 Top ends at 35% Al

LAYER MATSYS=0.1 XPERC=0.35 NLOSS=0.0 TL=2.1 !L28 AlGaAs at 35%
```

```
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.2   !L29 GaAs contact


!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0
OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set
GAMOUT LAYGAM=15 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set
!LOOPX1 ILX='TL' FINV=.5 XINC=-0.1 LAYCH=2
!LOOPX1 ILX='TL' FINV=.5 XINC=-0.1 LAYCH=28
!LOOPX1 ILX='TL' FINV=0.1 XINC=0.001 LAYCH=5
!GRINSCH 1
!LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=3
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=4
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=5
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=6
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=7
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=8
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=9
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=10
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=11
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=12
!LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=13
```

```
!GRINSCH 2
!LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=17
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=18
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=19
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=20
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=21
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=22
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=23
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=24
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=25
!LOOPX1 ILX='TL' FINV=0.015 XINC=-0.0005 LAYCH=26
!LOOPX1 ILX='TL' FINV=0.00 XINC=-0.00025 LAYCH=27


!LOOPZ Parameter Set
!LOOPZ1 ILZ="QZMR" FINV=11.0 ZINC=-0.01
!LOOPZ1 ILZ="WVL" FINV=1.1 ZINC=.005
END
```

The final near field plots of magnitude (NFREAL) and intensity (NFINT) are shown in Figure 5.3.7 and the plot of the far field is shown in Figure 5.3.8. Note that we did not optimize the far field for this particular structure. Other chapter examples in the manual discuss optimizing the far field or you can try it for yourself.

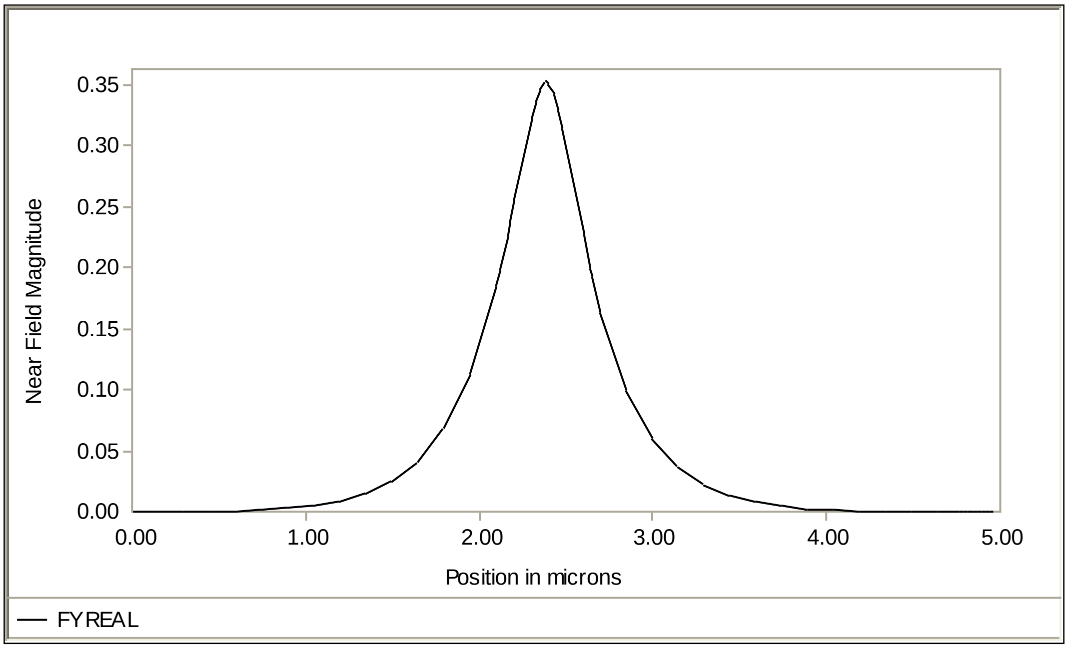


Figure 5.3.7 The near field magnitude (NFREAL) is plotted

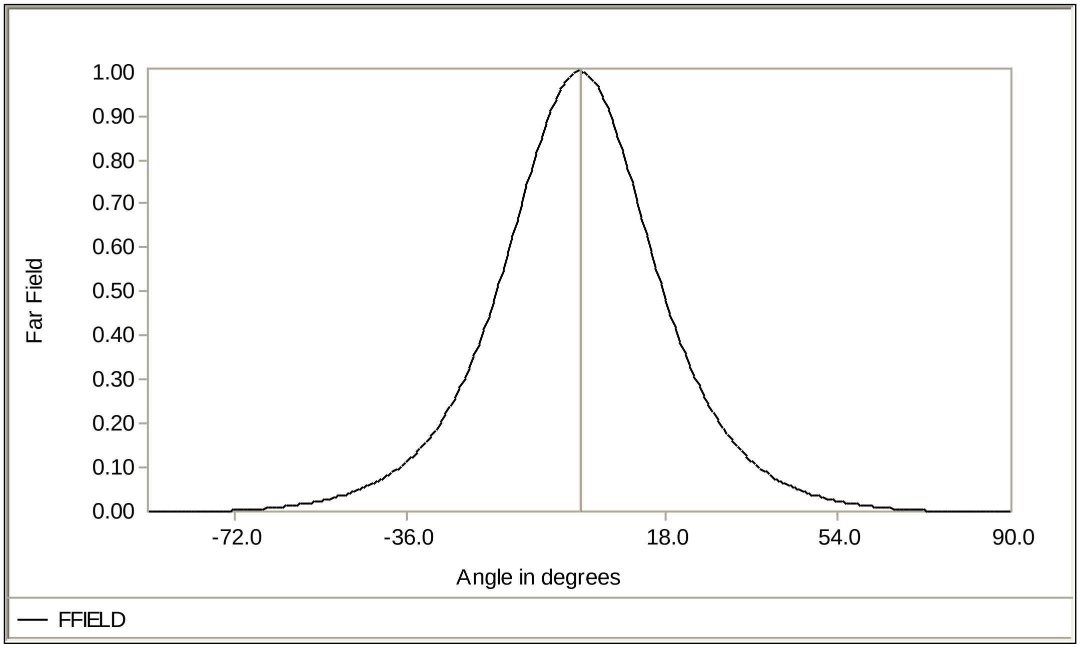


Figure 5.3.8 The far field plot has a full width half power max (FWHPF) of 34.8 degrees.

5.4 Multiple Quantum Well AlGaAs/AlGaAs/GaAs Structure at 820 nm

In this example, the initial WAVEGUIDE II input file (Example 5-3) is based on a structure (Table 5.4.1) analyzed in the GAIN program manual for material system 1. To get started in WAVEGUIDE II, the SCH and cladding layer thicknesses are arbitrarily selected. MATSYS is used for all the layers and again the Jenkins model for AlGaAs is selected.

Table 5.4.1

Layer	λ (μm)	Strain	Thickness (Å)
QW ($Al_xGa_{1-x}As$)	0.87	-	50
SCH ($Al_xGa_{1-x}As$)	0.74	-	60
Cladding($Al_xGa_{1-x}As$)	0.58	-	100

Example 3 – Input File

```
!WIF generated by WIFE (Waveguide Input File Editor)

!CASE Parameter Set - 820 nm Structure

CASE KASE=WIFE

CASE EPS1=1E-8 EPS2=1E-8 GAMEPS=1E-6 QZMR=12.15 QZMI=0

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30


!MODCON Parameter Set

MODCON KPOL=0 APB1=0.25 APB2=0.25


!STRUCT Parameter Set

STRUCT WVL=0.82


!LAYER Parameter Set

LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.0   !L1 Substrate and Buffer

LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=2.5 !L2 AlGaAs n-Cladding at 56% Al

LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.5 !L3 AlGaAs n-SCH at 20% Al

LAYER MATSYS=0.1 XPERC=0.10 TL=0.005                !L4 AlGaAs QW at 10% Al
```

```
LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.5 !L5 AlGaAs p-SCH at 20% Al
LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=2.5 !L6 AlGaAs p-Cladding at 56%
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.2   !L7 GaAs cap

!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0
OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1

!GAMOUT Parameter Set
GAMOUT LAYGAM=4 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
LOOPX1 ILX='TL' FINV=0.5 XINC=-0.01 LAYCH=2 !n Cladding
LOOPX1 ILX='TL' FINV=0.5 XINC=-0.01 LAYCH=6 !p Cladding

!LOOPZ Parameter Set
!LOOPZ1 ILZ="QZMR" FINV=11.0 ZINC=-0.01
!LOOPZ1 ILZ="WVL" FINV=1.1 ZINC=.005
END
```

The layer file is viewed to verify the structure is entered properly.

```
# of layers =        7

LAYER01  NLOSS= 0.00000    NREAL= 3.67080    TL=   0.00000
LAYER02  NLOSS= 0.00000    NREAL= 3.28629    TL=   2.50000
LAYER03  NLOSS= 0.00000    NREAL= 3.50104    TL=   0.50000
LAYER04  NLOSS= 0.00000    NREAL= 3.58503    TL=   0.00500
LAYER05  NLOSS= 0.00000    NREAL= 3.50104    TL=   0.50000
LAYER06  NLOSS= 0.00000    NREAL= 3.28629    TL=   2.50000
LAYER07  NLOSS= 0.00000    NREAL= 3.67080    TL=   0.00000
```

The cladding is varied from 2.5 μm to 0.5 μm to select a thickness with acceptable loss. A plot of the region with the lowest loss is shown in Figure 5.4.1. In this example, a cladding layer thickness of 1 μm is selected based on the negligible loss at that thickness.

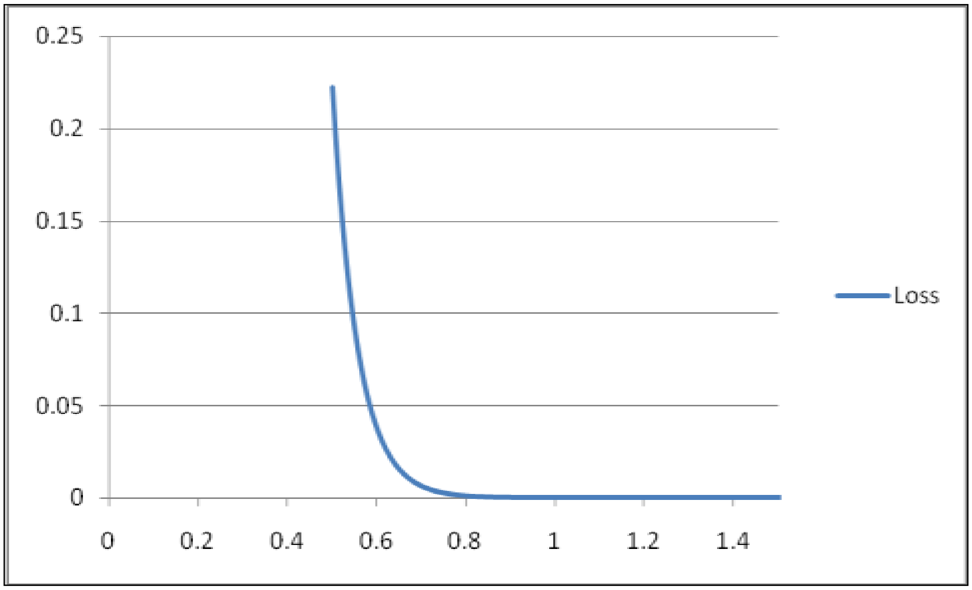


Figure 5.4.1 The cladding layer thickness is selected to be 1 μm and has negligible loss.

Next, we can optimize the quantum well confinement by varying the thickness of the SCH layers. The optimal confinement in the quantum well is 0.01899 and occurs at SCH layer thickness of 0.09 μm. The plot of confinement vs. layer thickness is shown in Figure 5.4.2.

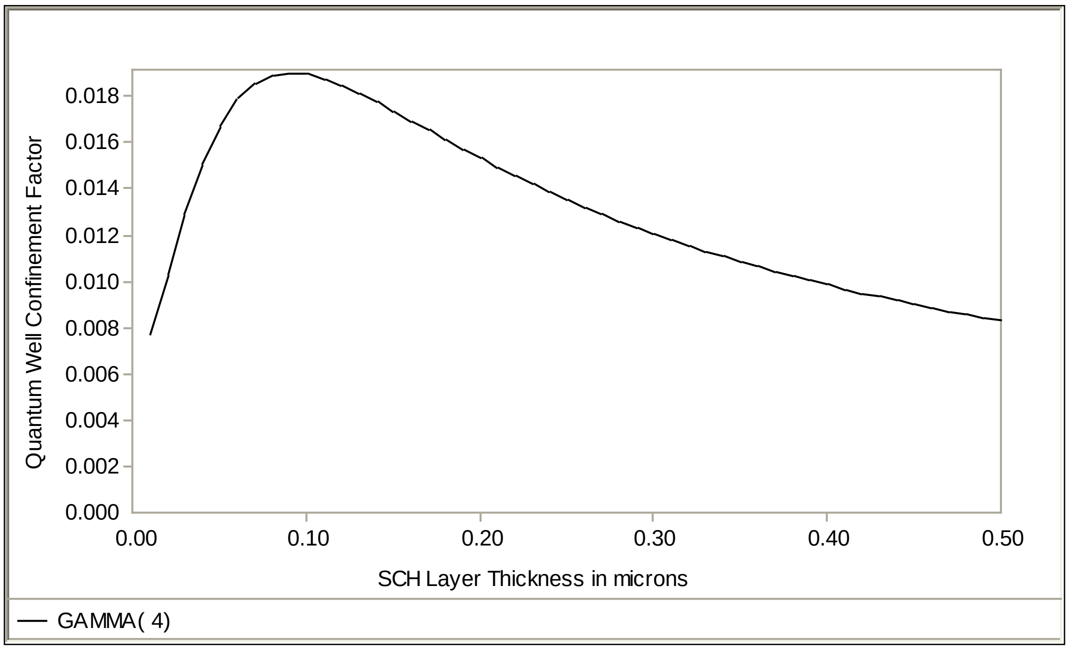


Figure 5.4.2 The maximum quantum well confinement occurs at SCH layer thickness 0.09 μm.

Next we show how to change this single quantum well structure (SQW) into a multiple quantum well structure (MQW). A simple modification to the input file will allow us to incorporate as many quantum wells as desired. For this example, we will add two quantum wells to the SQW structure for a total of 3 quantum wells.

The original structure:

```
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.0   !L1          Substrate and Buffer
LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=1.0 !L2          AlGaAs n-Cladding at 56% Al
LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.09             !L3 AlGaAs n-SCH at 20% Al
LAYER MATSYS=0.1 XPERC=0.10 TL=0.005                      !L4 AlGaAs QW at 10% Al
LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.09             !L5 AlGaAs p-SCH at 20% Al
LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=1.0 !L6          AlGaAs p-Cladding at 56%
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.2   !L7          GaAs cap
```

can be modified by inserting extra lines into the LAYER definition:

```
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.0   !L1          Substrate and Buffer
LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=1.0 !L2          AlGaAs n-Cladding at 56% Al
LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.09             !L3 AlGaAs n-SCH at 20% Al
LAYER MATSYS=0.1 XPERC=0.10 TL=0.005                      !L4 AlGaAs QW at 10% Al
LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.005  !L5 AlGaAs barrier at 20% Al
LAYER MATSYS=0.1 XPERC=0.10 TL=0.005                      !L6 AlGaAs QW at 10% Al
LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.005  !L7 AlGaAs barrier at 20% Al
LAYER MATSYS=0.1 XPERC=0.10 TL=0.005                      !L8 AlGaAs QW at 10% Al
LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.09             !L9 AlGaAs p-SCH at 20% Al
LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=1.0 !L10         AlGaAs p-Cladding at 56%
LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.2   !L11         GaAs cap
```

After inspecting the layer file to verify the structure is what I intended, I plotted the refractive index in Figure 5.4.3. Plotting the refractive index profile can be done by copying the data from the layer file and using your favorite plotting software.

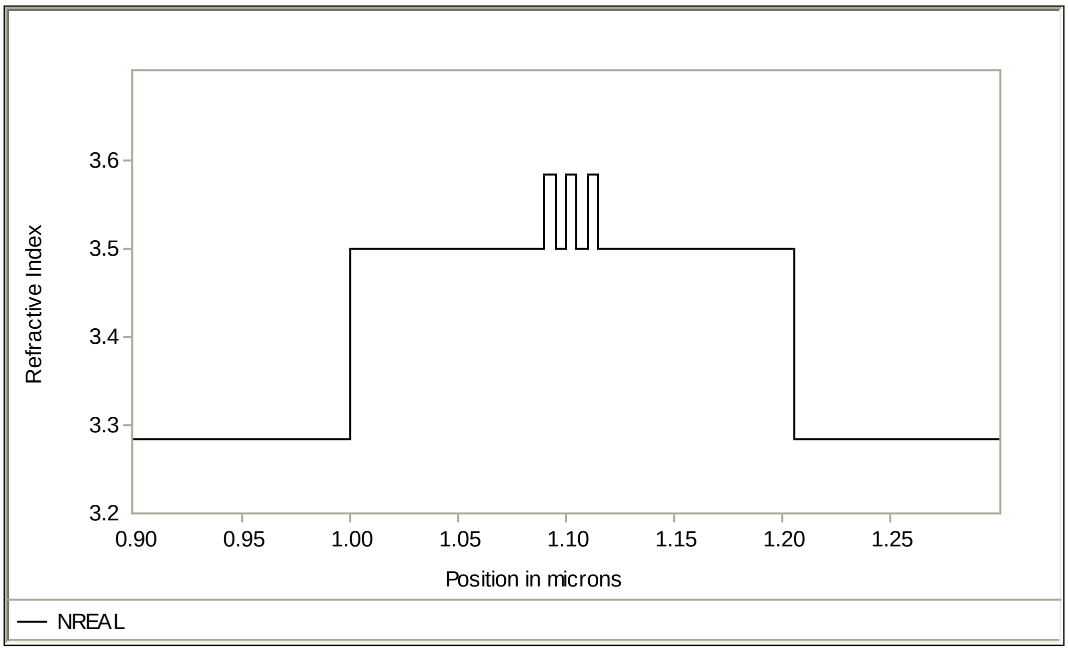


Figure 5.4.3 The refractive index profile is plotted for the cladding, SCH, barriers, and quantum well layers.

We can also modify the input file to output the confinement factor for each of the quantum wells. We can change the parameter LAYGAM=4 from the SQW case to LAYGAM=4,6,8. With this change, the *.db file (shown below) will now include the confinement factor for all three quantum wells. Since this is a symmetric structure, the center quantum well has the highest confinement and the other two quantum wells have slightly lower but equal confinement. The effective index (WZR) of this structure is 3.385398 and the KM=7 indicates the best numerical convergence.

Example 3 – Output file .db

GAMMA(4)	GAMMA(6)	GAMMA(8)	WZR	KM
1.919871E-02	1.932253E-02	1.919871E-02	3.385398E+00	7

The final input file for the 820 nm wavelength AlGaAs/AlGaAs/GaAs example is shown below.

Example 3 – Final Input File

```
!WIF generated by WIFE (Waveguide Input File Editor)

!CASE Parameter Set - 820 nm MQW Structure

CASE KASE=WIFE

CASE EPS1=1E-8 EPS2=1E-8 GAMEPS=1E-6 QZMR=11.46 QZMI=0

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30


!MODCON Parameter Set

MODCON KPOL=0 APB1=0.25 APB2=0.25


!STRUCT Parameter Set

STRUCT WVL=0.82
```

```
!LAYER Parameter Set

LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.0   !L1 Substrate and Buffer

LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=1.0 !L2 AlGaAs n-Cladding at 56% Al

LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.09          !L3 AlGaAs n-SCH at 20% Al

LAYER MATSYS=0.1 XPERC=0.10 TL=0.005           !L4 AlGaAs QW at 10% Al

LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.005         !L5 AlGaAs barrier at 20% Al

LAYER MATSYS=0.1 XPERC=0.10 TL=0.005           !L6 AlGaAs QW at 10% Al

LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.005         !L7 AlGaAs barrier at 20% Al

LAYER MATSYS=0.1 XPERC=0.10 TL=0.005           !L8 AlGaAs QW at 10% Al

LAYER MATSYS=0.1 XPERC=0.20 NLOSS=0.0 TL=0.09          !L9 AlGaAs p-SCH at 20% Al

LAYER MATSYS=0.1 XPERC=0.56 NLOSS=0.0 TL=1.0 !L10 AlGaAs p-Cladding at 56%

LAYER MATSYS=0.1 XPERC=0.0 NLOSS=0.0 TL=0.2   !L11 GaAs cap


!OUTPUT Parameter Set

OUTPUT PHMO=0 GAMMAO=1 WZRO=1 WZIO=0 QZRO=0 QZIO=0

OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=0

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set

GAMOUT LAYGAM=4,6,8 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set

!LOOPX1 ILX='TL' FINV=0.5 XINC=-0.01 LAYCH=2 !n Cladding

!LOOPX1 ILX='TL' FINV=0.5 XINC=-0.01 LAYCH=6 !p Cladding

!LOOPX1 ILX='TL' FINV=0.0 XINC=-0.01 LAYCH=3 !n SCH

!LOOPX1 ILX='TL' FINV=0.0 XINC=-0.01 LAYCH=5 !p SCH
```

```
!LOOPZ Parameter Set

!LOOPZ1 ILZ="QZMR" FINV=11.0 ZINC=-0.01

!LOOPZ1 ILZ="WVL" FINV=1.1 ZINC=.005

END
```

The near field magnitude and intensity are plotted in Figure 5.4.4 and the far field is plotted in Figure 5.4.5. Similar to example 2 in this chapter, the far field has not been optimized. Other chapters in this manual highlight optimizing the far field as well as the many additional features of WAVEGUIDE II.

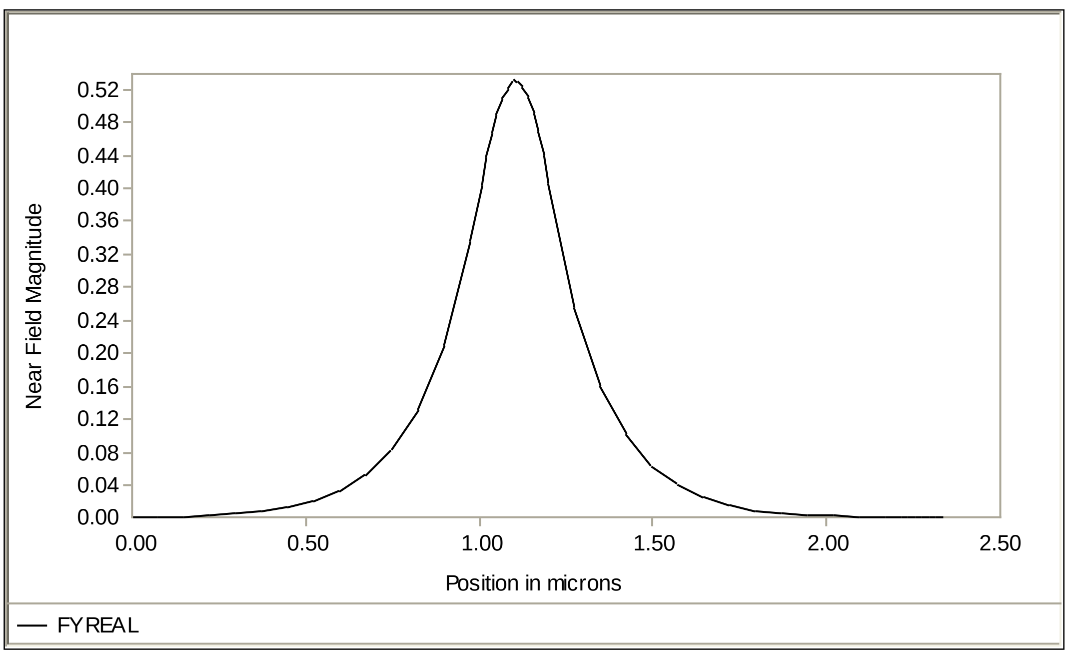


Figure 5.4.4 Near field magnitude is plotted for the MQW structure.

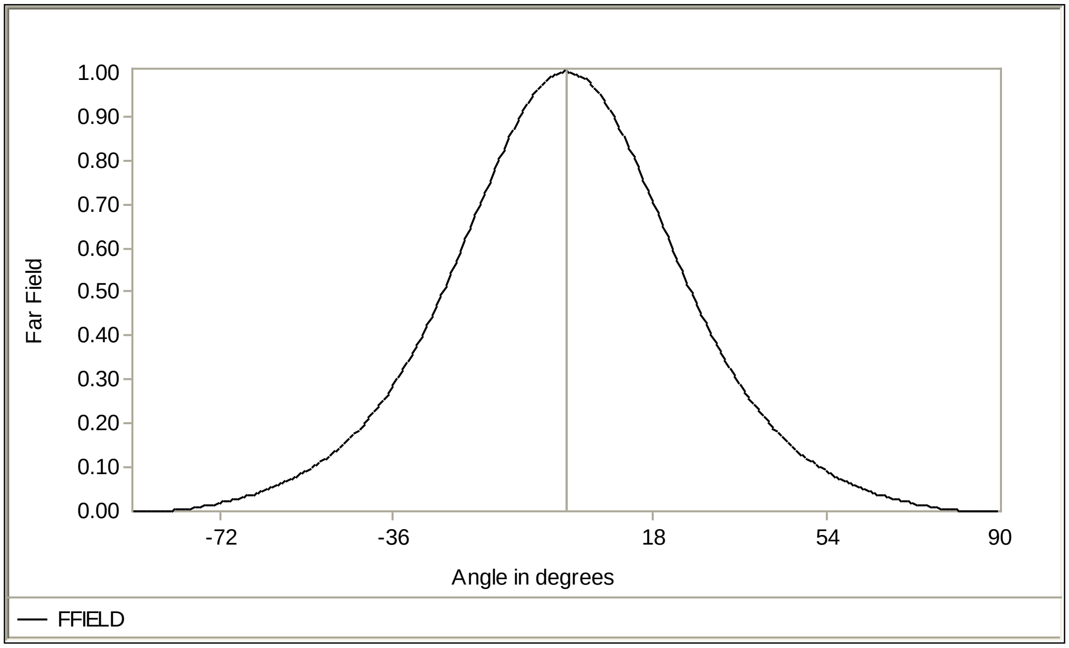


Figure 5.4.5 The far field is plotted for the MQW structure and the HWFPH parameter output in the *.db file indicates the divergence is 51.5 degrees.

5.5 Summary

This chapter has introduced two features of WAVEGUIDE II that are useful in the design and modeling of semiconductor lasers. The first feature discussed was the graded index separate confinement heterostructure (GRINSCH) which assumes a linear grade over the number of layers in the GRINSCH defined by the user. The second feature discussed was a multiple quantum well structure (MQW). Both of these features are used by directly modifying the WAVEGUIDE II input file. The examples in this chapter demonstrated how to change a simple laser structure to include the more complicated GRINSCH or MQW structures in your modeling efforts.

Chapter 6

INGAASP/INGAASP/INP LASER

6.1 InGaAsP/InGaAsP/InP (1310nm)

6.1.1 Introduction

InGaAsP/InP Multiple Quantum Well (MQW) lasers are of great interest in telecommunication systems. Using WAVEGUIDE II software, we present procedures for designing a broad area InGaAsP/InP 5-QW laser operating at 1310nm with fundamental TE mode. Three main steps are involved, and criterions for determining parameters in each step are also discussed. Firstly, we loop for QZMR to determine the effective refractive index of the fundamental TE mode. Second, thickness of the Separated Confinement Heterostructure (SCH) is looped and determined. Finally, loss in a highly doped layer is taken into account, and the thickness of the p-cladding layer is looped and determined. After using these determined parameters, we simulate optical confinement factor, near field/ far field, and loss. The simulation results indicate that the laser structure is acceptable, and good performances are obtained.

6.1.2 Initial input file

The waveguide structure of a laser shown in Table 6.1.1 consists of a p-cap layer, a p-cladding layer, an etch-stop layer, a p-spacer layer, a p-separate confinement heterostructure (p-SCH) layer, five quantum wells, four barriers, a n-SCH layer, a n-cladding layer, and a InP substrate. The composition and thickness of the quantum well, barrier, p-SCH, and n-SCH layers are determined by the GAIN software, and the initial input file is given in Table 6.1.2.

Table 6.1.1 Initial Laser structure (5-QW InGaAsP) for the 1310nm InGaAsP/InP laser structure.

Layer	Thickness (μm)	Refractive Index	Loss
n-substrate	0	3.20081	0
n-cladding	1.0	3.20081	0
n-SCH	0.08	3.33097	0
Quantum well	0.006	3.49722	0
Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0
Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0
Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0
Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0
p-spacer	0.08	3.33097	0
p-SCH	0.2	3.20081	0
Etch-stop	0.001	3.33097	0

p-cladding	1.0	3.20081	0
p-cap	0.2	3.20081	0

Table 6.1.2 Initial input file

```
!DESCRIPTION: lattice matched 5-QW InGaAsP/InP laser operating at 1310nm.
!CASE Parameter Set
CASE KASE=InGaAsP (5 wells)
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=12.3  QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=0     FFPLT=1
!MODCON Parameter Set
MODCON  KPOL=1   APB1=0.25   APB2=0.25
!STRUCT Parameter Set
STRUCT  WVL=1.3
!LAYER Parameter Set
!------------------- beginning of structure ----------------------
LAYER  MATSYS=1  XPERC=0 YPERC=0 TL=0.0 !n-substrate
LAYER  MATSYS=1  XPERC=0 YPERC=0 TL=2.0 !n-cladding
LAYER  MATSYS=12 XPERC=1.10  TL=0.09  !n- InGaAsP waveguide (SCH)
LAYER  MATSYS=12 XPERC=1.28   TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  TL=0.02  !barrier
LAYER  MATSYS=12 XPERC=1.28   TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  TL=0.02  !barrier
LAYER  MATSYS=12 XPERC=1.28   TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  TL=0.02  !barrier
LAYER  MATSYS=12 XPERC=1.28   TL=0.006 !QW
```

```
LAYER  MATSYS=12 XPERC=1.10  TL=0.02  !barrier

LAYER  MATSYS=12 XPERC=1.28   TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.09  !p-InGaAsP waveguide (SCH)

LAYER  MATSYS=1 XPERC=0 YPERC=0  TL=0.2   !P-spacer

LAYER  MATSYS=12 XPERC=1.10  TL=0.008 !etch stop

LAYER  MATSYS=1 XPERC=0.0 YPERC=0  TL=1.0   !P-cladding

LAYER  MATSYS=1 XPERC=0.53 YPERC=0 TL=0.2   !P-cap

!----------------------- end of structure ------------------------

!OUTPUT Parameter Set

OUTPUT  PHMO=1    GAMMAO=1   WZRO=1   WZIO=1   QZRO=1    QZIO=1

OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1    ITO=1

OUTPUT  MODOUT=1   LYROUT=1   SPLTFL=0

!GAMOUT Parameter Set

GAMOUT  LAYGAM=4   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=6   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=8   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=10   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=12   COMPGAM=0  GAMALL=0

LOOPZ1  ILZ='QZMR' FINV=10.24  ZINC=-0.01

!LOOPZ1  ILZ='WVL'  FINV=1.32  ZINC=0.001

!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=16

!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=3

!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=13

!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=2

END
```

6.1.3 QZMR looping and modes searching

The fundamental TE mode is searched by looping the QZMR defined as the square of the effective refractive index n_{eff}^2. The value of QZMR should be in the range of square of the minimum refractive index $n_{\min}^2$ and maximum refractive index $n_{\max}^2$; therefore, the QZMR is looped from the 10.245 ($n_{\min}^2$) to 12.23 ($n_{\max}^2$), and the input file is given in Table 6.1.3. After looping the QZMR, we obtain results shown in Table 6.1.4. To find the QZMR for the fundamental TE mode, several criterions including PHM < 1.0, KM=6 or 7, and IT < 10 are applied. Based on these criterions, the QZMR for the fundamental TE mode is 10.54, which is highlighted in this table. The near field and far fields are shown in Fig. 6.1.1 and Fig. 6.1.2.

Table 6.1.3 Input file

```
CASE KASE=InGaAsP (5 wells)

CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6

CASE    QZMR=12.23  QZMI=0.0

CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=0     FFPLT=1

MODCON  KPOL=1   APB1=0.25   APB2=0.25

STRUCT  WVL=1.3

LAYER  MATSYS=1  XPERC=0 YPERC=0 TL=0.0 !InP N-substrate

LAYER  MATSYS=1  XPERC=0 YPERC=0 TL=2.0 !InP N-cladding

LAYER  MATSYS=12 XPERC=1.10  TL=0.06    !InGaAsP waveguide

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.06   !InGaAsP waveguide

LAYER  MATSYS=1  XPERC=0 YPERC=0  TL=0.2   !P-spacer

LAYER  MATSYS=12 XPERC=1.10  TL=0.008      !etch stop

LAYER  MATSYS=1  XPERC=0.0 YPERC=0  TL=1.0   !P-cladding

LAYER  MATSYS=1  XPERC=0.53 YPERC=0 TL=0.2 !P-cap

OUTPUT  PHMO=1     GAMMAO=1   WZRO=1   WZIO=1   QZRO=1    QZIO=1

OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1    ITO=1
```

```
OUTPUT  MODOUT=1   LYROUT=1   SPLTFL=0

GAMOUT  LAYGAM=4   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=6   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=8   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=10  COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=12  COMPGAM=0  GAMALL=0

LOOPZ1  ILZ='QZMR' FINV=10.24  ZINC=-0.01

!LOOPZ1  ILZ='WVL'  FINV=1.32  ZINC=0.001

!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=16

!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=3

!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=13

!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=2

END
```

Table 6.1.4 QZMR looping results

QZMR	PHM	GAMMA(4)	GAMMA(6)	GAMMA(8)	GAMMA(10)
GAMMA(12)	WZR	WZI	QZR	QZI	FWHPN
FWHPF	KM	IT			
1.057000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	-3.072851E-21	1.054250E+01	-1.995461E-20	4.111841E-01
3.735181E+01	6	5			
1.056000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	-1.329509E-18	1.054250E+01	-8.633621E-18	4.111841E-01
3.735181E+01	6	4			
1.055000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02

1.105268E-02	3.246921E+00	-4.783436E-25	1.054250E+01	-3.106288E-24	4.111841E-01
3.735181E+01	7	4			
1.054000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	3.725483E-21	1.054250E+01	2.419270E-20	4.111841E-01
3.735181E+01	6	3			
1.053000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	-1.814708E-21	1.054250E+01	-1.178443E-20	4.111841E-01
3.735181E+01	6	4			
1.052000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	-1.662786E-17	1.054250E+01	-1.079787E-16	4.111841E-01
3.735181E+01	6	4			
1.051000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	3.657204E-22	1.054250E+01	2.374930E-21	4.111841E-01
3.735181E+01	6	5			
1.050000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	1.079717E-18	1.054250E+01	7.011514E-18	4.111841E-01
3.735181E+01	6	5			
1.049000E+01	3.665436E-01	1.100883E-02	1.145845E-02	1.161856E-02	1.148095E-02
1.105268E-02	3.246921E+00	-7.032987E-24	1.054250E+01	-4.567111E-23	4.111841E-01
3.735181E+01	7	6			
1.048000E+01	9.955389E-01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.204383E+00	6.645088E-03	1.026802E+01	4.258681E-02	0.000000E+00
0.000000E+00	4	30			
1.047000E+01	1.007016E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.203822E+00	6.471294E-03	1.026443E+01	4.146574E-02	0.000000E+00
0.000000E+00	4	30			

1.046000E+01	1.027998E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.202837E+00	6.116224E-03	1.025813E+01	3.917853E-02	0.000000E+00
0.000000E+00	4	30			
1.045000E+01	1.004694E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.200764E+00	3.984792E-03	1.024487E+01	2.550876E-02	0.000000E+00
0.000000E+00	4	30			
1.044000E+01	1.269679E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.198225E+00	5.515225E-03	1.022861E+01	3.527786E-02	0.000000E+00
0.000000E+00	4	30			
1.043000E+01	1.266302E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.198330E+00	5.603327E-03	1.022928E+01	3.584258E-02	0.000000E+00
0.000000E+00	4	30			
1.042000E+01	1.043582E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.200830E+00	4.631592E-03	1.024529E+01	2.964987E-02	0.000000E+00
0.000000E+00	4	30			
1.041000E+01	8.193327E-01	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.200864E+00	1.858133E-03	1.024553E+01	1.189526E-02	0.000000E+00
0.000000E+00	4	30			
1.040000E+01	5.991886E+00	0.000000E+00	0.000000E+00	0.000000E+00	0.000000E+00
0.000000E+00	3.110176E+00	2.580630E-01	9.606599E+00	1.605243E+00	0.000000E+00
0.000000E+00	3	30	…		

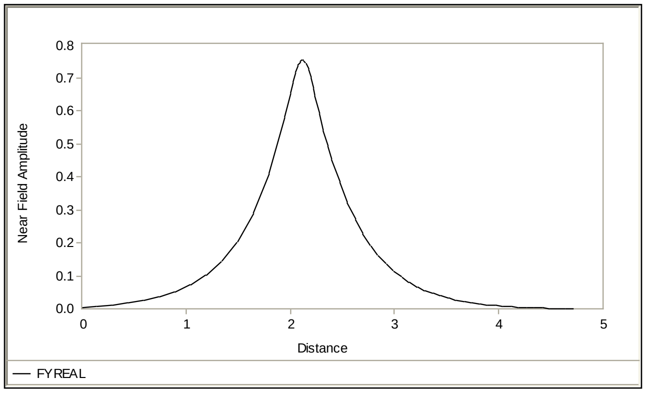


Figure 7.1.1. Fundamental mode near field plot for initial waveguide parameters.

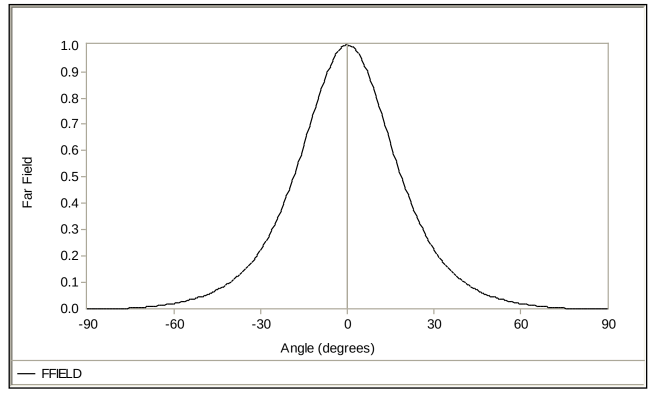


Figure 7.1.2. Fundamental mode far field plot for initial waveguide parameters.

The output parameters are:

PHM	= 3.665436E-01
GAMMA(4)	= 1.100883E-02
GAMMA(6)	= 1.145845E-02
GAMMA(8)	= 1.161856E-02
GAMMA(10)	= 1.148095E-02
GAMMA(12)	= 1.105268E-02
WZR	= 3.246921
WZI	= -5.741922E-19
FWHPF	= 3.735181E+01
KM	= 6
IT	= 3

6.1.4 Thickness of SCH layer (SCH-TL) looping

The p-SCH and n-SCH layers have strong effects on optical confinement factor (Gamma) and far field divergence (FWHPF). In this subsection, the thickness of the p-SCH and n-SCH (the 3th and the 13th layers) are looped and determined. The range of the thickness is from 0.06μm to 0.35μm, and the input file and looping results are shown in Table 6.1.5 and 6.1.6, respectively. The criterion for determining the SCH-TL is to obtain a large confinement factor and small far field divergence, but a higher optical confinement factor always leads to a larger far field divergence, and vice versa. Therefore, the SCH-TL is determined by optimizing the optical confinement factor and far field divergence. Fig. 6.1.3 shows the optical confinement factor and far field divergence versus SCH-TL. As can be seen, the far field divergence monotonously increases with SCH-TL. However, a peak value of optical confinement factor exists at 0.13μm, and the optical confinement factor decreases with either increasing or decreasing SCH-TL. The SCH-TL is taken as 0.09μm after comprising the optical confinement factor and far field divergence.

Table 6.1.5 Input file

```
CASE KASE=InGaAsP (5 wells)
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=10.54  QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=0     FFPLT=1
```

```
MODCON  KPOL=1   APB1=0.25   APB2=0.25

STRUCT  WVL=1.3

LAYER  MATSYS=1  XPERC=0 YPERC=0 TL=0.0 !InP N-substrate

LAYER  MATSYS=1  XPERC=0 YPERC=0 TL=2.0 !InP N-cladding

LAYER  MATSYS=12 XPERC=1.10  TL=0.06    !InGaAsP waveguide

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.02   !barrier

LAYER  MATSYS=12 XPERC=1.28  TL=0.006 !QW

LAYER  MATSYS=12 XPERC=1.10  TL=0.06   !InGaAsP waveguide

LAYER  MATSYS=1  XPERC=0 YPERC=0  TL=0.2   !P-spacer

LAYER  MATSYS=12 XPERC=1.10  TL=0.008      !etch stop

LAYER  MATSYS=1  XPERC=0.0 YPERC=0  TL=1.0   !P-cladding

LAYER  MATSYS=1  XPERC=0.53 YPERC=0 TL=0.2 !P-cap

OUTPUT  PHMO=1    GAMMAO=1   WZRO=1   WZIO=1   QZRO=1    QZIO=1

OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1    ITO=1

OUTPUT  MODOUT=1   LYROUT=1   SPLTFL=0

GAMOUT  LAYGAM=4   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=6   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=8   COMPGAM=0  GAMALL=0

GAMOUT  LAYGAM=10  COMPGAM=0  GAMALL=0
```

```
GAMOUT  LAYGAM=12  COMPGAM=0  GAMALL=0
!LOOPZ1  ILZ='QZMR' FINV=10.24  ZINC=-0.1
!LOOPZ1  ILZ='WVL'  FINV=1.32  ZINC=0.001
!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=16
LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=3
LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=13
!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=2
END
```

Table 6.1.6 SCH-TL looping results

TL(3)	TL(13)	PHM	GAMMA(4)	GAMMA(6)	GAMMA(8)	GAMMA(10)	GAMMA(12)	WZR	WZI	QZR	QZI	FWHPN	FWHPF	KM	IT
6.000000E-02	6.000000E-02	3.135298E-01	1.037769E-02	1.084085E-02	1.100744E-02	1.086821E-02	1.043089E-02	3.236279E+00	1.583542E-16	1.047350E+01	1.024956E-15	4.271949E-01	3.344259E+01	6	7
6.500000E-02	6.500000E-02	3.229414E-01	1.051575E-02	1.097820E-02	1.114423E-02	1.100473E-02	1.056737E-02	3.238097E+00	-2.368270E-21	1.048527E+01	-1.533738E-20	4.240111E-01	3.418434E+01	6	4
7.000000E-02	7.000000E-02	3.321173E-01	1.063964E-02	1.110067E-02	1.126589E-02	1.112638E-02	1.068967E-02	3.239901E+00	-1.617249E-21	1.049696E+01	-1.047945E-20	4.270800E-01	3.487698E+01	6	4
7.500000E-02	7.500000E-02	3.410613E-01	1.075014E-02	1.120911E-02	1.137331E-02	1.123400E-02	1.079859E-02	3.241688E+00	-1.084038E-21	1.050854E+01	-7.028224E-21	4.179002E-01	3.553005E+01	6	4

8.000000E-02 8.000000E-02 3.497774E-01 1.084800E-02 1.130434E-02 1.146734E-02 1.132842E-
02 1.089489E-02 3.243455E+00 -7.272668E-22 1.052000E+01 -4.717714E-21 4.168981E-01
3.615444E+01 6 4
8.500000E-02 8.500000E-02 3.582700E-01 1.093399E-02 1.138720E-02 1.154883E-02 1.141048E-
02 1.097935E-02 3.245200E+00 -4.805193E-22 1.053132E+01 -3.118762E-21 4.142864E-01
3.678144E+01 6 4
9.000000E-02 9.000000E-02 3.665436E-01 1.100883E-02 1.145845E-02 1.161856E-02 1.148095E-
02 1.105268E-02 3.246921E+00 -3.201700E-22 1.054250E+01 -2.079133E-21 4.111841E-01
3.735181E+01 6 4
9.500000E-02 9.500000E-02 3.746030E-01 1.107324E-02 1.151889E-02 1.167736E-02 1.154063E-
02 1.111561E-02 3.248617E+00 -2.117109E-22 1.055351E+01 -1.375535E-21 4.140151E-01
3.788866E+01 6 4
1.000000E-01 1.000000E-01 3.824529E-01 1.112789E-02 1.156923E-02 1.172595E-02 1.159022E-
02 1.116882E-02 3.250286E+00 -1.378439E-22 1.056436E+01 -8.960641E-22 4.093587E-01
3.841106E+01 7 4
1.050000E-01 1.050000E-01 3.900983E-01 1.117344E-02 1.161018E-02 1.176505E-02 1.163044E-
02 1.121296E-02 3.251928E+00 2.111198E-23 1.057503E+01 1.373093E-22 4.109993E-01
3.890644E+01 7 4
1.100000E-01 1.100000E-01 3.975440E-01 1.121051E-02 1.164240E-02 1.179535E-02 1.166195E-
02 1.124867E-02 3.253541E+00 1.484773E-22 1.058553E+01 9.661538E-22 4.138765E-01
3.937338E+01 7 4
1.150000E-01 1.150000E-01 4.047950E-01 1.123971E-02 1.166653E-02 1.181750E-02 1.168540E-
02 1.127654E-02 3.255124E+00 7.583282E-23 1.059583E+01 4.936905E-22 4.154525E-01
3.981403E+01 7 4
1.200000E-01 1.200000E-01 4.118563E-01 1.126158E-02 1.168316E-02 1.183211E-02 1.170137E-
02 1.129713E-02 3.256678E+00 -4.275982E-24 1.060595E+01 -2.785099E-23 4.173223E-01

4.023261E+01 7 4

1.250000E-01 1.250000E-01 4.187329E-01 1.127662E-02 1.169282E-02 1.183970E-02 1.171039E-

02 1.131094E-02 3.258201E+00 -1.468280E-23 1.061587E+01 -9.567902E-23 4.197118E-01

4.064002E+01 7 4

1.300000E-01 1.300000E-01 4.254295E-01 1.128549E-02 1.169620E-02 1.184098E-02 1.171315E-

02 1.131861E-02 3.259693E+00 5.611551E-27 1.062560E+01 3.658387E-26 4.221061E-01

4.101890E+01 7 4

1.350000E-01 1.350000E-01 4.319510E-01 1.128850E-02 1.169363E-02 1.183629E-02 1.170999E-

02 1.132047E-02 3.261155E+00 -6.765800E-24 1.063513E+01 -4.412865E-23 4.236742E-01

4.137542E+01 7 4

1.400000E-01 1.400000E-01 4.383023E-01 1.128615E-02 1.168564E-02 1.182616E-02 1.170142E-

02 1.131701E-02 3.262586E+00 -9.616109E-24 1.064447E+01 -6.274676E-23 4.268957E-01

4.171113E+01 7 4

1.450000E-01 1.450000E-01 4.444879E-01 1.127886E-02 1.167267E-02 1.181105E-02 1.168790E-

02 1.130865E-02 3.263986E+00 1.209900E-24 1.065361E+01 7.898193E-24 4.331586E-01

4.202610E+01 7 4

1.500000E-01 1.500000E-01 4.505125E-01 1.126703E-02 1.165512E-02 1.179137E-02 1.166982E-

02 1.129578E-02 3.265356E+00 2.489512E-24 1.066255E+01 1.625828E-23 4.321392E-01

4.233540E+01 7 4

1.550000E-01 1.550000E-01 4.563805E-01 1.125100E-02 1.163338E-02 1.176750E-02 1.164757E-

02 1.127876E-02 3.266695E+00 -2.160847E-24 1.067130E+01 -1.411766E-23 4.360687E-01

4.262063E+01 7 4

1.600000E-01 1.600000E-01 4.620964E-01 1.123113E-02 1.160781E-02 1.173981E-02 1.162150E-

02 1.125793E-02 3.268005E+00 -6.315428E-25 1.067985E+01 -4.127770E-24 4.391820E-01

4.288808E+01 7 4

1.650000E-01 1.650000E-01 4.676644E-01 1.120774E-02 1.157873E-02 1.170863E-02 1.159195E-

02 1.123362E-02 3.269284E+00 2.076899E-25 1.068822E+01 1.357995E-24 4.414560E-01

4.313849E+01 7 4

1.700000E-01 1.700000E-01 4.730887E-01 1.118096E-02 1.154630E-02 1.167411E-02 1.155906E-

02 1.120596E-02 3.270535E+00 4.965797E-25 1.069640E+01 3.248162E-24 4.478745E-01

4.337115E+01 7 4

1.750000E-01 1.750000E-01 4.783734E-01 1.115155E-02 1.151129E-02 1.163704E-02 1.152362E-

02 1.117570E-02 3.271756E+00 5.012743E-25 1.070439E+01 3.280095E-24 4.492329E-01

4.359009E+01 7 4

1.800000E-01 1.800000E-01 4.835225E-01 1.111928E-02 1.147347E-02 1.159718E-02 1.148538E-

02 1.114262E-02 3.272949E+00 1.115703E-26 1.071220E+01 7.303278E-26 4.526303E-01

4.379253E+01 7 4

1.850000E-01 1.850000E-01 4.885397E-01 1.108457E-02 1.143326E-02 1.155496E-02 1.144477E-

02 1.110713E-02 3.274114E+00 -7.063129E-26 1.071982E+01 -4.625098E-25 4.570439E-01

4.398171E+01 7 4

1.900000E-01 1.900000E-01 4.934289E-01 1.104763E-02 1.139089E-02 1.151060E-02 1.140201E-

02 1.106943E-02 3.275252E+00 2.199018E-26 1.072728E+01 1.440468E-25 4.604711E-01

4.416227E+01 7 4

1.950000E-01 1.950000E-01 4.981937E-01 1.100866E-02 1.134657E-02 1.146432E-02 1.135732E-

02 1.102974E-02 3.276363E+00 -4.394031E-26 1.073455E+01 -2.879288E-25 4.640410E-01

4.432859E+01 7 4

2.000000E-01 2.000000E-01 5.028376E-01 1.096786E-02 1.130048E-02 1.141632E-02 1.131088E-

02 1.098824E-02 3.277447E+00 -1.739460E-26 1.074166E+01 -1.140197E-25 4.695415E-01

4.448476E+01 7 4

2.050000E-01 2.050000E-01 5.073639E-01 1.092540E-02 1.125283E-02 1.136677E-02 1.126288E-

02 1.094512E-02 3.278506E+00 -2.421000E-25 1.074860E+01 -1.587453E-24 4.738053E-01

4.462305E+01 7 4

2.100000E-01 2.100000E-01 5.117761E-01 1.088146E-02 1.120376E-02 1.131586E-02 1.121349E-

02 1.090054E-02 3.279539E+00 5.534428E-26 1.075538E+01 3.630075E-25 4.755980E-01

4.475387E+01 7 4

2.150000E-01 2.150000E-01 5.160772E-01 1.083618E-02 1.115345E-02 1.126372E-02 1.116286E-

02 1.085464E-02 3.280548E+00 -1.388722E-27 1.076199E+01 -9.111541E-27 4.800963E-01

4.487420E+01 7 4

2.200000E-01 2.200000E-01 5.202705E-01 1.078970E-02 1.110203E-02 1.121051E-02 1.111113E-

02 1.080757E-02 3.281532E+00 -2.287986E-27 1.076845E+01 -1.501620E-26 4.834884E-01

4.498346E+01 7 4

2.250000E-01 2.250000E-01 5.243589E-01 1.074216E-02 1.104963E-02 1.115636E-02 1.105844E-

02 1.075946E-02 3.282493E+00 -4.649419E-26 1.077476E+01 -3.052338E-25 4.872286E-01

4.508195E+01 7 4

2.300000E-01 2.300000E-01 5.283453E-01 1.069368E-02 1.099638E-02 1.110139E-02 1.100491E-

02 1.071043E-02 3.283431E+00 9.936085E-28 1.078092E+01 6.524890E-27 4.912948E-01

4.517266E+01 7 4

2.350000E-01 2.350000E-01 5.322326E-01 1.064436E-02 1.094239E-02 1.104572E-02 1.095065E-

02 1.066059E-02 3.284347E+00 -9.941077E-29 1.078693E+01 -6.529989E-28 4.956547E-01

4.525296E+01 7 4

2.400000E-01 2.400000E-01 5.360234E-01 1.059432E-02 1.088776E-02 1.098944E-02 1.089576E-

02 1.061005E-02 3.285240E+00 4.237763E-27 1.079280E+01 2.784414E-26 4.987162E-01

4.532424E+01 7 4

2.450000E-01 2.450000E-01 5.397203E-01 1.054365E-02 1.083259E-02 1.093266E-02 1.084035E-

02 1.055889E-02 3.286113E+00 5.292082E-28 1.079854E+01 3.478075E-27 5.045558E-01

4.538764E+01 7 4

2.500000E-01 2.500000E-01 5.433260E-01 1.049243E-02 1.077697E-02 1.087546E-02 1.078449E-

02 1.050721E-02 3.286964E+00 -1.310371E-26 1.080413E+01 -8.614288E-26 5.077482E-01

4.544274E+01 7 4

2.550000E-01 2.550000E-01 5.468429E-01 1.044076E-02 1.072098E-02 1.081793E-02 1.072827E-

02 1.045508E-02 3.287795E+00 1.075372E-26 1.080960E+01 7.071207E-26 5.104236E-01

4.548559E+01 7 4

2.600000E-01 2.600000E-01 5.502734E-01 1.038870E-02 1.066469E-02 1.076013E-02 1.067176E-

02 1.040259E-02 3.288607E+00 -3.656380E-27 1.081494E+01 -2.404879E-26 5.145831E-01

4.552701E+01 7 4

2.650000E-01 2.650000E-01 5.536197E-01 1.033632E-02 1.060818E-02 1.070214E-02 1.061503E-

02 1.034980E-02 3.289399E+00 6.437741E-27 1.082015E+01 4.235260E-26 5.212965E-01

4.555926E+01 7 4

2.700000E-01 2.700000E-01 5.568841E-01 1.028369E-02 1.055150E-02 1.064402E-02 1.055815E-

02 1.029677E-02 3.290173E+00 -1.873556E-26 1.082524E+01 -1.232864E-25 5.220935E-01

4.558578E+01 7 4

2.750000E-01 2.750000E-01 5.600687E-01 1.023087E-02 1.049471E-02 1.058582E-02 1.050117E-

02 1.024357E-02 3.290928E+00 4.488132E-27 1.083021E+01 2.954023E-26 5.267691E-01

4.560529E+01 7 4

2.800000E-01 2.800000E-01 5.631757E-01 1.017792E-02 1.043788E-02 1.052760E-02 1.044414E-

02 1.019024E-02 3.291665E+00 8.202291E-27 1.083506E+01 5.399839E-26 5.312975E-01

4.561867E+01 7 4

2.850000E-01 2.850000E-01 5.662070E-01 1.012487E-02 1.038104E-02 1.046941E-02 1.038712E-

02 1.013684E-02 3.292386E+00 5.361304E-27 1.083980E+01 3.530296E-26 5.337885E-01

4.562548E+01 7 4

2.900000E-01 2.900000E-01 5.691647E-01 1.007178E-02 1.032424E-02 1.041129E-02 1.033014E-

02 1.008341E-02 3.293089E+00 5.568379E-27 1.084443E+01 3.667433E-26 5.389721E-01

4.562697E+01 7 4

2.950000E-01 2.950000E-01 5.720505E-01 1.001870E-02 1.026752E-02 1.035329E-02 1.027326E-

02 1.002999E-02 3.293776E+00 7.837625E-27 1.084896E+01 5.163076E-26 5.422380E-01

4.562060E+01 7 4

3.000000E-01 3.000000E-01 5.748663E-01 9.965651E-03 1.021092E-02 1.029543E-02 1.021650E-

02 9.976623E-03 3.294447E+00 -7.816185E-27 1.085338E+01 -5.150002E-26 5.453762E-01

4.561057E+01 7 4

3.050000E-01 3.050000E-01 5.776138E-01 9.912681E-03 1.015448E-02 1.023776E-02 1.015989E-

02 9.923346E-03 3.295102E+00 1.432111E-27 1.085770E+01 9.437907E-27 5.520966E-01

4.559585E+01 7 4

3.100000E-01 3.100000E-01 5.802949E-01 9.859820E-03 1.009822E-02 1.018029E-02 1.010348E-

02 9.870188E-03 3.295743E+00 -3.013041E-27 1.086192E+01 -1.986042E-26 5.534722E-01

4.557689E+01 7 4

3.150000E-01 3.150000E-01 5.829110E-01 9.807098E-03 1.004217E-02 1.012307E-02 1.004729E-

02 9.817179E-03 3.296369E+00 1.823822E-28 1.086605E+01 1.202398E-27 5.570976E-01

4.555153E+01 7 4

3.200000E-01 3.200000E-01 5.854639E-01 9.754542E-03 9.986368E-03 1.006612E-02 9.991347E-

03 9.764347E-03 3.296980E+00 1.331135E-27 1.087008E+01 8.777453E-27 5.624314E-01

4.552460E+01 7 4

3.250000E-01 3.250000E-01 5.879550E-01 9.702178E-03 9.930826E-03 1.000945E-02 9.935669E-

03 9.711716E-03 3.297578E+00 -8.052902E-28 1.087402E+01 -5.311014E-27 5.668779E-01

4.548984E+01 7 4

3.300000E-01 3.300000E-01 5.903859E-01 9.650028E-03 9.875569E-03 9.953100E-03 9.880280E-

03 9.659309E-03 3.298162E+00 4.691455E-19 1.087787E+01 3.094635E-18 5.687291E-01

4.545212E+01 6 3

3.350000E-01 3.350000E-01 5.927580E-01 9.598113E-03 9.820615E-03 9.897074E-03 9.825200E-

03 9.607145E-03 3.298732E+00 -4.685528E-19 1.088164E+01 -3.091261E-18 5.733445E-01

4.541119E+01 6 3

```
 3.400000E-01   3.400000E-01   5.950728E-01   9.546452E-03   9.765982E-03   9.841394E-03   9.770445E-
03   9.555245E-03   3.299290E+00   -3.863826E-19   1.088532E+01   -2.549576E-18   5.767745E-01
4.536582E+01   6   3
 3.450000E-01   3.450000E-01   5.973315E-01   9.495063E-03   9.711687E-03   9.786075E-03   9.716031E-
03   9.503624E-03   3.299836E+00   -3.367484E-19   1.088892E+01   -2.222429E-18   5.803909E-01
4.531668E+01   6   3
 3.500000E-01   3.500000E-01   5.995355E-01   9.443961E-03   9.657742E-03   9.731130E-03   9.661973E-
03   9.452299E-03   3.300369E+00   -2.889739E-19   1.089244E+01   -1.907441E-18   5.845563E-01
4.526526E+01   6   3
…
```

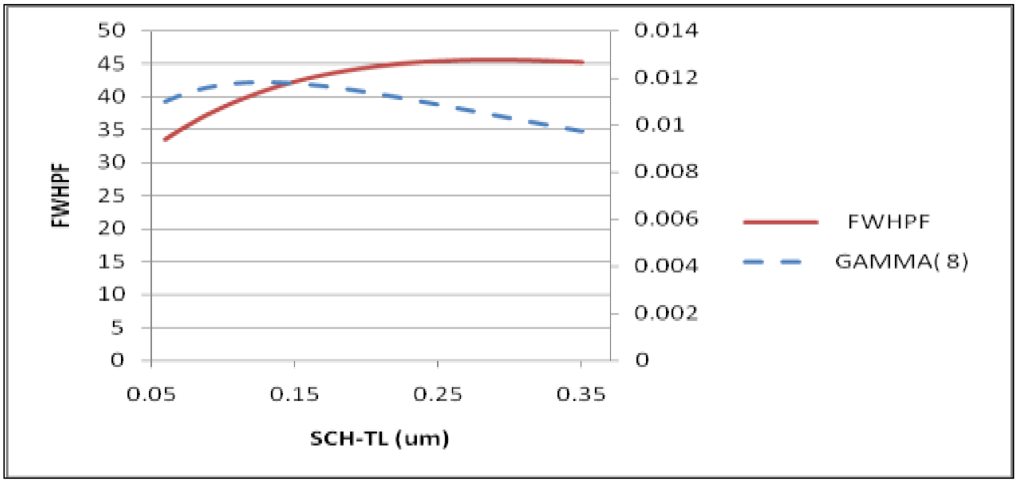


Figure 6.1.3. QW confinement factor and FWHPF vs. SCH thickness.

The output parameters are:

PHM	= 3.665436E-01
GAMMA(4)	= 1.100883E-02
GAMMA(6)	= 1.145845E-02
GAMMA(8)	= 1.161856E-02
GAMMA(10)	= 1.148095E-02
GAMMA(12)	= 1.105268E-02
WZR	= 3.246921E+00
WZI	= -3.201700E-22
FWHPF	= 3.735181E+01
KM	= 6
IT	= 4

6.1.5 Thickness of the p-cladding layer (p-cladding-TL) looping

In order to design a semiconductor laser with low threshold current density, the total loss within cavity should be carefully analyzed and reduced. Some physical originations, such as free carrier absorption and nonradioactive Auger recombination, contribute to the loss, which have been widely investigated. In addition, laser waveguide structure also affects the loss, especially the thickness of p-cladding layer.

In this subsection, the effect of the thickness of p-cladding layer on the loss is studied. After setting the QZMR and the thickness of SCH found in the previous subsections, we loop the thickness of p-cladding layer from 0 to 2.0μm. The input file and the looping results are shown in Table 6.1.7 and 6.1.8, respectively. It should be indicated that the loss of each layer should be included in the input file, especially in a high doping layer such as the p-cap layer. In order to make it brief, only the loss in the p-cap layer is considered in this demonstration, and users can include losses in all layers to obtain better results. Fig. 6.1.4 shows the relationship between loss, FWHPF and the thickness of the p-cladding layer. As it can be seen, the loss decreases with the thickness of the p-cladding layer. The loss reduces significantly at small thickness of the p-cladding layer, and stays almost constant when the thickness of the p-cladding layer is larger than 1.0μm. The reason may be the field penetration of the p-cap layer or even radiation from the transverse direction. Since the field decreases exponentially in transverse direction of the p-cladding layer, a significant amount of field penetrates and propagates in the lossy p-cap layer when the p-cladding layer is thin enough, which results in a high loss and threshold current density. However, when the p-cladding layer is thick enough, the field almost dies out in the p-cladding layer and the field in the p-cap layer can be neglected; therefore, the loss stays constant in a thick p-cladding layer.

Table 6.1.7 Input file

```
CASE KASE=InGaAsP (5 wells)
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=10.54  QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=0     FFPLT=1
MODCON  KPOL=1   APB1=0.25   APB2=0.25
STRUCT  WVL=1.3
LAYER  MATSYS=1  XPERC=0 YPERC=0 NLOSS=0.0 TL=0.0 !InP N-substrate
LAYER  MATSYS=1  XPERC=0 YPERC=0 NLOSS=0.0 TL=2.0 !InP N-cladding
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.0 TL=0.09    !InGaAsP waveguide
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02   !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02   !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02   !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02   !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
```

```
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.09   !InGaAsP waveguide
LAYER  MATSYS=1  XPERC=0 YPERC=0  NLOSS=0.000 TL=0.2   !P-spacer
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.008      !etch stop
LAYER  MATSYS=1  XPERC=0.0 YPERC=0  NLOSS=0.000 TL=0.0   !P-cladding
LAYER  MATSYS=1  XPERC=0.53 YPERC=0 NLOSS=0.01 TL=0.2 !P-cap
OUTPUT  PHMO=1    GAMMAO=1   WZRO=1   WZIO=1   QZRO=1    QZIO=1
OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1    ITO=1
OUTPUT  MODOUT=1   LYROUT=1   SPLTFL=0
!GAMOUT  LAYGAM=4   COMPGAM=0  GAMALL=0
!GAMOUT  LAYGAM=6   COMPGAM=0  GAMALL=0
GAMOUT  LAYGAM=8   COMPGAM=0  GAMALL=0
!GAMOUT  LAYGAM=10  COMPGAM=0  GAMALL=0
!GAMOUT  LAYGAM=12  COMPGAM=0  GAMALL=0
!LOOPZ1  ILZ='QZMR' FINV=10.24  ZINC=-0.1
!LOOPZ1  ILZ='WVL'  FINV=1.32  ZINC=0.001
LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=16
!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=3
!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=13
!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=2
END
```

Table 6.1.8 p-cladding-TL looping results

TL(16)	PHM	GAMMA(8)	WZR	WZI
QZR	QZI	FWHPF	KM	IT
0.000000E+00	3.701369E-01	1.161901E-02	3.246918E+00	1.779927E-04
1.054248E+01	1.155855E-03	3.876078E+01	6	3
5.000000E-02	3.693672E-01	1.161899E-02	3.246919E+00	1.367506E-04
1.054248E+01	8.880363E-04	3.850870E+01	7	3
1.000000E-01	3.687612E-01	1.161897E-02	3.246919E+00	1.050651E-04
1.054248E+01	6.822759E-04	3.850870E+01	7	3
1.500000E-01	3.682845E-01	1.161893E-02	3.246919E+00	8.072164E-05
1.054249E+01	5.241933E-04	3.829313E+01	7	3
2.000000E-01	3.679096E-01	1.161889E-02	3.246920E+00	6.201882E-05
1.054249E+01	4.027403E-04	3.811152E+01	7	2
2.500000E-01	3.676150E-01	1.161886E-02	3.246920E+00	4.764957E-05
1.054249E+01	3.094287E-04	3.811071E+01	7	2
3.000000E-01	3.673836E-01	1.161882E-02	3.246920E+00	3.660970E-05
1.054249E+01	2.377376E-04	3.795677E+01	7	2
3.500000E-01	3.672019E-01	1.161878E-02	3.246920E+00	2.812775E-05
1.054249E+01	1.826571E-04	3.782711E+01	7	2
4.000000E-01	3.670593E-01	1.161875E-02	3.246921E+00	2.161101E-05
1.054249E+01	1.403385E-04	3.782628E+01	7	2
4.500000E-01	3.669474E-01	1.161872E-02	3.246921E+00	1.660414E-05
1.054249E+01	1.078247E-04	3.772006E+01	7	2
5.000000E-01	3.668597E-01	1.161869E-02	3.246921E+00	1.275730E-05
1.054249E+01	8.284386E-05	3.763187E+01	7	2
5.500000E-01	3.667910E-01	1.161867E-02	3.246921E+00	9.801708E-06

1.054249E+01	6.365074E-05	3.763148E+01	7	2
6.000000E-01	3.667371E-01	1.161865E-02	3.246921E+00	7.530875E-06
1.054250E+01	4.890431E-05	3.755867E+01	7	2
6.500000E-01	3.666949E-01	1.161864E-02	3.246921E+00	5.786150E-06
1.054250E+01	3.757434E-05	3.749899E+01	7	2
7.000000E-01	3.666619E-01	1.161863E-02	3.246921E+00	4.445642E-06
1.054250E+01	2.886930E-05	3.749861E+01	7	2
7.500000E-01	3.666361E-01	1.161862E-02	3.246921E+00	3.415698E-06
1.054250E+01	2.218101E-05	3.745018E+01	7	2
8.000000E-01	3.666159E-01	1.161861E-02	3.246921E+00	2.624369E-06
1.054250E+01	1.704224E-05	3.741093E+01	7	2
8.500000E-01	3.666001E-01	1.161860E-02	3.246921E+00	2.016372E-06
1.054250E+01	1.309400E-05	3.741060E+01	7	2
9.000000E-01	3.665877E-01	1.161858E-02	3.246921E+00	1.549232E-06
1.054250E+01	1.006047E-05	3.737911E+01	7	2
9.500000E-01	3.665780E-01	1.161859E-02	3.246921E+00	1.190316E-06
1.054250E+01	7.729726E-06	3.735406E+01	7	2
1.000000E+00	3.665705E-01	1.161858E-02	3.246921E+00	9.145520E-07
1.054250E+01	5.938956E-06	3.735372E+01	7	2
1.050000E+00	3.665646E-01	1.161858E-02	3.246921E+00	7.026751E-07
1.054250E+01	4.563061E-06	3.733395E+01	7	2
1.100000E+00	3.665600E-01	1.161858E-02	3.246921E+00	5.398847E-07
1.054250E+01	3.505926E-06	3.731849E+01	7	2
1.150000E+00	3.665564E-01	1.161858E-02	3.246921E+00	4.148082E-07
1.054250E+01	2.693699E-06	3.731829E+01	7	2
1.200000E+00	3.665536E-01	1.161858E-02	3.246921E+00	3.187085E-07

1.054250E+01	2.069643E-06	3.730632E+01	7	2
1.250000E+00	3.665514E-01	1.161857E-02	3.246921E+00	2.448725E-07
1.054250E+01	1.590163E-06	3.729713E+01	7	2
1.300000E+00	3.665497E-01	1.161857E-02	3.246921E+00	1.881423E-07
1.054250E+01	1.221766E-06	3.729698E+01	7	2
1.350000E+00	3.665483E-01	1.161857E-02	3.246921E+00	1.445550E-07
1.054250E+01	9.387174E-07	3.729003E+01	7	2
1.400000E+00	3.665473E-01	1.161857E-02	3.246921E+00	1.110656E-07
1.054250E+01	7.212425E-07	3.728529E+01	7	2
1.450000E+00	3.665465E-01	1.161858E-02	3.246921E+00	8.533478E-08
1.054250E+01	5.541506E-07	3.728518E+01	7	2
1.500000E+00	3.665458E-01	1.161860E-02	3.246921E+00	6.556507E-08
1.054250E+01	4.257692E-07	3.728133E+01	7	2
1.550000E+00	3.665454E-01	1.161857E-02	3.246921E+00	5.037546E-08
1.054250E+01	3.271303E-07	3.727855E+01	7	2
1.600000E+00	3.665450E-01	1.161857E-02	3.246921E+00	3.870489E-08
1.054250E+01	2.513434E-07	3.727847E+01	7	2
1.650000E+00	3.665447E-01	1.161857E-02	3.246921E+00	2.973804E-08
1.054250E+01	1.931141E-07	3.727649E+01	7	2
1.700000E+00	3.665444E-01	1.161862E-02	3.246921E+00	2.284857E-08
1.054250E+01	1.483750E-07	3.727511E+01	7	2
1.750000E+00	3.665443E-01	1.161857E-02	3.246921E+00	1.755519E-08
1.054250E+01	1.140006E-07	3.727506E+01	7	2
1.800000E+00	3.665441E-01	1.161857E-02	3.246921E+00	1.348814E-08
1.054250E+01	8.758985E-08	3.727413E+01	7	2
1.850000E+00	3.665440E-01	1.161856E-02	3.246921E+00	1.036331E-08

1.054250E+01	6.729772E-08	3.727353E+01	7	2
1.900000E+00	3.665439E-01	1.161857E-02	3.246921E+00	7.962421E-09
1.054250E+01	5.170670E-08	3.727350E+01	7	2
1.950000E+00	3.665439E-01	1.161857E-02	3.246921E+00	6.117749E-09
1.054250E+01	3.972770E-08	3.727189E+01	7	2
2.000000E+00	3.665438E-01	1.161857E-02	3.246921E+00	4.700436E-09
1.054250E+01	3.052389E-08	3.727169E+01	7	2
2.050000E+00	3.665438E-01	1.161862E-02	3.246921E+00	3.611476E-09
1.054250E+01	2.345235E-08	3.727167E+01	7	2
2.100000E+00	3.665437E-01	1.161861E-02	3.246921E+00	2.774797E-09
1.054250E+01	1.801909E-08	3.727158E+01	7	2
2.150000E+00	3.665437E-01	1.161857E-02	3.246921E+00	2.131954E-09
1.054250E+01	1.384457E-08	3.727156E+01	7	2
2.200000E+00	3.665437E-01	1.161857E-02	3.246921E+00	1.638041E-09
1.054250E+01	1.063718E-08	3.727155E+01	7	2
2.250000E+00	3.665437E-01	1.161857E-02	3.246921E+00	1.258552E-09
1.054250E+01	8.172840E-09	3.727158E+01	7	2
2.300000E+00	3.665437E-01	1.161857E-02	3.246921E+00	9.669808E-10
1.054250E+01	6.279420E-09	3.727163E+01	7	2
2.350000E+00	3.665437E-01	1.161857E-02	3.246921E+00	7.429582E-10
1.054250E+01	4.824653E-09	3.727162E+01	7	2
2.400000E+00	3.665436E-01	1.161857E-02	3.246921E+00	5.708354E-10
1.054250E+01	3.706915E-09	3.727169E+01	7	2
2.450000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.385887E-10
1.054250E+01	2.848126E-09	3.727175E+01	7	2
2.500000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.369799E-10

1.054250E+01	2.188294E-09	3.727175E+01	7	2
2.550000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.589110E-10
1.054250E+01	1.681327E-09	3.727181E+01	7	2
2.600000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.989285E-10
1.054250E+01	1.291810E-09	3.727186E+01	7	2
2.650000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.528423E-10
1.054250E+01	9.925338E-10	3.727185E+01	7	2
2.700000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.174331E-10
1.054250E+01	7.625920E-10	3.727190E+01	7	2
2.750000E+00	3.665436E-01	1.161857E-02	3.246921E+00	9.022712E-11
1.054250E+01	5.859207E-10	3.726985E+01	7	2
2.800000E+00	3.665436E-01	1.161857E-02	3.246921E+00	6.932400E-11
1.054250E+01	4.501791E-10	3.726985E+01	7	2
2.850000E+00	3.665436E-01	1.161857E-02	3.246921E+00	5.326356E-11
1.054250E+01	3.458851E-10	3.726989E+01	7	2
2.900000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.092387E-11
1.054250E+01	2.657531E-10	3.726990E+01	7	2
2.950000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.144295E-11
1.054250E+01	2.041855E-10	3.726990E+01	7	2
3.000000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.415849E-11
1.054250E+01	1.568814E-10	3.726992E+01	7	2
3.050000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.856164E-11
1.054250E+01	1.205363E-10	3.726992E+01	7	2
3.100000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.426142E-11
1.054250E+01	9.261142E-11	3.726993E+01	7	2
3.150000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.095746E-11

1.054250E+01	7.115600E-11	3.726993E+01	7	2
3.200000E+00	3.665436E-01	1.161857E-02	3.246921E+00	8.418919E-12
1.054250E+01	5.467113E-11	3.726992E+01	7	2
3.250000E+00	3.665436E-01	1.161858E-02	3.246921E+00	6.468489E-12
1.054250E+01	4.200535E-11	3.726992E+01	7	2
3.300000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.969920E-12
1.054250E+01	3.227388E-11	3.726993E+01	7	2
3.350000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.818524E-12
1.054250E+01	2.479689E-11	3.726991E+01	7	2
3.400000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.933884E-12
1.054250E+01	1.905218E-11	3.726991E+01	7	2
3.450000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.254184E-12
1.054250E+01	1.463832E-11	3.726794E+01	7	2
3.500000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.731953E-12
1.054250E+01	1.124703E-11	3.726793E+01	7	2
3.550000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.330707E-12
1.054250E+01	8.641403E-12	3.726793E+01	7	2
3.600000E+00	3.665436E-01	1.161845E-02	3.246921E+00	1.022419E-12
1.054250E+01	6.639430E-12	3.726792E+01	7	2
3.650000E+00	3.665436E-01	1.161857E-02	3.246921E+00	7.855532E-13
1.054250E+01	5.101258E-12	3.726791E+01	7	2
3.700000E+00	3.665436E-01	1.161857E-02	3.246921E+00	6.035623E-13
1.054250E+01	3.919438E-12	3.726791E+01	7	2
3.750000E+00	3.665436E-01	1.161856E-02	3.246921E+00	4.637337E-13
1.054250E+01	3.011413E-12	3.726791E+01	7	2
3.800000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.562995E-13

1.054250E+01	2.313753E-12	3.726790E+01	7	2
3.850000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.737548E-13
1.054250E+01	1.777720E-12	3.726790E+01	7	2
3.900000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.103334E-13
1.054250E+01	1.365872E-12	3.726789E+01	7	2
3.950000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.616050E-13
1.054250E+01	1.049437E-12	3.726789E+01	7	2
4.000000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.241656E-13
1.054250E+01	8.063118E-13	3.726789E+01	7	2
4.050000E+00	3.665436E-01	1.161857E-02	3.246921E+00	9.539989E-14
1.054250E+01	6.195118E-13	3.726788E+01	7	2
4.100000E+00	3.665436E-01	1.161857E-02	3.246921E+00	7.329840E-14
1.054250E+01	4.759882E-13	3.726788E+01	7	2
4.150000E+00	3.665436E-01	1.161857E-02	3.246921E+00	5.631719E-14
1.054250E+01	3.657149E-13	3.726788E+01	7	2
4.200000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.327005E-14
1.054250E+01	2.809889E-13	3.726787E+01	7	2
4.250000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.324557E-14
1.054250E+01	2.158915E-13	3.726787E+01	7	2
4.300000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.554351E-14
1.054250E+01	1.658755E-13	3.726787E+01	7	2
4.350000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.962578E-14
1.054250E+01	1.274467E-13	3.726786E+01	7	2
4.400000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.507906E-14
1.054250E+01	9.792103E-14	3.726786E+01	7	2
4.450000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.158566E-14

1.054250E+01	7.523546E-14	3.726786E+01	7	2
4.500000E+00	3.665436E-01	1.161857E-02	3.246921E+00	8.901606E-15
1.054250E+01	5.780562E-14	3.726786E+01	7	2
4.550000E+00	3.665436E-01	1.161857E-02	3.246921E+00	6.839349E-15
1.054250E+01	4.441365E-14	3.726786E+01	7	2
4.600000E+00	3.665436E-01	1.161857E-02	3.246921E+00	5.254859E-15
1.054250E+01	3.412423E-14	3.726786E+01	7	2
4.650000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.037456E-15
1.054250E+01	2.621860E-14	3.726786E+01	7	2
4.700000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.102074E-15
1.054250E+01	2.014438E-14	3.726785E+01	7	2
4.750000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.383405E-15
1.054250E+01	1.547746E-14	3.726785E+01	7	2
4.800000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.831246E-15
1.054250E+01	1.189182E-14	3.726785E+01	7	2
4.850000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.406989E-15
1.054250E+01	9.136767E-15	3.726785E+01	7	2
4.900000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.081040E-15
1.054250E+01	7.020106E-15	3.726785E+01	7	2
4.950000E+00	3.665436E-01	1.161857E-02	3.246921E+00	8.305883E-16
1.054250E+01	5.393709E-15	3.726785E+01	7	2
5.000000E+00	3.665436E-01	1.161857E-02	3.246921E+00	6.381689E-16
1.054250E+01	4.144168E-15	3.726785E+01	7	2
5.050000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.903119E-16
1.054250E+01	3.184008E-15	3.726785E+01	7	2
5.100000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.767151E-16

1.054250E+01	2.446329E-15	3.721870E+01	7	2
5.150000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.894634E-16
1.054250E+01	1.879730E-15	3.721870E+01	7	2
5.200000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.223983E-16
1.054250E+01	1.444219E-15	3.721870E+01	7	2
5.250000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.708660E-16
1.054250E+01	1.109577E-15	3.721870E+01	7	2
5.300000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.312898E-16
1.054250E+01	8.525755E-16	3.721870E+01	7	2
5.350000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.008798E-16
1.054250E+01	6.550977E-16	3.721870E+01	7	2
5.400000E+00	3.665436E-01	1.161857E-02	3.246921E+00	7.750033E-17
1.054250E+01	5.032749E-16	3.721870E+01	7	2
5.450000E+00	3.665436E-01	1.161857E-02	3.246921E+00	5.954137E-17
1.054250E+01	3.866522E-16	3.721870E+01	7	2
5.500000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.575412E-17
1.054250E+01	2.971200E-16	3.721870E+01	7	2
5.550000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.515517E-17
1.054250E+01	2.282921E-16	3.721870E+01	7	2
5.600000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.700639E-17
1.054250E+01	1.753752E-16	3.721870E+01	7	2
5.650000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.075452E-17
1.054250E+01	1.347766E-16	3.721870E+01	7	2
5.700000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.595249E-17
1.054250E+01	1.035930E-16	3.721870E+01	7	2
5.750000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.225605E-17

1.054250E+01	7.958885E-17	3.721870E+01	7	2
5.800000E+00	3.665436E-01	1.161857E-02	3.246921E+00	9.420446E-18
1.054250E+01	6.117489E-17	3.721870E+01	7	2
5.850000E+00	3.665436E-01	1.161857E-02	3.246921E+00	7.227085E-18
1.054250E+01	4.693155E-17	3.721870E+01	7	2
5.900000E+00	3.665436E-01	1.161857E-02	3.246921E+00	5.559618E-18
1.054250E+01	3.610328E-17	3.721870E+01	7	2
5.950000E+00	3.665436E-01	1.161807E-02	3.246921E+00	4.275246E-18
1.054250E+01	2.776277E-17	3.721870E+01	7	2
6.000000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.291619E-18
1.054250E+01	2.137525E-17	3.721870E+01	7	2
6.050000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.509629E-18
1.054250E+01	1.629713E-17	3.721870E+01	7	2
6.100000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.946046E-18
1.054250E+01	1.263732E-17	3.721870E+01	7	2
6.150000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.483106E-18
1.054250E+01	9.631053E-18	3.721870E+01	7	2
6.200000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.142747E-18
1.054250E+01	7.420816E-18	3.721870E+01	7	2
6.250000E+00	3.665436E-01	1.161857E-02	3.246921E+00	8.761809E-19
1.054250E+01	5.689780E-18	3.721870E+01	7	2
6.300000E+00	3.665436E-01	1.161857E-02	3.246921E+00	6.795952E-19
1.054250E+01	4.413184E-18	3.721870E+01	7	2
6.350000E+00	3.665436E-01	1.161857E-02	3.246921E+00	5.138614E-19
1.054250E+01	3.336935E-18	3.721870E+01	7	2
6.400000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.923550E-19

1.054250E+01	2.547891E-18	3.721870E+01	7	2
6.450000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.068970E-19
1.054250E+01	1.992940E-18	3.721870E+01	7	2
6.500000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.401396E-19
1.054250E+01	1.559428E-18	3.721870E+01	7	2
6.550000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.853625E-19
1.054250E+01	1.203715E-18	3.721870E+01	7	2
6.600000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.485565E-19
1.054250E+01	9.647023E-19	3.721870E+01	7	2
6.650000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.129217E-19
1.054250E+01	7.332958E-19	3.721870E+01	7	2
6.700000E+00	3.665436E-01	1.161857E-02	3.246921E+00	8.673992E-20
1.054250E+01	5.632754E-19	3.721870E+01	7	2
6.750000E+00	3.665436E-01	1.161857E-02	3.246921E+00	6.103901E-20
1.054250E+01	3.963777E-19	3.721870E+01	7	2
6.800000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.901890E-20
1.054250E+01	3.183210E-19	3.721870E+01	7	2
6.850000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.843724E-20
1.054250E+01	1.846670E-19	3.721870E+01	7	2
6.900000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.065475E-20
1.054250E+01	1.990671E-19	3.721869E+01	7	2
6.950000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.386170E-20
1.054250E+01	9.001569E-20	3.721869E+01	7	2
7.000000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.070588E-20
1.054250E+01	6.952230E-20	3.721869E+01	7	2
7.050000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.025677E-20

1.054250E+01	6.660584E-20	3.713672E+01	7	2
7.100000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.634589E-20
1.054250E+01	1.061476E-19	3.713672E+01	7	2
7.150000E+00	3.665436E-01	1.161857E-02	3.246921E+00	2.349888E-20
1.054250E+01	1.525980E-19	3.713672E+01	7	2
7.200000E+00	3.665436E-01	1.161856E-02	3.246921E+00	2.003580E-20
1.054250E+01	1.301093E-19	3.713672E+01	7	2
7.250000E+00	3.665436E-01	1.161857E-02	3.246921E+00	9.678036E-22
1.054250E+01	6.284764E-21	3.713672E+01	7	2
7.300000E+00	3.665436E-01	1.161857E-02	3.246921E+00	7.724919E-21
1.054250E+01	5.016440E-20	3.713672E+01	7	2
7.350000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.324278E-21
1.054250E+01	2.808118E-20	3.713673E+01	7	2
7.400000E+00	3.665436E-01	1.161857E-02	3.246921E+00	-9.465150E-22
1.054250E+01	-6.146519E-21	3.713674E+01	7	2
7.450000E+00	3.665436E-01	1.161857E-02	3.246921E+00	-2.998619E-22
1.054250E+01	-1.947256E-21	3.713674E+01	7	2
7.500000E+00	3.665436E-01	1.161857E-02	3.246921E+00	7.320685E-21
1.054250E+01	4.753937E-20	3.713675E+01	7	2
7.550000E+00	3.665436E-01	1.161857E-02	3.246921E+00	-7.377462E-22
1.054250E+01	-4.790807E-21	3.713679E+01	7	2
7.600000E+00	3.665436E-01	1.161857E-02	3.246921E+00	4.927277E-21
1.054250E+01	3.199696E-20	3.713679E+01	7	2
7.650000E+00	3.665436E-01	1.161857E-02	3.246921E+00	-6.407254E-22
1.054250E+01	-4.160770E-21	3.713683E+01	7	2
7.700000E+00	3.665436E-01	1.161857E-02	3.246921E+00	3.908532E-21

1.054250E+01	2.538139E-20	3.713690E+01	7	2
7.750000E+00	3.665436E-01	1.161857E-02	3.246921E+00	1.156167E-23
1.054250E+01	7.507967E-23	3.713689E+01	7	2
7.800000E+00	3.665436E-01	1.161857E-02	3.246921E+00	7.312067E-21
1.054250E+01	4.748341E-20	3.713699E+01	7	2
7.850000E+00	3.665436E-01	1.161857E-02	3.246921E+00	-7.739488E-22
1.054250E+01	-5.025901E-21	3.713712E+01	7	2
7.900000E+00	3.665436E-01	1.161857E-02	3.246921E+00	-3.212459E-21
1.054250E+01	-2.086120E-20	3.713712E+01	7	2
7.950000E+00	3.665436E-01	1.161857E-02	3.246921E+00	8.819366E-21
1.054250E+01	5.727157E-20	3.713729E+01	7	2
8.000000E+00	3.665436E-01	1.161856E-02	3.246921E+00	1.002368E-20
1.054250E+01	6.509222E-20	3.713752E+01	7	2
8.050000E+00	3.665436E-01	1.161856E-02	3.246921E+00	-1.171123E-22
1.054250E+01	-7.605087E-22	3.713753E+01	7	2
8.100000E+00	3.665436E-01	1.161856E-02	3.246921E+00	-4.726619E-21
1.054250E+01	-3.069392E-20	3.713783E+01	7	2
8.150000E+00	3.665436E-01	1.161856E-02	3.246921E+00	-2.328987E-21
1.054250E+01	-1.512408E-20	3.713826E+01	7	2
8.200000E+00	3.665436E-01	1.161856E-02	3.246921E+00	-4.855524E-22
1.054250E+01	-3.153100E-21	3.713824E+01	7	2
8.250000E+00	3.665436E-01	1.161856E-02	3.246921E+00	1.287878E-21
1.054250E+01	8.363276E-21	3.713879E+01	7	2
8.300000E+00	3.665436E-01	1.161856E-02	3.246921E+00	-2.369923E-22
1.054250E+01	-1.538990E-21	3.713946E+01	7	2
8.350000E+00	3.665436E-01	1.161856E-02	3.246921E+00	5.483654E-22

1.054250E+01	3.560998E-21	3.713947E+01	7	2
8.400000E+00	3.665436E-01	1.161855E-02	3.246921E+00	-9.071542E-22
1.054250E+01	-5.890916E-21	3.714036E+01	7	2
8.450000E+00	3.665436E-01	1.161854E-02	3.246921E+00	-2.801497E-21
1.054250E+01	-1.819248E-20	3.714146E+01	7	2
8.500000E+00	3.665436E-01	1.161854E-02	3.246921E+00	-6.550973E-21
1.054250E+01	-4.254098E-20	3.714144E+01	7	2
8.550000E+00	3.665436E-01	1.161853E-02	3.246921E+00	1.234763E-21
1.054250E+01	8.018359E-21	3.714275E+01	7	2
8.600000E+00	3.665436E-01	1.161852E-02	3.246921E+00	-8.582415E-22
1.054250E+01	-5.573285E-21	3.714463E+01	7	2
8.650000E+00	3.665436E-01	1.161850E-02	3.246921E+00	7.191045E-22
1.054250E+01	4.669751E-21	3.714456E+01	7	2
8.700000E+00	3.665436E-01	1.161848E-02	3.246921E+00	-4.712503E-21
1.054250E+01	-3.060225E-20	3.714679E+01	7	2
8.750000E+00	3.665436E-01	1.161846E-02	3.246921E+00	5.592730E-21
1.054250E+01	3.631831E-20	3.714925E+01	7	2
8.800000E+00	3.665436E-01	1.161843E-02	3.246921E+00	-3.289705E-21
1.054250E+01	-2.136283E-20	3.714919E+01	7	2
8.850000E+00	3.665436E-01	1.161837E-02	3.246921E+00	-3.812018E-21
1.054250E+01	-2.475464E-20	3.715252E+01	7	2
8.900000E+00	3.665436E-01	1.161832E-02	3.246921E+00	-1.932426E-21
1.054250E+01	-1.254887E-20	3.715633E+01	7	2
8.950000E+00	3.665436E-01	1.161824E-02	3.246921E+00	3.631471E-21
1.054250E+01	2.358220E-20	3.715636E+01	7	2
9.000000E+00	3.665436E-01	1.161815E-02	3.246921E+00	-5.606208E-21

1.054250E+01	-3.640583E-20	3.716087E+01	7	2
9.050000E+00	3.665436E-01	1.161802E-02	3.246921E+00	1.014231E-21
1.054250E+01	6.586258E-21	3.716656E+01	7	2
9.100000E+00	3.665436E-01	1.161787E-02	3.246921E+00	2.633494E-21
1.054250E+01	1.710150E-20	3.716637E+01	7	2
9.150000E+00	3.665436E-01	1.161763E-02	3.246921E+00	4.088305E-21
1.054250E+01	2.654881E-20	3.717267E+01	7	2
9.200000E+00	3.665436E-01	1.161737E-02	3.246921E+00	-4.537103E-21
1.054250E+01	-2.946323E-20	3.718002E+01	7	2
9.250000E+00	3.665436E-01	1.161699E-02	3.246921E+00	4.743937E-21
1.054250E+01	3.080638E-20	3.718005E+01	7	2
9.300000E+00	3.665436E-01	1.161653E-02	3.246921E+00	-4.222374E-21
1.054250E+01	-2.741943E-20	3.718845E+01	7	2
9.350000E+00	3.665436E-01	1.161590E-02	3.246921E+00	-2.396496E-21
1.054250E+01	-1.556247E-20	3.719873E+01	7	2
9.400000E+00	3.665436E-01	1.161518E-02	3.246921E+00	-6.845167E-22
1.054250E+01	-4.445143E-21	3.719826E+01	7	2
9.450000E+00	3.665436E-01	1.161410E-02	3.246921E+00	6.162251E-22
1.054250E+01	4.001668E-21	3.720917E+01	7	2
9.500000E+00	3.665436E-01	1.161281E-02	3.246921E+00	1.359494E-21
1.054250E+01	8.828341E-21	3.722099E+01	7	2
9.550000E+00	3.665436E-01	1.161087E-02	3.246921E+00	-8.464516E-22
1.054250E+01	-5.496723E-21	3.721931E+01	7	2
9.600000E+00	3.665436E-01	1.160873E-02	3.246921E+00	-3.871305E-21
1.054250E+01	-2.513964E-20	3.723593E+01	7	2
9.650000E+00	3.665436E-01	1.160540E-02	3.246921E+00	-3.870114E-21

1.054250E+01	-2.513191E-20	3.725214E+01	7	2	
9.700000E+00	3.665436E-01	1.160181E-02	3.246921E+00	4.237051E-21	
1.054250E+01	2.751474E-20	3.682859E+01	7	2	
9.750000E+00	3.665436E-01	1.159682E-02	3.246921E+00	-1.246206E-21	
1.054250E+01	-8.092664E-21	3.684747E+01	7	2	
9.800000E+00	3.665436E-01	1.159068E-02	3.246921E+00	8.196939E-21	
1.054250E+01	5.322963E-20	3.686663E+01	7	2	
9.850000E+00	3.665436E-01	1.158125E-02	3.246921E+00	7.493463E-21	
1.054250E+01	4.866136E-20	3.686856E+01	7	2	
9.900000E+00	3.665436E-01	1.156971E-02	3.246921E+00	2.080122E-21	
1.054250E+01	1.350798E-20	3.689079E+01	7	2	
9.950000E+00	3.665436E-01	1.155594E-02	3.246921E+00	-1.573300E-21	
1.054250E+01	-1.021676E-20	3.691179E+01	7	2	
1.000000E+01	3.665436E-01	1.153681E-02	3.246921E+00	-8.494314E-22	
1.054250E+01	-5.516074E-21	3.691115E+01	7	2	…

In the looping results, the loss is represented by the WZI. The corresponding loss (/cm) is given by $\alpha = (WZI\cdot(4\pi/\lambda)\cdot 10^4)$ /cm. The loss is small (0.265/cm) when the thickness of p-cladding layer is larger than 1.0μm; therefore, the thickness of p-cladding layer is taken as 1.0μm.

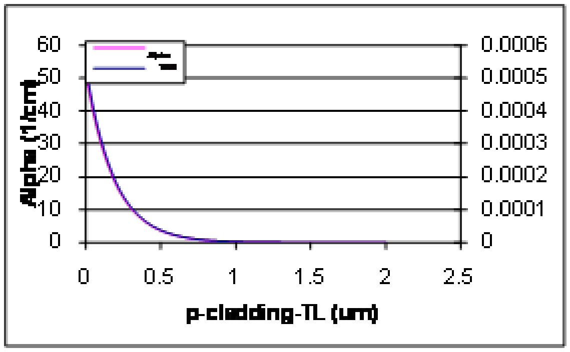


Figure 6.1.4 Loss and WZI vs. p-cladding thickness.

The output results are:

PHM	= 3.665990E-01
GAMMA(4)	= 1.100898E-02
GAMMA(6)	= 1.145860E-02
GAMMA(8)	= 1.161871E-02
GAMMA(10)	= 1.148110E-02
GAMMA(12)	= 1.105281E-02
WZR	= 3.246921E+00
WZI	= 2.729955E-06
FWHPF	= 3.749374E+01
KM	= 7
IT	= 4

6.1.6 Simulation results

After determining the values of the QZMR, thickness of p-SCH, n-SCH layers, and p-cladding layer, we set these values in the input files shown in Table 6.1.9. The near and far fields are shown in Fig. 6.1.5 and Fig. 6.1.6.

Table 6.1.9 Input file

```
CASE KASE=InGaAsP (5 wells)
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=10.53  QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=0     FFPLT=1
MODCON  KPOL=1   APB1=0.25   APB2=0.25
STRUCT  WVL=1.3
LAYER  MATSYS=1  XPERC=0 YPERC=0 NLOSS=0.0 TL=0.0 !InP N-substrate
LAYER  MATSYS=1  XPERC=0 YPERC=0 NLOSS=0.0 TL=1.0 !InP N-cladding
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.0 TL=0.09    !InGaAsP SCH
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02  !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02  !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02  !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.02  !barrier
LAYER  MATSYS=12 XPERC=1.28  NLOSS=0.000 TL=0.006 !QW
```

```
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.09  !InGaAsP SCH
LAYER  MATSYS=1  XPERC=0 YPERC=0  NLOSS=0.000 TL=0.2   !P-spacer
LAYER  MATSYS=12 XPERC=1.10  NLOSS=0.000 TL=0.008      !etch stop
LAYER  MATSYS=1  XPERC=0.0 YPERC=0  NLOSS=0.000 TL=1.0   !P-cladding
LAYER  MATSYS=1  XPERC=0.53 YPERC=0 NLOSS=0.03 TL=0.2 !P-cap
OUTPUT  PHMO=1    GAMMAO=1   WZRO=1   WZIO=1   QZRO=1    QZIO=1
OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1    ITO=1
OUTPUT  MODOUT=1   LYROUT=1   SPLTFL=0
GAMOUT  LAYGAM=4   COMPGAM=0  GAMALL=0
GAMOUT  LAYGAM=6   COMPGAM=0  GAMALL=0
GAMOUT  LAYGAM=8   COMPGAM=0  GAMALL=0
GAMOUT  LAYGAM=10  COMPGAM=0  GAMALL=0
GAMOUT  LAYGAM=12  COMPGAM=0  GAMALL=0
!LOOPZ1  ILZ='QZMR' FINV=10.24  ZINC=-0.1
!LOOPZ1  ILZ='WVL'  FINV=1.32  ZINC=0.001
!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=16
!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=3
!LOOPX1  ILX='TL'   FINV=0.35  XINC=0.005 LAYCH=13
!LOOPX1  ILX='TL'   FINV=2     XINC=0.05  LAYCH=2
END
```

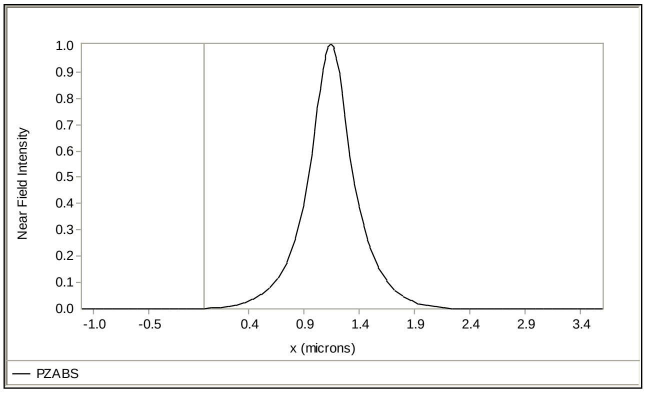


Figure 6.1.5. Fundamental mode near field plot for full structure.

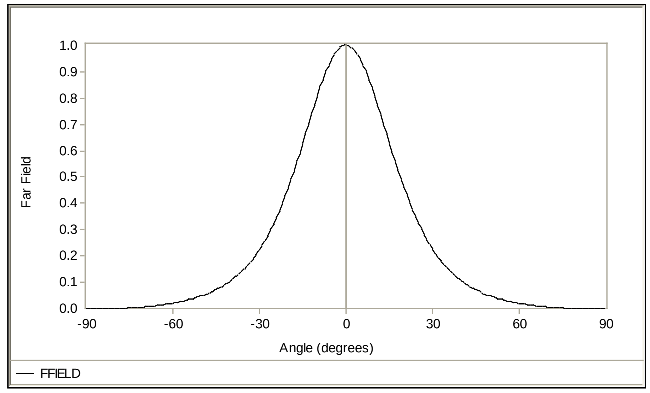


Figure 6.1.6. Fundamental mode far field plot for full structure.

The Final laser structure for this 1310nm InGaAsP laser design can be found in the table 6.1.2 as follows:

Table 6.1.2 Final Laser structure (5-QW InGaAsP) for the 1310nm InGaAsP/InP laser structure.

Layer	Thickness (μm)	Refractive Index	Loss
n-substrate	0	3.20081	0
n-cladding	1.0	3.20081	0
n-SCH	0.08	3.33097	0
Quantum well	0.006	3.49722	0
Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0

Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0
Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0
Barrier	0.02	3.33097	0
Quantum well	0.006	3.49722	0
p-spacer	0.08	3.33097	0
p-SCH	0.2	3.20081	0
Etch-stop	0.001	3.33097	0
p-cladding	1.0	3.20081	0
p-cap	0.2	3.20081	0.03

6.1.7 The Refractive Index Profile

According to the final structure, we can plot the refractive index profile according to the distance of the layers for the laser structure as following:

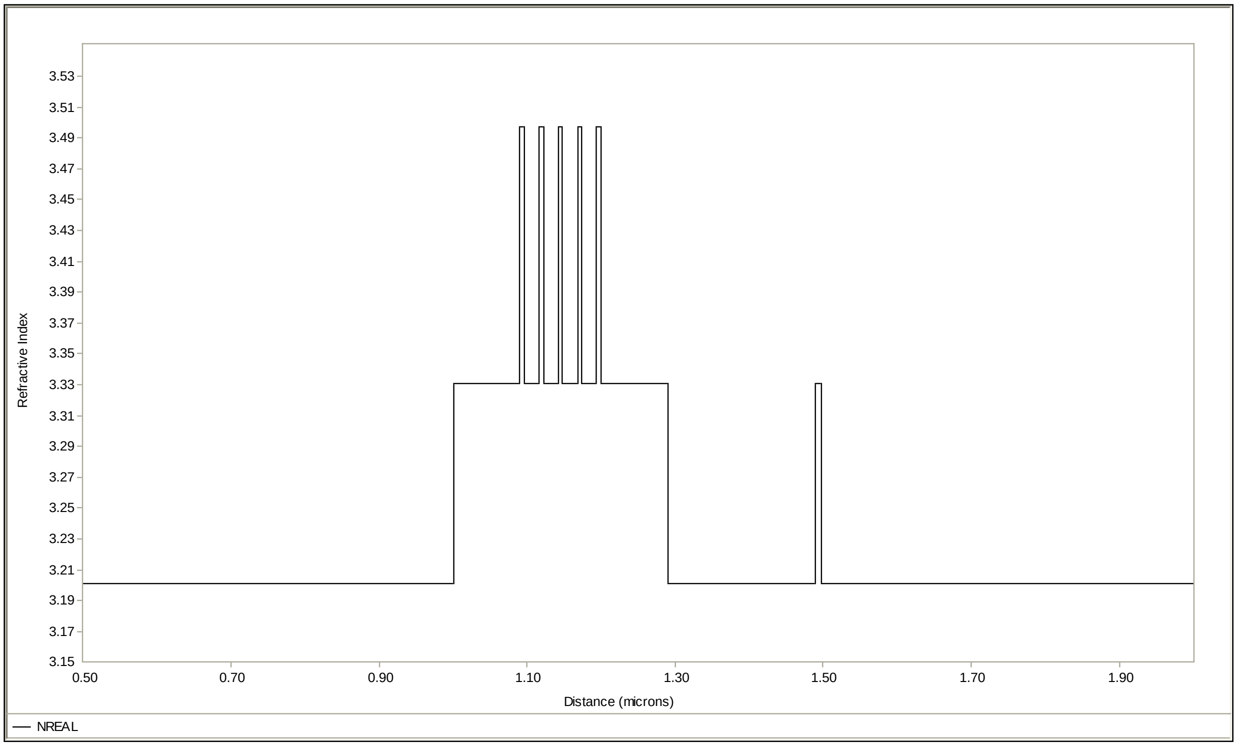


Figure 6.1.7 The laser structure of a 1310nm InGaAsP 5-QW Laser.

The output results are:

PHM	= 3.665990E-01
GAMMA(4)	= 1.100898E-02
GAMMA(6)	= 1.145860E-02
GAMMA(8)	= 1.161871E-02
GAMMA(10)	= 1.148110E-02
GAMMA(12)	= 1.105281E-02
WZR	= 3.246921E+00
WZI	= 2.729955E-06
FWHPF	= 3.749374E+01
KM	= 7
IT	= 4

6.2 InGaAsP/InGaAsP/InP (1550nm)

6.2.1 Introduction

In this section, the InGaAsP/InGaAsP/InP 1550 nm laser structure design will be introduced by using WAVEGUIDE II. The design procedures, input files and output will be explained in detail. The basic layers, the material compositions, layer thicknesses, QW numbers are designed in GAIN. The initial structure for the layers, the material compositions and layer thicknesses are shown in Table 6.2.1.

Table 6.2.1 Initial Laser structure (2-QW InGaAsP) for the 1.55um InGaAsP/InP laser structure.

Layer	Composition	Thickness (um)
n-substrate	InP	1.00
n-cladding	InP	0.50
n-SCH	$In_{0.0.748}Ga_{0.252}\ As_{0.547}\ P_{0.453}$	0.1
QW-1	$In_{0.49}Ga_{0.51}As_{0.939}\ P_{0.061}$	0.01
Barrier	$In_{0.0.748}Ga_{0.252}\ As_{0.547}\ P_{0.453}$	0.01
QW-2	$In_{0.49}Ga_{0.51}As_{0.939}\ P_{0.061}$	0.01
p-SCH	$In_{0.0.748}Ga_{0.252}\ As_{0.547}\ P_{0.453}$	0.1
p-spacer	InP	0.05
Etch stop layer	$In_{0.0.748}Ga_{0.252}\ As_{0.547}\ P_{0.453}$	0.01
p-cladding	InP	2.00
P cap	InP	1.00

6.2.2 The Initial Input File

The initial input file is based on the Table 6.2.1. The parameters for QW and barrier layers are fixed. The other layer thicknesses will be determined for the optimized laser operation. The initial input file is as follows:

```
CASE    KASE=WIFE
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=13.223   QZMI=0.0 !QZMR=13.223
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1
!CASE    DXIN=0.2 QZMR=10.932
!CASE    IL=100  KGSS=1

MODCON  KPOL=1   APB1=0.25   APB2=0.25

STRUCT  WVL=1.55

LAYER  NREAL=3.165   NLOSS=0.0012  TL=1.00   !N-sub, InP (layer 1)
LAYER  NREAL=3.165   NLOSS=0.00  TL=0.5      !n-cladding InP (layer 2)
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.1     !n-SCH (layer 3)
LAYER  NREAL=3.6363  NLOSS=0.00  TL=0.01   !QW, InGa1AsP (layer 4)
LAYER  NREAL=3.370   NLOSS=0.00  TL=0.01   !barrier InGa1AsP (layer 5)
LAYER  NREAL=3.6363  NLOSS=0.00  TL=0.01   !QW, InGa1AsP (layer 6)
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.1   !p-SCH (layer 7)
LAYER  NREAL=3.165   NLOSS=0.0   TL=0.05   !p-Spacer (layer 8)
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.01   !Etch stop layer (layer 9)
LAYER  NREAL=3.165   NLOSS=0.00  TL=2     !p-cladding InP (layer 10)
```

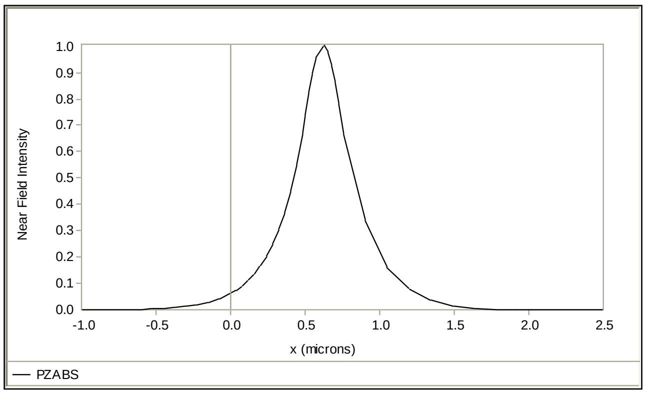
```
LAYER  NREAL=3.165   NLOSS=0.0012  TL=1.00   !p+cap, InP (layer 11)

!LAYER  NREAL=3.066696   NLOSS=0.00  TL=0.5    !p+cap, In0.53Ga0.47As



OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0

OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1  ITO=1

OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0

GAMOUT  LAYGAM=4    COMPGAM=0    GAMALL=0


!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=2

!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=10

!LOOPX1  ILX='TL' FINV=0.50 XINC=0.001  LAYCH=3

!LOOPX1  ILX='TL' FINV=0.50 XINC=0.001  LAYCH=7

LOOPZ1  ILZ='QZMR'  FINV=10.05  ZINC=-0.005  ! This loops to find initial guess

END
```

6.2.3 Searching the Fundamental Mode, Looping for QZMR

Now first to search for TE0 mode by Looping for QZMR from $N_{\max}^2 = 3.6363^2 =$ 13.22267769 to $N_{\min}^2 = 3.165^2 = 10.017225$.

Using the same criterion as already introduced in previous section, we loop the QZMR and find that: QZMR = 10.383 gives KM=7 and IT=3. So we change QZMR to 10.383 and end the looping.

The near field intensity and the far field plots are shown below:



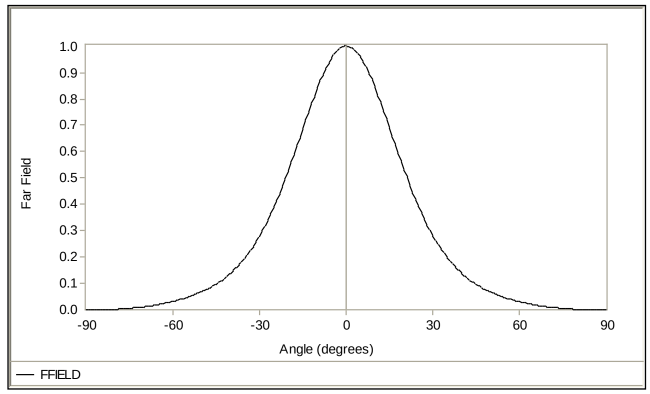


Figure 6.2.1. Fundamental mode near field plot for initial waveguide parameters.

Figure 6.2.2. Fundamental mode far field plot for initial waveguide parameters.

The output parameters are calculated and listed below:

PHM	= 3.234618E-01
GAMMA(4)	= 1.931755E-02
WZR	= 3.222567E+00
WZI	= 7.231057E-06
KM	= 7
IT	= 3

The layer structure is:

# of layers = 11

LAYER01	NLOSS= 0.00120	NREAL= 3.16500	TL= 1.00000
LAYER02	NLOSS= 0.00000	NREAL= 3.16500	TL= 0.50000
LAYER03	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.10000
LAYER04	NLOSS= 0.00000	NREAL= 3.63630	TL= 0.01000
LAYER05	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.01000
LAYER06	NLOSS= 0.00000	NREAL= 3.63630	TL= 0.01000
LAYER07	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.10000
LAYER08	NLOSS= 0.00000	NREAL= 3.16500	TL= 0.05000
LAYER09	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.01000
LAYER10	NLOSS= 0.00000	NREAL= 3.16500	TL= 2.00000
LAYER11	NLOSS= 0.00120	NREAL= 3.16500	TL= 0.00000

6.2.4 Looping the SCH layers to find the proper thickness for fundamental mode confinement

We Loop both the n-SCH and p-SCH layers from 0.1um to 0 um to find the proper thickness to get the maximum confinement in-QW. Note that we check for QW confinement and full-width at half-maximum power for far field (FWHPF) and make a proper choice. We cannot get high confinement and low FWHPF at the same time so it is a compromise. Generally the values are chosen according to design specifications.

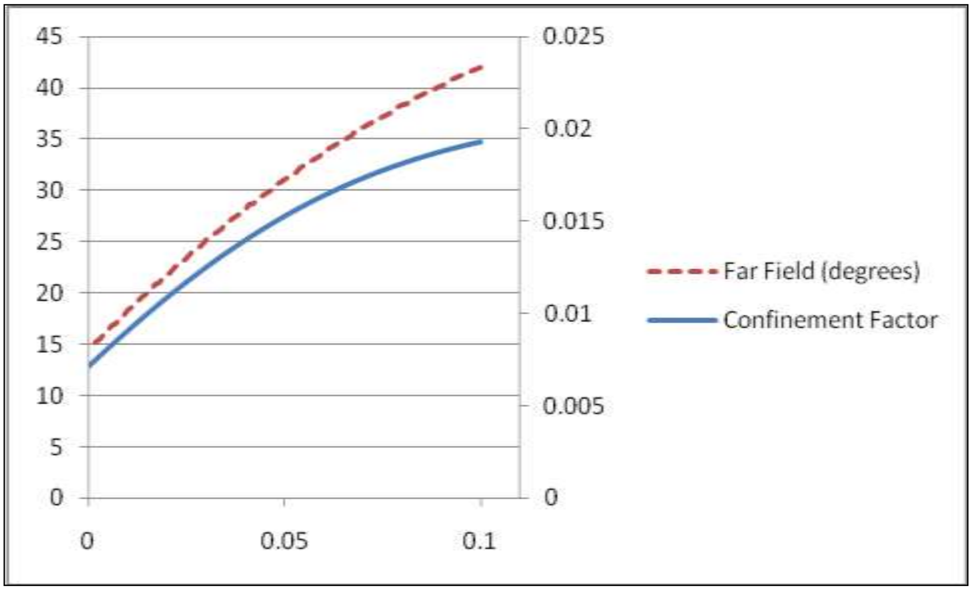


Figure 6.2.3. QW confinement factor and FWHPF vs. SCH thickness

From the figure 6.2.3, we can choose the proper thickness of the SCH layer as 0.09 um to keep high confinement factor and also keep the far field in an acceptable range.

The .db out file as below:

TL(3)	TL(7)	PHM	GAMMA(4)	WZR	WZI
QZR	FWHPN	FWHPF	KM	IT	
1.000000E-01	1.000000E-01	3.234618E-01	1.931755E-02	3.222567E+00	7.231057E-06
1.038494E+01	4.116993E-01	4.202424E+01	7	3	
9.900000E-02	9.900000E-02	3.214944E-01	1.927093E-02	3.221975E+00	7.375103E-06
1.038112E+01	4.132655E-01	4.186870E+01	6	3	

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9.000000E-02	**9.000000E-02**	**3.033277E-01**	**1.879699E-02**	**3.216602E+00**	**8.837192E-06**
1.034653E+01	**4.157555E-01**	**4.022596E+01**	**6**	**3**	

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4.000000E-02	4.000000E-02	1.871164E-01	1.397949E-02	3.187373E+00	2.679765E-05
1.015935E+01	5.251306E-01	2.811061E+01	6	3	
3.000000E-02	3.000000E-02	1.609835E-01	1.250472E-02	3.182239E+00	3.413880E-05
1.012664E+01	5.781233E-01	2.518284E+01	6	3	
2.000000E-02	2.000000E-02	1.341450E-01	1.085795E-02	3.177585E+00	4.384993E-05
1.009705E+01	6.537822E-01	2.174250E+01	6	3	
1.000000E-02	1.000000E-02	1.068947E-01	9.052941E-03	3.173525E+00	5.700401E-05
1.007126E+01	7.805903E-01	1.829568E+01	6	3	
7.632783E-17	7.632783E-17	7.983083E-02	7.112396E-03	3.170163E+00	7.561991E-05
1.004993E+01	9.856529E-01	1.443297E+01	6	2	

The output parameters are calculated and listed below:

PHM = 3.033277E-01

GAMMA(4) = 1.879699E-02

WZR = 3.216602E+00

WZI = 8.837192E-06

FWHPF = 4.022596E+01

KM = 6

IT = 3

The layer structure is:

# of layers = 11

LAYER01	NLOSS= 0.00120	NREAL= 3.16500	TL= 1.00000
LAYER02	NLOSS= 0.00000	NREAL= 3.16500	TL= 0.50000
LAYER03	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.09000
LAYER04	NLOSS= 0.00000	NREAL= 3.63630	TL= 0.01000
LAYER05	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.01000
LAYER06	NLOSS= 0.00000	NREAL= 3.63630	TL= 0.01000
LAYER07	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.09000
LAYER08	NLOSS= 0.00000	NREAL= 3.16500	TL= 0.05000
LAYER09	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.01000
LAYER10	NLOSS= 0.00000	NREAL= 3.16500	TL= 2.00000
LAYER11	NLOSS= 0.00120	NREAL= 3.16500	TL= 0.00000

The near field intensity and the far field plots are shown below:

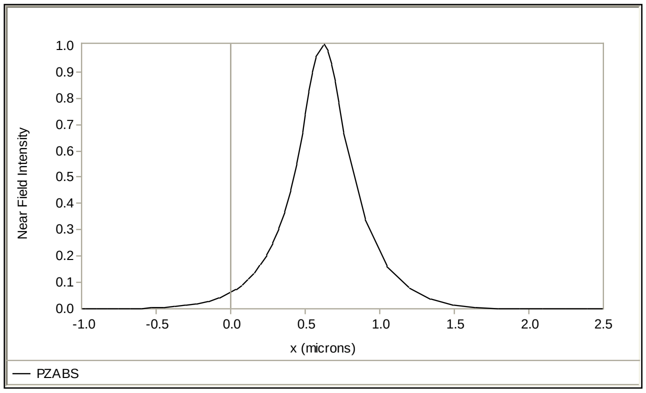


Figure 6.2.4. Fundamental mode near field plot with 0.16um SCH.

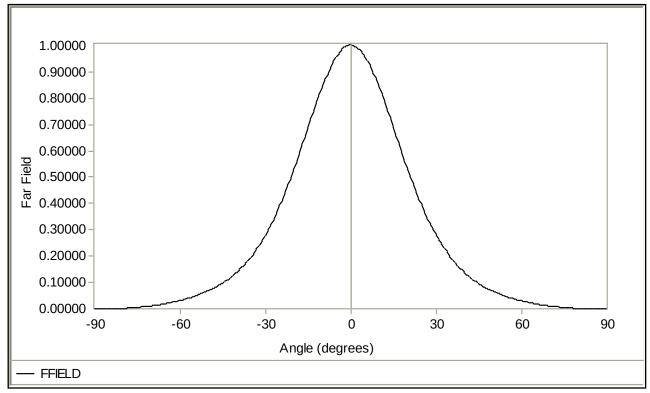


Figure 6.2.5. Fundamental mode far field plot with 0.16um SCH.

6.2.5 Making the Full Structure and Including Loss parameters

From the previous steps, the QZMR and the thickness of the SCH layer are decided, now we need to make the full structure and include the loss layers. Since we add the etch stop layer in the p-cladding layer and the original p-cladding layer is divided into first p-cladding (p-spacer) layer and second p-cladding layer. First we need to re-find the QZMR at the giving start thickness of the p-spacer and second p-cladding, then loop these two layers to find the proper thickness at the QZMR value. The input file for this structure is shown in the text box as follow:

```
CASE    KASE=WIFE
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=16   QZMI=0.0
```

```
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1
!CASE    DXIN=0.2 QZMR=10.932
!CASE    IL=100  KGSS=1
  MODCON  KPOL=1   APB1=0.25   APB2=0.25

STRUCT  WVL=1.55

LAYER  NREAL=3.165   NLOSS=0.00012  TL=1.00  !N-sub, InP
LAYER  NREAL=3.165   NLOSS=0.00  TL=0.5      !n-cladding InP
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.09     !n-SCH
LAYER  NREAL=3.6363  NLOSS=0.00  TL=0.01     !QW, InGa1AsP
LAYER  NREAL=3.370   NLOSS=0.00  TL=0.01     !barrier InGa1AsP
LAYER  NREAL=3.6363  NLOSS=0.00  TL=0.01     !QW, InGa1AsP
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.09     !p-SCH
LAYER  NREAL=3.165   NLOSS=0.0   TL=0.00     !p-Spacer
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.01     !Etch stop layer
LAYER  NREAL=3.165   NLOSS=0.00  TL=1.00     !p-cladding InP
LAYER  NREAL=3.165   NLOSS=0.0012  TL=1.00   !p+cap, InP
LAYER  NREAL=3.7        NLOSS=18.2415 TL=0.05  !Ti
LAYER  NREAL=4.64       NLOSS=26.6731 TL=0.12 !Pt
LAYER  NREAL=0.18       NLOSS=41.3474 TL=0.20 !Au


OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0
OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1  ITO=1
OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0
```

```
GAMOUT  LAYGAM=4    COMPGAM=0     GAMALL=0

!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=2

!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=10

!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=8

!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=9

!LOOPX1  ILX='TL' FINV=0.0 XINC=-0.001  LAYCH=3

!LOOPX1  ILX='TL' FINV=0.0 XINC=-0.001  LAYCH=7

LOOPZ1  ILZ='QZMR'  FINV=10.05  ZINC=-0.005

END
```

Same as in section 6.2.3, we loop the QZMR and find:

QZMR = 10.35 gives KM=6 and IT=2.

So we change the QZMR to 10.35 and close the looping QZMR .

The near field intensity and the far field plots are as follows:

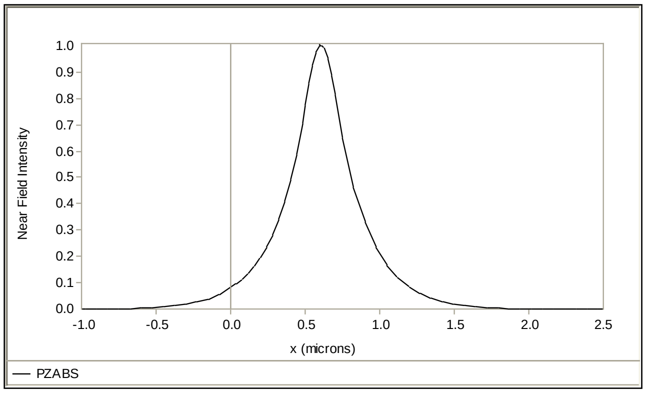


Figure 6.2.6. Fundamental mode near field plot for full structure.

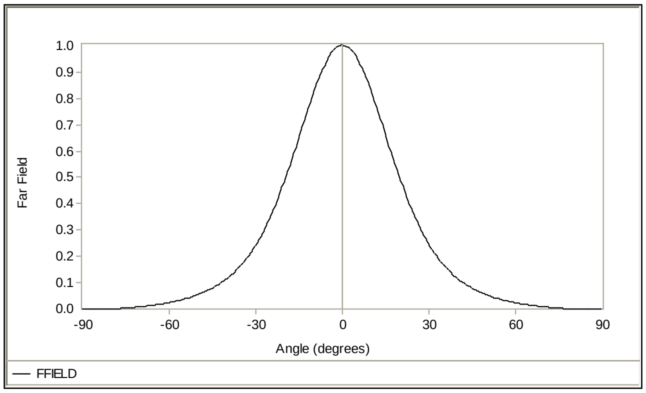


Figure 6.2.7. Fundamental mode far field plot for full structure.

We have to increase the p-cladding thickness so that the modal loss falls into acceptable limits. Looping the second p-clad thickness from 1.0 μm to 0.0 μm, we obtain the modal intensity loss as function of the p-cladding thickness as following figure:

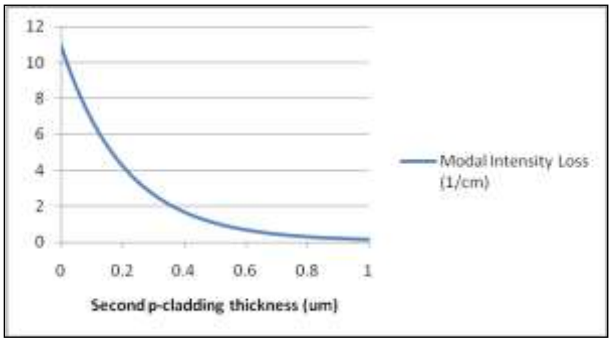


Figure 6.2.8. Modal intensity loss vs. p-clad thickness.

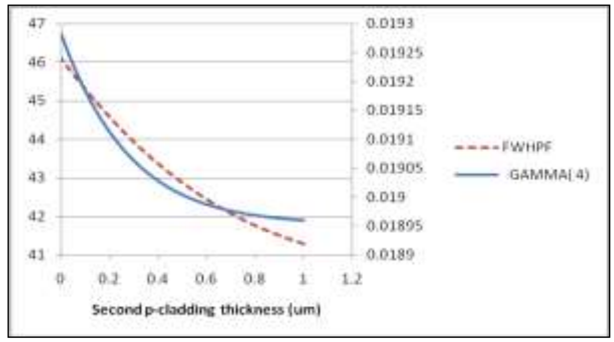
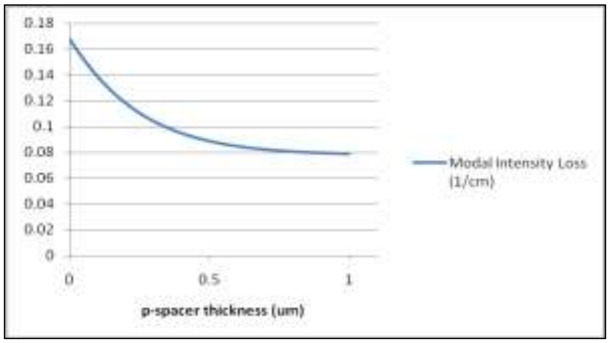


Figure 6.2.9. QW confinement factor and FWHPF vs. p-clad thickness.

Based on the plots shown in Figures 6.2.8 and 6.2.9, we can choose the thickness value of 1 μm for the second p-cladding since the loss curve drops to minimum and higher thickness will cause lower confinement factor. The intensity modal loss is calculated from WZI values (amplitude loss in μm^{-1}) as the formula:

$$\alpha = WZI \cdot (4\pi/\lambda) \cdot 10^4 \quad /cm$$

Since we choose the second p-cladding thickness as 1 um, we need to re-find the QZMR according to the new second-p cladding thickness as previous section. QZMR can be set to 10.35. Then we can find the proper p-spacer thickness by looping the p-spacer thickness from 0 to 1 um to check the modal loss and confinement factor.



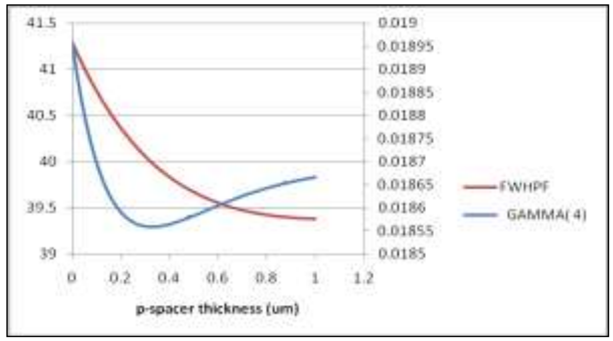


Figure 6.2.10. Modal intensity loss vs. p-spacer thickness.

Figure 6.2.11. QW confinement factor and FWHPF vs. p-spacer thickness.

Based on the plots shown in Figures 6.2.10 and 6.2.11, we can choose the thickness value of 1 μm for the p-spacer layer since the loss curve drops to minimum the confinement factor can also get high value at this point. The design will stop here!

6.2.6 Output Parameters and Plots

From the previous design to optimize the laser structure, we can get the final output values as listed below:

PHM = 1.178654E+00

GAMMA(8) = 1.866676E-02

WZR = 3.214231E+00

WZI = 9.756738E-07

FWHPF = 3.937932E+01

KM = 6

IT = 4

The layer structure is:

# of layers = 14

LAYER01	NLOSS= 0.00012	NREAL= 3.16500	TL= 1.00000
LAYER02	NLOSS= 0.00000	NREAL= 3.16500	TL= 0.50000
LAYER03	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.09000
LAYER04	NLOSS= 0.00000	NREAL= 3.63630	TL= 0.01000
LAYER05	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.01000
LAYER06	NLOSS= 0.00000	NREAL= 3.63630	TL= 0.01000
LAYER07	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.09000
LAYER08	NLOSS= 0.00000	NREAL= 3.16500	TL= 1.00000
LAYER09	NLOSS= 0.00000	NREAL= 3.37000	TL= 0.01000
LAYER10	NLOSS= 0.00000	NREAL= 3.16500	TL= 1.00000
LAYER11	NLOSS= 0.00120	NREAL= 3.16500	TL= 1.00000
LAYER12	NLOSS=18.24150	NREAL= 3.70000	TL= 0.05000
LAYER13	NLOSS=26.67310	NREAL= 4.64000	TL= 0.12000
LAYER14	NLOSS=41.34740	NREAL= 0.18000	TL= 0.20000

Near field and far field plots are shown as following for the final structure:

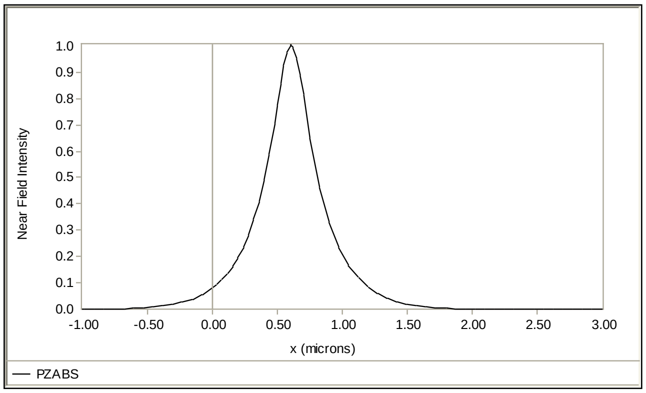


Figure 6.2.12. Fundamental mode near field plot for final structure.

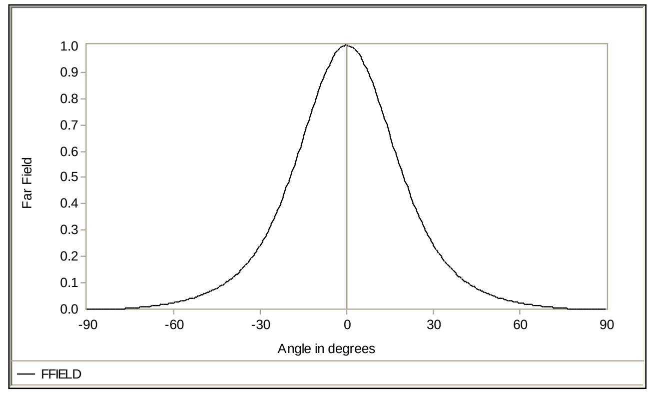


Figure 6.2.13. Fundamental mode far field plot for final structure.

The Final laser structure for this 1.55 um InGaAsP laser design can be found in the table 6.2.2 as follow:

Table 6.2.2 Final Laser structure (2-QW InGaAsP) for the 1.55um InGaAsP/InP laser structure.

Layer	Composition	Thickness (um)
n-substrate	InP	1.00
n-cladding	InP	0.50
n-SCH	$In_{0.0.748}Ga_{0.252}\,As_{0.547}\,P_{0.453}$	0.09
QW-1	$In_{0.49}Ga_{0.51}As_{0.939}\,P_{0.061}$	0.01
barrier	$In_{0.0.748}Ga_{0.252}\,As_{0.547}\,P_{0.453}$	0.01
QW-2	$In_{0.49}Ga_{0.51}As_{0.939}\,P_{0.061}$	0.01
p-SCH	$In_{0.0.748}Ga_{0.252}\,As_{0.547}\,P_{0.453}$	0.09
p-spacer	InP	1.00
Etch stop layer	$In_{0.0.748}Ga_{0.252}\,As_{0.547}\,P_{0.453}$	0.01
p-cladding	InP	1.00
P cap	InP	1.00

The final input file for WAVEGUIDE II is also shown as follows:

```
CASE    KASE=WIFE

CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6

CASE    QZMR=10.35   QZMI=0.0

CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1

!CASE    DXIN=0.2 QZMR=10.932

!CASE    IL=100  KGSS=1


MODCON  KPOL=1   APB1=0.25   APB2=0.25
```

```
STRUCT  WVL=1.55


LAYER  NREAL=3.165   NLOSS=0.00012  TL=1.00   !N-sub, InP
LAYER  NREAL=3.165   NLOSS=0.00  TL=0.5      !n-cladding InP
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.09     !n-SCH
LAYER  NREAL=3.6363  NLOSS=0.00  TL=0.01   !QW, InGa1AsP
LAYER  NREAL=3.370   NLOSS=0.00  TL=0.01   !barrier InGa1AsP
LAYER  NREAL=3.6363  NLOSS=0.00  TL=0.01   !QW, InGa1AsP
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.09   !p-SCH
LAYER  NREAL=3.165   NLOSS=0.0   TL=1.00   !p-Spacer
LAYER  NREAL=3.370   NLOSS=0.0   TL=0.01   !Etch stop layer
LAYER  NREAL=3.165   NLOSS=0.00  TL=1.00     !p-cladding InP
LAYER  NREAL=3.165   NLOSS=0.0012  TL=1.00   !p+cap, InP
LAYER  NREAL=3.7        NLOSS=18.2415 TL=0.05  !Ti
LAYER  NREAL=4.64       NLOSS=26.6731 TL=0.12 !Pt
LAYER  NREAL=0.18       NLOSS=41.3474 TL=0.20 !Au



OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0
OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1  ITO=1
OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0
GAMOUT  LAYGAM=4    COMPGAM=0     GAMALL=0


!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=2
!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=10
!LOOPX1  ILX='TL' FINV=1.00 XINC=0.001  LAYCH=8
```

```
!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.001  LAYCH=9

!LOOPX1  ILX='TL' FINV=0.0 XINC=-0.001  LAYCH=3

!LOOPX1  ILX='TL' FINV=0.0 XINC=-0.001  LAYCH=7

!LOOPZ1  ILZ='QZMR'  FINV=10.05  ZINC=-0.005

END
```

6.2.7 The Refractive Index Profile

According to the final structure, we can plot the refractive index profile according to the distance of the layers for the laser structure as following:

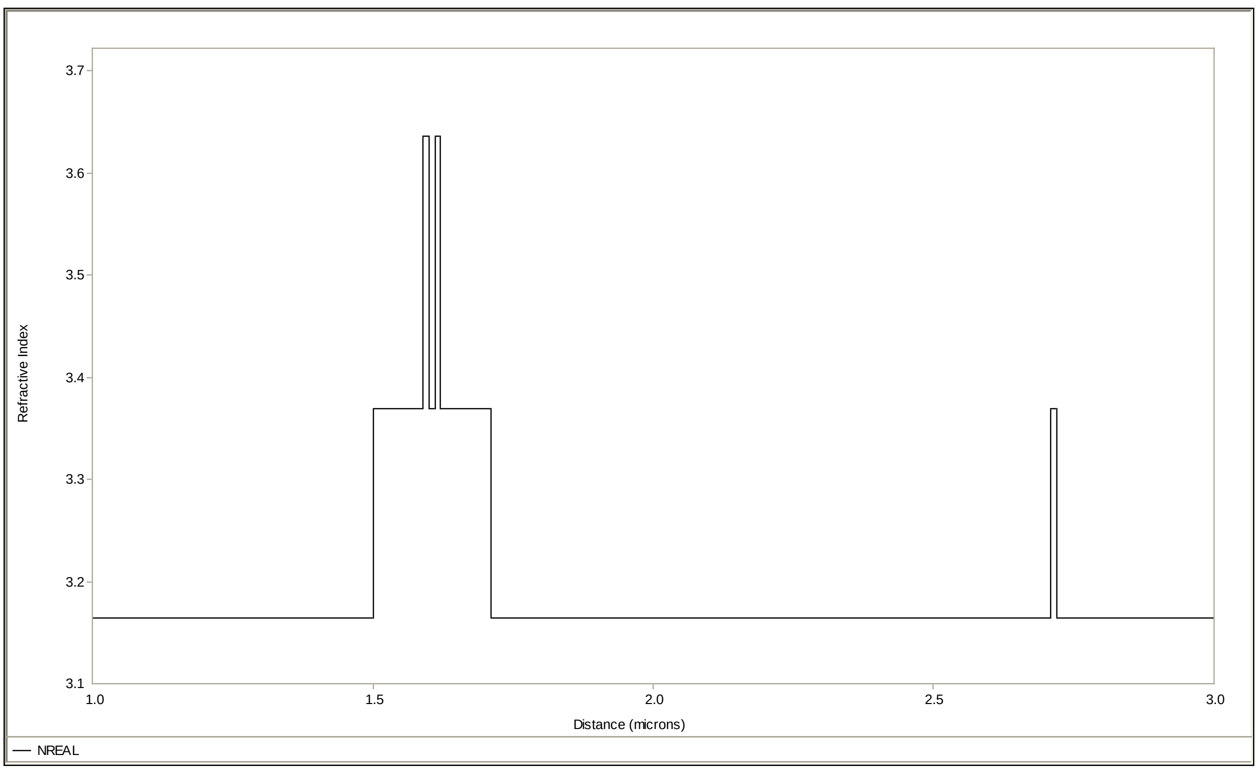


Figure 6.2.14 The laser structure of a 1.55 um InGaAsP 2-QW Laser.

Chapter 7

ALINGAAS / INP

Compared with the InGaAsP/InP system, which is introduced in Chapter 6, the AlInGaAs/InP system has some superior features, such as single element III, larger conduction band offset, and higher Schottky barriers. This material system is better for the device applications which require high temperature operation. It has also been shown that this system is a good challenger to InGaAsP for optoelectronic applications. Integration with microelectronic devices might make it even more attractive. It might turn out to be the best candidate for future OEICs.

This chapter includes two examples of using the AlInGaAs/InP material system. Section 7.1 introduces a 1550-nm laser structure design with TM mode, and Section 7.2 introduces a 1310-nm laser structure design with TE mode. **TE mode** is the transverse electric mode whose electric field vector is normal to the direction of propagation, while **TM mode** is the transverse magnetic mode whose magnetic field vector is normal to the direction of propagation.

7.1 TM-mode 1550-nm Semiconductor Laser Design

7.1.1 Introduction

TM polarization in semiconductor lasers can be achieved by having tensile strain in quantum wells. The active layers of the TM-mode laser operating at a wavelength of 1550 nm was designed earlier by SMU Photonics group [1, *Material System # 9 in Gain program*] using the GAIN program [2]. The input parameters to the GAIN program for this design are shown in Table 7.1.1 [1, *Table C.9.1*].

Table 7.1.1 Active Waveguide Layers (QWs, barrier and inner clad) for the Laser

Layer	**□ ((μm)**	**Strain**	**Thickness (Å)**
QW ($In_xGa_{1-x}As$)	1.51	5.1231E-003	150
SCH ($Al_xGa_yIn_{1-x-y}As$)	1.28	-	1500
Cladding ($Al_xGa_yIn_{1-x-y}As$)	0.83	-	380

The theoretical study for this laser, the energy levels, L-I curve of the laser, optical gain-λ curve of the laser and mode gain as a function of current density (J) can be found in details in [1]. Below is the final structure for the active layers, and the material compositions and layer thicknesses of the active layers are shown in Table 7.1.2.

Table 7.1.2 Active Layer Composition and Thickness Specification for the Laser.

Layer	**Composition**	**Thickness (μm)**
inner n-cladding	$Al_{0.48}In_{0.52}As$	0.0375
n-GRIN	$Al_{0.48}In_{0.52}As$ - $Al_{0.1392}Ga_{0.3408}In_{0.52}As$	0.15
QW	$Ga_{0.55}InAs$	0.015
barrier	$Al_{0.1392}Ga_{0.3408}InAs$	0.01
QW	$Ga_{0.55}InAs$	0.015
p-GRIN	$Al_{0.1392}Ga_{0.3408}In_{0.52}As$ - $Al_{0.48}In_{0.52}As$	0.15
inner p-cladding	$Al_{0.48}In_{0.52}As$	0.0375

7.1.2 The Initial Input File

The active layers are obtained from Table 7.1.2. The parameters for QW and barrier layers are fixed. The other layer thicknesses will be determined for the optimized laser operation. The initial input file is as follows:

```
!DESCRIPTION: -0.51 Tensile 2-QW InGaAs/AlGaInAs/InP laser operating at 1.55 μm.

!Material System is the Mondry's refractive index modeling which is MATSYS=13.0.


!CASE Parameter Set

CASE KASE=WIFE

CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=12.0 QZMI=0.001

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30


!MODCON Parameter Set
```

```
MODCON KPOL=2 APB1=0.25 APB2=0.25


!STRUCT Parameter Set

STRUCT WVL=1.55


!LAYER Parameter Set

!------------------- beginning of structure ----------------------

!n-sub InP LAYS: 1

LAYER MATSYS=1.0   XPERC=0.0          YPERC=0.0      NLOSS=0.0      TL=0.0


!n-GRIN LAYS: 2-12

STRUCT GRW = 0.0                                   ! graded width (microns)

! effective index of first slice (implicit):

LAYER MATSYS=13.0  XPERC=0.48         YPERC=0.0      NLOSS=0.0

LAYER NSLC = 10                                    ! number of slices

! effective index of last slice (implicit):

LAYER MATSYS=13.0  XPERC=0.1392       YPERC=0.0      NLOSS=0.0


!Active region 1 Barrier and 2 QWs InGaAs/AlGaInAs LAYS: 13-15

LAYER MATSYS=9.0   XPERC=0.55 YPERC=0.0      NLOSS=0.0      TL=0.015

LAYER MATSYS=13.0  XPERC=0.1392       YPERC=0.3408   NLOSS=0.0      TL=0.01

LAYER MATSYS=9.0   XPERC=0.55 YPERC=0.0      NLOSS=0.0      TL=0.015


!p-GRIN LAYS: 16-26

STRUCT GRW = 0.0                                   ! graded width (microns)

! effective index of first slice(implicit)
```

```
LAYER MATSYS=13.0  XPERC=0.1392           YPERC=0.0           NLOSS=0.0

LAYER NSLC = 10                                                ! number of slices

! effective index of last slice (implicit)

LAYER MATSYS=13.0  XPERC=0.48             YPERC=0.0           NLOSS=0.0


!p-clad LAYS: 27

LAYER MATSYS=1.0   XPERC=0.0              YPERC=0.0           NLOSS=0.0           TL=0.0

!----------------------- end of structure ------------------------


!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0

OUTPUT FWHPNO=0 FWHPFO=1 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=0 LYROUT=0


!GAMOUT Parameter Set

GAMOUT LAYGAM=13 LAYGAM=15 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set

!LOOPZ1 ILZ='QZMR'        FINV=10.0           ZINC=-0.01

!LOOPZ1 ILZ='WVL'         FINV=1.6            ZINC=0.001

!LOOPZ1 ILZ='GRW'         FINV=0.0            ZINC=-0.01

!LOOPX1 ILX='TL'          FINV=0.1            XINC=0.001          LAYCH=01


END
```

In the input file KPOL=2 is to set TM polarization (KPOL=1 corresponds to TE mode). The material system is InGaAs/AlGaInAs/AlGaInAs (substrate InP). WAVEGUIDE II has two models for the material system Al(x)Ga(y)In(1-x-y)As, the Adachi's (Material System 2) and Mondry's models (Material System 13). In our calculations we preferred the Mondry's model since the calculated refractive indices look closer to the values in the literature. One should check both models, compare the results to some measured (experimental) values and decide which to use. For a detailed description of material systems in WAVEGUIDE II, refer to Chapter 3.

Furthermore, the GRIN layers can be represented in a compact form as seen in the input file. Detailed explanations about the usage of GRIN can be found in Chapter 3. In the representation GRW is the total grin thickness, NSLC is the number of steps in the grin. One also should input the initial (first slice) and final (last slice) material compositions for the grin structure.

The refractive indices, the real and imaginary part loss terms, for the waveguide layers were initially calculated as follows. The number of layers is ten for both n-GRIN and p-GRIN sections, therefore there are 27 layers in the structure initially, which is shown below. The top layer is the n-substrate.

# of layers = 27

```
LAYER01  NLOSS= 0.00000    NREAL= 3.16492    TL=   0.00000
LAYER02  NLOSS= 0.00000    NREAL= 3.19969    TL=   0.00000
```

LAYER03	NLOSS= 0.00000	NREAL= 3.22246	TL=	0.00000
LAYER04	NLOSS= 0.00000	NREAL= 3.24523	TL=	0.00000
LAYER05	NLOSS= 0.00000	NREAL= 3.26800	TL=	0.00000
LAYER06	NLOSS= 0.00000	NREAL= 3.29077	TL=	0.00000
LAYER07	NLOSS= 0.00000	NREAL= 3.31354	TL=	0.00000
LAYER08	NLOSS= 0.00000	NREAL= 3.33631	TL=	0.00000
LAYER09	NLOSS= 0.00000	NREAL= 3.35907	TL=	0.00000
LAYER10	NLOSS= 0.00000	NREAL= 3.38184	TL=	0.00000
LAYER11	NLOSS= 0.00000	NREAL= 3.40461	TL=	0.00000
LAYER12	NLOSS= 0.00000	NREAL= 3.42738	TL=	0.00000
LAYER13	NLOSS= 0.00000	NREAL= 3.57493	TL=	0.01500
LAYER14	NLOSS= 0.00000	NREAL= 3.42738	TL=	0.01000
LAYER15	NLOSS= 0.00000	NREAL= 3.57493	TL=	0.01500
LAYER16	NLOSS= 0.00000	NREAL= 3.42738	TL=	0.00000
LAYER17	NLOSS= 0.00000	NREAL= 3.40461	TL=	0.00000
LAYER18	NLOSS= 0.00000	NREAL= 3.38184	TL=	0.00000
LAYER19	NLOSS= 0.00000	NREAL= 3.35907	TL=	0.00000
LAYER20	NLOSS= 0.00000	NREAL= 3.33631	TL=	0.00000
LAYER21	NLOSS= 0.00000	NREAL= 3.31354	TL=	0.00000
LAYER22	NLOSS= 0.00000	NREAL= 3.29077	TL=	0.00000
LAYER23	NLOSS= 0.00000	NREAL= 3.26800	TL=	0.00000
LAYER24	NLOSS= 0.00000	NREAL= 3.24523	TL=	0.00000
LAYER25	NLOSS= 0.00000	NREAL= 3.22246	TL=	0.00000
LAYER26	NLOSS= 0.00000	NREAL= 3.19969	TL=	0.00000
LAYER27	NLOSS= 0.00000	NREAL= 3.16492	TL=	0.00000

7.1.3 Searching the Fundamental Mode, Looping for QZMR

We started with GRIN thickness of 0.0 μm but we could start with a small value like 0.05 μm. We searched for TM_0 mode by looping for QZMR from $n_{max}^2 = (3.57493)^2 \approx 12.0$ to $n_{min}^2 = (3.16492)^2 \approx 10.0$, where n_{max} is the highest refractive index and is n_{min} the lowest refractive index in the structure.

A criterion is to look for a value where PHM becomes < 1.0. Here all the QZMR values looks OK, but this is not the usual case, that is PHM becomes <1.0 for certain QZMR values. Generally PHM criterion works for symmetric lossless structures. Other criteria are IT and KM. IT is the iteration number to find the root and usually a number less than 10 is good. We normally look for even lower values. KM is a qualitative indication and mostly it must be 6 or 7 (7 indicates the best case for the solution). Another parameter that might be helpful is WZR. It is the real part of the effective index and any guided mode must have an effective index value which is between the refractive indices of the core and the cladding. Therefore, if there is a block of values for WZR, which is between the refractive indices of the core and the cladding, there is a great chance that the mode is located there. In order to make sure that we get the desired mode (usually fundamental mode), we should check the near field plots, especially the real part of it.

The looping results are calculated as follow:

QZMR	PHM	GAMMA(13)	GAMMA(15)	WZR	WZI
FWHPF	KM	IT			
1.200000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	2.935066E-17
1.409274E+01	6	15			
1.199000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	-1.849002E-17
1.409274E+01	6	15			
1.198000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	-4.384558E-17
1.409274E+01	6	15			
1.197000E+01	8.089334E-02	9.608848E-03	9.608848E-03	3.168996E+00	-1.780146E-11
1.409274E+01	6	15			
		.			
		.			
		.			
1.008000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	3.340669E-12
1.409274E+01	6	4			
1.007000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	1.274324E-13
1.409274E+01	6	4			
1.006000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	7.214575E-16
1.409274E+01	6	4			
1.005000E+01	***8.089334E-02***	***9.608850E-03***	***9.608850E-03***	***3.168996E+00***	***2.574181E-12***
1.409274E+01	***6***	***3***			
1.004000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	-1.070434E-15
1.409274E+01	6	3			
1.003000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	1.266772E-12
1.409274E+01	6	4			

1.002000E+01	8.089334E-02	9.608852E-03	9.608852E-03	3.168996E+00	5.704662E-11
1.409275E+01	6	6			
1.001000E+01	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	-1.134112E-15
1.409274E+01	6	7			
1.000000E+01	8.089334E-02	9.608849E-03	9.608849E-03	3.168996E+00	4.161345E-11
1.409274E+01	6	6			

QZMR=10.05 gives KM=6 and IT=3. Also the WZR values repeated over this range. Then we end the looping and set the QZMR value to 10.05. For this fixed value we run the program and obtain the output parameters db file, near field and far field plots. For the TM_0 mode, near field (real part and intensity) and far field plots are in Figures 7.1.1 and 7.1.2 below.

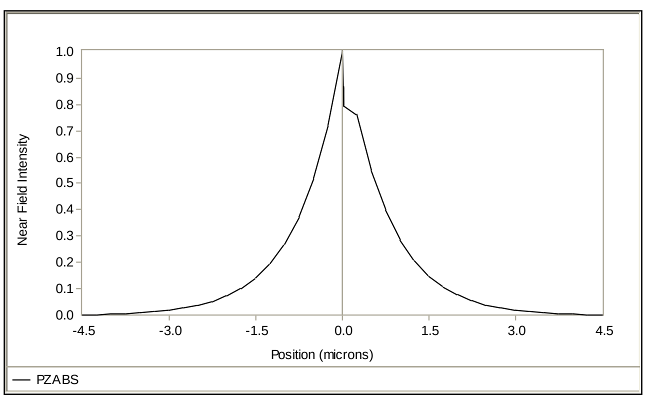


Figure 7.1.1 Fundamental mode near field plots for initial waveguide parameters. GRIN thickness=0.0 μm.

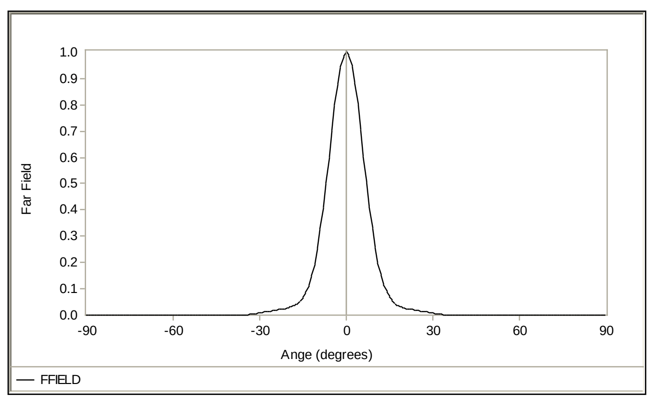


Figure 7.1.2 Fundamental mode far field plot for initial waveguide parameters. GRIN thickness=0.0 μm.

The calculated output parameters in the db file are listed below:

PHM	= 8.089334E-02
GAMMA(13)	= 7.661113E-03
GAMMA(15)	= 7.661113E-03
WZR	= 3.168996
WZI	= 2.538510E-12
FWHPF	= 1.409274E+01
KM	= 6
IT	= 3

7.1.4 Fundamental Mode Confinement and GRIN Looping

We loop for GRIN thickness (GRW) from 0.0 to 1.0 μm to get max confinement in QWs. Note that we check for QW confinement and full-width at half-maximum power for far field (FWHPF) and make a proper choice. We cannot get high confinement and low FWHPF at the same time so it is a compromise. Generally, the values are chosen according to design specifications.

GRW1	PHM	GAMMA(13)	GAMMA(15)	WZR	WZI
FWHPF	KM	IT			
0.000000E+00	8.089334E-02	9.608850E-03	9.608850E-03	3.168996E+00	2.538510E-12
1.409274E+01	6	3			
1.000000E-02	1.047463E-01	1.160557E-02	1.160557E-02	3.170928E+00	-5.036174E-20
1.698126E+01	6	4			
2.000000E-02	1.281249E-01	1.352827E-02	1.352827E-02	3.173196E+00	-1.879758E-14
1.981909E+01	6	3			

		.			
		.			
2.400000E-01	4.090194E-01	3.116812E-02	3.116812E-02	3.253860E+00	1.180554E-14
5.288010E+01	6	2			
2.500000E-01	4.140660E-01	3.119973E-02	3.119973E-02	3.257180E+00	2.472019E-15
5.298805E+01	6	2			
2.600000E-01	***4.181026E-01***	***3.121183E-02***	***3.121183E-02***	***3.260406E+00***	***-4.163405E-14***
5.360970E+01	***6***	***2***			
2.700000E-01	4.208223E-01	3.120034E-02	3.120034E-02	3.263540E+00	-1.905086E-14
5.393142E+01	6	2			
2.800000E-01	4.211745E-01	3.116917E-02	3.116917E-02	3.266581E+00	-3.143539E-14
5.422922E+01	6	2			
		.			
		.			
9.800000E-01	4.282952E-01	2.340898E-02	2.340898E-02	3.356311E+00	7.132523E-22
5.012366E+01	7	3			
9.900000E-01	4.265284E-01	2.333671E-02	2.333671E-02	3.356817E+00	-8.471022E-22
4.999298E+01	7	3			
1.000000E+00	4.243346E-01	2.326544E-02	2.326544E-02	3.357315E+00	-1.742098E-22
4.989145E+01	7	3			

The plots for QW confinement factor and FWHPF vs. GRIN thickness are shown in Figure 7.1.3. In this case, we picked a value that gives the maximum confinement factor in QWs so GRIN thickness=0.26 μm. This value should be determined according to design specifications.

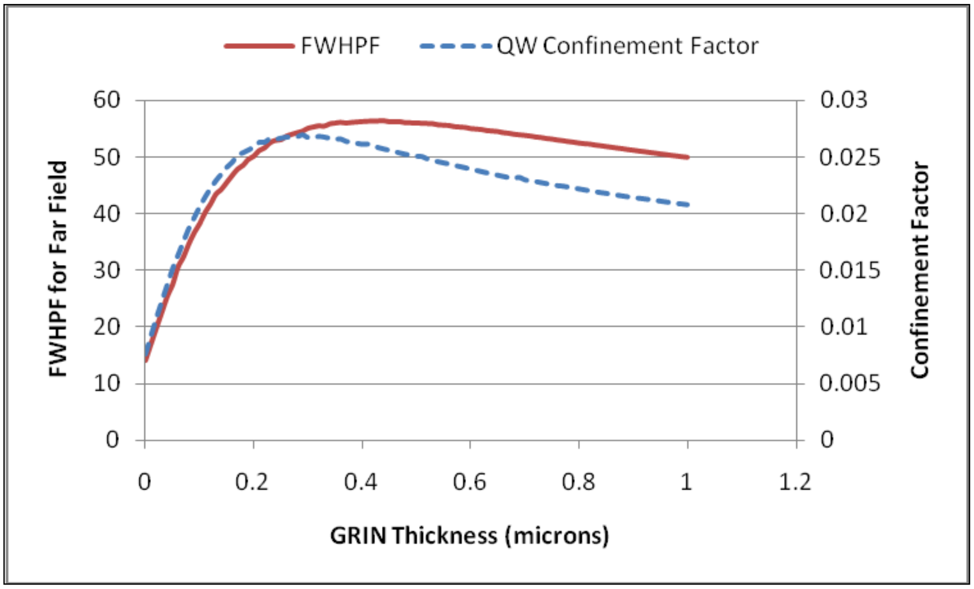


Figure 7.1.3 QW confinement factor and FWHPF vs. GRIN thickness.

Then we set QZMR to 10.63 and GRIN thickness to 0.26 μm. For this value the effective index for the fundamental mode is WZR=3.260406 and the output parameters in db file are as follows:

PHM = 4.181026E-01

GAMMA(13) = 2.675802E-02

GAMMA(15) = 2.675802E-02

WZR = 3.260406

WZI = 2.862518E-11

FWHPF = 5.360991E+01

KM = 6

IT = 1

The near field and far field plots for the GRIN thickness of 0.26 μm are shown in Figures 7.1.4 and 7.1.5, respectively.

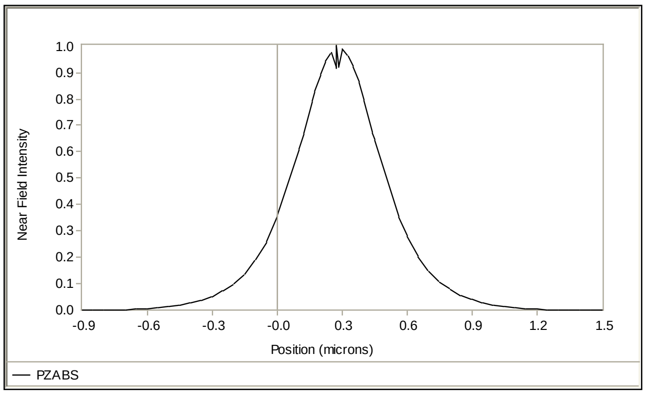


Figure 7.1.4 Fundamental mode near field plots for GRIN thickness=0.26 μm.

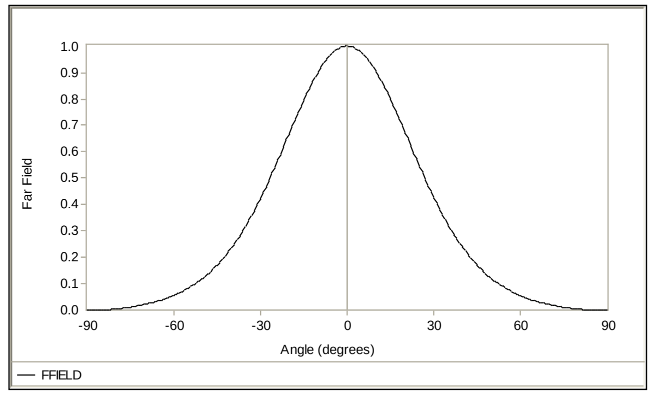


Figure 7.1.5 Fundamental mode far field plot for GRIN thickness=0.26 μm.

Now the layer parameters are calculated and listed below:

# of layers = 27

LAYER01 NLOSS= 0.00000 NREAL= 3.16492 TL= 0.00000

LAYER02 NLOSS= 0.00000 NREAL= 3.19969 TL= 0.01300

LAYER03 NLOSS= 0.00000 NREAL= 3.22246 TL= 0.02600

LAYER04 NLOSS= 0.00000 NREAL= 3.24523 TL= 0.02600

LAYER05 NLOSS= 0.00000 NREAL= 3.26800 TL= 0.02600

LAYER06 NLOSS= 0.00000 NREAL= 3.29077 TL= 0.02600

LAYER07 NLOSS= 0.00000 NREAL= 3.31354 TL= 0.02600

LAYER08 NLOSS= 0.00000 NREAL= 3.33631 TL= 0.02600

LAYER09 NLOSS= 0.00000 NREAL= 3.35907 TL= 0.02600

LAYER10 NLOSS= 0.00000 NREAL= 3.38184 TL= 0.02600

LAYER11 NLOSS= 0.00000 NREAL= 3.40461 TL= 0.02600

LAYER12 NLOSS= 0.00000 NREAL= 3.42738 TL= 0.01300

LAYER13 NLOSS= 0.00000 NREAL= 3.57493 TL= 0.01500

LAYER14 NLOSS= 0.00000 NREAL= 3.42738 TL= 0.01000

LAYER15 NLOSS= 0.00000 NREAL= 3.57493 TL= 0.01500

LAYER16 NLOSS= 0.00000 NREAL= 3.42738 TL= 0.01300

LAYER17 NLOSS= 0.00000 NREAL= 3.40461 TL= 0.02600

LAYER18 NLOSS= 0.00000 NREAL= 3.38184 TL= 0.02600

LAYER19 NLOSS= 0.00000 NREAL= 3.35907 TL= 0.02600

LAYER20 NLOSS= 0.00000 NREAL= 3.33631 TL= 0.02600

LAYER21 NLOSS= 0.00000 NREAL= 3.31354 TL= 0.02600

LAYER22 NLOSS= 0.00000 NREAL= 3.29077 TL= 0.02600

LAYER23 NLOSS= 0.00000 NREAL= 3.26800 TL= 0.02600

LAYER24 NLOSS= 0.00000 NREAL= 3.24523 TL= 0.02600

LAYER25 NLOSS= 0.00000 NREAL= 3.22246 TL= 0.02600

LAYER26 NLOSS= 0.00000 NREAL= 3.19969 TL= 0.01300

LAYER27 NLOSS= 0.00000 NREAL= 3.16492 TL= 0.00000

7.1.5 Building the Full Structure with Loss Parameters

The full structure includes cladding, transition, inner cladding and GRIN layers on both n and p sides, as well as active layers in between. The doping concentration is higher for the outmost layers and decreases as it gets closer to active layers. Therefore, the absorption losses for the outer layers are higher compared to inner layers. The loss figures for the layers were obtained from the work done by Babic and others [3], [4] on the absorption loss in GaAs and InP at different wavelengths of interest. The loss values for different doping levels were calculated and the updated input file is shown below. Here only the loss values in GRIN structure were not taken into account for simplicity of the calculations. Since the doping level is low the effect will be low, yet the field confinement is relatively high. Therefore, one should take into account all these considerations.

```
!The optimized structure for laser at 1.55 um.
!Material System based, Mondry's refractive index modeling is used.
!DESCRIPTION: -0.51 Tensile 2-QW InGaAs/AlGaInAs/InP.

!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.63 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=2 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=1.55

!LAYER Parameter Set
!------------------- beginning of structure ----------------------
!n-sub / n-clad are InP LAYS: 1/2
```

```
LAYER MATSYS=1.0   XPERC=0.0      YPERC=0.0        NLOSS=0.00025    TL=0.0

LAYER MATSYS=1.0   XPERC=0.0      YPERC=0.0        NLOSS=0.00025    TL=2.0


!n-transition LAYS: 3-5

LAYER MATSYS=13.0  XPERC=0.4128  YPERC=0.0672              NLOSS=0.00075    TL=0.0025

LAYER MATSYS=13.0  XPERC=0.44592 YPERC=0.03408            NLOSS=0.00075    TL=0.005

LAYER MATSYS=13.0  XPERC=0.48    YPERC=0.0                 NLOSS=0.00075    TL=0.0025


!inner n-clad LAYS: 6

LAYER MATSYS=13.0  XPERC=0.48    YPERC=0.0       NLOSS=0.000125  TL=0.0


!n-GRIN LAYS: 7-17 Optimized =0.26

STRUCT GRW = 0.26                                ! graded width (microns)

! effective index of first slice(implicit)

LAYER MATSYS=13.0  XPERC=0.48    YPERC=0.0       NLOSS=0.0000125

LAYER NSLC = 10                                  ! number of slices

! effective index of last slice (implicit)

LAYER MATSYS=13.0  XPERC=0.1392  YPERC=0.0       NLOSS=0.0000125


!Active region 1 Barrier and 2 QWs InGaAs/AlGaInAs LAYS: 18-20

LAYER MATSYS=9.0   XPERC=0.55    YPERC=0.0                 NLOSS=0.0          TL=0.015

LAYER MATSYS=13.0  XPERC=0.1392  YPERC=0.3408              NLOSS=0.0          TL=0.01

LAYER MATSYS=9.0   XPERC=0.55    YPERC=0.0                 NLOSS=0.0          TL=0.015


!p-GRIN LAYS: 21-31

STRUCT GRW = 0.26                                ! graded width (microns)
```

```
! effective index of first slice(implicit)
LAYER MATSYS=13.0  XPERC=0.1392  YPERC=0.0      NLOSS=0.00005
LAYER NSLC = 10                                 ! number of slices
! effective index of last slice (implicit)
LAYER MATSYS=13.0  XPERC=0.48    YPERC=0.0      NLOSS=0.00005


!inner p-clad LAYS: 32
LAYER MATSYS=13.0  XPERC=0.48    YPERC=0.0      NLOSS=0.0005    TL=0.0


!p-transition LAYS: 33-35
LAYER MATSYS=13.0  XPERC=0.48    YPERC=0.0      NLOSS=0.0005    TL=0.0025
LAYER MATSYS=13.0  XPERC=0.44592 YPERC=0.03408          NLOSS=0.0005    TL=0.005
LAYER MATSYS=13.0  XPERC=0.4128  YPERC=0.0672           NLOSS=0.0005    TL=0.0025


!p-clad LAYS: 36
LAYER MATSYS=1.0   XPERC=0.0     YPERC=0.0      NLOSS=0.00075   TL=2.0


!p-cap LAYS: 37
LAYER NREAL=3.52                        NLOSS=0.0125    TL=0.2


!AIR on top LAYS: 38
LAYER AIR=1.0                                           TL=0.0
!----------------------- end of structure ------------------------


!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0
```

```
OUTPUT FWHPNO=0 FWHPFO=1 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=0 LYROUT=0

!GAMOUT Parameter Set
GAMOUT LAYGAM=18 LAYGAM=20 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
!LOOPZ1 ILZ='QZMR'      FINV=10.0     ZINC=-0.01
!LOOPZ1 ILZ='WVL'       FINV=1.6      ZINC=0.001
!LOOPZ1 ILZ='GRW'       FINV=1.0      ZINC=0.01
!LOOPX1 ILX='TL'        FINV=0.1      XINC=0.001    LAYCH=06
!LOOPX1 ILX='TL'        FINV=0.1      XINC=0.001    LAYCH=32
!LOOPX1 ILX='TL'        FINV=0.1      XINC=0.001    LAYCH=02
!LOOPX1 ILX='TL'        FINV=0.1      XINC=0.001    LAYCH=36

END
```

7.1.6 Inner Cladding Optimization to Minimize Loss

First, the fundamental mode (TM_0) was sought by looping for QZMR for the updated structure. The initial values for the n and p inner-clad=0.0 μm, and clads=2.0 μm. The looping results are depicted below.

QZMR	PHM	GAMMA(18)	GAMMA(20)	WZR	WZI
FWHPF	KM	IT			
1.100000E+01	5.985674E+00	4.447605E-04	4.025810E-04	3.041720E+00	2.208746E-02
4.982005E+00	5	29			
1.099000E+01	5.985674E+00	4.447605E-04	4.025810E-04	3.041720E+00	2.208746E-02
4.982005E+00	5	29			
1.098000E+01	5.985674E+00	4.447605E-04	4.025810E-04	3.041720E+00	2.208746E-02
4.982005E+00	5	29			
		.			
		.			
1.065000E+01	7.595679E-01	3.113686E-02	3.113686E-02	3.261166E+00	3.083322E-05
4.982645E+01	6	4			
1.064000E+01	7.595679E-01	3.113686E-02	3.113686E-02	3.261166E+00	3.083322E-05
4.982645E+01	7	4			
1.063000E+01	**7.595679E-01**	**3.113686E-02**	**3.113686E-02**	**3.261166E+00**	**3.083322E-05**
4.982645E+01	**7**	**4**			
1.062000E+01	7.595679E-01	3.113686E-02	3.113686E-02	3.261166E+00	3.083322E-05
4.982645E+01	6	4			
1.061000E+01	7.595679E-01	3.113686E-02	3.113686E-02	3.261166E+00	3.083322E-05
4.982645E+01	7	5			
		.			
		.			
1.002000E+01	2.584146E+00	2.008284E-04	1.404630E-04	3.153059E+00	9.454015E-04
4.880579E+00	5	15			
1.001000E+01	2.584146E+00	2.008284E-04	1.404630E-04	3.153059E+00	9.454015E-04
4.880579E+00	5	16			

1.000000E+01	2.584146E+00	2.008284E-04	1.404630E-04	3.153059E+00	9.454015E-04
4.880579E+00	5	13			

For QZMR=10.63, WZR makes sense and KM=7 and IT=4 look reasonable. To verify that this corresponds to TM_0 mode near field and far field plots should be checked. These plots are shown in Figures 7.1.6 and 7.1.7 and the output parameters in db file are listed below:

PHM = 7.595679E-01

GAMMA(18) = 2.688899E-02

GAMMA(20) = 2.688899E-02

WZR = 3.261166

WZI = 3.083322E-05

FWHPF = 4.982645E+01

KM = 7

IT = 4

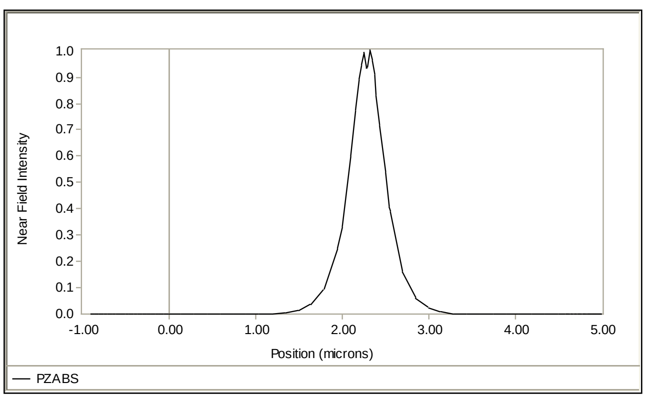


Figure 7.1.6 Fundamental mode near field plots for the updated structure including all the layers and loss figures.

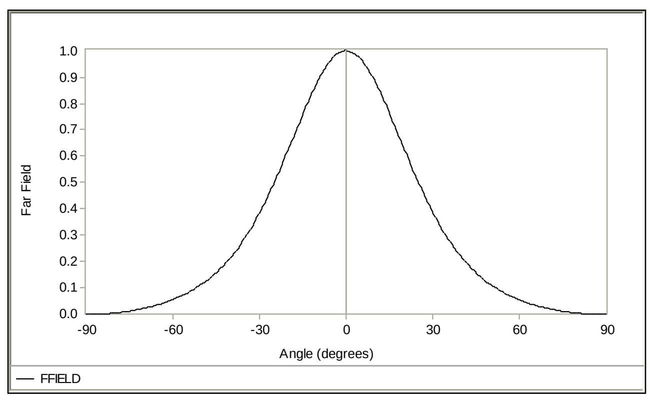


Figure 7.1.7 Fundamental mode far field plot for the updated structure including all the layers and loss figures.

We have to increase the inner-clad thickness so that the modal loss falls into acceptable limits. Looping for the inner-clad thickness from 0.0 μm to 1.0 μm, we obtain:

TL(6)	TL(32)	PHM	GAMMA(18)	GAMMA(20)	WZR
WZI	FWHPF	KM	IT		
0.000000E+00	0.000000E+00	7.595679E-01	3.113686E-02	3.113686E-02	3.261166E+00
3.083322E-05	4.982645E+01	7	4		
1.000000E-03	1.000000E-03	7.593857E-01	3.113179E-02	3.113179E-02	3.261214E+00
3.076259E-05	4.983146E+01	7	3		
2.000000E-03	2.000000E-03	7.592044E-01	3.112673E-02	3.112673E-02	3.261262E+00
3.069250E-05	4.983434E+01	7	3		
		.			
		.			
4.980000E-01	4.980000E-01	7.235864E-01	2.933575E-02	2.933575E-02	3.268938E+00
2.201114E-05	4.815140E+01	7	2		
4.990000E-01	4.990000E-01	7.235789E-01	2.933421E-02	2.933421E-02	3.268941E+00
2.201018E-05	4.814455E+01	7	2		
5.000000E-01	**5.000000E-01**	**7.235714E-01**	**2.933264E-02**	**2.933264E-02**	**3.268943E+00**
2.200922E-05	**4.813846E+01**	**7**	**2**		
5.010000E-01	5.010000E-01	7.235640E-01	2.933107E-02	2.933107E-02	3.268946E+00
2.200827E-05	4.813254E+01	7	2		
5.020000E-01	5.020000E-01	7.235566E-01	2.932951E-02	2.932951E-02	3.268949E+00
2.200734E-05	4.812778E+01	7	2		
		.			
		.			

9.980000E-01	9.980000E-01	7.225282E-01	2.896721E-02	2.896721E-02	3.269402E+00
2.198895E-05	4.582991E+01	7 2			
9.990000E-01	9.990000E-01	7.225284E-01	2.896702E-02	2.896702E-02	3.269402E+00
2.198907E-05	4.582669E+01	7 2			
1.000000E+00	1.000000E+00	7.225285E-01	2.896683E-02	2.896683E-02	3.269402E+00
2.198919E-05	4.582347E+01	7 2			

Based on the plots shown in Figures 7.1.8 and 7.1.9, we pick the thickness value of 0.5 μm for the inner-clad. In Figure 7.1.8, α is the intensity modal loss in cm^{-1} and it is calculated from WZI values (amplitude loss in μm^{-1}) as follows:

$$\alpha = WZI \cdot (4\pi/\lambda) \cdot 10^4 \quad /cm \qquad (7.1)$$

Modal intensity loss vs. inner-clad thickness, as well as FWHPF and Gamma for QW vs. inner-clad thickness plots are shown below and as we see from Figure 7.1.8, for the inner-clad thickness of 0.5 μm and higher, the loss curve does not change considerably. Therefore, 0.5 μm is a good choice, since for this value the loss is minimal and a higher value for inner cladding will result in the drop of QW confinement factor as seen from Figure 7.1.9.

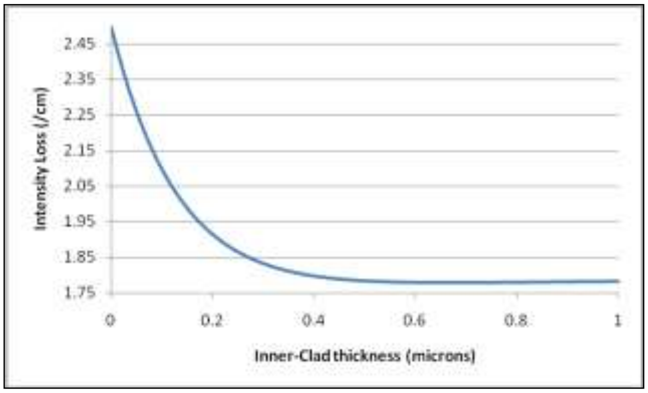


Figure 7.1.8 Modal intensity loss vs. inner-clad thickness.

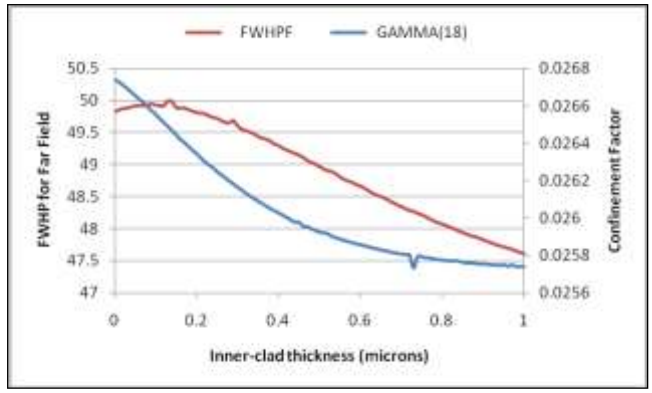


Figure 7.1.9 QW confinement factor and FWHPF vs. inner-clad thickness.

7.1.7 Cladding Optimization to Minimize Loss

The following is the calculated output parameters for inner-clad value of 0.5 μm in the output db file:

PHM	= 7.235714E-01
GAMMA(18)	= 2.504578E-02
GAMMA(20)	= 2.504578E-02
WZR	= 3.268943
WZI	= 2.200922E-05
FWHPF	= 4.813846E+01
KM	= 7
IT	= 6

Next the p-clad thickness will be optimized to obtain the minimum desired loss. Current loss is calculated as α=1.78 /cm, which corresponds to WZI=2.200922E-05.

TL(36)	PHM	GAMMA(18)	GAMMA(20)	WZR	WZI
FWHPF	KM	IT			
2.000000E+00	7.235714E-01	2.933264E-02	2.933264E-02	3.268943E+00	2.200922E-05
4.813846E+01	7	6			
1.990000E+00	7.235633E-01	2.929703E-02	2.929703E-02	3.268943E+00	2.200922E-05
4.813845E+01	7	2			
1.980000E+00	7.235552E-01	2.929591E-02	2.929591E-02	3.268943E+00	2.200922E-05
4.813846E+01	7	2			
		.			
		.			
1.020000E+00	7.227757E-01	2.932320E-02	2.932322E-02	3.268944E+00	2.202715E-05
4.822136E+01	7	2			
1.010000E+00	7.227674E-01	2.929339E-02	2.929341E-02	3.268944E+00	2.202835E-05
4.822470E+01	7	2			
1.000000E+00	**7.227592E-01**	**2.929591E-02**	**2.929594E-02**	**3.268944E+00**	**2.202963E-05**
4.822881E+01	**7**	**2**			
9.900000E-01	7.227509E-01	2.929920E-02	2.929923E-02	3.268944E+00	2.203100E-05
4.823252E+01	7	2			
9.800000E-01	7.227427E-01	2.929901E-02	2.929904E-02	3.268944E+00	2.203246E-05
4.823651E+01	7	2			
		.			
		.			
2.000000E-02	7.206226E-01	2.912019E-02	2.913829E-02	3.269347E+00	3.383818E-05
5.102692E+01	6	2			
1.000000E-02	7.205250E-01	2.912834E-02	2.914771E-02	3.269375E+00	3.464711E-05
5.111527E+01	6	2			

1.641048E-15	7.204211E-01	2.911967E-02	2.914038E-02	3.269405E+00	3.551305E-05
5.120447E+01	6	2			

Looping for p-cladding thickness from 0.0 µm to 2.0 µm, it looks like the optimum value is 1.0 um considering QW confinement factor, FWHPF, and WZI plots shown in Figures 7.1.10 and 7.1.11 below:

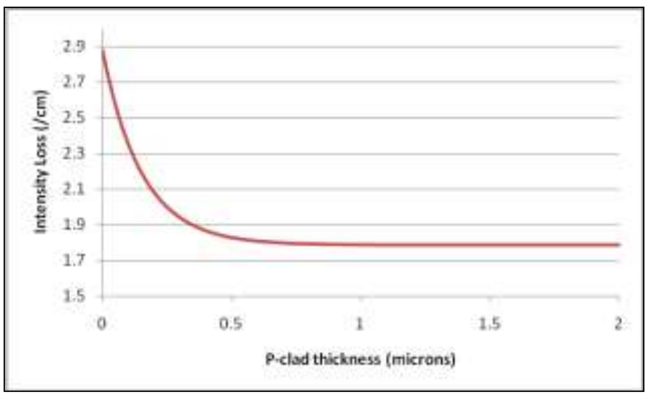


Figure 7.1.10 Modal intensity loss vs. p-clad thickness.

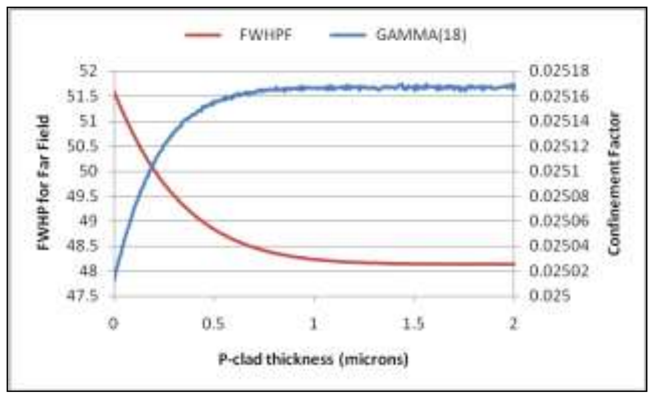


Figure 7.1.11 QW confinement factor and FWHPF vs. p-clad thickness.

7.1.8 Output Parameters and Plots

The optimized value for p-clad thickness is 1.0 µm and the modal loss is 1.78 /cm again. The output values are listed below:

PHM = 7.227592E-01

GAMMA(18) = 2.506622E-02

GAMMA(20) = 2.506622E-02

WZR = 3.268944

WZI = 2.202963E-05

FWHPF = 4.822881E+01

KM = 7

IT = 6

Near field and far field plots are shown in Figures 7.1.12 and 7.1.13 for the final structure:

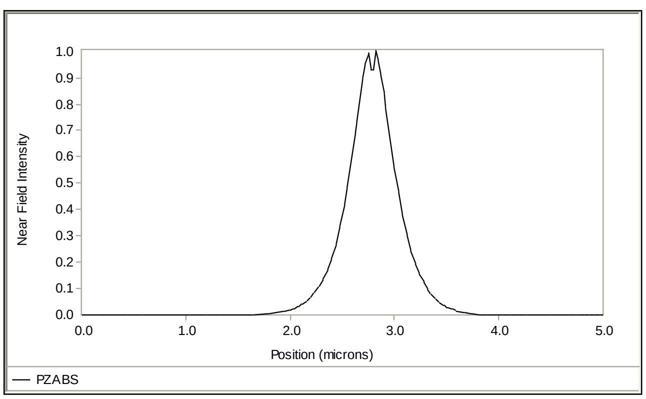


Figure 7.1.12 Fundamental mode near field plot for the final optimized structure.

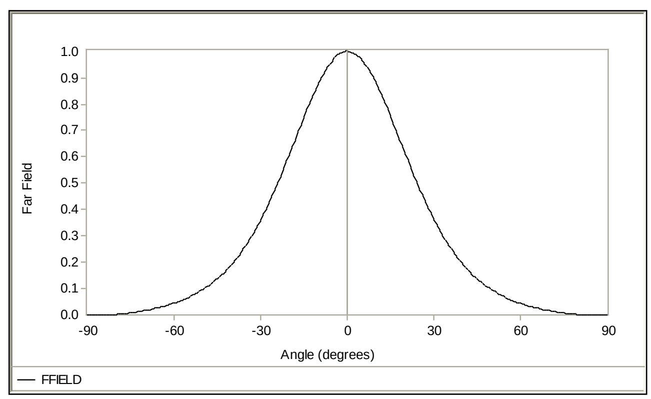


Figure 7.1.13 Fundamental mode far field plot for the final optimized structure.

The layer parameters for the final structure are listed below:

# of layers = 38

LAYER01 NLOSS= 0.00025 NREAL= 3.16492 TL= 0.00000

LAYER02 NLOSS= 0.00025 NREAL= 3.16492 TL= 2.00000

LAYER03 NLOSS= 0.00075 NREAL= 3.23470 TL= 0.00250

LAYER04 NLOSS= 0.00075 NREAL= 3.21713 TL= 0.00500

LAYER05 NLOSS= 0.00075 NREAL= 3.19969 TL= 0.00250

LAYER06 NLOSS= 0.00013 NREAL= 3.19969 TL= 0.50000

LAYER07 NLOSS= 0.00001 NREAL= 3.19969 TL= 0.01300

LAYER08 NLOSS= 0.00000 NREAL= 3.22246 TL= 0.02600

LAYER09 NLOSS= 0.00000 NREAL= 3.24523 TL= 0.02600

LAYER10 NLOSS= 0.00000 NREAL= 3.26800 TL= 0.02600

LAYER11 NLOSS= 0.00000 NREAL= 3.29077 TL= 0.02600

LAYER12 NLOSS= 0.00000 NREAL= 3.31354 TL= 0.02600

LAYER13 NLOSS= 0.00000 NREAL= 3.33631 TL= 0.02600

LAYER14 NLOSS= 0.00000 NREAL= 3.35907 TL= 0.02600

LAYER15 NLOSS= 0.00000 NREAL= 3.38184 TL= 0.02600

LAYER16 NLOSS= 0.00000 NREAL= 3.40461 TL= 0.02600

LAYER17 NLOSS= 0.00001 NREAL= 3.42738 TL= 0.01300

LAYER18 NLOSS= 0.00000 NREAL= 3.57493 TL= 0.01500

LAYER19 NLOSS= 0.00000 NREAL= 3.42738 TL= 0.01000

LAYER20 NLOSS= 0.00000 NREAL= 3.57493 TL= 0.01500

LAYER21 NLOSS= 0.00005 NREAL= 3.42738 TL= 0.01300

LAYER22 NLOSS= 0.00000 NREAL= 3.40461 TL= 0.02600

LAYER23 NLOSS= 0.00000 NREAL= 3.38184 TL= 0.02600

LAYER24 NLOSS= 0.00000 NREAL= 3.35907 TL= 0.02600

LAYER25 NLOSS= 0.00000 NREAL= 3.33631 TL= 0.02600

LAYER26 NLOSS= 0.00000 NREAL= 3.31354 TL= 0.02600

LAYER27 NLOSS= 0.00000 NREAL= 3.29077 TL= 0.02600

```
LAYER28  NLOSS= 0.00000    NREAL= 3.26800    TL=   0.02600
LAYER29  NLOSS= 0.00000    NREAL= 3.24523    TL=   0.02600
LAYER30  NLOSS= 0.00000    NREAL= 3.22246    TL=   0.02600
LAYER31  NLOSS= 0.00005    NREAL= 3.19969    TL=   0.01300
LAYER32  NLOSS= 0.00050    NREAL= 3.19969    TL=   0.50000
LAYER33  NLOSS= 0.00050    NREAL= 3.19969    TL=   0.00250
LAYER34  NLOSS= 0.00050    NREAL= 3.21713    TL=   0.00500
LAYER35  NLOSS= 0.00050    NREAL= 3.23470    TL=   0.00250
LAYER36  NLOSS= 0.00075    NREAL= 3.16492    TL=   1.00000
LAYER37  NLOSS= 0.01250    NREAL= 3.52000    TL=   0.20000
LAYER38  NLOSS= 0.00000    NREAL= 1.00000    TL=   0.00000
```

7.2 AlInGaAs/AlInGaAs/InP (1310-nm, TE mode)

7.2.1 Introduction

In this section the 1310-nm laser structure design will be introduced by using WAVEGUIDE II. The design procedures, input files and output will be explained in detail.

TE polarization in semiconductor lasers can be achieved by having compressive strain in quantum wells. The TE-mode laser operating at a wavelength of 1310 nm was designed according to Sandra R. Selmic's paper [5]. The initial structure for the layers, the material compositions and layer thicknesses are shown in Table 7.2.1.

Table 7.2.1 Initial laser structure (5-QW AlInGaAs) for the 1.3-μm AlInGaAs/InP.

Layer	**Composition**	**Thickness (μm)**
n-substrate	InP	---
Inner n-cladding	$Al_{0.48}In_{0.52}As$	0.30
n-SCH	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.50
QW-1	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-2	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-3	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-4	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-5	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
n-SCH	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.50
Inner n-cladding	$Al_{0.48}In_{0.52}As$	0.30

7.2.2 The Initial Input File

The initial input file is based on the parameters shown in Table 7.2.1. The parameters for QW and barrier layers are kept fixed. The other layer thicknesses will be determined for the optimized laser operation. The initial input file is as follows:

```
CASE    KASE=mqw-s-1

CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6

CASE    QZMR=12.145 QZMI=0.0

CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1

!CASE    DXIN=0.2 QZMR=10.932

!CASE    IL=100  KGSS=1


MODCON  KPOL=1   APB1=0.25   APB2=0.25


STRUCT  WVL=1.3


LAYER  NREAL=3.1987   NLOSS=0.00  TL=0.00    !N-sub, InP

LAYER  NREAL=3.2310   NLOSS=0.00  TL=0.30    !inner n-cladding AlInAs

LAYER  NREAL=3.3728   NLOSS=0.0   TL=0.50    !n-SCH,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.0   TL=0.50    !p-SCH,AlInGaAs

LAYER  NREAL=3.2310   NLOSS=0.00  TL=0.30    !inner p-cladding AlInAs

OUTPUT  PHMO=1     GAMMAO=1   WZRO=1   WZIO=1   QZRO=1    QZIO=0
```

```
OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1    ITO=1

OUTPUT  MODOUT=1   LYROUT=1   SPLTFL=0

GAMOUT  LAYGAM=8   COMPGAM=0  GAMALL=0


!LOOPX1  ILX='NREAL' FINV=3.6837  XINC=0.01    LAYCH=39

!LOOPX1  ILX='TL'    FINV=0.00    XINC=-0.02   LAYCH=2

!LOOPX1  ILX='TL'    FINV=0.00    XINC=-0.005  LAYCH=14

LOOPZ1   ILZ='QZMR'  FINV=10.230  ZINC=-0.025  ! This loops to find !initial guess

END
```

In the input file KPOL=1 is to set TE polarization. The material system is AlInAs/AlGaInAs/AlGaInAs (substrate InP).

7.2.3 Searching the Fundamental Mode, Looping for QZMR

First, we start with searching for TE_0 mode by looping for QZMR from $n_{max}^2 = (3.4850)^2 \cong 12.145$ to $n_{min}^2 = (3.1987)^2 \cong 10.232$.

Using the same criterion as already introduced in the previous section, we loop the QZMR and find the following:

QZMR = 11.22 gives KM=6 and IT=3.

So we change QZMR to 11.22 and end the looping. The near field (real part and intensity) and far field plots are shown in Figures 7.2.1 and 7.2.2.

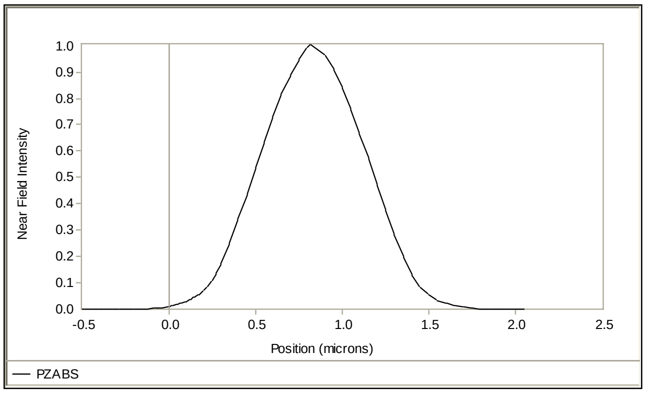


Figure 7.2.1 Fundamental mode near field plot for initial waveguide parameters.

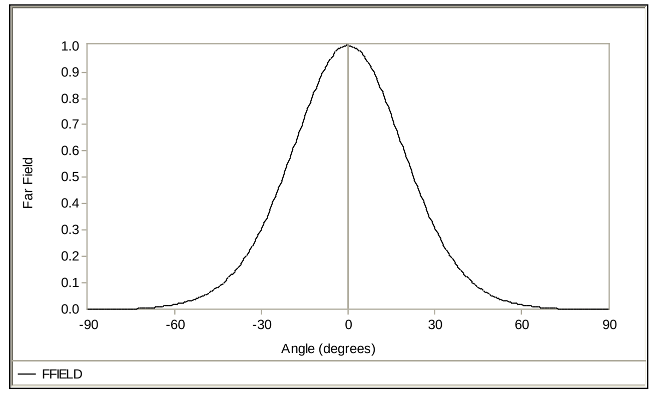


Figure 7.2.2 Fundamental mode far field plot for initial waveguide parameters.

The output parameters are calculated and listed below:

PHM = 6.780389E-01

GAMMA(8) = 6.923083E-03

WZR = 3.348926E+00

WZI = 1.629364E-21

FWHPF = 4.526491E+01

KM = 6

IT = 3

The layer structure is:

# of layers = 14

LAYER01 NLOSS= 0.00000 NREAL= 3.19870 TL= 0.00000

LAYER02 NLOSS= 0.00000 NREAL= 3.23100 TL= 0.30000

LAYER03 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.50000

LAYER04 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER05 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER06	NLOSS= 0.00000	NREAL= 3.48500	TL= 0.00500
LAYER07	NLOSS= 0.00000	NREAL= 3.37280	TL= 0.01000
LAYER08	NLOSS= 0.00000	NREAL= 3.48500	TL= 0.00500
LAYER09	NLOSS= 0.00000	NREAL= 3.37280	TL= 0.01000
LAYER10	NLOSS= 0.00000	NREAL= 3.48500	TL= 0.00500
LAYER11	NLOSS= 0.00000	NREAL= 3.37280	TL= 0.01000
LAYER12	NLOSS= 0.00000	NREAL= 3.48500	TL= 0.00500
LAYER13	NLOSS= 0.00000	NREAL= 3.37280	TL= 0.50000
LAYER14	NLOSS= 0.00000	NREAL= 3.23100	TL= 0.00000

7.2.4 Looping the SCH layers to find the proper thickness for the fundamental mode confinement.

We loop both the n-SCH and p-SCH layers from 0.5 μm to 0 μm to find the proper thickness to get maximum confinement in QWs. Note that we check for QW confinement and angle at full-width at half-maximum power for far field (FWHPF) and then make a proper choice. We cannot get high confinement and low FWHPF angle at the same time so it is a compromise. Generally, the values are chosen according to design specifications.

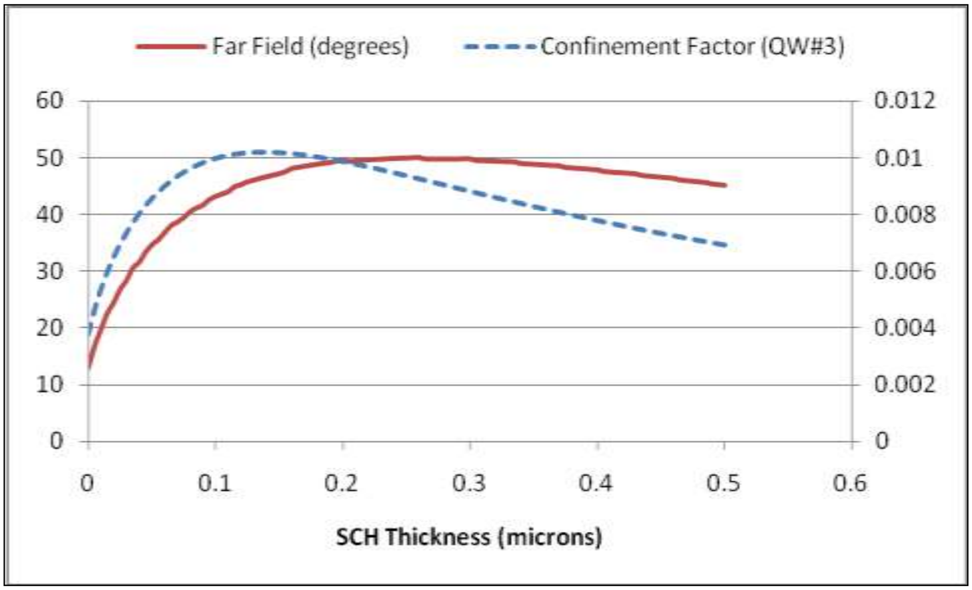


Figure 7.2.3 QW confinement factor and FWHPF vs. SCH thickness

From figures 7.2.3, we can decide the proper thickness of the SCH layer as 0.140 μm since the confinement factor has the maximum value and the far-field angle is satisfactorily low at this thickness.

The .db output file is as shown below:

TL(3)	TL(13)	PHM	GAMMA(8)	WZR	WZI
QZR	FWHPN	FWHPF	KM	IT	
5.000000E-01	5.000000E-01	6.780389E-01	6.923083E-03	3.348926E+00	1.629364E-21
1.121530E+01	7.045997E-01	4.526491E+01	6	3	
4.950000E-01	4.950000E-01	6.764395E-01	6.962301E-03	3.348584E+00	-5.397067E-16
1.121301E+01	7.002861E-01	4.538071E+01	6	2	
.					
1.400000E-01	**1.400000E-01**	**4.151027E-01**	**1.021052E-02**	**3.287700E+00**	**-4.496412E-15**
1.080897E+01	**4.094267E-01**	**4.677912E+01**	**6**	**2**	

.

.

2.000000E-02	2.000000E-02	1.593417E-01	4.911944E-03	5.085040E-03	5.198442E-03
5.249395E-03	5.236662E-03	3.236628E+00	-2.272725E-17	1.047576E+01	7.033353E-01
1.893432E+01	6	4			
1.734723E-16	1.734723E-16	1.081582E-01	1.539442E-03	1.606108E-03	1.653928E-03
1.681719E-03	1.688793E-03	3.233169E+00	-4.636668E-15	1.045338E+01	2.080428E+00
5.249361E+00	6	9			

The output parameters are calculated and listed below:

GAMMA(8) = 1.021052E-02

WZR = 3.287700E+00

WZI = 1.102329E-11

FWHPF = 4.677920E+01

KM = 6

IT = 2

The layer structure is:

# of layers = 14

LAYER01 NLOSS= 0.00000 NREAL= 3.19870 TL= 0.00000

LAYER02 NLOSS= 0.00000 NREAL= 3.23100 TL= 0.30000

LAYER03 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.14000

LAYER04 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER05 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER06 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER07 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER08 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER09 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER10 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER11 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER12 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER13 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.14000

LAYER14 NLOSS= 0.00000 NREAL= 3.23100 TL= 0.00000

The near field (real part and intensity) and far field plots are shown in Figures 7.2.4 and 7.2.5:

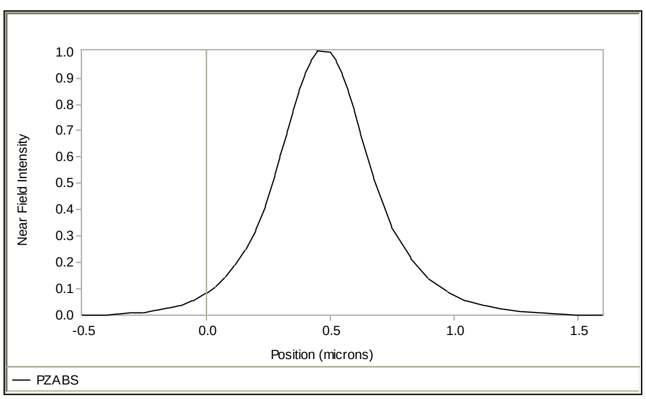


Figure 7.2.4 Fundamental mode near field plot with 0.16 µm SCH.

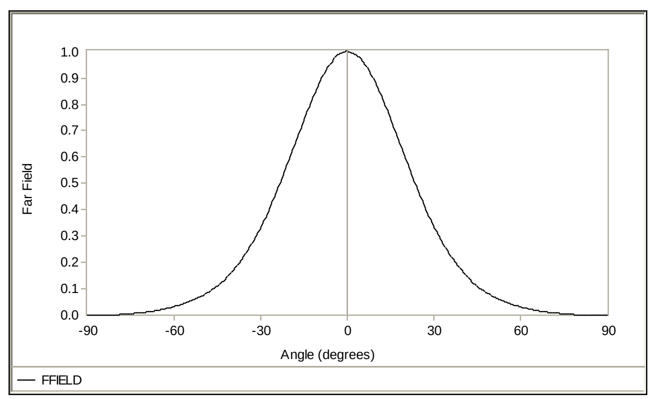


Figure 7.2.5 Fundamental mode far field plot with 0.16 µm SCH.

7.2.5 Making the Full Structure and Including Loss parameters

From the previous steps, the QZMR and the thickness of the SCH layer are decided. Now we need to form the full structure and include the loss layers and add the outer p-cladding layer and the p-cap layer. For the new structure we need to find the QZMR value again at the given start thicknesses of the outer p-cladding layer and the p-cap layer. Then we loop the inner n, p-cladding layers simultaneously to find the proper thickness at the QZMR value. The input file for this structure is shown below:

```
CASE    KASE=mqw-s-1
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=12.145 QZMI=0.0  !max is 12.145
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1
!CASE    DXIN=0.2 QZMR=10.932
!CASE    IL=100  KGSS=1

MODCON  KPOL=1   APB1=0.25   APB2=0.25
STRUCT  WVL=1.3

LAYER  NREAL=3.1987   NLOSS=0.0025  TL=0.00    !N-sub, InP
LAYER  NREAL=3.2310   NLOSS=0.00   TL=0.30    !inner n-cladding AlInAs
LAYER  NREAL=3.3728   NLOSS=0.00   TL=0.14   !n-SCH,AlInGaAs
LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs
LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs
LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs
```

```
LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs

LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs

LAYER  NREAL=3.3728   NLOSS=0.00   TL=0.14    !p-SCH,AlInGaAs

LAYER  NREAL=3.2310   NLOSS=0.00  TL=0.30    !inner p-cladding AlInAs

LAYER  NREAL=3.1987   NLOSS=0.0025  TL=1.25    ! outer p-cladding InP

LAYER  NREAL=3.0667   NLOSS=0.0025 TL=0.2     !p+cap, InGaAs

!LAYER  NREAL=1.8       NLOSS=0.00  TL=0.03     !Si3N4

LAYER  NREAL=3.7       NLOSS=18.2415 TL=0.05  !Ti

LAYER  NREAL=4.64      NLOSS=26.6731 TL=0.12 !Pt

LAYER  NREAL=0.18      NLOSS=41.3474 TL=0.20 !Au


OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0

OUTPUT  FWHPNO=1   FWHPFO=1   KMO=1  ITO=1

OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0

GAMOUT  LAYGAM=8    COMPGAM=0     GAMALL=0


!LOOPX1  ILX='TL' FINV=2.00 XINC=0.005  LAYCH=2

!LOOPX1  ILX='TL' FINV=2.00 XINC=0.005  LAYCH=14

!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.005  LAYCH=3

!LOOPX1  ILX='TL' FINV=0.00 XINC=-0.005  LAYCH=13

LOOPZ1  ILZ='QZMR'  FINV=9.405 ZINC=-0.025  ! This loops to find !initial guess

END
```

As we did in section 7.2.3, we loop the QZMR and find:

QZMR = 10.77 gives KM=6 and IT=4.

So change QZMR to 10.77 and close looping QZMR.

The near field (real part and intensity) and far field plots are shown in Figures 7.2.6 and 7.2.7:

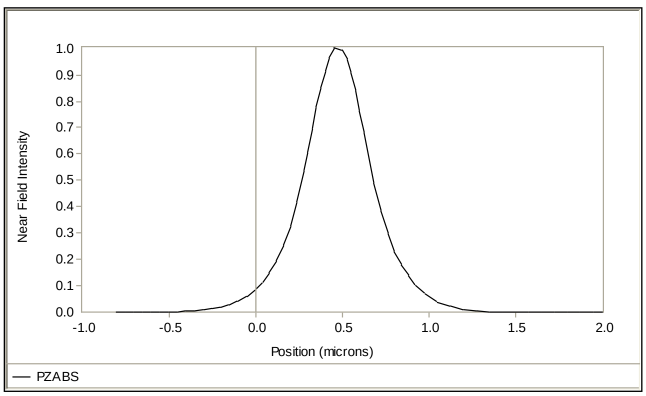


Figure 7.2.6 Fundamental mode near field plot for full structure.

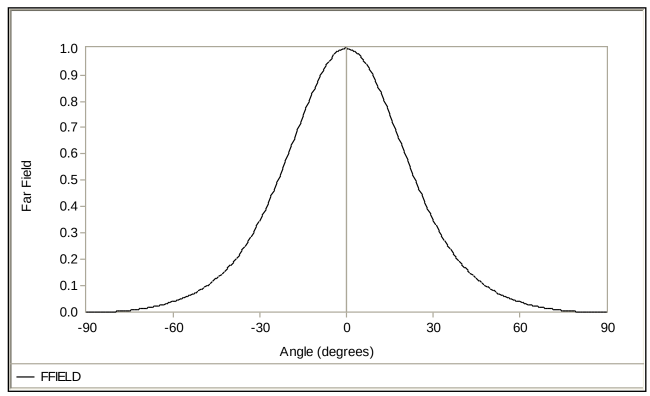


Figure 7.2.7 Fundamental mode far field plot for full structure.

We have to increase the p-cladding thickness so that the modal loss drops into acceptable limits. Looping the second p-clad thickness from 0.30μm to 2.00μm, we obtain the modal intensity loss as a function of the p-cladding thickness as shown in Figure 7.2.8. The QW confinement factor and FWHPF as a function of p-clad thickness for the updated structure is shown in Figure 7.2.9.

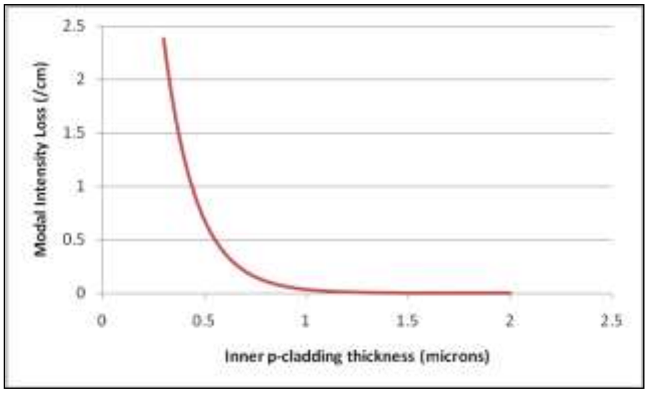


Figure 7.2.7 Modal intensity loss vs. Inner p-clad thickness.

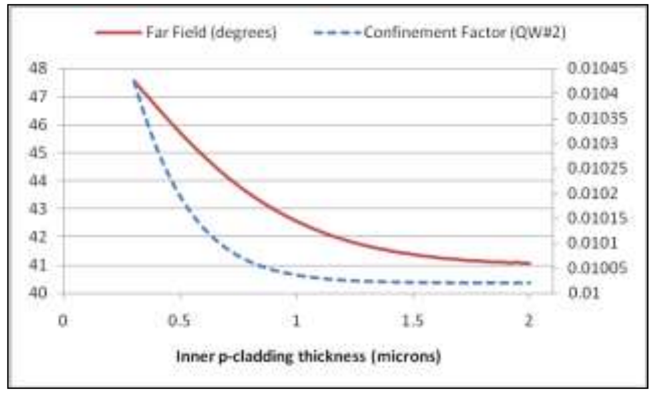


Figure 7.2.9 QW confinement factor and FWHPF vs. Inner p-clad thickness.

Based on the plots shown in Figures 7.2.8 and 7.2.9, we can choose the thickness value of 0.5 μm for the inner p-cladding since the loss curve drops to 0.5 and higher thickness will cause a lower confinement factor. The intensity modal loss is calculated from WZI values (amplitude loss in μm^{-1}) using the formula below:

$$\alpha = WZI \cdot (4\pi/\lambda) \cdot 10^4 \quad /cm$$

Since we choose the inner p-cladding thickness as 0.5 μm, we need to calculate the QZMR for the new inner p-cladding thickness as done in the previous section. QZMR can be set to 10.820.

7.2.6 Output Parameters and Plots

Now we can get the final output values as listed below:

PHM = 1.428585E+00

GAMMA(8) = 1.019220E-02

WZR = 3.288050E+00

WZI = 7.078846E-06

FWHPF = 4.568929E+01

KM = 7

IT = 4

The layer structure is:

# of layers = 19

LAYER01 NLOSS= 0.00250 NREAL= 3.19870 TL= 0.00000

LAYER02 NLOSS= 0.00000 NREAL= 3.23100 TL= 0.50000

LAYER03 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.14000

LAYER04 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER05 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER06 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER07 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER08 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER09 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER10 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER11 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.01000

LAYER12 NLOSS= 0.00000 NREAL= 3.48500 TL= 0.00500

LAYER13 NLOSS= 0.00000 NREAL= 3.37280 TL= 0.14000

LAYER14 NLOSS= 0.00000   NREAL= 3.23100   TL=   0.50000

LAYER15 NLOSS= 0.00250   NREAL= 3.19870   TL=   1.25000

LAYER16 NLOSS= 0.00250   NREAL= 3.06670   TL=   0.20000

LAYER17 NLOSS=18.24150   NREAL= 3.70000   TL=   0.05000

LAYER18 NLOSS=26.67310   NREAL= 4.64000   TL=   0.12000

LAYER19 NLOSS=41.34740   NREAL= 0.18000   TL=   0.00000

Near field and far field plots for the final structure are shown in Figures 7.2.12 and 7.2.13 below:

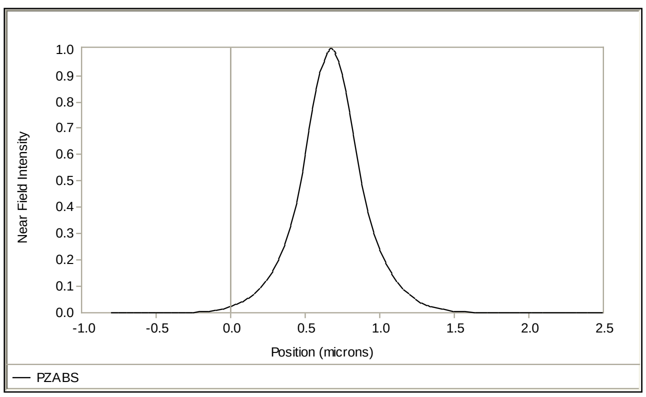


Figure 7.2.12 Fundamental mode near field plot for final structure.

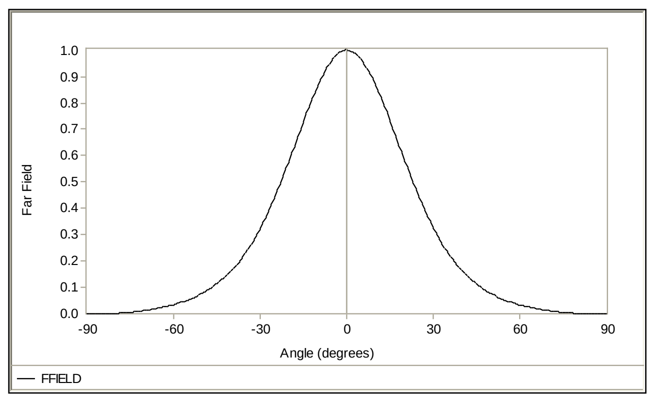


Figure 7.2.13 Fundamental mode far field plot for final structure.

The Final laser structure for this 1.3 µm AlInGaAs laser design can be found in Table 7.2.2 as follow:

Table 7.2.2 Final laser structure (5-QW AlInGaAs) for the 1.3 µm AlInGaAs/InP.

Layer	**Composition**	**Thickness (µm)**
n-substrate	InP	---
Inner n-cladding	$Al_{0.48}In_{0.52}As$	0.50
n-SCH	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.14
QW-1	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-2	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-3	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-4	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
barrier	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.010
QW-5	$Al_{0.161}Ga_{0.102}\ In_{0.737}As$	0.005
n-SCH	$Al_{0.267}Ga_{0.203}\ In_{0.53}As$	0.14
Inner n-cladding	$Al_{0.48}In_{0.52}As$	0.50
Outer n-cladding	InP	1.25
P-cap	InGaAs	0.2

The final input file for WAVEGUIDE II is also shown as follow:

```
CASE    KASE=mqw-s-1
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR=10.820 QZMI=0.0  !max is 12.145
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1
!CASE    DXIN=0.2 QZMR=10.932
!CASE    IL=100  KGSS=1
  MODCON  KPOL=1   APB1=0.25   APB2=0.25

STRUCT  WVL=1.3

LAYER  NREAL=3.1987   NLOSS=0.0025  TL=0.00    !N-sub, InP
LAYER  NREAL=3.2310   NLOSS=0.00   TL=0.50    !inner n-cladding AlInAs
LAYER  NREAL=3.3728   NLOSS=0.00   TL=0.14   !n-SCH,AlInGaAs
LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs
LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs
LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs
LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs
LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs
LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs
LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs
LAYER  NREAL=3.3728   NLOSS=0.00  TL=0.010   !barrier,AlInGaAs
LAYER  NREAL=3.4850   NLOSS=0.00  TL=0.005   !QW, AlInGaAs
LAYER  NREAL=3.3728   NLOSS=0.00   TL=0.14   !p-SCH,AlInGaAs
LAYER  NREAL=3.2310   NLOSS=0.00  TL=0.50    !inner p-cladding AlInAs
LAYER  NREAL=3.1987   NLOSS=0.0025  TL=1.25   ! outer p-cladding InP
```

```
LAYER  NREAL=3.0667   NLOSS=0.0025 TL=0.2     !p+cap, InGaAs

!LAYER  NREAL=1.8     NLOSS=0.00  TL=0.03  !Si3N4

LAYER  NREAL=3.7      NLOSS=18.2415 TL=0.05 !Ti

LAYER  NREAL=4.64     NLOSS=26.6731 TL=0.12 !Pt

LAYER  NREAL=0.18     NLOSS=41.3474 TL=0.20 !Au


OUTPUT  PHMO=1    GAMMAO=1    WZRO=1   WZIO=1   QZRO=1    QZIO=0

OUTPUT  FWHPNO=1   FWHPFO=1    KMO=1    ITO=1

OUTPUT  MODOUT=1   LYROUT=1    SPLTFL=0

GAMOUT  LAYGAM=8   COMPGAM=0   GAMALL=0


!LOOPX1  ILX='TL'    FINV=2.00  XINC=0.005   LAYCH=2

!LOOPX1  ILX='TL'    FINV=2.00  XINC=0.005   LAYCH=14

!LOOPX1  ILX='TL'    FINV=0.00  XINC=-0.005  LAYCH=3

!LOOPX1  ILX='TL'    FINV=0.00  XINC=-0.005  LAYCH=13

!LOOPZ1  ILZ='QZMR'  FINV=9.405 ZINC=-0.025  ! This loops to find !initial guess

END
```

7.2.7 The Refractive Index Profile

Now we can plot the refractive index profile according to the distance of the layers for the laser structure as following:

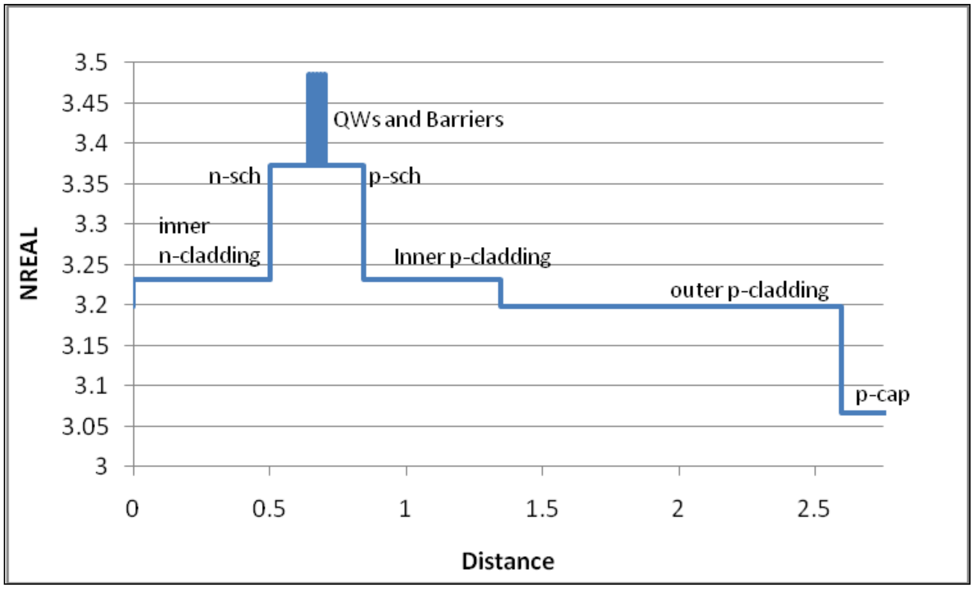


Figure 7.2.14 The structure of 1.3-um AlInGaAs 5-QW Laser.

REFERENCES

[1] http://engr.smu.edu/ee/smuphotonics/GainManualAppendixC/AppendixC.htm

[2] http://engr.smu.edu/ee/smuphotonics/Gain.htm

[3] Z.-L. Liau and J. N. Walpole, "Mass-transported GaInAsP/InP lasers", Lincoln Laboratory Journal, vol.2, 77, 1989.

[4] E. R. Hegblom, D. I. Babic, B. J. Thibeault, and L. A. Coldren, "Scattering losses from dielectric apertures in vertical-cavity lasers", *IEEE Journal of Selected Topics in Quantum Electronics*, vol.3, 379, 1997.

[5] Sandra R. Selmic, Tso-Min Chou, JiehPing Sih, Jay B.Kirk, Art Mantie, Jerome K. Bulter, David Bour, and Gary A. Evans, "Design and Characterization of 1.3-μm AlGaInAs-InP Multiple-Quantum-Well Lasers", *IEEE Journal of Selected Topics in Quantum Electronics*, vol. 7, no. 2, March/April 2001.

Chapter 8

TE-MODE, 635-NM RED LASER OPTIMIZATION

This chapter gives an example on how to design a 635-nm, GaInP/AlGaInP/GaAs broad-area red laser structure with the WAVEGUIDE II software to achieve optimized key laser parameters such as quantum well confinement factor and far field.

8.1 The Initial Input File and Layer Parameters

Before simulation, we need to construct a WAVEGUDE II input file with desired lasing wavelength, material system and compositions for each layer. For each layer, we have to set up an initial layer thickness in the input file. Using WAVEGUIDE II to find out the optimized layer thickness to achieve the desired design is our ultimate target. The structure and the index profile of the TE-mode, 635nm GaInP/AlGaInP/GaAs broad-area red laser is shown below in Table 8.1.1 and Figure 8.1.1. The material compositions for each layer and the quantum well thickness can be calculated with our GAIN software. The initial input file is provided in Table 8.1.2. And the layer parameters are listed in Table 8.1.3. Readers can refer to chapter 2.4 for the method on how to create and evaluate an input file from WAVEGUIDE II.

Table 8.1.1 The structure of the TE-mode, 635nm GaInP/AlGaInP/GaAs red laser.

#	Layer name	Material compositions	Refractive index	Energy bandgap
1	Substrate	GaAs	3.82357	1.424
2	n-cladding	$Al_{.5}In_{.5}P$	3.27693	1.897
3	SCH	$(Al_{.6}Ga_{.4})_{.5}In_{.5}P$	3.40423	1.862
4	Quantum well	$Ga_{.6}In_{.4}P$	3.49147	1.896
5	SCH	$(Al_{.6}Ga_{.4})_{.5}In_{.5}P$	3.40423	1.862
6	p-cladding	$Al_{.5}In_{.5}P$	3.27693	1.897
7	p-cap	GaAs	3.82357	1.424

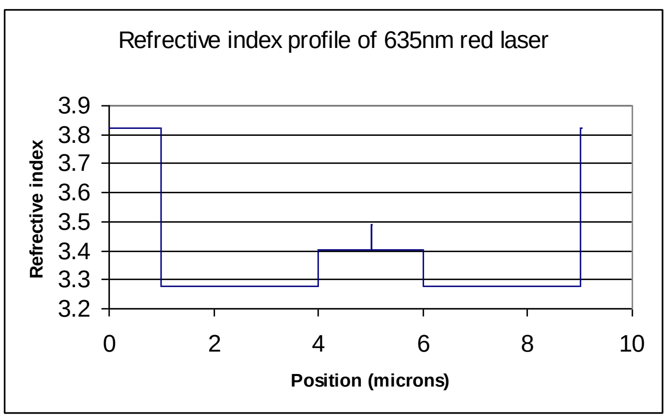


Figure 8.1.1 Index profile of TE mode, 635nm red laser.

Table 8.1.2 Initial input file of TE-mode, 635-nm red laser structure.

```
!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=14.62QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=2 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=0.635
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set
LAYER MATSYS=0.1  XPERC=0   YPERC=0 TL=1.0   !GaAs substrate
LAYER MATSYS=8.0  XPERC=1   YPERC=0 TL=3.0   !Al.5In.5P n-cladding
LAYER MATSYS=8.0  XPERC=0.6 YPERC=0 TL=1     !(Al.6Ga.4).5In.5P SCH
LAYER MATSYS=11.0 XPERC=0.6 YPERC=0 TL=0.008 !Ga.6In.4P QW
LAYER MATSYS=8.0  XPERC=0.6 YPERC=0 TL=1     !(Al.6Ga.4).5In.5P SCH
LAYER MATSYS=8.0  XPERC=1   YPERC=0 TL=3.0   !Al.5In.5P p-cladding
LAYER MATSYS=0.1  XPERC=0   YPERC=0 TL=0.05  !GaAs P cap
```

```
!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0

OUTPUT FWHPNO=0 FWHPFO=1 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=0 LYROUT=0
```

```
!GAMOUT Parameter Set
GAMOUT LAYGAM=4 COMPGAM=0 GAMALL=0


!LOOPZ Parameter Set
LOOPZ1 ILZ='QZMR' FINV=10.74 ZINC=-0.005
END
```

Table 8.1.2 Layer parameters for TE-mode, 635-nm red laser structure

```
# of layers =     07
LAYER01  NLOSS= 0.00000   NREAL= 3.82357   TL=  1.00000
LAYER02  NLOSS= 0.00000   NREAL= 3.27693   TL=  3.00000
LAYER03  NLOSS= 0.00000   NREAL= 3.40423   TL=  1.00000
LAYER04  NLOSS= 0.00000   NREAL= 3.49147   TL=  0.00800
LAYER05  NLOSS= 0.00000   NREAL= 3.40423   TL=  1.00000
LAYER06  NLOSS= 0.00000   NREAL= 3.27693   TL=  3.00000
LAYER07  NLOSS= 0.00000   NREAL= 3.82357   TL=  0.05000
```

For the purpose of simplicity, in this WAVEGUIDEII simulation, we don't include the doping loss for the claddings and the substrate. The main loss for the structures arises from the substrate photon absorption due to the large bandgap of GaAs as relative to that of the active material (see Table 8.1.1).

8.2 Mode Searching, Looping for QZMR

After creating the input file, we search for TE0 mode by looping for QZMR. The upper bound of QZMR is normally approximated by the square of the maximum NREAL of the structure, and the lower bound of QZMR is approximated by the square of the minimum NREAL of the structure. From the layer information above, we have

QZMR_up = (3.82357)^2 = 14.62

QZMR_bottom = (3.27693)^2 = 10.74.

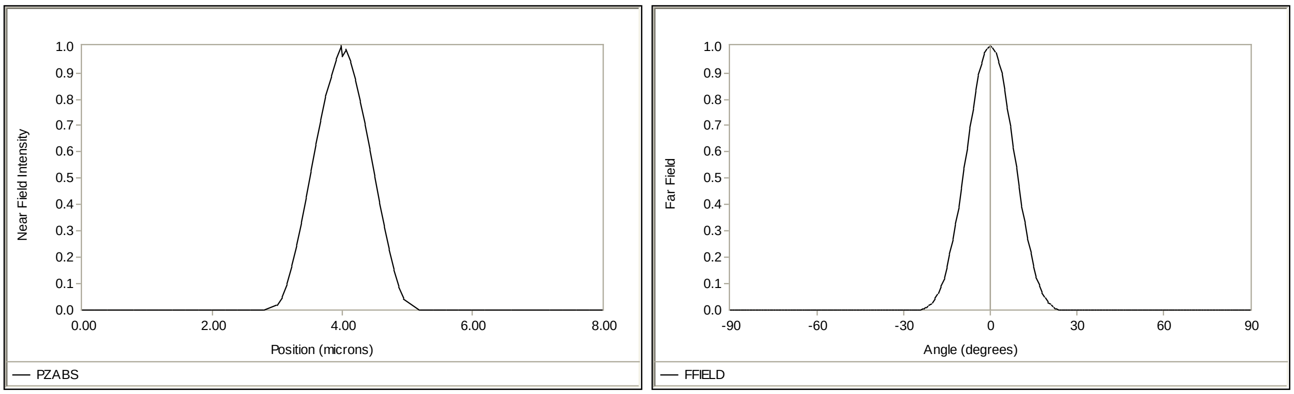
The looping results calculated by WAVEGUIDE II can be found in the WAVEGUIDE II ".db" data file. Part of the results is also listed in Table 8.2.1.

Table 8.2.1 QZMR looping results.

QZMR	PHM	GAMMA(4)	WZR	WZI	FWHPF	KM	IT
.							
.							
1.159500E+01	5.471711E+00	0.000000E+00	3.344715E+00	1.516096E-02	0.000000E+00	3	30
1.159000E+01	5.474535E+00	0.000000E+00	3.343377E+00	1.460778E-02	0.000000E+00	3	30
1.158500E+01	8.230724E-01	7.600046E-03	3.401844E+00	1.219445E-20	1.907207E+01	7	8
1.158000E+01	8.230724E-01	7.600046E-03	3.401844E+00	6.442830E-20	1.907207E+01	7	6

1.157500E+01	8.230724E-01	7.600046E-03	3.401844E+00	1.219476E-20	1.907207E+01
7	5				
1.157000E+01	**8.230724E-01**	**7.600048E-03**	**3.401844E+00**	**-1.556602E-19**	**1.907216E+01**
7	**4**				
1.156500E+01	8.230724E-01	7.600048E-03	3.401844E+00	7.624785E-19	1.907219E+01
7	5				
1.156000E+01	8.230724E-01	7.600050E-03	3.401844E+00	-2.792398E-19	1.907227E+01
7	6				
1.155500E+01	1.825985E+00	3.247787E-07	3.392150E+00	-8.319370E-21	1.459226E+01
6	9				
.					
.					
.					

The general criteria to look for a proper QZMR value are: (1) PHM < 1.0, (2) KM = 6 or 7. Four QZMR values in above Table meet the criteria. And we can choose the first one that reaches the minimum iteration number, which is IT = 4 in this case. QZMR = 11.57 gives PHM = 8.230724E-01, KM=7 and IT=4. After we change QZMR to 11.57, we close the looping and run the input file again, plot the near field and far field (Figure 8.2.1) to check that we do get TE0 mode at QZMR = 11.57.



(a) (b)

Figure 8.2.1 (a) Near field intensity of TE0 mode (b) Far field of TE0 mode for the red laser structure.

8.3 SCH Thickness Determination to Achieve Desired Quantum Well Confinement Factor (GAMMA) and Full-Width-Half-Power Far Field (FWHPF)

First of all, we will optimize the thickness of SCH layers to obtain the desired GAMMA and FWHPF in transverse plane. As shown in the Table 8.3.1, we loop the thickness of n-SCH layer and p-SCH layers by decreasing it from 1 µm to 0.09 µm. Then we plot the quantum well confinement factor GAMMA (4) and FWHPF as a function of the thickness of SCH layers, and find the SCH thickness corresponds to the desired GAMMA and FWHPF. The output file is shown in Table 8.3.2. The quantum well confinement and far field are depicted in Figure 8.3.1.

Table 8.3.1 Input file for looping the SCH layer thickness

```
!DESCRIPTION: 635nm red laser design

!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=11.575 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=2 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=0.635
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set
LAYER MATSYS=0.1  XPERC=0   YPERC=0 TL=1.0   !GaAs substrate
LAYER MATSYS=8.0  XPERC=1   YPERC=0 TL=3.0   !Al.5In.5P n-cladding
LAYER MATSYS=8.0  XPERC=0.6 YPERC=0 TL=1.0   !(Al.6Ga.4).5In.5P SCH
LAYER MATSYS=11.0 XPERC=0.6 YPERC=0 TL=0.008 !Ga.6In.4P QW
LAYER MATSYS=8.0  XPERC=0.6 YPERC=0 TL=1.0   !(Al.6Ga.4).5In.5P SCH
LAYER MATSYS=8.0  XPERC=1   YPERC=0 TL=3.0   !Al.5In.5P p-cladding
LAYER MATSYS=0.1  XPERC=0   YPERC=0 TL=0.05  !GaAs P cap

!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0
OUTPUT FWHPNO=0 FWHPFO=1 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=0 LYROUT=0
!GAMOUT Parameter Set
GAMOUT LAYGAM=4 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
LOOPX1 ILX='TL' FINV=0.09 XINC=-0.005 LAYCH=3
LOOPX1 ILX='TL' FINV=0.09 XINC=-0.005 LAYCH=5
END
```

Table 8.3.2 Quantum well confinement factor and far field for varied SCH thickness.

SCH thickness	QW confinement	Far field angle
	.	
	.	
	.	
0.165	0.02573464	43.90352
0.16	0.02457271	**44.5087**
0.155	0.0263067	43.73485
0.15	0.02647409	43.61582
0.145	0.02678366	43.48656
0.14	0.0278569	43.30508
0.135	0.02732821	43.06164
0.13	0.02753008	42.82628
0.125	0.02783832	42.42262
0.12	0.02799404	42.70239
0.115	0.0279276	41.83623
0.11	0.02817008	41.18996
0.105	0.02821955	40.73937
0.1	**0.02836**	40.16159
0.095	0.02835031	39.19299
0.09	0	0

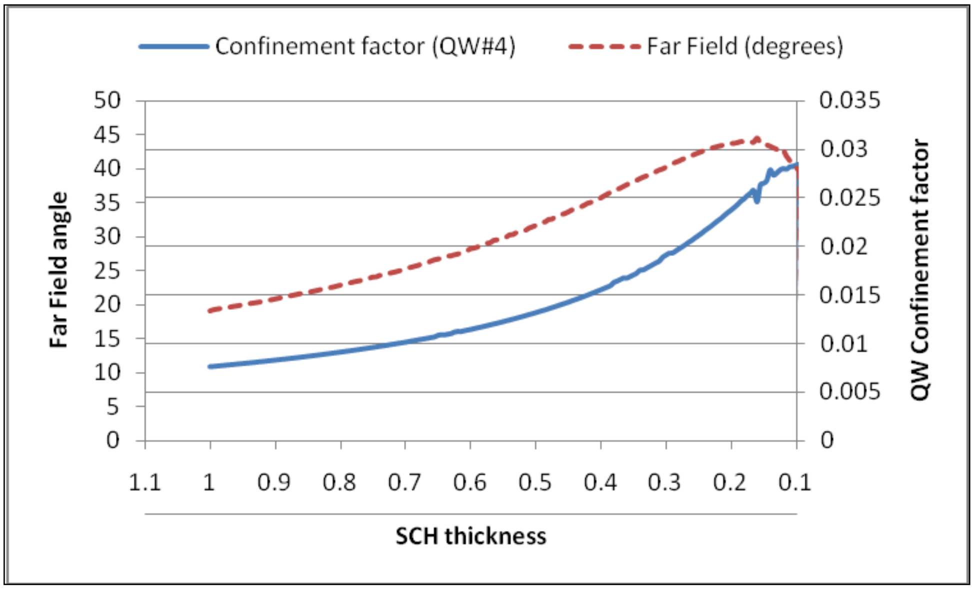


Figure 8.3.1 The quantum well confinement factor and far field as a function of SCH layer thickness.

From the Figure 8.3.1, we can see that the far field angle decreases and the quantum confinement increases as the SCH layers' thickness decreases from 0.16 μm to 0.1 μm. Normally, what specific values we should choose for the quantum well GAMMA and FWHPF is case by case and it may rely on the purpose of your structure. For example, if it is a broad area red laser, it will not be too critical on the far field, and we may want the quantum well confinement factor to be as large as possible. On the other hand, if it is an edge emitter, we usually want to confine the far field angle such that it is not too large. In this case, we choose the SCH layer thickness to be of 0.1 μm, which is the case of largest QW confinement factor.

After we find the proper SCH layer thickness, we need to loop the QZMR values again and find the proper QZMR for the TE0 mode of the new structure. The looping results are calculated as in Table 8.3.3. By using the criteria described in section 8.1, we get QZMR = 11.10.

Table 8.3.3 QZMR looping results.

QZMR	PHM	GAMMA(4)	WZR	WZI	FWHPF
KM	IT				
.					
.					
1.113000E+01	5.598808E+00	0.000000E+00	3.279893E+00	2.397366E-02	0.000000E+00
3	30				
1.112500E+01	5.612344E+00	0.000000E+00	3.279250E+00	2.350777E-02	0.000000E+00
3	30				
1.112000E+01	4.661907E-01	2.795471E-02	3.331836E+00	1.786231E-17	4.034399E+01
7	8				
1.111500E+01	4.661907E-01	2.830316E-02	3.331836E+00	1.572292E-17	4.018570E+01
7	7				
1.111000E+01	4.661907E-01	2.806523E-02	3.331836E+00	1.715480E-17	4.029929E+01
7	6				
1.110500E+01	4.661907E-01	2.836000E-02	3.331836E+00	1.795569E-17	4.016027E+01
7	5				
1.110000E+01	**4.661907E-01**	**2.800219E-02**	**3.331836E+00**	**1.734069E-17**	**4.032949E+01**
7	**4**				
1.109500E+01	4.661907E-01	2.830316E-02	3.331836E+00	1.570487E-17	4.018570E+01
7	5				

1.109000E+01	4.661907E-01	2.836000E-02	3.331836E+00	1.795568E-17	4.016027E+01
7	6				
1.108500E+01	4.661907E-01	2.860052E-02	3.331836E+00	1.599952E-17	4.001120E+01
7	6				
1.108000E+01	6.206837E+00	0.000000E+00	3.272644E+00	2.188191E-02	0.000000E+00
3	30				
.					
.					
.					

8.4 Cladding Thickness Determination to Minimize the Loss

After we find the proper QZMR for the TE0 mode, we will optimize the cladding thickness to minimize the loss under certain value. As mentioned in the last section, the loss is mainly caused by the transparency of the substrate to the photons generated at the active layer. The input file is shown in Table 8.4.1. We loop the n-cladding and p-cladding from 3 to 0.5 um simultaneously. Then from the imaginary part of the effective refractive index (WZI) in the output file, we can calculate the loss as a function of cladding layer thickness. The loss is calculated in terms of the WZI as follows:

$$\alpha = WZI * 2\pi / \lambda * 10^4 \qquad (8.4.1)$$

where α is the amplitude loss and has the unit of cm^{-1}, λ is the wavelength in free space and has the unit of micron. Power loss is 2α. Figure 8.4.1 shows the plot of the loss as a function of the cladding thickness, and the corresponding data are given in Table 8.4.2.

Table 8.4.1 Input file for looping the thickness of cladding layers.

```
!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=11.11 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=2 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=0.635
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set
LAYER MATSYS=0.1  XPERC=0   YPERC=0 TL=1.0   !GaAs substrate
LAYER MATSYS=8.0  XPERC=1   YPERC=0 TL=3.0   !Al.5In.5P n-cladding
LAYER MATSYS=8.0  XPERC=0.6 YPERC=0 TL=0.1   !(Al.6Ga.4).5In.5P SCH
LAYER MATSYS=11.0 XPERC=0.6 YPERC=0 TL=0.008 !Ga.6In.4P QW
LAYER MATSYS=8.0  XPERC=0.6 YPERC=0 TL=0.1   !(Al.6Ga.4).5In.5P SCH
LAYER MATSYS=8.0  XPERC=1   YPERC=0 TL=3.0   !Al.5In.5P p-cladding
LAYER MATSYS=0.1  XPERC=0   YPERC=0 TL=0.05  !GaAs P cap

!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=0 QZIO=0
OUTPUT FWHPNO=0 FWHPFO=1 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=0 LYROUT=0



!GAMOUT Parameter Set
GAMOUT LAYGAM=4 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
LOOPX1 ILX='TL' FINV=0.5 XINC=-0.05 LAYCH=2
LOOPX1 ILX='TL' FINV=0.5 XINC=-0.05 LAYCH=6
```

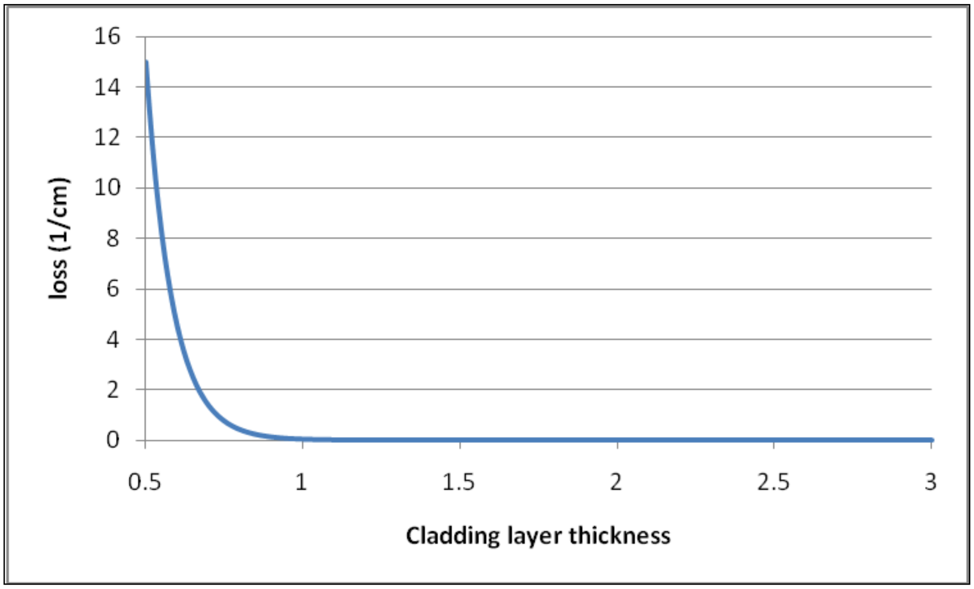


Figure 8.4.1 Loss as a function of n (p) cladding layer thickness for red laser structure.

Table 8.4.2 WZI and loss values for different cladding layer thickness.

TL(2) (microns)	WZI	Loss (1/cm)
3	1.42766E-17	1.41264E-12
2.99	2.20334E-17	2.18016E-12
2.98	2.19546E-17	2.17236E-12
2.97	2.31587E-17	2.2915E-12
. . .		
1.13	8.16284E-08	0.008076954
1.12	**9.19632E-08**	**0.009099557**
1.11	1.03606E-07	0.010251625

1.1	1.16724E-07	0.011549553
1.09	1.31502E-07	0.013011824
1.08	1.48151E-07	0.014659216
1.07	1.66908E-07	0.016515199
.		
.		
.		

Normally, it is sufficient to confine the loss to be less than 10^{-2}. Based on the plot and the data above, we pick 1.12 μm as the cladding thickness. We should recalculate the QZMR value every time we change the structure. Once we fix the p-cladding and n-cladding layer thickness, we loop the QZMR values again, and the looping results are calculated as in Table 8.4.3. And we find that the QZMR value for TE0 mode is still 11.10.

Table 8.4.3 QZMR looping results.

	QZMR	PHM	GAMMA(4)	WZR	WZI
FWHPF	KM	IT			
.					
.					
.					
1.118000E+01	4.870494E+00	1.979211E-03	3.223972E+00	6.727938E-03	1.615454E+01
5	29				

1.117000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	7	9
1.116000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	7	8
1.115000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	6	7
1.114000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	7	7
1.113000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	7	6
1.112000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	7	5
1.111000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	6	4
1.110000E+01	**4.661945E-01**	**2.831004E-02**	**3.331836E+00**	**9.196321E-08**	**4.022698E+01**	**6**	**3**
1.109000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	6	4
1.108000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	7	5
1.107000E+01	4.661945E-01	2.831004E-02	3.331836E+00	9.196321E-08	4.022698E+01	6	5

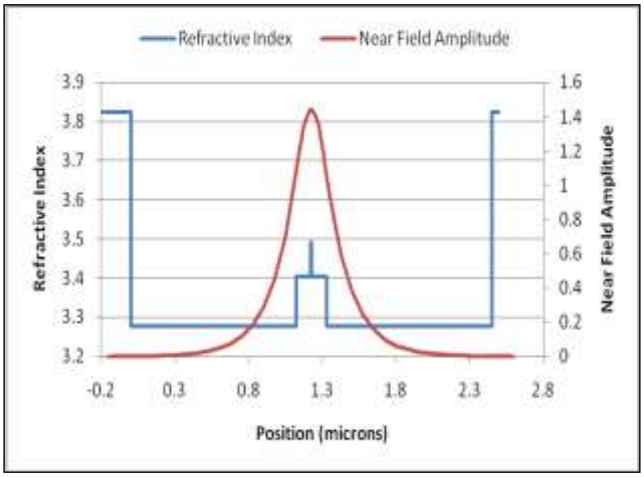
.
.

The layer parameter for the final optimized structure of 635nm broad-area red laser is listed in Table 8.4.4. The refractive and near field index profile are given in Figure 8.4.2. This optimization is based on achieving the largest quantum confinement factor for the broad-area lasers. However, for edge emitters, we need to consider far field and lateral confinement of the structure as well. Readers can refer to chapter 11 for the edge emitter lasers design with WAVEGUIDE II.

Table 8.4.4 Layer parameters for optimized 635-nm broad-area red laser structure

# of layers = 07

LAYER01	NLOSS= 0.00000	NREAL= 3.82357	TL= 1.00000
LAYER02	NLOSS= 0.00000	NREAL= 3.27693	TL= 1.12000
LAYER03	NLOSS= 0.00000	NREAL= 3.40423	TL= 0.10000
LAYER04	NLOSS= 0.00000	NREAL= 3.49147	TL= 0.00800
LAYER05	NLOSS= 0.00000	NREAL= 3.40423	TL= 0.10000
LAYER06	NLOSS= 0.00000	NREAL= 3.27693	TL= 1.12000
LAYER07	NLOSS= 0.00000	NREAL= 3.82357	TL= 0.05000

<table>
<tr><td rowspan="3">
</td><td>Quantum well confinement factor : 2.831004E-02</td></tr>
<tr><td>Effective index: 3.331836</td></tr>
<tr><td>Loss: 0.009099557 (cm^{-1})</td></tr>
<tr><td>Figure 8.4.2 Refractive index and near field profile of broad-area red laser.</td><td>Far field divergence angle: 4.022698E+01</td></tr>
</table>

Chapter 9

ASYMMETRIC WAVEGUIDE NITRIDE LASERS

A design of asymmetric waveguide structure for nitride laser diodes is introduced here. This chapter is based on a journal paper authored by Dr.Bour [1]. We reproduce the computation results of the optical mode in the paper for the asymmetric waveguide by using the WAVEGUIDE II, which is the windows version of MODEIG. The consideration of finite n-cladding layer for the asymmetric structure is also discussed in this chapter. For infinite n-cladding layer, the total optical confinement factors are almost identical with the semi-infinite n-cladding layer.

Section 9.1 gives the introduction about the reference journal paper and the asymmetric waveguide structure. Section 9.2 describes the input file and the material system we use for the calculation of the optical mode for different cladding layer consideration. Section 9.3 demonstrates the plots of the near field and confinement factors for the asymmetric waveguide. Section 9.4 gives the conclusion of this chapter.

9.1 Introduction

The leakage current for the nitride inplane laser is one of the major concerns for the high threshold current and the sensitivity of the temperature. A good design of the waveguide structure can confine the electrons from diffusion from the active region and reduce leakage current. The shorter minority carrier diffusion length makes the nitride material laser have a different waveguide design consideration than other arsenide and phosphide laser materials.

Conventionally, a high bandgap AlGaN is used as the tunnel barrier layer, which is placed over the active region for the confinement of the injected electrons. In reality, the decrease of hole concentrations with the increase in AlN alloy content makes the AlGaN difficult to be an ideal tunnel barrier layer. The asymmetric waveguide structure is introduced for the confinement of electrons. In the asymmetric structure, the p-cladding layer is placed immediately next to the multiple quantum wells for the purpose of confining the electrons. From the paper [1], we can see the total confinement factor for the asymmetric structure is higher than the conventional structure. However, this chapter will give the transverse optical mode analysis for the asymmetric waveguide structure, especially for the confinement factors.

For simplification of analysis, we assume the n-cladding layer has semi-infinite thickness as the ideal case because the number of mode solutions is more than the full epitaxial structure case. The full epitaxial structure case considers the finite n-cladding layer. This approximation of n-cladding layer is calculated for 1um-thick or semi-infinite n-cladding layers.

Another assumption of this analysis is that we don't consider the QW gain and the mode loss associated with the metal contact. The optical confinement factor is not significantly affected by the absorbing of metal contact because of the low real part of refractive index with the metal.

9.1.1 Asymmetric Waveguide Structure

Table 9.1 shows the asymmetric waveguide layer structure used in this chapter. There are five quantum well layers; in addition, the p-cladding layer is located adjacent to the quantum well barrier layer. The thickness of the waveguide layer is undecided here. For the semi-infinite n-cladding layer case, there are 14 layers for the WAVEGUIDE II input file. On the other hand, for the finite n-cladding layer, additional two layers will be added to the structure. From Table 9.1.1.1, we notice that the refractive index difference (Δn) between the GaN waveguide and AlGaN cladding is about 0.05. Such a small Δn makes the laser to be insensitive to QW's asymmetry property in the structure because of the weak transverse waveguiding.

In the simulation of the asymmetric structure, we use the semi-infinite n-cladding layer as the ideal case to calculate the transverse optical field distribution. Then, we also calculate the total optical confinement for the finite n-cladding layer to compare with the semi-finite case. The total optical confinement factor values for finite cladding layer are nearly close to those computed for semi-infinite n-cladding layer.

Table 9.1.1.1 List of refractive index for the layers in the waveguide structure [1]

Layer	**N**	**Thickness**	
		Semi-∞ case	Finite case
Sapphire	1.78	--	Semi-∞
GaN:Si	2.51	--	4 um
$Al_{0.07}Ga_{0.93}N$:Si cladding	2.46	Semi-∞	1 um
GaN:Si waveguide	2.51	t_n	t_n
$In_{0.02}Ga_{0.98}N$:Si barrier	2.52	6 nm	6 nm
$In_{0.1}Ga_{0.9}N$ QW	2.56	3.5 nm	3.5 nm
$In_{0.02}Ga_{0.98}N$:Si barrier	2.52	6 nm	6 nm
$In_{0.1}Ga_{0.9}N$ QW	2.56	3.5 nm	3.5 nm
$In_{0.02}Ga_{0.98}N$:Si barrier	2.52	6 nm	6 nm
$In_{0.1}Ga_{0.9}N$ QW	2.56	3.5 nm	3.5 nm
$In_{0.02}Ga_{0.98}N$:Si barrier	2.52	6 nm	6 nm
$In_{0.1}Ga_{0.9}N$ QW	2.56	3.5 nm	3.5 nm
$In_{0.02}Ga_{0.98}N$:Si barrier	2.52	6 nm	6 nm
$In_{0.1}Ga_{0.9}N$ QW	2.56	3.5 nm	3.5 nm
$In_{0.02}Ga_{0.98}N$:Si barrier	2.52	6 nm	6 nm
$Al_{0.07}Ga_{0.93}N$:Mg Cladding	2.46	Semi-∞	Semi-∞

9.2 Structure Analysis

In the optical mode analysis, we use a conventional way of finding the best n-waveguide thickness for a good confinement factor of five quantum wells for the semi-infinite case. We also give the procedure of calculation of the optical confinement factor for the finite n-cladding layer. In this section, we describe the needed parameters and procedure for the calculation of semi-∞ and finite cladding layer.

9.2.1 Material System

Currently, the WAVEGUIDE II does not have InGaN material system for the choice. Therefore, we directly use the refractive index for each layer instead of using the MATSYS function in the input file.

9.2.2 Semi-infinite cladding layer

a) Searching for a good QZMR value

We can loop QZMR for an assumption of 0.4um thickness, which might be the maximum thickness, of n-cladding layer. In the output "*.db" file, we can look for a certain block where the PHM value is less than one and the resulted QZMR converges to a certain value. The following is the sample input file.

Input:

--

!CASE Parameter Set

CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=6.5536 QZMI=0.00

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set

MODCON KPOL=1 APB1 =0.25 APB2=0.25

!STRUCT Parameter Set

STRUCT WVL=0.4

!LAYER Parameter Set

LAYER NREAL=2.46 NLOSS=0.0 TL=20

LAYER NREAL=2.51 NLOSS=0.0 TL=0.4

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.46 NLOSS=0.0 TL=20

!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1

!GAMOUT Parameter Set

GAMOUT LAYGAM=4 LAYGAM=6 LAYGAM=8 LAYGAM=10

GAMOUT LAYGAM=12 LAYGAM=2 COMPGAM=0 GAMALL=1

!LOOPZ Parameter Set

LOOPZ1 ILZ='QZMR' FINV=6.0516 ZINC=-0.001

END

Figure 9.2.2.1 Input file of finding QZMR for semi-infinite

Output

QZMR PHM WZR WZI QZR QZI KM

IT

6.325600E+00 6.355566E-01 2.496297E+00 5.398004E-17 **6.231501E+00** 2.695004E-16

6 6

6.324600E+00 6.355566E-01 2.496297E+00 -2.182691E-17 **6.231501E+00** -1.089729E-16

6 6

6.323600E+00 6.355566E-01 2.496297E+00 -5.444048E-17 **6.231501E+00** -2.717993E-16

6 6

6.322600E+00 6.355566E-01 2.496297E+00 -6.303027E-17 **6.231501E+00** -3.146846E-16

6 6

…………………………

6.162600E+00	6.355566E-01	2.496297E+00	1.844258E-20	**6.231501E+00**	9.207635E-20
6	5				
6.161600E+00	6.355566E-01	2.96297E+00	2.871621E-20	**6.231501E+00**	1.433684E-19
6	5				
6.160600E+00	6.355566E-01	2.496297E+00	4.381670E-20	**6.231501E+00**	2.187590E-19
6	5				

Figure 9.2.2.2 "*.db" output file

b) Total confinement factors within the quantum well regions

From Figure 9.2.2.2, the converged QZMR is 6.2316. We can then use this value to find the confinement factors in the quantum well region for different n-cladding thickness. The following input file shows the looping through the n-cladding waveguide thickness to find the optimal n-cladding waveguide layer with the highest total confinement factor values.

```
!CASE Parameter Set
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=6.2316 QZMI=0.00
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30
!MODCON Parameter Set
MODCON KPOL=1 APB1 =0.25 APB2=0.25
!STRUCT Parameter Set
STRUCT WVL=0.4
```

```
!LAYER Parameter Set
LAYER NREAL=2.46 NLOSS=0.0 TL=20
LAYER NREAL=2.51 NLOSS=0.0 TL=0
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.46 NLOSS=0.0 TL=20
!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1
OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1
!GAMOUT Parameter Set
GAMOUT LAYGAM=4 LAYGAM=6 LAYGAM=8 LAYGAM=10
GAMOUT LAYGAM=12 LAYGAM=2 COMPGAM=0 GAMALL=1
!LOOPX Parameter Set
LOOPX1 ILX='TL' FINV=0.4 XINC=0.01 LAYCH=2
END
```

Figure 9.2.2.3 Input file of varied thickness for semi-infinite layer

From the generated “*.db” file, we can find the confinement factors (GAMMA(#)) for different thickness. The summation of GAMMA(4), GAMMA(6), GAMMA(8), GAMMA(10) and GAMMA(12) is the total confinement factors for the quantum well region. Figure 9.3.2.1 shows the relation of the total confinement factors with the waveguide layer thickness.

c) The input file for getting the near field plot

From Figure 9.3.2.1, we found the maximum confinement factor is at 0.09um n-waveguide layer thickness. We can then fix the n-waveguide thickness to 90nm and the QZMR value to get one set of results and produce the near field data for this structure. Figure 9.2.2.4 is the input file to get the near field plot.

```
-----------------------------------------------
!CASE Parameter Set
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=6.2315 QZMI=0.00
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30
!MODCON Parameter Set
MODCON KPOL=1 APB1 =0.25 APB2=0.25
!STRUCT Parameter Set
STRUCT WVL=0.4
!LAYER Parameter Set
LAYER NREAL=2.46 NLOSS=0.0 TL=20
LAYER NREAL=2.51 NLOSS=0.0 TL=0.09
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
```

```
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.46 NLOSS=0.0 TL=20
!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1
OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1
!GAMOUT Parameter Set
GAMOUT LAYGAM=4 LAYGAM=6 LAYGAM=8 LAYGAM=10
GAMOUT LAYGAM=12 LAYGAM=2 COMPGAM=0 GAMALL=1
---------------------------------------------------------------------
```

Figure 9.2.2.4 Input file at thickness of 0.09um

There is no looping in this input file. The output file, **"*.nf"**, gives the near field intensity (NFINT) and the position (XXFT) information. Figure 9.3.1.1 shows this plot. The above method of finding the relation of confinement factor and n-waveguide thickness is good for the structure without leakage wave into the outside of active region. As an alternative, users can try to loop the n-waveguide layer and QZMR at the same time. In this method, if smaller steps are used in the looping, the computation will consume more time and memory. User should be careful about using this method. We do not recommend users to use this method for a bounded mode waveguide structure. An example of QZMR value for the semi-infinite cladding layer, 6.3186, can be obtained by looping the thickness and QZMR at the same time. Next section, we will apply this method for finite n-cladding layer which contain standing wave in the structure.

9.2.3 Finite n-cladding layer

For the comparison to the semi-infinite n-cladding layer, we use a finite n-cladding layer of thickness 1um, add a GaN:Si layer of thickness 4um and make the sapphire layer to be semi-infinite for the finite n-cladding layer structure. In this structure, the total layer becomes 14 layers. This finite n-cladding layer is more close to a full epi-structure.

a) Finding QZMR

The addition of the thick GaN layer makes this structure a leakage structure which causes the difficulty of finding an initial QZMR guess if we follow the previous procedure of semi-finite structure. By using the previous method, the PHM value is difficult to be less than one for all different thickness. Even though some QZMR has a KM value of 7, we found that light is confined mostly in the GaN layer not in waveguide or active layers in this case. Light leaks out into the GaN layer. From the above observations, which cannot satisfy our laser design, we need to find some quasi-leaky modes that can confine most of the light in the waveguide and active layer. From looping the QZMR value from lowest to highest at the maximum n-waveguide thickness, we found that at some range of QZMR the structure has a high loss value. However, since we know that the structure should not be very lossy, we choose the QZMR range with very low loss as the start point. The QZMR ranges from 6.07 to 6.3, which is the similar QZMR range for the semi-finite structure with different n-waveguide layer thickness. Figure 9.2.3.1 and 9.2.3.2 are the input file and partial output values.

```
!CASE Parameter Set
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=6.5536 QZMI=0.00
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30
!MODCON Parameter Set
MODCON KPOL=1 APB1 =0.25 APB2=0.25
!STRUCT Parameter Set
STRUCT WVL=0.4
!LAYER Parameter Set
LAYER NREAL=1.78 NLOSS=0.0 TL=20
LAYER NREAL=2.51 NLOSS=0.0 TL=4
LAYER NREAL=2.46 NLOSS=0.0 TL=1
LAYER NREAL=2.51 NLOSS=0.0 TL=0.4
LAYER NREAL=2.52 NLOSS=0.0 TL=0.006
LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035
```

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.56 NLOSS=0.0 TL=0.0035

LAYER NREAL=2.52 NLOSS=0.0 TL=0.006

LAYER NREAL=2.46 NLOSS=0.0 TL=20

!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1

!GAMOUT Parameter Set

GAMOUT LAYGAM=4 LAYGAM=6 LAYGAM=8 LAYGAM=10

GAMOUT LAYGAM=12 LAYGAM=14 COMPGAM=0 GAMALL=1

!LOOPZ Parameter Set

LOOPZ1 ILZ='QZMR' FINV=3.1684 ZINC=-0.01

END

Figure 9.2.3.1 Input file

QZMR PHM WZR WZI QZR QZI KM

IT

6.323600E+00 5.384547E+00 2.498514E+00 **-1.250029E-21** 6.242573E+00 -6.246430E-21

6 30

6.313600E+00 4.323808E+00 2.502647E+00 **-3.539787E-20** 6.263244E+00 -1.771768E-19

6 23

6.303600E+00 2.201863E+00 2.508162E+00 **-1.053702E-20** 6.290874E+00 -5.285709E-20

6 13

…………………….

6.073600E+00 1.061256E+01 2.464580E+00 **-1.661331E-18** 6.074157E+00 -8.188970E-18

5 3

6.063600E+00 1.080366E+01 2.462906E+00 **-1.502795E-18** 6.065908E+00 -7.402486E-18

5 4

6.053600E+00 1.061256E+01 2.464580E+00 **-1.892112E-16** 6.074157E+00 -9.326526E-16

5 6

Figure 9.2.3.2 Output data

For the convenience purpose, we will not put the input file for the rest of input and output file description. The major part of input file is similar to Figure 9.2.3.1 except for the different value of QZMR, initial TL value for waveguide layer and LOOP parameters. We will address the corresponding values of the above variables for running the rest of the simulation.

If we check the range of QZMR values with the resulted QZMR value from the semi-∞ case for different n-waveguide thickness, we find that the QZMR value for semi-

∞ case is from 6.23 to 6.07, which is in the range from the result of figure 9.2.3.2. We assume that the modal effective index value might be close to the semi-∞ case. Therefore, we can use the range 6.23-6.07 to be our initial guess range. After choosing the QZMR range, we need to have some initial guess points of QZMR value to start with. Here, we introduce a method of looping the QZMR and n-waveguide layer thickness at the same time to find a converged QZMR values as our starting point. As mentioned before, this method is not recommended by regular usage of non-leaky waveguide structure. If the computer speed and memory is not quick or large enough, users can loop through a smaller interval of thickness and QZMR.

Table 9.2.3.1 Input file parameters

	Parameters
Initial guess QZMR	QZMR=6.23
n-waveguide (4th) layer parameter LAYER	TL=0.4
LOOPX1	ILX='TL' FINV=0.01 XINC=-.01 LAYCH=4
LOOPZ1	FINV=6.06 ZINC=-0.01

From the “*.db” file, we can find about 9 converged QZR points. We use the QZMR of semi-infinite structure as the range reference and then chose 6.116, 6.154, 6.188, 6.217 and 6.242 as our QZMR guess value for looping through the n-waveguide layer. From the latter analysis, we can see these QZMRs are related to the resonant outcoupling occurrences at a certain n-waveguide thickness.

b) Looping of n-waveguide layer

In this step, we only loop through the n-waveguide layer with the initial QZMR values from part a. For the first point, 6.116, we use "**QZMR=6.12**" and looping through the n-waveguide thickness from 0.4um to 0.001um. The "*.db" file gives a result of confinement factor for each layer. From this "*.db" file, we find that at certain range of thickness, from 0.001um to 0.077um, the total confinement has some significant values and the resulted QZR value changes with the thickness in this range. On the other hand, for the section of the small, almost zero, total confinement value, the QZR values, which have the value of 6.1155, are almost the same for different thickness. At this point, we know that the relation of the total confinement factors with the waveguide thickness might not be a smooth line.

We loop the thickness from 0.001um to 0.4um for the same "**QZMR=6.12**". The total confinement factor that is larger than 4.5E-4 occurs at different section of thickness range, about from 0.067um to 0.144um. From these two runs of same QZMR but different thickness looping order, we get the total confinement factor in the thickness range from 0.001um to around 0.144um. We then repeated the same operations with the other four points. For the point, **"QZMR=6.23"**, we found the total confinement factors with significant values in the range of 0.4um to 0.33um. For the other three initial QZMR values, most of the total confinement values are about 10E-7 except for one thickness point which is the resonant point with >4.5E-4 confinement factor. These resonant points happen at 0.26 um and 0.33um. From these results, the confinement vs. thickness curve exists four resonant points at around 0.076um, 0.144um, 0.26um and 0.33um.

Searching for a new QZMR value

Until this point, we have found three segments for the confinement factor verse n-waveguide thickness curve. For finding the other two segments, we need to find a new initial QZMR values. We repeat the procedure of a. to loop through the QZMR and thickness at the same time with small looping step. The looping steps, XINC and ZINC, change from 0.01 to 0.001. We run this operation for different segments, which are from 0.144um to 0.26um and 0.26um to 0.33um. Table 9.2.3.2 shows the QZMR and thickness parameters we use for these two operations. The rest of the input file is the same with Figure 9.2.2.1.

Table 9.2.3.2 QZMR and layer thickness

	0.144~0.26 um	0.26~0.33um
Initial guess QZMR	QZMR=6.11	QZMR=6.19
n-waveguide (4th) layer parameter	TL=0.2	TL=0.328
LAYER		
LOOPX1	ILX='TL' FINV=0.14 XINC=-.001	ILX='TL' FINV=0.2 XINC=-.001
	LAYCH=4	LAYCH=4
LOOPZ1	FINV=6.17 ZINC=0.001	FINV=6.22 ZINC=0.001

After the simulation, we get the desired total confinement factor varied with the thickness for some good initial QZMR guess values. All information now can be combined to plot the total confinement factors vary with n-waveguide thickness as Figure 9.3.2.1.

The basic idea of finding the quasi-leaky mode with the total confinement of mode profile within the active region is the choice of initial QZMR value for looping the n-waveguide thickness. Figure 9.2.3.3 shows the process flow. This figure gives a schematic view of the previous description of finding the quasi-leaky mode that has zero loss and field is mostly confined in the active region.

Users can also try to pick some QZMR values from the semi-finite layer case to run for the looping of the n-waveguide thickness to get the similar result because we expect the finite case has the similar modal effective index. With good luck, Users might be able to get the answer within a few guess of QZMR value. A good initial QZMR value might need to have three digits precision after the decimal point. This means that the users can end up with 1000 times QZMR guess, if in bad luck. However, the above operations, from step a to step c, can give users more systematic procedure to find quasi-leaky mode solutions from WAVEGUIDE II`.

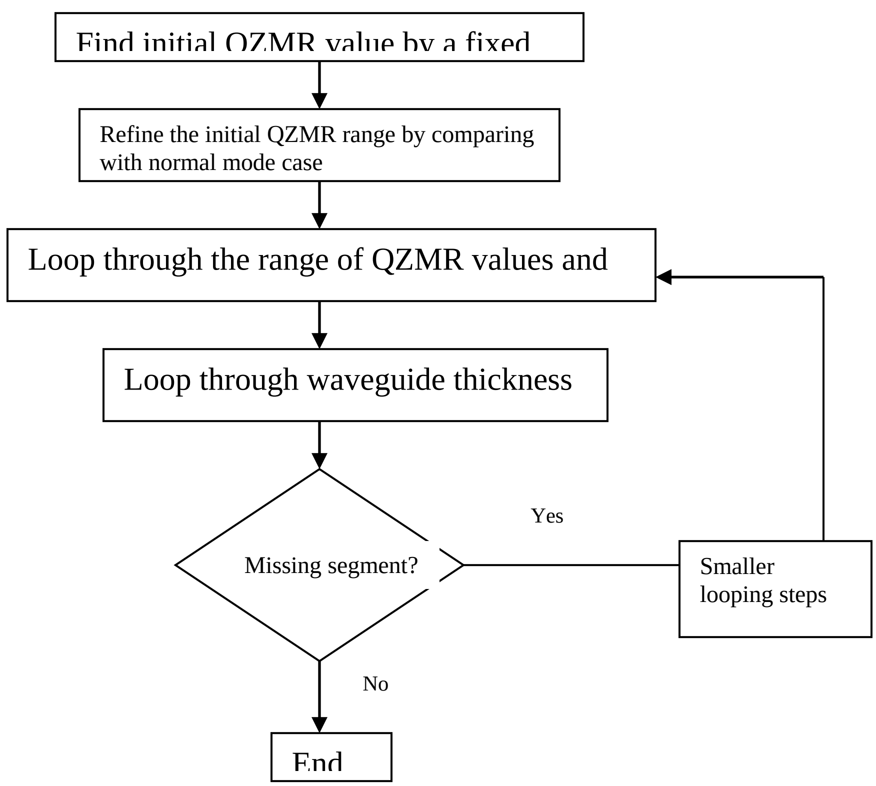


Figure 9.2.3.3 Process flow for the finite n-cladding case

9.3 Output plots

A near field plot for the optimized structure is provided in this section. We also analyze the effect of n-waveguide thickness on confinement factor.

9.3.1 Near field

Figure 9.3.1.1 shows the near field intensity plot verse the layer structure distance and the layer refractive index structure for the semi-infinite n-cladding layer and the waveguide thickness is 90nm. The total confinement factor for five quantum wells is 5.3%. Even though the QWs are displaced from the peak of the mode, the total confinement factor is not degraded much. The total confinement factor still exceeds the confinement factor for the conventional structure with AlGaN layer[1].

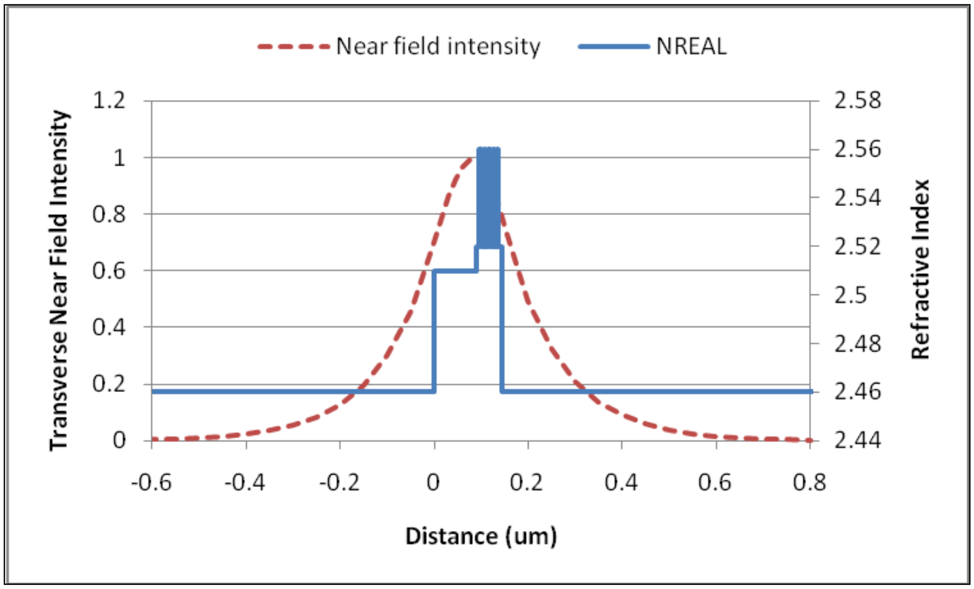


Figure 9.3.1.1 Optical mode intensity profile and refractive index for semi-∞ at 0.09um. [1]

9.3.2 Confinement factor for semi-∞ and finite cladding layer

By looping the waveguide thickness, we find that the highest confinement factor happens at waveguide thickness=90nm. From Figure 9.3.2.1, we also compare the confinement factor for the finite n-cladding layer case. Both cases have the almost identical confinement factor except for several resonant points where the confinement factor has the lowest value. From Figure 9.3.2.2, we can find the field profile for both cases. The finite case has some light leaks out from the waveguide cladding layer at the resonance point where the waveguide thickness is 0.144um. When we plot Figure

9.3.2.2, we can use “DXIN=0.01” to refine the field solution and get a better resonant field.

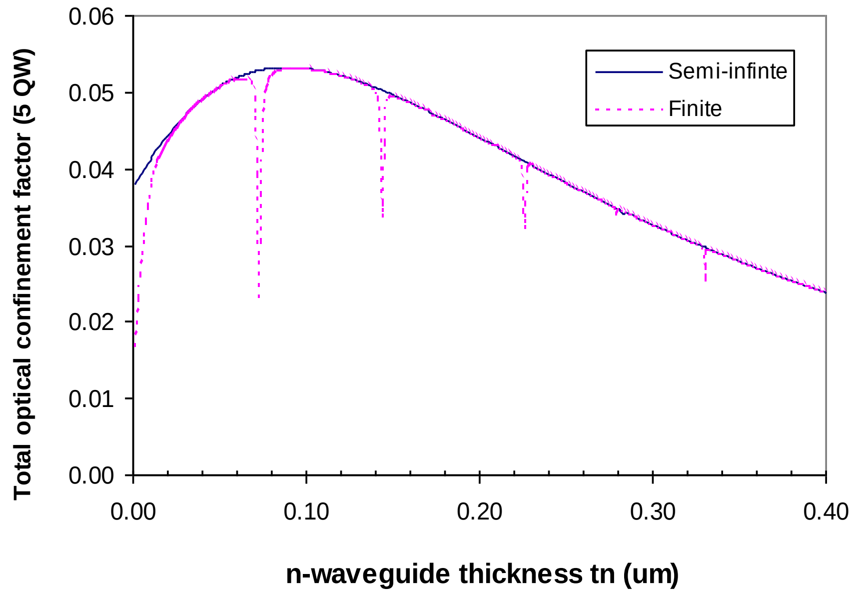


Figure 9.3.2.1 Total confinement factor for finite and semi-∞ n-cladding layer. [1]

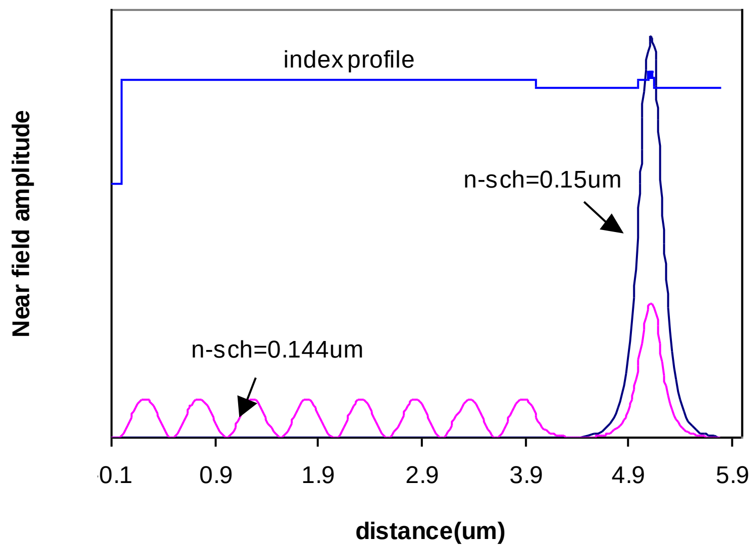


Figure 9.3.2.2 Near field plot for finite n-cladding layer structure at different n-sch thickness. After [1]

9.4 Conclusion

We give the analysis of asymmetry waveguide structure for nitride laser by using WAVEGUIDE II. In the analysis of the structure, the assumption of the semi-infinite n-cladding layer obtains almost the same confinement factor result for the more realistic finite n-cladding layer except for some resonance points in the finite cladding layer case. The resonance points reproduced here give the agreement of the resonance points in the paper. These resonance points can be eliminated by using thick AlGaN:Si instead of GaN:Si.

REFERENCES

[1] D.P.Bour, M.Kneissl, C.G. Van de Walle, G.A. Evans, L.T.Romano, J.Northrup, M.Teepe,R.Wood,T.Schmidt,S.Schoffberger, and N.M.Johnson, “Design and performance of asymmetric waveguide nitride laser diodes”, IEEE Journal of Quantum Electronics, vol 36, no. 2, pp184-191, 2000.

Chapter 10

DESIGNING A RIDGE WAVEGUIDE LASER USING WAVEGUIDE II PROGRAM

Chapter 10 mainly focuses on how to design a ridge waveguide laser using WAVEGUIDE II Program. As index-guided lasers, ridge waveguide lasers have the advantages of high confinement factor, high quantum efficiency, low threshold current density, single-mode- operation, and good temperature performance [1].

Figure 10.1.1 illustrates a ridge waveguide laser with cleaved facets. The wave propagates in the z direction, and the laser is a Febry-Perot laser formed by the resonance cavity and the two cleaved facets as reflective mirrors. In the transverse plane (xy plane), the material compositions in ridge region and channel regions are different, and accordingly the effective refractive indices of the fundamental mode in the regions are different, which is equivalent to a three-layer-dielectric waveguide. By careful design, single-lateral-mode operation of a ridge waveguide laser can be achieved.

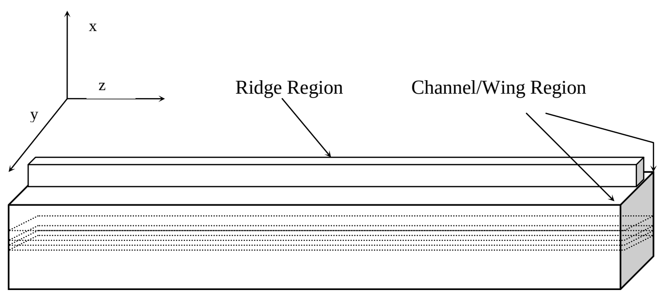


Figure 10.1.1 A ridge waveguide laser

In this chapter, an outline and explanations of how to design a ridge waveguide laser using WAVEGUIDE II program are presented first in Section 10.1, including the design of a basic waveguide laser, optimization of the position of an etch stop layer, and considerations in determining ridge width and channel width.

Then an example to design a ridge waveguide multi-quantum-well laser using WAVEGUIDE II program is provided in the section 10.2. The design steps outlined and explained in Section 10.1 are demonstrated by the example with simulation details. And in the end, a summary of the chapter is provided.

10.1 Outline and explanations of the design

In this chapter, an example is provided to illustrate how to design a ridge waveguide laser using WAVEGUIDE II program. In the example, the quantum well structure of AlGaInAs material systems with peak lasing wavelength at 1.52um on InP substrate is used, which is designed in the Appendix C.4 of GAIN Program User's Manual [2]. The quantum well structure is shown in Table 10.1.1. In simulations of the GAIN program, the cladding layers are equivalent to the inner cladding layers in the WAVEGUIDE II program, which have infinite thicknesses in the GAIN program as outermost layers.

Table 10.1.1 the quantum well structure designed in the Appendix C.4 of GAIN program User's Manual**.**

Layer	Material Composition	Strain	Thickness (Å)
QW ($Ga_xAl_yIn_{1-x-y}As$)	x = 0.22, y = 0.08	-0.011705	60
Barrier ($Ga_xAl_yIn_{1-x-y}As$)	x = 0.35, y = 0.25	0.0087769	50
Cladding ($Ga_xAl_yIn_{1-x-y}As$)	x = 0, y = 0.48		100

The design of a ridge waveguide laser is summarized into several steps. The first step is to design a basic waveguide, which is explained in section 10.1.1, and the design details corresponding to this step is provided in section 10.2.1. Second, the position of a etch stop layer is optimized to achieve the required lateral effective refractive index difference, as is explained in section 10.1.2 and 10.2.2. Third, the channel width and ridge width are designed to maintain single-lateral-mode and low loss, which is discussed in section 10.1.3 and 10.2.3.

10.1.1 Design a basic waveguide laser

A typical basic waveguide laser is composed of active layers, including quantum wells and barriers, and passive layers, including SCH layers, inner cladding layers, outer cladding layers, n- substrate, and p- cap. As we already have a designed quantum well structure, we can start with a design of a basic waveguide laser. The active region of the designed ridge waveguide laser in our example is made of six quantum wells using the quantum well laser design in the GAIN program [2], shown in Table 10.1.1. Besides the quantum wells, the waveguide structure of a basic waveguide laser is composed of two SCH layers, two inner cladding layers, two outer cladding layers, n- substrate, and p- cap. Figure 10.1.2 shows the refractive index profile of a basic waveguide laser in x direction defined in Figure 10.1.1, illustrating the layers of the waveguide laser structure mentioned above.

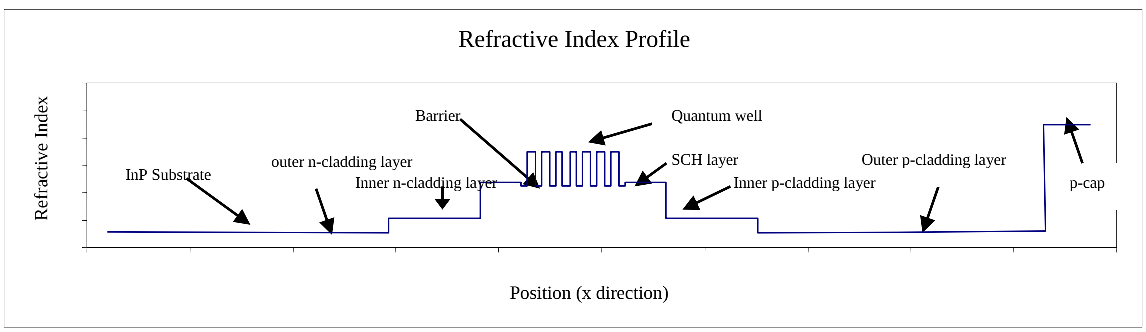


Figure 10.1.2 Refractive index profile of a waveguide laser

The material compositions and thicknesses of quantum wells and barriers have already been designed in the GAIN program, so we can use them in WAVEGUIDE II program. The inner n-cladding layer and inner p-cladding layer are n and p doped $Al_{0.48}In_{0.52}As$ as designed in the GAIN program. The outer n- and p- cladding layers are made of n- and p- doped InP respectively. In the WAVEGUIDE II program, we can optimize the thicknesses of SCH layers, inner cladding layers, and outer cladding layers to achieve high confinement factor, low loss, and narrow far-field divergence.

From Figure 10.1.2, we can find that p-cap is the top layer of the ridge of the laser. Usually, for AlGaInAs material system on InP substrate, highly doped InGaAs is used as p-cap to reduce sheet resistance of the laser and the thickness is usually 0.1-0.2 um. As explained in the previous chapters, the two outermost layers, n-substrate and p-cap in our case, are deemed infinite thick in WAVEGUIDE II program. Usually, the substrate thickness is not critical to the waveguide structure of a laser, so it is not simulated in this example. If users want to simulate the thicknesses of p-cap and n-substrate, it is advised that p- and n- metal material be added beyond them as outermost layers, and sometimes, to be simple, air can be used for simulations instead of p- and n-metal.

After description of a basic waveguide laser structure, it is clear that the thicknesses of SCH layers, inner cladding layers, and outer cladding layers need to be simulated in the WAVEGUIDE II program. In our example, we simulate SCH layer thickness first, and then inner cladding layer thickness, and outer cladding layer thickness. The details will be provided in Section 10.2.1.

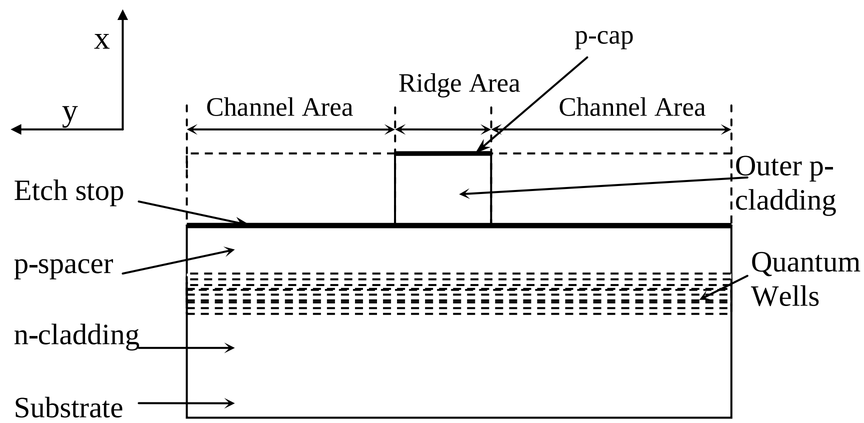


Figure 10.1.3 Diagram of the cross section of a ridge waveguide laser

10.1.2 Position of an etch stop layer: Δneff vs. p-spacer thickness

Figure 10.1.3 shows the side view (transverse view) of a ridge waveguide laser. In order to fabricate the ridge, an etch stop layer is added in the p- cladding layer of the basic waveguide laser. As shown in Figure 10.1.3, by addition of the etch stop layer, the p-cladding layer is divided into two parts called p-spacer layer and outer p-cladding layer respectively. The layer compositions in the ridge area and channel area are different, resulting in different effective refractive indices in the two regions, neff and neff'.

The refractive index profiles in the channel region (also called wing region) and in the ridge region are illustrated in Figure 10.1.4 and 10.1.5. In the wing region, a thin dielectric layer such as Si3N4 is deposited on top of the p-spacer layer for insulation.

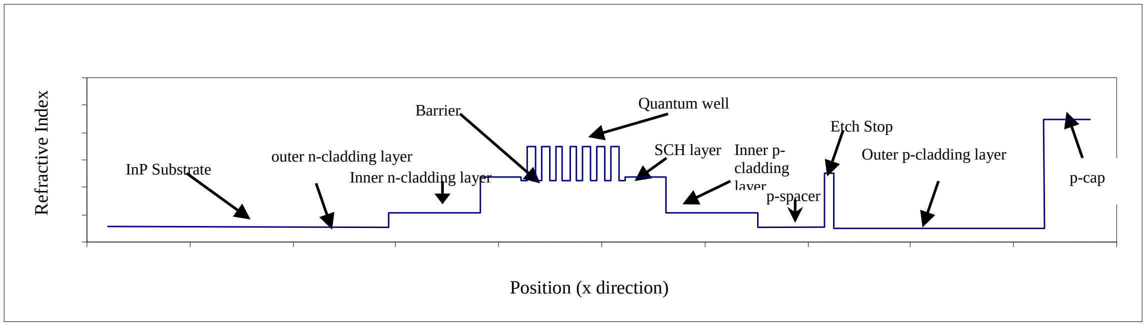


Figure 10.1.4 Refractive index profiles in the channel region

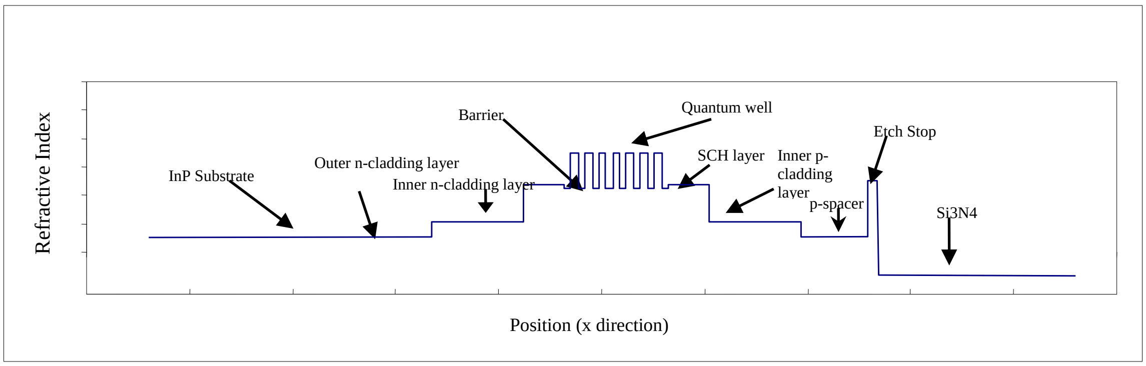


Figure 10.1.5 Refractive index profiles in the ridge region

The layer thickness of the p-spacer, indicating the position of etch stop, influence the effective refractive indices and therefore the difference between them, □neff. In addition, the position of an etch stop layer affects the far-field divergence of the ridge waveguide laser. Consequently, knowing the desired or acceptable □neff and far-field divergence, the position of the etch stop layer can be determined. The details of simulations will be provided in Section 10.2.2.

10.1.3 Determine ridge width and channel width.

In addition to the design of a ridge waveguide laser discussed in section 10.1.1 and 10.1.2, the ridge width and channel width need to be designed. As shown in Figure 10.1.3, 10.1.4, and 10.1.5, the effective refractive indices in the ridge region and channel regions are different. Therefore, in y direction of the transverse plane shown in Figure 10.1.3, the ridge waveguide laser is equivalent to a three-layer dielectric slab waveguide with the refractive indices of the core layer (center layer) and the cladding layers (outer layers) equal to the effective refractive indices of the ridge and channel regions respectively, neff and neff', as illustrated in Figure 10.1.6.

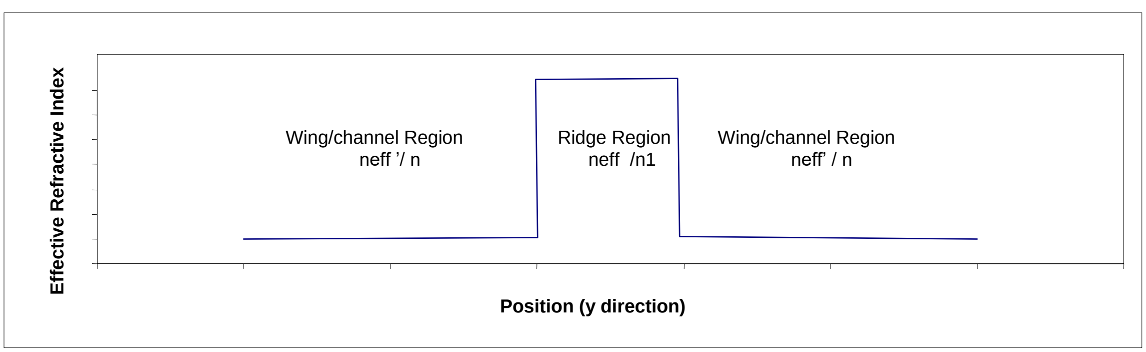


Figure 10.1.6 Refractive index profile of the equivalent three-layer dielectric slab waveguide.

Ridge Width

As we know, by solving Maxwell equations and matching boundary conditions of the three-layer dielectric slab waveguide, the graphical solutions can be found for Equation 10.1, 10.2, and 10.3 for TE polarization [1].

$$\alpha \frac{d}{2} = \frac{\mu}{\mu_1}\left(k_x \frac{d}{2}\right)\tan\left(k_x \frac{d}{2}\right)$$ for even modes (Equation 10.1)

$$\alpha \frac{d}{2} = -\frac{\mu}{\mu_1}\left(k_x \frac{d}{2}\right)\cot\left(k_x \frac{d}{2}\right)$$ for odd modes (Equation 10.2)

$$\left(\alpha \frac{d}{2}\right)^2 + \left(k_x \frac{d}{2}\right)^2 = \omega^2\left(\mu_1\varepsilon_1 - \mu\varepsilon\right)\left(\frac{d}{2}\right)^2$$ (Equation 10.3)

where □ is the decay constant in the cladding layer I and III as shown in Figure 10.1.7, k_x is the x component of k in the core layer II, d is the thickness of the core layer II, □ and □ are the permeability and permittivity of layer I and III, and □□ and □□ are the permeability and permittivity of layer II, □ is the angular momentum of the modes in layer II.

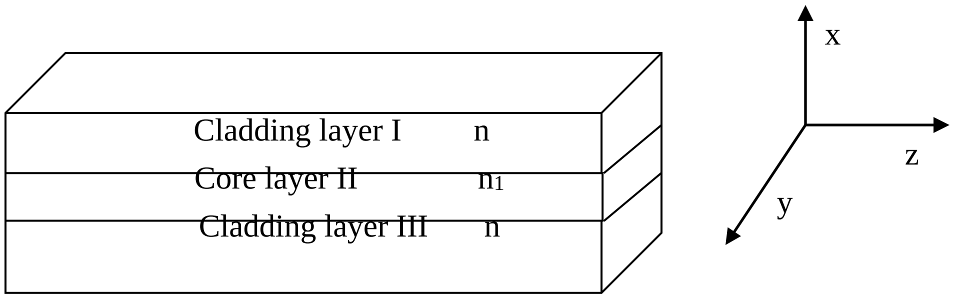


Figure 10.1.7 Diagram of a three-layer dielectric slab waveguide

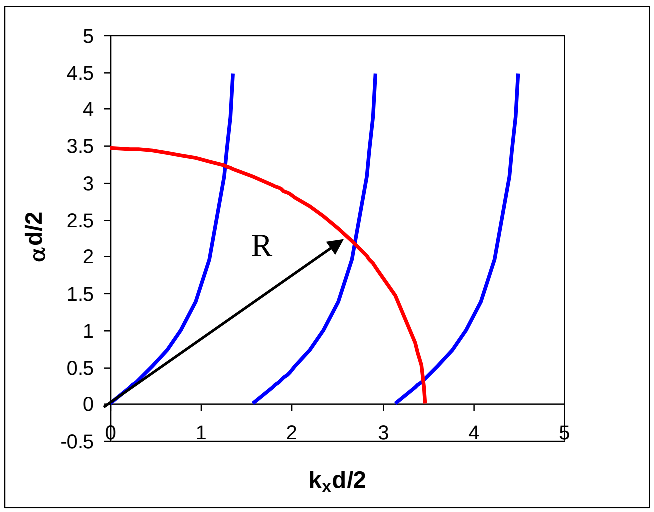


Figure 10.1.8 A graphical solution to the Equations 10.1.1-10.1.3 for a three-layer dielectric slab waveguide

As shown Figure 10.1.8, the number of modes allowed to propagate in the three-layer dielectric slab waveguide is determined by the radius of the quarter circle R, which is $R = \left(k_x \frac{d}{2}\right)\sqrt{n_1^2 - n^2} < \frac{\pi}{2}$. Therefore, the cutoff condition for the 1^{st} TE mode TE1 is derived as $d < \frac{\lambda}{2\sqrt{n_1^2 - n^2}}$ (Equation 10.4). In other words, only one mode, TE0 mode, can propagate for the 3-layer dielectric waveguide with the core thickness (ridge width) that meets the condition set by Equation 10.4.

Accordingly, the maximum ridge width for the designed ridge waveguide laser to maintain single-TE-mode operation can be calculated by Equation 10.4. The details of how to determine the ridge width is provided in section 10.2.3.1.

Wing/Channel Width

In order to determine the wing/channel width, we simulate a five-layer dielectric waveguide as shown in Figure 10.1.8. In this way, minimum separation between ridges can be simulated in the WAVEGUIDE II program by observing the loss variation as a function of channel width. If the ridges are too close to one another, the effects of neighboring ridges are not negligible, and accordingly the loss of the fundamental mode is huge. On the other hand, if the ridges are far enough, their effects to one another are negligible so that it is equivalent to a three-layer dielectric slab waveguide. Hence, in this step, the channel width is chosen by looping channel width to observe loss variation as a function of channel width. The details of simulations are discussed in section 10.2.3.2.

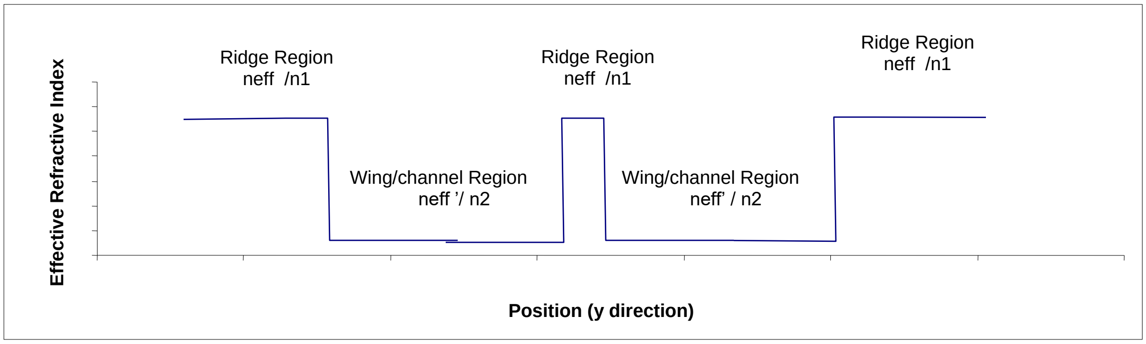


Figure 10.1.8 Refractive index profile of the equivalent five-layer dielectric waveguide

10.2 Simulation details for the design of a ridge waveguide laser using WAVEGUIDE II program

After the discussion and overview of the ridge waveguide laser design in section 10.1, the details of simulations using WAVEGUIDE II program will be provided in this section. Input and output files will be discussed to demonstrate how to optimize layer thicknesses. As discussed in 10.1, we begin with the design of a basic waveguide laser structure.

10.2.1 Design of a basic waveguide laser

10.2.1.1 Optimization of SCH layer thickness

First, we need to optimize the thicknesses of the two SCH layers. Usually, we choose the same thickness for the two SCH layers. As illustrated in Figure 10.1.2, the layer structure of the designed laser includes quantum well and barrier layers, SCH layers, n- and p-cladding layers, n- substrate, and p- cap.

Quantum well and barrier layer thicknesses have been designed using GAIN program, which is shown in Table 10.1.1. As a start, we first give guess thicknesses to the other layers according to experience and find the effective refractive index of the fundamental mode. The initial laser structure is listed in Table 10.2.1. And after that, we loop the thicknesses of the two SCH layers simultaneously to study the variation of confinement factor and far-field divergence with the variation of the SCH layer thickness.

Table 10.2.1 Layer composition and thickness table for the initial structure of the designed basic waveguide laser

Layer	Material Composition	Layer Thickness (TL) (um)
n-substrate	InP	200
Outer n-cladding	InP	2
Inner n-cladding layer	$Al_{0.48}In_{0.54}As$	0.5
SCH layer	$Al_{0.24}In_{0.24}As$	0.5
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005

Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
SCH layer	$Al_{0.24}In_{0.24}As$	0.5
Inner p-cladding layer	$Al_{0.48}In_{0.54}As$	0.5
Outer p-cladding	InP	2
p-cap	InP	0.

As instructed in Chapter 2, we can generate input file using WIFE or modifying existing input file and then loop for QZMR to find the effective refractive index of the fundamental mode. After finding good QZMR, which is 10.95964, we loop the thicknesses of SCH layers (layer 4 and layer 18) from 0.5 um to 0.01 um at an increment of -0.01 um simultaneously. The input file is listed in Table 10.2.2. After evaluation of the input file, we can plot total confinement factor of six quantum wells and far-field divergence (FWHM) contained in .db file as a function of SCH layer thickness, as shown in Figure 10.2.1.

Table 10.2.2 Input file to optimize SCH layer thicknesses

```
CASE KASE=AlGaInAs (6 wells)

CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6

CASE    QZMR= 10.95964 QZMI=0.0

CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1


!CASE    DXIN=0.2

!CASE    IL=100  KGSS=1

MODCON  KPOL=1   APB1=0.25   APB2=0.25


STRUCT  WVL=1.55


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=200.0   !n-substrate

LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=2.0   !n-cladding


LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=0.5  !n-inner-cladding

LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.5  !sch


LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005   !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier
```

```
LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier


LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.5  !sch

LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=0.5 !p-inner-cladding


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=2.0   !p-cladding

LAYER  NREAL=3.65 NLOSS=0.0 TL=0.2  !P-cap. InGaAs n from website Adachi's model


OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0

OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1  ITO=1

OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0

GAMOUT  LAYGAM=5,7,9,11,13,15   COMPGAM=0     GAMALL=0


!LOOPZ1  ILZ='WVL'  FINV=1.33  ZINC=0.005

!LOOPZ1 ILZ='QZMR' FINV=10.0 ZINC=-0.01

LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=4

LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=18

!LOOPX1 ILX='TL' FINV=0.3 XINC=-0.01 LAYCH=40
```

```
END
```

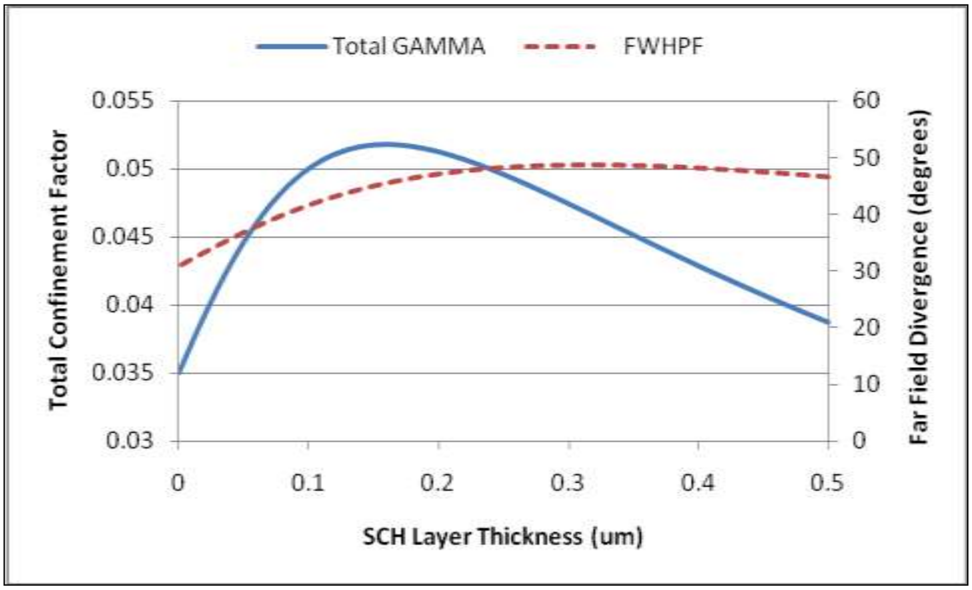


Figure 10.2.1 Plots of the total confinement factor (total □) and Far-Field Divergence FWHP (Degree) vs. SCH layer thickness

From Figure 10.2.1, we can see that the maximum total confinement factor, □ = 0.0518, happens at SCH layer thickness equal to 0.16 um, where FWHM of far field intensity equals 45.5 degree. As revealed in Figure 10.2.1, both confinement factor and far-field beam divergence increase with the increase of the SCH layer thickness in the range of 0 to 0.16 um. Therefore, a balance between confinement factor and far-field beam divergence is required to determine the SCH layer thickness. In this example we choose SCH layer thickness to be 0.16 um to maximize the confinement factor.

10.2.1.2 Optimization of inner cladding layer thickness

After the SCH layer thickness is determined, we need to optimize the inner p- and n- cladding layer thicknesses by plotting of loss vs. the inner cladding layer thickness. Usually, we choose the same thickness for inner p- and n- cladding layers.

To be simple, we can generate a new input file by modifying the previous input file. We can first find the QZR of the fundamental mode for SCH layer thickness of 0.16 um from the previous .db file as an initial guess for QZMR in the new input file, and then loop the thicknesses of inner cladding layers (layer 3 and layer 19) from 1.0 um to 0.0 um with an increment of -0.01 um simultaneously. The new input file is listed in Table 10.2.3 with modified parts highlighted.

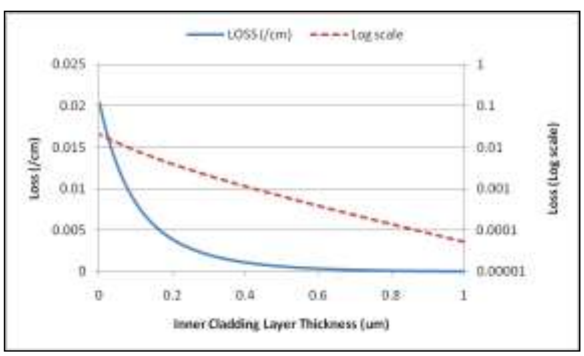
After evaluation of the input file, the .db file is plotted, and the plots of loss, the total confinement factor and Far-Field Divergence FWHP as a function of cladding layer thickness are shown in Figure 10.2.2 (a) and (b) respectively.

Table 10.2.3 Input file to optimize inner cladding layer thicknesses.

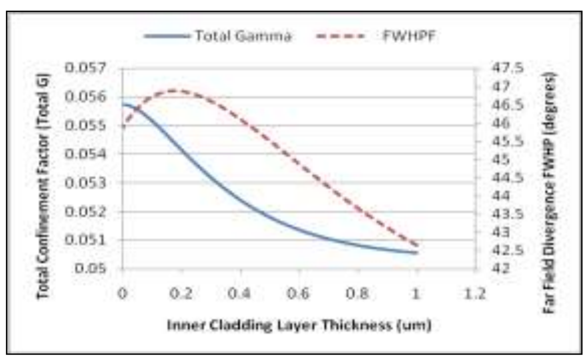
```
CASE KASE=AlGaInAs (6 wells)
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR= 10.58612 QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1


!CASE    DXIN=0.2
!CASE    IL=100  KGSS=1
```

```
MODCON  KPOL=1   APB1=0.25   APB2=0.25


STRUCT  WVL=1.55


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=200.0   !n-substrate

LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=2.0   !n-cladding


LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=1  !n-inner-cladding

LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.16  !sch


LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005   !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier


LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.16  !sch

LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=1 !p-inner-cladding
```

```
LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=2.0   !p-cladding

LAYER  NREAL=3.65 NLOSS=0.0 TL=0.2  !P-cap. InGaAs n from website Adachi's model


OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0

OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1  ITO=1

OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0

GAMOUT  LAYGAM=5,7,9,11,13,15   COMPGAM=0     GAMALL=0


!LOOPZ1  ILZ='WVL'  FINV=1.33  ZINC=0.005

!LOOPZ1 ILZ='QZMR' FINV=10.0 ZINC=-0.01

LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=3

LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=19

!LOOPX1 ILX='TL' FINV=0.3 XINC=-0.01 LAYCH=40


END
```



(a)



(b)

Figure 10.2.2 Plots of (a) loss, (b) the total confinement factor (total □) and Far-Field

Divergence FWHP (Degree) vs. inner cladding layer thickness

As shown in Figure 10.2.2, as SCH layer thickness increases from 0 to 1 um, loss and confinement factor decreases, and far-field divergence increases first and then drops. Therefore, a compromise among low loss, high confinement factor, and narrow far-field divergence is required to determine the SCH layer thickness. In this example, the layer thickness is chosen to be 0.05 um, when WZI = 3.141394E-07, Loss= 0.012734 /cm, total □□= 0.05556, and FWHP = 46.41147˚.

10.2.1.3 Optimization of outer cladding layer thickness

After we chose layer thicknesses of SCH layers and inner cladding layers, the only unknown thicknesses of the laser structure are outer cladding layer thicknesses that need to be simulated in WAVEGUIDE II program. Again, we choose the same thickness for the outer n-cladding and the outer p-cladding layers.

Similar to the step in 10.2.1.2, we can use the QZR of the fundamental mode for inner cladding layer thickness of 0.44 um from the previous .db as an initial guess for QZMR file in the new input file, and then loop the thicknesses of outer cladding layers (layer 2 and layer 20) from 2.0 um to 0.0 um at an increment of -0.01 um simultaneously. A new input file is generated by modifying the previous input file as listed in Table 10.2.4 with modified parts highlighted.

Table 10.2.4 Input file to determine the outer cladding layer thickness

```
CASE KASE=AlGaInAs (6 wells)

CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6

CASE    QZMR= 10.52369 QZMI=0.0

CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1


!CASE    DXIN=0.2

!CASE    IL=100  KGSS=1

MODCON  KPOL=1   APB1=0.25   APB2=0.25


STRUCT  WVL=1.55


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=200.0   !n-substrate

LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=2.0   !n-cladding


LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=0.05  !n-inner-cladding

LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.16  !sch


LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005   !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier
```

```
LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well
LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier
LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well
LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier
LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well
LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.16  !sch
LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=0.05 !p-inner-cladding

LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=2.0   !p-cladding
LAYER  NREAL=3.65 NLOSS=0.0 TL=0.2  !P-cap. InGaAs n from website Adachi's model

OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0
OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1  ITO=1
OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0
GAMOUT  LAYGAM=5,7,9,11,13,15   COMPGAM=0     GAMALL=0

!LOOPZ1  ILZ='WVL'  FINV=1.33  ZINC=0.005
!LOOPZ1 ILZ='QZMR' FINV=10.0 ZINC=-0.01
LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=2
LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=20
!LOOPX1 ILX='TL' FINV=0.3 XINC=-0.01 LAYCH=40

END
```

A plot of loss and far-field divergence FWHP as a function of outer cladding layer thickness is shown in Figure 10.2.3. It is demonstrated that loss and FWHP decrease with the increase of outer cladding layer thickness while the total □ first increases to a maximum value and then doesn't vary much. The thickness can be determined if there are any requirements on far-field divergence and loss considering a balance between total confinement factor, loss, and far-field divergence.

As can be seen in Figure 10.2.3, loss, far-field divergence, and confinement factor decrease slowly as the outer cladding layer thickness increases to certain values. In other words, up to certain thickness, loss and far-field divergence don't improve much and total confinement factor doesn't decrease much as the thickness is increased. Therefore, in this example, an optimized thickness of 1.87 um is chosen, where loss= 0.02697 /cm, FWHP = 46.552˚, and total □ = 0.055565.

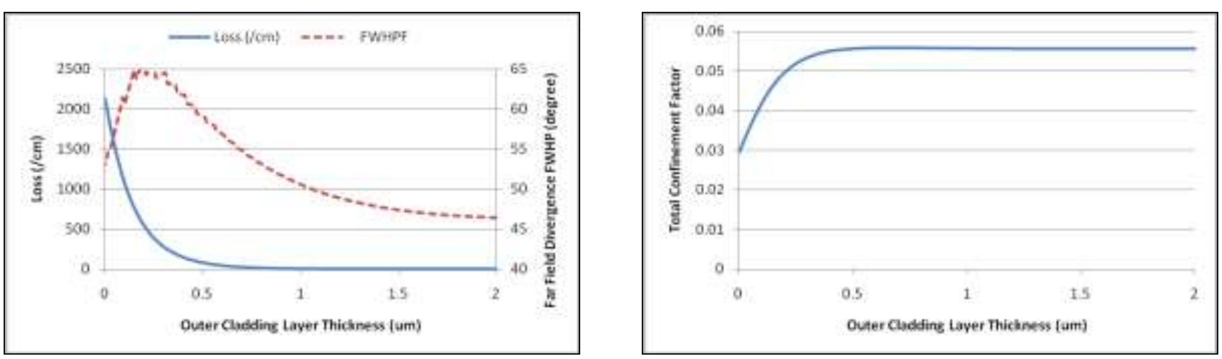


Figure 10.2.3 Plots of (a) loss and far-field divergence FWHP (Degree), (b) the total confinement factor (total □) vs. outer cladding layer thickness

10.2.1.4 Summary

A basic waveguide laser has been designed so far with the structure summarized in Table 10.2.5. In the simulations, the thicknesses of SCH layers, inner cladding layers, and outer cladding layers are varied in order to observe variations of loss, far-field divergence, and the total confinement factor as functions of layer thicknesses. In the example, compromises among low loss, narrow far-field divergence, and high confinement factor are made to optimize layer thicknesses.

Table 10.2.5 Layer composition and thickness table for the designed basic waveguide laser

Layer	Material Composition	Layer Thickness (TL) (um)
n-substrate	InP	200
Outer n-cladding	InP	1.87
Inner n-cladding layer	$Al_{0.48}In_{0.54}As$	0.05
SCH layer	$Al_{0.24}In_{0.24}As$	0.16
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005

Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
SCH layer	$Al_{0.24}In_{0.24}As$	0.16
Inner p-cladding layer	$Al_{0.48}In_{0.54}As$	0.05
Outer p-cladding	InP	1.87
p-cap	InP	0.2

10.2.2 Position of an etch stop layer, Δneff vs. p-spacer thickness

As explained in section 10.1.2, an etch stop layer divides p- cladding layer of a basic waveguide laser into p-spacer layer and outer p-cladding layer. Therefore, after defining ridge area through photolithography and etching to the etch stop to form the ridge, a lateral effective refractive index difference exists between the ridge region the wing regions of a ridge waveguide laser, as shown in Figure 10.1.3.

The lateral effective refractive index difference □n_{eff} is simulated in the waveguide by several steps. We can first (1) calculate the effective refractive index variation as a function of p-spacer layer thickness in the ridge region, (2) calculate that in the wing region, and then (3) calculate the lateral effective refractive index difference □n_{eff} and plot □n_{eff} and far-field divergence FWHP as a function of p-spacer thickness.

1) Calculate the effective refractive index variation as a function of p-spacer layer thickness in the ridge region

In the first step, we loop p-spacer layer thickness from 0.1 to 1.85 at an increment of +0.01 and outer p-cladding layer thickness from 1.85 to 0.1 at an increment of -0.01 simultaneously so that the total layer thickness of p-spacer, etch stop, and outer p-cladding layers is constant (1.87 um) during the loop. We can create a new input file by modifying the previous input file as shown in Table 10.2.6 with changes highlighted in bold.

First, find the initial guess QZMR of the fundamental mode for the initial laser structure with a 0.01-um p-spacer and a 1.85-um outer p-cladding as explained in section 2.3 in Chapter 2. Second, change the layer thicknesses of the previous input file according to the results simulated in section 10.2.1.

Next, add an etch stop layer between p-spacer layer and outer p-cladding layer. In this example, an InGaAsP etch stop of 0.1 um thick is chosen because its different etchant solution is different from that of InP material. Finally, in 'LOOPX1", set 'FINV=1.85 XINC= 0.01 LAYCH=20' for p-spacer layer, and 'FINV=0.01 XINC= -0.01 LAYCH=22' to outer p-cladding layer.

After evaluation of the input file, the effective refractive index (neff) variation as a function of p-spacer layer thickness in the ridge region is plotted and the .db output file is saved.

Table 10.2.6 input file for the effective refractive index (neff') variation as a function of p-spacer layer thickness in the ridge region

```
CASE KASE=AlGaInAs (6 wells)

CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6

CASE    QZMR= 10.58371 QZMI=0.0

CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1     FFPLT=1


!CASE    DXIN=0.2

!CASE    IL=100  KGSS=1

MODCON  KPOL=1   APB1=0.25   APB2=0.25


STRUCT  WVL=1.55


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=200.0   !n-substrate

LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=1.87   !n-cladding


LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=0.05  !n-inner-cladding

LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.16  !sch


LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005   !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well
```

LAYER MATSYS=13 XPERC=0.25 YPERC=0.35 TL=0.005 !barrier

LAYER MATSYS=13 XPERC=0.08 YPERC=0.22 TL=0.006 !Q-well

LAYER MATSYS=13 XPERC=0.25 YPERC=0.35 TL=0.005 !barrier

LAYER MATSYS=13 XPERC=0.08 YPERC=0.22 TL=0.006 !Q-well

LAYER MATSYS=13 XPERC=0.25 YPERC=0.35 TL=0.005 !barrier

LAYER MATSYS=13 XPERC=0.08 YPERC=0.22 TL=0.006 !Q-well

LAYER MATSYS=13 XPERC=0.25 YPERC=0.35 TL=0.005 !barrier

LAYER MATSYS=13 XPERC=0.24 YPERC=0.24 **TL=0.16 !sch**

LAYER MATSYS=13 XPERC=0.48 YPERC=0.0 **TL=0.05 !p-inner-cladding**

LAYER MATSYS=1 XPERC=0.0 YPERC=0.0 **TL=0.01 !P-spacer**

LAYER MATSYS=12 XPERC=1.1 TL=0.01 !etch stop

LAYER MATSYS=1 XPERC=0.0 YPERC=0.0 **TL=1.85   !outer p-cladding**

LAYER NREAL=3.65 NLOSS=0.0 TL=0.2 !P-cap. InGaAs n from website Adachi's model

OUTPUT PHMO=1   GAMMAO=1 WZRO=1 WZIO=1   QZRO=1   QZIO=0

OUTPUT FWHPNO=0   FWHPFO=1   KMO=1 ITO=1

OUTPUT MODOUT=1 LYROUT=1 SPLTFL=0

GAMOUT LAYGAM=5,7,9,11,13,15   COMPGAM=0   GAMALL=0

!LOOPZ1 ILZ='WVL' FINV=1.33 ZINC=0.005

!LOOPZ1 ILZ='QZMR' FINV=10.0 ZINC=-0.01

LOOPX1 ILX='TL' FINV=1.85 XINC= 0.01 LAYCH=20

LOOPX1 ILX='TL' FINV=0.01 XINC= -0.01 LAYCH=22

!LOOPX1 ILX='TL' FINV=0.3 XINC=-0.01 LAYCH=40

```
END
```

2) The second step is to calculate the effective refractive index (neff') variation as a function of p-spacer layer thickness in the wing region.

In the wing region, the p-cap and outer p-cladding layers are etched above the etch stop with p-spacer left, and a dielectric layer SiNx is deposited on the top of the etch stop for insulation, preventing current injection into the wing region.

Again, we can create a new input file by modifying the previous input file as shown in Table 10.2.7. Similarly, first, find the initial guess QZMR of the fundamental mode for the initial laser structure with a 0.01-um p-spacer layer and a 0.2-um SiNx layer on top of it. Next, delete the outer p-cladding layer, p-cap layer, and 'LOOPX1' for layer 20 which is outer p-cladding layer.

After evaluation of the input file, the effective refractive index (neff') variation as a function of p-spacer layer thickness in the wing region is plotted and the .db output file is saved.

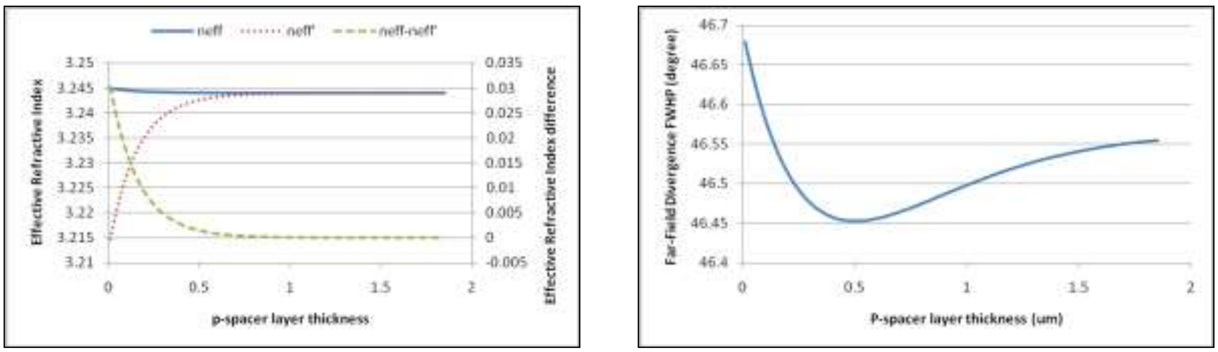
Table 10.2.7 the input file for the effective refractive index (neff') variation as a function of p-spacer layer thickness in the wing region

```
CASE KASE=AlGaInAs (6 wells)
CASE    EPS1=1E-8  EPS2=1E-8  GAMEPS=1E-6
CASE    QZMR= 10.33209 QZMI=0.0
CASE    PRINTF=0   INITGS=0  AUTOQW=0 NFPLT=1 FFPLT=1 IL=30
```

```
!CASE    DXIN=0.2

!CASE    IL=100  KGSS=1

MODCON  KPOL=1   APB1=0.25   APB2=0.25


STRUCT  WVL=1.55


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=200.0   !n-substrate

LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=1.87   !n-cladding


LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=0.05  !n-inner-cladding

LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.16  !sch


LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005   !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier

LAYER  MATSYS=13 XPERC=0.08 YPERC=0.22  TL=0.006  !Q-well

LAYER  MATSYS=13 XPERC=0.25 YPERC=0.35  TL=0.005 !barrier
```

```
LAYER  MATSYS=13 XPERC=0.24 YPERC=0.24  TL=0.16  !sch

LAYER  MATSYS=13 XPERC=0.48 YPERC=0.0  TL=0.05 !p-inner-cladding


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0  TL=0.01 !P-spacer

LAYER  MATSYS=12 XPERC=1.1 TL=0.01 !etch stop

LAYER  NREAL=1.8 NLOSS=0.0 TL=0.2 !Dielectric layer: SiNx


LAYER  MATSYS=1 XPERC=0.0 YPERC=0.0 TL=1.84   !outer p-cladding

LAYER  NREAL=3.65 NLOSS=0.0 TL=0.2  !P-cap. InGaAs n from website Adachi's model


OUTPUT  PHMO=1   GAMMAO=1  WZRO=1  WZIO=1   QZRO=1    QZIO=0

OUTPUT  FWHPNO=0   FWHPFO=1   KMO=1  ITO=1

OUTPUT  MODOUT=1  LYROUT=1  SPLTFL=0

GAMOUT  LAYGAM=5,7,9,11,13,15   COMPGAM=0     GAMALL=0


!LOOPZ1  ILZ='WVL'  FINV=1.33  ZINC=0.005

!LOOPZ1 ILZ='QZMR' FINV=10 ZINC=-0.01

LOOPX1 ILX='TL' FINV=1.85 XINC= 0.01 LAYCH=20

!LOOPX1 ILX='TL' FINV=0.01 XINC= -0.01 LAYCH=22

!LOOPX1 ILX='TL' FINV=0.3 XINC=-0.01 LAYCH=40


END
```

3) In this step, the two .db output files are combined to calculate lateral effective refractive index difference □n_{eff} . the plots of n_{eff}, n_{eff}’, and □n_{eff} and far-field divergence FWHP vs. p-spacer thickness are shown in Figure 10.2.4 (a) and (b).



(a) (b)

Figure 10.2.4 (a) Plot of neff, neff’ and □neff (b) far-field divergence FWHP as a function of p-spacer layer thickness

From Figure 10.2.4 (b) and the .db file in the ridge region, we can find that the far-field divergence reaches a minimum value of 46.452˚ when the p-spacer layer thickness equals 0.48 um, but □n_{eff} equals 0.0016, which is too small a step for a ridge waveguide laser to maintain single lateral mode operation. For an acceptable □n_{eff} of 0.010, the p-spacer layer thickness is 0.18 um. Therefore, we choose the p-spacer layer thickness to be 0.18 um

In summary, the wafer structure of the designed ridge waveguide laser is listed in Table 10.2.8 and Table 10.2.9. Besides, Table 10.2.10 summarizes simulation results of the laser in ridge and wing regions.

Table 10.2.8 Layer composition and thickness table for the ridge region of the designed ridge waveguide laser.

Layer	Material Composition	Layer Thickness (TL) (um)
n-substrate	InP	200
Outer n-cladding	InP	1.87
Inner n-cladding layer	$Al_{0.48} In_{0.54} As$	0.05
SCH layer	$Al_{0.24} In_{0.24} As$	0.16
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
SCH layer	$Al_{0.24} In_{0.24} As$	0.16
Inner p-cladding layer	$Al_{0.48} In_{0.54} As$	0.05
P-spacer	InP	0.18
etch stop	InGaAsP	0.01
Outer p-cladding	InP	1.68

p-cap	InP	0.2

Table 10.2.9 Layer composition and thickness table for the wing region of the designed ridge waveguide laser.

Layer	Material Composition	Layer Thickness (TL) (um)
n-substrate	InP	200
Outer n-cladding	InP	1.87
Inner n-cladding layer	$Al_{0.48} In_{0.54} As$	0.05
SCH layer	$Al_{0.24} In_{0.24} As$	0.16
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
Barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
Quantum well	$Al_{0.08} Ga_{0.22} In_{0.7} As$	0.006
barrier	$Al_{0.25} Ga_{0.35} In_{0.4} As$	0.005
SCH layer	$Al_{0.24} In_{0.24} As$	0.16
Inner p-cladding layer	$Al_{0.48} In_{0.54} As$	0.44

P-spacer	InP	0.18
etch stop	InGaAsP	0.01
Dielectric layer	SiNx	0.02

Table 10.2.10 the simulation results of the designed ridge waveguide laser

Confinement factor	0.0554
Far-field divergence FWHP	46.52˚
Loss	0.02735 /cm
n_{eff} in ridge region	3.244
n_{eff}' in wing region	3.234
lateral effective refractive index difference □n_{eff}	0.010

10.2.3 Determine ridge width and channel width.

10.2.3.1 Ridge Width

As discussed in section 10.1.3.1, the theoretical calculation of maximum ridge width for single-lateral-TE-mode operation is as follows:

$$d < \frac{\lambda}{2\sqrt{n_1^2 - n^2}} = \frac{1.55}{2\sqrt{3.244^2 - 3.234^2}} = 3.0um$$

Using WAVEGUIDE II program, we can prove the validity of the calculation: for a 3um-ridge, only single lateral mode propagates in the three-layer dielectric slab waveguide, and for a ridge greater than 3um, more than one mode propagate.

As simulated in the previous section and shown in Table 10.2.10, n_1 = neff = 3.244, and n = neff' = 3.234. The input file for the three-layer dielectric slab waveguide with n_1 = 3.244 and n = 3.234 looping QZMR from n_1^2 (=10.523536) to n^2 (=10.458) are listed in Table 10.2.11. After evaluation of the input file, we open .db file and find that only fundamental mode (TE0) with an effective refractive index of 3.240409 is allowed to propagate in the waveguide.

Then we modify the thickness of the core layer of the previous input file into 4um, as listed in Table 10.2.12, and simulate it. We can find that in the .db file that two propagating modes exist with an effective refractive index of 3.241455 (TE0) and an effective refractive index of 3.235244 (TE1) respectively.

Table 10.2.11 the input file for the three-layer waveguide with a core layer thickness of 3 um looping QZMR from n_1^2 to n^2

```
!WIF generated by WIFE (WAVEGUIDE II Input File Editor)

!------------------------------------------------------------------

!FILENAME:    C:\Waveguide\work\input\example.wgi

!DESCRIPTION: WAVEGUIDE II Example File

!Last Modified: 3/28/2004 10:34:26 PM

!------------------------------------------------------------------


!CASE Parameter Set

CASE KASE=WIFE
```

```
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.523536 QZMI=0.001

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30


!MODCON Parameter Set

MODCON KPOL=1 APB1=0.25 APB2=0.25


!STRUCT Parameter Set

STRUCT WVL=1.55

STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0

STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0


!LAYER Parameter Set


LAYER NREAL=3.234 NLOSS=0.0 TL=10.0

LAYER NREAL=3.244 NLOSS=0.0 TL=3.0

LAYER NREAL=3.234 NLOSS=0.0 TL=10.0


!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set

GAMOUT LAYGAM=3 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set
```

```
!LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=2

!LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=4

LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2


!LOOPZ Parameter Set

LOOPZ1 ILZ=17 FINV=10.458 ZINC=-0.001

LOOPZ2 ILZ=0 FINV=0 ZINC=0.1

LOOPZ3 ILZ=0 FINV=0 ZINC=0.1

LOOPZ4 ILZ=0 FINV=0 ZINC=0.1


END
```

Table 10.2.12 the input file for the three-layer waveguide with a core layer thickness of 4 um looping QZMR from n_1^2 to n^2

```
!WIF generated by WIFE (WAVEGUIDE II Input File Editor)

!-------------------------------------------------------------------

!FILENAME:    C:\Waveguide\work\input\example.wgi

!DESCRIPTION: WAVEGUIDE II Example File

!Last Modified: 3/28/2004 10:34:26 PM

!-------------------------------------------------------------------


!CASE Parameter Set

CASE KASE=WIFE

CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.523536 QZMI=0.001

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30
```

```
!MODCON Parameter Set
MODCON KPOL=1 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=1.55
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set

LAYER NREAL=3.234 NLOSS=0.0 TL=10.0
LAYER NREAL=3.244 NLOSS=0.0 TL=4.0
LAYER NREAL=3.234 NLOSS=0.0 TL=10.0

!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1
OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1

!GAMOUT Parameter Set
GAMOUT LAYGAM=3 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
!LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=2
!LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=4
```

```
LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2


!LOOPZ Parameter Set

LOOPZ1 ILZ=17 FINV=10.458 ZINC=-0.001

LOOPZ2 ILZ=0 FINV=0 ZINC=0.1

LOOPZ3 ILZ=0 FINV=0 ZINC=0.1

LOOPZ4 ILZ=0 FINV=0 ZINC=0.1


END
```

If the channel width of a ridge waveguide laser is not infinite, the effects of neighboring ridges must be taken into account. Therefore, a five-layer dielectric waveguide shown in Figure 10.1.8 is simulated to prove that only fundamental mode propagates with low loss for a ridge width of 3 um or less, and more than one mode propagate with low loss for a ridge width greater than 3um. The input file is modified as shown in Table 10.2.13, with two outer layers added to the three-layer waveguide with refractive index of 3.244.

Table 10.2.13 the input file for the five-layer waveguide with a core layer thickness of 3 um, looping QZMR from n_1^2 to n^2.

```
!WIF generated by WIFE (Waveguide Input File Editor)
```

```
!-----------------------------------------------------------------
!FILENAME:    C:\Waveguide\work\input\example.wgi
!DESCRIPTION: WaveGuide Example File
!Last Modified: 3/28/2004 10:34:26 PM
!-----------------------------------------------------------------

!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.523536 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=1 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=1.55
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set

LAYER NREAL=3.244 NLOSS=0.0 TL=100.0
LAYER NREAL=3.234 NLOSS=0.0 TL=10.0
LAYER NREAL=3.244 NLOSS=0.0 TL=3.0
LAYER NREAL=3.234 NLOSS=0.0 TL=10.0
LAYER NREAL=3.244 NLOSS=0.0 TL=100.0
```

```
!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1
OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1

!GAMOUT Parameter Set
GAMOUT LAYGAM=3 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
!LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=2
!LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=4
LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2

!LOOPZ Parameter Set
LOOPZ1 ILZ=17 FINV=10.458 ZINC=-0.001
LOOPZ2 ILZ=0 FINV=0 ZINC=0.1
LOOPZ3 ILZ=0 FINV=0 ZINC=0.1
LOOPZ4 ILZ=0 FINV=0 ZINC=0.1

END
```

After evaluation of the input file, we open the .db file, calculate and plot the loss as a function of effective refractive indices of the modes including real and complex solutions to the eigen-equations of the five-layer waveguide. As can be seen in Figure 10.2.5, only fundamental mode with an effective refractive index of 3.240409 propagates with a low loss of 1.07593E-05. All other modes have high losses and cannot propagate long, and the higher order the mode is, the higher loss it propagates with.

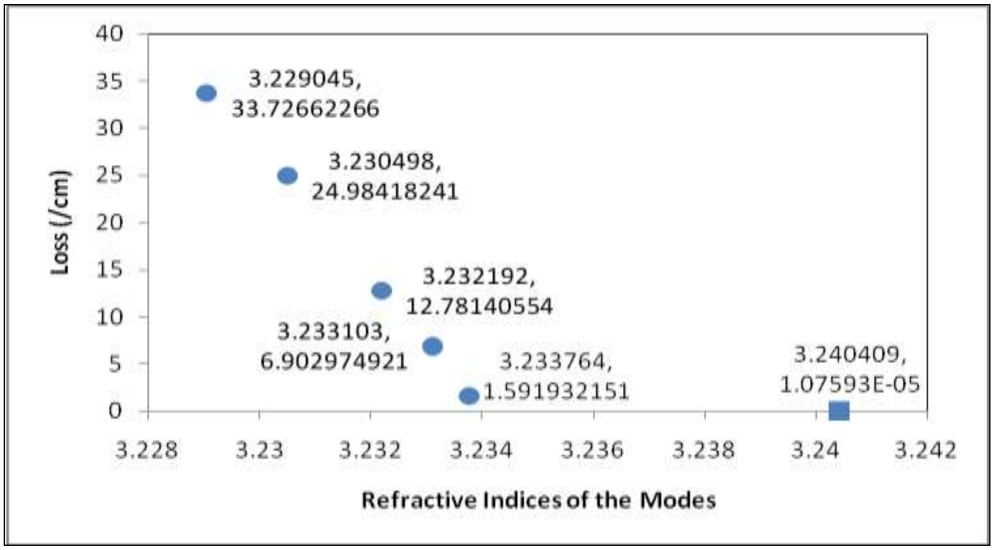


Figure 10.2.5 Loss as a function of effective refractive indices of the modes including real and complex solutions for a five-layer dielectric waveguide with a core layer thickness of 3 um.

Next, we change the core layer thickness from 3 um to 4 um, and repeat the previous step. The input file is listed in Table 10.2.14. As shown in Figure 10.2.6, two modes propagate with low loss, TE0 with effective refractive indices of 3.241455 at a low loss of 1.7709E-06 /cm and 3.235243 at a low loss of 0.04713674 /cm respectively. The near field profiles of the two modes are shown in Figure 10.2.7 (a) and (b).

Table 10.2.14 the input file for the five-layer waveguide with a core layer thickness of 4 um, looping QZMR from n_1^2 to n^2

```
!WIF generated by WIFE (Waveguide Input File Editor)
!---------------------------------------------------------------------
!FILENAME:    C:\Waveguide\work\input\example.wgi
!DESCRIPTION: WaveGuide Example File
!Last Modified: 3/28/2004 10:34:26 PM
!---------------------------------------------------------------------

!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.523536 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=1 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
STRUCT WVL=1.55
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0

!LAYER Parameter Set

LAYER NREAL=3.244 NLOSS=0.0 TL=100.0
LAYER NREAL=3.234 NLOSS=0.0 TL=10.0
```

```
LAYER NREAL=3.244 NLOSS=0.0 TL=4.0

LAYER NREAL=3.234 NLOSS=0.0 TL=10.0

LAYER NREAL=3.244 NLOSS=0.0 TL=100.0


!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set

GAMOUT LAYGAM=3 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set

!LOOPX1 ILX=’TL’ FINV=100.0 XINC= 0.1 LAYCH=2

!LOOPX1 ILX=’TL’ FINV=100.0 XINC= 0.1 LAYCH=4

LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2


!LOOPZ Parameter Set

LOOPZ1 ILZ=17 FINV=10.458 ZINC=-0.001

LOOPZ2 ILZ=0 FINV=0 ZINC=0.1

LOOPZ3 ILZ=0 FINV=0 ZINC=0.1

LOOPZ4 ILZ=0 FINV=0 ZINC=0.1


END
```

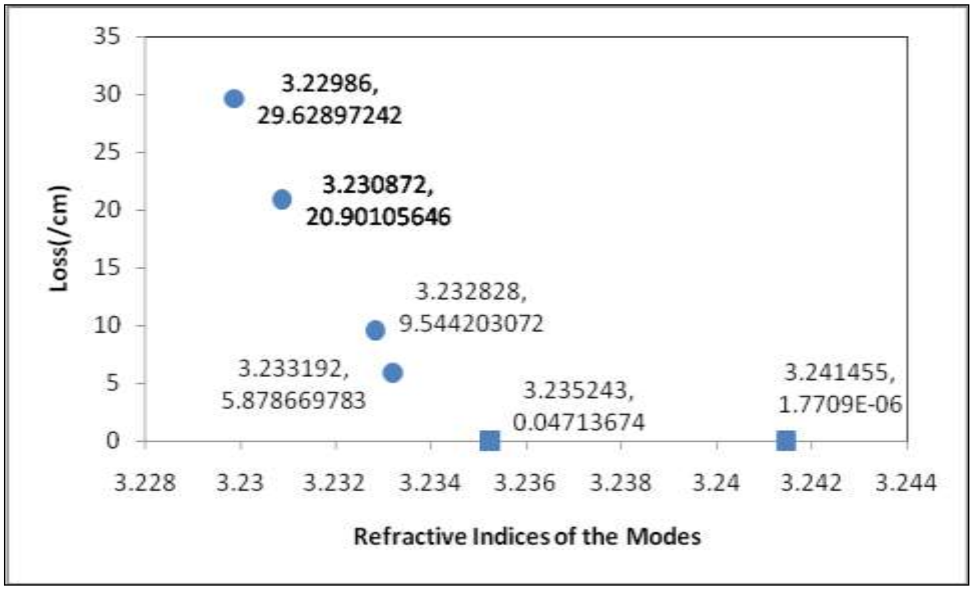


Figure 10.2.6 loss as a function of effective refractive indices of the modes including real and complex solutions for a five-layer dielectric waveguide with a core layer thickness of 4 um.

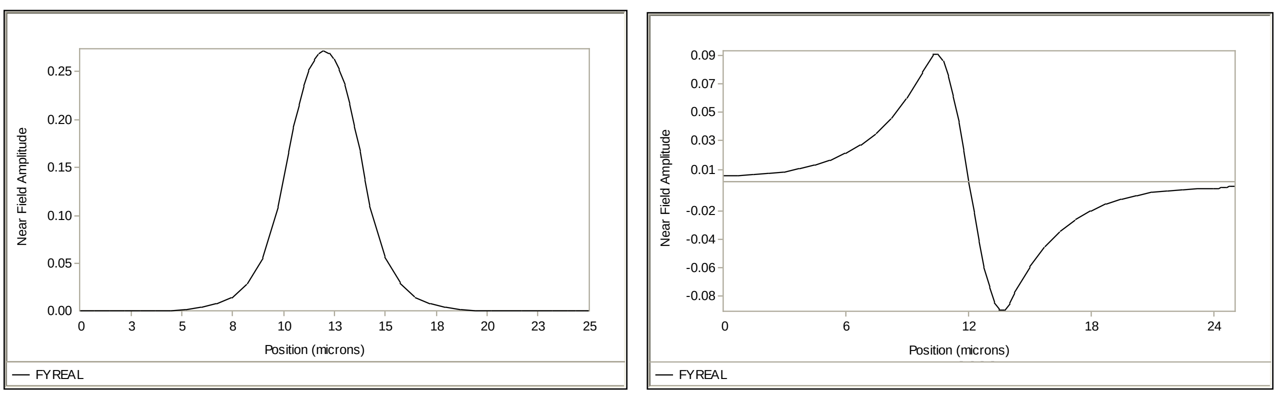


Figure 10.2.7 Near field profile of the propagating modes (a) TE0 and (b) TE1 with effective refractive indices of 3.241455 and 3.235243 respectively.

In summary, the ridge width of the designed ridge waveguide laser is chosen to be 3 um to maintain single-lateral-TE0-mode propagation.

Wing and Channel Width

As explained in section 10.1.3.2, channel width is required to be thick enough so that the effects of neighboring ridges are negligible. In order to optimize the channel width, we vary the channel width and plot the loss as a function of channel width.

First, we modify the previous input file as shown in Table 10.2.15 with changes highlighted. As calculated in the previous section 10.2.3.1 and shown in Figure 10.2.5, the fundamental mode has an effective refractive index of 3.240409, therefore, we change the value of QZMR in previous file to 10.50025, which is the square of 3.240409. Another change is to loop the thicknesses of layer 2 and layer 4 from 10 um to 0 um with an increment of -0.01.

Next, we loop the channel width from 10 um to 100 um with an increment of 0.1 um as listed in Table 10.2.16. After the evaluation, we combine the .db file together with the one from the input file in Table 10.2.15, so that we have the data of the waveguide with channel width changing from 0 um to 100 um. Then we can calculate and plot loss as a function of channel width as shown in Figure 10.2.8.

Table 10.2.15 the input file for the five-layer waveguide looping thickness of channel width from 10 um to 0 um with an increment of -0.01.

```
!WIF generated by WIFE (Waveguide Input File Editor)

!-----------------------------------------------------------------

!FILENAME:    C:\Waveguide\work\input\example.wgi
```

```
!DESCRIPTION: WaveGuide Example File

!Last Modified: 3/28/2004 10:34:26 PM

!----------------------------------------------------------------


!CASE Parameter Set

CASE KASE=WIFE

CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.50025 QZMI=0.001

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30


!MODCON Parameter Set

MODCON KPOL=1 APB1=0.25 APB2=0.25


!STRUCT Parameter Set

STRUCT WVL=1.55

STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0

STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0


!LAYER Parameter Set


LAYER NREAL=3.244 NLOSS=0.0 TL=100.0

LAYER NREAL=3.234 NLOSS=0.0 TL=10.0

LAYER NREAL=3.244 NLOSS=0.0 TL=3.0

LAYER NREAL=3.234 NLOSS=0.0 TL=10.0

LAYER NREAL=3.244 NLOSS=0.0 TL=100.0


!OUTPUT Parameter Set
```

```
OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set

GAMOUT LAYGAM=3 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set

LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=2

LOOPX1 ILX='TL' FINV=0.0 XINC= -0.01 LAYCH=4

LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2


!LOOPZ Parameter Set

!LOOPZ1 ILZ=17 FINV=10.458 ZINC=-0.01

LOOPZ2 ILZ=0 FINV=0 ZINC=0.1

LOOPZ3 ILZ=0 FINV=0 ZINC=0.1

LOOPZ4 ILZ=0 FINV=0 ZINC=0.1


END
```

Table 10.2.16 the input file for the five-layer waveguide looping thickness of channel width from 10 um to 100 um with an increment of 0.1.

```
!WIF generated by WIFE (Waveguide Input File Editor)

!------------------------------------------------------------------

!FILENAME:    C:\Waveguide\work\input\example.wgi

!DESCRIPTION: WaveGuide Example File

!Last Modified: 3/28/2004 10:34:26 PM

!------------------------------------------------------------------



!CASE Parameter Set

CASE KASE=WIFE

CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.50025 QZMI=0.001

CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30



!MODCON Parameter Set

MODCON KPOL=1 APB1=0.25 APB2=0.25



!STRUCT Parameter Set

STRUCT WVL=1.55

STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0

STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0



!LAYER Parameter Set



LAYER NREAL=3.244 NLOSS=0.0 TL=100.0

LAYER NREAL=3.234 NLOSS=0.0 TL=10.0

LAYER NREAL=3.244 NLOSS=0.0 TL=3.0
```

```
LAYER NREAL=3.234 NLOSS=0.0 TL=10.0

LAYER NREAL=3.244 NLOSS=0.0 TL=100.0


!OUTPUT Parameter Set

OUTPUT PHMO=1 GAMMAO=1 WZRO=1 WZIO=1 QZRO=1 QZIO=1

OUTPUT FWHPNO=1 FWHPFO=1 KMO=1 ITO=1

OUTPUT SPLTFL=0 MODOUT=1 LYROUT=1


!GAMOUT Parameter Set

GAMOUT LAYGAM=3 COMPGAM=0 GAMALL=0


!LOOPX Parameter Set

LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=2

LOOPX1 ILX='TL' FINV=100.0 XINC= 0.1 LAYCH=4

LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2

LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2


!LOOPZ Parameter Set

!LOOPZ1 ILZ=17 FINV=10.458 ZINC=-0.01

LOOPZ2 ILZ=0 FINV=0 ZINC=0.1

LOOPZ3 ILZ=0 FINV=0 ZINC=0.1

LOOPZ4 ILZ=0 FINV=0 ZINC=0.1


END
```

From Table 10.2.17, we can see that for channel width smaller than 0.24 um, the code doesn't converge in 30 iterations, meaning it couldn't find a root near an initial guess WZR = 3.240409. As the channel width increases from 0.25 um, the loss of the fundamental mode in the waveguide decreases from 78.5444 /cm. When the channel width increases to 5.87 um, the loss is about 0.009861/cm $\leq$ 0.01 /cm, which is an acceptable value for the designed ridge waveguide laser. In other words, as long as the channel width is greater than 5.87 um, the laser can operate at low loss, resulting in a low threshold current density.

In our example, we choose the channel width to be 50.0 um, where the loss is close to zero so that effects of the neighboring ridges are negligible.

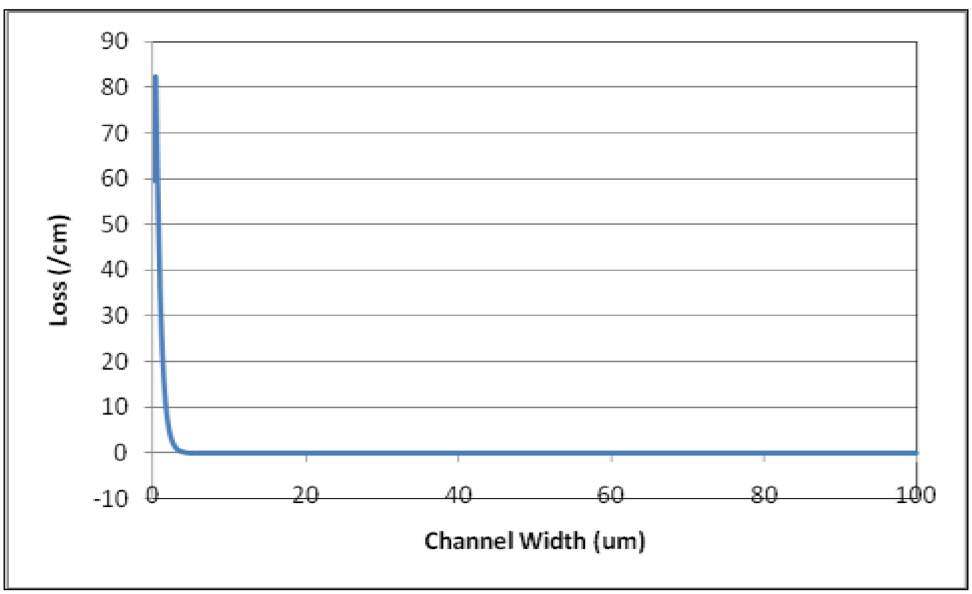


Figure 10.2.8 Plot of loss as a function of channel width

Table 10.2.17 List of loss as a function of channel width

TL(2)	GAMMA (3)	WZR	WZI	Loss	FWHPN	FWHPF	KM	IT
1.6889E-13	0	3.244	8.20814E-07	0.03327307	0	0	4	30
0.01	0	3.244	2.34766E-05	0.951663002	0	0	4	30
0.02	0	3.244005	2.22246E-05	0.90091189	0	0	4	30
0.03	0	3.244001	8.2942E-05	3.362191641	0	0	4	30
0.04	0	3.244027	4.16561E-05	1.688599971	0	0	4	30
0.05	0	3.244061	0.000111478	4.518943893	0	0	4	30
0.06	0	3.244	0.000233176	9.452192917	0	0	4	30
0.07	0	3.244036	0.00019258	7.806549665	0	0	4	30
0.08	0	3.244018	0.000279378	11.3250402	0	0	4	30
0.09	0	3.24402	0.000360515	14.61406071	0	0	4	30
0.1	0	3.244042	0.000314899	12.76496386	0	0	4	30
0.11	0	3.244032	0.000282421	11.44841764	0	0	4	30
0.12	0	3.244118	0.00036136	14.6483142	0	0	4	30
0.13	0	3.243999	0.000380002	15.40403546	0	0	4	30
0.14	0	3.24452	0.000315952	12.80764088	0	0	4	30
0.15	0	3.244012	0.000723358	29.32254755	0	0	4	30
0.16	0	3.244039	0.000677506	27.46384757	0	0	4	30
0.17	0	3.243996	0.00067146	27.2187547	0	0	4	30
0.18	0	3.244074	0.001908128	77.34917299	0	0	4	30
0.19	0	3.243902	0.002014814	81.67386917	0	0	4	30
0.2	0	3.243986	0.001913873	77.58205622	0	0	4	30
0.21	0	3.243912	0.001875876	76.04178401	0	0	4	30

0.22	0	3.24403812	0.00159885	64.81208432	0	0	4	30
0.23	0	3.24403827	0.001687336	68.39898956	0	0	4	30
0.24	0	3.24403842	0.001775821	71.98589479	0	0	4	30
0.25	0	3.24403857	0.001864307	75.57280002	0	0	4	30
0.26	0	3.24403873	0.001952792	79.15970526	0	0	4	30
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…
5.83	0.8389797	3.240409	2.59863E-07	0.010533987	2.542285	13.15553	7	2
5.84	0.8389852	3.240409	2.55607E-07	0.010361467	2.541595	13.15397	6	1
5.85	0.8389907	3.240409	2.51421E-07	0.010191764	2.541011	13.15242	7	2
5.86	0.8389961	3.240409	2.47303E-07	0.010024842	2.540535	13.1509	6	1
5.87	0.8390013	3.240409	2.43253E-07	0.009860653	2.540164	13.14939	7	2
5.88	0.8390065	3.240409	2.39269E-07	0.00969915	2.539899	13.14784	6	1
5.89	0.8390115	3.240409	2.3535E-07	0.009540295	2.53974	13.14633	7	2
5.9	0.8390164	3.240409	2.31495E-07	0.009384039	2.539687	13.14491	6	1
5.91	0.8390212	3.240409	2.27704E-07	0.009230344	2.53974	13.14345	7	2
5.92	0.8390259	3.240409	2.23974E-07	0.009079166	2.539898	13.14201	6	1
5.93	0.8390305	3.240409	2.20306E-07	0.00893047	2.540162	13.14058	7	2
5.94	0.839035	3.240409	2.16698E-07	0.008784205	2.540531	13.13915	6	1
5.95	0.8390394	3.240409	2.13149E-07	0.008640332	2.541008	13.13774	7	2
5.96	0.8390437	3.240409	2.09658E-07	0.008498819	2.54159	13.13634	6	1
5.97	0.8390479	3.240409	2.06224E-07	0.00835962	2.54228	13.13498	7	2
5.98	0.839052	3.240409	2.02846E-07	0.008222703	2.543103	13.13363	6	1
5.99	0.839056	3.240409	1.99524E-07	0.008088028	2.544094	13.13229	7	2
6	0.8390599	3.240409	1.96256E-07	0.007955558	2.545252	13.12969	6	1

6.01	0.8390637	3.240409	1.93041E-07	0.007825257	2.544093	13.12837	7	2
6.02	0.8390675	3.240409	1.8988E-07	0.007697093	2.543102	13.12708	6	1
6.03	0.8390711	3.240409	1.8677E-07	0.007571032	2.542278	13.12581	7	2
6.04	0.8390746	3.240409	1.83711E-07	0.00744703	2.541587	13.12456	6	1
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…
…	…	…	…	…	…	…	…	…

10.2.4 Summary

As an implementation to section 10.1, section 10.2 has provided an example of how to design a ridge waveguide laser using WAVEGUIDE II program. In summary, the optimized wafer structure of the designed laser is again listed in Table 10.2.18 (a) and (b) with a 3-um ridge width and 50-um channel width. The laser performance simulation results are shown in Table 10.2.19. The refractive index profiles in the ridge and channel regions are shown in Figure 10.2.9 (a) and (b).

Table 10.2.18 Layer composition and thickness for (a) the ridge region and (b) channel regions of the designed ridge waveguide laser.

(a)

Layer	Material Composition	Thickness (um)
n-substrate	InP	200
Outer n-cladding	InP	1.87

(b)

Layer	Material Composition	Thickness (um)
n-substrate	InP	200
Outer n-cladding	InP	1.87

Inner n-cladding layer	$Al_{0.48}In_{0.54}As$	0.05
SCH layer	$Al_{0.24}In_{0.24}As$	0.16
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}$	0.006

Inner n-cladding layer	$Al_{0.48}In_{0.54}As$	0.05
SCH layer	$Al_{0.24}In_{0.24}As$	0.16
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}As$	0.006
Barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
Quantum well	$Al_{0.08}Ga_{0.22}In_{0.7}$	0.006

	As	
barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
SCH layer	$Al_{0.24}In_{0.24}As$	0.16
Inner p-cladding layer	$Al_{0.48}In_{0.54}As$	0.05
P-spacer	InP	0.18
etch stop	InGaAsP	0.01
Outer p-cladding	InP	1.68
p-cap	InP	0.2

	As	
barrier	$Al_{0.25}Ga_{0.35}In_{0.4}As$	0.005
SCH layer	$Al_{0.24}In_{0.24}As$	0.16
Inner p-cladding layer	$Al_{0.48}In_{0.54}As$	0.44
P-spacer	InP	0.18
etch stop	InGaAsP	0.01
Dielectric layer	SiNx	0.02

Table 10.2.19Simulation results of the performance of the ridge waveguide laser

Confinement factor	0.0554
Far-field divergence FWHP	46.52˚
Loss	0.02735 /cm
n_{eff} in ridge region	3.244
n_{eff}’ in wing region	3.234
lateral effective refractive index difference Δn_{eff}	0.010

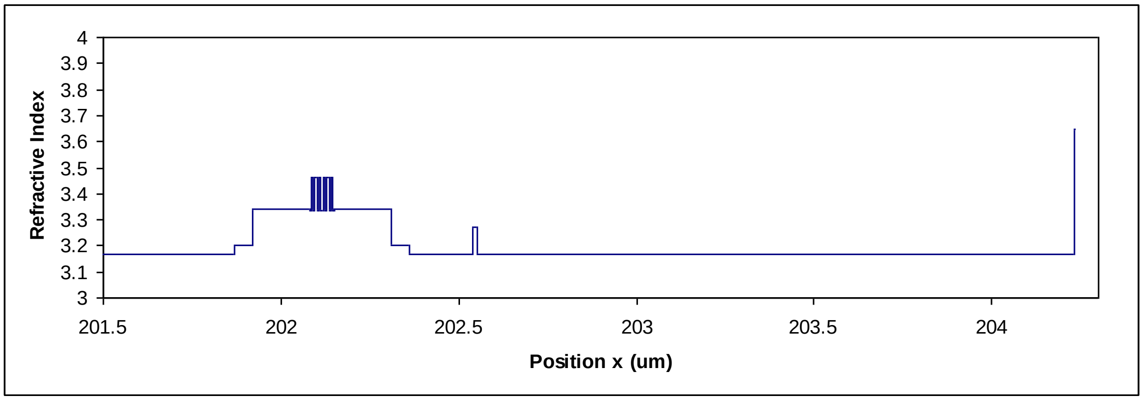


Figure 10.2.9 (a) The refractive index profiles in the ridge.

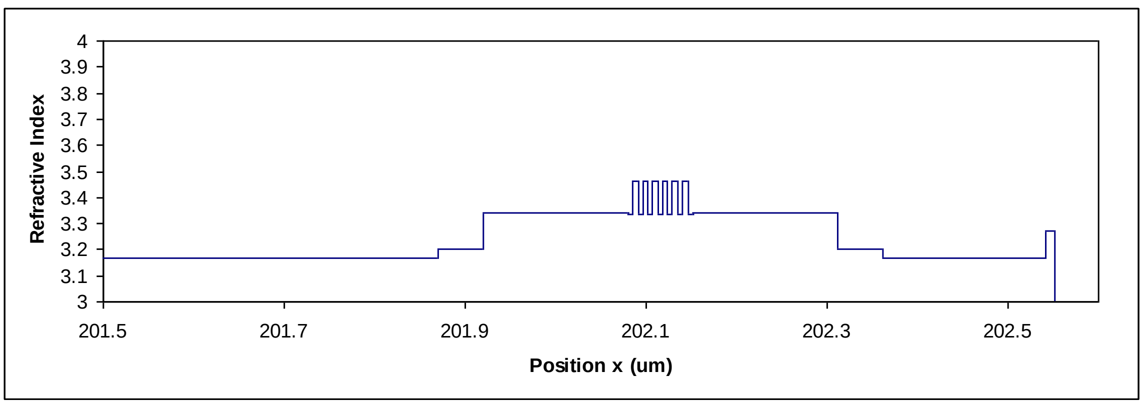


Figure 10.2.9 (b) The refractive index profiles in the channel regions

10.3 Summary

This chapter has explained how to design a ridge waveguide MQW laser using WAVEGUIDE II program. Simulations details such as input files, output files and plots are provided and the optimization results are interpreted. The example in this chapter demonstrates the flexibility and versatility of the WAVEGUIDE II program and how to use it to simulate laser waveguide characteristics such as loss, confinement factor, and far-field divergence. From the example and explanations, users should be able to develop an experience of how to use WAVEGUIDE II program for simulation to achieve design requirements.

REFERENCES

[1] S.-L. Chuang, *Physics of Optoelectronic Devices*, 1, 421 and 245-246 (1995)

[2] http://engr.smu.edu/ee/smuphotonics/GainManualAppendixC/AppendixC.htm

Chapter 11

EFFECT OF METAL CONTACT ON INP LASERS

11.1 Metal covered slab waveguide in semiconductor lasers

11.1.1 Introduction

Dielectric properties of metals used as electrical contacts in semiconductor lasers are much different form common dielectric materials. Evolving metal layers into semiconductor waveguide can bring different result from laser structure without metal cover.

The epitaxial structure of the laser used in this chapter is shown in the Fig.1 below. The structure is composed of five quantum wells, four barriers, two graded-index (GRIN) layers, inner cladding layers, transition GRIN layers, one p-spacer, etch stop and outer cladding. The schematic representation of a ridge waveguide laser is shown in figure 2.

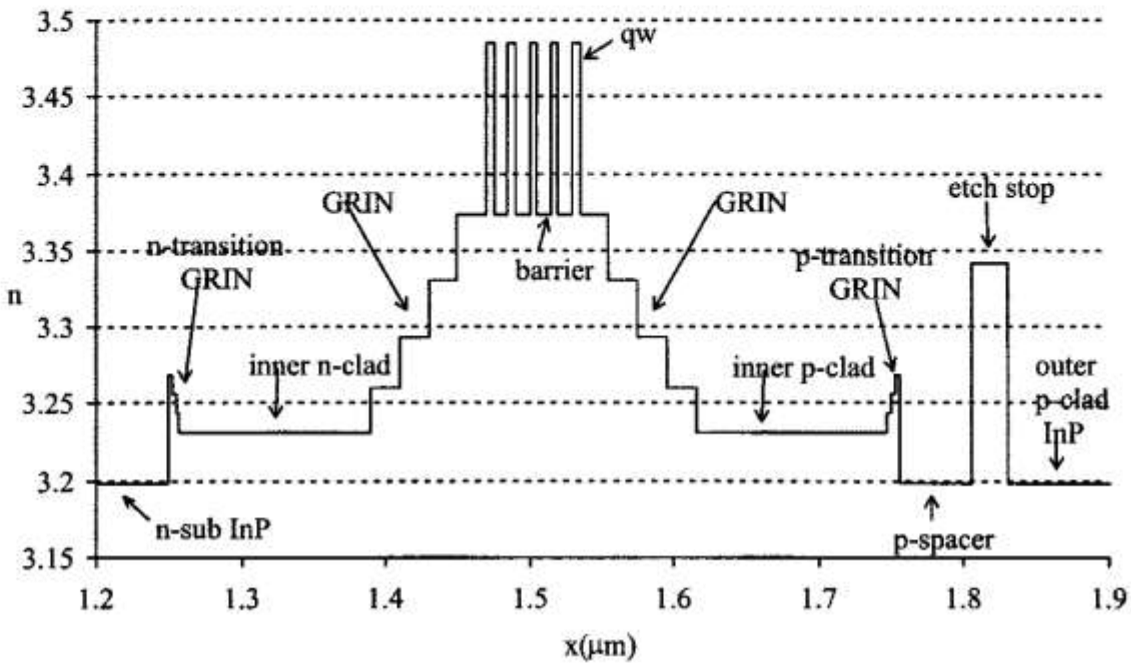


Figure 11.1.1 Index of refraction along the epitaxial structure. [2]

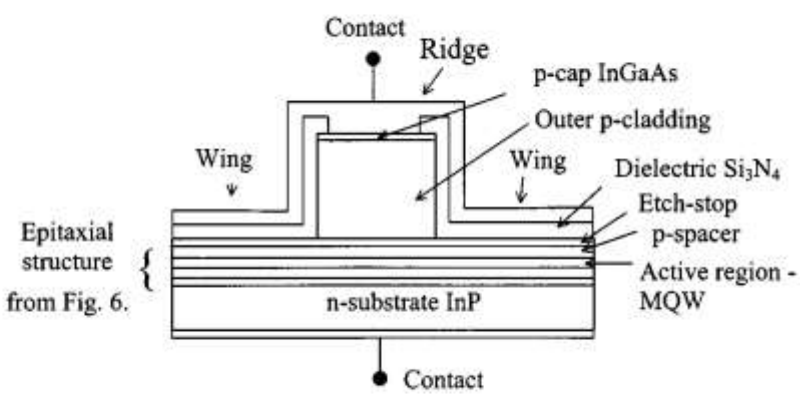


Figure 11.1.2 Schematic representation of a ridge-waveguide laser. [2]

The power loss is shown in Figure 11.3.4. It is calculated using the following formula (WZI is taken from the .db output file):

$$\alpha = WZI \cdot (4\pi/\lambda) \cdot 10^4 \text{ /cm}$$

We use the input file in table 11.1.1 for the ridge region. The power loss plot is generated by using the WZI from the .db output file. We can see from figure 3 below that as long as the p-clad thickness is greater than 1um, the loss is going to be minimal.

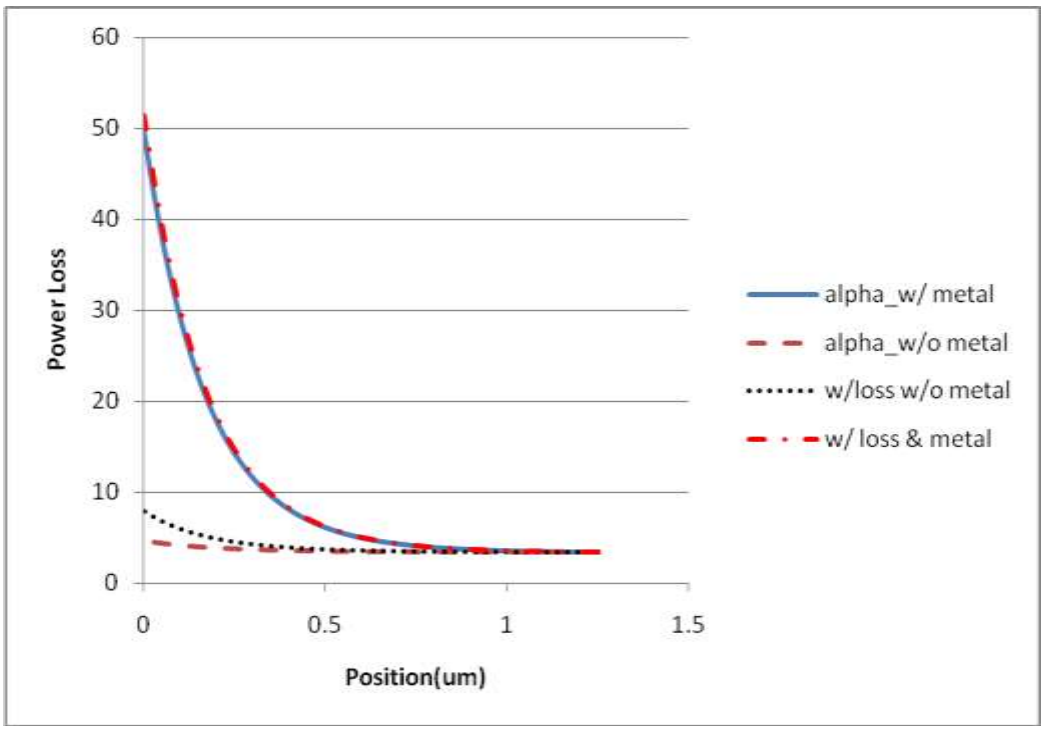


Figure 11.1.3 Power loss plot for the Ridge waveguide lasers

11.1.2 The input file for the ridge waveguide

The structure of a 1310nm semiconductor laser that includes the metal layers on top of the ridge for electrical contact is shown in table 11.1.1. In this structure Ti, Pt and

Au layers are commonly metal materials used as electrical contact. QZMR was looped from $n_{QW}^2 = 3.535976^2 \approx 12.50$, $\mathrm{n}_{\min}^2 = 10$ to with step size -0.05, which is very small.

Table 11.1.1 Input file of 1310nm laser structure with metal cover at ridge region

```
!CASE Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=12.40 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30
!MODCON Parameter Set
MODCON KPOL=0 APB1=0.25 APB2=0.25
!STRUCT Parameter Set
STRUCT WVL=1.31
STRUCT XPERC1=0.0 XPERC2=0.0 XPERC3=0.0 XPERC4=0.0
STRUCT YPERC1=0.0 YPERC2=0.0 YPERC3=0.0 YPERC4=0.0
!LAYER Parameter Set
LAYER NREAL=3.1987 NLOSS=0.0012 TL=1.0        !n-Sub
LAYER NREAL=3.2689 NLOSS=0 TL=0.002           !n-Transition GRIN structure
LAYER NREAL=3.2595 NLOSS=0 TL=0.002
LAYER NREAL=3.2500 NLOSS=0 TL=0.002
LAYER NREAL=3.2405 NLOSS=0 TL=0.002
LAYER NREAL=3.2310 NLOSS=0 TL=0.002
LAYER NREAL=3.2310 NLOSS=0 TL=0.11            !Inner n cladding
LAYER NREAL=3.2310 NLOSS=0 TL=0.02            !n-GRIN
LAYER NREAL=3.2665 NLOSS=0 TL=0.02
LAYER NREAL=3.3019 NLOSS=0 TL=0.02
```

```
LAYER NREAL=3.3374 NLOSS=0 TL=0.02
LAYER NREAL=3.3728 NLOSS=0 TL=0.02
LAYER NREAL=3.4850 NLOSS=0 TL=0.005          !QW
LAYER NREAL=3.3728 NLOSS=0 TL=0.01           !barrier
LAYER NREAL=3.4850 NLOSS=0 TL=0.005          !QW
LAYER NREAL=3.3728 NLOSS=0 TL=0.01           !barrier
LAYER NREAL=3.4850 NLOSS=0 TL=0.005          !QW
LAYER NREAL=3.3728 NLOSS=0 TL=0.01           !barrier
LAYER NREAL=3.4850 NLOSS=0 TL=0.005          !QW
LAYER NREAL=3.3728 NLOSS=0 TL=0.01           !barrier
LAYER NREAL=3.4850 NLOSS=0 TL=0.005          !QW
LAYER NREAL=3.3728 NLOSS=0 TL=0.02           !p-GRIN
LAYER NREAL=3.3374 NLOSS=0 TL=0.02
LAYER NREAL=3.3019 NLOSS=0 TL=0.02
LAYER NREAL=3.2665 NLOSS=0 TL=0.02
LAYER NREAL=3.2310 NLOSS=0 TL=0.02
LAYER NREAL=3.2310 NLOSS=0 TL=0.11           !Inner p cladding
LAYER NREAL=3.2310 NLOSS=0 TL=0.002          !p transition GRIN
LAYER NREAL=3.2405 NLOSS=0 TL=0.002
LAYER NREAL=3.2500 NLOSS=0 TL=0.002
LAYER NREAL=3.2595 NLOSS=0 TL=0.002
LAYER NREAL=3.2689 NLOSS=0 TL=0.002
LAYER NREAL=3.1987 NLOSS=0 TL=0.05           !p-spacer

LAYER NREAL=3.3414 NLOSS=0 TL=0.025          !Etch stop
LAYER NREAL=3.1987 NLOSS=0 TL=1.25           !Outer p-cladding
```

```
LAYER NREAL=3.0667 NLOSS=0 TL=0.2                    !P-cap


LAYER NREAL=3.7 NLOSS=18.2415 TL=0.05                !Ti
LAYER NREAL=4.64 NLOSS=26.6731 TL=0.12               !Pt
LAYER NREAL=0.18 NLOSS=41.3474 TL=1.0                !Au
!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=0 WZRO=1 WZIO=1 QZRO=1 QZIO=0
OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=0 LYROUT=1
!GAMOUT Parameter Set
GAMOUT LAYGAM=8 COMPGAM=0 GAMALL=0
!LOOPX Parameter Set
LOOPX1 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX2 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2
!LOOPZ Parameter Set
LOOPZ1 ILZ=17 FINV=10 ZINC=-0.05          !QZMR
LOOPZ2 ILZ=0 FINV=0 ZINC=0.1
LOOPZ3 ILZ=0 FINV=0 ZINC=0.1
LOOPZ4 ILZ=0 FINV=0 ZINC=0.1
END
```

For lateral confinement factor, we need a delta_n of about 0.01. [2] Using our 1310 um structure, Figure 4 shows the WZR plot with and without metal.

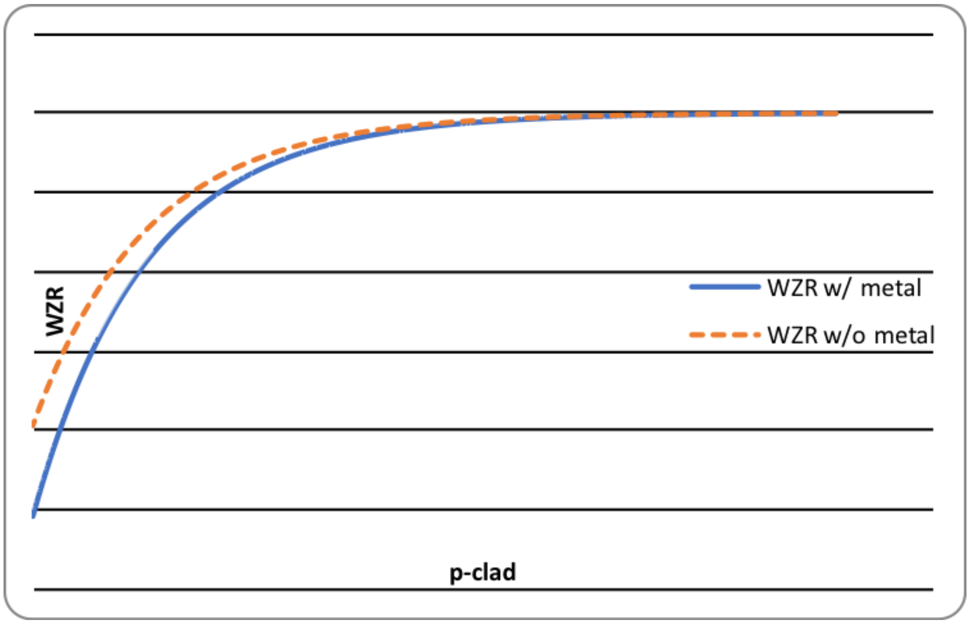


Figure 11.1.4 Plot of WZR with and without metal.

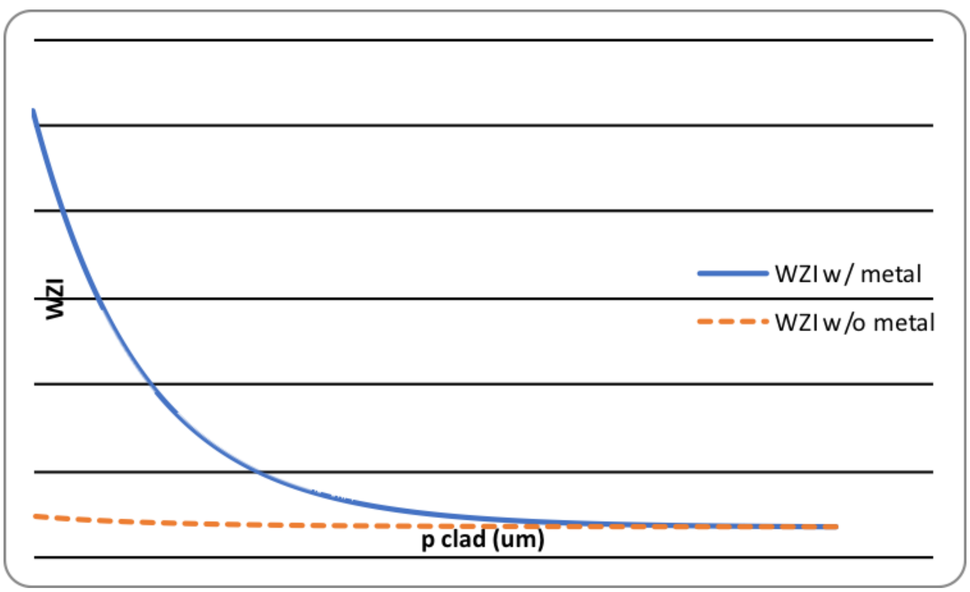


Figure 11.1.5 Plot of WZI with and without metal.

11.1.3 Fundamental mode in ridge region with metal

In figure 11.1.6, the near field intensity and amplitude are plotted with the phase for the ridge waveguide with metal cover. Figure 11.1.7 shows the comparison between the near field amplitude and the refractive index at ridge region.

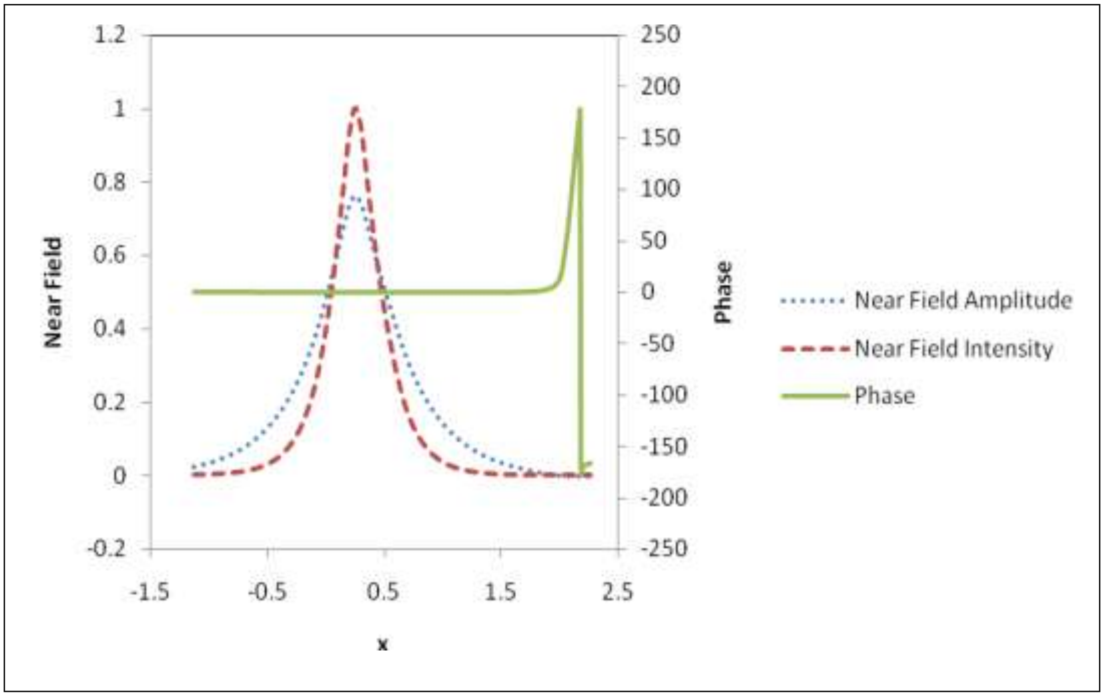


Figure 11.1.6 Fundamental mode near field plots at ridge region.

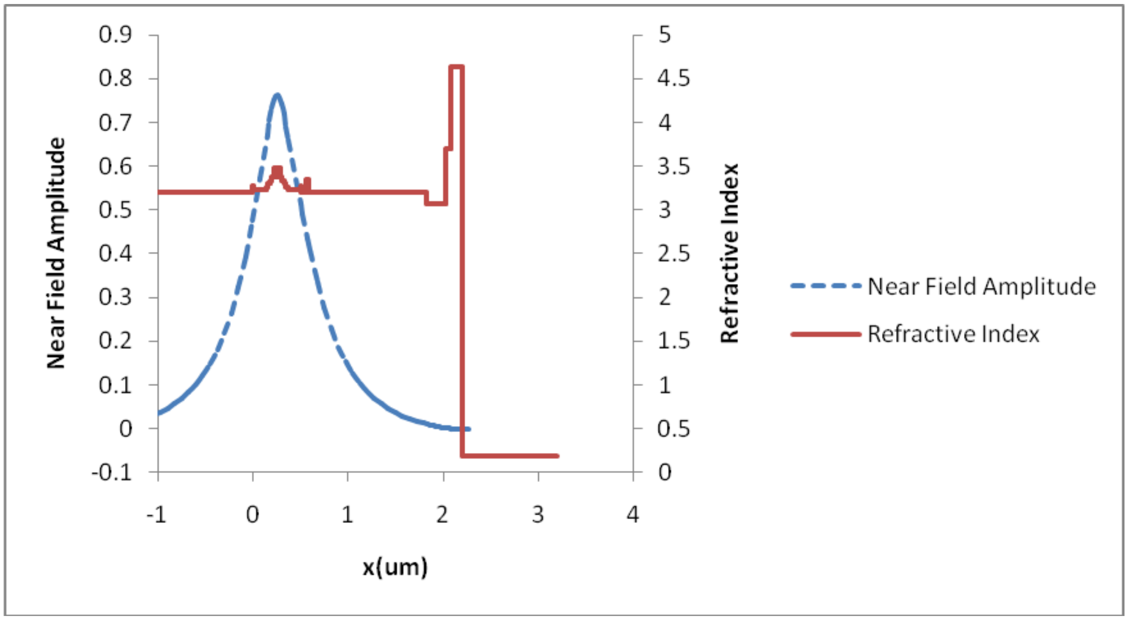


Figure 11.1.7 Comparison of near field and refractive index at ridge region.

11.1.4 Fundamental mode in wing region with metal

From the result of mode searching we can see that when KM>5, the WZI value is at the order of 10^{-3}. When QZMR = 11.15, KM=7 and IT=7. Therefore we end the looping and set the QZMR value to 11.15. For this fixed value we run the program and obtain the output parameters db file, near field and profile of indices of each layer. For the TE_0 mode, near field (real part and intensity) is plotted in figure 11.1.1.

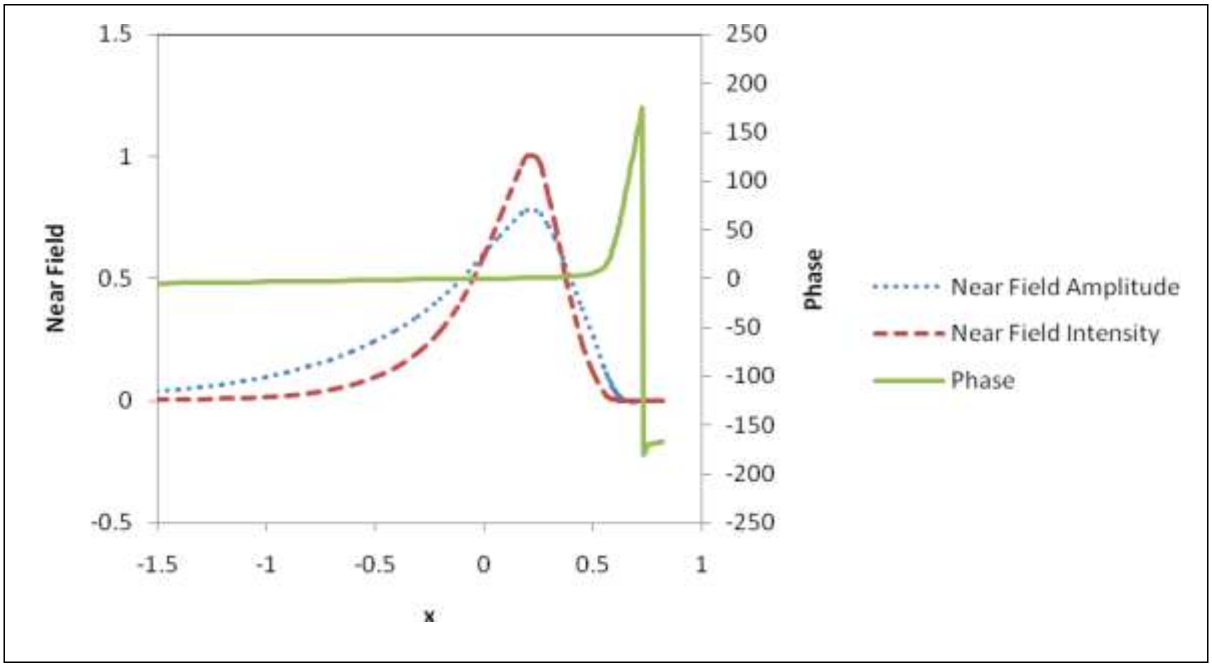


Figure 11.1.8 Fundamental mode near field plots for wing region

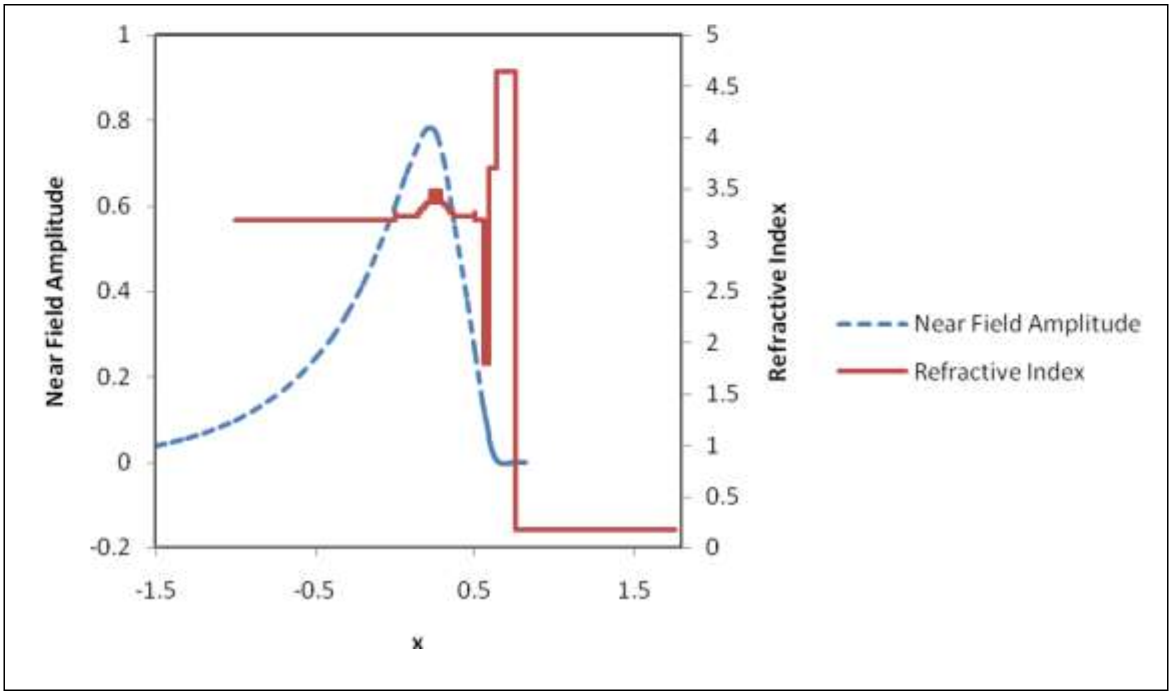


Figure 11.1.9 The comparison of refractive index and field

From the result, we note that there is a phase change at the dielectric-metal interface. Because of the existence of metal layers, the mode is leaky with WZI being in the order of 10^{-3}. Also we can see, the 180 degrees phase change at the interface of platinum layer and gold layer.

11.1.5 Result analysis

In wing region, there is no outer p-spacing but a low refractive index Si_3N_4 layer, we got result as WZR=3.233878 and WZI=5.175776*10^{-4}. In ridge region, there is a relatively thick outer p-spacing layer but no nitride layer, and we have WZR=3.243997 and WZI=3.562671*10^{-5}. There is big difference between these two kinds of slab waveguide. It can be seen that the etch stop layer, outer p-spacing and p-cap layers reduce the leak of mode caused by metal covers for two orders. The attenuation in ridge region is mainly caused by the absorption of n-substrate. We will verify this argument in section 11.3, in which calculation was done on almost identical slab waveguides with no metal covers.

11.2 Ridge waveguide with metal covers

Lateral mode of ridge waveguide with metal cover layers is studied in this section. Use the effective refractive indices calculated for wing and ridge region. That is, in wing region, NREAL=3.233878 and NLOSS=0.004965, in ridge region, NREAL= 3.243997 and NLOSS=0.000342. Another difference is that when calculating lateral mode for global TE mode in ridge waveguide device, TM mode should be used [1,2]. The input file for this calculation is shown in table 11.1.3. Because the small difference between two refractive indices of two regions, only a small range of QZMR was looped for mode searching. The db file after looping QZMR is shown below. The result shows for lateral mode $WZR = 3.24$ and WZI=5.289655*10^{-5}. The attenuation coefficient is similar to that of ridge region. This is because most energy of light is confined in ridge region. The near field is plotted in figure 11.2.1. From the figure, we can see that there is no phase change at any interface.

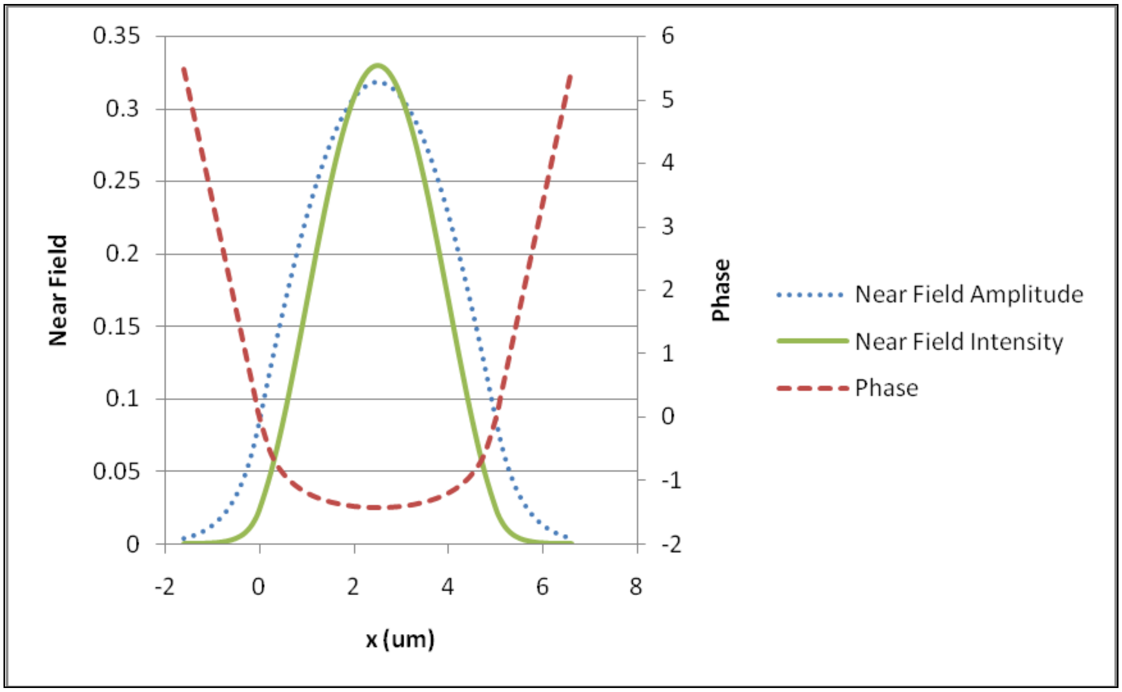


Figure 11.2.1. Fundamental mode near field plots for at ridge waveguide.

Table 11.1.3 Input file for ridge waveguide

```
!WIF generated by WIFE (Waveguide Input File Editor)
!-----------------------------------------------------------------
!FILENAME:    C:\Waveguide\work\input\ridgeguide.wgi
!DESCRIPTION: RidgeGuide
!Last Modified: 5/5/04 PM 6:21:34
!-----------------------------------------------------------------
Parameter Set
CASE KASE=WIFE
CASE EPS1=1E-9 EPS2=1E-9 GAMEPS=1E-3 QZMR=10.55 QZMI=0.001
CASE PRINTF=1 INITGS=0 AUTOQW=0 NFPLT=1 FFPLT=1 IL=30

!MODCON Parameter Set
MODCON KPOL=1 APB1=0.25 APB2=0.25

!STRUCT Parameter Set
LAYER NREAL=3.233878 NLOSS=0.004965    TL=1.0
LAYER NREAL=3.243997 NLOSS=0.000342    TL=5
LAYER NREAL=3.233878 NLOSS=0.004965    TL=1.0

!OUTPUT Parameter Set
OUTPUT PHMO=1 GAMMAO=0 WZRO=1 WZIO=1 QZRO=1 QZIO=1
OUTPUT FWHPNO=0 FWHPFO=0 KMO=1 ITO=1
OUTPUT SPLTFL=0 MODOUT=0 LYROUT=0

!GAMOUT Parameter Set
GAMOUT LAYGAM=2 COMPGAM=0 GAMALL=0

!LOOPX Parameter Set
LOOPX1 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX2 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX3 ILX=0 FINV=0 XINC=0.1 LAYCH=2
LOOPX4 ILX=0 FINV=0 XINC=0.1 LAYCH=2

!LOOPZ Parameter Set
LOOPZ1 ILZ=17 FINV=10.39 ZINC=-0.01 !QZMR
LOOPZ2 ILZ=0 FINV=0 ZINC=0.1
LOOPZ3 ILZ=0 FINV=0 ZINC=0.1
LOOPZ4 ILZ=0 FINV=0 ZINC=0.1

END
```

11.3 Ridge waveguide without metal cover

The counterpart ridge waveguide without metal cover is studied in this section. We can see obvious difference from the metal covered structure.

11.3.1 Fundamental mode in wing region

First, remove all three metal layers from the input file of wing region with metal covered slab waveguide. Then do the same loop for QZMR form 13 to 10 with step size –0.05, the output of QZMR looping is shown as below:

QZMR	PHM	WZR	WZI	QZR	KM	IT
1.300000E+01	2.635683E+00	2.317423E+00	1.665053E+00	2.598047E+00	5	19
1.295000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	18
1.290000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	18
1.285000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	18
1.280000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	18
1.275000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	18
…….						
1.170000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.165000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.160000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.155000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.150000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.145000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.140000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.135000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	15
1.130000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	14
1.125000E+01	1.783650E+00	2.668391E+00	5.611743E-01	6.805393E+00	5	14
1.120000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6
1.115000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6

1.110000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6
1.105000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6
1.100000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6
1.095000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6
1.090000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	5
1.085000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	5
1.080000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	5
1.075000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	5
1.070000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	4
1.065000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	4
1.060000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	4
1.055000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	4
1.050000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	4
1.045000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	3
1.040000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	2
1.035000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	3
1.030000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	4
1.025000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	5
1.020000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6
1.015000E+01	3.997537E-01	3.223538E+00	7.276849E-05	1.039120E+01	6	5
1.010000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	5
1.005000E+01	3.997537E-01	3.223538E+00	7.276851E-05	1.039120E+01	6	5
1.000000E+01	3.997537E-01	3.223538E+00	7.276850E-05	1.039120E+01	6	6

Select the fundamental mode with following parameters, near field is plotted as figure 11.2.1

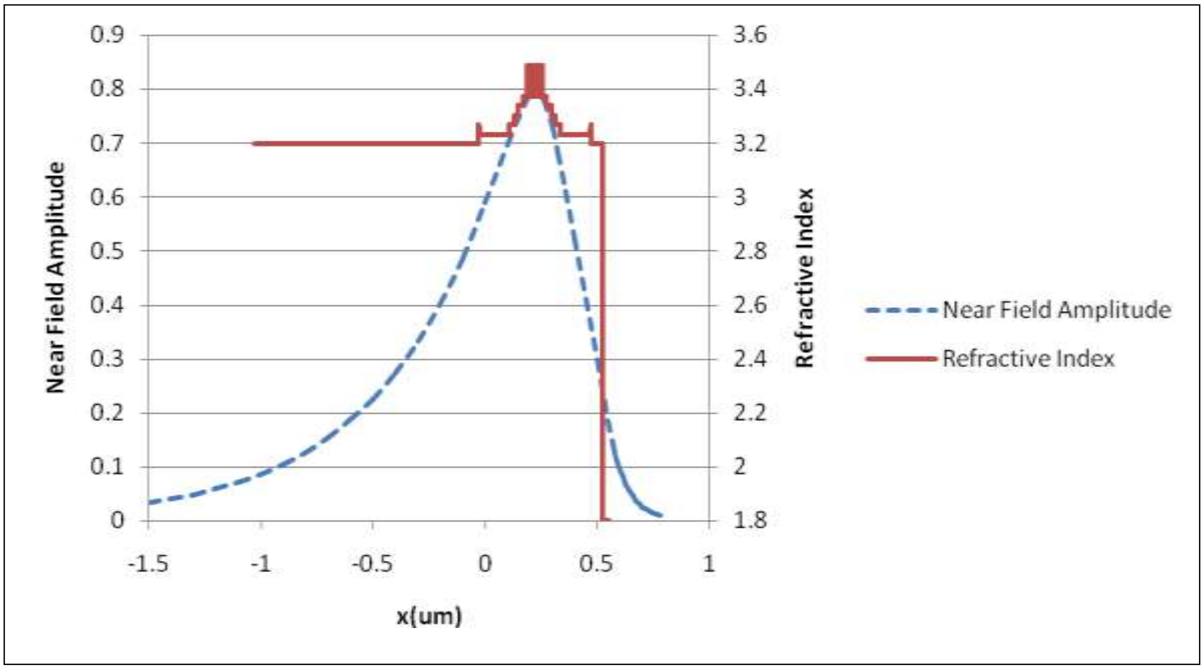


Figure 11.3.1. Near field of fundamental mode at wing region

11.3.2 Fundamental mode in ridge region

First, remove all three metal layers from the input file of ridge region with metal covered slab waveguide. Then do the same loop for QZMR as in 11.1.5, the output of QZMR looping is shown as below.

QZMR	PHM	WZR	WZI	QZR	KM
IT					

1.250000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	25
1.245000E+01	4.223206E+00	2.862570E+00	1.416567E-01	8.174242E+00	3	30
1.240000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	24
1.235000E+01	4.223235E+00	2.862565E+00	1.416616E-01	8.174213E+00	3	30
1.230000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	24
1.225000E+01	4.223235E+00	2.862565E+00	1.416616E-01	8.174213E+00	5	30
1.220000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	23
1.215000E+01	4.223235E+00	2.862565E+00	1.416616E-01	8.174213E+00	5	30
1.210000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	22
1.205000E+01	4.223235E+00	2.862565E+00	1.416616E-01	8.174213E+00	5	29
1.200000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	22
1.195000E+01	4.223235E+00	2.862565E+00	1.416616E-01	8.174213E+00	5	28
1.190000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	7	22
1.185000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	21
1.180000E+01	4.223235E+00	2.862565E+00	1.416616E-01	8.174213E+00	5	28
1.175000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	20
1.170000E+01	4.223235E+00	2.862565E+00	1.416616E-01	8.174213E+00	5	27
1.165000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	20
1.160000E+01	3.074584E+00	3.033089E+00	6.051963E-02	9.195964E+00	5	25
1.155000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	19
1.150000E+01	3.074584E+00	3.033089E+00	6.051963E-02	9.195964E+00	5	24
1.145000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	18
1.140000E+01	3.074584E+00	3.033089E+00	6.051963E-02	9.195964E+00	5	23
1.135000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	18
1.130000E+01	3.074584E+00	3.033089E+00	6.051963E-02	9.195964E+00	5	22
1.125000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	17

1.120000E+01	3.074584E+00	3.033089E+00	6.051963E-02	9.195964E+00	5	22
1.115000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	16
1.110000E+01	2.331442E+00	3.110294E+00	1.274339E-02	9.673764E+00	5	19
1.105000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	16
1.100000E+01	2.331442E+00	3.110294E+00	1.274339E-02	9.673764E+00	5	18
1.095000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	15
1.090000E+01	2.331442E+00	3.110294E+00	1.274339E-02	9.673764E+00	5	17
1.085000E+01	2.331442E+00	3.110294E+00	1.274339E-02	9.673764E+00	5	16
1.080000E+01	2.331442E+00	3.110294E+00	1.274339E-02	9.673764E+00	5	16
1.075000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	13
1.070000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	7	12
1.065000E+01	3.069611E-01	3.244000E+00	3.508623E-05	1.052353E+01	6	7
1.060000E+01	3.069611E-01	3.244000E+00	3.508623E-05	1.052353E+01	6	5
1.055000E+01	3.069611E-01	3.244000E+00	3.508623E-05	1.052353E+01	6	4
1.050000E+01	3.069611E-01	3.244000E+00	3.508623E-05	1.052353E+01	6	4
1.045000E+01	3.069611E-01	3.244000E+00	3.508623E-05	1.052353E+01	6	5
1.040000E+01	3.069611E-01	3.244000E+00	3.508623E-05	1.052353E+01	7	6
1.035000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	7
1.030000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	6
1.025000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	6
1.020000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	5
1.015000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	4
1.010000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	3
1.005000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	7	4
1.000000E+01	1.435656E+00	3.174719E+00	2.637810E-03	1.007883E+01	6	4

Select the fundamental mode with parameters as QZMR value highlighted above, near field is plotted as figure 11.3.2.

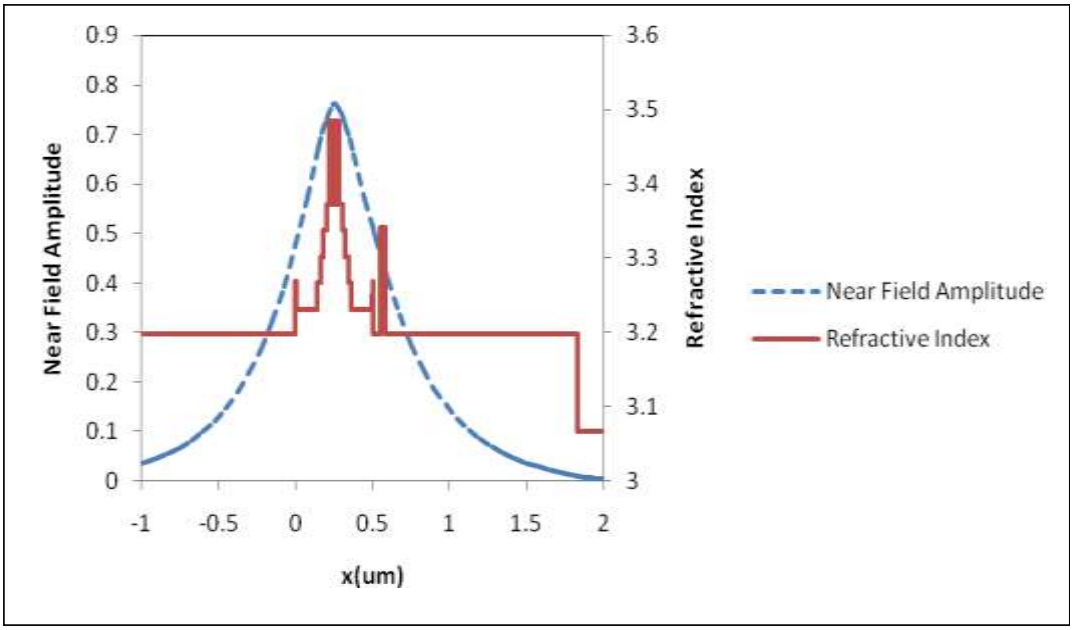


Figure 11.3.2 Near field of fundamental mode at ridge region

11.3.3 Fundamental mode in non-metal covered ridge waveguide

Effective refractive index method should be used for lateral mode search. Another change that should be appreciated is that this time we should change the polarization to TM mode for lateral direction. Use the following structure:

Wings: NREAL= 3.236149 NLOSS= 0.0004605

Ridge: NREAL= 3.244 NLOSS= 0.0003365

And the ridge width is 5um.

Loop QZMR from $3.244^2 = 10.52$ to $3.236^2 = 10.47$ with step size –0.01. The result is shown below:

QZMR	PHM	WZR	WZI	QZR	QZI
KM	IT				
1.052000E+01	8.078474E-01	3.243307E+00	4.474336E-05	1.051904E+01	2.902329E-04
7	4				
1.051900E+01	8.078474E-01	3.243307E+00	4.474336E-05	1.051904E+01	2.902329E-04
6	3				
1.051800E+01	8.078474E-01	3.243307E+00	4.474336E-05	1.051904E+01	2.902329E-04
7	4				
1.051700E+01	8.078474E-01	3.243307E+00	4.474336E-05	1.051904E+01	2.902329E-04
6	4				
1.051600E+01	8.078474E-01	3.243307E+00	4.474336E-05	1.051904E+01	2.902329E-04
7	5				
1.051500E+01	8.078474E-01	3.243307E+00	4.474336E-05	1.051904E+01	2.902329E-04
6	5				
1.051400E+01	1.599402E+00	3.241283E+00	4.575276E-05	1.050591E+01	2.965953E-04
5	6				
1.051300E+01	1.599402E+00	3.241283E+00	4.575276E-05	1.050591E+01	2.965953E-04
6	6				
1.051200E+01	1.599402E+00	3.241283E+00	4.575276E-05	1.050591E+01	2.965953E-04
5	5				
1.051100E+01	1.599402E+00	3.241283E+00	4.575276E-05	1.050591E+01	2.965953E-04
5	5				

1.051000E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

6 5

1.050900E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5 4

1.050800E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5 4

1.050700E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5 3

1.050600E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5 3

1.050500E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5 3

1.050400E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

6 4

1.050300E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5 4

1.050200E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5 4

1.050100E+01 1.599402E+00 3.241283E+00 4.575276E-05 1.050591E+01 2.965953E-04

5

4

.

.

.

.

Select the parameters of highlighted line, which corresponds to fundamental mode in lateral mode. The near field plot is shown in figure 11.3.3.

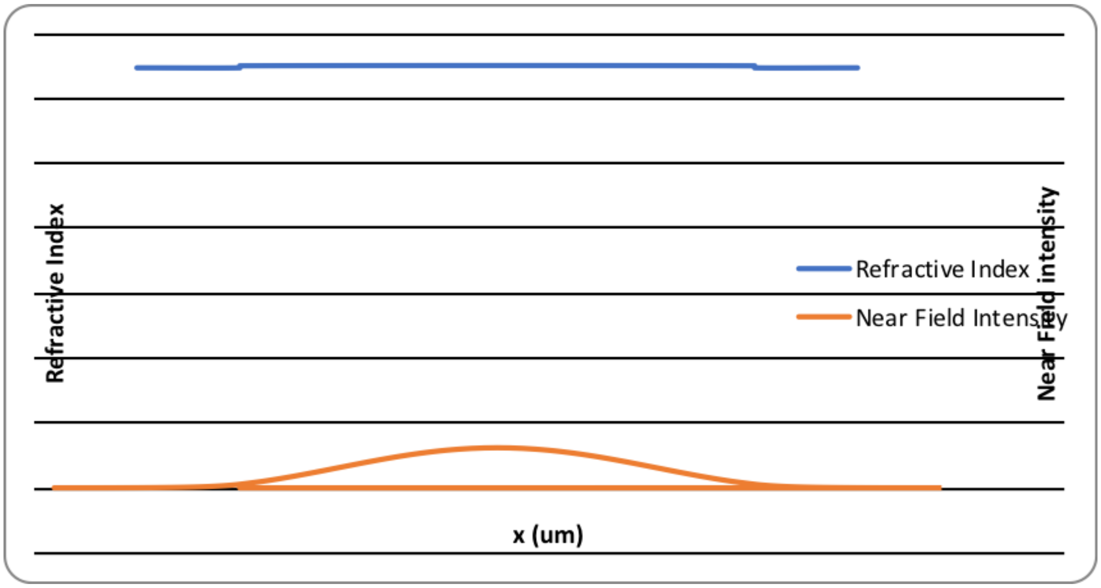


Figure 11.3.3 Near field of fundamental mode at ridge region

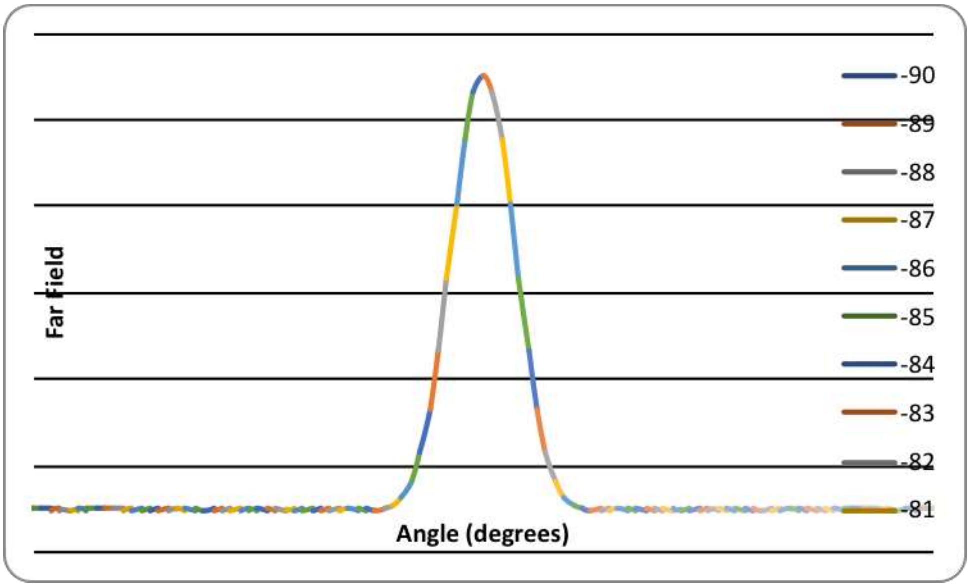


Figure 11.3.4 Far field of fundamental mode at ridge region

11.3.4 Result discussion

We see big difference at wing area in attenuation coefficient. The mode is a leaky mode. But at ridge region, the effect of metal is relatively not obvious. Instead, in ridge region, the lossy n-substrate is the main source of attenuation.

However, the global effect of metal cover to the ridge waveguide is not so big. The lateral mode calculation eventually gives the global attenuation. The attenuation of the device with and without metal is in same order. That is because light is mostly confined in ridge region. And ridge region doesn't give much difference with or without metal cover. So that it is safe for us to add metal cover on ridge laser device.

REFERENCES

[1] Agrawal G P and Dutta N K, *Semiconductor lasers* 2nd ed, New York: Wan Nostrand-Reinhold S. 1993 R. Selmic et al.

[2] Sandra R. Selmic, Tso-Min Chou, JiehPing Sih, Jay B. Kirk, Art Mantie, Jerome K. Butler, David Bour, and Gary A. Evans, "Design and Characterization of 1.3 μm AlGaInAs/InP Multiple Quantum Well Lasers," IEEE Journal of Special Topics in Quantum Electronics, Vol. 7, No. 2, March/April 2001.

Appendix

Subprograms for Refractive Indices Calculation

Chapter 3 of this manual describes the material system feature of WAVEGUIDE II called Matsys. This appendix lists the software source code from WAVEGUIDE II that Matsys uses to calculate the refractive index of a layer given the layer composition defined by the user. The heading of each section listed below corresponds with the drop down list in WAVEGUIDE II that shows the available material systems that can be selected.

Al(x)Ga(1-x)As 1

```
 SUBROUTINE sALGAAS1(WVL,XPERCENT,EFFINDX)
    ! calculates the effective index given the wavelength (WVL) and
    ! the percent (PERC)

    USE INFO_MOD
    IMPLICIT NONE
    REAL(KIND=8), INTENT(IN)  :: XPERCENT,WVL
    REAL(KIND=8), INTENT(OUT) :: EFFINDX
    REAL(KIND=8)              :: X,OMEGA,ENERGY,ENDEL,CHI,CHISO
    REAL(KIND=8)              :: FCHI,FCHISO,AO,BO,EPSI
    REAL(KIND=8) :: C=3.0E+14, PI
    REAL(KIND=8) :: HBAR
    !MM-Notify

    WRITE(STDOUT_RD,*) 'Using AlGaAs-1 Material System'
    !MM-Notify
    PI=4.0*ATAN(1.0)
    HBAR=4.14E-15/(2.0*PI)

!   !---- finds something (N vs. lamda) ----
          X=XPERCENT
          OMEGA=2.0*PI*C/WVL
          ENERGY=1.425+1.155*X+0.37*X*X
          ENDEL=1.765+1.115*X+0.37*X*X
          CHI=HBAR*OMEGA/ENERGY
          CHISO=HBAR*OMEGA/ENDEL
             IF(((1-CHI)<=0.0).OR.((1-CHISO)<=0.0)) THEN
               WRITE(STDOUT_RD,*) ' CHI RANGE ERROR!'
          ELSE
               FCHI=(2-SQRT(1+CHI)-SQRT(1-CHI))/(CHI*CHI)
```

```
        FCHISO=(2-SQRT(1+CHISO)-SQRT(1-CHISO))/(CHISO*CHISO)
            AO=6.3+19.0*X
            BO=9.4-10.2*X
        EPSI=AO*(FCHI+.5*(FCHISO*((ENERGY/ENDEL)**1.5)))+BO
            IF(EPSI<=0) THEN
              WRITE(STDOUT_RD,*) 'EPSI RANGE ERROR!'
            ELSE
              EFFINDX=SQRT(EPSI)
            END IF
        END IF
    RETURN
    END SUBROUTINE sALGAAS1
```

Al(x)Ga(1-x)As 2

```
   SUBROUTINE sALGAAS2(WVL,P,NEFF)

    ! calculates the effective index given the wavelength (WVL) and
    ! the percent (PERC)

    USE INFO_MOD
    IMPLICIT NONE
    REAL(KIND=8), INTENT(IN)  :: P,WVL
    REAL(KIND=8), INTENT(OUT) :: NEFF
    REAL(KIND=8)     :: A,B1,B2,B11,B22,C,D,E1,Ec,Eic,einf,E1c,T,f,fi
    REAL(KIND=8)     :: E0,Ei,D0,D1
    REAL(KIND=8)     :: E, G, EE, EEI, EP1E01, EP1E02, EP1E0, EP2E0
    REAL(KIND=8)     :: EP1E11, EP1E12, EP2E11, EP2E12, EP1E1, EP2E1
    REAL(KIND=8)     :: EP2EC, EP2EI, EP1EC, EQ1, EPSILON1, EPSILON2
    COMPLEX(KIND=8)  :: ARG1,ARG2
    COMPLEX(KIND=8)  :: CE00,CEC,CE,CE0,CEXP0,CEXP00
    REAL(KIND=8), PARAMETER :: PI = 3.1415926535898D0
    !MM-Notify
    WRITE(STDOUT_RD,*) 'Using AlGaAs-2 Material System'
   !MM-Notify

!     {parameters calculated using equation  Qi(x)=Q0+(Q1*(P-.5))+(Q2*(P-.5)^2)
    A=4.264374+(4.402701*(P-.5))+(9.160232*((P-.5)*(P-.5)))
```

```
      B1=8.256268+(-0.585350*(P-.5))+(-1.901850*((P-.5)*(P-.5)))
      B2=0.462866+(0.012206*(P-.5))+(1.047697*((P-.5)*(P-.5)))
      B11=19.788257+(-3.706511*(P-.5))+(2.990894*((P-.5)*(P-.5)))

      B22=0.539077+(-0.172307*(P-.5))+(1.031416*((P-.5)*(P-.5)))
      C=3.078636+(-1.598544*(P-.5))+(-0.742071*((P-.5)*(P-.5)))
      D=29.803617+(-22.124036*(P-.5))+(-57.863105*((P-.5)*(P-.5)))
      E1=3.212414+(0.804397*(P-.5))+(0.228317*((P-.5)*(P-.5)))
      Ec=4.724383+(0.024499*(P-.5))+(0.030653*((P-.5)*(P-.5)))
      Eic=3.160138+(0.138046*(P-.5))+(1.066214*((P-.5)*(P-.5)))
      einf=-0.494941+(-0.030802*(P-.5))+(0.486201*((P-.5)*(P-.5)))
      E1c=6.413109+(0.571119*(P-.5))+(-0.735610*((P-.5)*(P-.5)))
      T=0.263476+(0.090532*(P-.5))+(-0.254099*((P-.5)*(P-.5)))
      G=0.147517+(-0.068764*(P-.5))+(0.047345*((P-.5)*(P-.5)))
      f=1.628226+(-1.682422*(P-.5))+(-2.081273*((P-.5)*(P-.5)))
      fi=0.507707+(-0.070165*(P-.5))+(-0.122169*((P-.5)*(P-.5)))

!    {parameters calculated using equation  Qi(x)=Q0+(Q1*P)+(Q2*P^2)
      E0=1.425000+(1.155000*P)+(0.370000*(P*P))
      Ei=1.734000+(0.574000*P)+(0.055000*(P*P))
      D0=0.340000+(0.0*P)+(0.0*(P*P))
      D1=0.230000+(-0.030000*P)+(0.0*(P*P))
      E=(4.135701327D-15*2.99792458D14)/WVL

      EE=E*E
      EEI=1.0/EE

!     REAL PART OF DIELECTRIC FUNCTION: DIRECT EDGE (E0)
      ARG1=CMPLX(1.+E/E0,0.0,8)
      ARG2=CMPLX(1.-E/E0,0.0,8)
      EP1E01=A*EEI*REAL(SQRT(E0)*(2.-SQRT(ARG1)-SQRT(ARG2)))
      ARG1=CMPLX(1.+E/(E0+D0),0.0,8)
      ARG2=CMPLX(1.-E/(E0+D0),0.0,8)
      EP1E02=A*EEI*REAL(.5*SQRT(E0+D0)*(2.-SQRT(ARG1)-
SQRT(ARG2)))
      EP1E0=EP1E01+EP1E02

!     IMAGINARY PART OF DIELECTRIC FUNCTION: DIRECT EDGE (E0)
!     TAKING THE REAL PART IS LIKE A HEAVYSIDE FUNCTION
```

```
      ARG1=CMPLX(E-E0,0.0,8)
      ARG2=CMPLX(E-E0-D0,0.0,8)
      EP2E0=REAL((2*SQRT(ARG1)+SQRT(ARG2))*EEI)*A/3.0

!     REAL PART OF THE DIELECTRIC FUNCTION: L [K=PI/A] (E1)
!     ADD A LINEWIDTH GAM
      CE00=E*(1.0,0.0)+T*(0.0,1.0)
      CEC=1.0/((1.0,0.0)-((CE00/E1c)*(CE00/E1c)))
      CE=CE00*CE00
      CE0=CE/((E1+D1)*(E1+D1))
      CE=CE/(E1*E1)
      CEXP0=MIN(EXP(-f*(E-E1)),REAL(1.0,8))/CE
      CEXP00=MIN(EXP(-f*(E-E1-D1)),REAL(1.0,8))/CE0
      EP1E11=-B1*REAL(LOG(((1.0,0.0)-CE)*CEC)*CEXP0)
      EP1E12=-B2*REAL(LOG(((1.0,0.0)-CE0)*CEC)*CEXP00)
      EP1E1=EP1E11+EP1E12

!     IMAGINARY PART OF DIELECTRIC FUNCTION: L [K=PI/A] (E1)
!     DON'T ALLOW A NEGATIVE IMAGINARY PART

!mm   ARG1=CMPLX(E1-CE00,0.0,8)   - CE00 is already complex...
!mm   ARG1=CMPLX(E1-CE00,0.0,8)   - CE00 is already complex...

      ARG2=E1+D1-CE00
      ARG2=E1+D1-CE00
      EP2E11=PI*MAX(REAL((B1-B11*SQRT(ARG1))*CEXP0),REAL(0.0,8))

      EP2E12=PI*MAX(REAL((B2-B22*SQRT(ARG2))*CEXP00),REAL(0.0,8))
      EP2E1=MAX(EP2E11+EP2E12,REAL(0.0,8))

!     REAL PART OF DIELECTRIC FUNCTION: (Ec)
      CE=(1.0,0.0)-EE/(Ec*Ec)
      EP2EC=REAL(C/(CE*CE+EE*((G/Ec)*(G/Ec))))
      EP1EC=REAL(CE*EP2EC)

!     IMAGINARY PART OF DIELECTRIC FUNCTION: (Ec)
      EP2EC=(E*G/Ec)*EP2EC

!     IMAGINARY PART OF DIELECTRIC FUNCTION: INDIRECT EDGE
```

```
K=[2*PI/A] (X->GAMMA)
        EQ1=E-Ei
        EP2EI=(D*EEI*(EQ1*EQ1))*MIN(EXP(-fi*(E-Eic)),REAL(1.0,8))

!       DO ALL THE HEAVYSIDE FUNCTIONS
        IF (E<E0) THEN
           EP2E0=0.0
           EP2E1=0.0
           EP2EC=0.0
           EP2EI=0.0
        END IF

        IF (E<E1) THEN
           EP2E1=0.0
        END IF



!       MULTIPLY THE IMAGINARY PART BY HEAVYSIDE FUNCTION
!       INDEX IS THE REAL PART OF THE SQUARE ROOT
!       OF THE COMPLEX DIELECTRIC FUNCTION
        EPSILON1=einf+EP1E0+EP1E1+EP1EC
        EPSILON2=EP2E0+EP2E1+EP2EC+EP2EI
        ARG1=EPSILON1*(1.0,0.0) + EPSILON2*(0.0,1.0)
        NEFF=REAL(SQRT(ARG1))
        RETURN
        END SUBROUTINE sALGAAS2
```

In(1-X)Ga(X)As(Y)P(1-Y)

```
      SUBROUTINE sInGaAsP(XLAMBDA,X,Y,XN,I)
      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,Y,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
      INTEGER, INTENT(IN)  :: I
```

```
      REAL(8) :: HV,A,B,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4

      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using InGaAsP Material System'
      !MM-Notify

!  10 WRITE(*,*)' INPUT X,Y AND PHOTON WAVELENGTH FOR InGaAsP'
!     WRITE(*,*) ' X=, Y=, LAMBDA='
!     READ (*,*) X,Y,XLAMBDA
!     WRITE(*,*) ' InGaAsP'
      HV=1.24/XLAMBDA
!     WRITE(*,*) ' FOR LATTICE MATCHED, INPUT 1,--STRAIN INPUT 2'
!     WRITE(*,*) ' INPUT = ?'
!     READ (*,*) I
      IF (I.EQ.1) THEN
        A=8.4-3.4*Y
        B=6.6+3.4*Y
        EO=1.35-0.72*Y+0.12*(Y**2)
        EDD=1.466-0.557*Y+0.129*Y**2
      ELSE IF (I.EQ.2) THEN
        A=(1-X)*Y*5.14+(1-X)*(1-Y)*8.4+X*Y*6.3+X*(1-Y)*22.25
        B=(1-X)*Y*10.15+(1-X)*(1-Y)*6.6+X*Y*9.4+X*(1-Y)*0.9
!c      EO=(1-X)*Y*0.36+(1-X)*(1-Y)*1.35+X*Y*1.424+X*(1-Y)*2.74
        EO=1.35-0.72*Y+0.12*(Y**2)
        EDO=(1-X)*Y*0.38+(1-X)*(1-Y)*0.11+X*Y*0.34+X*(1-Y)*0.08
        EDD=EDO+EO
      ELSE
      END IF
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/(EDD))**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
```

```
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
      END SUBROUTINE sInGaAsP
```

Al(X)Ga(Y)In(1-X-Y)As

```
      SUBROUTINE sAlGaInAs(LAMBDA,XX,QY,XN)
      USE INFO_MOD

      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: XX,QY,LAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
      REAL(8) :: HV,EO,EDO,XO,EDD,XSO,A,B,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using AlGaInAs Material System'
      !MM-Notify

!  10 WRITE(*,*) ' INPUT XX, QY AND PHOTON WAVELENGTH FOR AlGaInAs'
!     WRITE(*,*) ' XX= , QY=, LAMBDA='

!     READ (*,*) XX,QY,LAMBDA
!C    XLAMBDA=LAMBDA*1000.D0
!C    X=XX/0.48
!C    IF ((X.LT.0.3).AND.(LAMBDA.EQ.1.3)) THEN
!C    XN=DSQRT((1.-XX-QY)*14.6+QY*13.2+XX*10.06)-0.17d0
!C    ELSEIF ((X.LT.0.3).AND.(LAMBDA.EQ.1.55)) THEN
!C    XN=DSQRT((1.-XX-QY)*14.6+QY*13.2+XX*10.06)-0.31D0
```

```
!C    PRINT*, ' XN=',XN
!C    ELSEIF (X.GE.0.3) THEN
!C    A=9.689-1.012*X
!C    B=1.590-0.376*X
!C    C=1102.4-702.0*X+330.4*(X*X)
!C    XN=DSQRT(A+((B*XLAMBDA**2)/(XLAMBDA**2-C**2)))
!C    ELSE
!C    ENDIF

!     WRITE(*,*) ' AlGaInAs'
      HV=1.24D0/LAMBDA
      EO=0.75D0+1.548D0*XX
      EDO=XX*0.28+QY*0.34+(1-XX-QY)*0.38
      XO=HV/EO
      EDD=EDO+EO
      XSO=HV/EDD
      A=XX*25.30+QY*6.30+(1-XX-QY)*5.14
      B=XX*(-0.80)+QY*9.40+(1-XX-QY)*10.15
      F1=(XO**(-2.D0))*(2.D0-((1.D0+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2.D0))*(2.D0-((1.D0+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/EDD)**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' THE REFRACTIVE INDEX IS=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
      END SUBROUTINE sAlGaInAs
```

Al(X)Ga(1-X)In(Y)As(1-Y) 2

```
SUBROUTINE sAlGaInAs2(LAMBDA,XX,QY,XN)
USE INFO_MOD

implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
REAL(8), INTENT(IN)  :: XX,QY,LAMBDA
REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
REAL(8) :: HV,EO,EDO,XO,EDD,XSO,A,B,C,X,XLAMBDA
!MM-Notify
WRITE(STDOUT_RD,*) 'Using AlGaInAs (Mondrys) Material System'
!MM-Notify
XLAMBDA=LAMBDA*1000.D0
 X=XX/0.48
 IF ((X < 0.3d0).AND.(LAMBDA == 1.3d0)) THEN
 XN=SQRT((1.-XX-QY)*14.6+QY*13.2+XX*10.06)-0.17d0
 ELSE IF ((X < 0.3d0).AND.(LAMBDA == 1.55d0)) THEN
 XN=SQRT((1.-XX-QY)*14.6+QY*13.2+XX*10.06)-0.31D0
 ELSE IF ((X < 0.3d0).AND.(LAMBDA == 1.4d0)) THEN
 XN=SQRT((1.-XX-QY)*14.6+QY*13.2+XX*10.06)-0.226d0
 ELSE IF (X >= 0.3) THEN
 A=9.689-1.012*X
 B=1.590-0.376*X
 C=1102.4-702.0*X+330.4*(X*X)
 XN=SQRT(A+((B*XLAMBDA**2)/(XLAMBDA**2-C**2)))
 ELSE
 END IF
 RETURN
 END SUBROUTINE sAlGaInAs2
```

Al(X)Ga(1-X)P(Y)Sb(1-Y)

```
      SUBROUTINE sAlGaPSb(XLAMBDA,X,Y,XN)
      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,Y,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I

      REAL(8) :: HV,A,B,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using AlGaPSb Material System'
      !MM-Notify
!  10 WRITE(*,*) ' INPUT X,Y AND PHOTON WAVELENGTH FOR AlGaPSb'
!     WRITE(*,*) ' X=, Y=, LAMBDA='
!     READ (*,*) X,Y,XLAMBDA
!     WRITE(*,*) ' AlGaPSb'
      HV=1.24/XLAMBDA
      A=(1-X)*Y*22.25+(1-X)*(1-Y)*4.05+X*Y*24.10+X*(1-Y)*59.68
      B=(1-X)*Y*0.9+(1-X)*(1-Y)*12.66+X*Y*(-2.0)+X*(1-Y)*(-9.53)
!c    EO=(1-X)*Y*2.74+(1-X)*(1-Y)*0.72+X*Y*3.58+X*(1-Y)*2.22
      EO=0.885+2.33*X-1.231*(X**2)
      EDO=(1-X)*Y*0.08+(1-X)*(1-Y)*0.82+X*Y*0.07+X*(1-Y)*0.65
      EDD=EDO+EO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/EDD)**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
```

```
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
      END SUBROUTINE sAlGaPSb
```

Al(X)Ga(1-X)As(Y)Sb(1-Y)

```
      SUBROUTINE sAlGaAsSb(XLAMBDA,X,Y,XN)

      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,Y,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
      REAL(8) :: HV,A,B,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using AlGaAsSb Material System'
      !MM-Notify
!  10 WRITE(*,*) ' INPUT X,Y AND PHOTON WAVELENGTH FOR AlGaAsSb'
!     WRITE(*,*) ' X=, Y=, LAMBDA='
!     READ (*,*) X,Y,XLAMBDA
!     WRITE(*,*) ' AlGaASSb'
      HV=1.24/XLAMBDA
      A=(1-X)*Y*6.30+(1-X)*(1-Y)*4.05+X*Y*25.30+X*(1-Y)*59.68
      B=(1-X)*Y*9.4+(1-X)*(1-Y)*12.66+X*Y*(-0.8)+X*(1-Y)*(-9.53)
!C    EO=(1-X)*Y*1.42+(1-X)*(1-Y)*0.72+X*Y*2.95+X*(1-Y)*2.22
      EO=0.829+1.822*X-0.22*(X**2)
      EDO=(1-X)*Y*0.34+(1-X)*(1-Y)*0.82+X*Y*0.28+X*(1-Y)*0.65
```

```
      EDD=EDO+EO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/EDD)**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
    RETURN
   END SUBROUTINE sAlGaAsSb
```

Al(X)In(1-X)As(Y)Sb(1-Y)

```
  SUBROUTINE sAlInAsSb(XLAMBDA,X,Y,XN)

    USE INFO_MOD

    implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,Y,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
```

```
      REAL(8) :: HV,A,B,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4

     !MM-Notify
      WRITE(STDOUT_RD,*) 'Using AlInAsSb Material System'
      !MM-Notify

!  10 WRITE(*,*) ' INPUT X,Y AND PHOTON WAVELENGTH FOR AlInAsSb'
!     WRITE(*,*) ' X=, Y=, LAMBDA='
!     READ (*,*) X,Y,XLAMBDA
!     WRITE(*,*) ' AlInAsSb'
      HV=1.24/XLAMBDA
      A=(1-X)*Y*5.14+(1-X)*(1-Y)*7.91+X*Y*25.30+X*(1-Y)*59.68
      B=(1-X)*Y*10.15+(1-X)*(1-Y)*13.07+X*Y*(-0.8)+X*(1-Y)*(-9.53)
!C    EO=(1-X)*Y*0.36+(1-X)*(1-Y)*0.17+X*Y*2.95+X*(1-Y)*2.22
      EO=-0.173+4.014*X-1.418*(X**2)
      EDO=(1-X)*Y*0.38+(1-X)*(1-Y)*0.81+X*Y*0.28+X*(1-Y)*0.65
      EDD=EO+EDO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/EDD)**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='
!     READ (*,*) I

!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
```

```
      END SUBROUTINE sAlInAsSb
```

Ga(X)In(1-X)P(Y)Sb(1-Y)

```
      SUBROUTINE sGaInPSb(XLAMBDA,X,Y,XN)
      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,Y,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
      REAL(8) :: HV,A,B,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using GaInPSb Material System'
      !MM-Notify
!  10 WRITE(*,*) ' INPUT X,Y AND PHOTON WAVELENGTH FOR GaInPSb'
!     WRITE(*,*) ' X=, Y=, LAMBDA='
!     READ (*,*) X,Y,XLAMBDA
!     WRITE(*,*) ' GaInPSb'
      HV=1.24/XLAMBDA
      A=(1-X)*Y*8.4+(1-X)*(1-Y)*7.91+X*Y*22.25+X*(1-Y)*4.05
      B=(1-X)*Y*6.6+(1-X)*(1-Y)*13.07+X*Y*0.9+X*(1-Y)*12.66
!C    EO=(1-X)*Y*1.35+(1-X)*(1-Y)*0.17+X*Y*2.74+X*(1-Y)*0.72
      EO=1.326-0.018*X-0.34*(X**2)
      EDO=(1-X)*Y*0.11+(1-X)*(1-Y)*0.81+X*Y*0.08+X*(1-Y)*0.82
      EDD=EDO+EO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/EDD)**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)

!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
```

```
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
      END SUBROUTINE sGaInPSb
```

AlAs(X)Sb(1-X)

```
      SUBROUTINE sAlAsSb(XLAMBDA,X,XN)

      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
      REAL(8) :: HV,A,B,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using AlAsSb Material System'
      !MM-Notify
!  10 WRITE(*,*) ' INPUT X,Y AND PHOTON WAVELENGTH FOR AlAsSb'
!     WRITE(*,*) ' X= ?,  LAMBDA='
!     READ (*,*) X,XLAMBDA
!     WRITE(*,*) ' AlAsSb'
      HV=1.24/XLAMBDA
      A=(1-X)*59.68+X*25.30
      B=(1-X)*(-9.53)+X*(-0.80)
      EO=1.7+0.53*X
      EDO=(1-X)*0.65+X*0.28
```

```
      EDD=EDO+EO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/EDD)**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!      ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
      END SUBROUTINE sAlAsSb
```

Al(x)Ga(1-x))0.5In(0.5)P

```
      SUBROUTINE sAlGaInP(XLAMBDA,X,XN)
      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
      REAL(8) :: HV,EO,ED
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using AlGaInP Material System'
      !MM-Notify
```

```
!  10 WRITE(*,*) ' (AlxGa(1-x))0.5In0.5P--Eg=1.9+0.6*X'
!     WRITE(*,*) ' INPUT X AND PHOTON WAVELENGTH FOR AlGaInP'
!     WRITE(*,*) ' X= ?,  LAMBDA='
!     READ (*,*) X,XLAMBDA
!     WRITE(*,*) ' (AlxGa(1-x))0.5In0.5P--Eg=1.9+0.6*X'
      HV=1.24/XLAMBDA
      EO=3.39+0.62*X
      ED=28.07+1.72*X
      XN=SQRT((EO*ED/(EO**2-HV**2))+1)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN

!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
      END SUBROUTINE sAlGaInP
```

In(1-x)Ga(x)As [matched to InP]

```
      SUBROUTINE sInGaAs1(XLAMBDA,X,XN)
      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
      REAL(8) :: A,B,HV,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using InGaAs-1 Material System'
      !MM-Notify
!  10 WRITE(*,*) ' In(1-x)Ga(x)As/InP'
```

```
!     WRITE(*,*) ' INPUT X AND PHOTON WAVELENGTH FOR In(1-x)Ga(x)As'
!     WRITE(*,*) ' X= ?,  LAMBDA='
!     READ (*,*) X,XLAMBDA
!     WRITE(*,*) ' In(1-x)Ga(x)As/InP'
      A=(1-X)*5.14+X*6.30
      B=(1-X)*10.15+X*9.40
      HV=1.24/XLAMBDA
      EO=0.324+0.7*X+0.4*(X**2)
      EDO=(1-X)*0.38+X*0.34
      EDD=EDO+EO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/(EDD))**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='

!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
      RETURN
      END SUBROUTINE sInGaAs1
```

In(1-x)Ga(x)As [matched to GaAs]

```
      SUBROUTINE sInGaAs2(XLAMBDA,X,XN)
      USE INFO_MOD
```

```
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: X,XLAMBDA
      REAL(8), INTENT(OUT) :: XN
!     INTEGER :: I
      REAL(8) :: A,B,HV,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using InGaAs-2 Material System'
      !MM-Notify
!  10 WRITE(*,*) ' In(1-x)Ga(x)As/GaAs'
!     WRITE(*,*) ' INPUT X AND PHOTON WAVELENGTH FOR In(1-x)Ga(x)As'
!     WRITE(*,*) ' X= ?,  LAMBDA='
!     READ (*,*) X,XLAMBDA
!     WRITE(*,*) ' In(1-x)Ga(x)As/GaAs'
      A=(1-X)*5.14+X*6.30
      B=(1-X)*10.15+X*9.40
      HV=1.24/XLAMBDA
      EO=0.36+0.509*X+0.555*(X**2)
      EDO=(1-X)*0.38+X*0.34
      EDD=EDO+EO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/(EDD))**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
      X4=X3+B
      XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
```

```
!  20 RETURN
      RETURN
      END SUBROUTINE sInGaAs2
```

Ga(x)In(1-x)P [matched to GaAs]

```
      SUBROUTINE sGaInP(XLAMBDA,X,XN)
      USE INFO_MOD
      implicit none
!mm   IMPLICIT REAL*8 (A-H,O-Z)
      REAL(8), INTENT(IN)  :: XLAMBDA, X
      REAL(8), INTENT(OUT) :: XN
!     REAL(8) :: X,XLAMBDA
!     INTEGER :: I
      REAL(8) :: A,B,HV,EO,EDO,EDD,XO,XSO,F1,F2,X1,X2,X3,X4
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using GaInP Material System'
      !MM-Notify
!  10 WRITE(*,*) ' GaxIn(1-x)P/GaAs'
!     WRITE(*,*) ' INPUT X AND PHOTON WAVELENGTH FOR GaxIn(1-x)P'
!     WRITE(*,*) ' X= ?,  LAMBDA='
!     READ (*,*) X,XLAMBDA
!     WRITE(*,*) ' GaxIn(1-x)P/GaAs'
      A=(1-X)*8.4+X*22.25
      B=(1-X)*6.6+X*0.9
      HV=1.24/XLAMBDA
!c    EO=1.351+0.643*X+0.786*(X**2)
      EO=1.35*(1-X)+2.74*X
      EDO=(1-X)*0.11+X*0.08
      EDD=EDO+EO
      XO=HV/EO
      XSO=HV/EDD
      F1=(XO**(-2))*(2-((1+XO)**0.5)-((1-XO)**0.5))
      F2=(XSO**(-2))*(2-((1+XSO)**0.5)-((1-XSO)**0.5))
      X1=((EO/(EDD))**(1.5))/2
      X2=F1+X1*F2
      X3=A*X2
```

```
     X4=X3+B
!c    EO=(3.39+0.62*X)
!c    ED=(28.07+1.72*X)
!c    X4=(EO*ED/(EO**2-HV**2))+1
     XN=SQRT(X4)
!     WRITE(*,*) ' REFRACTIVE INDEX=', XN
!     WRITE(*,*) ' FOR NEW INPUT I=1, STOP I=2'
!     WRITE(*,*) ' I='
!     READ (*,*) I
!     IF (I.EQ.1) THEN
!       GO TO 10
!     ELSE IF (I.EQ.2)  THEN
!       GO TO 20
!     ELSE
!     END IF
!  20 RETURN
     RETURN
     END SUBROUTINE sGaInP
```

InGaAsP using PL [matched to InP]

```
     (See reference 8 in Section 3.3)
     SUBROUTINE sInGaAsPPL(WVL,XPERCENT,EFFINDX)
       implicit none
       REAL(8), INTENT(IN)  :: WVL, XPERCENT
       REAL(8), INTENT(OUT) :: EFFINDX

       REAL(8)              :: e1,e2,ep,e,a1,a2,xtemp
       xtemp=0.00000000000000
       xtemp=XPERCENT
       e1=2.5048
       e2=0.1638
       ep=1.24/xtemp
       e =1.24/WVL
```

```
        a1=13.3510-5.4554*ep+1.2332*(ep**2)
        a2=0.7140-0.3606*ep

        EFFINDX=(1+(a1/(1-((e/(ep+e1))**2)))+(a2/(1-((e/(ep+e2))**2))))**0.5
        RETURN
      END SUBROUTINE sInGaAsPPL
```

InGaAsP [matched to InP]

```
      SUBROUTINE sInGaAsPInP(WVL, XPERCENT, EFFINDX)

      USE INFO_MOD
      implicit none

      REAL(8), INTENT(IN)  :: WVL, XPERCENT
      REAL(8), INTENT(OUT) :: EFFINDX
!
      REAL(8) :: H,A1,A2,EP,E1,E2,C,EC,TERM1,TERM2
      REAL(8) :: EPSILON,E
      !MM-Notify
      WRITE(STDOUT_RD,*) 'Using InGaAsPInP Material System'
      !MM-Notify
      IF (WVL <= XPERCENT) THEN
        WRITE(STDOUT_RD,*) ' ERROR: This Material System not valid for lambda <=
lambdapl'
WRITE(STDOUT_RD,*) WVL, XPERCENT
        WRITE(STDOUT_RD,*) ' ERROR: Please use the InGaAsP MatSys '
        RETURN
      END IF

! All energies are in Electron Volts
! Speed of light 'C', Plank's constant 'H' and electron charge 'EC'

        C = 2.9979E8
        H = 6.6261E-34
        EC = 1.6022E-19
        EP = (H*C)/(XPERCENT*1E-6*EC)
        A1 = 13.3510 - (5.4554*EP) + 1.2332*(EP**2)
```

```
  A2 = 0.7140 - 0.3606*EP
  E1 = 2.5048
  E2 = 0.1638
  E = (H*C)/(WVL*1E-6*EC)
  TERM1 = A1/(1 - ((E/(EP + E1))**2))
  TERM2 = A2/(1 - ((E/(EP + E2))**2))
  EPSILON = 1 + TERM1 + TERM2
  EFFINDX = SQRT(EPSILON)
RETURN
END SUBROUTINE sInGaAsPInP
```