Low-distortion hybrid optical shuffle concept

Marc P. Christensen, Predrag Milojkovic, and Michael W. Haney

Department of Electrical and Computer Engineering, George Mason University, Fairfax, Virginia 22030-4444

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A hybrid micro–macro-optical shuffle interconnection approach is described. The new concept minimizes distortion in multichip smart-pixel shuffle interconnection systems that use macro-optics to link dense arrays of vertical-cavity surface-emitting laser (VCSEL) sources and matching arrays of detectors. The typical narrow-beam cones of VCSEL's are exploited by use of beam-deflecting micro-optics to create an optical system that is symmetric about its aperture. Since symmetric systems are well known to cancel distortion, this novel concept provides the means to achieve the required high degree of interchip registration accuracy.

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Free-space optical interconnections are projected to provide bandwidth densities of the order of a terabit per second per square centimeter.[1] Scalable multiterabit interconnection fabrics can be achieved with multiple optoelectronic integrated circuits linked to one another in a global high-bisection-bandwidth pattern,[2] as depicted in Fig. 1. In this configuration each lens links the optical input–output (I/O) from a single chip located at the lens's focal plane to all chips in the receiving array. Clusters of emitters, such as vertical-cavity surface-emitting lasers (VCSEL's), and detectors are imaged onto corresponding clusters on other chips such that many point-to-point links are established in an interleaved optical shuffle pattern across the multichip plane. Monolithically integrated VCSEL–detector arrays, with emitter and receiver elements of 10 and 50 μm, respectively, and with element-to-element spacing as small as 100 μm, have been evaluated in a prototype shuffle system.[3] With such I/O density and pitch, the global optical interconnection module must provide flat, high-resolution, nearly distortion-free image fields across a wide range of ray angles to avoid cross talk and maintain high link efficiency.

Although modern optical design and manufacture techniques provide approaches to achieving high resolution, registration accuracy is more problematic. Registration accuracy can be defined as the difference between the location of the image of a VCSEL and the location of its corresponding detector. Registration must be maintained at a level less than the size of the detector ($\sim$50 μm) across the entire multichip plane ($\sim$10 cm wide). Distortion in the optical system will cause poor registration performance in the system. It is well known that holosymmetric systems (systems with radial symmetry about their optical axis and symmetry along their optical axis about the aperture) cancel distortion.[4–6] Although the interconnection system depicted in Fig. 1 appears to be symmetric, the aperture of the system is not at the midpoint between the transmitting and the receiving lens planes. As depicted in Fig. 2(a), this asymmetry results from the normal orientation of the VCSEL beams, parallel to the optical axis. To cancel distortion one must move the effective aperture to the midpoint between the transmitting and the receiving lens planes. Unfortunately, placing the aperture at this location causes the narrow VCSEL beams to miss the aperture entirely or to be severely vignetted. This vignetting can be corrected if the VCSEL's are steered to emit at angles that cause them to propagate through the new central aperture, as shown in Fig. 2(b). This correction is possible only because the VCSEL's have narrow-beam divergence. Once the VCSEL's have been steered through the central aperture no physical aperture is needed at this location. The proposed method for implementing the beam steering is depicted in Fig. 2(c). A linear diffraction grating or prism is placed above each VCSEL and detector. In this configuration the beam of each VCSEL is deflected by an angle that causes its beam to cross the optical axis at the halfway point between the transmitting and the receiving lenses. To maintain symmetry and hence eliminate distortion one must employ identical microelements at the detector plane as well, as depicted in Fig. 2(c).

Figure 3 shows the deflection angle, ϕ, as it relates to the geometry of the other variables of the

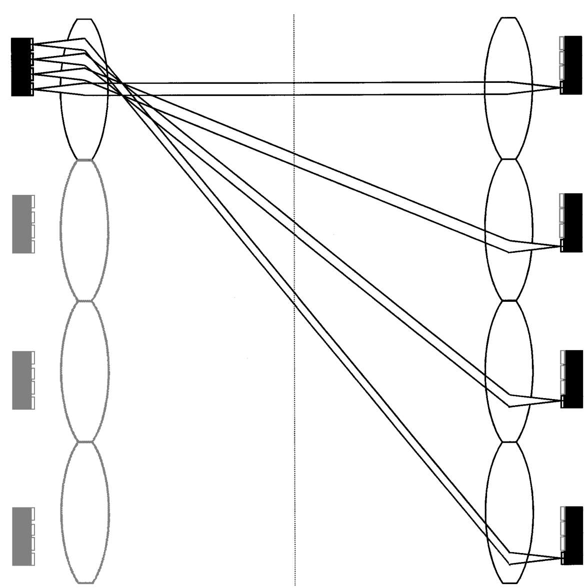

Fig. 1. Schematic side view of global optical shuffle interconnection. There is one lens over each chip. Each chip communicates with every chip in the receiving array. The system can be folded along the dotted line to facilitate packaging and alignment.[3]

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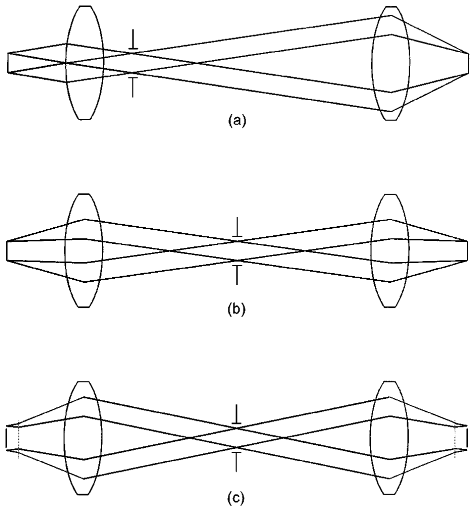

Fig. 2. VCSEL beams as they pass through the on-axis interconnection system. The VCSEL planes are on the left, and the detector planes are on the right. (a) telecentric interconnection system, (b) symmetric interconnection system, (c) symmetric interconnect system with auxilliary microbeam deflection elements.

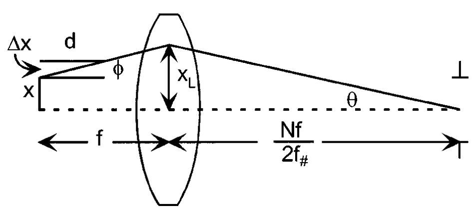

Fig. 3. Geometry for deflection-angle calculation.

interconnect system for the on-axis cluster. The off-axis distance of the VCSEL under consideration is x, the focal length of the lens is f, $f_{\#}$ is the ratio of this focal length to the lens diameter, θ is the angle of the collimated beam with respect to the optical axis from the VCSEL, N is the number of chips on one side of the square array (see Fig. 1), x_L is the height at which the deflected beam hits the lens plane, d is the distance from the VCSEL plane to the diffraction grating, and Δx is the effective displacement of a VCSEL emitting parallel to the optical axis.

In Fig. 3 there are two congruent relationships:

$$\tan\theta = \frac{x}{f} = \frac{2x_L f_{\#}}{Nf}, \tag{1}$$

$$\tan\phi = \frac{\Delta x}{d} = \frac{(x_L - x)}{f}. \tag{2}$$

From Eqs. (1) and (2), the required deflection angle, as a function of x, is

$$\phi = \arctan\left[\frac{x}{f}\left(\frac{N}{2f_{\#}} - 1\right)\right]. \tag{3}$$

Figure 4 demonstrates that as x varies along the cluster the deflection angle varies in such a way as to make the collection of prisms or gratings act as a negative lens. The focal length (f_{eff}) of this effective lens is given by

$$f_{\text{eff}} = \frac{f}{(N/2f_{\#}) - 1}. \tag{4}$$

The above analysis can be extended to the general multichip and off-axis case for interchip connections as depicted in Fig. 1. In this case the aperture remains at the midpoint between the two lenses, but the lens offset breaks the condition of holosymmetry. Instead, this system has a single plane of symmetry.[7] However, placing the system aperture at the midpoint of the transmitting and the receiving lens planes still provides a high degree of symmetry in the system and is therefore worth pursuing. Figure 5 depicts the off-axis interconnection setup. There is a separate aperture for each lens pair in the interconnection module, and both clusters utilize the same region of the transmitting lens.

The geometry for analyzing the off-axis interconnection is depicted in Fig. 6. The variables retain their original meanings in this figure, with the addition of (1) the lateral distance from the lens center to the center of the cluster under examination, x_c; (2) the offset from the lens center to the aperture center (half the lateral distance to the receiving lens), x_{off}; and (3) two beam angles, θ_1 and θ_2. The angle from the

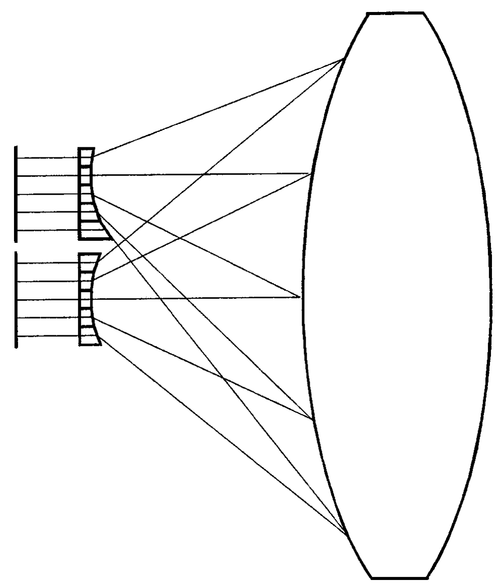

Fig. 4. A collection of deflecting prisms or gratings forms a discrete negative lens.

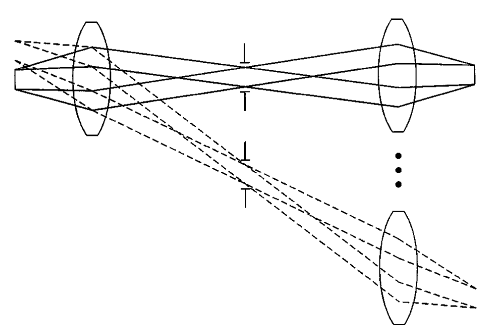

Fig. 5. Multichip off-axis interconnection with VCSEL beam deflection to effect a central system aperture.

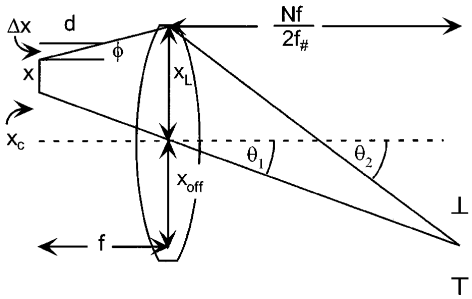

Fig. 6. Geometry for off-axis analysis.

center of the cluster is θ_1, and the angle of the beam from the element under question is θ_2.

In this case the congruence relationships are

$$\tan\theta_1 = \frac{x_c}{f} = \frac{2x_{\mathrm{off}}f_\#}{Nf}\,, \tag{5}$$

$$\tan\theta_2 = \frac{x_c + x}{f} = \frac{2(x_{\mathrm{off}} + x_L)f_\#}{Nf}\,, \tag{6}$$

$$\tan\phi = \frac{\Delta x}{d} = \frac{(x_L - x - x_c)}{f}\,. \tag{7}$$

Using Eqs. (5)–(7) to solve for the diffraction angle as a function of x, we obtain

$$\phi = \arctan\left[\frac{1}{f}\left(\frac{Nx}{2f_\#} - x - x_c\right)\right]. \tag{8}$$

This is the same as Eq. (3), except that an angular offset proportional to x_c has been added.

Inspection of Figs. 3 and 5 reveals that the effective size of the cluster is slightly increased. This effect stems from the finite distance, d, between the VCSEL and the diffraction grating. For simplicity one can examine the on-axis case in detail. The fractional increase in the cluster size is given by

$$\frac{\Delta x}{x} = \frac{d}{f}\left(\frac{N}{2f_\#} - 1\right). \tag{9}$$

Assuming $N = 4$ and an $f/1$ optical system, the term in parentheses is equal to 1. The remaining term (d/f) is a small magnification, i.e., an increase of the order of 5% when $f = 1$ cm and $d = 0.5$ mm. If the optical layout uses a regular grid pattern, this small cluster growth poses a problem. However, since the optical I/O in the proposed approach is laid out on a self-similar fractal grid geometry,[8] the small magnification of cluster size does not create any overlap between adjacent clusters.

The symmetry of the new hybrid optical shuffle concept minimizes distortion; this is the most stringent requirement of the high-density optical interconnection module. To achieve this minimization, this approach takes advantage of the narrow-beam nature of VCSEL's to effect a symmetric interconnection system for each point-to-point link in the shuffle pattern, without the need for any real apertures in the system. The net result is a hybrid micro–macro-optical approach that has optimum light efficiency and achieves high registration accuracy across the multichip smart pixel. The required micro-optical elements amount to a discrete negative lens above each I/O cluster. Such elements can be readily fabricated with established diffractive optical techniques. As these elements are simple gratings or microprisms, the absolute alignment of such elements is not a critical aspect of this concept. Furthermore, since resolution requirements can be easily achieved by use of detectors that are somewhat larger than the VCSEL's (50 as opposed to 10 μm), the overall design of the macro-optical lenses above the array will be significantly simplified.

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