Analysis of free-space optical interconnects for the three-dimensional optoelectronic stacked processor

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Abstract

Performance of free-space optical interconnect for the three-dimensional optoelectronic stacked processor (3DOESP) has been analyzed. The wave propagation in the optical interconnection system has been investigated by utilizing rigorous scalar diffraction theory. The effects of ghost talk caused by the superposition of the delayed reflections of the original signal due to the multiple propagation of the wave between the vertical-cavity surface-emitting laser (VCSEL) and metal-semiconductor-metal (MSM) detector have been analyzed. The conducted study indicates that even in the presence of significant amount of ghost talk a high performance free-space optical interconnect can be realized in this system by employing a receiver architecture that allows for DC level adjustment of the signal at the input of the transimpedance amplifier stage. © 2002 Published by Elsevier Science B.V.

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1. Introduction

Current electronic interconnection technology cannot keep pace with the continuous performance improvement of VLSI circuits enabled by the scaling down of device feature size and the increase of integration density and processor clock speed. The bandwidth of the electronic interconnection is limited by the inherent characteristics of the electronic circuit and its two-dimensional (2D) topology. Optical interconnection using 2D dense optoelectronic device arrays and the third dimension for beam propagation has been proved to be a solution to this problem [1,2]. In the last decade, technologies such as array fabrication of vertical-cavity surface-emitting lasers (VCSEL) and metal-semiconductor-metal (MSM) detectors, hybrid integration of GaAs optoelectronic device arrays with silicon transmitter and receiver circuits, fabrication and integration of micro-optical components, system packaging, etc. have experienced tremendous progress and improvement [3–11]. Moreover, advances in 3D VLSI packaging technologies have enabled the integration of multiple
electronic chips into a smaller volume by stacking them on top of each other [12,13]. By combining the powerful processing capability of the 3D silicon chip stacks and the high bandwidth of the free space optical modules, a scalable optoelectronic switching system [14] (Fig. 1) has been built under the 3D optoelectronic stacked processor (3DOESP) consortium. In this system, a folded micro-/macro-optical module with a concave reflection mirror that can tolerate a relative large misalignment of the components has been designed.

The interconnection density and the data bit-rate of the free space interconnect systems are affected by the maximum optical power incident on the photodetector and the associated circuits, which, in turn, depends on the power of the emitter and the efficiency of the optical system. It is desired that all the energy emitted from the laser is confined within the micro-optical channel that guides light from the VCSEL to the detector. However, due to the diffraction of the beam in free-space propagation, part of the energy may be clipped by the aperture of the micro lens. Clipping of the beam at the aperture not only causes a loss of energy and thus decreases the efficiency of the optical system, but also results in cross talk if the beam is incident on the adjacent detectors. Furthermore, when the surfaces of the detector and the VCSEL have high reflection coefficients the light will bounce back and forth between the two devices, a phenomenon called ghost talk [15], and may therefore limit the maximum speed of operation. For these reasons, accurate analysis of the beam propagation through the optical system is significant for characterization of the optical link. Three numerical models, namely ray tracing, Gaussian beam propagation, and scalar diffraction theory have been utilized for this purpose [16]. When subwavelength structures are involved, the utilization of vector diffraction theory that takes into account the polarization dependence of diffraction is necessary for achieving accurate characterization of the optical interconnect [17,18]. For the aforementioned modeling tools, it has been shown that simulation based on the rigorous scalar diffraction theory is more accurate and matches well with the experimental results. In this paper, the scalar diffraction theory has been employed to analyze the microbeam propagation in folded hybrid micro-/macro-optical system. The effects of ghost talk on the performance of high-speed free-space interconnect have been investigated via SPICE simulations that take into account the high

![Fig. 1. Schematic diagram of the 3D optoelectronic processor using 3D chip stacks and free-space optical interconnects.](image-url)
reflectivity of the optoelectronic devices. By using a receiver architecture that allows for DC level adjustment of the signal at the input of the transimpedance amplifier stage, the ghost talk effect in this system can be compensated.

2. Optical Simulation

Our demonstration system (Fig. 1) includes three assembled 3D VLSI functional chip stacks and an optical module for global communication. It is designed for data switching with low power, small volume, high-density, and high bandwidth. Each stack consists of 16 VLSI chips and a single 16 × 16 VCSEL/MSM detector array flip-chip bonded on top of the chip stack and each chip in the stack supports 16 optical I/Os at 1 Gb/s. Furthermore, the 16 × 16 electronic crossbar switch that can arbitrarily route data packets between its inputs/outputs and the associated driver/receiver circuits have all been implemented in the same electronic layer. Processors with more powerful functionality can also be embedded into the chip for various application specific systems. The chips in the central stack are perpendicular to those in the other two stacks so that a signal in one end stack can be routed to any chip on the opposite end stack. To realize communication with both the left and the right neighbors, the optoelectronic array is separated into two logical halves and the beams in the two halves are directed to the left and the right neighbors, respectively. The main advantages of this optical interconnection layer are that it provides means of implementing a global communication among neighboring stacks and achieves more scalable and higher bandwidth interconnect compared to the all-electronic systems. The adoption of a 3D architecture and the use of chip stack enable a significant footprint area reduction of the overall system in comparison with the 2D implementation. The general requirements of a high-density free-space optical system are high resolution (small spot size), low loss (high link efficiency), low cross talk, large field of view, low cost, small volume, large misalignment tolerance, cascadability (modular design). To satisfy these requirements, a novel hybrid micro/macro-optical system using a concave reflection mirror is designed. The methodology adopted in the system design is very versatile and can therefore be easily extended to accommodate the design constraints of similar applications.

The schematic diagram of the optical module that interconnects the two neighboring stacks is shown in Fig. 2. The system is a combination of a pair of small field, low f/number microlenses, a pair of large field, high f/number macrolenses, a pair of deflecting elements (prisms or gratings), and a concave reflection mirror. In this system, the microlens array collimates the beams emitting from the VCSELs and refocuses the beams onto the detectors whereas the macrolenses adjust the interconnection distance. Both the microlens and macrolens are used at infinite conjugates and the beams are focused at the common focal plane of the two macrolenses. The performance requirements on the macrolenses are greatly reduced due to the fact that the microlenses provide high resolution and therefore the macrolenses need only resolve the aperture of the microlenses. By combining the strengths of macro- and micro-optical configurations the system not only outperforms the conventional macro-optical imaging in applications that utilize large dilute arrays with large field but also overcomes the cross talk imposed limitations on the interconnect length that are present in purely microoptical imaging.

Since the choice of optical elements has significant performance impact, a careful consideration of various performance trade-offs imposed by the selected optical components is essential for achieving a high performance system. In our system the deflecting elements have been inserted in the collimated beam path between the micro- and macro-lenses so that they do not generate additional aberrations. Since the aberrations of an imaging system increase with increasing numerical aperture, it is helpful to utilize a large f/number macrolens to improve the imaging quality. The microlens should be chosen to match the VCSEL beam property so that there is no beam clipping at the aperture of the microlens. However, in this configuration the small f/number microlenses that are necessary for satisfying the VCSELs beam...
characteristics have severe mechanical tolerance constraints and hence a small alignment error of the microlens may greatly deteriorate the images. To compensate the aberrations caused by the misalignment of the microlens, instead of using a flat reflection mirror, a concave reflection mirror with radius close to the focal length of the macrolens has been employed. Both the f/2.9 macrolens (KPX088) and the concave mirror (KPC031, with reflection coating on the concave side) have been selected among readily available Newport optical components.

Based on Huygen’s scalar diffraction theory, a generalized form of paraxial wave optics [19] has been developed to analyze the wave propagation through an arbitrary complex optical system consisting of a cascaded series of optical elements. The paraxial optical system can be characterized by an overall ray matrix or ABCD matrix, which can be derived according to geometric optics. The wave propagation from plane $z_1$ to plane $z_2$ can be mathematically expressed by

$$u_2(x_2, y_2) = -\frac{j}{\lambda B} \int \int u_1(x_1, y_1) e^{jkL} \exp \left\{ (jk/2B)[A(x_1^2 + y_1^2) + D(x_2^2 + y_2^2) - 2(x_1x_2 + y_1y_2)] \right\} \, dx_1 \, dy_1$$

in which $u_1(x_1, y_1)$ and $u_2(x_2, y_2)$ are the optical field distributions in plane $z_1$ and plane $z_2$, respectively, $\lambda$ is the optical wavelength in free space, $k (= 2\pi/\lambda)$ is the wave number, $L$ is the total optical path length for a ray travelling exactly on the axis through the system, and $A$, $B$, $D$ are the elements of the ray matrix.
The radius of the concave reflection mirror is \( M = \frac{1}{C_0} \) be written as propagation through the system. The system matrix can for simplicity, we consider the coaxis wave propagation through the system. The system matrix can be arranged in reverse order from the one in which the ray encounters the components. The transfer matrix for free space is written as

\[
\begin{bmatrix}
1 & d/n \\
0 & 1 \\
\end{bmatrix},
\]

where \( d \) is the thickness and \( n \) is the refractive index of the medium, and the refraction matrix for a refractive surface takes the form

\[
\begin{bmatrix}
1 & 0 \\
-(n_t - n_i)/r & 1 \\
\end{bmatrix},
\]

where \( n_t \) and \( n_i \) are the indices of refraction for the incident medium and the transmitting medium, respectively, \( r \) is the radius of the refracting surface and it obeys the commonly used sign convention. Therefore the ray matrix of a lens is the product of the transfer and the two refraction matrices in the reverse order. The ray matrix for a reflecting surface can be readily obtained by substituting \( n_t = -n_i \) into Eq. (3).

In our system, the VCSEL works at 850 nm and the beam has a waist of 1.03 \( \mu \)m. The substrate between the VCSEL and the microlens has a thickness of about 637 \( \mu \)m and a refractive index of 1.523. The plano-convex microlens has a sag of 50 \( \mu \)m, a radius of \(-250 \) \( \mu \)m, a diameter of about 330 \( \mu \)m, and a refractive index of 1.52. The parameters for the plano-convex macrolens are \( d_4 = 5.122 \) mm, \( n = 1.51 \), and \( r_4 = -39.07 \) mm. The radius of the concave reflection mirror is \( r_5 = -75.69 \) mm. The aperture of the VCSEL and that of the detector are 5 and 50 \( \mu \)m, respectively. For simplicity, we consider the coaxis wave propagation through the system. The system matrix can be written as

\[
M = T_{10}M_9T_8M_7T_6R_6T_5M_4T_3M_2T_1,
\]

in which \( T \) is for the transfer matrix of a layer of medium, \( M \) the functional matrix of a lens, and \( R \) the reflection matrix of a mirror. The amplitude of the beam emitted from the VCSEL is assumed to single-mode Gaussian function as

\[
u_0(x, y) = \exp \left( -\frac{(x + y)^2}{w_0^2} \right),
\]

where \( w_0 \) is the waist of the Gaussian beam.

The beam emitted from the VCSEL plane is first collimated by a microlens and after the propagation through the optical channel it is finally refocused to the detector by another microlens. To check the beam clipping at the aperture of the microlenses, the ray matrices for the subsystems between the VCSEL plane and the respective front surfaces of the two microlenses can be calculated separately and substituted into Eq. (1) to observe the field distribution at the front surfaces. In our case, the energy loss due to the beam clipping is negligible. The intensity distribution when the beam arrives at the detector plane for the first time is shown in Fig. 3. The diameter is about 18 \( \mu \)m, which is much smaller than the aperture of the detector. Note that the detector has periodic electrodes deposited on the GaAs substrate, and the reflectances of the electrodes and the substrate are approximately 81% and 36%, respectively. Thus, part of the beam will be reflected from the MSM detector. The detector can be regarded as an amplitude grating with the amplitude response

\[
g(x) = \text{rect} \left( \frac{x}{a} \right) \left[ r_1 \left( \text{comb} \left( \frac{x}{p} \right) \ast \text{rect} \left( \frac{x}{p_1} \right) \right) + r_2 \left( \text{comb} \left( \frac{x}{p} \right) \ast \text{rect} \left( \frac{x - p_1}{p - p_1} \right) \right) \right],
\]

where \( a \) is the aperture size of the detector, \( r_1 = 0.9 \) and \( r_2 = 0.6 \) are the reflection coefficients of the metal and the substrate, respectively, \( p \) and \( p_1 \) are the pitch and the width of the electrodes, respectively, and the symbol \( \ast \) represents convolution. The reflected field is assumed to be the conjugate of the incident wave modulated by the grating and since the link is symmetric, the system matrix for back propagation is the same as that for front propagation. The simulated density distribution of
the reflected beam that reaches the VCSEL plane (Fig. 4) indicates that the size of beam is not bigger than the window of the device. Moreover, because of the significant distortion of the reflected beam in a real system, the coupling of the reflected beam into the VCSEL cavity mode is expected to be low. Subsequently, the effect of coupling between the reflected beam and the VCSEL has not been included in the ghost talk analysis. Since in general the VCSEL’s top surface has a high reflectance, the worst case ghost talk analysis is conducted under the assumption that the reflectivity is 100%. The beam incident on the VCSEL will be reflected and propagated through the system to the detector again. Fig. 5 shows the intensity distribution when the beam arrives at the detector for the second

Fig. 3. Intensity distribution when the beam hits the detector for the first time.

Fig. 4. Intensity distribution when the reflected beam hits the VCSEL.
time. The beam will be transmitted back and forth several times until it is totally absorbed at the detector. According to the numerical simulations and the experimental results, in this system the cross talk among adjacent channels is negligible. Therefore, the ghost talk, which is caused by superposition of signals of different delays, will have a dominant effect on the high-speed optical interconnection.

3. Effect of the ghost talk on optical interconnection

To study the effect of the ghost talk in our system, a SPICE model of the optical link that includes the characteristics of the VCSEL/MSM devices and their corresponding driver/receiver circuits and surface reflectivities has been developed. In the link, the VCSEL has a 0.45 mA threshold current and 0.8 W/A efficiency whereas the MSM detector has 0.25 A/W responsivity at 5 V. The performance of the transmitter/receiver circuits also plays a critical role in the optical interconnection. The primary criteria for transmitter/receiver are high speed, small area and low power dissipation. The current mirror style transmitter (Fig. 6) employed in our system provides the flexibility of individually controlling the threshold and modulation currents of the laser, characteristics that are very useful in prototype systems. The transimpedance receiver (Fig. 7) converts the weak photocurrent generated by the detector to voltage. Then the signal is amplified and the thresholding stage restores the CMOS logic levels of the data. The detector dark current from the input of the transimpedance amplifier is redirected with a feedback provided by an NMOS transistor and the gain of the transimpedance stage is regulated by the control voltage $V_{rs}$. Local generation of reference voltage for thresholding makes the receiver self-adapted to power fluctuations. The eye diagrams of the transmitter and the

Fig. 5. Intensity distribution when the beam hits the detector for the first time.

Fig. 6. Current mirror style transmitter.
receiver both working at 1 Gb/s are shown in Figs. 8 and 9, respectively.

The optical path length from the VCSEL to the detector is 175 mm, so the delay of a single round-trip is about 1.2 ns. The numerical simulations described in the last section indicate that 40% of the beam incident on the detector will be reflected. Assuming that the intensity of the beam hitting the detector for the first time is 1, then the intensity values for the successive delayed signals are 0.4, 0.16, etc. The total optical signal received by the detector is the summation of the original and the delayed waveforms. The responses of the MSM detector and its corresponding receiver operating at 500 Mb/s for the cases when the ghost talk is/not present in the system are summarized in Fig. 10. Depending on the delay in the optical path and the period of the transmitted signal, the effect of the reflections of one symbol can extend to next few symbols and thus cause intersymbol interference (Fig. 10(a)). This, on the other hand, results in a change of the DC level and the amplitude of the photogenerated current (Fig. 10(b)) and masquerades as a duty cycle variation (24% instead of 50%) at the output of the receiver (Fig. 10(c)). The duty cycle variation can be balanced by adjusting the DC level of the photogenerated current through the NMOS transistor at the front stage of the transimpedance amplifier. Figs. 11 and 12 depict simulations of free-space links operating at 500 Mb/s and 1 Gb/s in which the effects of ghost talk have been compensated for by increasing the bias voltage of the NMOS transistor from 1.6 to 2.05 V.

The analysis conducted in this study indicates that the intersymbol interference caused by the presence of significant amount of ghost talk in a free-space optical interconnect can be compensated for by employing a receiver architecture that allows for DC level adjustment of the photocurrent. The ghost talk effect depends on several system parameters such as the transmission efficiency, the surface reflectance of the
optoelectronic devices, and the delay of the signals incident on the detector, which is related to the optical path length from the VCSEL to the detector. Actually in the case when each channel is operated at the speed of 1 Gb/s, the ghost talk effect in the above simulation is very severe, since the single round-trip delay is close to the half of the signal period. The method has also been proved to be effective for our system when the delay is smaller.
4. Conclusion

In this paper, we have analyzed the performance of free-space optical interconnect for the three-dimensional optoelectronic stacked processor (3DOESP). The wave propagation in the optical interconnection system has been studied based on rigorous scalar diffraction theory. With suitable design of the optical system, the cross talk can be negligible. By employing a receiver architecture that allows for DC level adjustment at the input of the transimpedance amplifier stage, the effects of the ghost talk in the system can be compensated for and thus a high performance free-space optical interconnect at high speed can be achieved even in the presence of significant amount of ghost talk.

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