Three-Dimensionally Interconnected Bidirectional Optical Backplane

Gicherl Kim and Ray T. Chen, *Member, IEEE*

***Abstract*—The concept of a three-dimensionally interconnected bidirectional optical backplane for a high performance system containing multichip module boards is introduced. The backplane reported here employs one-dimensional (1-D) and two-dimensional (2-D) vertical-cavity surface-emitting laser (VCSEL), and photodetector arrays as transceivers. By integrating VCSEL, lens, doubly multiplexed holographic gratings, and photodetector arrays, we have demonstrated this architecture while using the third dimension as the signal propagating direction. Packaging related issues such as misalignment, crosstalk, and signal-to-noise ratio are studied. The frequency response of our device shows a bandwidth of 2.5 THz. Eye diagrams for a single bus line up to 1.5 GHz are demonstrated with clear eyes. An aggregate bandwidth of 6 GHz is thus confirmed with 2 × 2 bus lines.**

***Index Terms*—Gratings, holographic optical components, optical arrays, optical interconnections, optoelectronic devices.**

OPTICAL interconnections have been of interest at all levels in digital computers for interconnects between mainframes, modules, boards, chips, and even points within a chip [1], [2]. Optics is ideally suited for implementing these interconnection networks because of its inherent characteristics such as high speed, high-spatial bandwidth, and low-signal crosstalk. Although optoelectronics is increasingly attractive for backplane applications, difficulties associated with optoelectronic packaging preclude the implementation of optics into interconnection systems.

In this letter, a bidirectional optical backplane with two-dimensional (2-D) bus lines is investigated. Packaging related issues such as misalignment and crosstalk are studied. The performance of a developed optical backplane is characterized by measuring its bandwidth and data transmission integrity. Finally, we report a three-dimensionally interconnected bidirectional optical backplane with an aggregate bandwidth of 6 GHz.

Current efforts in enhancing the performance of the backplane are mainly devoted to increasing the aggregate bandwidth. By incorporating arrays of transmitter and receiver multichip modules on each side of the waveguiding channel, a multibus line backplane architecture can easily be constructed as shown in Fig. 1. This figure shows the detailed diagram of the optical backplane with multibus lines using vertical-cavity surface-emitting laser (VCSEL) and photodetector arrays, and also indicates the necessary components integrated into the transmitter and receiver multichip modules. The light propagation in our optical backplane is a combination of the consecutive diffraction and reflection processes [3]. After having recorded the two sets of multiplexed hologram arrays, two grating vectors are formed in the DuPont photopolymer film (HRF-600X001-20) on the waveguiding quartz plate (refractive index $= 1.52$). If a surface-normal light beam is incident onto the surface of the designed hologram, it is then converted into two substrate guided waves, propagating along two opposite directions as shown in Fig. 1. When the substrate guided wave interacts with the gratings for the next boards, a portion of the light beam will be diffracted out of the substrate to the detector and the rest continues to propagate along the original direction. Therefore, this architecture using doubly multiplexed holographic gratings [4] provides the bidirectionality of the device.

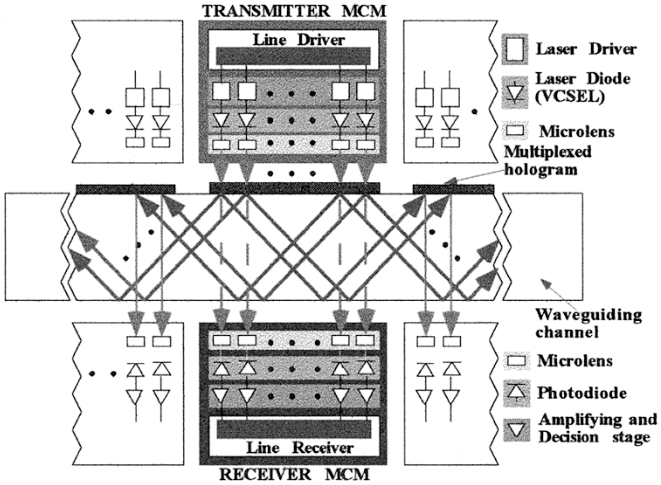


Fig. 1. Detailed diagram of waveguiding structure and transmitter and receiver modules of the proposed backplane with multibus lines.

Unfortunately, when the guided optical signals are packed closely with each other, crosstalk between the adjacent bus lines may degrade the performance of the system. Therefore, the minimum separation should be justified according to the requirement of the signal-to-noise ratio (SNR). If there are two adjacent detectors with a radius of R and a separation of d in a polar coordinate system as shown in Fig. 2, we obtain the

---

Manuscript received February 8, 1999; revised April 6, 1999. This work was supported by the Defense Advanced Research Projects Agency, by the Office of Naval Research, by the Air Force Office of Scientific Research, by the BMDO, by the Army Space and Missile Defense Command, by 3M Foundation, by Cray Research, and by the ATP program of the state of Texas.

The authors are with the Microelectronic Research Center, Department of Electrical and Computer Engineering, University of Texas, Austin, TX 78758 USA.

Publisher Item Identifier S 1041-1135(99)05158-7.

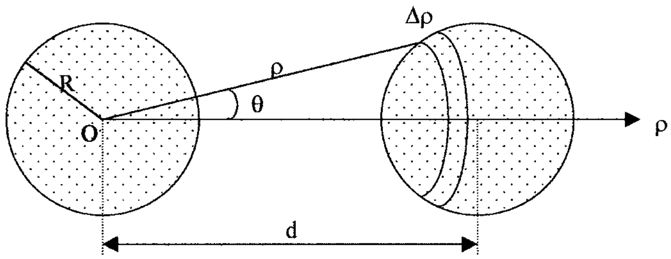


Fig. 2. Schematics for crosstalk study with two adjacent detectors.

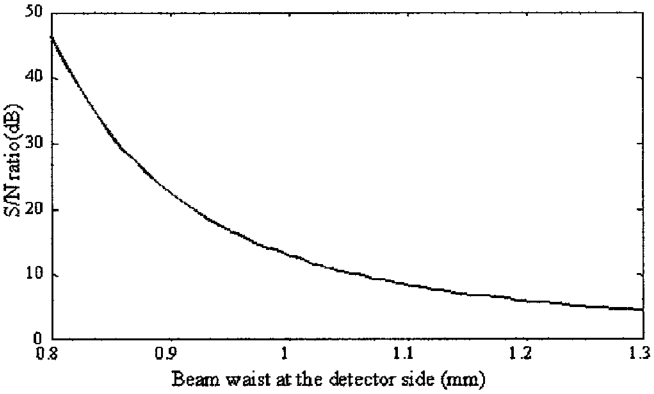


Fig. 3. SNR with the variation of beam waists.

total noise collected by detector as

$$P_{\text{noise}} = 2\int_{d-R}^{d+R}\int_{-\arccos((\rho^2+d^2-R^2)/2\rho d)}^{\arccos((\rho^2+d^2-R^2)/2\rho d)} P\cdot\rho\, d\theta\, d\rho \quad (1)$$

where ρ and θ are the polar radius and angle, respectively. Upon inserting the Gaussian intensity distribution into (1) and integrating with respect to θ, we have

$$P_{\text{noise}} = 4P_0\int_{d-R}^{d+R} e^{-2(\rho^2/w^2)}\arccos\frac{\rho^2+d^2-R^2}{2\rho d}\,\rho\, d\rho. \quad (2)$$

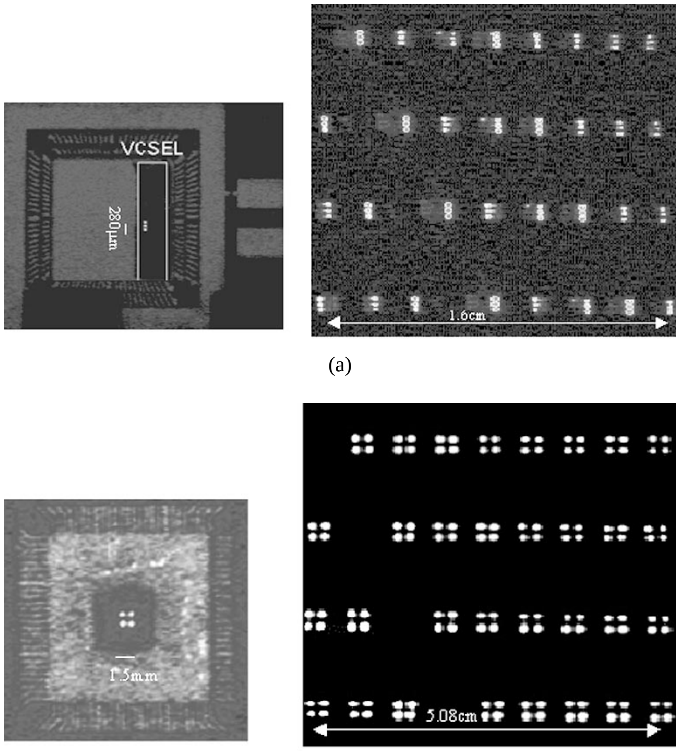
The signal intensity collected by each detector is

$$P_{\text{signal}} = \int_0^R P\cdot 2\pi\rho\, d\rho = \frac{\pi w^2}{2}P_0\Big(1-e^{-2(R^2/w^2)}\Big). \quad (3)$$

For the backplane with 2-D VCSEL and photodetector arrays, if only crosstalk from nearest lasers are considered, the noise power can easily be obtained as

$$\begin{aligned} P_{\text{noise}} &= 8P_0\Bigg(\int_{d-R}^{d+R} e^{-}2(\rho^2/w^2)\arccos\frac{\rho^2+d^2-R^2}{2\rho d}\,\rho\, d\rho \\ &\quad + \int_{\sqrt{2}\,d-R}^{\sqrt{2}\,d+R} e^{-2(\rho'^2/w^2)}\arccos\frac{\rho'^2+2d^2-R^2}{2\sqrt{2}\,\rho' d}\,\rho\, d\rho'\Bigg). \end{aligned} \quad (4)$$

The result of the simulation showing the SNR as a function of the beam waist at the detection plane is shown in Fig. 3. From this result, we see that for our experiment, in which the radius of the lens is 0.5 mm, the crosstalk is negligible until beam waist reaches 1 mm at which SNR $\approx$ 15 dB.



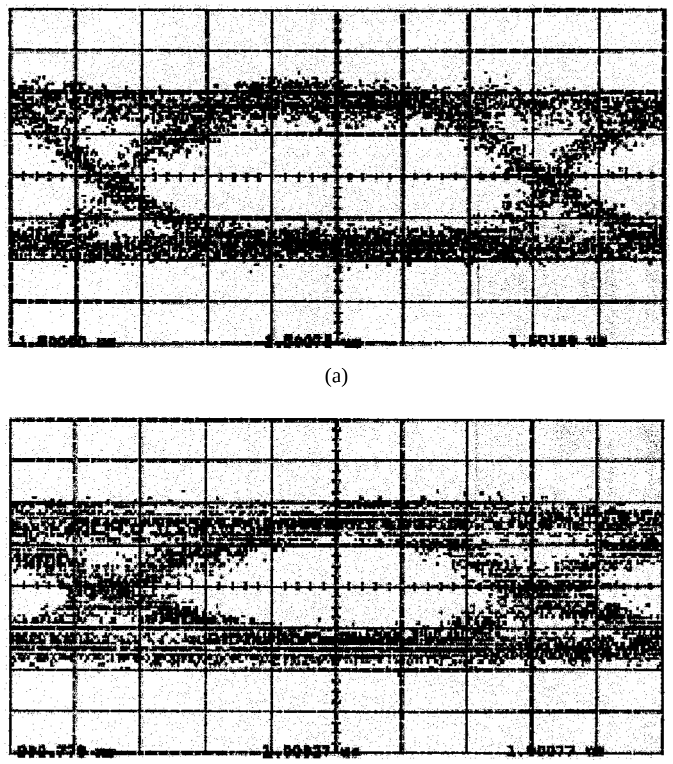
(a)

(b)

Fig. 4. (a) Photograph of bidirectional optical backplane with three nearest VCSEL's of 140-μm pitch. (b) Photograph of bidirectional optical backplane with 2-D matrix (4 for this case) bus lines with first-, second-, third-, and fourth-channel functioning as the input couplers.

A packaged linear VCSEL array, operating at the wavelength of 0.85 μm, is employed first to demonstrate a 1-D bus line. Fig. 4(a) shows the experimental results of such a backplane with three bus lines. The separation between bus lines is 140 μm, which corresponds to the pitch of the 1-D VCSEL arrays we used in our lab. A 1–9 fanout is observed for each VCSEL. A further improvement in the performance of the backplane with multibus lines can be achieved by using 2-D VCSEL and photodetector arrays instead of one-dimensional (1-D) arrays. This idea is demonstrated by the experimental results in Fig. 4(b), where the input/output configurations of the backplane have four bus lines (but 2×2). But the beam propagation performance depends on the emitting spot radius and the divergence angle of the VCSEL, the focal length of lens array, and the traveling distance [5]. In order to avoid overlapping with the nearest beams, the possible choices of focal length of lens turned out to be from 1.0 to 2.0 mm and the separation between bus lines should be over 500 μm when the maximum traveling distance for nine boards is 5.08 cm.

Several factors affect the packaging of an optical interconnection device when integrated with source lasers and photodetectors. Once coupled into the substrate, the signal beam travels toward the photodetector and a lateral misalignment results in an equivalent spatial shift of the output signal beam. The influence of the angular misalignment on the lateral misalignment arises from the phase mismatch between the


(a)

(b)

Fig. 5. Eye diagrams of the system output as a function of data rate (a) without and (b) with the interconnection device at 1.5 GHz.

input signal beam and the grating vector when the incident angle deviates from the Bragg condition. In our calculation, we see that within a small angular misalignment $\Delta\theta$ of the input light beam, ΔL changes linearly with $\Delta\theta$. To keep the spatial shift of the output signal beam below an error range of ± 50 μm, the angular misalignment should be within $\pm 0.1°$.

To demonstrate the performance of our optical backplane, eye diagrams at the speeds of 500 MHz, 1 GHz, and 1.5 GHz were measured with and without the device for comparison. The final experimental results of 1.5 GHz are shown in Fig. 5. By comparing the eye diagrams before and after propagating through the backplane from the first board to the ninth board, we see that the signal noise is mainly from the test system, and the device contributes no noticeable distortion to the signal. Even up to data speeds as high as 1.5 GHz, our experiment with a single data bus line shows very clear open eyes, both with and without the device. With the 2×2 bus lines demonstrated, we have an aggregate bandwidth of 6 GHz.

Bandwidth was measured in our experiment by the frequency response of the device. In our experimental setup, a laser beam from an Argon laser is used to pump a Clark-MXR Ti:Sapphire mode-locked femtosecond (10^{-15}) laser whose output is fed into the optical interconnection device. Due to the dispersion of the backplane material, the pulse from the backplane experiences a broadening effect relative to the reference pulse. By making a fast Fourier transform (FFT) of the output pulses, the frequency response of the optical interconnection device can be determined. Fig. 6 shows the FFT results for the reference and the device output pulses. It is clear from this result that a 2.5-THz bandwidth of our device is expected out of a single bus line.

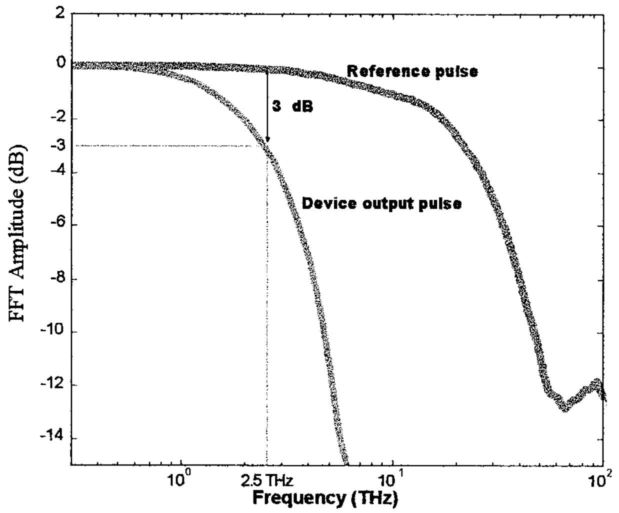


Fig. 6. Bandwidth measurements of a single bus line of optical backplane using the FFT technique.

In summary, we reported the formation of a three-dimensionally interconnected bidirectional optical backplane with multibus lines. By employing VCSEL and photodetector arrays, we presented a backplane with 1-D and 2-D bus lines using doubly multiplexed holographic gratings. Such approaches greatly increase the aggregate bandwidth of the backplane. We also characterized our optical backplane from considerations of the alignment and data transfer integrity. Eye diagram up to 1.5 GHz has been demonstrated with a clear eye. Therefore, a 6-GHz aggregate bandwidth is experimentally achieved for the three-dimensionally interconnected optical backplane with 2×2 bus lines. Frequency response of our device shows a bandwidth of 2.5 THz. The bandwidth of system is thus limited by the bandwidth limitation of the current available optical sources and detectors, not by the developed device.

ACKNOWLEDGMENT

The authors wish to thank Dr. B. Davies and C. Zhao for their helpful recommendations and acknowledge the members of the JOP program from OIDA for providing the 2-D VCSEL, driver, and detector array.

REFERENCES

[1] J. W. Goodman, F. J. Leonberger, S. Y. Kung, and R. A. Athale, “Optical interconnects for VLSI systems,” *Proc. IEEE,* vol. 72, pp. 850–866, 1984.
[2] R. K. Kostuk, J. W. Goodman, and L. Hesselink, “Optical imaging applied to microelectronic chip-to-chip interconnection,” *Appl. Opt.,* vol. 24, pp. 2851–2858, 1985.
[3] S. Natarajan, C. Zhao, and R. T. Chen, “Bidirectional optical backplane bus for general purpose multiprocessor board-to-board optoelectronic interconnects,” *J. Lightwave Technol.,* vol. 13, pp. 1031–1040, 1995.
[4] S. K. Case, “Coupled-wave theory for multiply exposed thick holographic gratings,” *J. Optical Soc. Amer.,* vol. 65, pp. 724–729, 1975.
[5] K. Hirabayashi, T. Yamamoto, and S. Hino, “Optical backplane with free-space optical interconnections using tunable beam deflectors and a mirror for bookshelf assembled terabit per second class asynchronous transfer mode switch,” *Opt. Eng.,* vol. 37, no. 4, pp. 1332–1334, 1998.