

An 8-Gb/s Optical Backplane Bus Based on Microchannel Interconnects: Design, Fabrication, and Performance Measurements

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Abstract—We describe the characteristics of a microchannel-based optical backplane including signal-to-noise ratio (SNR), interconnect distances, and data transfer rates. The backplane employs 250- μm -spacing two-dimensional (2-D) vertical cavity surface emitting lasers (VCSELs) and a microlens array to implement 500 μm -, 750 μm -, and 1-mm optical beam arrays. By integrating the transmitter and a multiplexed polymeric hologram as a deflector/beam-splitter for the guided-wave optical backplane, the result demonstrates a multibus line architecture and its high-speed characteristics. Maximum interconnect distances of 6 cm and 14 cm can be achieved to satisfy 10^{-12} bit error rate (BER) using 2×2 beams of 500- μm - and 1 mm-spacing array devices. The total data transfer rate of the developed backplane has shown 8 Gb/s from eye diagram measurements.

Index Terms—Holographic gratings, microchannel optics, optical backplane, vertical cavity surface emitting laser (VCSEL) arrays.

I. INTRODUCTION

THE PERFORMANCE requirements of computer, telecommunication, and data communication systems have increased considerably in recent years to a point at which large-scale electronic systems now suffer from an interconnection bottleneck. Large computational systems with tens of nodes are composed of many chip-to-chip, module-to-module, or both interconnections. These complex interconnection systems must be efficient and fast for good overall system performance.

One of the simplest and most widely used interconnect systems for data exchanges between boards or cards is the passive backplane. As the computing power of the microprocessor increased, the bus traffic increases greatly. As a result, the limited bus bandwidth becomes the major bottleneck to efficient communication among processing components, memory modules, and other I/O interface units [1], [2]. In the conventional electrical backplane, the bus bandwidth or bandwidth of communication path is limited by signal propagation delay, skew, power consumption, and capacitive effects. As an example, a typical personal computer memory bus operates at a frequency of 100 MHz but the processors are reaching speeds of 1 GHz. This trend of computing speed outpacing the interconnect speed will

be more serious in near future. In a standard backplane interface that simplifies integration of data processing, data storage, and peripheral devices in a tightly coupled hardware configuration, for example, in VMEbus, the bus width varies from 16–64-bit, but the maximum bandwidth remains 100 Mb/s. Although the throughput increased three times using more bus lines compared to earlier VMEbus, we can not expect to increase the bus width more and more. Therefore, it is necessary to search the backplane implementation technologies for higher bandwidth, not bus width.

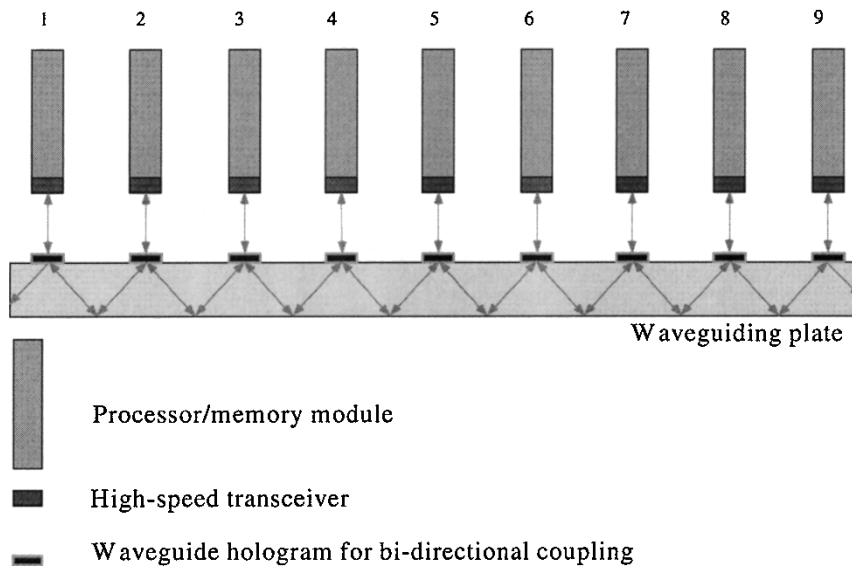
Optical interconnection has been thought to be one of the better alternatives for solving these problems in the electrical interconnects [3]–[5]. At the level of computer-to-computer interconnects, i.e., several meters or more, optical means have already been implemented in order to improve connection speed. These are based on an optical fiber solution [6], as implemented in Gigabit Ethernet standards and telecom standards such as ATM. Where shorter distances are involved, the need to interconnect individual boards in larger computers is motivating the development of optical backplane bus system. The typical optical implementation of a backplane bus has an optical bandwidth of 2.5 THz. This frequency bandwidth exceeds that of today's electronic bus by a factor of 2.5×10^4 , which indicates that an optical interconnection system is potentially capable of much greater speed than an electronic one. Of course, the opto-electronic transmitters and receivers in the present generation are not capable of 2.5 THz bandwidths. There are available near-infrared lasers and detectors that have bandwidths of the order of 1–5 GHz [7], [8], so that an optical backplane bus could be expected to send signals at these speeds instead. These distinct advantages of optical backplane are due to the elimination of transmission line effects, which occur in the electrical interconnects. There are, as well, other advantages.

In an effort to move past the major bottleneck in current computer architectures represented by existing backplane interconnects, an optical backplane based on photopolymeric hologram-based waveguiding plates in conjunction with two-dimensional (2-D) arrays of optical transmitters and receivers was proposed and demonstrated [9], [10], as shown in Fig. 1. It should be noted that this is the bus architecture: each board can send and receive the signals by signal broadcast [Fig. 1(b)]. In this implementation, the transmitter arrays transmit short pulses of near-infrared energy through an optical waveguide to receiver arrays on other boards. These pulses are made to travel in opposite directions along the waveguide by being coupled into it by means of a doubly multiplexed hologram [11], [12]. A near infrared

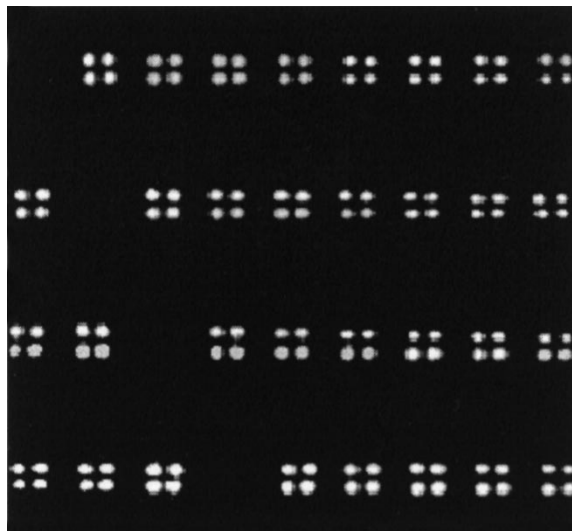
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(a)



(b)

Fig. 1. (a) Generalized bidirectional optical backplane architecture and (b) experimental demonstration using 2-D array with first, second, third, and fourth channel functioning as the input coupler.

digital signal leaving an array of vertical cavity surface emitting lasers (VCSEL) operating at 850 nm is then collimated by an array of lenses and diffracted by a hologram, and so enters a waveguiding plate. The energy is reflected several times by total internal reflection so as to reach circuit boards other than the one originating the energy. When infrared energy reaches a designated board, some of it is diffracted by the hologram and impinges on an array of receivers. So the holographic gratings work as deflector and beam splitter [13]. Because some of the energy is used up at each board, the number of boards to be connected is limited by the power budget. As a result of using multisignals and the divergence of VCSEL output, there is inevitable cross talk between adjacent signals, which limits either the interconnect distance or the number of board to be interconnected [10], [14]. There is also limitation in the data-transfer rate for the optical backplane system because of maximum bandwidth of transmitter and receiver, and bandwidth reduction due to packaging and alignment.

In this paper, we specify the maximum interconnect distance for microchannel-based board-to-board interconnects, studying first the characteristics of a transmitter without and with collimation lens. We describe the design and fabrication of a transmitter using VCSEL and a microlens array, and measure beam propagation performance with three different array spacings. After the measurement of beam propagation performance, we follow cross talk and BER analysis. Finally, the high-speed measurement of an eye diagram is demonstrated using the VCSEL as transmitter to specify the operating data transfer rate.

II. DESIGN AND FABRICATION OF A TRANSMITTER USING ARRAY DEVICES AND ESTIMATION OF OPTICAL SIGNAL PROPAGATION

Adopting the wider bus width increases the throughput of the electrical bus system. Similarly, the performance of the optical backplane can be enhanced by applying such array devices

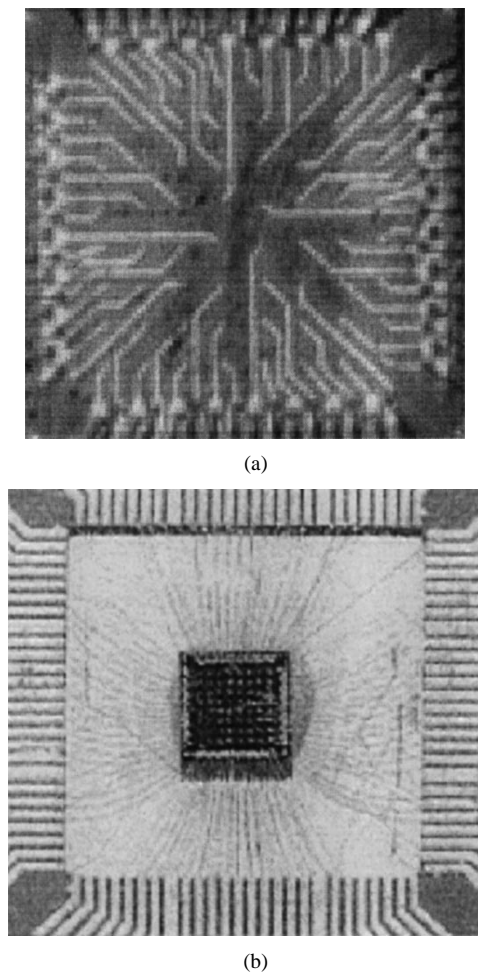


Fig. 2. (a) 2-D 8×8 VCSELs with $250 \mu\text{m}$ spacing. (b) PGA packaged VCSEL array with wire bonding

as one-dimensional (1-D) and 2-D arrays. We expect array devices to prove useful in increasing the aggregate bandwidth of backplane even though there is tradeoff between the packing density and cross talk or the interconnect distance. Several approaches utilize array devices, among which the VCSEL as a transmitter source has proved to be an efficient and reliable device. A VCSEL is advantageous for an optical interconnect because of its small size, low threshold current, small divergence angle, circular symmetric emission pattern, stability, and also individually addressable 1-D or 2-D arrays [8].

A. Design of a Transmitter Using VCSELs and Microlens

Fig. 2 shows 2-D VCSEL arrays before and after PGA packaging, which has a total of 64 VCSEL elements with $250 \mu\text{m}$ -spacing. The experimental curves of current versus voltage and output power versus current of the selected VCSEL elements at room temperature, appear in Fig. 3. From these typical LIV characteristics of laser, a threshold voltage of 1.4 V and threshold current of 6 mA can be estimated. At about a 32 mA current, the optical power from a VCSEL reaches a maximum power of 7 mW. After saturation, the output power decreases as the current increases. All the VCSEL elements in the array show identical LIV characteristics within the fabrication errors. From these results, we can determine the

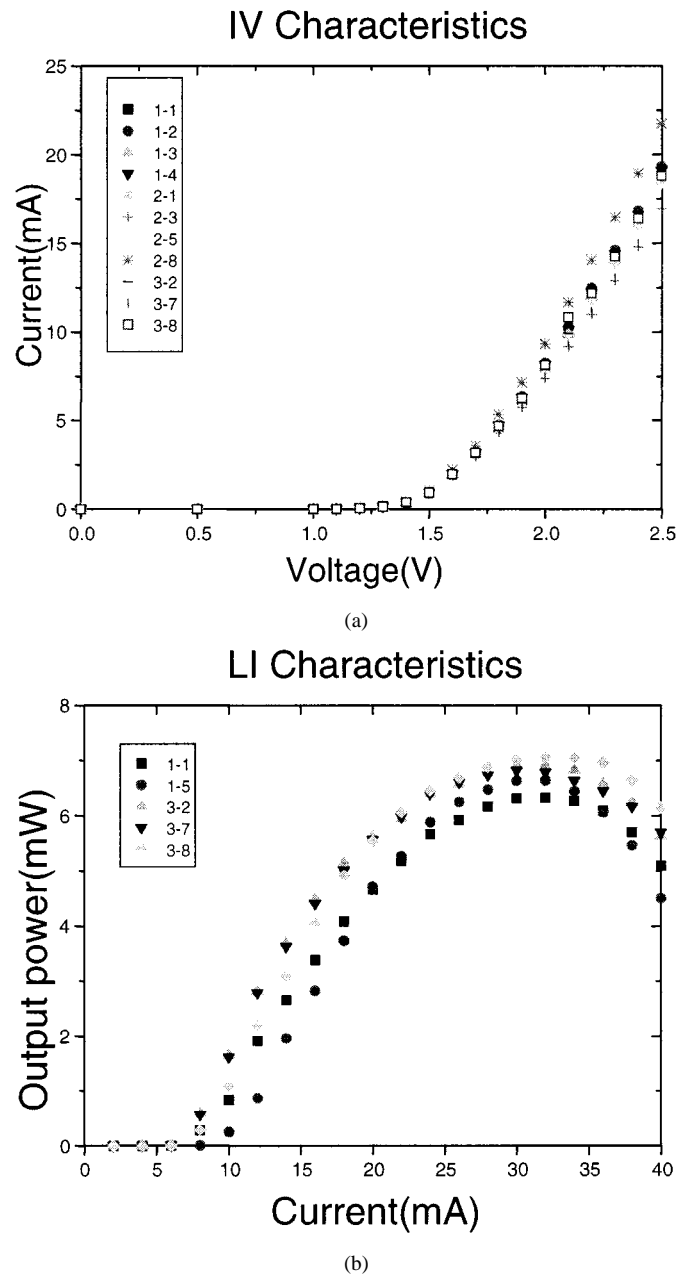


Fig. 3. LIV characteristics of PGA packaged VCSELs. (a) IV characteristics. (b) LI characteristics.

modulation currents of each addressable VCSEL elements and the sensitivity of photodiodes for the power budget.

Fig. 4 shows another important result of the divergence measurements and the far-field output profiles of PGA packaged VCSEL arrays. The output profiles were measured at distances of 1 mm, 2 cm, 4 cm, and 6 cm from the emission window. By measuring the full width at half maximum (FWHM) of the spot sizes, the divergence angle of VCSEL can be determined to be 7.5° . From the results of the divergence measurements, a maximum propagation distance of beam array without severe overlapping with the adjacent beams can be calculated, as shown in Table I. The table shows that even for 1mm-pitch beam array, the optical beams or output power from VCSELs will overlap beyond 7.6 mm propagation. This is actually too short for contemporary standards of board-to-board intercon-

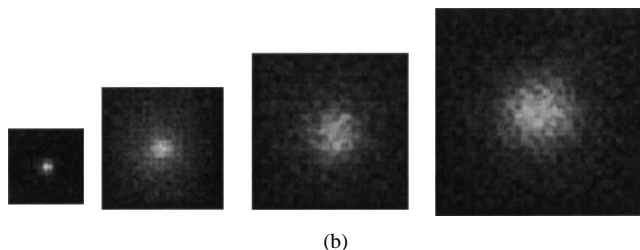
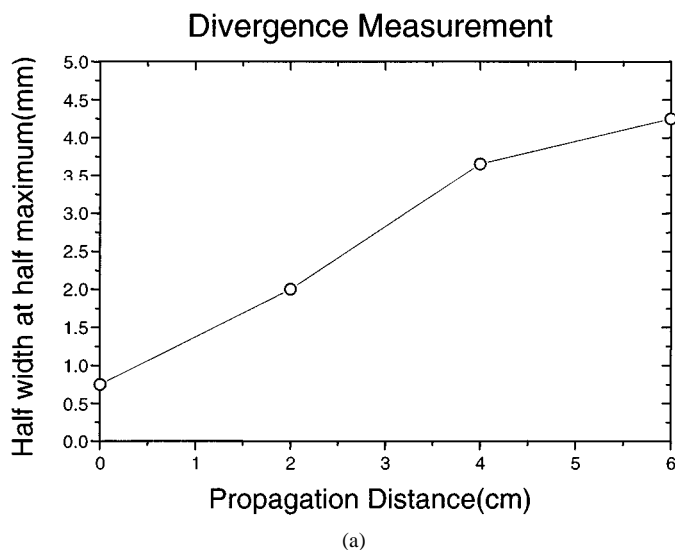


Fig. 4. (a) Divergence measurements of PGA packaged VCSELs. (b) Far field output beam profiles at 1 mm, 2 cm, 4 cm, and 6 cm.

TABLE I
MAXIMUM INTERCONNECT DISTANCE WITHOUT COLLIMATING LENS

Beam Pitch	Max. Interconnect Distance
250 μm	1.9 mm
500 μm	3.8 mm
750 μm	5.7 mm
1.0 mm	7.6 mm
1.5 mm	11.4 mm

nects passing through a number of PCBs. Hence, to increase the interconnect distance or the number of boards to be connected, typical beam propagation performances should be considered with various focal lengths of lens.

In the optical bus design, the diverging laser beam is collimated, transmitted through a deflector and beam splitter, and then focused onto the detector. The beam radius after passing through a lens should be designed to be a nearly constant value, to minimize performance degradation at different board locations.

For a collimated Gaussian beam with a beam radius of W'_0 , after collimating through the lens, the beam radius is expressed as

$$W = W'_0 \left\{ 1 + \frac{(d - z')^2}{(\pi W'^2_0 / \lambda)^2} \right\}^{1/2} \quad (1)$$

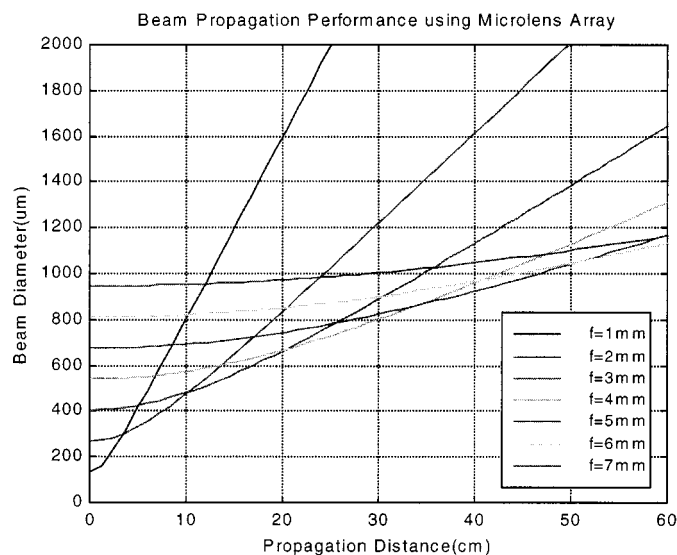


Fig. 5. Gaussian beam propagation performance using lens to collimate

TABLE II
MAXIMUM INTERCONNECT DISTANCE WITH COLLIMATING LENS

Beam Pitch	Maximum Interconnect Distance	Focal Length of Lens Used
250 μm	3cm	1mm
500 μm	12cm	3mm
750 μm	25cm	4mm
1.0mm	45cm	5mm
1.5mm	> 60cm	> 4mm

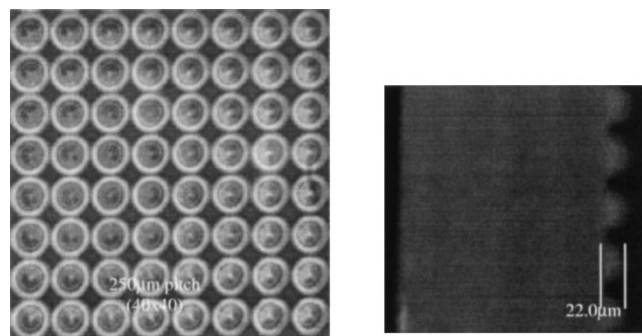


Fig. 6. Convex refractive microlens array in use.

where

- W'_0 beam waist radius after lens which is determined by the lens parameters and beam waist radius of VCSEL;
- d distance from lens location or a detector location;
- z' beam waist location;
- λ wavelength of VCSEL.

From the measured divergence angle of 7.5° , the emitting window radius of VCSEL in use also turns out to be $4 \mu\text{m}$. With these measured parameters and focal lengths of the lens, the simulated beam propagation is shown in Fig. 5 and summarized in Table II. Fig. 5 and Table II show that the best choices for the

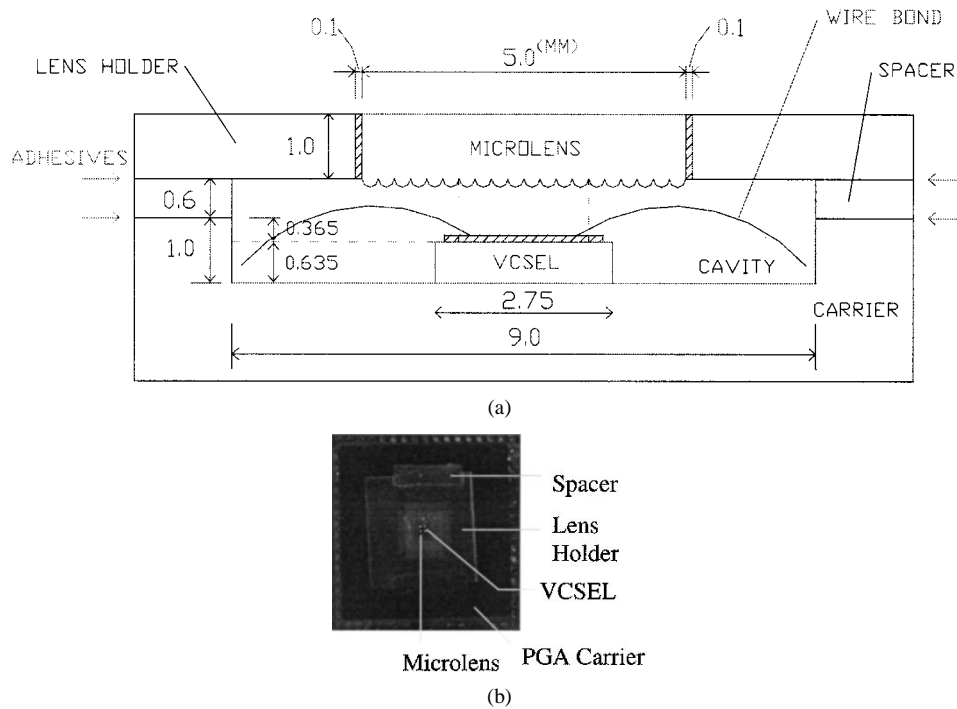


Fig. 7. (a) A detailed drawing for a transmitter packaging. (b) Photo of packaged VCSEL with microlens array.

lenses range from focal lengths of 4–5 mm in order to achieve maximum propagation distances for more than 750 μm beam spacing. But increased difficulties in choosing the lens array arise when using smaller beam spacing ($<500\mu\text{m}$). In these cases, the interconnect distance without severe overlapping is less than 12 cm, considered for research purposes to be five-board interconnects. It is important to note that the maximum focal length to be used or the distance of the lens from VCSELs is limited by the maximum propagation distance from VCSELs to the lens array. That is, with a given array spacing, an output beam from a VCSEL element can touch the edge of its own lens or of adjacent lenses. Therefore, the longest suitable focal lengths for 250 μm , 500 μm , 750 μm , 1 mm array spacing are 2 mm, 3.5 mm, 5.5 mm, 7.5 mm, respectively. For example, given a window radius of VCSEL and 5 mm in focal length of lens for 1mm array spacing, Fig. 5 shows the maximum interconnect distance to be 45 cm. In this case, if a lens with a shorter focal length is used instead, optical beams are less collimated, resulting in a shorter interconnect distance. On the other hand, if a lens with a longer focal length, e.g., 7 mm, is used, it actually diverges at the lens position and reaches 1 mm of beam diameter at approximately 30 cm propagation. Therefore, there is an optimum value of lens parameter for each array spacing. If a larger array spacing of 1.5 mm is available and a lens focal length longer than 4 mm is used, the achievable interconnect distance without serious cross talk can reach more than 60 cm. Thus, in the optical implementation of a bus system, there is always a tradeoff between interconnect density and interconnect distance.

B. Fabrication of a Transmitter Using a Microlens to Collimate

Microchannel optics is a broad term that comprises both passive and active optical elements. In order to implement the

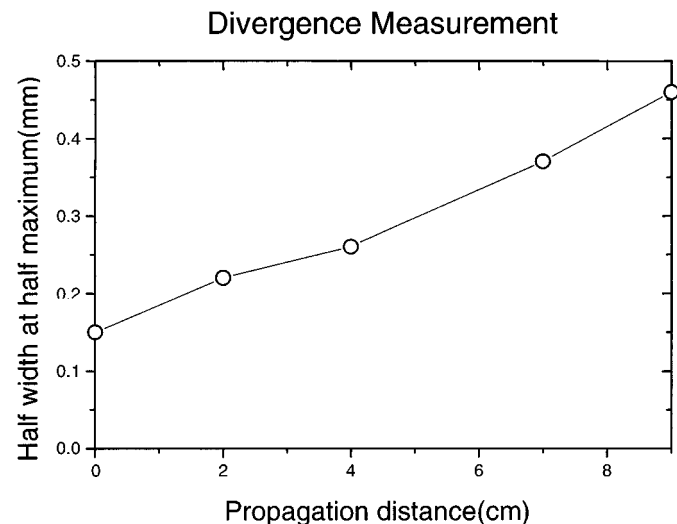


Fig. 8. Divergence measurements of packaged VCSELs with microlens

optical backplane, such passive optical elements as refractive or diffractive microlens and holograms for the deflector/beam splitter are needed. Laser drivers, VCSELs, and photodetectors used to modulate and detect optical signals are some of the active optical elements.

Among several techniques for making refractive microlenses, this miniaturized version of the classical convex refractive lens is generally fabricated by patterning a substrate (fused silica) with small cylinders of photoresist. In our transmitter design (VCSEL + lens array), we used the commercially available refractive microlens array from Mems Optical, Inc. to collimate diverging beams, as shown in Fig. 6. The lens is fabricated by means of photoresist melting and surface relief techniques. It has 250 μm in array spacing, 22 μm in sag height, and 1 mm in focal length. The microlens arrays, which have longer focal

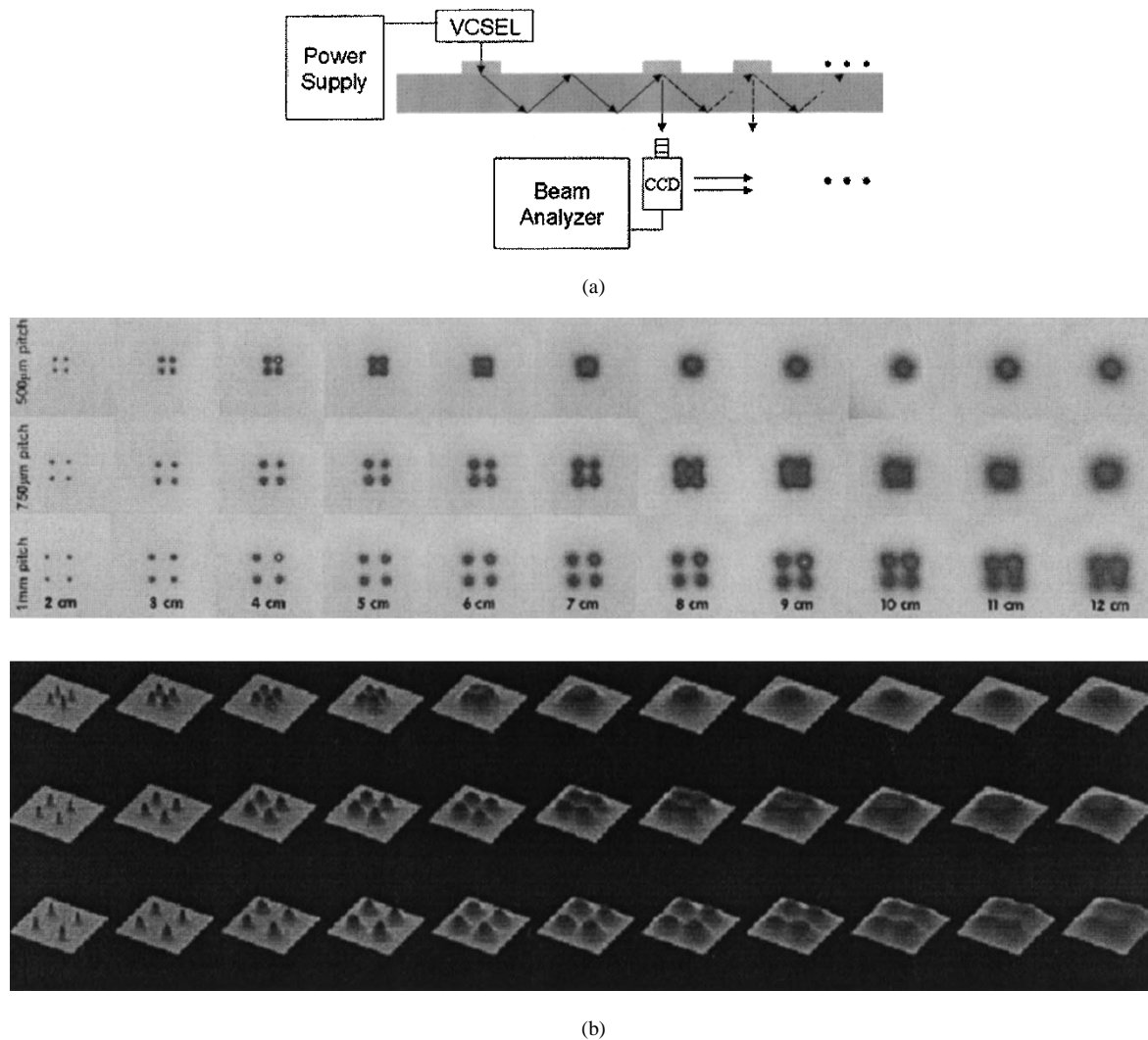


Fig. 9. (a) Measurement setup and (b) degree of overlapping between 2×2 optical beams.

length, all require a semicustom order, take extra time to fabricate, and are very expensive.

The package containing the PGA carrier, VCSELs, and microlens array is carried by the Melles Griot 6-axis aligner and UV curable epoxy machine. First, the microlens is held in a transparent plastic carrier or lens holder as shown in Fig. 7(a). This package is mounted to allow translation in x -, y -, and z -axes and rotation in roll, pitch, and yaw. A CCD camera is used to trace the output beam array after passing through a lens. The spacers have a thickness of 0.6 mm and are attached to the top of PGA VCSEL carriers with an application of UV curable epoxy. After finishing the package of each element, the microlens holder is brought down or up to the surface of VCSEL to place the microlens at approximately the focal length of the lens. Thereafter, the package is translated and rotated to obtain the best set of collimated beam arrays. The beam symmetry is used to monitor the relative position of microlens and VCSELs. Finally the UV curable epoxy is applied between spacers and a lens holder fixed into position. Fig. 7(b) shows the final packaged transmitter including wire-bonded VCSELs, PGA carrier, and microlens array. The divergence of a packaged transmitter is measured again and results in 0.6° of FWHM angle, as shown in

Fig. 8. The performance of beam propagation is improved from 7.5° to 0.6° , which means the FWHM is less than 1 mm at approximately 10 cm.

III. EXPERIMENTS OF DATA TRANSFER PERFORMANCE IN CONTINUOUS AND MODULATED SIGNALS

The overall performance of multibus optical interconnect devices is characterized by the data modulation rate of the transmitter, the efficiencies of holograms for the power budget, the bandwidth of optical path and receiver, and environmental noises, as well as other factors. In our implementation of an optical bus, the microlens array is used to collimate the lights from VCSELs and to focus the beam onto the detector array. It is important to note that the diverging array beams not only cause the loss of some detectable amounts of power, but also generate the optical cross talk that degrades bit-error-rate (BER). On the other hand, the high speed modulation may cause a signal distortion due to rising time, falling time, and timing jitter of active devices. Hence, in this section, we analyze the cross talk and discuss eye diagram measurements to explain the experimental performance of our devices.

A. Crosstalk, Signal-to-Noise Ratio (SNR), and Bit Error Rate (BER)

Even though the lenses are used to collimate the diverging laser beam in order to focus the light onto the detector, there is some cross talk between the adjacent optical bus lines in array optical implementation because of the nature of the Gaussian beam of VCSEL. Analysis of this kind of cross talk produces the SNR, so that the BER can be estimated. Fig. 9(a) shows the measurement setup for beam profiles and the cross talk or the degree of overlap between 2×2 bus lines with various propagation distances and selectable array spacing. It should be noted that these measurements include VCSEL, lens, hologram arrays and substrate. The 2×2 beams from VCSELs were collimated by the microlens array, coupled into the substrate through a hologram (recorded in DuPont photopolymer film using two beam interference methods), then the total internal reflection was taken inside the substrate, coupled out through another hologram and finally detected by the CCD camera. As we would have expected, in Fig. 9(b) the 2×2 beams of $500 \mu\text{m}$ -, $750 \mu\text{m}$ -pitch overlap completely after 7 cm and 11 cm propagation and appear as a single Gaussian beam spot. For 1 mm-pitch beams, the detected beam is discernible up to 11 cm, even though more accurate estimation of optical crosstalk should be considered from measured beam radius with propagation distances. With attention to the Gaussian shape of VCSEL output, the beam radius at the detector position can be measured from the three-dimensional (3-D) images of Fig. 9(b). Therefore, if there are 2×2 photodetectors with an active radius of R and spacing d , the signal to noise ratio (SNR) can be estimated [9]. The SNR contours from measured and calculated beam radius, which can be obtained from the lens formula, are simulated on the basis of previous theoretical and experimental studies. The variation of the SNR with that of the active radius of the detector and the calculated beam radius from the lens formula are shown in Fig. 10(a) for $500 \mu\text{m}$ spacing implementation. Fig. 10(b) is obtained from the measured beam radius while all other parameters for calculations are same as those in Fig. 10(a). In both cases, the variation of the SNR is much more sensitive to the propagation distance than to the active area of the detector, especially in Fig. 10(b), which shows sharper drops of equi-SNR lines as the propagation distance increases in comparison to the calculated one. Fig. 10(a) shows that the maximum interconnect distance using a lens array can theoretically reach 8 cm with $50 \mu\text{m}$ in the active area of the detector. Unfortunately, the maximum interconnect distance in our implementation as shown in Fig. 10(b) turned out to be less than 8 cm due to the misalignment of VCSEL and microlens arrays. Even though the VCSEL and microlens arrays proved in our experiment to be somewhat misaligned, the maximum interconnect distance in our implementation is 6 cm. The interconnect distance can be increased with increases of the array spacing. For 1 mm array spacing in Fig. 11(a) and (b), the interconnect distance is more than 12 cm to satisfy a SNR of 7.2 and the SNR is once again less sensitive to the active area of detector. Total 354 data points in Matlab S/W is used to draw both contours in Figs. 10 and 11 (The crosses indicate the markers for text values, not measured

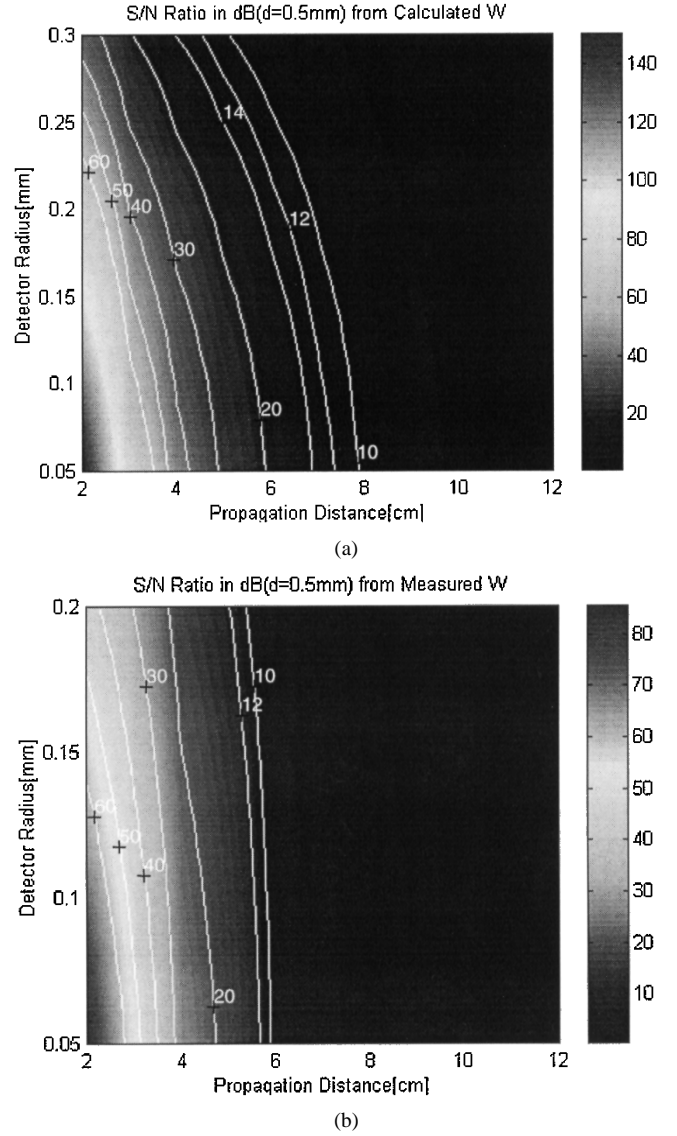


Fig. 10. Signal to noise ratio (SNR) simulation for $500 \mu\text{m}$ array spacing (a) From calculated beam radius. (b) From measured beam radius.

data points in Matlab). It should be noted that the diagonal elements have negligible contribution to noise compared to the nearest VCSEL elements. Hence, for more bus lines of a 2-D array implementation, it is enough to consider only the nearest elements for cross talk analysis.

If the detected signals follow Gaussian statistics, The BER can be written as [11], [15]

$$\text{BER} \cong \frac{1}{\sqrt{2\pi}Q} \exp\left(-\frac{Q^2}{2}\right) \quad (2)$$

where Q is a measure of the SNR. From (2), we find that a value of $\text{BER} = 10^{-12}$ corresponds to the value $Q = 7.2$ and that a value of $Q = 6.1$ corresponds to the value $\text{BER} = 10^{-9}$. Fig. 12 shows the results of calculation of BER from measured beam radius. It can be seen from this figure that the maximum interconnect distances for 2×2 bus lines of $500 \mu\text{m}$ -, $750 \mu\text{m}$ -, and 1 mm-pitch are 6 cm, 9 cm, 14 cm to satisfy 10^{-12} in BER. In practical terms, these results match the beam propagation simulation using the 1 mm focal length of the lens in Fig. 5. It is

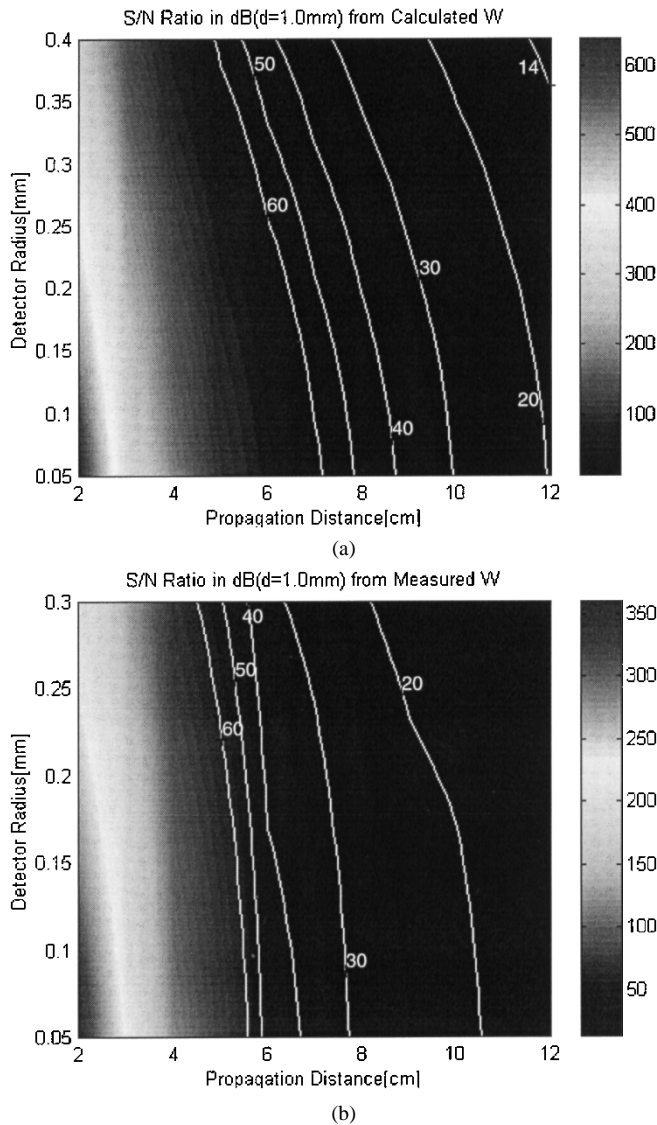


Fig. 11. SNR simulation for 1 mm array spacing (a) From calculated beam radius. (b) From measured beam radius.

important to note from the agreement between theoretical and experimental results that the interconnect distance can be even longer if we use a 5 mm lens focal length. It follows from a simple calculation of SNR and BER that the interconnect distance for 10^{-12} BER is more than 45 cm for 1 mm-spacing when using a lens with 5 mm focal length. Therefore, proper choice and usage of the lens array will be the key issue for longer distance board-to-board interconnects.

B. Eye Diagram Measurements

Fig. 13 shows the setup for eye diagram measurements. The pseudorandom bit sequence (PRBS) from a 3-GHz pulse generator (HP8183A) is used to modulate commercially available semiconductor laser and 2-D VCSELs for comparison. After being collimated by the microlens array and passing through the device, the optical signal is focused onto the optical module in a digital communication analyzer (HP83480A), and the output of the receiver is then analyzed. To demonstrate the performance of our system, the eye diagrams at data transfer rate of 500 Mb/s, 1 Gb/s, 1.25 Gb/s, 1.5 Gb/s, 2 Gb/s, and 2.5 Gb/s were

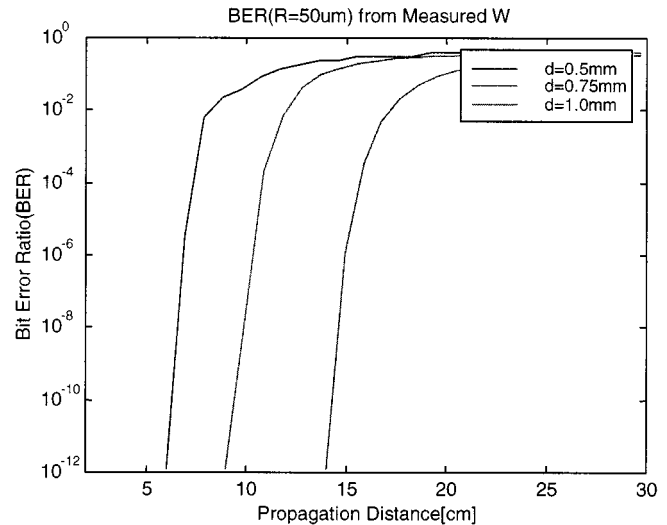


Fig. 12. BER to determine the interconnect distance.

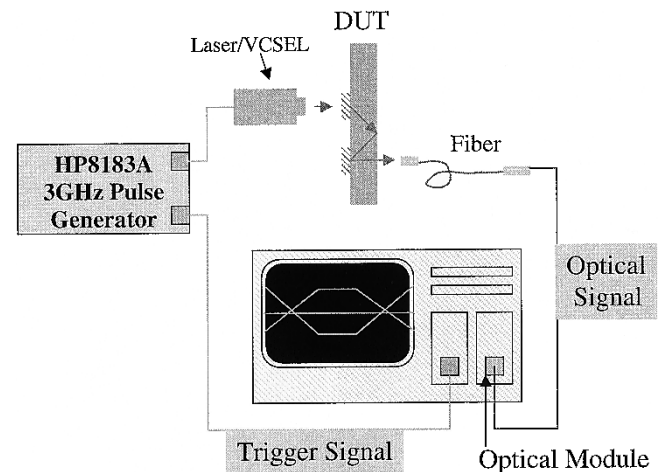


Fig. 13. Experimental setup for eye diagram measurements.

measured both with and without the insertion of a backplane device for comparison. Fig. 14 shows the results of eye diagram measurements at 500 Mb/s, 1.25 Gb/s, and 2.0 Gb/s of the modulated PRBS. By comparing the eye shape before and after the insertion of the optical backplane device, we conclude that the signal noise is mainly from the test equipment, and that the device contributes no noticeable distortion to the signal even up to data transfer rates as high as 2 Gb/s. The results show a clear, open eye for VCSEL and microlens array as a transmitter with and without the device. When each optical bus line operates at 2.5 Gb/s, the eye diagram starts to show some distortion, caused mainly by a decrease of output power of VCSEL and the relative increase of background noise. We believe that the operation limit of the transmitter may be the speed limit of VCSELs used or the wire-bonded PGA packaging, which has some electrical delay from the conversion of high-speed electrical signal to optical power. Therefore by using more advanced VCSEL technologies and high speed packaging techniques such as flip-chip bonding, the digital data transfer rate of 2.5 Gb/s can be improved. As a conclusion based on modulated signal performance, it can be guaranteed that the total data transfer rate of our optical bus is 8 Gb/s with 2×2 multibus line architecture.

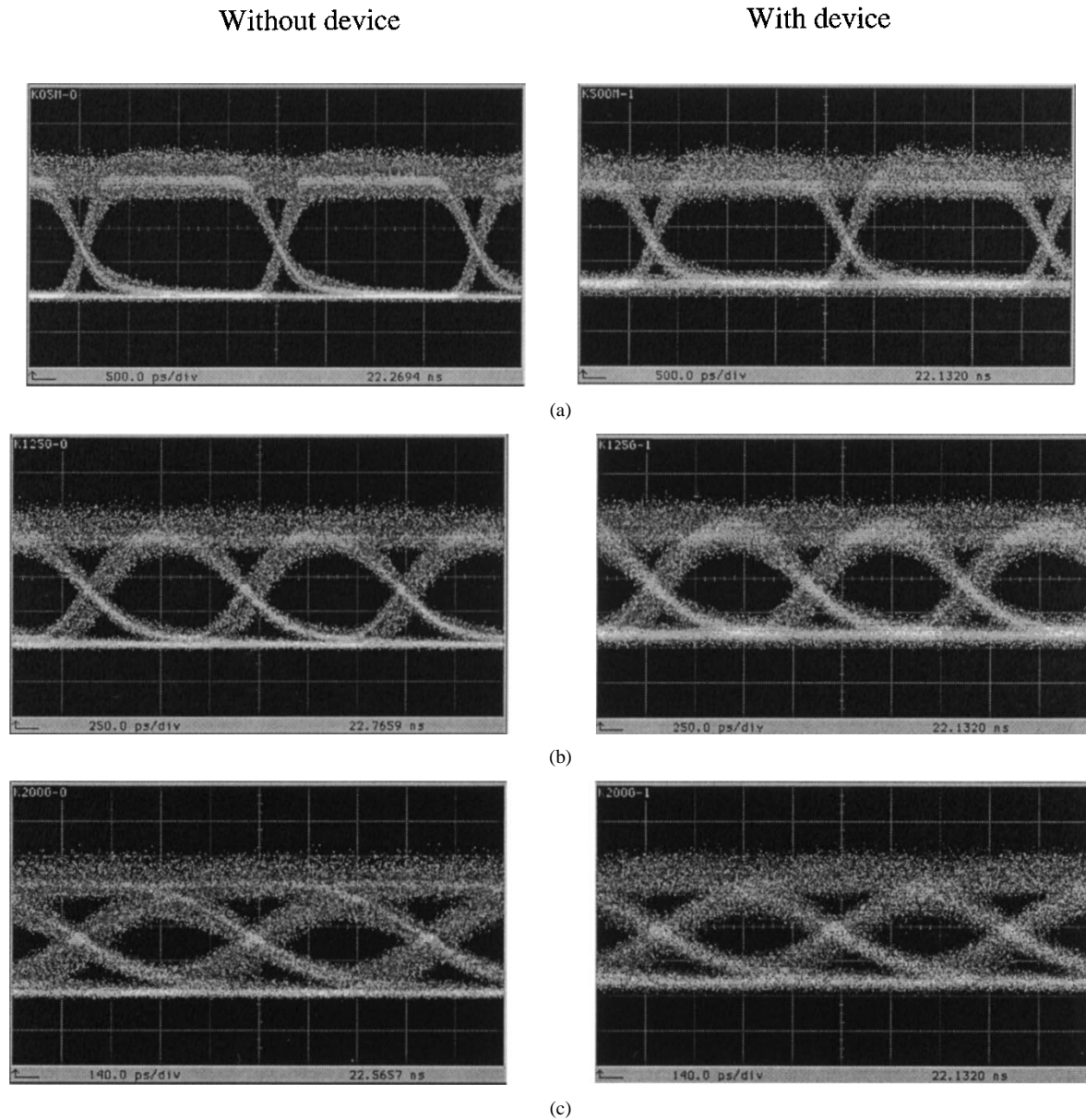


Fig. 14. Results of eye diagram measurements for optical bus using VCSELs (left eye diagrams were measured without the insertion of device while right eye diagrams were measured with the insertion of device): (a) at 500 Mb/s. (b) at 1.25 Gb/s. (c) 2.0 Gb/s.

IV. DISCUSSION AND SUMMARY

We have described a microchannel-based optical bus system implemented with 2-D array devices, which include passive and active optical elements. The holographic gratings are designed for optical signal broadcasting and each board in the bus system has its own transmitter and receiver arrays to send and receive the optical signals through a substrate. The design of a transmitter using VCSELs and microlens array to implement 500 μm , 750 μm , and 1 mm 2-D bus spacing has some limitations of the maximum interconnect distance due to the divergent nature of the laser source. Even with 1 mm bus spacing, the optical signal from VCSELs cannot be delivered to a detector located at more than 7.5 mm without collimating optics. Therefore, to increase interconnect distance or the number of boards to be connected, the diverging optical beams should be collimated by means of a lens. The fabrication of a transmitter employing a

refractive microlens array has been described, along with the improvement of beam propagation which has reached 0.6° of divergence with 1 mm focal length of lens. Optical cross talk caused by divergence and misalignment has also been analyzed using a developed transmitter. It has been shown that 2×2 array beams overlap completely after 7 cm and 11 cm propagations in cases of 500 μm and 750 μm optical bus spacing. On the other hand, the implementation of a 2-D bus line of 1 mm optical bus spacing still has some margin for cross talk with 11 cm interconnect distance. The more accurate analysis between BER and interconnect distance has shown that 6 cm, 9 cm, and 14 cm optical interconnects for 10^{-12} in BER are maximum achievable distances with 500 μm , 750 μm , and 1 mm 2-D bus spacing, respectively, while using a 1 mm focal length of microlens. A longer interconnect distance can be developed using from 4–5 mm of focal lengths of lens within the same design and fabrication concepts. By adopting a lens 3 mm in focal length, the inter-

connect distance can reach approximately 12 cm for 500 μm bus spacing. For 1 mm and 1.5 mm array spacing, 45 cm and 60 cm interconnects are possible to implement by using a lens of 5 mm focal length. The major problem in usage of larger array spacing is the packing density. Therefore, the tradeoff between packing density and required interconnect distance are major concerns for a future approach to multibus line optical backplane.

On the other hand, the experimental demonstration of high-speed performance using VCSELs as a transmitter source has shown a signal operation at a data rate of 2 Gb/s. By using 2×2 bus lines, the aggregate throughput of 8 Gb/s has been achieved with the same bus architecture. Possible improvement of data transfer rates in the future has been discussed. Since the bandwidth limitation of an optical backplane is not caused by optical paths, a bus-line greater than 2.5 Gb/s can be achieved through two approaches. The larger number of arrays can be used to increase the number of bus lines, so as to increase the aggregate bandwidth. More advanced VCSEL technologies, packaging techniques such as flip-chip bonding to reduce the electrical interconnect lines between devices, and more accurate optical alignment can be used to improve the high-speed performance.

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