Crosstalk and Interconnection Distance Considerations for Board-to-Board Optical Interconnects Using 2-D VCSEL and Microlens Array

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***Abstract*—We describe the design and experimental characterization of a substrate-mode optical backplane using 0.5 -, 0.75- and 1-mm spacing two-dimensional (2-D) optical beam arrays. The system uses arrays of multiplexed holograms to implement free space board-to-board interconnects, and employs 250-μm pitch 2-D vertical-cavity surface-emitting lasers (VCSEL) and microlens array as a transmitter to provide 0.5- to 1–mm spacing 2-D beam array, operating at 850 nm. By comparing the optical beam properties at the detector plane including the spot size and power uniformity of the optical beam array, as well as signal-to-noise ratio (SNR), the maximum interconnect distances are justified. Furthermore, we point out the improvement of the throughput that can be achieved by 2-D crosstalk analysis within the same design concept. The results of crosstalk analysis obtained here can be used for application to the standard five-board free-space optical backplane system.**

***Index Terms*—Holographic gratings, microchannel optics, optical backplane, VCSEL arrays.**

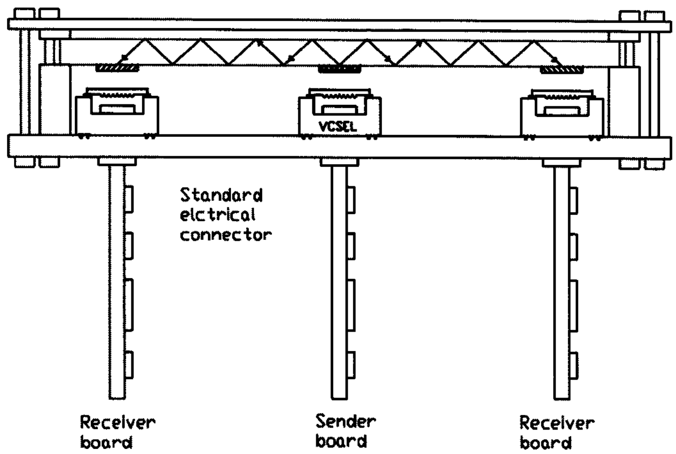

Fig. 1. Generalized optical backplane architecture for board-to-board interconnects.

I. Introduction

FUTURE digital systems such as massively parallel processing computers and asynchronous transfer mode (ATM) switches will require large printed circuit board (PCB)-to-PCB connectivity to support the large throughput demands [1]. Current electronic technology may not be capable of supporting the connection densities and the required bandwidth because of the fundamental limitations of the electrical backplane.

Based on the fact that the throughput of the electrical bus system has increased by adopting the wider bus width, for example, from 8 to 64 bits, the performance enhancement of the optical backplane can be achieved applying the array devices. A two-dimensional (2-D) free-space optical interconnect based on substrate mode holograms has been proposed and demonstrated in short distance (less than 6 cm) applications [2], [3]. In this implementation (Fig. 1), 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 because they are coupled into it by means of a doubly multiplexed hologram. A near-infrared digital signal leaves an array of vertical-cavity surface-emitting lasers (VCSEL) operating at 850 nm which is then collimated by an array of lenses, is diffracted by a hologram, and so enters a waveguiding plate. The energy is reflected several times by the total internal reflection so as to reach circuit boards other than the one at which the energy originates. When infrared energy reaches a designated board, some of it is diffracted by the hologram and impinges on an array of receivers. As a result of using multisignals and the divergence of VCSEL output, there is inevitably crosstalk between adjacent signals, which limits the interconnect distance or, alternatively, the number of boards that can be interconnected.

In this letter, the critical issue of interconnect distance for optical backplane is considered in forms of 2×2 array beams. We analyze the experimental results based on a multibus line optical backplane including VCSEL, microlens array, and substrate mode holograms. We describe the design and fabrication of a transmitter, and report the measurement of array beam propagation performance with three different array spacings. Based on these measurements, we consider the tradeoff between packing densities and crosstalk.

II. Fabrication of a Transmitter Using Array Devices and Estimation of Optical Signal Propagation

The pin grid array (PGA)-packaged 2-D VCSEL array in use has a total of 64 elements with 250-μm spacing. In order to

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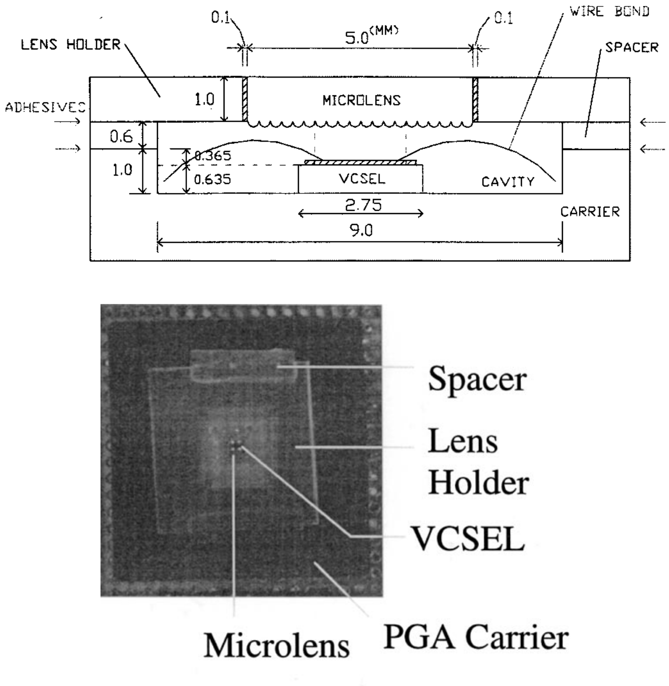


Fig. 2. (a) A detailed drawing for a transmitter packaging and (b) photo of packaged VCSEL with microlens array.

specify the acceptable interconnect distance in free-space implementation using array devices, the divergence and far field output profiles were measured at distances of 1 mm and 2, 4, and 6 cm from the emission window of VCSEL. By estimating the full width at half maximum (FWHM) spot size, the divergence angle is determined to be 7.5°. Based on these results, the maximum propagation distance of beam array, without severe overlapping with the adjacent beams, cannot be longer than 7.5 mm, even for 1-mm spacing array of beams. Hence, the diverging laser beams should be collimated in the free-space optical bus. Given the window radius of VCSEL (4 μm in our case) and the optimal focal lengths of lens for 250-, 500-, and 750-μm-, and 1- and 1.5-mm array beams, the simulation results of beam propagation performance show that the interconnect distances can reach 3, 12, 25, 45, and 60 cm, respectively [4]. We chose commercially available microlens array, which has a 1-mm focal length and a 250-μm pitch, to generate 2×2 500-μm and 750 μm and 1-mm array beams.

The package containing the PGA-packaged VCSEL and the microlens array is carried by the Melles Griot six-axis aligner and ultraviolet (UV) curable epoxy. First, the microlens is held in a transparent plastic carrier or lens holder as shown in Fig. 2(a). This package is mounted to allow translation in x, y, and z axis and rotation in roll, pitch, and yaw. The spacers, which have a thickness of 0.6 mm, are attached to the top of PGA VCSEL carriers applying UV curable epoxy. After the package of each element is complete, the microlens holder is brought down or up to the surface of the 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. Fig. 2(b) shows the final packaged transmitter including wire-bonded VCSEL's, PGA carrier, and microlens array. With a packaged transmitter, the FWHM

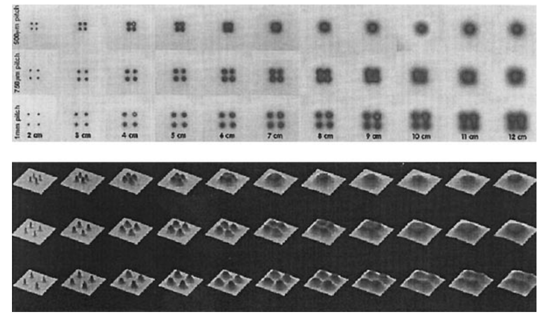


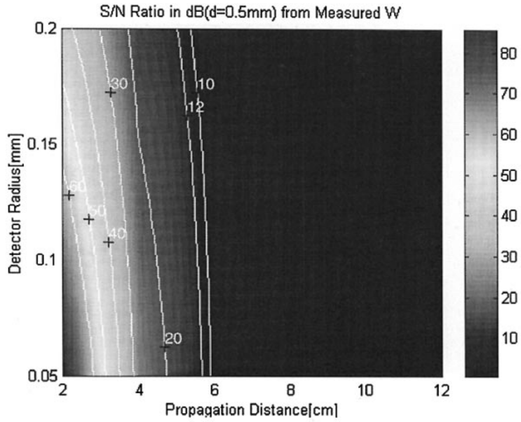
Fig. 3. Degree of overlapping between 2×2 optical beams.

divergence is measured to be 0.6°. The beam propagation is improved from 7.5° to 0.6°, which means the FWHM spot size is less than 1 mm at around a distance of 10 cm.

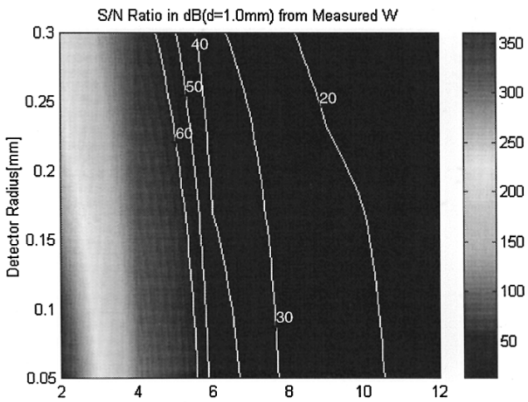
III. Experiments of Data-Transfer Performance in Continuous Signals

The overall performance of a multibus optical interconnect device depends on the data modulation rate of the transmitter, the power budget efficiency, the bandwidth of the optical path and receiver, environmental noise, and other factors. In our implementation of the optical bus, a microlens array is used to collimate the lights from VCSEL's 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 detectable amounts of power, but also generate the optical crosstalk that degrades bit-error-rate (BER).

Fig. 3 shows the results of crosstalk measurements between 2×2 bus lines in terms of propagation distances and selectable array spacing in our transmitter. It should be noted that the measurement setup includes VCSEL, microlens, hologram arrays, and substrate. The 2×2 beams from the PGA-packaged VCSEL were collimated by the microlen array, coupled into substrate through a hologram (recorded on DuPont photopolymer film using two beam interference method), then taken through total internal reflection inside substrate (BK7 and 0.5 cm in thickness), coupled out through another hologram, and finally detected by a CCD camera. As can be expected from beam propagation simulation, the 2×2 beams of 500- and 750-μm spacing overlap completely after 7- and 11-cm propagation and resemble a single Gaussian beam spot. For 1-mm spacing beams, the detected profiles seem to be discernible up to 11 cm. By considering the circular symmetric shape of VCSEL output, the beam radius at the detector position can be measured from three-dimensional images. If there is a 2×2 photodetector with an active radius of R and spacing d, the signal-to-noise ratio (SNR) can be estimated [4]. The SNR contours from measured and calculated beam radius, which are obtained from the lens formula, are simulated from previous theoretical and experimental studies. Among them, Fig. 4(a) and (b) shows the variation of SNR with those of the active radius of a detector and measured beam radius from output profiles from 500-μm and 1-mm spacing 2-D bus lines. In all cases, the variation of SNR is much more sensitive to the propagation distance than to the active area of a detector, i.e., equi-SNR lines drop sharply as the interconnect distance increases. The interconnect



(a)



(b)

Fig. 4. SNR simulation (a) for 500 μm array spacing and (b) for 1-mm array spacing from measured beam radius.

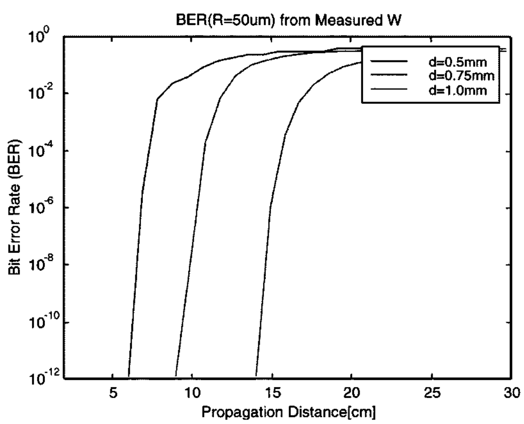


Fig. 5. BER to determine the interconnect distance.

distance can be increased also by increasing the array spacing, which decreases packing density. For 1-mm array spacing, the interconnect distance may be longer than 12 cm to satisfy a SNR of 7.2.

The BER can be calculated from the results of SNR estimations. SNR must be larger than 7.2 to satisfy the value of BER$= 10^{-12}$, (required for data communication) and 6.1 for BER$= 10^{-9}$. Fig. 5 shows the calculation results of BER from measured beam radius. These results match the beam propagation simulation using a 1-mm focal length lens. The agreement between theoretical and experimental results shows that the interconnect distance can be even longer if we use a 5-mm focal length lens for 1-mm array spacing. It clearly follows from a simple estimation of SNR and BER that the interconnect distance for 10^{-12} BER is more than 45 cm with optimal lens parameters. Therefore, the proper choice and usage of the lens array will be a key issue for a longer distance interconnection in free-space application.

IV. Summary

We have described a microchannel-based optical bus system implemented with 2-D array devices, which include passive and active optical elements. The design of a transmitter using VCSEL and microlens array to implement 500- and 750-μm, and 1-mm 2×2 bus spacing limits the maximum interconnect distance due to the divergent nature of the laser source in free-space board-to-board interconnects. Therefore, to increase the number of boards to be connected, the fabrication of a transmitter employing a refractive microlens array permitted the improvement of beam propagation to 0.6° of divergence with a 1-mm focal length. The optical crosstalk caused by the divergence and misalignments have also been studied using a microlens packaged VCSEL. It has been shown that 2×2 array beams overlap completely after 7- and 11-cm propagation in cases of 500- and 750-μm optical bus spacing. On the other hand, the implementation of 2-D bus lines of 1-mm optical bus spacing still has some margin for crosstalk with an 11-cm interconnect distance. The more accurate analysis between BER and interconnect distance has shown that 6-, 9-, and 14-cm optical interconnects for 10^{-12} in BER are achievable distances with 500- and 750-μm and and 1-mm 2-D bus spacing, respectively. A longer interconnect distance can be achieved using lens with focal lengths from 4 to 5 mm within the same design and fabrication concept. It is possible to implement 45- and 60-cm interconnects with 1- and 1.5-mm array spacing. The primary problem that arises in using larger array spacing is packing density. Therefore, the tradeoff between packing density and optimum interconnect distance will be a major consideration in future approaches to multibus line optical backplane for free-space board-to-board interconnects.

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