A Method for Rebroadcasting Signals in an Optical Backplane Bus System

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***Abstract*—A guided-wave optical backplane bus system intended for use in high-performance board-to-board interconnects is described. Its multiplexed polymeric holograms can implement optical signal broadcast between boards so that all boards share common optical channels. By introducing an active coupler to the doubly multiplexed hologram at the center board, signals received from any board can be rebroadcast to all other boards.**

We describe the design concepts for a centralized optical backplane and the resulting performance and assembly advantages over previously developed guided-wave and free-space optical backplane bus systems used for broadcasting signals. These advantages include equalized fan-out power, increased interconnect distance, and simpler fabrication.

***Index Terms*—Broadcasting, hologram, optical backplane.**

I. INTRODUCTION

THE CURRENT generation of computers is limited by the speed at which information can be transmitted between such electronic components as processor and memory chips. Under current conditions, bus traffic increases as the computing power of the microprocessor increases. Therefore, the limited bus bandwidth constitutes a major bottleneck to efficient communications among board-to-board data interface. The development of technologies for communications within a box that would replace the conventional passive backplane is desirable in order to achieve higher data throughputs. There are two major approaches to the optical backplane to overcome this limitation. The free-space optical backplane bus system [1] uses free-space channels and diffractive optical elements (DOEs) to direct the signal beams. In the guided-wave optical backplane system [2], [3], optical beams travel by way of total internal reflection (TIR) within the waveguiding substrate, and DOEs are used as beam-splitter/deflectors.

The main function of a backplane bus is to provide the signal path for broadcasting. Any board should be capable of sending and receiving the signals. The signal that is broadcast in an optical backplane is generally realized by implementing a bidirectional signal path and one-to-many fan-outs. In a one-to-many fan-out optical interconnect including an optical backplane, the uniformity of fan-out power distribution is critical to its applications because the nonuniformity of fan-out power makes it more difficult to integrate with optical detector arrays and with other optical signal-processing elements. No successful results of uniform fan-outs in the bidirectional optical broadcasting devices have been reported yet. The difficulty in achieving uniform fan-outs for the bidirectional optical backplane is mainly due to the bidirectionality of signal flows. Optimizing the diffraction efficiencies of DOEs was applied before, but it was impossible to obtain evenly distributed powers for all boards in the bidirectional optical backplane [3].

We describe a new method for broadcasting signals based on a guided-wave optical backplane approach (see Fig. 1 for a schematic diagram). In this system, the conventional electrical connectors take their usual positions, in which the active optoelectronic modules including transmitters and receivers are placed on the bottom of the electrical backplane board. Thus, the insertion or removal of circuit boards during the normal operation does not affect their alignment. This approach also provides bidirectional signal broadcast distribution, which means any board can send and receive the signals. In this way, this system is compatible with existing electrical boards. This method for broadcasting signals is discussed in greater detail in Section II. In Section III, we compare the applicability and advantages of this method to other approaches, and in Section IV, offer a summary.

II. DESIGN OF THE CENTRALIZED OPTICAL BACKPLANE

By introducing an active coupler at the position of a center board, we can implement a centralized optical backplane wherein signals are broadcast from the center board to all other boards. Any signal transmitted from all boards is first delivered to a receiver on a center board (called, by us, a "distributor"). Then, the transmitter on the distributor sends the same or modified signals to all the other boards. In other words, this centralized optical backplane bus utilizes two optical signal paths: one sends signals from a board to a distributor, and the other broadcasts them to all boards that are designed to receive the signals. It should be noted that the latency is the same as in any other optical backplane bus, because latency, like bandwidth in the optical backplane bus, is determined by the longest signal path.

Fig. 2(a) shows a signal flowing from the boards to a center distributor. This is part of the backplane system shown in its entirety in Fig. 1, and its purpose is to collect data transmitted from the boards. In this figure, five boards are connected, but they could represent any number of boards. Only the distributor (a center board) requires a doubly multiplexed hologram (DH). All the other boards accommodate single holograms (SHs). The holograms for Boards 1 and 2 are designed to direct the optical beams to the right ($+x$ axis); holograms for Boards 3 and 4

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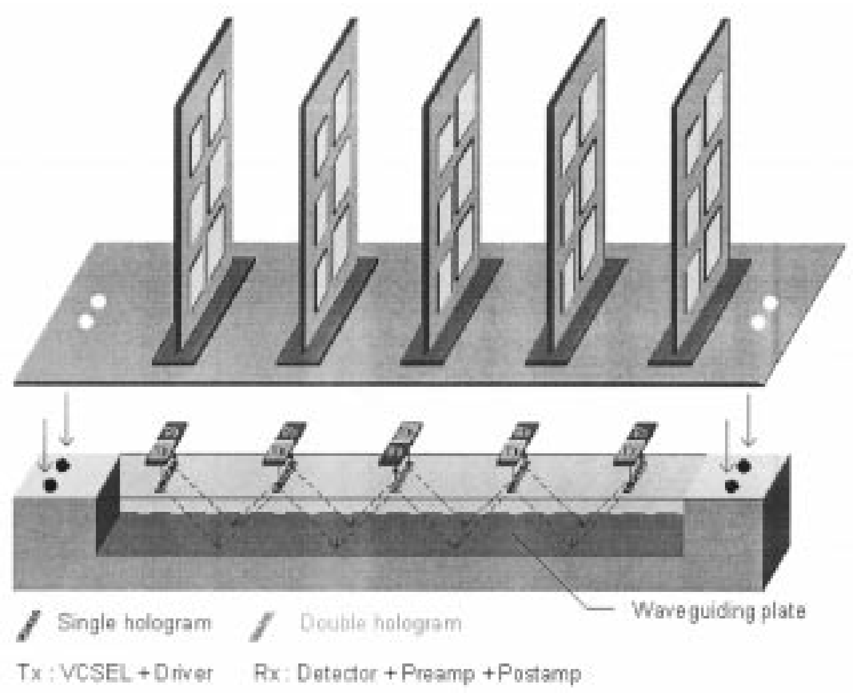


Fig. 1. Schematic diagram of the centralized optical backplane bus system for board-to-board interconnects. The distributor in a center board has functions of collecting and rebroadcasting optical signals by virtue of a doubly multiplexed hologram.

are fabricated so that optical signals travel leftward ($-x$ axis). As explained later, the same holograms rebroadcast the signals from the distributor to the designated boards. The distributor and other boards differ in type of active devices. The transmitter is used for boards that are intended to send signals, while the receiver is used for the distributor to collect optical signals. The signals received by the distributor are transferred to electronic circuitry, which in turn drives the laser source [here, the vertical cavity surface emitting laser (VCSEL) and the line driver] to broadcast signals to all boards.

Fig. 2(b) shows the signal distribution from a transmitter in the distributor to receivers in the boards. Optical beams from the transmitter in the distributor divide in two directions by way of the 50/50% doubly multiplexed hologram, acting here as beam splitter and deflector. After optical beams are coupled into the substrate, they travel by total internal reflection inside the guiding plates until they reach the designated position of the single hologram. A portion of optical power is coupled out to the receiver through an SH, and the remainder continues to propagate to the next hologram positions. The amount of power coupled out depends on the diffraction efficiencies of the holograms, which can be controlled for an efficient power budget. It should be noted that the left- and right-placed optical element (OE) modules are symmetrically arranged around the distributor: symmetrical as to their positions, the diffraction efficiencies of their hologram, and the type of active optical device.

III. CHARACTERISTICS OF THE CENTRALIZED OPTICAL BACKPLANE

A multiplexed system is always limited as to its power budget by the output channel with the minimum power. Due to the bidirectionality of the optical bus, which is implemented with doubly multiplexed holograms (Fig. 3), it is impossible to obtain fan-outs of uniform intensity for all the cases where the modulated optical signals originate from different boards. Even optimizing the diffraction efficiencies of the holographic gratings still results in nonuniformity among output signals in earlier reported optical backplane designs based on the guided-wave approach [3]–[5]. In a free-space optical bus system [6], [7], optimization is also required, as well as a large number of holograms to provide signal broadcasting (Fig. 4). These systems' maximum broadcasting efficiency is 25% with 75% power loss, and the detected power variation is 2.8–11.3% for four-board interconnects [6]. Thus, each output requires different receiver gain and sensitivity to detect the signals. This complexity limits the performance of the multiboard interconnect system and complicates the corresponding receiver fabrication.

In the centralized optical backplane, the power of fan-outs is equalized by simple control of the diffraction efficiencies for single gratings. This feature is its main advantage and is due to the symmetric configuration of DOEs. Fig. 5(a) shows that the fan-out power is equalized when the distributor broadcasts signals to all boards. The DH for the distributor directs 50% of the power toward the left and the right, respectively, equalizing power distribution in both directions by virtue of a 50/50% DH. In addition, the symmetric configuration of SHs satisfies

$$\eta_i = \eta_{-i}. \tag{1}$$

Further, because all remaining power at the nth board and $-n$th board is coupled out through holograms, the final holograms at each end require 100% diffraction efficiency. With this conceptual basis, the output power in the ith board is expressed as

$$0.5 \cdot (1-\eta_1)(1-\eta_2)\cdots(1-\eta_{i-1})\eta_i \tag{2}$$

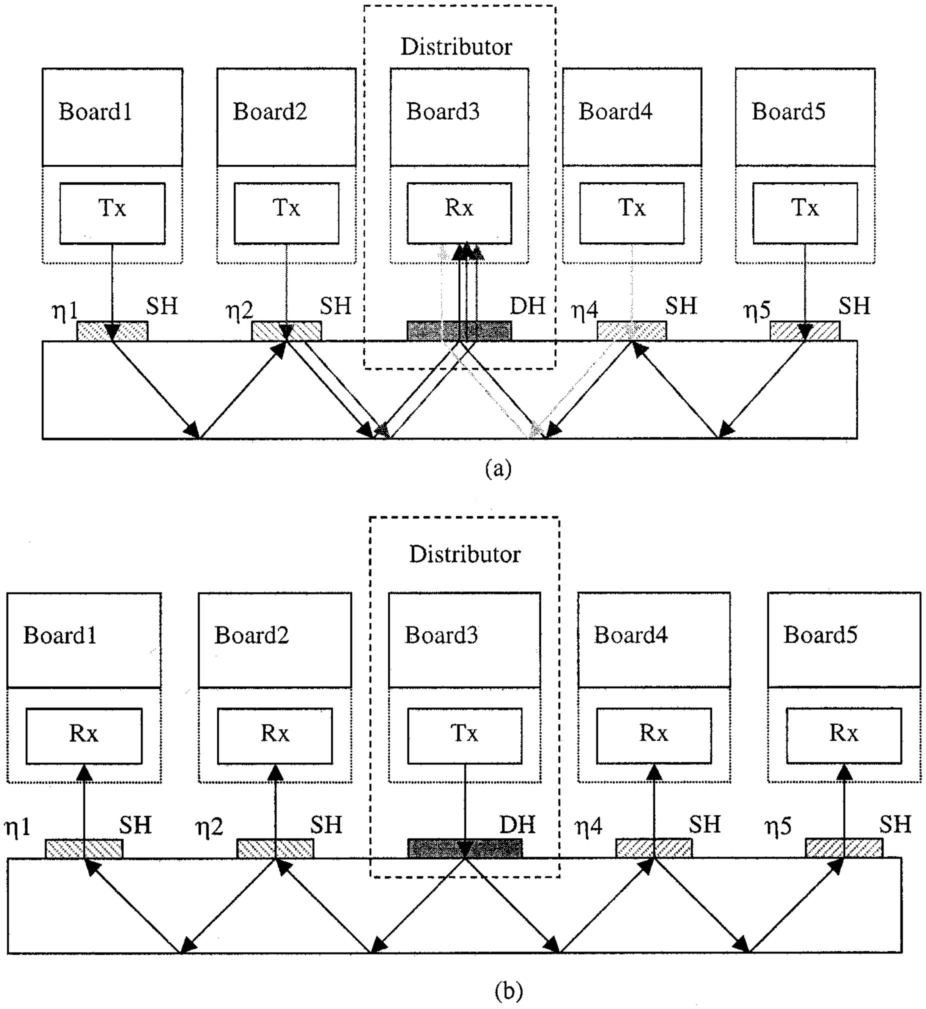


Fig. 2. (a) Signal flows from any boards to a receiver in distributor. (b) Signal rebroadcasts from a transmitter in distributor to all boards.

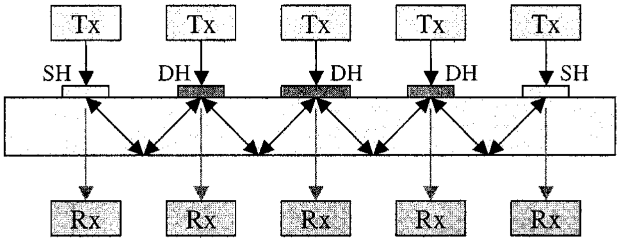


Fig. 3. Signal broadcast in guided-wave optical backplane implemented with doubly multiplexed holograms [3].

and the output power in the $(i{+}1)$th board as

$$0.5\cdot(1-\eta_1)(1-\eta_2)\cdots(1-\eta_{i-1})(1-\eta_i)\eta_{i+1}. \quad (3)$$

To equalize power output to the receiver, the two power equations [(2) and (3)] must be equal. Therefore, the condition for equalized fan-out power is simplified by

$$\eta_{i+1}=\frac{\eta_i}{1-\eta_i}, \text{ or equivalently, } \eta_i=\frac{\eta_{i+1}}{1+\eta_{i+1}}. \quad (4)$$

Basically, this is the same equation as the condition in the unidirectional surface-normal even fan-outs device. This similarity is a logical result because a centralized backplane uses all single holograms for both propagating directions of its optical beams. For example, the diffraction efficiencies of all five holograms in a five-board interconnect system are easily calculated, starting from 100% for η_{-2} and η_{+2}, then 50% of efficiency for η_{-1} and η_{+1} by applying (4), and finally 50/50% for center doubly multiplexed hologram. In this example, all output powers share 25% of input power ($0.5 \times 0.5 \times P_{\text{in}}$).

It is of interest that the power delivered from a transmitter in any board to a receiver in the distributor is automatically equalized under the conditions of the same hologram configurations as in the equalized fan-out scheme. Consider the optical signals from the ith and $(i{+}1)$th boards, as shown in Fig. 5(b). To deliver the same amount of power to the distributor, $\eta_i P_i$ should be equal to $\eta_{i+1}(1-\eta_i)P_{i+1}$. The ratio of $(1-\eta_i)$ comes from the diffraction loss that occurs after TIR takes place between the ith hologram film and the air interface. Therefore, the same power will be delivered to the distributor if $P_i = P_{i+1}$ (with the same input power). As a result, the condition for delivering equalized optical power from a board to the distributor is automatically satisfied with the same configuration of hologram efficiencies.

Another issue we have to consider is the polarization dependency on the diffraction efficiency. As the efficiency varies

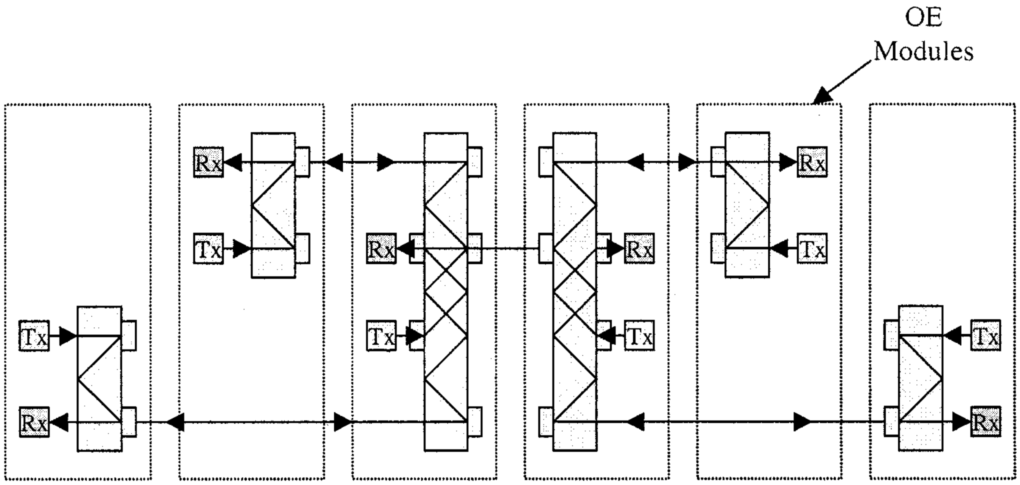
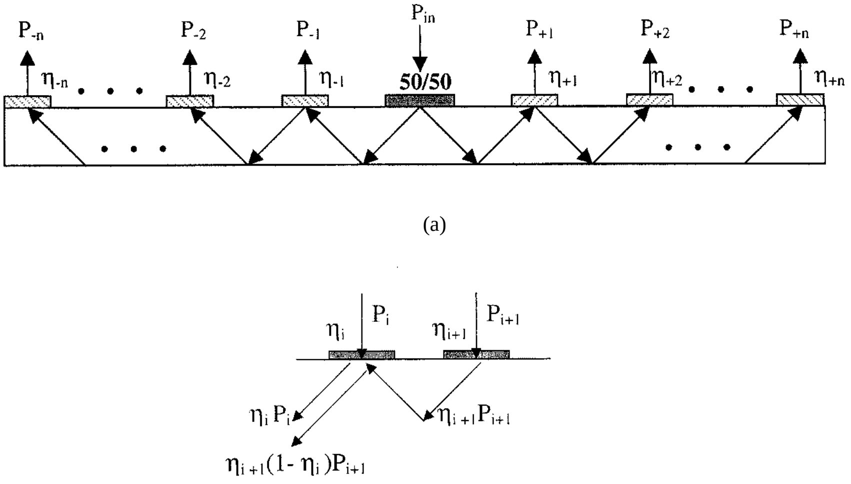


Fig. 4. Signal broadcast in free-space optical backplane implemented with many holograms [6].



(a)

(b)

Fig. 5. (a) Equalized fan-out scheme for $(2n+1)$ boards interconnects. The output power is delivered to all boards with equal amount of power. (b) Power delivery from ith and $(i+1)$th boards. The same power is delivered to the distributor wherever the optical signal originates.

with the state of the polarization of input optical signal, there is a tradeoff between energy equalization and polarization sensitivity. For a five-board interconnect system designed for the randomly polarized optical signal, the equalized fan-out power distribution will be changed because of the migration of the corresponding efficiencies of the output holograms. Therefore, in designing equalized fan-out devices, the polarization of an input beam has to be specified.

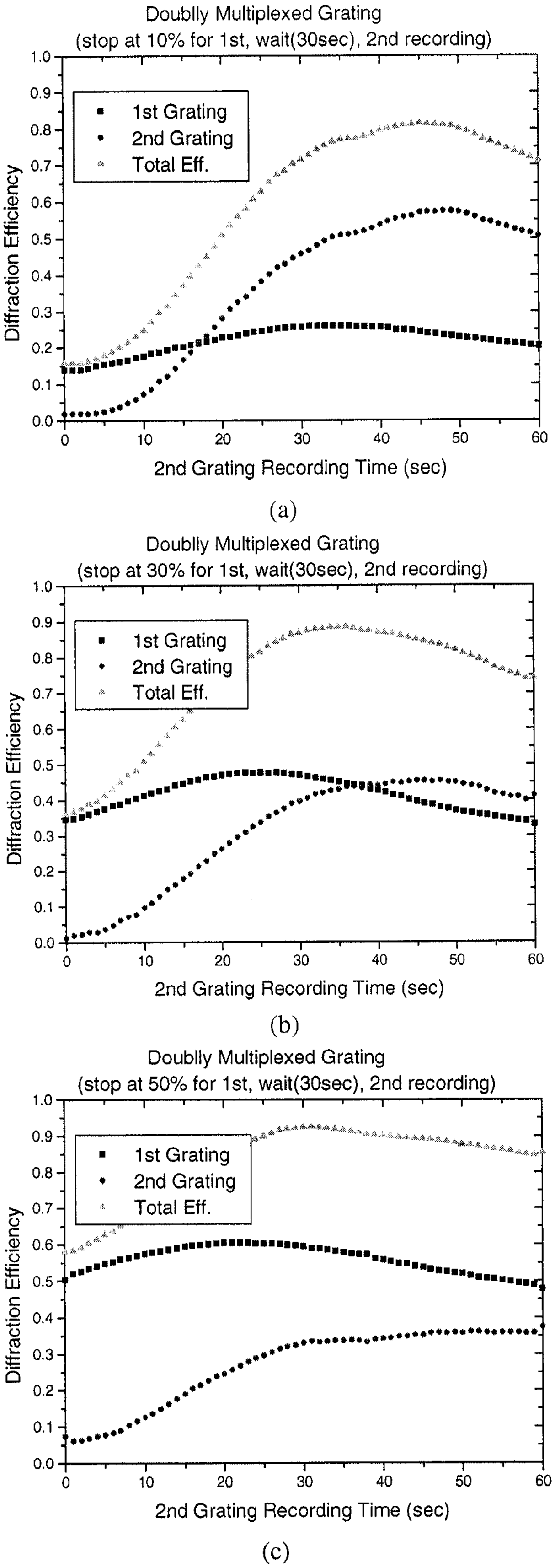
Holograms were formed in DuPont HRF600X001-20 and 20-μm-thick photopolymer films on a mylar backing. This material is sensitized for recording at 514 and 532 nm and has much lower sensitivity to 632.8 and 850 nm, allowing for real-time monitoring during hologram formation [8]. Samples were prepared by removing the thin cover and then laminating the film surface onto a quartz substrate. The substrate was then mounted on a right-angle prism, which could be rotated on a rotation stage and a goniometer. The power ratio of two recording beams is controlled by using a polarization beam splitter. By introducing a right-angle prism, we can detect the powers of the diffracted beam and the undiffracted beam through detectors, and the results are saved in a graphic recorder.

The recording setup for the fabrication of a doubly multiplexed hologram is similar to that of single gratings except that two diffracted beams are detected in the former. Because the two gratings are recorded in the same plotopolymer film, the first grating is fabricated as usual, and then the substrate is rotated 180° for the second exposure. Fig. 6 shows the results of real-time monitored efficiencies versus exposure time for the second grating with the 10%, 30%, and 50% stop efficiency of the first grating. It can be seen that the diffusion of monomers increases the efficiency of the first grating under lower exposure. If the exposure was stopped at a point lower than 50%, we could expect a 5% efficiency increase during the waiting time. Another interesting phenomenon can be seen from the variation of the first grating efficiency during the second exposure for the second grating. The efficiency of the first grating increased during the second exposure, but it decreased soon after it reached the maximum. The required times for maximum efficiencies in the first gratings during the second exposure are different from each other. As the first grating's stop efficiency increases, the first grating was saturated earlier.

With the help of the real-time monitoring technique, the doubly multiplexed grating with equalized strength can be fabricated easily. The corresponding time for a second grating is the crossing points in the efficiency curves. For example, if the first grating has an efficiency of 30%, we can stop recording immediately after 37 s of exposure, and then there is a 45/45% doubly multiplexed hologram. It should be noted that the crossing points never occur when there is an efficiency of higher than 30% in the first grating. This value is approximately at one-third of the total maximum efficiency. In the experiments described here, the maximum of total efficiency is 90%, so we can achieve a 45/45% doubly multiplexed hologram, fabricated with 30% of the first grating's efficiency. This result seems to be reasonable, because the first grating has effects on the second grating at 1/3 of total efficiency. If the efficiency of the first grating is higher than this value, the second exposure could not be enough to overcome the strength of the first grating. On the other hand, if the efficiency of the first grating is lower than one-third of the total maximum efficiency, the second grating is much stronger. Even though the efficiency of the first grating still increases by virtue of diffusion, the polymerization from the second exposure becomes more significant. In conclusion, it can be said that equal strength of a double grating can be obtained easily with real-time efficiency monitoring, and the efficiency is controlled by changing the first grating strength.

Fig. 7 shows photographs of the outputs from centralized optical backpalne channels with (a) three boards and (b) five boards in a single bus line. An 850-nmVCSEL in TO-46 can with a dome lens (VCT-B85B20 from Lasermate Corp.) was used as a tramsmitter in the distributor. The diffraction efficiencies of doubly multiplexed holograms are equalized (45/45%), and the efficiency of single grating for five-board interconnection is designed to be 50%. The output variation observed from three-dimensional photographs and an optical power meter could be controlled within 2% by virtue of an evenly distributed power scenario. Fig. 7(c) shows the broadcasted optical signals in a multibus-line centralized optical backplane. The detected output variation is the same as that in a single bus line, making it possible to increase the aggregate throughput using two-dimensional (2-D) active array devices with the same backplane device. It should be noted that the total length of the device, or total interconnect distance, is 9.2 cm, and the spacing between boards is matched with the standard spacing in a VME bus backplane specified by IEEE 1014–1987 and ANSI/VITA1–1994.

To demonstrate the data transfer performance of our device, eye diagrams at data rates of 155 Mb/s, 500 Mb/s, 622 Mb/s, 1 Gb/s, 1.25 Gb/s, 1.5 Gb/s, 2 Gb/s, and 2.5 Gb/s (nonreturn-to-zero with a $2^{31}-1$ pseudorandom bit sequence) were measured. Much information can be obtained from the measurement of the eye diagram, such as bit error rate (BER) and jitter in an HP83480A. The eye openings are 212, 216, 206, 203, 218, 200, 182, and 149 mV, respectively. Even up to a data speed as high as 2.5 Gb/s, our experimental results showed sufficient eye openings. The measured values of the

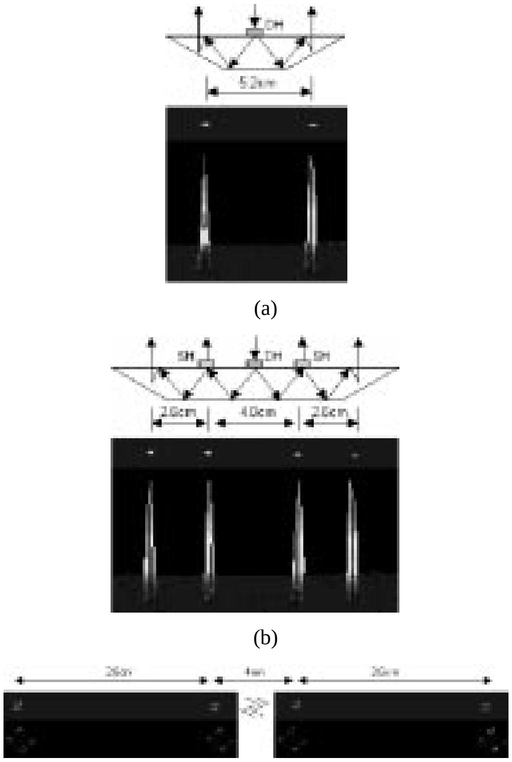


(a)

(b)

(c)

Fig. 6. Variations in the diffraction efficiencies when the second exposure is applied. The first exposure was stopped when the efficiency of first grating reached (a) 10%, (b) 30%, and (c) 50%, and then the second exposure started to achieve the equalized efficiency of double grating.



(a)

(b)

(c)

Fig. 7. Photographs of surface-normal outputs in a centralized optical backplane bus for (a) three-board and (b) five-board interconnects with single VCSEL and (c) five-board interconnects with 2 × 2 VCSEL arrays (1 mm array spacing).

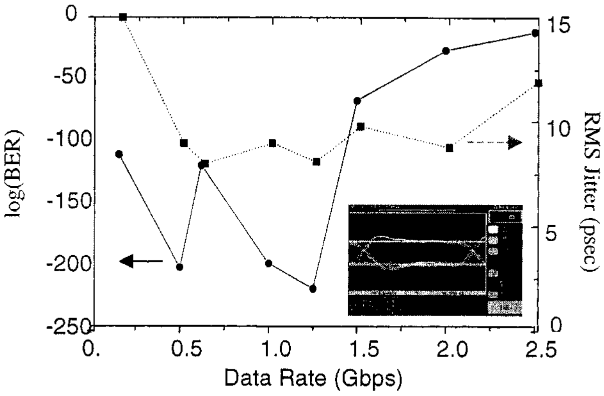


Fig. 8. Results of data transfer performance in digitally modulated signals.

Q-factor and the results of conversion to BER are shown in Fig. 8. Fig. 8 also shows the results and jitter measurements based on the measured eye diagrams. The experimental values of BERs at all data rates are less than 10^{-15}, and the jitter in the worst case is 15 ps. With speeds of less than 1.5 Gb/s, we may see the error-free region. Starting from 1.5 Gb/s in the data rates, the BER is not very sensitive to the increase of the data rate, but finally it does reach 10^{-12} at a rate of 3 Gb/s. It is here concluded that our optical devices for board-to-board interconnect meet the performance requirements to transfer data at 2.5 Gb/s per channel.

Another important advantage of this rebroadcasting method arises out of the function of the distributor. The distributor consists of a receiver, a doubly multiplexed hologram, and a transmitter. In our design, the interconnect distance increases twice by virtue of the distributor and the distributor is similar to a dedicated regenerator in a fiber-optic system. It may be used to detect a weak optical input signal and regenerate a sharp and clear signal waveform. Therefore, the maximum interconnect distance can be 45 cm, which corresponds to a 15-board interconnect system, with 2-D bus lines if we use a 5-mm focal length lens [5], [9].

Our approach also reduces the number of fabrication steps required by other, earlier designs. Because the fabrication of a DH takes twice the time as that of an SH and requires significant effort to reach exact diffraction efficiency, it is better if we can reduce the usages of DHs. A centralized optical backplane for n-board interconnects requires $(n-1)$ SHs and one DH. By contrast, a previously reported guided-wave optical backplane has required $(n-2)$ DHs and two SHs [3]. Also, a free-space optical backplane is even more demanding; 10SHs and one DH would be needed to implement even a four-board broadcasting system.

IV. CONCLUSION

We have introduced a new method for broadcasting signals in an optical backplane bus system based on guided-wave interconnects. By introducing a distributor in the center board, which consists of a receiver, a DH, and a transmitter, all signals coming from boards are collected in a receiver in the distributor and then rebroadcast from the transmitter in the distributor to all boards. This method shows a variety of advantages.

1) The power broadcast to the designated boards is uniform. We consistently achieved the equalized fan-out intensity by simply controlling the diffraction efficiencies of single holograms.
2) We were able to double the interconnect distance over previous implementations. The distributor can serve also to amplify weak signals, to reshape them, and to broadcast clean signals to all the boards.
3) The total number of holograms and the number of doubly multiplexed holograms are fewer in our approach, decreasing the number of steps to fabrication.

A centralized optical backplane may be modified using bulk optics. The two single holograms in the last two boards at the edge must have 100% diffraction efficiency. These holograms can be replaced using a substrate with a 22.5° bevel angle that provides 100% coupling to the substrate. This is more convenient because 100% diffraction efficiency of SH is difficult to achieve in practice. It is possible also to use a right-angle prism instead of a receiver and a transmitter in the distributor. In regard to routing signals, this prism has the same function as the combination of receiver and transmitter.

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