3.2Gbps multi-channel optical backplane bus demonstrator using photopolymer volume gratings

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ABSTRACT

A 3-slot optical backplane bus demonstrator based on glass substrate with photopolymer volume gratings array (PVGA) on top surface is built to allow 16 channels of data to be broadcast from central slot to two daughter slots or uploaded from any daughter slot to central slot. VCSELs and photodetectors packaged in the form of TO-46 can are assembled on top of each PVG and interleaved to reduce the crosstalk to below noise level. By carefully aligning the fabrication system, the incident angle deviation from Bragg condition is reduced to below 0.1° to maximize optical power delivery. The orientation and period of hologram fringes are uniform in the active area by collimating recording beams.

Above 4.8Gbps aggregated data transmission is successfully demonstrated using the multi-channel system. Three computer mother boards using FPGA are made to verify the data transmission among the slots. Interface boards between the FPGA boards and optical transceivers are designed and fabricated to separate the implementation of digital layer and optical layer. Single channel transmissions with 3.2Gbps and even 10Gbps data rate are also tested with above 100uW input power, showing the potential to improve the total two-way bandwidth to above 102.4Gbps. Alignment tolerance of the optical interconnect system is investigated theoretically and experimentally. By analyzing the diffractive characteristics, the bandwidth limit of the optical layer is determined to be in the order of Terahertz. Design and fabrication issues are discussed for future optical backplane bus to make terahertz bandwidth into reality. Based on the experiments for Bit-interleaved Optical Backplane bus and Multi-channel optical backplane bus demonstrators, theoretical analysis of the bandwidth limit of the optical backplane bus using photopolymer volume gratings has been carried out.

Keywords: Optical Backplane Bus, Optical Interconnect, Multi-Channel, Photopolymer Volume Gratings

1. INTRODUCTION

It is widely accepted that optical interconnects will penetrate into the computer box at least for high performance computing (HPC) systems as the product of distance and bandwidth surpasses the capacity of electrical interconnects. At the board-to-board hierarchical level, the centralized optical backplane bus architecture successfully demonstrated using photopolymer volume gratings (PVGs) at a data rate of 1.25Gbps [1] possesses advantages including the ability to broadcast information without sacrificing bandwidth. Bit-interleaved optical backplane bus was also implemented using centralized architecture [2] to provide high speed secure data transmission. Basically, in optical backplane bus, there is a center board which we call the "distributor", performing data collection and re-broadcast, as shown in Fig. 2. The data output from any CPU or memory modules is first converted into optical signal, then the hologram gratings will bend the light that is perpendicular to the glass substrate surface by 45° so that the light signal can propagate along the glass substrate and reach another piece of hologram designated for other boards. The function of the hologram grating is to fan-in and fan-out partial of the light signal so that the data could be delivered to all boards except the transmitter board.

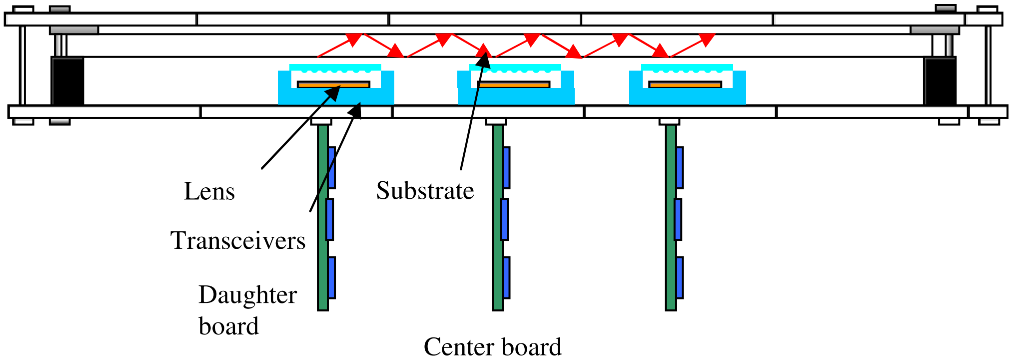


Fig. 1. Illustration of optical backplane bus with three boards: Hologram gratings on the surface of glass substrate can bend the propagation direction of light. Light emitted by the VCSEL, collimated by lens , projected normally to the surface of hologram films will be diffracted by 45° into the glass substrate and reach another piece of hologram designated for another board. The center board collects data and re-broadcast to all daughter boards.

As the clock frequency of CPU, the number of cores within one CPU, and the bit width increasing at a rapid rate, the demand on the communication bandwidth is still rising in the supercomputing industry. It has been widely recognized that optical interconnects are required to supply multi-Terahertz data transmission among the processor boards inside a box. During the work previously demonstrated, we have shown that the data rate for a single channel can be in the order 10Gbps, which is mainly limited by the speed of optoelectronic components and high-speed TIA sensitivity.

In this paper, we continue to investigate the bandwidth limit in the optical backplane bus. Based on the theoretically simulations and experiments, we designed and implemented the first 16-channel-3-board optical backplane bus system based on photopolymer hologram grating arrays. The final data density is determined by the optical crosstalk and signal power.

2. ANALYSIS OF BANDWIDTH LIMIT OF POLYMER GRATINGS BASED OPTICAL BACKPLANE BUS

For a high-channel-count high-density optical backplane bus, the most important factors that ensure the delivery of sufficient optical power to each channel and low channel-to-channel crosstalk are angular misalignment and lateral tolerance. In the Fig. 1 which shows the architecture of the optical backplane bus based on PVG, the physical layer includes a glass substrate to confine light beam, hologram grating to fan-in and fan-out light, lasers and detectors with lens for data transmission, and mechanical components for alignment. Using another layer called interface layer which includes laser driver and trans-impedance amplifier, the digital communication layer works as if it is using electrical interconnect. The layered architecture helps to delineate the optical design from the electrical design. Both multi-channel and the bit-interleaved demonstrator can share the common physical layer and interface layer. Therefore, the study of the optical property of the hologram diffraction will help to investigate the optical crosstalk and power issues for both cases. Several parameters that influence the ultimate bandwidth in polymer grating based optical backplane have been mentioned in reference [2].

2.1. Diffraction properties of hologram gratings and angular tolerance

In the Fig. 2. that illustrates the beam directions when diffraction happens in hologram grating, the angle from surface normal to the incident light is $\pi + \theta'$, and the angle from surface normal to the grating vector **K** is ϕ. The propagation constant of the incident light is β.

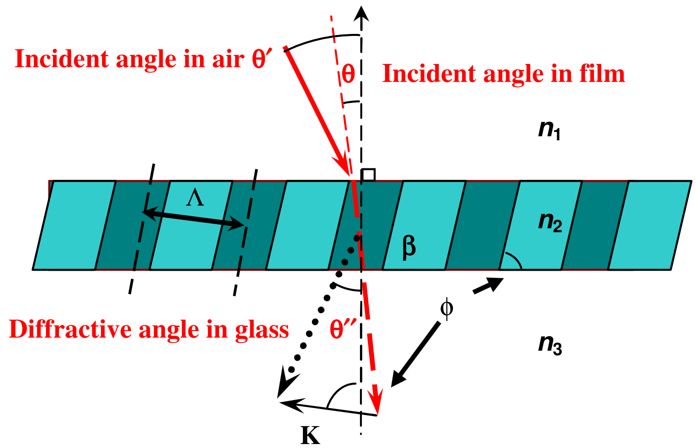
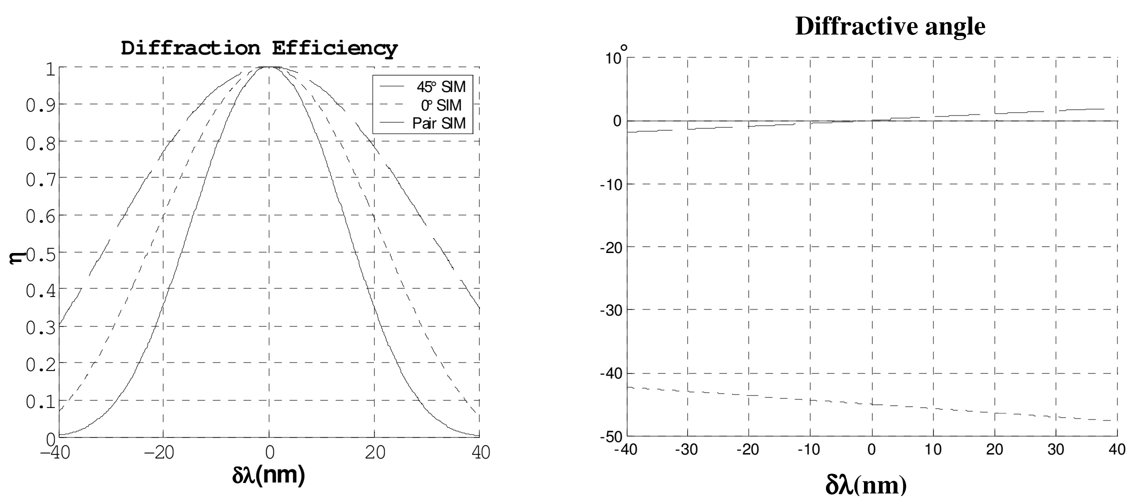


Fig. 2. Illustration of the geometry of the diffraction: The solid light shows the incident light which is $\theta°$ from surface normal. The grating vector **K** is $\phi°$ from surface normal. In the current configuration in this figure, the angles take positive values.

Among the analysis of the optical properties such as diffractive efficiency, bandwidth, optical crosstalk, and power, the diffractive efficiency versus wavelength or incident angle is the basic of all analysis. According to Kogilnik's theory [3], the diffraction efficiency can be calculated and diffractive angles are related to the incident angle according to formula (1):

$$n_3 \sin\theta'' = n_1 \sin\theta' - \frac{\lambda}{\Lambda}\sin\phi \tag{1}$$

Fig. 3(a) shows the simulation result of diffraction efficiency versus wavelength deviation from 850nm for TE mode. The hologram grating in the simulation is assigned with a thickness parameter of 20nm and index modulation depth of



(a) (b)

Fig. 3. (a) Diffraction efficiency versus wavelength for TE mode: dotted line is for light with 0° incident angle, dashed line is for light with 45° incident angle and solid line for a light beam to go through a pair of hologram grating; (b) diffractive angle versus wavelength deviation for TE mode: dotted line for a scenario with 0° incident angle and dashed line for 45° incident angle.

0.018 so that the maximum diffractive efficiency could be 100% at 850nm. The 3-dB fan-in bandwidth for 0° incident angle is around 45nm, and the bandwidth for 45° fan-out process is around 62nm. Fig. 3(b) shows that for an input beam with 0° incident angle but a wavelength other than the 850nm design wavelength, the diffractive angle will be different with 45°. The calculation of the diffractive angle based on formula (8), could be re-applied as the incident angle of the fan-out process to obtain the fan-out diffractive efficiency. Then we could obtain the ratio of throughput optical power, as shown in the solid line in Fig. 3(a), defined as the ratio of a light beam to go through a pair of hologram gratings with mirrored fringe pattern. The 3dB throughput optical bandwidth is 36nm according to the calculations.

The fan-in diffraction efficiency versus incident angle is plot in Fig. 4 to show the angular dependency of TE and TM mode. From the calculation, the maximum efficiency of TM mode is only 82% while it is 100% for TE mode with same index modulation depth. However, the normalize TM efficiency curve almost overlaps with the TE fan-in curve, as illustrated in Fig. 4, which means the TM mode diffractive efficiency is almost proportional to that of TE mode for different incident angle. According to this result, instead of using both TE and TM formulars, we use TE mode only in all calculations and it is accurate enough for angular bandwidth. However, the fan-in and fan-out efficiency will not reach 100% if the laser light has both TE and TM mode. In the worst case, the laser output consists equal amount of TE and TM power, the final throughput efficiency will be (100% × 100% + 82% × 82%) / (100%+100%) = 83%. Fig. 4 also shows that the fan-in angular bandwidth of 0° incident angle is around 2° and it's 2.8° for fan-out. The throughput angular bandwidth is 1.4° in the hologram and glass medium and it is equivalent to 2° in the air.

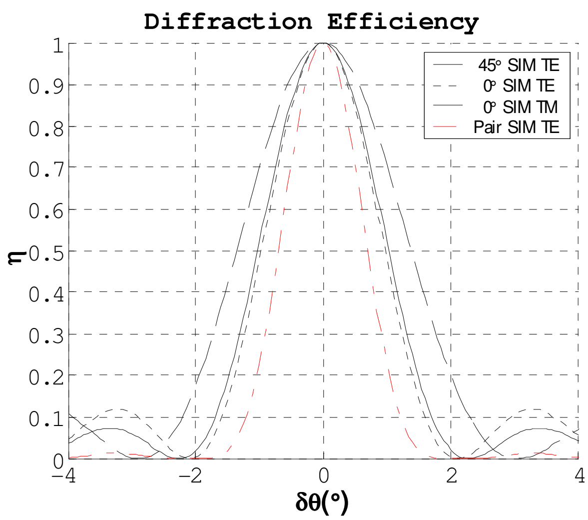
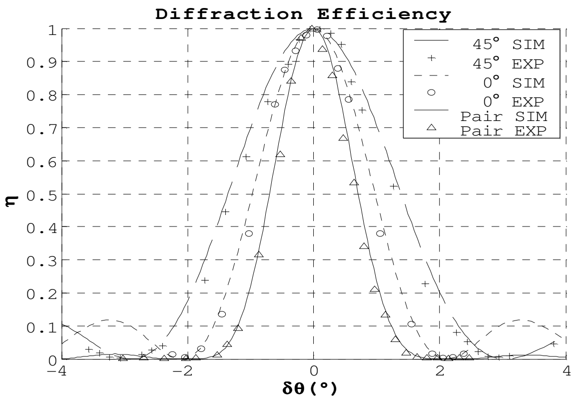


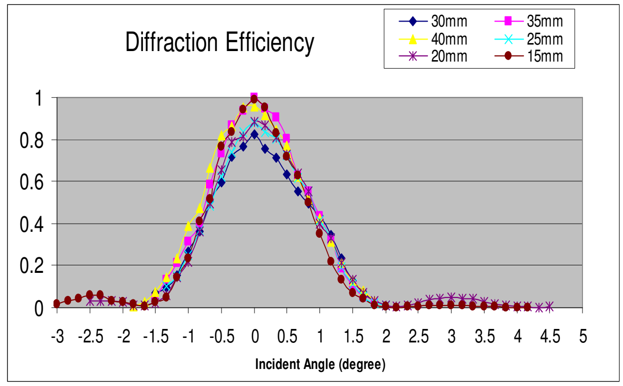
Fig. 4. Diffraction efficiency versus input angle for TE and TM mode: the solid line shows TM mode which is almost proportional to TE mode in dotted line. The dashed line shows the diffractive efficiency versus deviation of incident angle around 45°.

2.2. Issues in hologram grating recording and measurement of the grating properties

A 532nm Verdi laser was used to generate the desired fringe patterns in the photopolymer films. The diffraction efficiency versus incident angle can be calculated based on the Kogelnik theory [3]. The divergence angle of recording beam is measured to be less than 0.05° and power density profile has a 2.5cm 3dB radius. The comparison of the normalized diffraction efficiency of the hologram from theoretical calculation and from experimental measurement is shown in Fig. 5(a). The 4° angular range between the first two minimums in our simulation for a 20μm thick hologram agrees reasonably well with the experimental measurement. We also measured the deviation of the Bragg condition of the incident angle along the *x* direction in a range of 2.5cm, as shown in Fig. 5(b). The measured η-θ_0 curves almost overlap, which implies that the recording beams were well collimated and the exposure was reasonably uniform all over the 3cm×5cm area.



(a)



(b)

Fig. 5 (a) Calculated and measured diffraction efficiency; (b) Measurement of incident angle deviation along horizontal direction

For an optical beam to be fanned in or fanned out by a PVG with maximum efficiency, the incident angle has to satisfy the Bragg condition, and we call it Bragg incident angle. The fan-out hologram should have a mirrored fringe pattern in reference to the fan-in hologram as shown in Fig. 6. We can see that if there is no need to broadcast data to two opposite directions, the laser in the transmitter board could be aligned to match the non-zero Bragg incident angle to achieve maximum efficiency. But in the centralized architecture, for the central distributor board to deliver balanced optical signal to both sides, the Bragg incident angle at the central hologram film should be precisely controlled to be 0°. We have aligned the fabrication system so that the Bragg incident angle was maintained below 0.1°. After exposure under the 532nm laser beams for about 1 minute, the index modulation reached to the desired value. The K vector of the fabricated hologram is more sensitive to the divergence of the recording beams in the *x* direction, as defined in Fig. 1, than in the *y* direction, because the collimator lens are aligned in *x* direction.

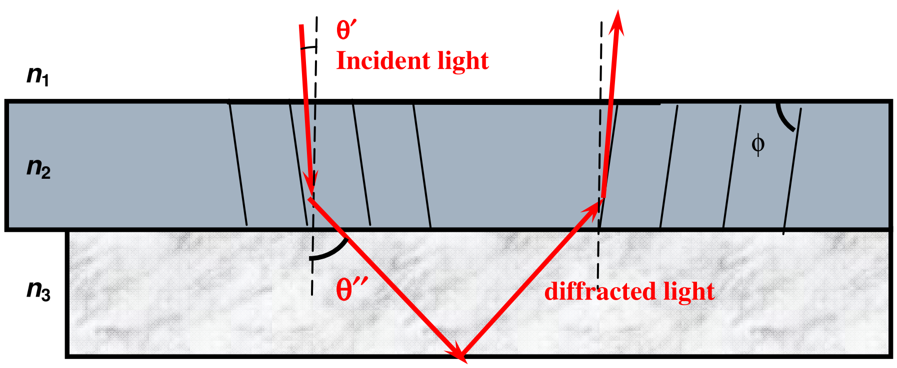


Fig. 6. Illustration of the necessity that the incident angle for Bragg condition has to be 0°

2.3. Analysis of lateral tolerance and bandwidth limit

Due to the divergence of the input laser beam, we must use collimation to restrict the area of the output laser beam. Usually a collimator lens has a divergence angle of around 0.5° to 2° determined by whether the laser is single mode or multi-mode. In order to calculate the beam spot size after fan-out, we used formula (8), to first calculate the diffractive angle deviation versus incident angle deviation, shown in Fig. 7, and then to calculate the fan-out spot displacement. According to the result, ±1° incident angle deviation will cause the first fan-out beam spot to move by ±1mm due to the change of diffractive angle. The deviation of the fan-out beam spot can be calculated by $s=2dN(\tan 45° - \tan\theta'')$ in which,

d is the thickness of the glass substrate, N is the number of the fan-out hologram the beam encountered, and θ'' is the diffractive angle in side the glass.

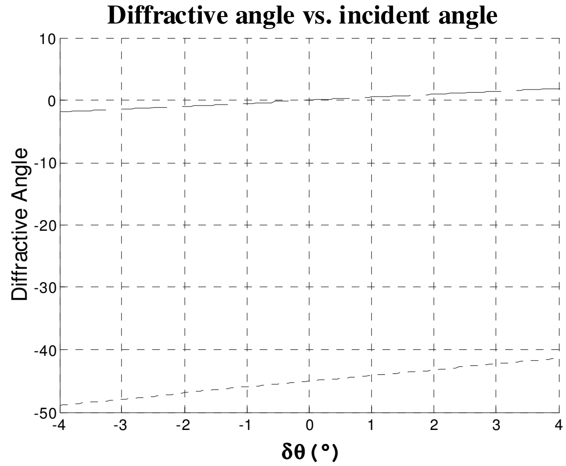


Fig. 7. Deviation of incident angle inside glass versus incident angle deviation in the air

If a wideband laser pulse is used to determine the bandwidth limit of the optical backplane, the difference of the diffractive angle according to formula (8) will cause different wavelength component to experience different optical path length, as shown in Fig. 8. In the calculation, we assumed that the light that is fanned into the glass substrate will propagate along the glass for 3cm in the x direction, defined in Fig. 1. For a short pulse with around 6nm bandwidth, the final time expansion will be around 0.4ps which is equivalent to the 2.5 THz bandwidth we have demonstrated in [4]. Also, we have noticed that the collimation lens should collect the beam with diameter larger than 0.4mm so that most of the fan-out power could go into the photodetector.

If DWDM technology is used with a large area collimator lens, the total bandwidth is then still 36nm, as calculated from simulation section, which is equivalent to 15THz.

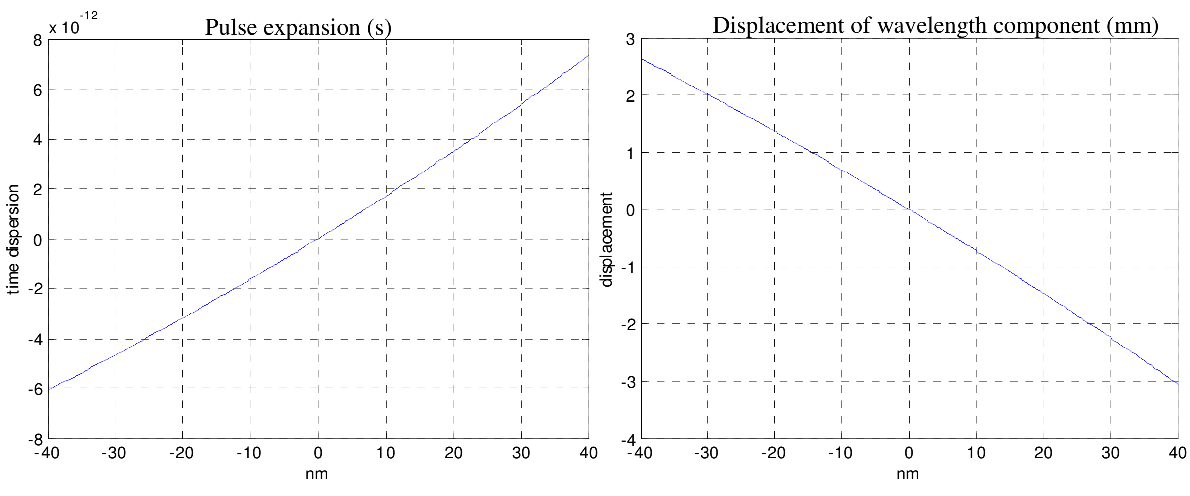


Fig. 8. 850nm wideband laser pulse expansion in time and space domain after fan-in and propagating for 4.2cm: (a) Time delay of different wavelength components when the short pulse is fanned out; (b) displacement of different wavelength components in the fan-out beam spot for different wavelength components.

2.4. Summary of the analysis of the optical characteristics of hologram gratings

From our analysis, we conclude that the hologram film used in our experiments possess an input angular bandwidth around 2° in the air, and will cause the fan-out beam to expand about ±1mm for the laser beam with 2° divergence angle. From simulation, we also find that the diffraction angle deviation for wideband source caused the signal pulse dispersion and limit the bandwidth of the optical backplane bus based on PVG to Terahertz range. A DWDM approach will improve the available bandwidth to 15THz in the 850nm spectrum region. A more thoroughly discussion of the bandwidth issue in a real system will involve not only the optical property of the grating, glass, lens, but also the optical to electrical converters such as lasers, modulators, and trans-impedance amplifiers..

3. DESIGN, ASSEMBLY AND PERFORMANCE OF THE SYSTEM

3.1 Hologram fabrication and system architecture

The demonstrator consists of three computer boards using optical backplane bus to allow 16 communication channels for every of them to exchange data. There are three DuPont photopolymer (HRF-600X100-20) volume gratings arrays each covering an area of 3cm×5cm between the electro-optical (EO) converter boards and the waveguiding glass substrate. The photopolymer film used in the system has a thickness of 20μm, and an index modulation depth of at least 0.01 designed to fan-in and fan-out light beam with maximum efficiency at 840nm. Because of the centralized architecture, the central slot either requires a doubly multiplexed hologram, which was demonstrated before in [1], or two layers of single hologram with mirrored fringe patterns.

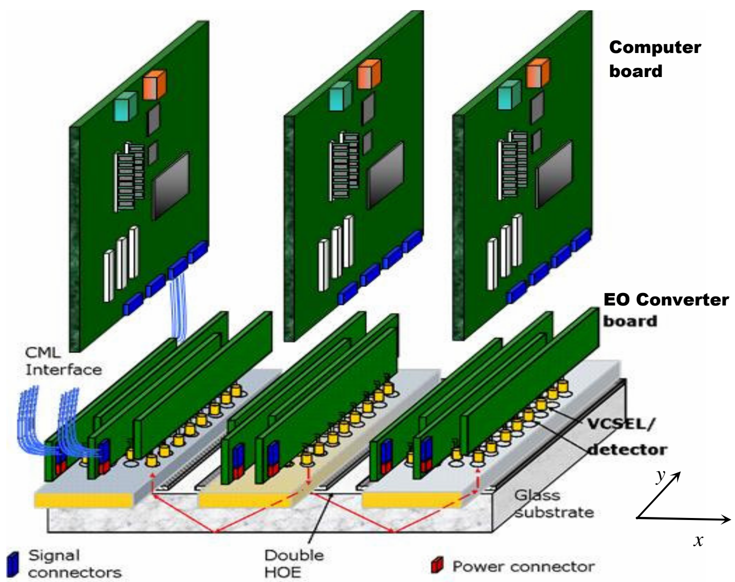


Fig 9. Diagram of the 16-channel optical backplane using VHG

The thickness of the waveguiding glass substrate d is 1.5cm, and thus the slot separation is $2d$=3cm when the diffraction angle within the substrate is exactly 45°. The length of the waveguiding glass substrate is 15cm so that there are five 4×8 hologram grating arrays available in the system, but only the center 3 arrays were used for the demonstrator. While in previous research, we demonstrated system using one Vertical Cavity Surface Emitting Laser (VCSEL) or VCSEL array with only one piece of hologram grating film for each slot [4, 5], this time we fabricated a grating array with channel pitch of 5.5mm, so that the 16 pairs of individually packaged transceivers, in a 4×8 array, would fit within a 3×5cm area allocated for each computer board, for us to study the fan-out power variation in multiple channels. We interleaved the transmitter and receiver to simplify the design of the electro-optical interface board within the compact space at this initial research stage. In the next stage, the channel density will be improved using a VCSEL array with a smaller pitch or DWDM technology.

3.2 Single channel operation

Using a laser at 840nm, we measured that the loss for every channel of hologram pair varied from 12dB to 15dB. The loss for a light beam around 840nm includes 6dB splitting loss, around 2 to 3B grating coupling loss for diverged beam, and about 3dB variations due to recording uniformity issue. Single channel 3.2Gbps transmission with 60μW minimum power delivered was successfully tested for every hologram pair using collimator. For 10Gbps VCSEL Advanced Optical Components with 3dBm output power, the detector optical power is about -12dBm which is just at the boundary of most 10Gbps detector sensitivity to recover the signal with 10^{-12} Bit Error Rate. Therefore, we conclude that 10Gbps is the single channel bandwidth limit of our hologram grating based optical backplane bus system with 5 boards due to the transmitter power limit and detector sensitivity. An improvement of the laser output power is expected for higher data rate.

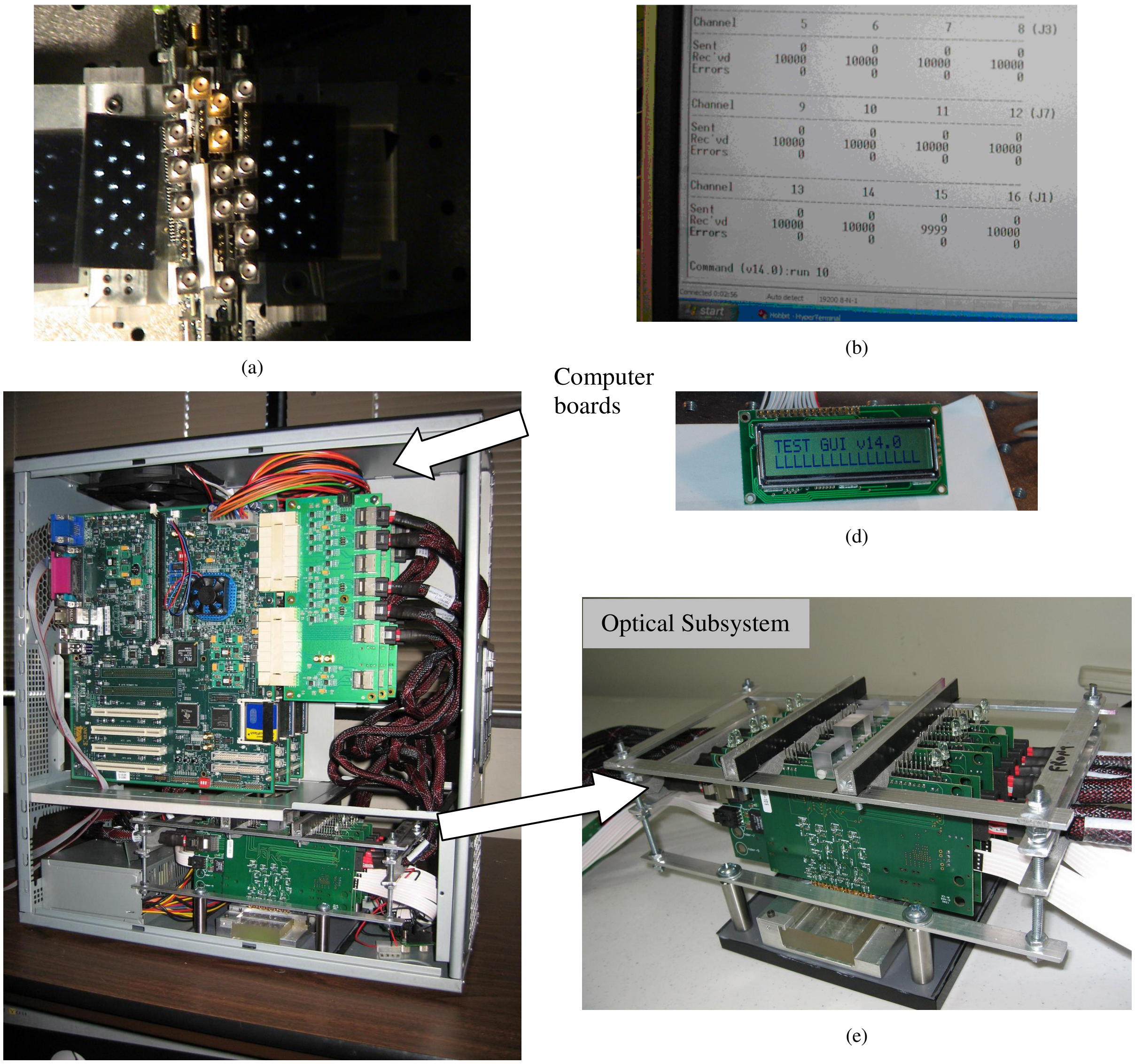
3.3 16-Channel system design and operation

We chose the 1.5GHz VCSEL packaged with dome lens from Advanced Optical Components (AOC SV5637-001) and the 622MHz detector also packaged with dome lens from Advanced Photonix Inc (SD008-17-51-214) to build up our prototype demonstrator. These are the fastest transceivers we could get with dome lens packaged. Among TIAs with different data rate and sensitivity, we tested the ones from Maxim-ic with 622Mbps and 155Mbps and chose the latter one in the 16-channel system design because it can output the average input power for us to monitor the channel optical stability in real time. (Recently, a new 622Mbps TIA with averaged input power monitor ability is also available and we will integrate these chips if another system demonstrator is needed.) VCSELs were controlled to emit 2mW DC optical power with ac amplitude of 1mW. The receivers on the central distributor slot collect the signal from any daughter slot, and then deliver the information to the upper layer FPGA board. Distributor also broadcasts the signal from the FPGA board to all daughter boards. There are 4 pairs of transceivers on each of the EO converter boards and all driver ICs are using current mode logic (CML) for interfacing with upper layer board through an electrical signal connector (Molex 75586-0009) with 8 pairs of differential I/O signal pins. Three upper layer boards designed by Advanced Communication Concepts uses Xilinx FPGA chip to verify the integrity of data transmission among the 3 slots through VHG. Serial port of each computer board is used to allow a laptop control console to send command to start or stop data transmission.

Since the VCSEL packaged with dome lens has an output beam divergence angle around 2°, a portion of the beam that is outside the acceptance angular range of the hologram will experience bigger loss. The estimation of the power loss, which is similar to the [6, 7], shows that the channel loss is at least 1.4dB for a single hologram and approaches more than 3dB for the light signal to go through two holograms. Fig. 10(a) shows 16 channels of optical fan-out beam spots with accurate diffraction efficiency control [8]. A measurement of the fan-out beam power for 16 channels of the two daughter boards shows that the maximum fan-out power is almost two times the weakest one. This result comes from the laser output power variation, the polarization variation and also the hologram grating efficiency variation. At current stage, this 3dB variation doesn't affect the performance of the system because the input power requirement for 150Mbps TIA is almost 1μW while the minimum fan-out power among the channels is around 60μW.

This prototype demonstrator used the FPGA chips working only at 150MHz so that we could test the uniformity of the hologram diffraction and the channel-to-channel crosstalk among the 16 channels. The system was finally assembled as shown in Fig. 10(b) in a computer chassis. Fig. 10(c) is a photo of a channel indicator for each slot to show whether or not the data transmission of that channel is locked according to the 10B/8B coding scheme. Fig. 10(d) shows the result of transmission test with long packets used for the bit error rate (BER).

The channel-to-channel optical crosstalk is below -25dB from the test. Minimum delivered power is above 60μW and is stable during continuous operation tests. The channel density in this demonstration is 1.65channels /cm^2, which is limited by the size of the transceivers used. Using a clock at 150MHz, the system can perform 16-channel transmission with a total bandwidth of 2.4Gbps for point-to-point uploading and 4.8Gbps for multi-drop downloading communication. The anticipated channel density in the next stage of this research should be greater than 10/cm^2 when array transceivers packaged with graded-index (GRIN) lens are used [4], and there can be 150 channels available. With 10Gbps per channel availability, the total bandwidth will reach 1.5Tbps. The bandwidth can still be improved if we use DWDM technology to allow multiple channels of transmission to share one collimator lens pair. The major bottlenecks in electrical interconnects such as size and power of amplifier array would be resolved simultaneously to bring more data transmission channels into reality.



(c)

Fig. 10 (a) Photo of fan-out spots; (b) Testing results ; (c) Chassis of the multi-slot system; (d) Channel indicator; (e) Optical sub-system

4. CONCLUSION

In this work, we used hologram as fan-in and fan-out method and verified the diffraction effect from both theoretical calculation and experiments. An array of 4×8 transceivers are interlaced assembled on a VHG as large as 3cm×5cm. By carefully aligning the fabrication system, the deviation of incident angle from Bragg condition is reduced to below 0.1°.

Recording beam is collimated so that the orientation and period of hologram fringes are uniform in the active area. A single channel data rate of 10Gb/s transmission shows that fan-out power is large enough for high speed.

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