Board-Level Optical Clock Signal Distribution Based on Guided-Wave Optical Interconnects in Conjunction with Waveguide Holograms

Ray T. Chen[†*], Suning Tang[*], Ting Li[†], Feiming[†] Li, Linghui Wu, and Randy Wickman[§]

*Radiant Research, Inc.
3925 W. Braker Lane, Suite 420
Austin, Texas 78759
Tel: 512-305-0297

†Microelectronics Research Center
Department of Electrical and Computer Engineering
University of Texas, Austin, Texas 78712-1084
Tel: 512-471-7035

§Cray Research, Inc.
655 Lone Oak Dr.
Eagan, MN 55121

Abstract

In this paper, we represent our effort to construct an optoelectronic interconnection layer for high-speed optical clock signal distribution in a Cray supercomputer board. The optoelectronic interconnection layer under investigation employs optical channel waveguides and 3 dB waveguide splitters in conjunction with surface-normal waveguide couplers. The difficulties associated with the complicated 3-D multiple alignments are significantly reduced by the surface-normal fanout beams and the unique planar device feature. 1-GHz clear optical clock signal is demonstrated experimentally with a guided-wave interconnection length of 45 cm. Some new techniques to fabricate large-area optical channel waveguides and surface-normal waveguide grating couplers are also presented.

Keywords: compression-molding, holographic grating, optoelectronic interconnect, polymeric waveguide.

1. Introduction

The speed and complexity of integrated circuits are increasing rapidly as integrated circuit technology advances from very large scale integrated (VLSI) circuits to ultra large scale integrated (ULSI) circuits. As the number of components per chip, the number of chips per board, the modulation speed and the degree of integration continue to increase, electrical interconnections are facing their fundamental bottle-necks, such as speed, packaging, fanout, and power dissipation. Multichip module (MCM) technology is employed to provide higher clock speeds and circuit densities[1,2]. But the state-of-the-art technologies based on electrical interconnects still fail to provide the required clock speed and communication distance in intra-MCM and inter-MCM hierarchies. For example, for clock speed above 500 MHz, it is very difficult to design and implement high fanout board-level electrical interconnects[3-5]. There are many severe problems for electrical interconnects in high-speed, large-area, massive clock signal distributions. These include (a) the impedance mismatch caused by multi-stage electrical fanout (b) the transmission reflection (noise) at each fanout junction as well as at the end of each transmission line, (c) the electromagnetic interference with other interconnection lines and other interconnection layers, and (d) the high transmission loss resulting in a large driving power. For clock signal distribution in a multichip module and a Cray supercomputer board, a successful interconnect network should employ little real estate of the board/wafer surface that has already been intensively occupied by electronic devices[1,2].

For a multiprocessor computer system, such as Cray supercomputers, the synchronous global clock signal distribution is highly desirable to simplify the architecture and enable a higher speed performance. It has been found that it is extremely difficult to obtain high-speed synchronous clock distribution using electrical interconnections due to large fanout (128) and long interconnection length (30 cm)[6,7]. High-speed, large-area massive fanout optoelectronic interconnects may overcome many of problems associated with electrical interconnects and outperform electrical interconnects in these interconnection scenarios[3-11]. An array of novel optical interconnect architecture have been proposed

0-8194-2292-4/96/$6.00

and then reported by earlier researchers[11-14], which may partially satisfy the above requirements for a massive clock signal distribution in board-level.

In this paper, we present the demonstration of planarized guided-wave optical interconnects for board-level massive optical clock signal distribution. Integrated board-level fanout optoelectronic interconnects are constructed by using optical channel waveguides in conjunction with a two-dimensional (2-D) waveguide hologram arrays. The surface-normal feature among fanout beams and the planar compact device structure convert the most difficult three spatial and three angular multiple alignment problem into a single step 2-D planar one. This optoelectronic interconnect network will be inserted into the Cray supercomputer board and become an additional interconnection layer among the electrical interconnection layers. The approaches demonstrated herein minimizes the employment of real estate of the board surface that has already been occupied by existing electronic components. Multimode channel waveguides have been fabricated with interconnection length up to 45 cm. It was shown that 1-GHz optical clock signal could be transmitted through this 45 cm long channel waveguide with little wavefront distortion. Key waveguide components including surface-normal waveguide grating couplers and Y-branch waveguide couplers for system integration have also been demonstrated. Some new techniques have been developed to fabricate channel waveguides and waveguide gratings at board-level.

2. Optical Clock Signal Distribution for Cray Supercomputer

The Cray supercomputer T-90 board that consists of more than 50 electrical interconnection layers is shown in Fig.1. The dimension of board is 14.2 x 26.7 cm^2. Our approach is to construct an additional optoelectronic interconnection layer (OIL) for high-speed optical clock signal distribution. Process compatibility and planarization of the OIL are two major concerns. The optoelectronic interconnection layer consists of a polymer-based waveguide H-tree system as shown in Fig. 2. The optical clock signal delivered by an optic fiber will be coupled into the OIL using a holographic coupler. The optical components required for constructing such a H-tree system include low loss polymer-based channel waveguides, waveguide holograms, Y-branch waveguide couplers. These components allow the formation of a H-tree waveguide structure for the optical clock signal distribution, where all the optical paths have the same length to reduce the clock skew problem. The use of optical channel waveguides and surface-normal waveguide gratings provides a compact, mechanically stable system. Due to the massive fanout nature (N=128) over a large area (30 cm), the waveguide propagation loss must be minimized while the waveguide grating coupling efficiency has to be optimized. This is very important to ensure enough optical power at the end of photodetectors for high-speed operation. If a 10 dBm laser diode and a Vitesse 1.3 GHz optical receiver[15] are employed, which has a sensitivity of -18 dBm at 1 GHz (BER = 10^{-12}), the total insertion loss and grating coupling loss should be less than 10 dB. To improve the waveguide grating coupling efficiency, polymer-based tilted gratings are needed. Note that a 45° waveguide end mirror is not suitable in this case because of the requirement of planarization imposed by the vertical integration of more than 50 electrical interconnection layers.

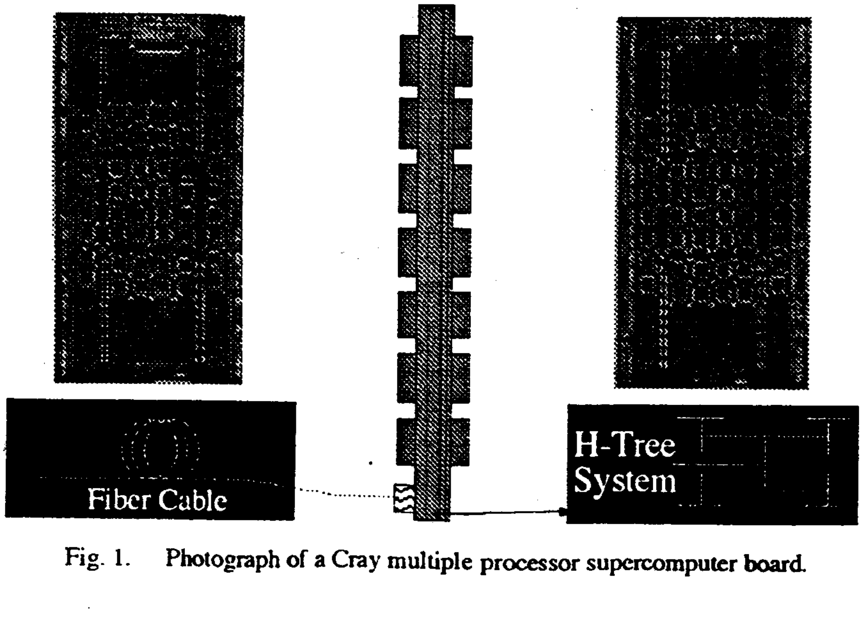

Fig. 1. Photograph of a Cray multiple processor supercomputer board.

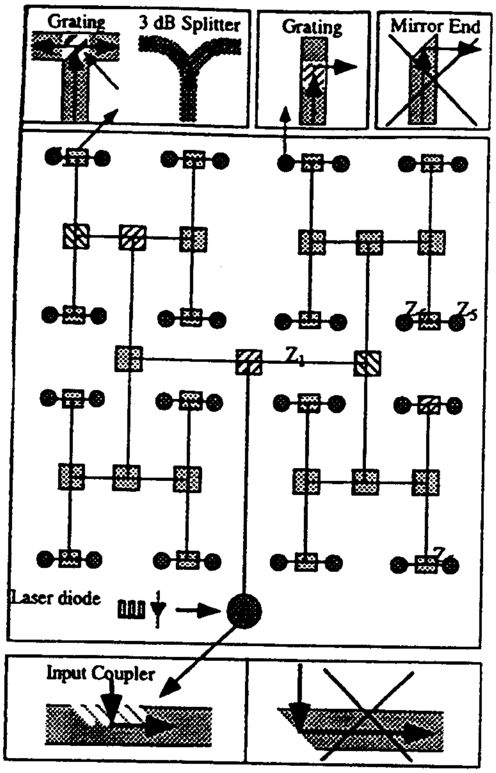

Fig. 2. Schematic diagram of an optical waveguide H-tree system.

2.1 Board-Size Polymer-Based Optical Channel Waveguides

Because the Cray supercomputer board is 26.7 cm in length (beyond the field limit of current VLSI microlithography) and have a variety of customised arrangements, large-area optical waveguides are required with various patterns. Conventional waveguide fabrication methods can not satisfy these requirements, where channel waveguides are patterned using photomasks. We have developed a compression-molding technique for fabricating large-size polymer-based channel waveguides[9]. A 45-cm long polymer-based compression-molded channel waveguide made on a glass substrate is illustrated in Fig. 3 where a microprism[16] is employed to coupled a HeNe laser beam (0.6328 μm) into the waveguide. The phase matching angle was set at the mode. The ambient light displayed along the rib waveguide (see Fig. 3) is in the planar waveguide region T_2 shown in the inset of Fig. 3. Waveguide propagation losses of different samples were measured using the two-prism method. Loss figures from 0.5 to 2.0 dB/cm were experimentally confirmed at 0.6328 μm. Waveguide loss at 1.3 μm was measured from 0.2 to 1.0 dB/cm. In Fig. 3, the channel waveguide fabricated had a rib width (W) of 110 μm, groove depth (T_2) of 8 μm and base layer thickness (T_1) of 2 μm.

Besides the compression-molding technique, a laser-beam waveguide writing system is also developed for large-area optical waveguide fabrication. The laser-beam writing system consists of a dual-wavelength HeCd laser $(\lambda_1 = 325$ nm and $\lambda_1 = 442$ nm), beam-shaping optics, an electronic shuttle and an X-Y-Z translation stage. The translation stage with a stroke of 30 x 30 x 2.5 cm^3, is driven by DC motors through a computer. The stage translation speed is continuously adjustable below 1.0 cm/s. The positioning resolution is 0.1 μm and 0.01 μm for the X-Y stage and Z stage, respectively. The Z-stage is employed to control the focused laser beam size.

To ensure the desired electrical and mechanical properties imposed by the Cray supercomputer board, and the required optical properties for low loss waveguide formation, Photosensitive polyimides provided by Amoco Chemicals are used for waveguide fabrication. Such polyimides have excellent thermal stability (Tg = 400 °C) and optical transparency when they are thermally or photochemically cross-linked. To fabricate the channel waveguides, the positive photosensitive polyimides is first spin-coated on the substrate, followed by a soft-cured process to remove solvent. The exposure is conducted by a focused HeCd UV laser beam (λ = 325 nm) writing, directed by the X-Y precision microtranslation stage. The coated film is finally etched using organic solvent developers into the desired channel pattern. The fabricated waveguide is post-baked at 300-350 °C to remove residual solvent and improve solvent resistance. Fig. 4(a) is the photograph of polyimide channel waveguides fabricated with a channel width of 100 µm. The waveguide loss is determined about 0.4 dB/cm at 1.3 µm. Fig. 4(b) shows the Y-branch 3 dB splitter (part of the H-tree system) previously fabricated with a 100 µm width.

2.2 1-GHz Optical Clock Signal Over Board-Size

To verify the bandwidth of the 45-cm long multimode optical channel waveguide, an 1-GHz optical signal generated by a laser diode at 1.3 µm was launched into the waveguide. Fig. 5(a) and (b) are the photographs of the input and output signals from a Tektronics 11403 Digitizing Oscilloscope. High speed transmitter (2556T, Force Inc.) and receive (2556R, Force Inc.) were employed to generate and detect the optical signal. The sinuous 1-GHz modulation applied on the transmitter was provided by a HP 8656B signal generator. In the experiment, the speed of the optical signal was limited by the transmitter bandwidth (1.3-GHz) and the speed limitation of the (HP 8656B) signal generator (1-GHz), rather than the 45-cm long channel waveguide itself. Very clear signal was obtained with very little wavefront distortion, which indicated a much larger bandwidth achievable for the device under measurement.

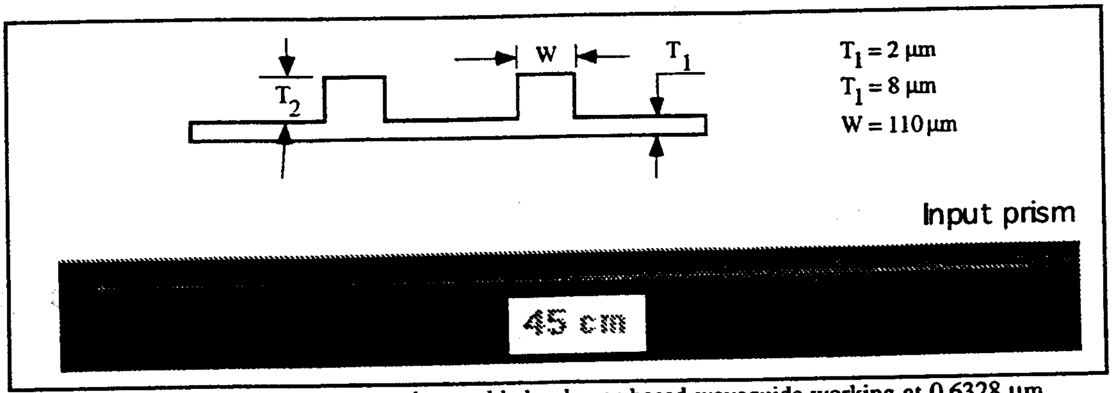

Fig. 3. A 45 cm long compression-molded polymer-based waveguide working at 0.6328 µm.

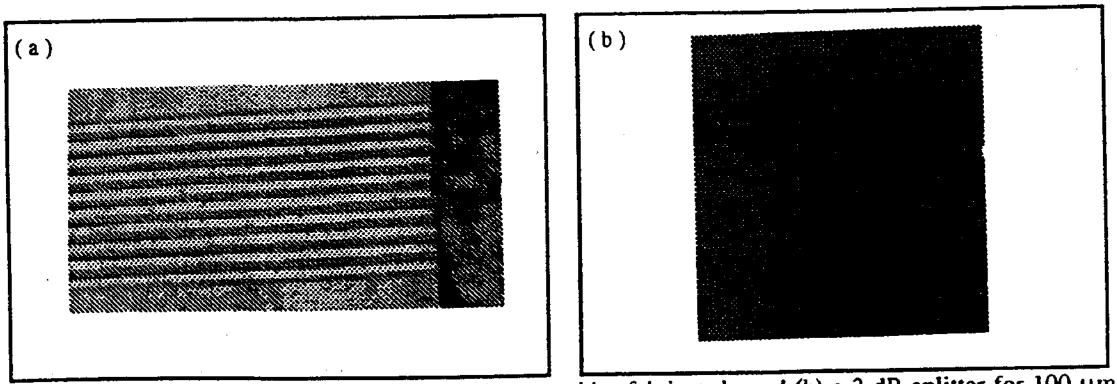

Fig. 4. Photograph of (a) polyimide channel waveguides fabricated, and (b) a 3 dB splitter for 100 µm waveguides.

2.3 Surface-Normal Waveguide Holograms

The waveguide holograms, required to couple the optical signal out of the waveguide with surface-normal conversion, have also been investigated. Because most high-speed vertical cavity surface emitting lasers (VCSELs) and photodectors require surface-normal input/output, such surface-normal waveguide couplers are very important to ensure efficient optical coupling. More importantly, the surface-normal feature of fanout beams and the planar compact device structure convert the most difficult three spatial and three angular multiple alignment problem into a single step 2-D planar one. Such surface-normal waveguide grating couplers were demonstrated on a planar waveguide as input and output coupling gratings. Fig. 6 shows the nearly surface-normal couplings from a free-space HeNe laser (λ = 632.8 nm) to a planar waveguide and from the planar waveguide back to free-space using waveguide gratings. In the experiment, the total insertion loss is 8 dB which includes 4.2 dB coupling loss and 3.8 dB waveguide propagation loss. Our theoretical calculation based on coupled-mode theory shows that the coupling loss can be as low as 1.3 dB when the microstructure of the grating is optimized.

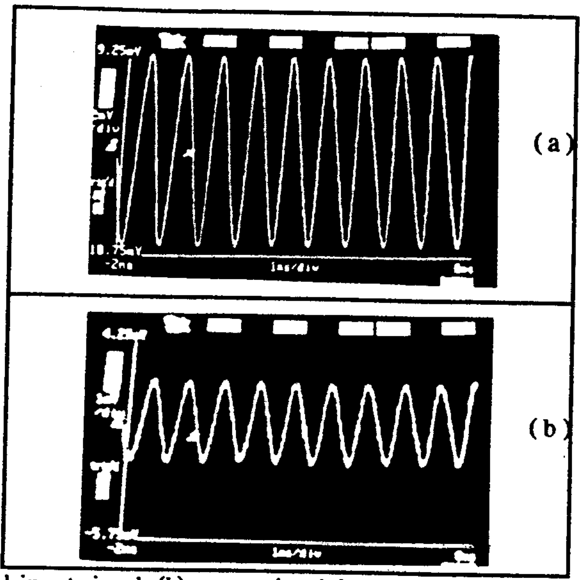

Fig. 5.(a) 1-GHz optical input signal, (b) output signal from the transceiver at the end of waveguide.

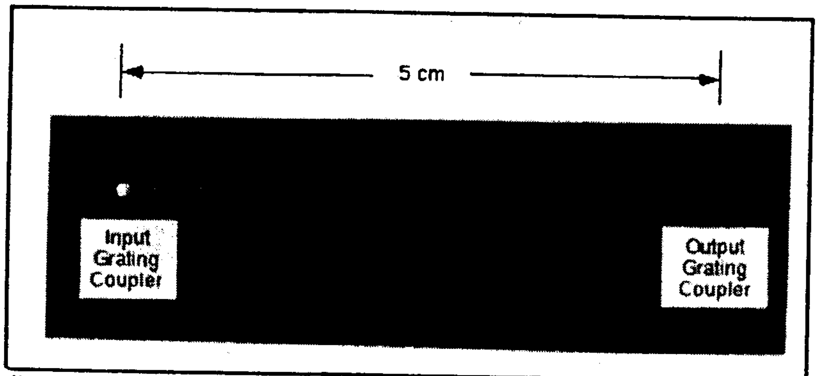

Fig. 6. Surface-normal coupling using two holographic waveguide gratings.

To fabricate the optical waveguide H-tree with a 2-D array of holographic waveguide couplers as shown in Fig. 2, it is very important to fabricate the holographic couplers at the desired positions where the high-speed photodetectors are located. Because of the dimension of the Cray supercomputer board under consideration is well beyond the field size of conventional photolithographic tools, free-space holographic lithography using two-beam interference method has to be employed. To enhance spatial frequency of a recorded hologram, a special phase mask with alignment marks has been designed at normal incident. The recording substrate (with waveguides) can be pre-aligned with the phase mask, and then recorded by a plane wave from a UV laser as shown in Fig. 7.

Another important advantage of this technique is the grating period doubling that causes a factor of two relaxation in the resolution demands of the mask writing process. This is very critical for fabricating waveguide gratings with very short grating period. For a normal incident on the phase grating, the phase match condition can be write as [17]

$$\sin\beta = m\,\lambda/\Lambda_m \tag{1}$$

where β is the diffraction angle of the m-th transmitted beam, λ is the wavelength of the diffracted light, and Λ_m is the period of the phase-mask diffraction grating. The combination of the two first-order diffracted beams result in a standing wave pattern with a period Λ_{pr}, given as

$$\Lambda_{pr} = (\lambda/2\sin\beta) \tag{2}$$

Substituting (1) in (2) gives

$$\Lambda_{pr} = \Lambda_m/2\ , \tag{3}$$

which shows the doubling of grating period. Further experimental results for grating couplers will be presented in the conference.

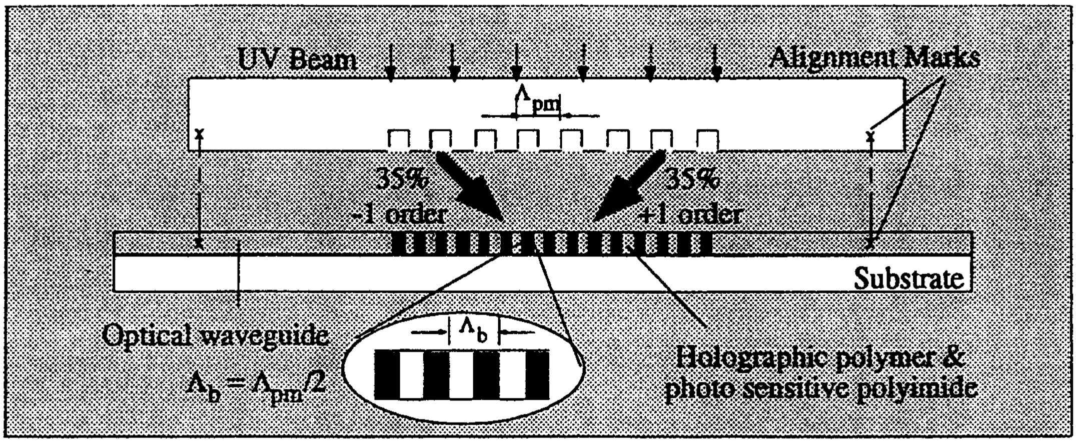

Fig. 7. Schematic setup using a phase mask with alignment marks designed at normal incident.

3. Concluding Remarks

In summary, we represent our effort to construct an optoelectronic interconnection layer for Cray supercomputer board for high-speed massive clock signal distribution. The optical interconnection layer under investigation employs optical multimode channel waveguides in conjunction with surface-normal waveguide grating couplers. The difficulties associated with the complicated 3-D multiple alignments are significantly reduced through the parallelism among the surface-normal fanout beams and the unique planar device feature. 1-GHz clear optical clock signal was demonstrated experimentally with interconnection length of 45 cm. Some new techniques to fabricate multimode channel waveguides and 2-D array of waveguide gratings in board-level are also presented.

4. Acknowledgement

This research is sponsored by BMDO, Cray Research, Inc. and the University of Texas at Austin, Texas.

5. References

1. D. P. Seraphim and D. E. Barr, "Interconnect and packaging technology in the 90's," Proc. SPIE 1390, pp. 39-54, 1990.

2. C. Neugerbauer, R. O. Carlson, R. A. Fillion, and T. R. Haller, "Multichip module designs for high performance applications," in Multichip Modules, Compendium of 1989 Papers, pp. 149-163, International Electronic Packaging Society, 1989.

3. J. W. Goodman, F. I. Leonberger, S. Y. Kung, and R. A. Athale, "Optical interconnections for VLSI systems," Proc. IEEE 72, pp. 850-866, 1984.

4. M. R. Feldman, S. C. Esener, C.C. Guest, and S. H. Lee, "Comparison between optical and electrical interconnects based on power and speed considerations," Appl. Opt., vol. 27, pp. 1742-1751, 1988.

5. Founad E. Kiamilev, Philippe Marchand, Ashok V. Krishnamoorthy, Sadik C. Esener, and Sing H. Lee, "Performance comparison between optoelectronic and VLSI multistage interconnects networks," IEEE J. of Light. Technol., vol. 9, pp. 1674-1692, 1993.

6. Paola Cinato, Kenneth C. Young, Jr., "Optical interconnections within multichip modules," Opt. Eng., vol. 32, pp. 852-860, 1993.

7. Bradley D. Clymer and Joseph W. Goodman, "Optical clock distribution to silicon chips," Opt. Eng., vol. 25, pp. 1103-1108, 1986.

8. Suning Tang, Ray T. Chen and Mark Peskin, "Packing density and interconnection length of a highly parallel optical interconnect using polymer-based single-mode bus arrays," Opt. Eng., vol. 33, pp. 1581-1586, 1994.

9. Ray. T. Chen, Suning Tang, T. Jannson and J. Jannson, "A 45 cm long compression molded polymer-based optical bus," Appl. Phys. Lett., vol. 63, pp. 1032-1034, 1993.

10. R. T.. Chen, Suning Tang, Maggie M. Li, David Gerald and Strikanth Natarajan, "1-to-12 surface normal three-dimensional optical interconnects," Appl. Phys. Lett., vol. 63, no. 14, pp. 1883-1885, 1993.

11. Ray. T. Chen, H. Lu, D. Robinson, Michael Wang, Gajendra Savant, and Tomasz Jannson, "Guided-wave planar optical interconnects using highly multiplexed polymer waveguide holograms," IEEE J. Light. Technol., vol. 10, pp. 888-897, 1992.

12. R. W. Wickman, "Implementation of optical interconnects in GibaRing supercomputer channel", Proc. SPIE, vol. CR62, pp. 343-356, 1996.

13. M. R. Feldman, "Holographic optical interconnects for multichip modules," Proc. SPIE, vol., 1390, pp. 427-433, 1990.

14. Suning Tang and Ray T. Chen, "1-to-42 optoelectronic interconnection for intra-multichip-module clock signal distribution," Appl. Phys. Lett., vol. 64, pp. 2931-2933, 1994.

15. Data Sheet of VSC7810, Vitesse Semiconductor Corporation.

16. Ray T.,Chen H. Lu, D. Robinson, Z. Sun, T. Jannson, D. Plant and H. Fetterman, "60 GHz board to board optical interconnection using polymer optical buses in conjunction with microprism coupler," Appl. Phys. Lett. vol. 60, pp. 536-538, 1992.

17. M. V. Klein and T. E. Furtak, Optics, Second Ed., New York: Wiley, pp. 282, 1986.