1-GHz Clock Signal Distribution for Multi-Processor Super Computers

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Abstract

In this paper, we present our efforts to construct an optoelectronic interconnection layer for high-speed optical clock signal distribution in a Cray T-90 supercomputer board. The optoelectronic interconnection layer under investigation employs optical channel waveguides and cascaded 3 dB 1-to-2 waveguide splitters in conjunction with surface-normal waveguide grating couplers. The planarization requirement for the optical interconnection layer required by multi-layer integration is fulfilled. Furthermore, the difficulties associated with the complicated 3-D multiple alignments are significantly reduced by the surface-normal fanout beams and the unique planarized device feature. An 1-GHz optical clock signal operating at 1.3 μm was transmitted through a 45 cm long polymer-based channel waveguide. Some new techniques to fabricate large-area optical channel waveguides and surface-normal waveguide grating couplers are also presented.

1. Introduction

The speed and complexity of integrated circuits are increased 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 continues 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]. However, the state-of-the-art technologies based on electrical interconnects fail to provide the required clock speed and communication distance in intra-MCM and inter-MCM hierarchies. 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 fanouts (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[1,2]. For a multiprocessor computer system, such as a Cray T-90 supercomputer board, the synchronous global clock signal distribution is highly desirable to simplify the architecture and enable a higher speed performance. It is extremely difficult to obtain high-speed (>500 MHz) synchronous clock distribution using electrical interconnections due to large fanouts (94) and long interconnection lengths (>15 cm)[3-7]. High-speed, large-area massive fanout optoelectronic interconnects may overcome many of the problems associated with electrical interconnects in these interconnection scenarios[3-11]. An array of novel optical interconnect architecture has been proposed and then demonstrated 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 optical clock signal distribution. Integrated board-level fanout optoelectronic interconnects are constructed by using polymer-based optical channel waveguides in conjunction with waveguide holograms. The surface-normal feature of the fanout beams and the planarized compact device structure convert the most difficult three spatial and three angular multiple alignment problems into a single step 2-D planar one. Furthermore, the planarized surface-normal grating couplers are compatible with the Si CMOS fabrication process that makes the reported findings highly feasible for further system integration. The guided optoelectronic interconnect network reported herein will be inserted into the Cray supercomputer boards to become an additional

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interconnection layer among the electrical interconnection layers. Multimode channel waveguides have been fabricated with the waveguide length up to 45 cm. An 1-GHz optical clock signal operating at 1.3 μm was transmitted through a 45 cm long channel waveguide. Key waveguide components including surface-normal waveguide grating couplers and 1-to-2 waveguide splitters for system integration have also been demonstrated. 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 T-90 supercomputer board consists of 52 vertical electrical interconnection layers with the board size of 14.48 x 26.67 cm^2 as shown in Fig. 1. Our approach is to construct an additional optoelectronic interconnection layer (OIL) for high-speed optical clock signal distribution. Si CMOS process compatibility and planarization of the OIL are the two major concerns. This optoelectronic interconnection layer is made out of a polymer-based waveguide H-tree system as shown in Fig. 2(a), to be replacing the existing electrical fanout interconnect network shown in Fig. 2(b). The optical clock signal delivered by an optic fiber will be coupled into the OIL using an input holographic grating coupler. The optical components required for constructing such an H-tree system include low loss polymer-based channel waveguides, waveguide holograms, and 1-to-2 3 dB waveguide splitters. These components allow the formation of a waveguide H-tree for the optical clock signal distribution, where all the optical paths have the same length to minimize the clock skew problem. The employment of optical channel waveguides and surface-normal waveguide gratings provides a compact, mechanically stable system. Due to the nature of massive fanouts (N > 94) over a large area, the waveguide propagation loss must be minimized while the waveguide grating coupling efficiency has to be maximized. This is very important to ensure enough optical power at the end of photodetectors for high-speed operation. For example, the total optical splitting power budget is 18 dB (3x6) in an optical H-tree system (capable of providing 128 fanouts), which consists of six stages of 1-to-2 (3 dB) optical fanout and one stage of 1-to-2 electrical fanout. 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 (grating coupling loss plus waveguide propagation loss) should be less than 10 dB. The compression-molding technique and laser writing technique [9] have been developed for fabricating low loss, board-area optical polymeric waveguides. To improve the waveguide grating coupling efficiency, polymer-based tilted waveguide gratings are employed. 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 the other electrical interconnection layers.

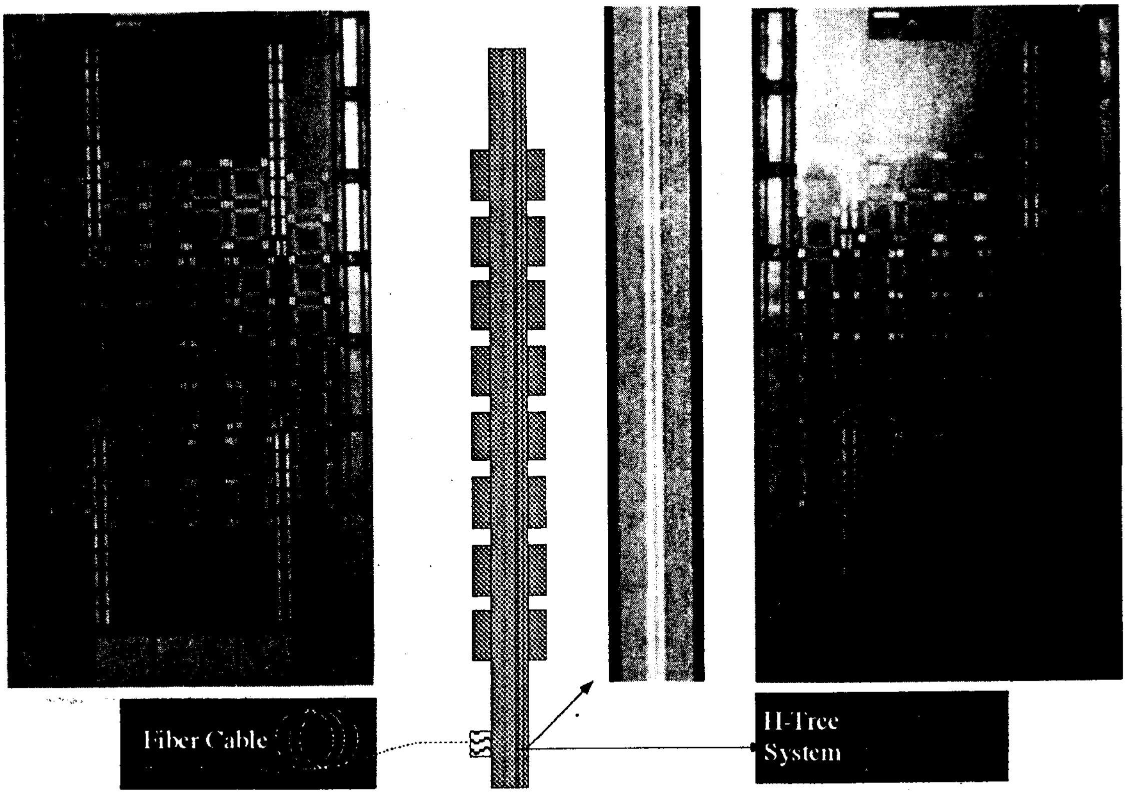

Fig. 1. Photograph of a Cray T-90 multi-processor supercomputer board.

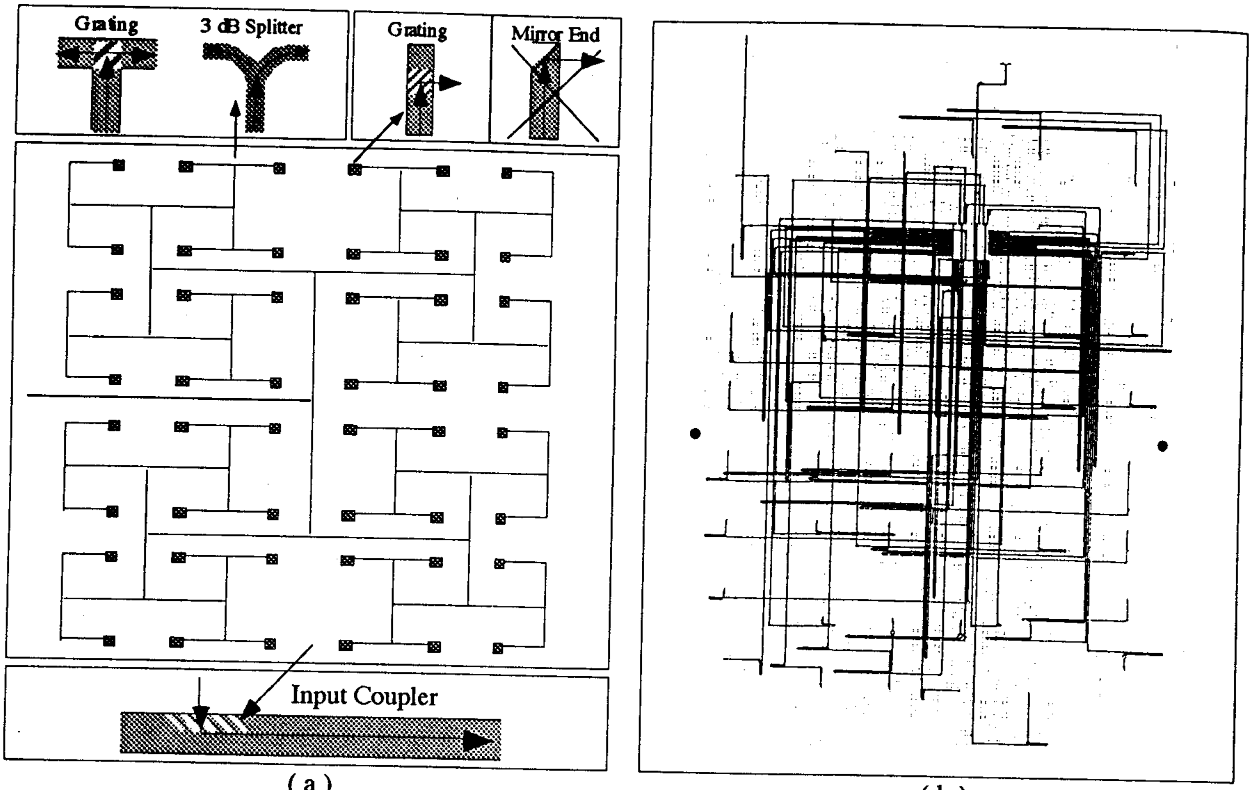

Fig. 2. Schematic diagrams of massive clock signal distribution networks using (a) an optical waveguide H-tree and (b) an electrical transmission line network.

2.1 Board-Area Polymer-Based Optical Channel Waveguides

Because the Cray supercomputer board is 26.67 cm in length, which is beyond the field size of the current VLSI microlithography, large-area optical waveguides are required to build an optical clock signal distribution layer. Conventional waveguide fabrication methods through which channel waveguides are patterned using photomasks can not satisfy this requirement. Two methods have been investigated to solve the problem. First, we have developed a compression-molding technique for fabricating large-area polymer-based channel waveguides[9]. A 45-cm long polymer-based compression-molded channel waveguide was fabricated on a glass substrate as shown in Fig. 3 where a microprism was employed to coupled a HeNe laser beam (0.6328 μm) into the waveguide[16]. The phase matching angle was set for the E^{x}_{11} waveguide mode. The ambient light displayed in Fig. 3 along the rib waveguide illustrated the region T_2 in the inset of Fig. 3. Waveguide propagation losses of different samples were measured using the two-prism method[16]. 0.5 dB waveguide loss was experimentally confirmed at 0.6328 μm. Waveguide loss at 1.3 μm was measured from 0.2 to 0.5 dB/cm. In Fig. 3, the channel waveguide fabricated had a rib width (W) of 110 μm, a groove depth (T_2) of 8 μm and a cladding layer thickness (T_1) of 2 μm.

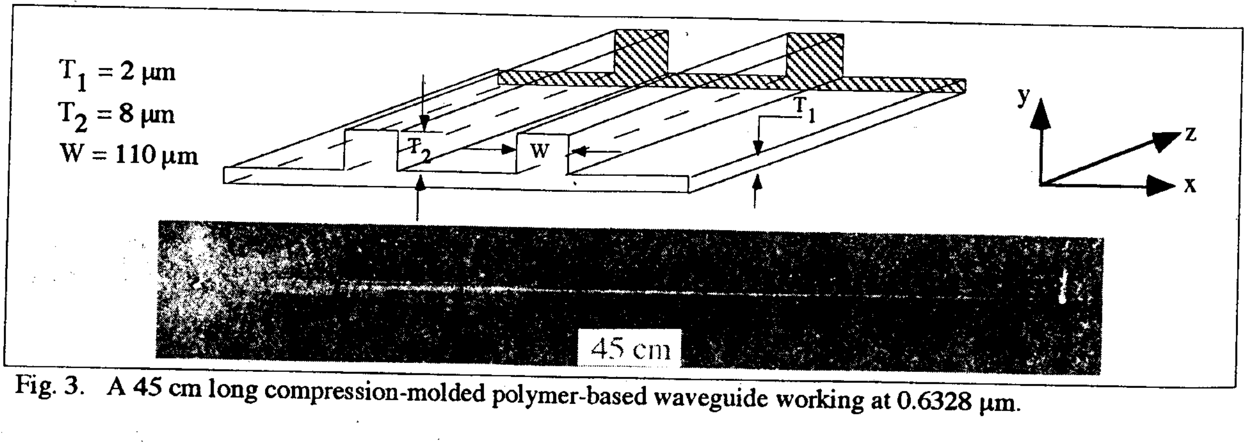

Fig. 3. A 45 cm long compression-molded polymer-based waveguide working at 0.6328 μm.

Besides the compression-molding technique, a laser-beam waveguide writing system was also developed for fabrication of large-area, polymer-based channel waveguides. The laser-beam writing system consists of a dual-wavelength HeCd laser (λ_1 = 325 nm and λ_2 = 442 nm), beam-shaping optics, an electronic shuttle and a computer-controlled X-Y-Z translation stage with a stroke of 30 x 30 x 2.5 cm^3. The stage translation speed is continuously adjustable below 1.0 cm/s. The positioning resolution is 0.5 μm and 0.01 μm for the X-Y axes and Z axis, respectively. The Z-stage is employed to precisely control the focused laser beam sizes. Fig. 4 shows the schematic diagram of the laser waveguide writing system.

To ensure the desired electrical and mechanical properties imposed by the Cray supercomputer board, and to meet the required optical properties for the low loss waveguide formation, the photosensitive polyimide provided by Amoco Chemicals[18] is used for the waveguide fabrication. The polyimide employed has an excellent thermal stability (Tg = 400 °C) and optical transparency when they are thermally or photochemically cross-linked. To fabricate the channel waveguides, the photosensitive polyimide was first spin-coated on the substrate, followed by a soft-cured process to remove the solvent. The exposure was conducted by a focused HeCd UV laser beam (λ = 325 nm) writing, directed by the computer controlled X-Y-Z precision microtranslation stage. The photo-crosslinked polyimide film was finally etched using organic solvent developers into the desired channel pattern. The fabricated waveguide was post-baked at 300-350 °C to remove residual solvent and to improve its solvent resistance. Fig. 5(a) is the photograph of polyimide channel waveguides fabricated with a channel width of 100 μm. The measured waveguide loss is about 0.4 dB/cm at 1.3 μm. Fig. 5(b) shows the 1-to-2 3 dB waveguide splitter (part of the H-tree system) fabricated with a 100 μm width.

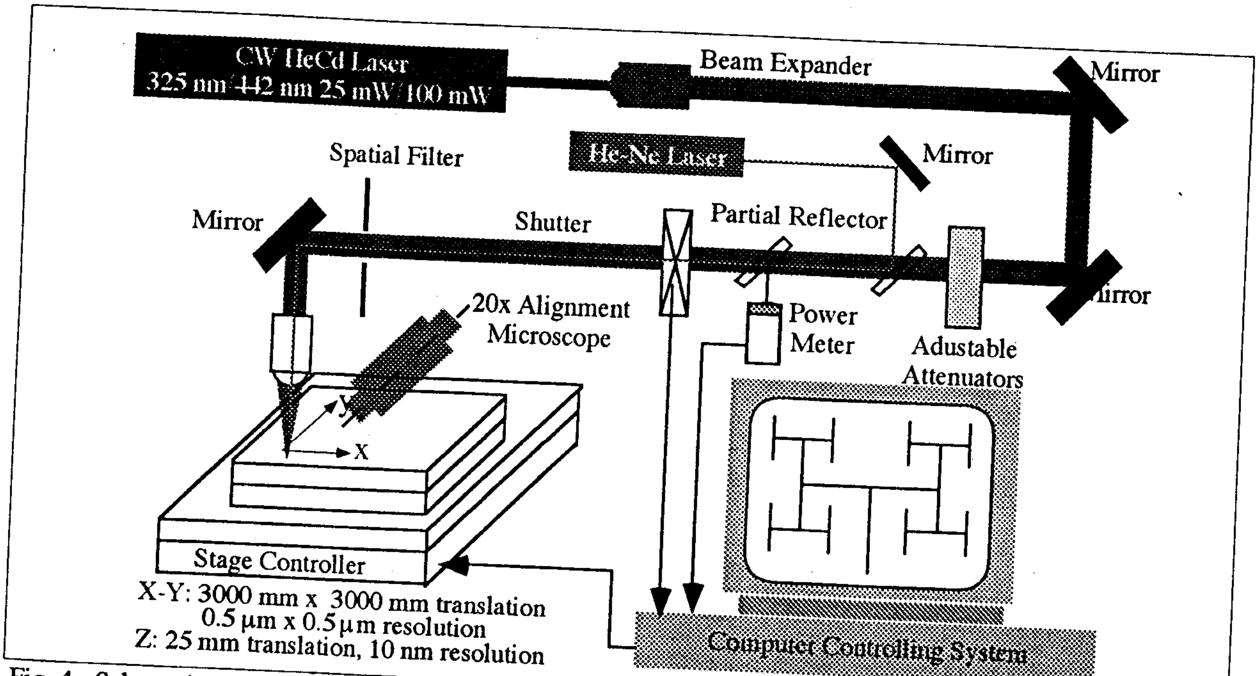

Fig. 4. Schematic of a laser waveguide writing system.

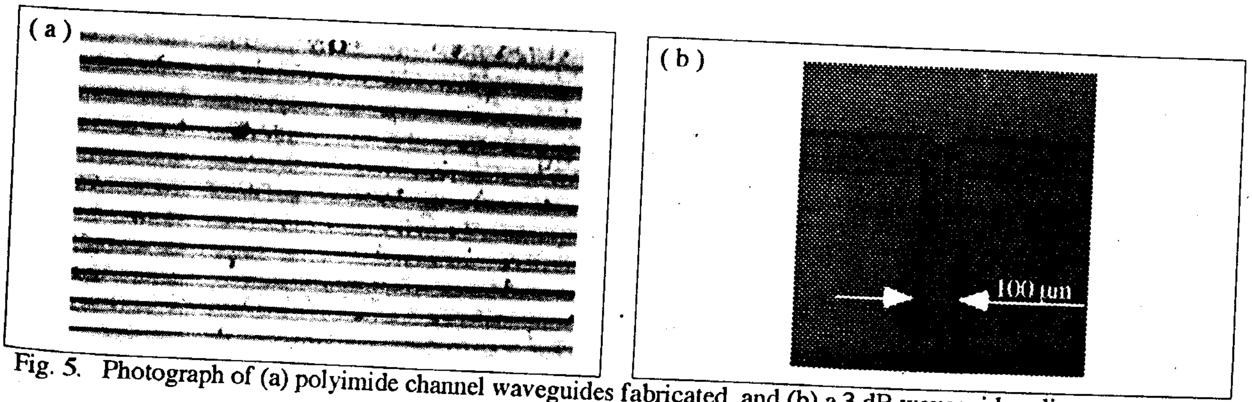

Fig. 5. Photograph of (a) polyimide channel waveguides fabricated, and (b) a 3 dB waveguide splitter.

2.2 Surface-Normal Waveguide Holograms

The waveguide holograms that can surface-normally couple the optical signal into and out of a channel waveguide, have also been investigated. Because most high-speed photodectors require a surface-normal input, such planarized waveguide couplers with the surface-normal conversion are very important to ensure an efficient optical coupling and packaging. It is also useful to couple optical signal from a vertical cavity surface emitting laser (VCSEL) into an optical waveguide. The surface-normal feature of fanout beams and the planar compact device structure convert the most difficult three spatial and three angular multiple alignment problems into a single step 2-D planar one. More importantly, the polarized structure is compatible with the Si CMOS fabrication process which makes the system integration highly feasible based on the reported technology. Such surface-normal waveguide grating couplers were demonstrated on a polyimide waveguide as input and output coupling gratings. Fig. 6 shows the surface-normal couplings from a free-space HeNe laser (λ = 632.8 nm) to a polymer-based planar waveguide and from the planar waveguide back to free-space using two waveguide gratings. In the experiment, the total insertion loss was 8 dB that includes 4.4 dB coupling loss and 3.6 dB waveguide propagation loss over a 9 cm long waveguide. Our theoretical calculation based on coupled-mode theory shows that the coupling loss could be as low as 1.3 dB when the microstructure of the grating is optimized. Due to the large dimension of the Cray T-90 supercomputer board, the free-space holographic lithography based on the two-beam interference method was employed for the grating fabrication[14]. The waveguide grating fabrication was performed in two steps. The first step is the design and recording of a grating pattern based on holographic interference; the second is the transfer of this recorded pattern to the polymeric waveguide using photolithography. To improve the grating coupling efficiency, tilted gratings were investigated and fabricated using Amoco photosensitive optical polyimide. Gratings with 0.5 μm period have been demonstrated.

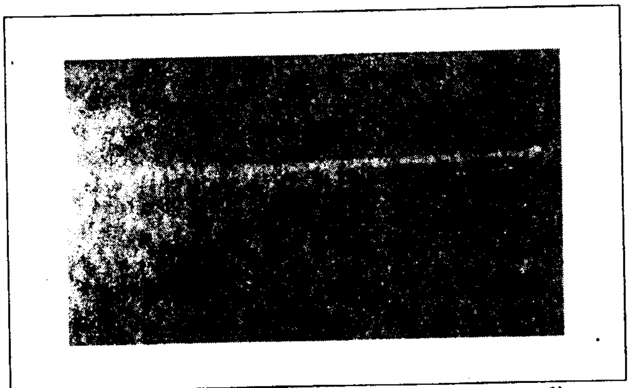

Fig. 6. Surface-normal coupling-in and coupling-out using two holographic waveguide gratings. The separation between two gratings is 9 cm.

2.3 An 1-GHz Optical Clock Signal Over Board-Size

To verify the bandwidth of optical multimode channel waveguides fabricated, an 1-GHz optical signal generated by a laser diode at 1.3 μm was launched into a 45-cm long waveguide. Fig. 7(a) and 7(b) are the photographs of the input and output signals from a Tektronics 11403 Digitizing Oscilloscope. A high-speed transmitter (2556T, Force Inc.) and a high-speed receiver (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. 18 dB signal-to-noise ratio (SNR) was obtained with very little wave front distortion.

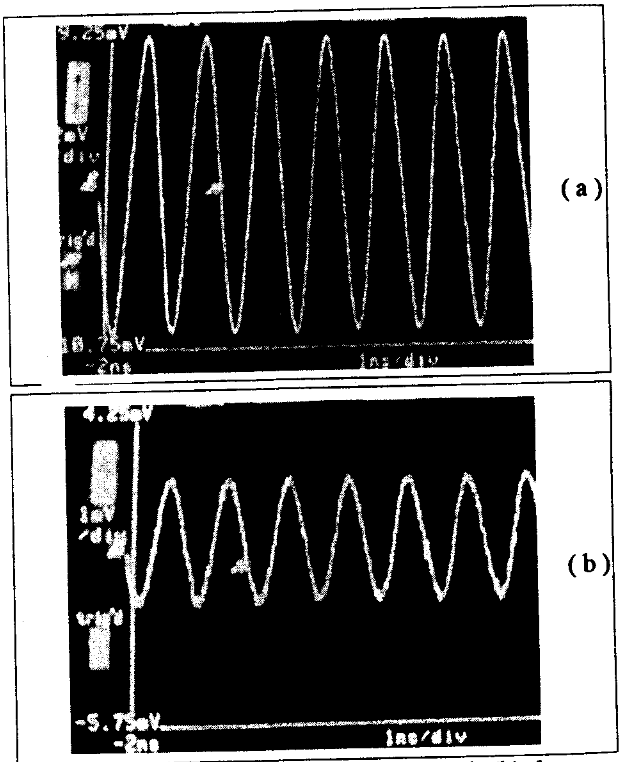

Fig. 7. (a) The 1-GHz optical input signal, (b) the output signal from the transceiver at the waveguide end.

3. Concluding Remarks

In summary, we represented our effort to construct an optoelectronic interconnection layer for the high-speed massive clock signal distribution on the Cray T-90 supercomputer board. The optical interconnection layer under investigation employs optical multimode channel waveguides in conjunction with surface-normal waveguide grating couplers. Equalized optical paths were realized using an optical H-tree structure having 48 optical fanouts. 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. The planarization of the OIL makes the inserting fully compatible with the Si CMOS microlithography process with processing temperature up to 350 °C. The transmission of 1-GHz optical clock signal was demonstrated experimentally with a 45 cm long interconnection length. Some new techniques to fabricate multimode channel waveguides and waveguide gratings in board-level are also presented.

4. Acknowledgment

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