Polymer waveguide based 1-GHz clock signal distribution system

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ABSTRACT

We present our effort to construct an optoelectronic interconnection layer for Cray supercomputer board for board-level fast optical clock signal distribution. The optical interconnection layer under investigation employs optical channel waveguides with surface-normal waveguide 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 optical clock signal is demonstrated experimentally with a guided-wave interconnection length of 45 cm. Some new techniques to fabricate multimode optical channel waveguides and 2-D array of surface-normal waveguide holographic gratings on board-level are also presented.

Keywords: polyimide, holographic grating, surface-normal coupler, optoelectronic interconnection layer, compression molding.

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 bottlenecks, such as speed, packaging, fanout, and power dissipation. Multichip module (MCM) technology is employed to provide higher clock speeds and circuits densities.[1,2] The state-of-the-art electrical interconnection and packaging technologies, however, still fail

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to provide the required clock speeds and communication distances in intra-MCM and inter-MCM hierarchies. With a clock speed of 500 MHz, for example, electrical interconnects can only provide us with ~10 cm communication distance.[3-5] Other problems for electrical interconnects in the application of high-speed, massive clock signal distributions include impedance mismatch for each fanout, signal reflection (noise) at each fanout junction as well as at the end of each transmission line, electromagnetic interference with other interconnection lines and other interconnection layers, high transmission loss, and large driving power. For clock signal distribution in MCM board, a successful interconnect network should also 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 supercomputer and intra-wafer MCMs, the synchronous global clock signal distribution is highly desirable to simplify the architecture and enable 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-scale massive fanout optoelectronic interconnects can overcome many problems associated with electrical interconnects and outperform electrical interconnects in these interconnection scenarios.[3-11] An array of novel optical interconnect architectures have been proposed,[11-14] which may partially satisfy the above-mentioned requirements for large scale clock signal distribution on board-level.

In this paper, we present the demonstration of planarized guided-wave optical interconnects for massive optical clock signal distribution. Integrated board-level fanout optoelectronic interconnects are constructed by using optical channel waveguides with a two-dimensional (2-D) waveguide hologram arrays. The surface-normal feature among fanout beams and the planar compact device structure convert the 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 displayed herein minimizes the employment of real estate of the wafer/board surface that has already been occupied by existing electronic components. Multimode channel waveguides have been fabricated with interconnection length up to 45 cm, over which we have demonstrated 1-GHz optical clock signal with little wavefront distortion. Key waveguide components including surface-normal waveguide grating couplers and Y-branch couplers for system integration have also been fabricated.

2 OPTICAL CLOCK SIGNAL DISTRIBUTION FOR CRAY SUPERCOMPUTER

Figure 1 is the picture of a Cray supercomputer T-90 board (14.2x26.7cm) that consist of more than 50 interconnection layers. Our approach for high-speed optical clock signal distribution is to construct an additional optoelectronic interconnection layer (OIL). Process compatibility and planarization of the OIL are two major concerns for this project. The optical clock signal delivered by an optic fiber will be coupled into the OIL using a holographic grating coupler. The optoelectronic interconnection layer consists of a polymer-based waveguide H-tree system as shown in Figure 2, in which all the optical paths have the same length, helping to reduce the skew problem. Optical components required for constructing such a H-tree system include low loss, very long polymer-based channel waveguide, holographic grating couplers, and Y-branch waveguide couplers. This guided-wave approach provides a compact and mechanically stable system due to planar layout of optical components and the use of waveguides. Note that a 45° waveguide end mirror is not suitable here because of the polarization requirement of vertical integration where multiple interconnection layers are stacked together. Surface-normal waveguide grating couplers on board-level are also presented in this paper.

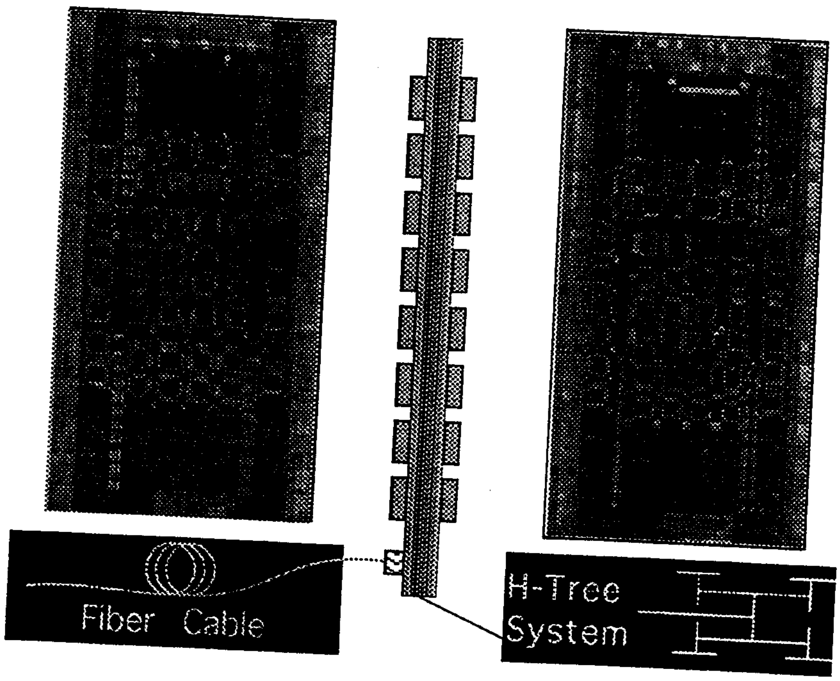

Figure 1: Photograph of a Cray multiple processor supercomputer board.

2.1 Board-size polymer-based channel waveguides

Because of the large size of the Cray supercomputer board, which is beyond the field limit of VLSI microlithography, we have developed a compression-molding technique for fabricating large-scale polymer-based channel waveguides.[9] A 45-cm long polymer-based compression-molded channel waveguide made on a glass substrate is illustrated in Figure 3, in which microprism[15] is employed to couple the 0.6328 μm HeNe laser beam into the guiding medium. The phase matching angle was set at the E^x_{11} mode. The ambient light displayed along the rib waveguide is the planar waveguide region T_2 shown in the inset of Figure 3. Waveguide propagation losses of different samples were measured using the two-prism method. Loss figures from 0.5 to 2 dB/cm were experimentally confirmed at 0.6328 μm. Waveguide loss at 1.3 μm was measured from 0.2 to 1 dB/cm.

Another option that we are pursuing is to adopt photosensitive polyimides and 'write' the waveguide patterns with a focused UV laser beam on a 2-D precision micro-translation stage. The fluorinated polyimides from Amoco Chemicals have a T_g approaching 400°C and retain excellent optical transparency when they are thermally or photochemically cross-linked.[16] Initial results are promising. In addition, the photo-sensitivity of the materials can be utilized to record holographic gratings, which makes the integration of the grating couplers intrinsic.

2.2 1-GHz optical clock signal over board size

To verify the bandwidth of the 45-cm long multimode optical channel waveguide at 1.3 μm, a 1-GHz optical signal generated by a laser diode was launched into the waveguide. Figure 4(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 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 an 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

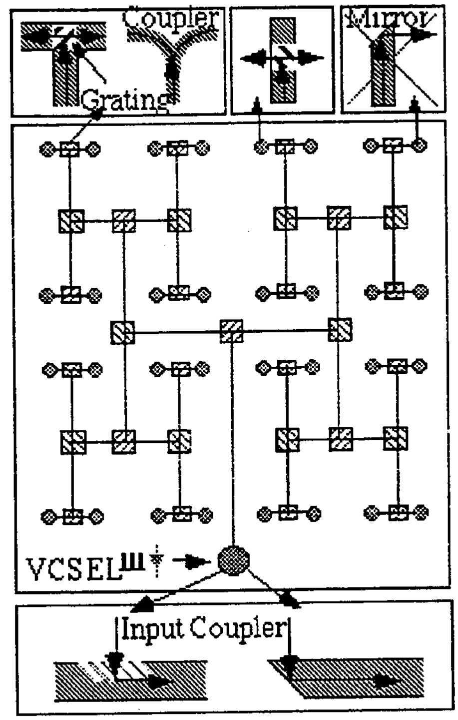

Figure 2: Schematic diagram of an optical waveguide H-tree system.

the (HP 8656B) signal generator (1-GHz), rather than the 45-cm long channel waveguide itself. Clear signal was obtained with very little wavefront distortion, which suggests much larger bandwidth achievable for the device under measurement.

2.3 Surface-normal waveguide holographic gratings

The surface-normal waveguide holographic gratings, required to couple the optical signal into and out of the waveguide with surface-normal conversion, have also been investigated. Since most high-speed vertical cavity surface emitting lasers (VCSELs) and photo-detectors require surface-normal input/output, such a surface-normal device configuration is very important to providing efficient coupling. More important, the surface-normal feature of fanout beams and the planar compact device structure convert the difficult three spatial and three angular multiple alignment problem into a single step 2-D planar one. The surface-normal waveguide grating couplers are demonstrated on a planar waveguide with an input and an output coupling hologram. The experimental result is shown in Figure 5 where the Fresnel reflection from the input port is also observed. In the experiment, the total insertion loss is 8 dB that 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.

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 recorded by a single plane UV laser beam as shown in Figure 6. An important advantage of this technique is the grating frequency doubling that causes a great relaxation in the resolution demands of the mask writing

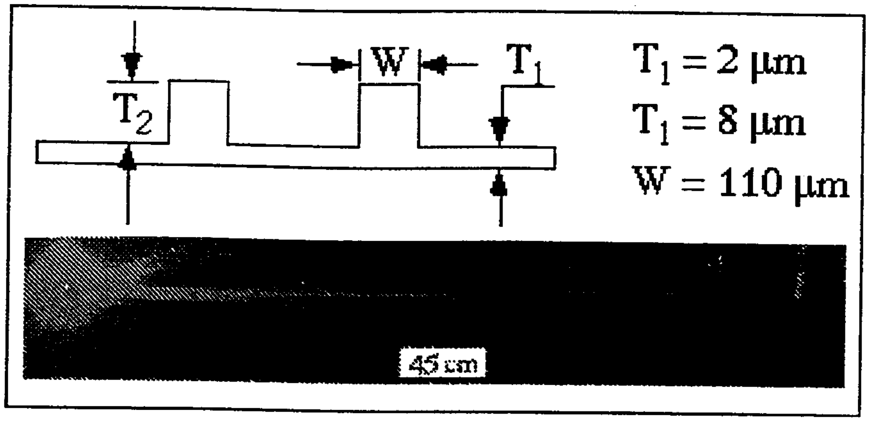

Figure 3: A 45 cm long compression-molded polymer-based waveguide working at 0.6328 μm.

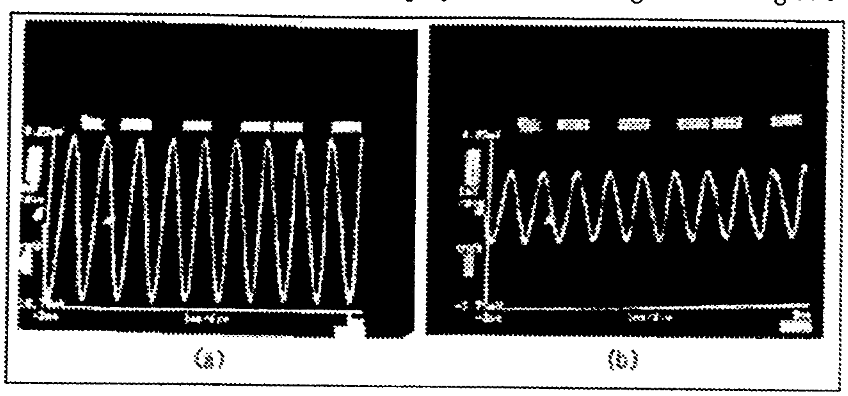

Figure 4: (a) Photographs of the 1-GHz optical input signal, (b) output signal from the transceiver system incorporating the 45 cm long polymer-based waveguide.

process by a factor of two. This is very critical for fabricating waveguide holograms where the short grating period is required. For normal incident on the phase grating, the phase match condition can be written 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 results in a standing wave pattern with a period Λ_{pr}, given as

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

Substituting Eqn.(1) in (2) gives

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

which shows the doubling of grating frequency.

To fabricate the optical waveguide H-tree with a 2-D array of holographic waveguide couplers as shown in Figure 2, it is very important to fabricate the holographic couplers at the desired positions where the high-speed photo-detectors are. Because 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 used.

Figure 5: Surface-normal coupling using two holographic waveguide gratings.

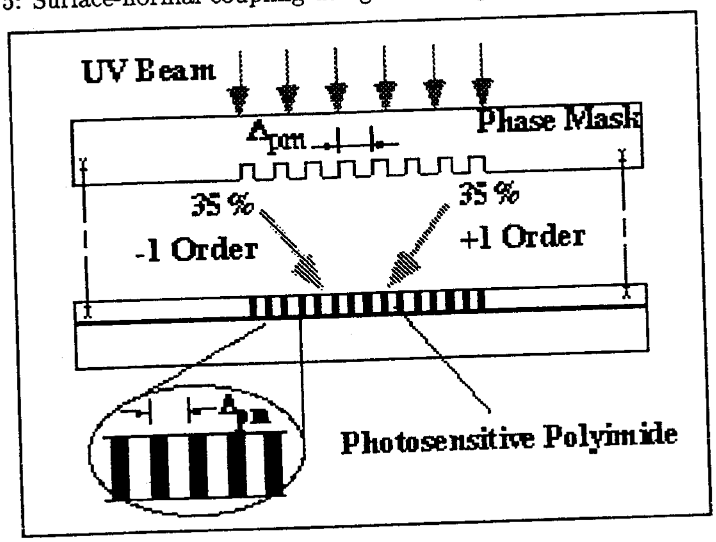

Figure 6: Schematic setup using a phase mask with alignment marks designed at normal incident.

3 CONCLUDING REMARKS

In summary, we present our effort to construct an optoelectronic interconnection layer for Cray supercomputer board for board-level fast clock signal distribution. The optical interconnection layer under investigation employs multimode optical channel waveguides with surface-normal waveguide 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 up to 45 cm. Some new techniques to fabricate multimode channel waveguides and 2-D array of waveguide gratings on board-level are also presented.

4 ACKNOWLEDGMENT

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