Polymer waveguide based high speed clock signal distribution system

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ABSTRACT

The increasing demand for clock speed is rapidly exhausting capabilities of interconnection techniques currently employed for high performance supercomputers. In order to address the bottleneck problem at the board level, we have taken a system's approach in developing optoelectronic interconnection layer for board-level high speed optical clock signal distribution. The reported approach employs polymer based optical channel waveguides, waveguide splitters, and surface-normal waveguide couplers. This paper describes the system architecture, material choice, and fabrication process of board-level waveguides devices to achieve a synchronous global clock signal distribution.

Keywords: polyimide, surface-normal coupler, optoelectronic interconnection layer, compression molding, direct laser writing

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. 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 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 clock signal distributions include impedance mismatch for each fanout, signal reflection (noise) at each fanout junction and at the end of each transmission line, electromagnetic interference with other interconnection lines, 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]

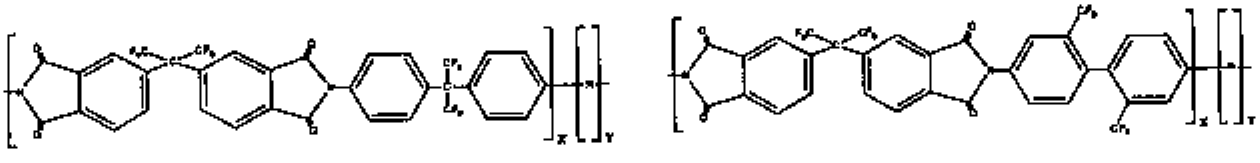
For a multiprocessor computer system, such as Cray T-90 supercomputer, the synchronous global clock signal distribution is highly desirable to simplify the architecture and enable higher speed performance. It has been found that it is extremely difficult to obtain high-speed synchronous clock distribution using electrical interconnections due to large number of fanouts (128) and long interconnection length (30 cm).[6,7] High-speed massive fanout optoelectronic interconnects can overcome many problems associated with electrical interconnects and outperform electrical interconnects in this interconnection scenario.[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 our current effort to build a planarized guided-wave optical interconnection layer for massive optical clock signal distribution. Polymer-based optical channel waveguides are adopted for an optical H-tree system. Our current work on the high speed photo-detectors and surface-normal grating couplers will be presented elsewhere.[18]

2. MATERIAL SYSTEM

The top concerns when choosing the material system include high thermal stability, high temporal stability, high solvent resistance, low optical loss and compatibility with other materials. Ultradel 9020D/9120D polyimides, originally developed by Amoco Chemicals for making electro-optical polymers, are two highly fluorinated crosslinkable polyimides with optimized optical properties for optical interconnect applications. Their chemical structures are illustrated in Figure 1. Due to the introduction of the perfluoro (CF_3) groups to the polymer backbone, optical absorption losses by photo-thermal deflection spectroscopy are reduced to 0.1-0.3 dB/cm for 9120D and 0.3-0.5 dB/cm for 9020D at 830nm.

However, fluorination also causes the fully imidized material to be susceptible to organic solvents as the CF_3 groups increases the solubility of polyimides. This presents a problem in multi-layer structure fabrications. The photocrosslinking group in Ultradel 9020/9120D polyimides was incorporated to serve two purposes: first, the solvent resistance is improved through formation of a three dimensional structure; second, it introduces pattenability with the solubility difference between the crosslinked and uncrosslinked areas.



(a) 9020D

(b) 9120D

Figure 1. Chemical structures of Ultradel 9020D/9120D (R=alkylated aromatic crosslinking group as described in Ref.[16].

Their excellent thermal stability (the glass transition temperatures are around 400°C) is critical for them to survive wire-bonding and metal deposition processes, which makes them compatible with silicon CMOS processing. In short, because of the excellent optical, mechanical and thermal properties of Ultradel 9020D/9120D polyimides, we have selected them for fabrication of our waveguide system.

3. OPTICAL CLOCK SIGNAL DISTRIBUTION SYSTEM DESIGN

Figure 2 is the picture of a Cray supercomputer T-90 board (14.2x26.7cm) that consist of more than 52 integration 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 optoelectronic interconnection layer consists of a polymer-based waveguide H-tree system as shown in Figure 3, in which all the optical paths have the same length, helping to reduce the skew problem. The optical clock signal is delivered by an optical fiber at the input end. At present both grating couplers and end mirrors are being investigated for the input and output couplers. Optical components required and developed for constructing such a H-tree system include low loss, board scale polymer-based channel waveguide, holographic grating couplers, end mirrors, Y-branch waveguide splitters, and high speed photo-detectors.

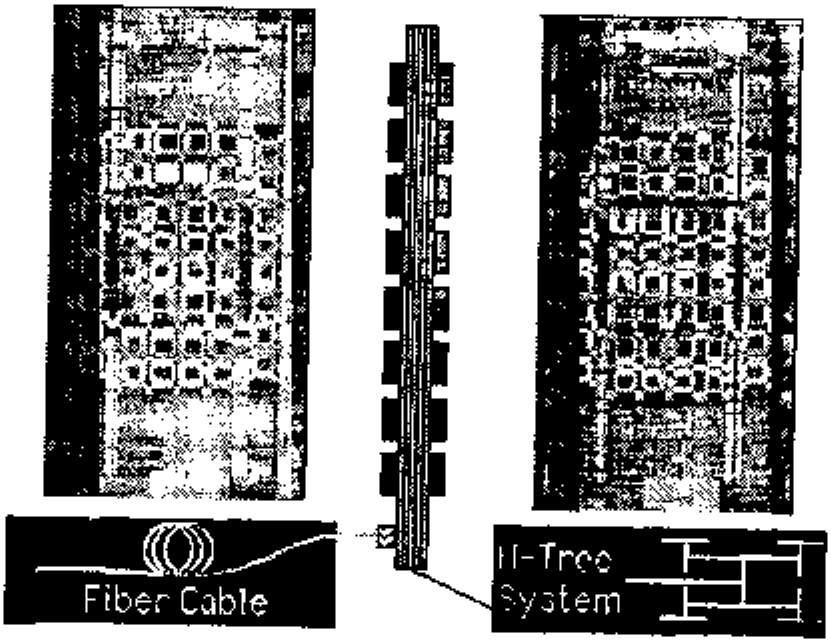


Figure 2. A Cray multiple processor supercomputer board with schematics of the optical interconnection layer.

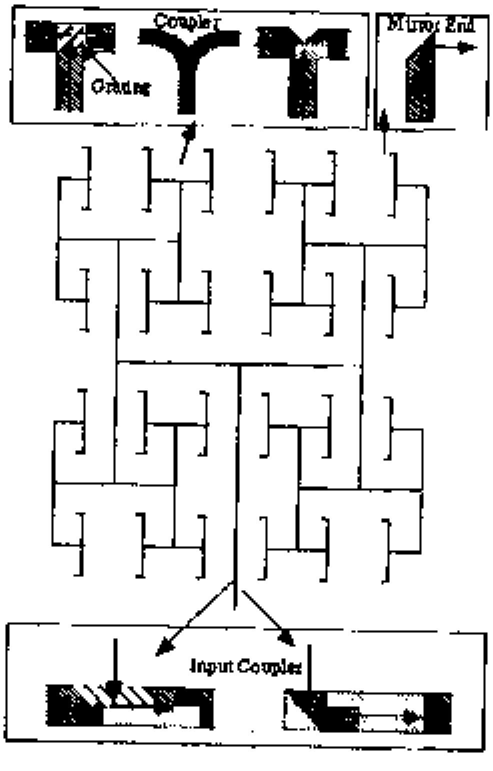


Figure 3. Schematic diagram of an optical waveguide H-tree system.

This guided-wave approach provides a compact and mechanically stable system due to planar layout of optical components and the use of waveguides. 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. The approaches displayed herein minimizes the employment of real estate of the board layers that has already been occupied by existing electrical interconnection. Unlike the existing multi-layer electrical interconnect approach, only one optoelectronic layer is required for optical clock signal distribution. More important, the performance of this optoelectronic interconnection layer is independent of its cost and complexity, providing a wide bandwidth for future improvement.

4. FABRICATION OF BOARD-SCALE POLYMER WAVEGUIDES

4.1. Direct laser writing method

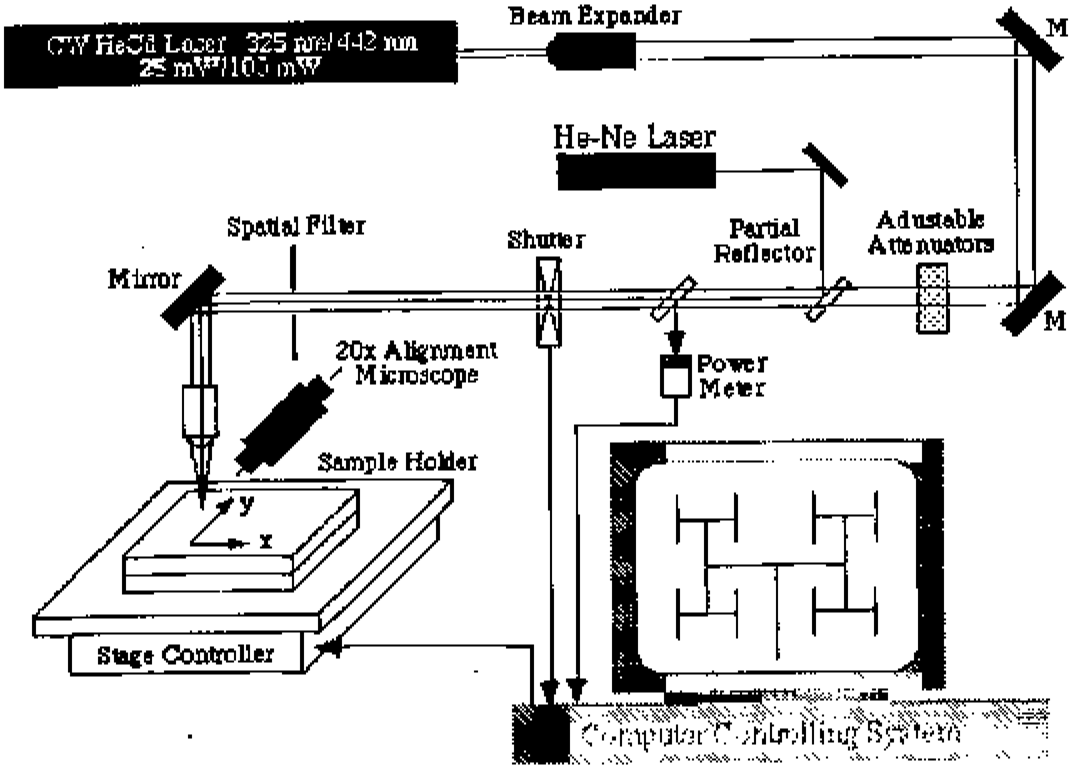
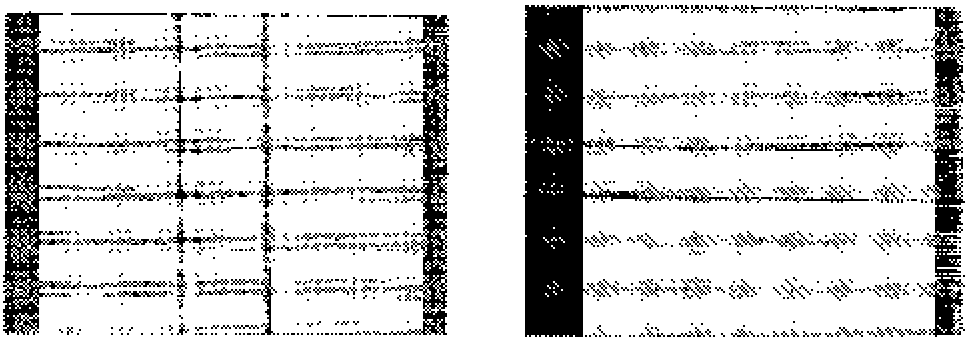


Figure 4. Schematics for the direct laser writing system.

The photo-sensitivity of the polyimides provides two options in terms of exposure method: conventional photolithography and direct laser writing method. Because of the large size of the H-tree waveguide system, we have developed a large-scale optical waveguide fabrication system based on the direct laser writing method as shown in Figure 4. The 325nm line of the He:Cd laser is employed as the exposure light source. The focused UV laser beam directly "writes" the waveguide pattern on a two dimensional precision micro-translation stage, which is controlled by the computer system. The beam power is monitored to provide adjustment to the stage motion speed to ensure a uniform exposure dose. A He:Ne laser is also adopted for alignment purpose.

A two waveguide array made with direct laser writing method is shown in Figure 5(a) with a separation of 3mm. Another waveguide having a linewidth of 50μm is shown is Figure 5(b). The typical cross-section profile will be discussed in section 4.2.



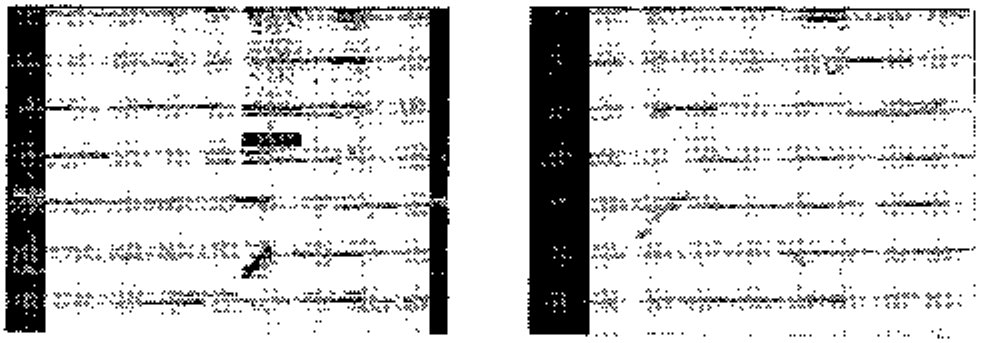
(a) A two-waveguide array.

(b) Waveguide of 60 μm linewidth.

Figure 5. Waveguide samples fabricated with the direct laser writing method.

4.2. Photolithography method

The conventional photolithographic technique has also been employed to fabricate the optical H-tree structure as shown in Figure 3. We have made a 7" photo-mask based on the system design as discussed in the above. The size of the H-tree structure was designed to match the chip positions on the Cray T-90 board. The total path from the input end to each output end measures 20.8cm.



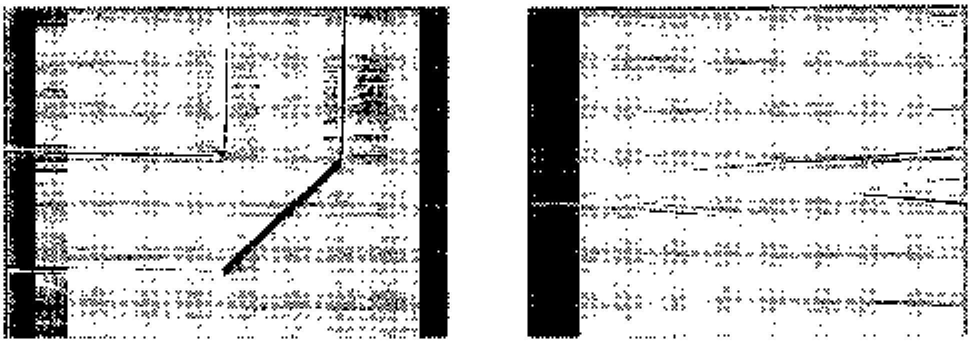
(a) T-shaped splitter (50 μm linewidth).

(b) T-shaped splitter (200 μm linewidth).

Figure 6. The 1-to-2 splitters fabricated with polyimide waveguide.

Two 1-to-2 T-shaped splitters of different waveguide dimensions, which are under testing as part of the H-tree system, are shown in Figure 6. Figure 7 shows two other test structures.

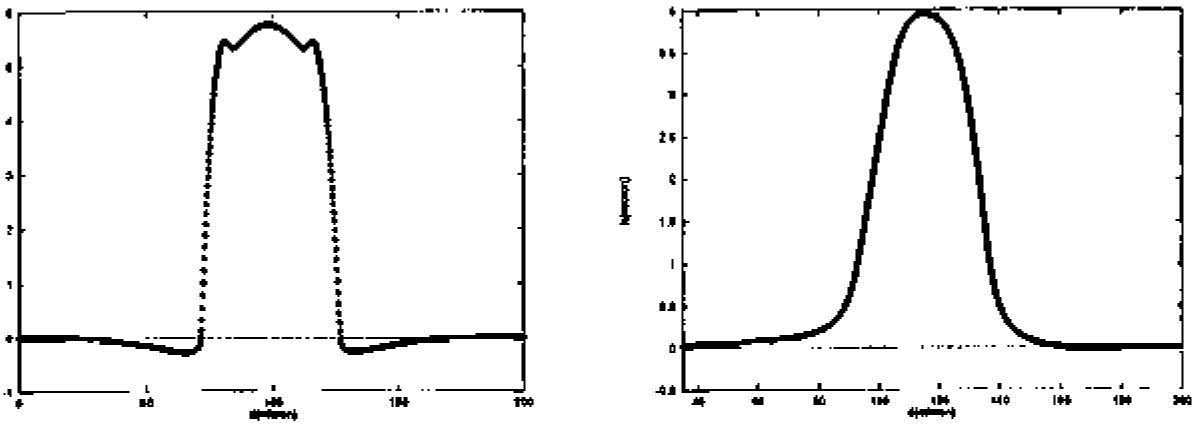
We have fabricated multi-mode waveguides of 10μm in ridge height with the photolithography method. The typical cross-section profiles, measured on a Alpha-Step surface profiler, are shown in Figure 8 for waveguides fabricated with the photolithography technique and the direct laser writing method, respectively. Both samples have a bottom polyimide cladding (Ultradel 9020D) of 6μm in thickness. The clean and sharp sidewall profile in Figure 8(a) is critical for the fabrication of low loss operation of the 1-to-2 splitters. The sidewall profile in Figure 8(b) was obtained for a single pass exposure with a defocused laser beam. Multiple pass exposure with a focused laser beam spot of less than 5μm has yielded waveguides of profile similar to Figure 8(a).



(a) 90° bend.

(b) Y-junction.

Figure 7. Two other test structures with polyimide waveguide.



(a) Photolithography method.

(b) Direct laser writing.

Figure 8. Cross-section profiles of ridge polyimide waveguides.

4.3. Compression-molding

We have also developed a compression-molding technique for fabricating large-scale polymer-based channel waveguides.[9] The advantage of this technique is that both the waveguide depth and dimension can be well controlled, which is beyond the limit of the above two method. A 45-cm long polymer-based compression-molded channel waveguide made on a glass substrate is illustrated in Figure 9, in which a 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_{11}^{x} mode. The ambient light displayed along the rib waveguide is the planar waveguide region T_2 shown in the inset of Figure 9. 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.

4.4. 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 10(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

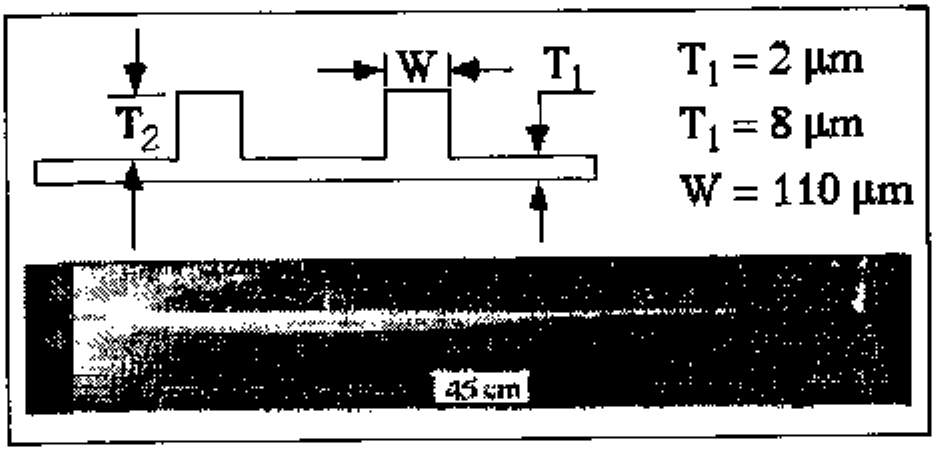
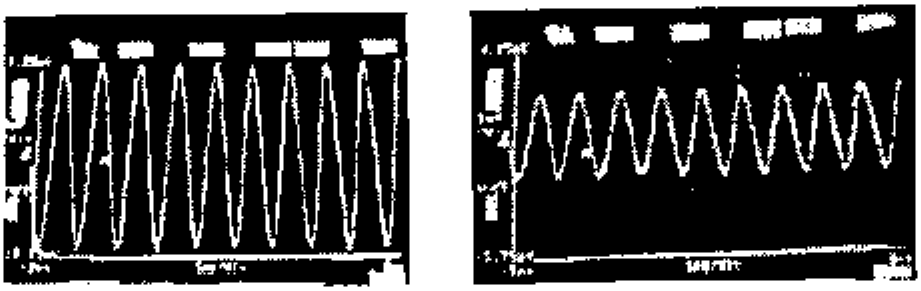


Figure 9. A 45cm long compression-molded polymer-based waveguide working at 0.6328 μm.

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



(a) (b)

Figure 10. Photographs of (a)the 1-GHz optical input signal, and (b)the output signal from the transceiver system incorporating the 45 cm long polymer waveguide.

5. CONCLUDING REMARKS

In summary, we present our effort to construct an optoelectronic interconnection layer for Cray supercomputer board for board-level high speed clock signal distribution. Based on this approach, the clock signal speed can be significantly increased to improve the supercomputer performance. Three waveguide fabrication techniques have been investigated to construct the required waveguide H-tree system. With all these waveguide components demonstrated, a high speed optical clock signal distribution system can be constructed to fulfill the bandwidth needs of future supercomputers.

6. ACKNOWLEDGMENT

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