Board-level optical clock signal distribution using Si C-MOS Compatible polyimide-based 1-to-48 fanout H-tree

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Abstract

Si-CMOS compatible polymer-based waveguides for optoelectronic interconnects and packaging have been fabricated and characterized. A 1-to-48 fanout optoelectronic interconnection layer (OIL) structure based on Ultradel 9120/9020 for the high-speed massive clock signal distribution for a Cray T-90 supercomputer board has been constructed. The OIL employs multimode polymeric channel waveguides in conjunction with surface-normal waveguide output coupler and 1-to-2 splitter. A total insertion loss of 7.98 dB at 850 nm was measured experimentally.

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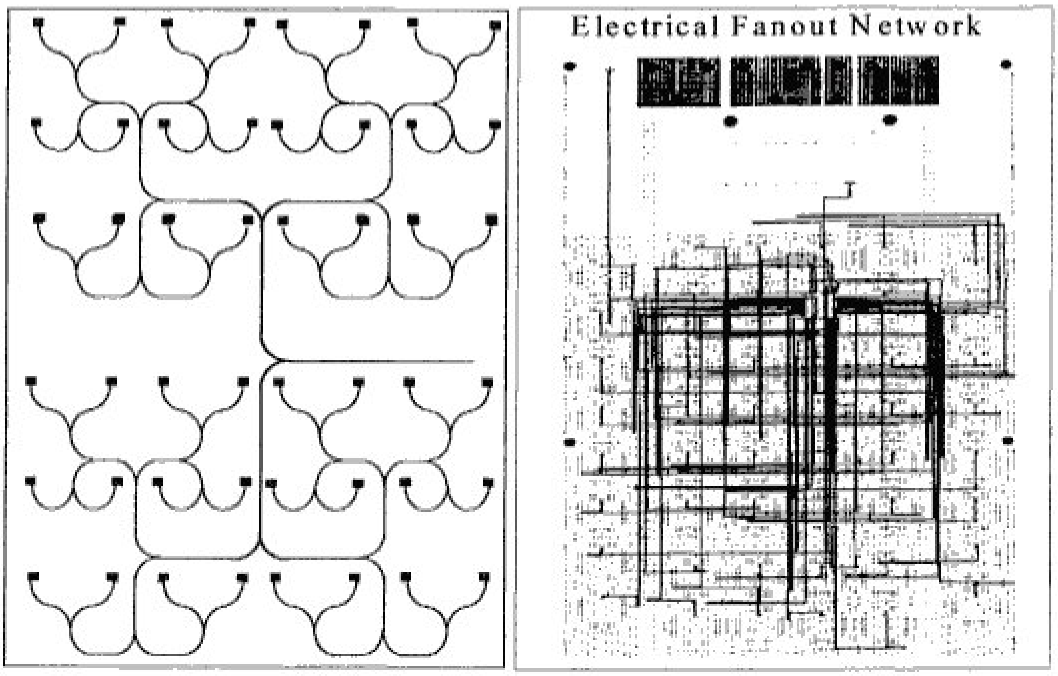
Introduction:

The most important parameter to determine the performance of a CPU is CPU time, which equals to Clock rate * Instruction count * CPI. CPI stands for average clock cycles per instruction. For a certain software program, the instruction count * CPI will be almost constant. Thus, increasing the system clock frequency directly enhances system performance in high-speed computing environments. State-of-the-art VLSI circuits are capable of operating and generating ultra-high clock rates (> 1 GHz). However, clock signal distribution systems based on electrical interconnect technologies fail to keep up with the cycle times and pulse widths needed to synchronize the operation of logic devices over long distances[1-3]. This timing bottleneck is a consequence of the variations in the transmission line propagation losses and dispersion, different packaging environments, and impedance discontinuities at the interfaces of the chips and boards. Further, capacitive loading, switching noise and signal cross-talk alter the clock signal waveform and become critical at high clock rates and large system lengths. These bottlenecks manifest themselves as clock skew and timing jitter in synchronous clock signal distribution systems. For example, the latest T-90 microprocessor machines from Cray Research Inc. has up to 36 processor-boards with a system clock speed of 500 MHz. All the boards in this system are synchronized to a central clock using an optical clock signal distribution system utilizing a high power semiconductor laser operating in conjunction with a single-mode optical fiber array at 1.3 μm. Within each board the clock signal distribution is still all electrical which puts a limitation on further improvements in the overall system speed. It is extremely difficult to obtain high-speed (>500 MHz), synchronous intra-board clock distribution using electrical interconnections due to large fanouts(48) and long interconnection lengths (> 15 cm) [1-5] . A fanout chip is required to provide mass intraboard electrical fanout. A synchronous global clock signal distribution is highly desirable to simplify the architecture and to enable higher speed performance. High-speed, large-area massive fanout optoelectronic interconnects may overcome many of the problems associated with electrical interconnects in this interconnection scenario[1-9] . Some optical interconnect architecture has been proposed and demonstrated by earlier researchers [9-12] which may partially satisfy the above requirements for a massive clock signal distribution.

We have developed a guided-wave optoelectronic interconnect network for optical clock signal distribution in board-level multi-processor systems as shown in Fig.1(a). In the H-tree, all the optical paths have to be of equal length in order to minimize the clock skew problems. For comparison, the electrical interconnect network currently employed by Cray Research is shown in Fig. 1(b) which shows the existing 500 MHz 1-to-48 clock signal distribution realized in one of the 52 vertical integration layers within the Cray T-90 supercomputer board.



(a) (b)

Fig.1 Schematic diagrams of massive clock signal distribution networks using (a) an optical waveguide H-tree and (b) an electrical transmission line network.

Results and Discussions:

The optoelectronic interconnect network are based on polymeric 1-to-48 fanout channel waveguides in conjunction with waveguide output couplers and fast photo-detectors. The guided-wave optoelectronic interconnect network under development will be inserted into the Cray supercomputer boards to become an additional interconnection layer along with the electrical interconnection layers. The Cray T-90 supercomputer board consists of 52 vertical electrical interconnection layers with the board size of 14.48 x 26.67cm^2. In order to implement an additional optoelectronic interconnection layer (OIL), Si-CMOS process compatibility and planarization of the OIL are the two major concerns that need to be addressed. These two issues could be effectively handled by application of polyimide-based waveguide structures. Our approach utilizes low-loss polyimides for optical channel waveguides which are Si-CMOS process compatible and all associated components including waveguides, waveguide output couplers and waveguide splitters can be easily planarized.

The optical components required for constructing an H-tree system such as the one shown in Fig. 1(a) include low loss polymer-based channel waveguides, waveguide output couplers, and 3 dB 1-to-2 splitter waveguides. The basic design goals include:

1: Minimizing the clock skew
2: Low waveguide propagation loss
3: Low 1-to-2 splitting and bending loss
4: Low input and output coupling loss
5: Large fanout and uniformity

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, Ultra-9000 series photosensitive polyimides (Amoco Chemicals) [15] are used for the waveguide fabrication. Fully cross-linked polyimides have excellent thermal stability (Tg = 400 °C) and optical transparency. The high glass transition temperature(Tg) is critical for the polymer to survive wire-bonding and metal deposition process, which makes it compatible with CMOS processing. Ultra-9000 series photosensitive polyimides are transparent in the visible and near infrared regions, which allows us to employ VCSELs, having output wavelength around 850 nm, and employ silicon-based photodetectors. The photosensitivity of these polyimides also enables us to fabricate the waveguide using conventional photolithography.

To achieve the required 1-to-48 fanout , we have used a 6-stage 90° bend 1-to-2 splitter. Figure 2 shows the diagrams of 90° bend 1-to-2 splitter. The splitter includes a 3 mm-long tapered waveguide and two curved waveguides with radius of curvature of 3mm. The tapered waveguides have a width of 50 μm at one end and 100 μm at the other end. Compared to the conventional Y-branch design[16] ,We have shown experimentally that this structure can effectively reduce the splitting loss from >2dB to 0.4 dB per splitter.

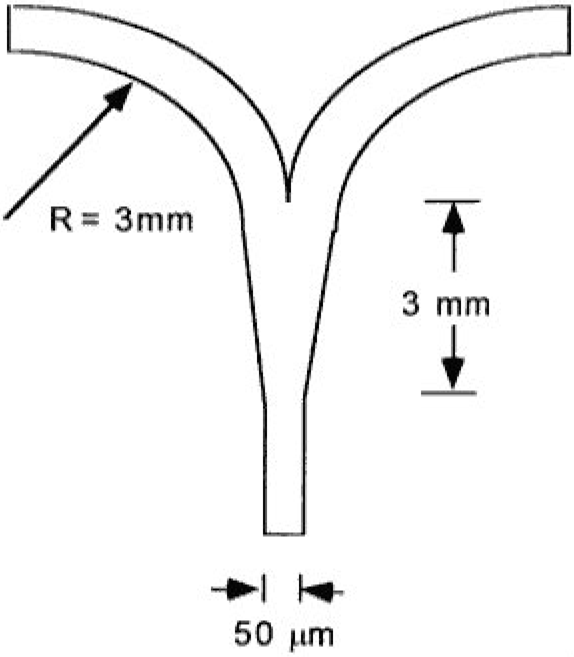


Fig.2 Schematic diagram of 1-to-2 y-branch. The waveguide have width of 50 μm.

To select the bending curvature, we need a minimized curvature in order to reduce the area of the splitter. On the other hand, to minimize the bending loss a large curvature is prefered. The curvature of the splitter in our H-tree design is 3 mm. The width of waveguide is 50 μm. The bending loss can be estimated as[17]:

$$\frac{2}{\pi}\frac{1}{\sqrt{100\Delta}}10^{2.29-2.17R_n-0.58R_n^2}(\mathrm{dB/rad})$$

with $\Delta = \Delta N / Nb$

and

$$R_n = (N_b R/\lambda)\Delta^{\frac{3}{2}} * 1.137^{\Delta-0.01}$$

where ΔN is the refractive index difference of waveguide and buffer, Nb is the refractive index of substrate and R is the radius of the waveguide curvature. With ΔN equal to 0.07 and R equal to 3mm, theoretically, the bending loss is negligible($< 10^{-10}$ dB/rad).

We have constructed a 1-to-48 fanout H-tree waveguide structure using polyimide planarization and photolithography.

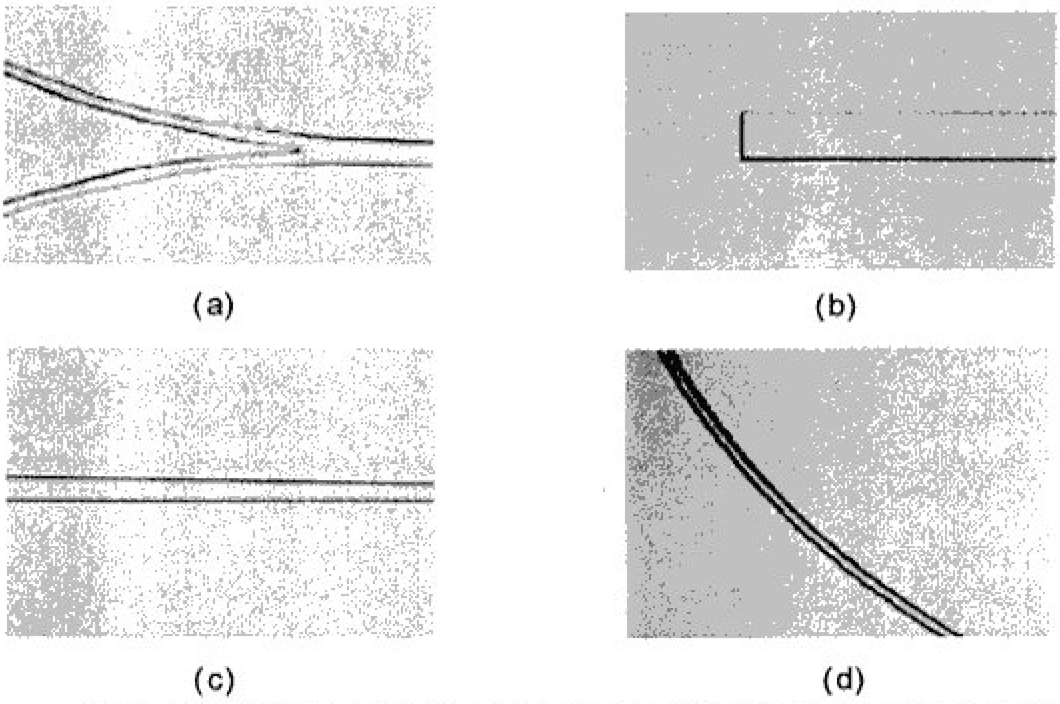


Fig 3. Microscope pictures of the H-tree structure. (a) is the picture of splitter. (b) is the picture of the end of the H-tree. (c) and (d) show the tapered and curved waveguides. All the waveguides have width of 50 μm except the tapered regions.

Figure.3 shows microscope pictures of the H-tree we fabricated. The 3dB 1-to-2 splitter structure is shown in (a). Figure 3(b) shows the fanout end of the waveguide. Figure 3(c) and (d) shows the tapered portion and curved portion of the waveguides.

Figure. 4 shows a coupling photograph of the waveguide H-tree system constructed on Si-substrate using Ultradel 9120 polyimide. A layer of Ultradel 9020 polyimide is spin coated on the Si substrate as a buffer. The refractive index of the 9020 layer is 0.02 lower than the index of 9120D at the wavelength 633 nm and 850 nm. The thickness of the 9020D buffer layer is 5 μm. The 633 nm laser light from the He-Ne laser was butt-coupled into the input end of the OIL. We can clearly see the fairly uniform light distribution to the 48 fanout .

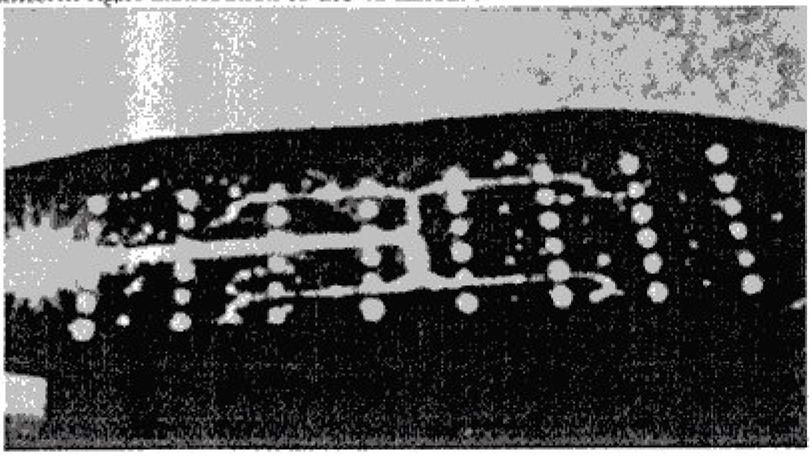


Fig.4 Photograph of the 1-to-48 fanout H-tree on Si substrate using Ultradel 9120 polyimide. A He-Ne laser beam at λ=633 nm was butt-coupled into the input end.

High-speed operation and massive fanout requirements impose stringent conditions on the material selection, minimization of waveguide propagation loss, and optimization of output coupling efficiencies. Ensuring that enough optical power reaches the photodetectors for high-speed operation is essential. For example, the total optical splitting power budget is 18 dB (3x6) in an optical H-tree system (capable of providing 64 fanouts), which consists of six stages of 1-to-2 (3 dB) optical fanout. If the optical power at the input end is 10 dBm, and a 10 GHz optical receiver (having a sensitivity of -20 dBm at 10 GHz)[18] is used at the output end for signal detection, the total insertion loss (output coupling loss plus waveguide propagation loss) should be less than 12 dB.

In the H-tree design, the total length from input to the fanout end is 10.4 cm. The propagation loss measured are 0.21 dB/cm at 850 nm and 0.58 dB/cm at 633 nm. This results in a total propagation loss of 2.18 dB at 850 nm and 6.03 dB at 633 nm. The splitting and bending loss for 6 stages is 2.4 dB. (6 * 0.4 dB). Assuimng a 3 dB input coupling loss and 90% output coupling efficiency, we project a total insertion loss of 7.98 dB at 850 nm and 11.83 dB at 633nm which is less than the required 12 dB insertion loss.

Conclusion:

Polymer-based waveguides for optoelectronic interconnects and packagings have been fabricated and characterized. The fabricarion process is compatible with Si CMOS packaging process. An optoelectronic interconnection layer (OIL) for the high-speed massive clock signal distribution for the Cray T-90 supercomputer board has been constructed. The optical interconnection layer under development employs optical multimode channel waveguides in conjunction with surface-normal waveguide grating couplers and a 1-to-2 3 dB splitter. Equalized optical paths are realized using an optical H-tree structure having 48 optical fanouts. This device could be increased to 64 without introducing any additional complication. A 1-to-48 fanout H-tree structure using Ultradel 9000D series polyimide has been fabricated. The propagation loss and splitting loss have been measured as 0.21 dB/cm and 0.4 dB/splitter at 850 nm. The power budget has been discussed. The H-tree waveguide fully satisfies the power budget requirement.

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