Integration of 45-degree Micro-couplers in Guided-wave Optical Clock Distribution System for Supercomputer

Jianhua Gan, Linghui Wu, Hongfa Luan, Bipin Bihari and Ray T. Chen
Microelectronics Research Center, R9900
Department of Electrical and Computer Engineering
The University of Texas at Austin
Austin, Texas 78712
Phone: 512-471-4349
Fax: 512-471-8575
E-mail: gan@ece.utexas.edu

Abstract

The clock skew and bandwidth limitations are serious problems for electrical interconnects when the clock rate in computer is pushed toward 1GHz and the beyond. Clock signal distribution using guided-wave optics provides a solution for these problems. The optical clock signals can be distributed to various locations using an H-tree polyimide waveguide structure with same delay time due to the equalized optical paths in the H-tree configuration. Surface-normal couplers are indispensable parts of such a system for the coupling of optical clock signals into and out from the waveguides while facilitating the packaging. A 45-degree surface-normal coupler was fabricated at the each fanout end of the H-tree structure. The waveguide is 10μm thick and 50 μm wide. The coupler is a 45 degree slanted end surface of the polyimide waveguide. The optical clock signals can be coupled out from the polyimide waveguides through the couplers surface-normally due to total internal reflection. The 45-degree surface-normal coupler can also couple the optical clock signal into the waveguide efficiently when the mode-matching condition is met. The coupler works for a wide range of wavelength. The measured output coupling efficiency is nearly 100%.

Key words: optical clock distribution, guided-wave optical interconnects, clock skew, 45-degree micro-coupler, H-tree polyimide waveguide

Introduction

As the clock rates in high performance computing systems are approaching GHz range, electrical interconnects are facing more and more problems such as clock skew, cross talk and electromagnetic interference[1]. Optical interconnects can overcome these bottlenecks. Optical interconnects for intra-chip, inter-chip and inter-board interconnects are desirable for high data rates [2, 3, 4]. While free space optical interconnects using conventional opto-mechanical technology are vulnerable to vibration and have limited degrees of freedom, the guided-wave optical interconnects show great potentials for the high data rate interconnects. Ease of fabrication, thermal and mechanical stability, and high glass transition temperature (Tg ≈ 400°C) make polyimide a promising material in guided-wave optical interconnects. Surface-normal micro-coupler is a key component in the planar integrated optical systems. Surface-normal micro-couplers facilitate the integration of vertical cavity surface-emitting lasers (VCSEL) and photo diodes with optical waveguides. Unlike grating couplers [5, 6], 45-degree surface-normal micro-couplers are easy to fabricate, reproducible and relatively insensitive to wavelength variations. Here, we describe the integration of 45-degree micro-couplers in guided-wave clock distribution system. This guided-wave optical interconnection network is designed to be added to the supercomputer boards to become an additional interconnection layer among many other electrical interconnection layers. This optical clock distribution system may be able to deliver clock signal to other chips at Gbit/s speed with very small clock skew.

Materials

Polyimides are widely used in Si CMOS processing as protective coatings. They are thermally stable. For waveguide application, the polyimides should have low optical loss and good thermal stability. We have used Ultradel 9120D to fabricate the H-tree waveguides. 9120D is a negative-acting, photosensitive polyimide. It is characterized by high optical transparency, high thermal stability and ease of fabrication. At the wavelength of 1.310μm, the refractive indices are 1.5364 and 1.5073 for TE and TM wave respectively. The optical losses are 1.04dB/cm at 633nm, 0.13dB/cm at 830nm, 0.09dB/cm at 1064nm, 0.34dB/cm at 1300nm and 1.21dB/cm at 1550nm. The glass transition temperature is 390°C. The coefficient of thermal expansion at 300°C is 27ppm/°C. The moisture uptake at 100% relative humidity is 3.0%. Polyimides with lower refractive indices are also available for cladding and buffer coatings.

The preparation and photolithography of 9120D film are briefly described below. Five ml of filtered (0.2μm) Ultradel A600 adhesion promoter is dispensed on clean substrate. 5-second-spin at 500 RPM is followed by 30-second-spin at 4000 RPM. It is bake at 100°C for 60 seconds to remove residual moisture. Next, 5 ml of 9120D is applied and 30-second-spin at 500 RPM is followed by 60-second-spin at the desired spin speed. The 9120D coating is baked for 3 minutes on a 100°C hotplate. Then the coating is ready for imaging and development. The exposure dosage is approximately 300-900mJ/cm^2 with broadband ultraviolet (UV) light. Post-exposure bake at 175°C for 30 minutes in a nitrogen-urged oven can be used to improve fine feature resolution. Spray development for 90-180 seconds is used to develop the 9120D film. Spin dry for 20 seconds at 4000 RPM and baking at 300°C for 30-60 minutes in a nitrogen-purged oven conclude the process.

Fabrication Using Reactive Ion Etching (RIE)

A novel board-level optical clock distribution system based on polyimide waveguides, 45- degree surface-normal micro-couplers and fast photo detectors will be the enabling technology to boost the clock rate in supercomputer and other high performance digital systems to GHz range. One major concern need to be addressed is the Si-CMOS packaging compatibility [1]. The thermal stability of polyimide renders the polyimide waveguide and micro-couplers compatible with Si-CMOS packaging. In order to minimize the clock skew in the clock distribution system, we use H-tree configuration to equalize the paths to all the fanout points. The schematic of a 1-to-48 H-tree structure is shown in Fig.1. We fabricated 45-degree micro-couplers at 48 fanout positions. All the associated components including waveguides, 45-degree surface-normal micro-couplers and waveguide splitters can be integrated together. The optical clock signal will be coupled out by 45-degree surface-normal micro-couplers and will be converted into the electrical signal by photo detectors.

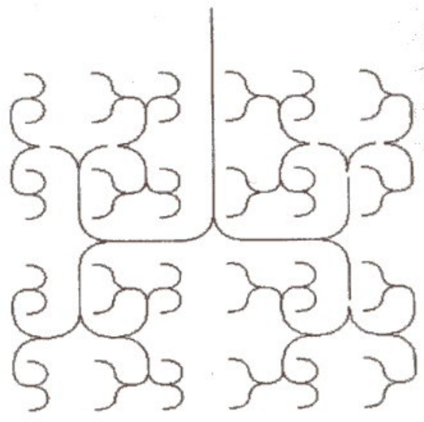


Fig.1. 1-to-48 H-tree polyimide waveguide for optical clock distribution

The H-tree waveguides can be fabricated using photolithography. Silicon wafer with 2μm thick silicon dioxide was used as substrate. Silicon dioxide layer acts as buffer layer. As an alternative, other low index polyimide can be used as cladding and buffer layers. About 10-μm-thick polyimide 9120D was spin-coated on the clean substrate. H-tree structure mask is a dark field mask. H-tree structure was patterned to the polyimide layer using UV photolithography described above. The waveguide without 45-degree micro-couplers at all the fanout was obtained after this step. We used RIE to fabricate the 45-degree micro-coupler at the end of each branch of the waveguide. The corresponding processing steps are shown in Fig. 2. A 0.3nm-thick aluminum film was coated over the H-tree waveguides. Photoresist AZ5206E was coated over aluminum. A mask was used to pattern the end portions of the 48 branches of the waveguides. The pattern was then transferred to aluminum layer by wet etching. This opened a square window at each end of the 48 branches of the waveguide. One edge of the window was parallel to the end of the branch. Aluminum layer acted as a mask in reactive-ion etching (RIE) chamber. The sample was mounted 45 degree with respect to the electrode plate of the RIE chamber. A Faraday cage [7] was used to cover the sample so that the directional high-speed ion could attack the polyimide at 45 degree. The RIE parameters were set to 20mTorr of oxygen and 200W of RF power. The etch time was 120 minutes. The aluminum mask was removed by aluminum etchant, leaving a 45-degree slanted end surface on each end of the 48 branches of the waveguide. This 45-degree slanted end surface serves as the micro-coupler.

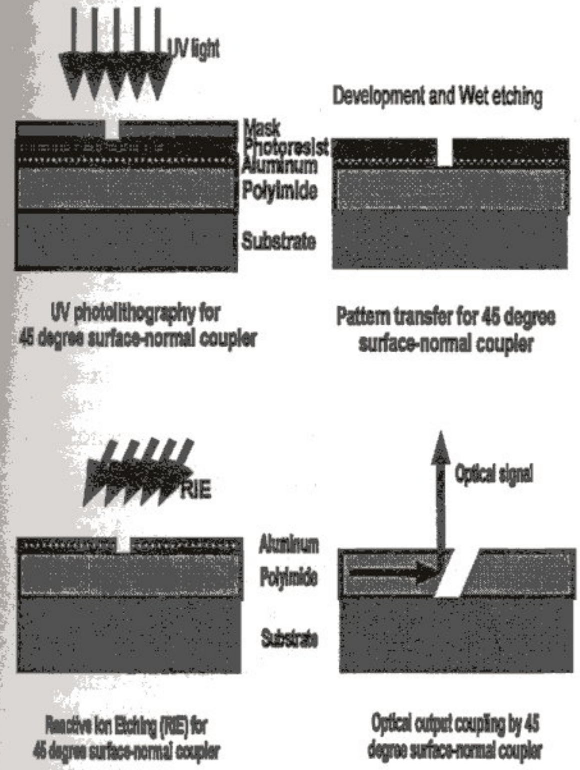


Fig. 2. The processing steps of making 45 degree micro-coupler using RIE

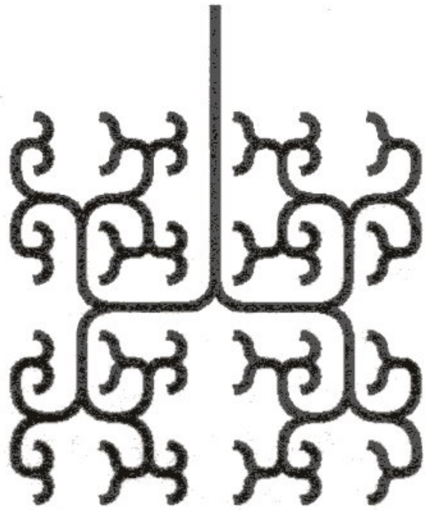


Fig. 3. "Mask-1" used to block the line portions of the waveguides during first 45-degree-slanted exposure

Fig.4 "Mask-2" used to block the end portions of waveguides during second exposure

Fabrication Using Double Exposure Method

We have developed an alternative approach to fabricate the H-tree waveguide and 45-degree surface-normal micro-coupler using double exposure method. In double exposure method, the H-tree mask was put over the sample and the lines of the H-tree mask were blocked using "mask-1"(see Fig. 3). Only the end portions of the 48 branches were exposed to 45-degree-slanted UV light. The exposure time was set to 2.5 minutes. Then we blocked the end portions of the 48 branches using "mask-2"(see Fig. 3), let the line portions of the H-tree waveguides expose to normal-incident UV light. After post-exposure bake at 175°C for 30 minutes in a nitrogen-purged oven, we developed the sample using spray development. We performed spin dry and final bake in the end. The polyimide waveguides after final bake is stable and resistant to moisture.

Measurement and Theoretical Calculation

To demonstrate the functionality, butt coupling was used to couple the light (633nm wavelength) into the waveguide. The surface-normal outputs from 48 output micro-couplers can be seen in Fig.5. However, the waveguide is also visible due to the high scattering loss at 633nm wavelength. The 48 surface-normal outputs from the 45-degree micro-couplers are shown. The output coupling efficiency is nearly 100%. The waveguide loss is much lower when we use 850nm wavelength. The output wavelength of VCSEL is 850nm and the surface-emitting characteristic of VCSEL is a natural match to 45-degree surface-normal micro-coupler.

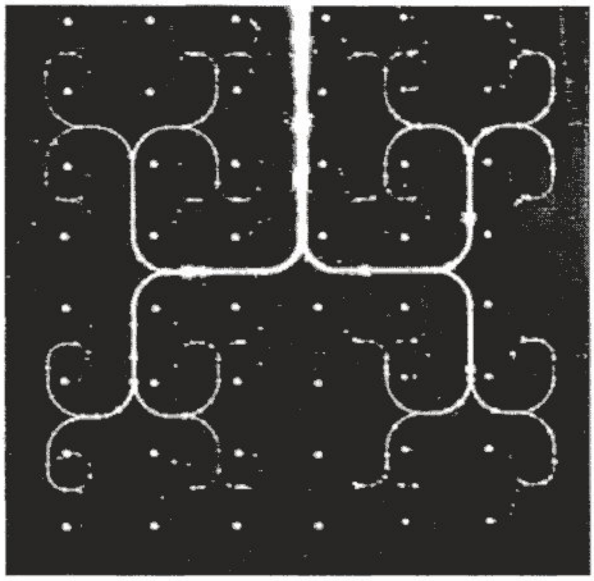


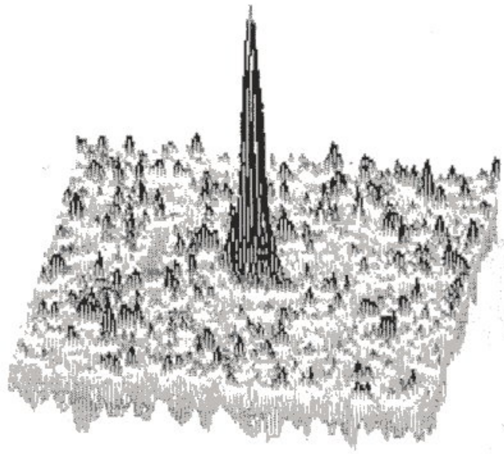
Fig. 5. A photography showing the 48 surface-normal outputs

The output profile from one of the 45-degree micro-couplers is shown in Fig. 6(a). The output coupling efficiency of this 45-degree micro-coupler is nearly 100%. The spot size of the output light at the micro-coupler is about 60μm, which is comparable with the active region of silicon-based photo detector. If the photo detectors are mounted closely to the micro-couplers, then most of the light can reach the photo detectors and thus the coupler-to-detector coupling efficiency is very high.

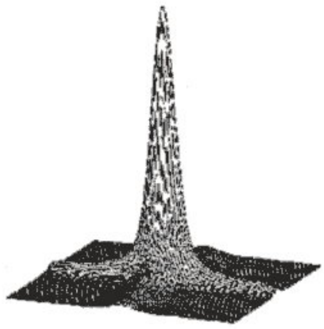
The output profile from the 45-degree micro-coupler can be calculated using diffraction theory. We used Fresnel approximation [8, 9] to get the near field distribution.

$$U(x,y) = \frac{\exp(jkz)}{jz\lambda} \int_{-\infty}^{\infty} U(\xi,\eta) \exp\{(j\frac{k}{2z}[(x-\xi)^2 + (y-\eta)^2]\} d\xi d\eta$$

$U(\xi,\eta)$ is the complex amplitude of the excitation at point (ξ,η) on the 45-degree micro-coupler. $U(x,y)$ is the complex amplitude of the observed field at point (x,y). k is the magnitude of wave vector and z is the distance from the 45-degree micro-coupler to observing point. The theoretical output profile from the 45-degree micro-coupler is shown in Fig. 6(b). In this calculation, the input to the micro-coupler was assumed to be the fundamental mode of the waveguide. It turned out that most of the energy was in fundamental mode in our case. The theoretical result and the experimental result agree with each other.



(a)



(b)

Fig. 6. The output profile from the 45-degree micro-coupler (a) experiment (b) theory

Conclusion and Future Work

In summary, the integration of 45-degree micro-couplers in guided-wave optical clock distribution system is shown. Both RIE and double exposure method were used to fabricate the 45-degree micro-couplers. The 1-to-48 surface-normal output coupling is demonstrated. The output coupling efficiency is nearly 100%. If the photo detectors are mounted close to the micro-couplers, then most of the light can reach the photo detectors and thus the coupler-to-detector coupling efficiency is very high. This optical clock distribution system will be able to deliver the clock signal at tens of GHz with very small clock skew. The final planarization step involving top cladding layer and the integration of VCSEL and photo detectors with H-tree waveguide and 45-degree micro-couplers are in progress. The high efficiency of surface-normal coupling is an obvious advantage when the optical clock distribution system is integrated with lasers and photo detectors for intra-chip, inter-chip and inter-board interconnects.

References

[1] R. Chen, L. Wu, F. Li, S. Tang, M. Dubinovsky, J. Qi, C. Schow, and J. Campbell, R. Wickman, B. Picor, M. Hibbs-Brenner, J. Bristow, Y. Liu, S. Rattan, and C. Noddings, "Si CMOS process compatible guided-wave multi-Gbit/sec optical clock signal distribution system", 1997 IEEE International conference on "Massively Parallel Processing using Optical Interconnects", Montreal, Canada, June 22-24, 1997.

[2] R. Chen, "Polymer-based photonic integrated circuits", Optics & Laser Technology, Vol. 25, No.6, 347(1993).

[3] R. Chen, H. Lu, D. Robinson, M. Wang, G. Savant, and T. Jannson, "Guided-wave planar optical interconnections using highly multiplexed polymer waveguide holograms", IEEE Journal of Lightwave Technology, Vol. 10, No.7, 1(1992).

[4] J. Cook, G. Este, F. Shepherd, W. Westwood, J. Arrington, W. Moyer, J. Nurse, and S. Powell, "Stable, low-loss optical waveguides and micromirrors fabricated in acrylate polymers", Applied Optics, Vol. 37, 1220(1998).

[5] R. Waldhausl, B. Schnabel, P. Dannberg, E. Kley, A. Brauer, and W. Karthe, "Efficient coupling into polymer waveguides by gratings", Applied Optics, Vol. 36, 9383(1997).

[6] J. Miller, N. de Beaucoudrey, P. Chavel, J. Turunen, and E. Cambril, "Design and fabrication of binary slanted surface-relief gratings for a planar optical interconnection", Applied Optics, Vol. 36, 5717(1997).

[7] G. D. Boyd, L. A. Coldren, F. G. Storz, "Directional reactive ion etching at oblique angles", Applied Physics Letter, Vol. 36, No.7, 583(1980).

[8] M. Sypek, "Light propagation in the Fresnel region: new numerical approach", Optics Communications, Vol. 116, 43(1995).

[9] J. W. Goodman, "Introduction to Fourier Optics", McGraw-Hill Publishers, second edition, New York, Chapter 4, 63(1996).