Si-Based Surface-Relief Polygonal Gratings for 1-to-Many Wafer Scale Optical Clock Signal Distribution

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***Abstract*— In contrast to volume holographic material where 1-to-many fanouts are realized using multiplexed volume holograms, we report in this paper the first Si-based surface-relief polygonal gratings aiming at optical clock signal distribution application. Surface-relief gratings with 1-μm period (0.5 μm feature size) were fabricated using reactive ion beam etching (RIE). Both hexagonal and square gratings were demonstrated for 1-to-4 and 1-to-6 fanouts. Surface-normal input and output coupling schemes were carried out with an combined coupling efficiency of 65%. Employment of substrate modes in silicon greatly releases the required grating spacing for the demonstrated two-way surface-normal coupling. 7.5 GHz 1-to-4 clock signal distribution operating at 1.3 μm was demonstrated with a signal-to-noise ratio as high as 60 dB. The intensity fluctuation among fanout beams was measured to be within 1dB. Generalization of 1-to-many fanout can be realized by implementing a polygonal grating with an equivalent number of facets.**

WITH THE ADVENT of higher clock speeds and distributed multiprocessor computer architectures, a great deal of interest has arisen in synchronously distributing a clock signal over all the processors in a computer with an acceptable clock skew [1]. Unfortunately, at clock speeds above 500 MHz, a synchronous global clock distribution system is very difficult to attain using electrical interconnects due to skin-effect induced losses, impedance-mismatch due to large fanouts, and RLC-related charging times that are detrimental for the realization of such an electrically interconnected high-speed system. Because of the high bandwidth inherent in optical signals, various guided-wave optical clock distribution schemes have been investigated to alleviate such a problem. Photopolymer-based multiplexed volume holograms [2] have been employed to achieve massive fanouts up to 59/node [3]. Surface-relief materials have also been employed by using different diffraction orders of surface-relief gratings [4] to achieve the required fanout. Due to the nature of nonmultiplexibility, a surface-relief grating is primarily employed as a 1-to-1 interconnect device with a relatively low interconnectivity [5]. For 1-to-many fanout optical interconnects employing surface relief material with a single fanout node, a new device configuration is needed to solve this problem.

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In this letter, we demonstrate the first Si-based polygonal gratings for 1-to-many fanouts with a surface normal configuration. A linear grating was converted into a polygonal format with the required grating vector for each predestined fanout direction. A central polygonal input coupling grating and surrounding linear output coupling gratings were employed to provide the desired optical clock signal distribution. As shown in Fig. 1, equivalent optical paths (and thus minimized clock skew) are provided through this approach. A double-side polished Si wafer is used to minimize the surface scattering losses as the signal travels through the bulk of the Si wafer. The number of fanouts is determined by the total facets associated with the polygonal grating needed to realize the 1-to-many clock signal distribution. The basic coupling configuration is illustrated in the inset of Fig. 1 that provides a substrate guided wave with a bouncing angle Θ_t within the silicon substrate from the surface normal incident direction. For an operating wavelength of 1.3 μm with air as the cladding medium, the critical angle for total internal reflection is less than 16.6° which makes a grating period of 1 μm applicable for this demonstration. Note that the zigzag bouncing mode described in this paper is the substrate guided waves which were defined as "substrate modes" in the conventional terminology of integrated optics [6]. Employment of these modes significantly releases the grating spacing requirement for surface-normal coupling and therefore facilitates the fabrication process. Both the central polygonal and linear output gratings have a period of 1 μm, allowing optical signals to be efficiently coupled into and out of the Si wafer substrate guided modes in the surface normal direction.

In this lettter, 1-to-4 and 1-to-6 fanouts were experimentally demonstrated. A photoresist pattern was used as the masking material for the etch process. The first stage of the RIE process was the removal of SiO_2 layer using CF_4 gas and the second stage was the formation of the grating microstructure using RIE with Cl_2 and He as the active gasses with flow rates of 30.0 cm^3/s and 94.2 cm^3/s, respectively. In using this technique with 1-μm period gratings, careful process control must be used to insure that the photoresist is removed all the way down to the wafer in the exposed stripes of the grating.

To characterize etch rate of RIE samples, diffraction efficiencies of grating samples were measured as a function of etch time for three different wavelengths: 0.632, 1.06, and

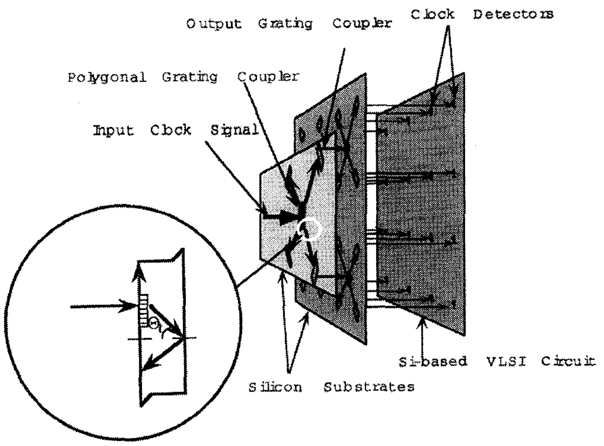

Fig. 1. Schematic of Si-based optical clock distribution system using Si-based polygonal gratings and substrate guided waves with surface-normal coupling configuration.

1.32 μm. This was done to determine the actual depth of the fabricated gratings. An accurate evaluation of the grating depth at various etch times was determined using the multiple wavelength approach [7], [8]. Based on the etch rate data, 1-to-4 and 1-to-6 fanout gratings were successfully fabricated using RIE. With an operating wavelength at 1.3 μm, the grating with 1-μm period will be sufficient to provide the required TIR beams within silicon substrate for the proposed optical clock signal distribution. The microstructure of the fabricated 1-to-4 square grating and the 1-to-6 hexagonal grating are further illustrated in Fig. 2(a) and (b) where equal partitions of the real estate of the gratings are clearly indicated. An SEM photograph containing a linear section of a typical 1-to-many fanout grating attained with this technique is further illustrated in Fig. 2(c). An etching depth of 0.5 μm was experimentally confirmed for both square and hexagonal gratings. 1-to-4 and 1-to-6 fanouts were realized using these devices that convert surface-normal incident beams to substrate guided waves with a bouncing angle of 21.6°. A 1.3-μm Nd:YAG laser beam with a circular polarization was coupled into the Si substrate through the center polygonal grating. Fig. 3 is a three-dimensional (3-D) photograph of a 1-to-4 fanout device in operation. The 1-to-6 fanout was also observed with a two-way fanout distance of 8 cm which is beyond the diameter of the CCD image head and therefore, a picture like that of 1-to-4 fanout can not be provided. Individual output of the 1-to-6 fanout was measured independently and the result is very similar to that of Fig. 3. The central peak of Fig. 3 is corresponding to the zeroth-order beam, four others to the first-order output diffracted beams. The modulated 1.3-μm laser beam is collimated and then coupled by a lens with a focal length of 100-mm surface-normally into the 1-to-4 surface-normal fanout grating as indicated in Fig. 1. The four zigzag substrate guided waves were then coupled out through four separate output gratings. Note that each surface normal fanout beam shown in Fig. 3 contains +1 and −1 diffraction orders from two separate triangle gratings having the same grating vector. In the considered case, 65% of the light incident on the polygonal grating is coupled into the substrate. The peak

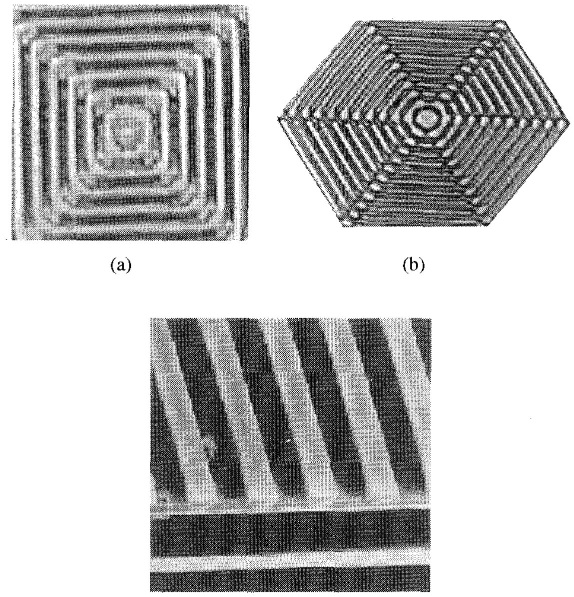

Fig. 2. Microstrucures of polygonal gratings with 0.5-μm feature size; (a) a square grating for 1-to-4 fanout, (b) a hexagonal grating for 1-to-6 fanout, and (c) scanning electron microscope (SEM) picture of a section of a polygonal grating with 1-μm feature having an etched depth of 0.5 μm.

intensities of output beams are about 20% of peak intensity of the zero-order undiffracted beam. The intensity uniformity of the four surface-normal fanout beams were found to be primarily determined by the quality of grating and the accuracy of the position adjustment of the incident beam with respect to the central square grating. The diffraction efficiency uniformity for both 1-to-4 and 1-to-6 fanout beams was measured to be within 1 dB, i.e., 10%, fluctuation. The scenario with 1-to-many interconnects having an arbitrary fanout number can be realized by constructing a corresponding polygonal grating with an equivalent number of facets.

We performed diffraction efficiency measurements for incident beams with transverse electric (TE) and transverse magnetic (TM) polarization states. Fig. 4 depicts the measured diffraction efficiencies of TE and TM incident beams as a function of the grating groove depths. Note that the data presented in Fig. 4 provide us with the net diffraction efficiency for the incident beam with an arbitrary intensity and beam polarization through appropriately decomposing the ratio of TE and TM polarized incident beams. The ratio of $\eta_{\mathrm{TE}}/\eta_{\mathrm{TM}}$ fits well with the relationship $\eta_{\mathrm{TE}}/\eta_{\mathrm{TM}} \propto (d/\lambda)^2$ [9], [10].

The optical clock signal coupled into the Si substrate was generated using an HP 8703A lightwave component analyzer and detected using an Epitax ETX-25B high-speed InGaAs PIN-photodiode. This particular prototype device was fabricated in a single lithographic step followed by an RIE step with the etch time set to produce a grating depth of 0.3 μm, optimizing the coupling efficiency into the substrate.

The detected signal at the output was analyzed using a sampling scope and a microwave spectrum analyzer. The measured 7.5-GHz clock speed shown in the analyzer is further

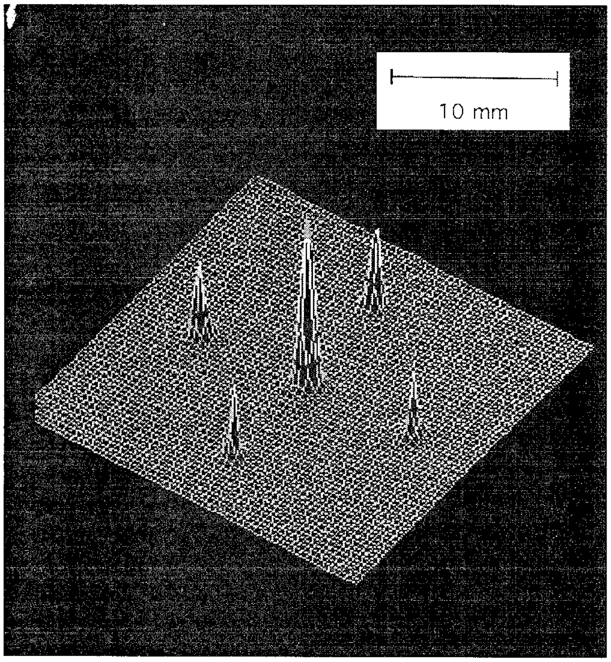

Fig. 3. Three-dimensional intensity profile of the Si-based 1-to-4 surface-normal fanout; the center peak is corresponding to the zeroth-diffraction-order of the incident beam (Fig. 1) and the four other equally separated ones are the surface normal fanout beams coupled out from the four output Si-based surface relief gratings. Power fluctuation of the four fanout beams is within 1 dB.

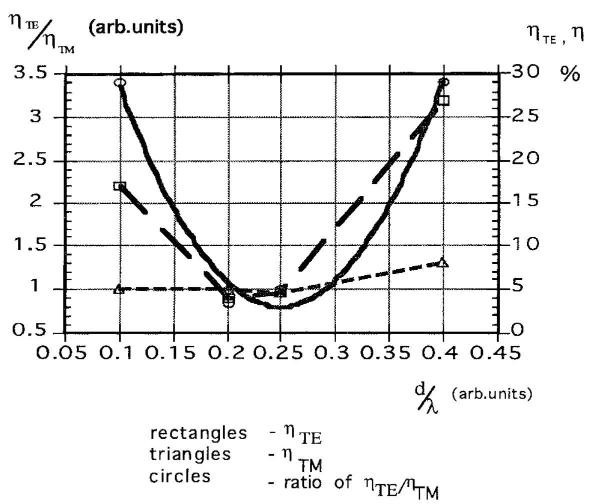

Fig. 4. Measured diffraction efficiencies of $\eta_{\rm TE}$ and $\eta_{\rm TM}$ as a function of the grating groove depth using different beam polarizations as parameters. The ratio of $\eta_{\rm TE}/\eta_{\rm TM}$ is also provided, which follows the $(d/\Lambda)^2$ and $(d/\lambda)^2$ dependence (d = grating groove depth, Λ = grating period and λ = wavelength).

illustrated in Fig. 5. To understand the bandwidth coverage of the optical clock distribution system, we further measured the frequency response of the photodiode. The result concludes that the 7.5 GHz was due to the bandwidth of the photodiode rather than the optical clock signal distribution system itself.

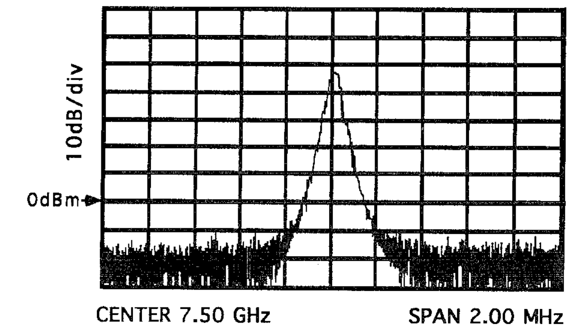

Fig. 5. 7.5-GHz clock signal detected at the surface-normal direction from one of the fanout gratings (Fig. 1).

In conclusion, we have demonstrated a novel architecture for optical clock signal distribution. Employment of substrate modes instead of conventional guided mode significantly releases the grating spacing for the required phase-matching condition. Surface relief gratings on silicon substrate with multiple grating vectors were fabricated using square and hexagonal patterns. 1-to-4 and 1-to-6 fanouts with uniform intensities were demonstrated at 1.3 μm. Using this method, a prototype device with an input/output coupling efficiency of 65% having a measured 7.5-GHz clock speed with interconnection distance of up to 8 cm was demonstrated.

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