0.88 THz Skew-free 1-to-32 Optical Clock Distribution on Adhesively Bonded Silicon Nanomembrane

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Abstract—Silicon photonics is a promising solution for on-chip optical clock distribution. We developed an adhesive bonding process to integrate silicon nanomembranes onto silicon chips. The single-mode strip waveguide fabricated on this adhesively bonded silicon membrane has a propagation loss of 4.3 dB/cm. A grating-coupled 1-to-32 H-tree optical distribution is experimentally demonstrated. Each branch includes 1.1 cm long strip waveguides, five Y-splitters, and three 90° bends. This optical distribution has an insertion loss of 13.9 dB, a uniformity of 0.72 dB, and a 3 dB bandwidth of 880 GHz determined by optical autocorrelation.

Index Terms—Optical clock distribution, Silicon nanomembrane, Adhesive bonding

I. INTRODUCTION

Optical interconnects offers potential benefits compared to conventional metallic interconnects in the continuing trend toward higher bandwidth in advanced VLSI circuits. Optics can deliver particularly precise timing of signals because of the low dispersion in optical channels, which is ideal for clock signal distribution [1-3]. Board-level and inter-chip optical clock distribution have been studied extensively [4-6]. On-chip optical clock distribution using an H-tree structure has been demonstrated on the silicon-on-insulator (SOI) platform [7, 8]. However, these demonstrations limit the optical clock distribution network and the electronic components to the same SOI substrate, which is not compatible with a typical CMOS bulk process. In order to maximize the design flexibility of an optical clock distribution network, it is preferable to stack photonic layers vertically on other electronic layers.

Back-end integration of photonics has been suggested to realize 3D integration of photonics on bulk silicon and has been demonstrated recently in [9, 10], where deposited silicon nitride was used as a waveguiding material. Ultra-low loss silicon nitride waveguide can be fabricated by annealing and thermal cycling of low-pressure chemical vapor deposition (LPCVD) silicon nitride. However, this process is not compatible with the thermal budget of CMOS back-end processes. Plasma enhanced chemical vapor deposition (PECVD) is compatible with CMOS back-end process, but PECVD deposited silicon nitride waveguide shows 6 dB/cm propagation loss in the C-band due to Si-H and N-H bond absorption harmonics [11]. Moreover, silicon nitride lacks any mechanism for high-speed modulation, limiting it to either passive devices or slower devices using the thermo-optic (TO) effect.

Single-crystalline silicon offers the best set of optical and electrical properties for 3D integration of silicon photonics. In this letter, we present the experimental demonstration of a 1-to-32 H-tree optical distribution on a single-crystalline silicon nanomembrane. The silicon nanomembrane is adhesively bonded onto a silicon chip to serve as a platform for 3D integration of silicon photonics. By using the presented method, high-performance optical clock distribution networks can be vertically integrated onto existing electronic chips.

II. DEVICE DESIGN

The 1-to-32 optical distribution follows an H-tree geometry, in which the waveguide lengths, the number of 90° bends and splitters are identical for the input to each outputs of the optical distribution. Strip silicon waveguides with a cross-sectional dimension of 500 nm × 250 nm are used, which provide stronger light confinement compared to shallow etched rib waveguides. The H-tree geometry includes compact Y-splitters based on arc-shaped branching waveguides [12]. This kind of 1-to-2 splitter is not sensitive to refractive index variations due to temperature and/or thickness variations of silicon layers and also insensitive to unwanted residues and air voids in the junction region comparing to Y-splitters based on straight branching waveguides. The radii of the arcs are chosen to be 10 μm to avoid significant bending loss [13]. This value is also used in the 90° bends in the H-tree geometry.

A schematic of the designed 1-to-32 H-tree optical distribution is shown in Fig. 1. The 32 outputs cover an area of 4 mm × 4 mm. In order to perform optical characterization, subwavelength nanostructure based grating couplers described in [14] with 900 μm linear tapers are connected to all input and output waveguides to couple light in and out of the H-tree structure. All output waveguides are folded to align in one direction to simplify alignment between the grating couplers.
and optical fibers.

III. DEVICE FABRICATION

The process flow is shown in Fig. 2. Two SOI chips, which are both from a SOI wafer with a 250 nm thick silicon layer and a 3 \( \mu \)m buried oxide (BOX) layer, were used in the adhesive bonding process, as shown in Fig. 2(a). \(-1.5 \mu m\) thick SU-8 layers were spun onto both the SOI chips, followed by a 2 minute pre-bake at 95°C to evaporate the solvent. Next, the two substrates were brought in close contact using a home-made chip bonder, which uniformly applied pressure and was kept in a 90°C oven to ensure sufficient reflow of SU-8 for trapped air bubble removal to give a high quality bond (Fig. 2(b)).

The silicon handle of the top SOI chip was first mechanically polished to \(-100 \mu m\) thick and then completely removed by deep reactive ion etching (DRIE). After DRIE, the top SOI chip without silicon handle became transparent to ultraviolet (UV) light. The sample was illuminated by 365 nm UV light through the top SOI chip to crosslink the SU-8 polymer. A post exposure bake at 65 °C was done to achieve a full crosslink of the SU-8. Once crosslinked, SU-8 has been proved to be very robust, which ensures the reliability of the clock distribution. After that, the BOX of the top SOI chip was removed by hydrofluoric acid wet etching, leaving a 250 nm thick silicon nanomembrane adhesively bonded to the bottom SOI chip for device fabrication, as shown in Fig. 2(c). When apply this technology on electronic chips, further investigation is required to verify the thermal compatibility and long term reliability.

IV. DEVICE CHARACTERIZATION

The propagation loss of 500 nm wide single-mode waveguides fabricated on the adhesively bonded silicon nanomembranes was first measured using the cut-back method. Serpentine patterns with the same number of bends but different waveguide lengths (10 mm, 20 mm, 30 mm, 40 mm and 50 mm) were fabricated. Subwavelength nanostructure based grating couplers were utilized for input and output light coupling. A polarization maintaining fiber (PMF) was used to couple transverse-electric (TE) polarized light at 1550 nm wavelength into the waveguides. The output light was collected by a single-mode fiber (SMF) and was measured by an optical power meter. The result is presented in Fig. 4. The propagation loss of the single-mode waveguide on the adhesively bonded silicon nanomembrane is 4.3 dB/cm at 1550 nm wavelength. This value is 1.2 dB/cm higher than that of single-mode waveguides fabricated on SOI wafers using the same processing equipment and recipes [15]. In order to investigate the source of this additional loss, the top surface roughness of...
the adhesively bonded silicon nanomembranes was measured using atomic force microscopy (AFM). The surface roughness of the adhesively bonded silicon nanomembrane was 0.629 nm, while it was 0.128 nm for SOI [15]. We conclude that the additional propagation loss is from the increased surface roughness of the adhesively bonded silicon nanomembrane. The propagation loss can be reduced by replacing our RIE with inductively coupled plasma (ICP) etching, which reduces the sidewall roughness of etched waveguides by lowering the required radio frequency (RF) bias voltage in etching [16].

In order to characterize the total excess loss of the H-tree optical distribution, TE polarized light was used as the input, and a power meter was used to detect the output power from each output at 1550 nm wavelength. The total excess loss, which excludes the fiber-to-waveguide coupling loss and the waveguide propagation loss, is defined as $-\log\left(\frac{\sum I_m}{I_{in}}\right)$, where $I_m$ is the intensity of the $m$th output channel, and $I_{in}$ is the output intensity of a reference waveguide on the same chip with the same input and output grating couplers and waveguide length as the H-tree structure. The excess loss of the H-tree optical distribution at 1550 nm wavelength was measured to be 2.2 dB, which is mainly from the excess losses of five 1-to-2 Y-splitters. The average excess loss per Y-splitter is 0.44 dB, which is comparable to the results presented in [12].

The transmission spectrum of the H-tree optical distribution was also characterized. TE polarized light from a broadband amplified spontaneous emission (ASE) source was coupled to the H-tree structure through an input grating coupler, and the output light from one output of the H-tree structure was analyzed by an optical spectrum analyzer (OSA). The transmission spectrum obtained by normalizing the output signal to the light source has a peak value of -29 dB at around 1550 nm wavelength, as shown in Fig. 5. This -29 dB includes the device's insertion loss induced by grating couplers, Y-splitters, and waveguide, and the fanout loss of a 1-to-32 geometry. The two grating couplers' transmission spectrum was obtained by the method described in [17] and is shown in Fig. 5. The grating coupler has a peak efficiency of 45% (-3.5 dB) at 1550 nm operating wavelength. Considering the excess loss of five Y-splitters to be 2.2 dB, the waveguide propagation loss to be 4.7 dB (4.3 dB/cm × 1.1 cm), and the fanout loss to be 15 dB, the transmission spectrum agrees well with our previous loss characterizations. The transmission spectra of grating couplers and H-tree optical distribution have similar profiles through an 80 nm bandwidth, meaning the Y-splitters and waveguide have nearly constant loss in this wide bandwidth.

A top-down infrared (IR) image of the entire optical distribution is shown in Fig. 6(a). At each output of the optical distribution, TE polarized light at 1550 nm wavelength was coupled out from the grating coupler, and the near field image was collected by an IR CCD camera suspended above the grating coupler. The observation clearly shows 32 outputs. Quantitative measurements of the intensities from each output were performed to characterize the uniformity of this H-tree optical distribution, as shown in Fig. 5(b). The uniformity, which is defined as $10\log(1_{max}/1_{min})$, is calculated to be 0.72 dB.

The bandwidth of the H-tree optical distribution was characterized by optical autocorrelation as described in [18]. In order to obtain enough optical signal for autocorrelation, a testing waveguide, which has the exact geometry and
couplers. The bandwidth could be larger because the average of the femtosecond pulse.

The single-mode waveguide fabricated on this platform has a propagation loss of 4.3 dB/cm. The H-tree structure has an insertion loss of 13.9 dB and an output uniformity of 0.72 dB. This grating-coupled H-tree structure has a 3 dB bandwidth of 880 GHz measured by autocorrelation, which is sufficient to support the interconnect bandwidth requirement in future VLSI chips.

**References**