

Hard-molded 51 cm long waveguide array with a 150 GHz bandwidth for board-level optical interconnects

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We demonstrated a 51 cm long waveguide array on a poly(methyl methacrylate) sheet fabricated by silicon hard-molding technology. To reduce the silicon sidewall roughness, a wet-oxidation followed by a buffered oxidation etchant etching process is adopted, achieving a surface roughness of 1.2 nm. The waveguide obtained a total insertion loss of -15.1 dB and an adjacent channel cross talk below -31 dB. The 3 dB optical bandwidth is determined to be 150 GHz by the optical autocorrelation method. © 2007 Optical Society of America

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High-density interconnect printed circuits are now being designed in ever-increasing quantities because of the limited interconnection bandwidth of very high-speed systems. Traditional copper track link fails to provide a bandwidth beyond 3 GHz, which is limited by the intrinsic skin effect and FR4 substrate dielectric loss. Optical interconnects naturally become the alternate implementation by offering an attractive solution with high bit rate, low loss, and immunity to electromagnetic interference. Many optical interconnect schemes have been proposed and investigated in the past two decades, including free space,¹ embedded fiber connection,² and so forth³; however, few of them can provide a seamless interface with electrical counterparts. A fully embedded optical layer that is laminated inside printed circuit board layers can relieve the package difficulty and ensure a reliable performance.⁴ One of the key issues to commercialize this technology relies on the fabrication of low-cost, mass-producible, and high-quality optical layers. We previously demonstrated a soft-molded waveguide layer with 45° coupling mirrors that is suitable for the embedded structure.⁵ Yoon *et al.*⁶ and Mizuno *et al.*⁷ also fabricated a straight waveguide array by hot embossing with low propagation loss. However, the length of these reported waveguides is less than 6 cm, which cannot show obvious advantage over copper tracks. To stay competitive and deliver the products favorably requires tens of centimeters of waveguide length. A greater than 1 m long waveguide based on a photobleaching polymer has been demonstrated,⁸ but not by molding or embossing, which can afford a lower cost. Molding a long

waveguide needs to overcome the technical issues such as uniformity, defects, and handling. In this Letter, we successfully demonstrated a 51 cm long waveguide array by the silicon hard-molding method. Compared with the flexible molds—usually made of elastomeric polydimethylsiloxane (PDMS) for pattern transfer, silicon hard molds stand out in durability and size precision.

The 5 cm long waveguide array curves inside a 4 in. mask. The pattern is composed of an array of twelve 50 μm wide parallel waveguides with 250 μm pitch. With the contact photolithography, the pattern is transferred to a 1 mm thick silicon wafer with a 0.5 μm top SiO₂ layer. It is then etched down by reactive ion etching (RIE) to the silicon layer to obtain the protected SiO₂ hard mask. To produce the desired 50 μm depth pattern, Deep RIE (DRIE) is employed to etch the silicon with acceptable processing time. The high etch rate up to 2 μm/min and the alternating etching-passivation step will result in rough silicon sidewalls. The roughness will be transferred to the poly(methyl methacrylate) (PMMA), Cryo Company substrate, causing scattering losses. To smooth the surface, the silicon wafer is wet oxidized at 1050°C for 4 h and then etched by buffered oxidation etchant (BOE) to strip away the SiO₂.⁹ With this approach the surface root mean square (rms) is reduced from 6.9 to 1.2 nm. Figures 1(a) and 1(b) show the atomic force microscopy (AFM) images of the sidewall profile after DRIE and the oxidation-smoothing process.

The 200 μm thick PMMA film was used as the waveguide substrate, with a refractive index of 1.489

at 850 nm. The hot embossing process was carried out on a specially designed molding machine with controllable pressure and temperature. This machine is capable of handling sample sizes as large as 36 cm × 24 cm. Limited by the silicon mold size, we can only work on 4 in. wafers at this moment. The PMMA film was heated to 150°C, 40°C above the glass transition temperature. A pressure of 0.5 MPa was applied to the silicon master mold and the PMMA film with a holding time of 3 min. To deliver the pressure homogeneously across the sample, a PDMS buffer layer was inserted between the PMMA film and the embossing template. By the water-cooling system, the template temperature ramped down at a rate of 10°C/min to room temperature, and then de-embossed the PMMA film with the master mold. This process would release the internal stress and ensure the pitch distance exactly at 250 μm. After preparing the multimode waveguide patterns on a PMMA sheet by hot embossing, they were filled with a UV curable fluorinated polymer

(WIR30-500 from ChemOptics, with a refractive index of 1.50 at 850 nm) as the core material. The excess material was scraped off. After UV curing in the nitrogen atmosphere, the PMMA sheet was coated with another layer of top cladding material, WIR30-470 with a refractive index of 1.47 at 850 nm. The sample was UV cured and finally cleaved and polished for testing. Figure 2 shows the 51 cm long waveguide array on the PMMA sheet, with the microscopy image of the cross section.

To measure the light transmission over the waveguide, a 9 μm single-mode fiber coupled with a VCSEL diode was aligned with the input surface. The near-field pattern at the output surface was observed through a CCD camera. The profile shown in Fig. 3 corresponds completely with the 50 μm × 50 μm cross section, confirming the confinement and propagation of the light. To measure the propagation loss of the molded waveguide, a cutback method was used to extrapolate the value over a section of evaluating waveguide with similar curvatures. A multimode fiber with a 62.5 μm core diameter was used to capture the output light. As Fig. 3 shows, the propagation loss is estimated to be 0.26 dB/cm. This value is higher than the 0.16 dB/cm result in Ref. 5, attributed to the waveguide curvature in the current structure and the residue sidewall roughness. The 0.72 dB intersection with vertical axis corresponds with the coupling loss caused by reflection and scattering. The total insertion loss of the 51 cm long waveguide, fiber-in-fiber-out, is −15.1 dB, with adjacent channel cross talk lower than −31 dB.

The bandwidth-limiting factors of optical waveguides are either the optical loss or the optical dispersion. With the improved quality of the polymer materials, the large modal dispersion of the multimode waveguide could become the dominant bottleneck that prevents a higher-speed signal, compared with the optical loss. A widely used measuring method will compare a 10 Gbit/s or a pulse signal before and after propagating through the waveguide, usually in terms of jitter variation⁸ and pulse width.¹⁰ However, the measurement precision is directly limited by the responsivity of the photodetector and the oscilloscope. Optical autocorrelation can pro-

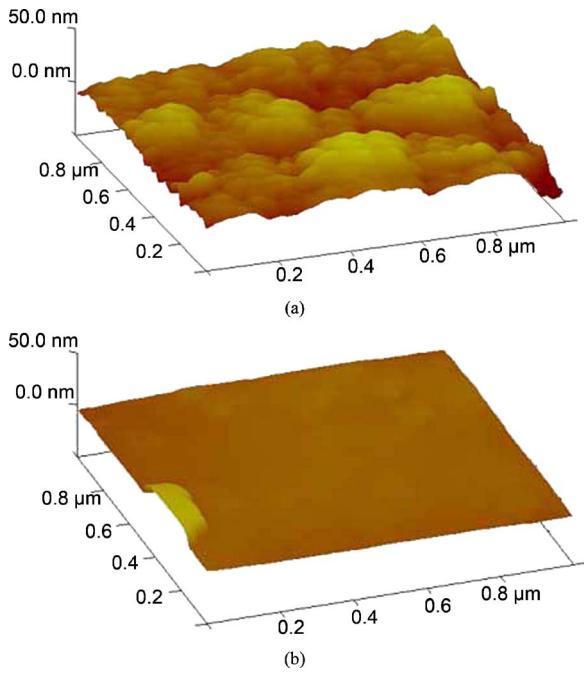


Fig. 1. (Color online) AFM images of the silicon side wall after (a) DRIE and (b) oxidation-smoothing process.

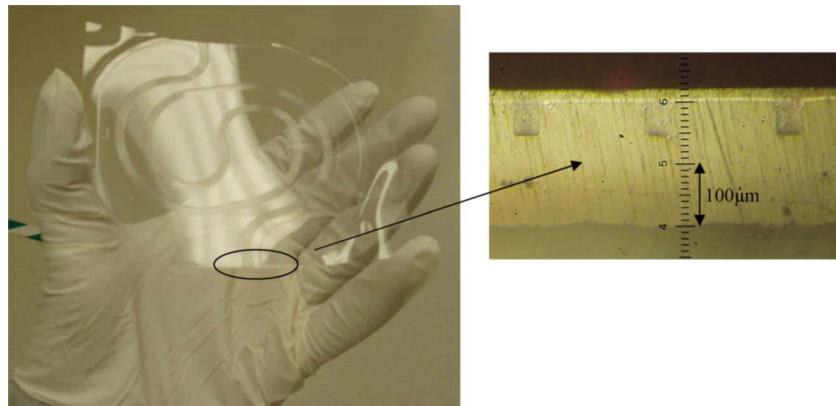


Fig. 2. (Color online) Waveguide array 51 cm long on a PMMA sheet with a microscopy image of the cross section.

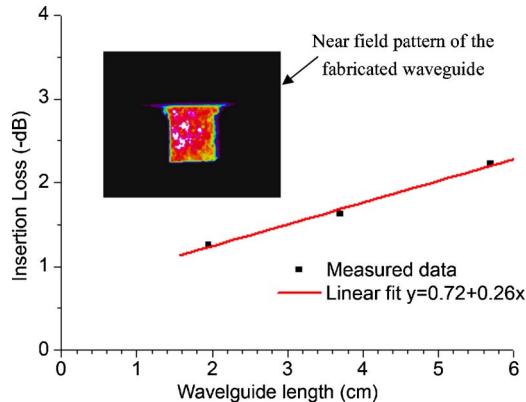


Fig. 3. (Color online) Insertion loss as a function of waveguide length and the near-field patterns of the multimode waveguide.

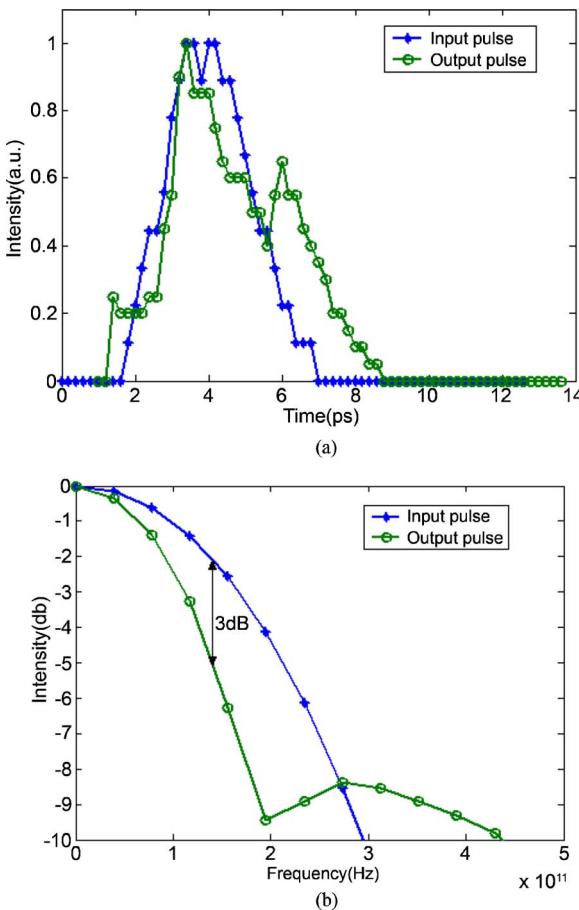


Fig. 4. (Color online) (a) Input and output pulses in the time domain. (b) Input and output pulses in the frequency domain.

vide a much better measurement accuracy up to the femtosecond level.¹¹ In our measurement, an optical pulse generated from a femtosecond laser is launched to the 51 cm long waveguide through a 9 μm core single-mode fiber. The output power is connected by a 62.5 μm core multimode fiber and finally fed into an FR-103MN autocorrelator from Femtochrome Research Inc. The optical pulses in time domain with and without the waveguide were recorded in Fig. 4(a). The input pulse has double peaks and a half-

width of 2.2 ps, which is much longer than the pulse directly from the laser source, indicating the dispersion from the 62.5 μm core multimode fiber. The output pulse after inserting the waveguide is broadened in the time domain with the separation of the second peak. The frequency domain responsivity of the two pulses are shown in Fig. 4(b). The 3 dB bandwidth of the 51 cm long waveguide is found to be 150 GHz. Compared with multimode fibers, a similar cross-section multimode waveguide has a much larger modal dispersion, which is a reasonable result of the high-order modes existence shown in Fig. 3. However, a single waveguide channel can still provide at least 100 Gbit/s signal transmission, leaving a sufficient overhead bandwidth for board-level optical interconnects.

In conclusion, we have fabricated a 51 cm long waveguide array on a PMMA sheet by the silicon hard-molding method. With the oxidation-smoothing process, the silicon surface roughness is reduced. Very precise replication from the original silicon master mold to the PMMA sheet was achieved across the entire 4 in. wafer through hot embossing. The hard-molded waveguides demonstrated a propagation loss of 0.26 dB/cm at 850 nm. To the best of our knowledge, this is the longest successfully molded waveguide that has ever been reported. The 150 GHz optical bandwidth of the waveguide will provide a sufficient overhead for high-speed signal transmission. Besides the low fabrication cost and mass producibility, the waveguide array shows great potential for board-level optical interconnects.

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