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Fabrication of single-mode Y-branch waveguides in photosensitive polymer with reduced Y-junction residue

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ABSTRACT

Single-mode small-core (~2 μm × 2 μm) Y-branch waveguide structures in photosensitive polymer have been fabricated. Y-branch waveguides are designed by the beam propagation method and Y-branch waveguides are obtained on development after a cross-linkable negative tone epoxy SU-8 2002 polymer is exposed to UV through a photomask. Optical Adhesive NOA 61 is used as under- and over-clad. The fabrication process is optimized to avoid polymer residue at the Y-junction. The average insertion loss obtained for a 7.2 mm 1 × 2 device at chip-level is ~13 dB at 1550 nm.

1. Introduction

Polymer material has been accepted as a new-generation material for an optical integrated circuit due to its various advantages as compared to other optical materials. Excellent tailorable optical, mechanical, and physical properties are achievable through using proper polymer and process. Photonic polymer-based devices are particularly attractive because of low temperature process for fabrication, process compatibility to electronic packaging [1], their ability to be processed rapidly, they are cost effective, and they give high yields [2]. SU-8 is transparent for wavelengths above 400 nm, and has an index of refraction of 1.57 at 1550 nm. The main advantage with SU-8 is patterning of structurally stable thin films with thickness <5 μm at higher aspect ratios in a single step of photolithography is possible. In order to have a guided mode in the SU-8 layer, the SU-8 must be surrounded by cladding material of a lower index. An optical adhesive, NOA61 with refractive index of 1.54 at 1550 nm is chosen to be used as cladding. After aging at 50 °C for 12 h, UV cured NOA 61 can withstand temperatures from −150 °C to 125 °C.

In this paper, we report fabrication of Y-branch waveguides with reduced residue at the branching point to ensure low transmission loss at Y-branch outputs. An analysis of a polymeric 1 × 2 optical power splitter is presented here to show the effect of residual polymer at a Y-junction. For our design inputs, we used the refractive index of cured NOA 61 as 1.54 while that of SU-8 2002 as 1.57 at 1550 nm, verified over a Metricon 2010 Prism coupler. The Y-branch based splitter presented in this work is designed for single mode operation at 1550 nm. Thus in order to ensure only fundamental mode operation at the desired wavelength, the guide thickness is kept below 2.5 μm .The modal characteristics of the waveguides were independently verified by beam propagation method (BPM) software BeamPROP^{TM} (RSoft Design), the same software being used to design and optimize segment lengths of the 1 × 2 power splitters.

2. Design and analysis

1 × N splitters consisting of Y-branches [3–8] are now widely used for optical signal distribution in broadband passive optical networks. A Y-branch provides advantages, such as low excess loss, low wavelength dependent loss, and low polarization dependent loss. A conventional Y-branch waveguide is comprised of a straight guide followed by a Y-branch with cosine s-bend arms [9] and is generally referred to as a 1 × 2 power splitter. Such a conventional 1 × 2 power splitter is shown in Fig. 1. A 1 × N power splitter is realized by cascading N symmetrical Y-branching guides. The major limitation when designing a conventional Y-branch is transmission loss due to the minimum width of the gap between the two branching waveguides limited by photolithography and etching process [10].

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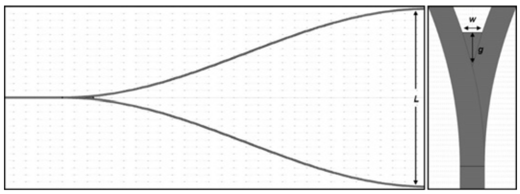

Fig. 1. Schematic (a) Y-branch waveguide (b) Y-junction with residual polymer.

The major losses in a Y-branch power divider occurs at the Y-junction, i.e. where cosine s-bend branches start separating from each other. Polymer residues are generally left in the Y-junctions of the conventional Y-branch waveguides. Here in this work, we assumed minimum trench width achievable due to limitation from photolithography as $w \sim 2\,\mu$m due the limitation of lithographic resolution of SU-8 and the mask aligner used in fabrication. So, g may be defined as the length of residue from the point when $w \sim 0$ to $w \sim 2\,\mu$m. Towards the Y-junction, g approaches to zero and increases, as gap between s-bend branches increase in the direction of propagation of light through the device as shown in Fig. 1.

Due to polymeric residue at Y-junction, the evanescent fields of both guides exist in this region between the branches. The overlap of the fields in the two branches causes the power coupling between the two branches. The spread of the evanescent fields of both guides in the region between the branches near the branching point is the origin of the radiation loss. More residual polymer if left at Y-junction will lead to more coupling, and more is the radiation loss. Fig. 2 shows effect of residual resist when it is not present at the branching point of the splitter in Fig. 2(a) and when it is present in Fig. 2(b). The radiation loss is visible in Fig. 2(b) when residue is present at the Y-junction of a conventional 1×2 splitter. One of the ways to minimize the radiation loss caused by residue is to optimize the fabrication process to etch out the residual polymer from the Y-junction.

Inspection of the optimized segments of the Y-branch schematic designed in beam propagation method software indicates that $g \sim 130\,\mu$m when the trench width at Y-junction lies in between $0 \le w \le 2\,\mu$m, and $L \sim 254\,\mu$m at the output ends of the device. The output ends of the device if are further widened for a common device length, i.e. value of L is increased, degraded performance is achieved at a lower value of g. Also, change in g is directly proportional to change in length of s-bend segments. Fig. 2(b) displays the radiation loss due the presence of residue at Y-junction when $w \sim 2\,\mu$m, $g \sim 130\,\mu$m and $L \sim 254\,\mu$m. The insertion loss (IL) of a 1×2 device degrades from 3 dB to 4 dB when the residue-affected area increases from the branching point ($g \sim 0$, $w \sim 0$) to the point when ($g \sim 130\,\mu$m, $w \sim 2\,\mu$m) in as shown in Fig. 3.

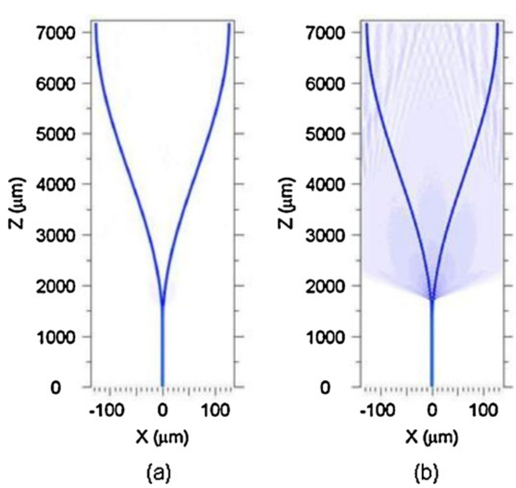

Fig. 2. BPM Simulation: radiation loss increases in presence of residue.

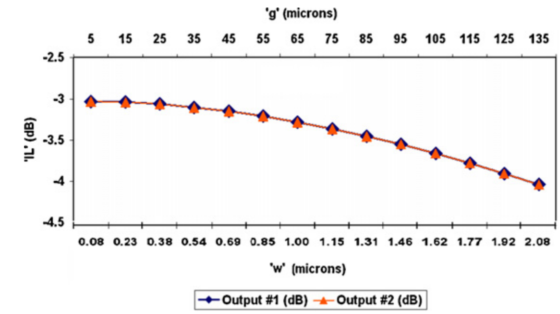

Fig. 3. BPM Simulation: insertion loss vs. 'g'.

3. Fabrication

Fabrication of single mode SU-8 optical waveguides is based on simple direct UV photolithography process [11,12]. Preparation of the substrate surface for under-clad coating with NOA 61 is followed by UV curing and baking. Prior to coating NOA61 on Si wafer, the wafers for samples were thoroughly cleaned using piranha-etch at room temperature. The cleaned wafers were then dehydrated at 120–140 °C in oven. Adhesion of NOA61 to the substrate is critically dependent on the wafer surface. NOA-61 was spin-coated at 4000 rpm for 30 s followed by UV curing for 10 min at an average intensity of 48 mW cm^{-2}, then left for stabilization at 60 °C for 15 h. For UV curing of NOA61, we used a high wattage (400 W) UV lamp (Dymax 5000EC).

The SU-8 2002 core material was spun on top of NOA 61 coated silicon substrate at 1400 rpm for 30 s to achieve a thickness of $\sim$2.5 μm and then soft baked using two-step process (65 °C for 5 min and 95 °C for 20 min) to remove any traces of solvent after exposure. The temperature and the duration of softbake determine the residual solvent concentration in SU-8 at the moment of UV exposure. For small durations $\sim$5 min, poor resolution and bad definition of sidewalls is observed while for long durations >1 h, insufficient cross-linking occurs due to partial development of SU-8 [13].

Y-branch waveguides are realized by UV exposure for 90 s in contact with photomask using a Karl Suss MA56 mask aligner with a mercury lamp providing intensity $\sim$10 mW cm^{-2}. After exposure, a post exposure bake $\ge$90 °C is required to cross link the resist. The issue with thin SU-8 films is that this results in cracking or delamination mainly due to thermal stress. One way to overcome the issue is to use high exposure dose as it corresponds to a higher photo-acid concentration and improves cross-linking. For a post exposure bake $\ge$60 °C, the thickness of the SU-8 layer stays constant while the tensile stress increases linearly. However, the absolute stress values are considerably low at higher exposure doses. The duration of post exposure bake has only minor influence on the film thickness and stress [13]. However, high exposure dose has a negative influence on the lithographic resolution. High exposure dose leads to waveguide broadening and a reduced trench width due to optical effects such as diffraction at the mask and reflection on the substrate [14]. A post exposure two-step baking process (65 °C for 2 min and 95 °C for 5 min) is used to crosslink the polymer.

Development times were varied to observe the effect of chemical etching on waveguide dimensions and surface and the duration for development was optimized to obtain minimum residual residue at Y-junction. The photoresist-coated UV-exposed

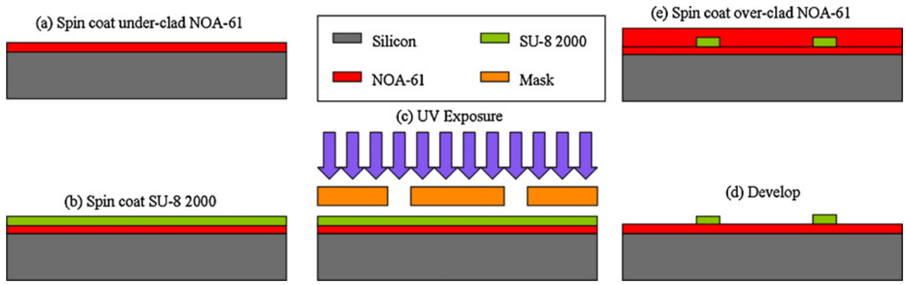

Fig. 4. Fabrication steps (a–e) for polymeric waveguides.

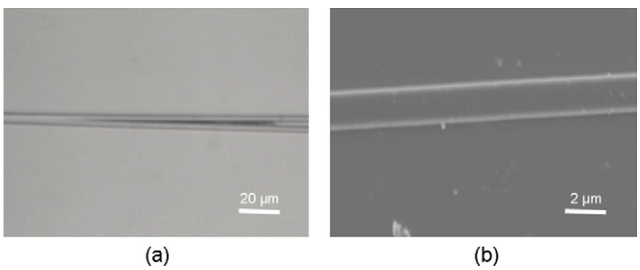

Fig. 5. (a) Y-Junction of 1 × 2 device (b) SEM of waveguide.

substrate is developed in PGMEA for 70 s and then rinsed in IPA for 10–15 s. Coating of NOA61 as over-clad is the final step in waveguide development and is done as under-clad is coated, cured and baked. Finally, a hard bake at 140 °C for 1 h is good enough to remove any traces of developer or solvent left behind. The fabrication process is summarized in Fig. 4.

4. Characterization

The thickness of channel before exposure and hard bake was found to be 2.4 μm when measured using Metricon 2010 Prism Coupler and after pattern development before hard bake the height of waveguides lies in range from 2 μm–2.4 μm. Optical micrograph of a portion of Y-branch is shown in Fig. 5(a). As evident from the SEM image in Fig. 5(b), the fabricated waveguides are smooth walled. There are neither cracks nor any kind of defects in the fabricated waveguides.

As mentioned in Section 2, g is 130 μm when $w \sim 2$ μm but as the fabrication process is optimized for minimum residual polymer at branching point of Y-waveguide, we obtained a residue affecting the area to 90 μm only. At $g \sim 90$ μm, we observe in Fig. 3 that insertion loss is ~3.5 dB. The advantage gets bigger as we observe the power splitting in cascaded Y-branch structures to obtain high-order power splitting.

Propagation losses were estimated using cut-back measurements [11,12] for TE polarizations at 1550 nm for planar slab waveguides. At 1550 nm, the propagation loss was estimated to be 0.125 dB/mm. Due to the small cross-section of about 2 μm by 2 μm of waveguides, it was very difficult to measure how much light is coupled into the waveguide, unless the input end is pigtailed and the input face of the waveguide is polished to a very high quality. Polishing soft-materials such as polymers is very challenging and has not been taken up in this work. The input and output ends of the waveguides were simply prepared by cleaving the Si-wafer on they were patterned and the light was input from an optical fiber by butt coupling. The average insertion loss obtained at chip-level is ~13 dB for a 7.2 mm 1 × 2 device at 1550 nm. The Y-branches of the 1 × 2 device areseparated by 254 μm at the output ends. Besides 1 dB of propagation loss, the coupling losses estimated were 7.4 dB including field mismatch losses of 3.5 dB/port and fresnel reflection losses of 0.2 dB per port. Around a dB additional loss may account for radiation losses in the waveguides.

5. Conclusion

Process to fabricate single mode polymeric Y-branch waveguides using simple direct ultraviolet (UV) photolithography is optimized and presented. Waveguide widths of 2–2.4 μm are obtained on development after a crosslinkable negative tone epoxy SU-8 2002 polymer is exposed to UV through a photomask. Optical Adhesive NOA 61 was used as under- and over-clad. The average insertion loss obtained at chip-level is ~13 dB for a 7.2 mm 1 × 2 device at 1550 nm.

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