Fabrication of Polymeric Multimode Waveguides and Devices in SU-8 Photoresist Using Selective Polymerization

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Abstract

Large cross section multimode waveguides have been realized in SU-8 using selective polymerization. SU-8 is a negative photoresist, which has shown good optical properties and it is mechanically and chemically stable. The fabricated waveguides have very smooth sidewalls and exhibit low optical losses. The fabrication method is simple and potentially very cost effective. N x N and 1 x N multimode power splitters have been realized using this fabrication technology.

1. Introduction

Optical multimode planar waveguide technologies are increasingly employed in short-distance communication applications such as local area networks and optical interconnects. The revival of the use of multimode optical technologies in this area is driven and stimulated by the need for higher bit rates and the low-cost perspective of these technologies. Several factors contribute to the low-cost prospects of the optical multimode technologies including: relaxed alignment tolerances, less stringent fabrication precision, availability of cheap light sources and very importantly existence of very low-cost fabrication technologies.

Polymer planar waveguide technology tends out to be a cost effective technology for fabrication of large cross sectional multimode devices. The low-cost potential of this technology stems out of 1) commercial availability of wide range of cheap optical polymers 2) ease of fabrication of thick waveguides using very simple equipments and 3) its adequacy for mass fabrication especially when techniques such as molding and photochemical delineation are used.

In this paper we report the fabrication of large cross sectional multimode waveguides by photochemical delineation using SU-8 photoresist. SU-8 is based on a multifunctional bisphenol A novolak epoxy resin and can be patterned using I-line lithography [1]. SU-8 has interesting properties, which make it a very attractive material for a wide range of applications including micro-machining, micro-optics, micro-fluidity and packaging [2]. It is highly transparent for wavelengths > 600 nm, has shown heat resistance to temperature > 200 °C and it is chemically and mechanically stable. SU-8 exhibits a huge potential for micro-technologies because it can be spin coated at a thickness ranging from a millimeter to a few microns and it gives very high aspect ratios (1:20) when patterned. In the next section the fabrication procedure will be outlined. Structural and optical characterizations of the fabricated waveguide will be given in section 3. In section 4, we will present characterization results of multimode power splitters and star couplers as application examples. The conclusions will be given in section 5.

2. Fabrication

In this work we have used a type of SU-8 called NANO™ SU-8-25 [3], which has high viscosity and is therefore suitable for spin coating of thick layers. SU-8 was spin coated on a cleaned 10x10 mm^2 borosilicate substrate. A 40-µm-thick layer was spin coated using an experimentally determined curve of thickness versus spin speed. The coated film was then pre-baked to evaporate the solvent. The prepared film was patterned using I-line lithography. The UV exposure creates acid radicals, which act as catalyst for the polymerization. Following the UV exposure the film was post-baked. In this post exposure baking step the crosslinking of the polymer takes place. The SU-8 film was developed in RER 600 (PGMEA). Hereafter, the wafer was rinsed with isopropyl alcohol and then dried with stream of nitrogen. The created waveguide structures were then subjected to a flood exposure of 30 seconds and a hard-bake step. Details of the bake process can be found in table 1.

Bake step	Temp 1 [°C]	Time1 [min]	Temp 2 [°C]	Time 2 [min]	End Temp [°C]
Pre-bake	65	5	95	15	25
Post-bake	65	2	95	4	25
Hard-bake	95	2	150	240	25

Table 1: Bake process, all bake steps start at room temperature.

The final structure was coated with PMMA dissolved in chlorobenzene (1:10). The film was dried at room temperature and finally the wafer was diced. The end-faces were cleaned with isopropyl alcohol. This end-face preparation results into smooth end-faces, see figure 1.

3. Structural and optical characterizations

Figure 2 shows an electron microscope picture of a SU-8 waveguide. The picture shows that the film surface is very smooth. In general, spin coating of SU-8 gives smooth surface and very uniform thickness except for an edge bead. The SU-8 fabrication process also resulted into vertical and smooth sidewalls as can be seen in figures 1 and 2.

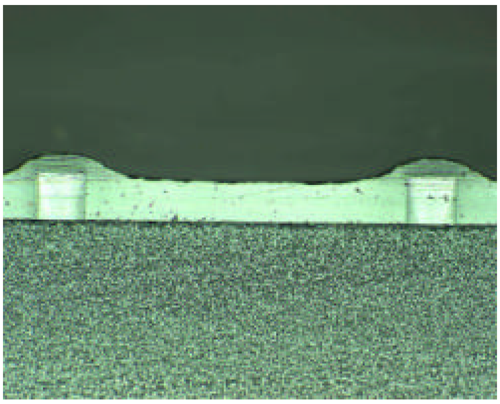

Fig. 1: Photograph of diced end-face of SU-8 40x40 μm^2 waveguides covered with PMMA.

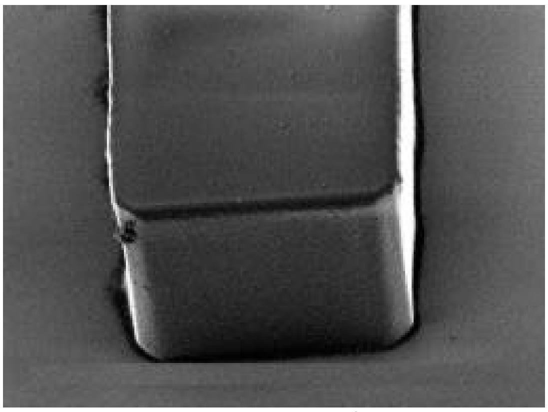

Fig. 2: An electron micrograph of SU-8 waveguide fabricated using photopolymerization.

Refractive indices of SU-8 films have been measured using Abbe refractometer [4]. Figure 3 shows the refractive indices of a SU-8 film prepared using the previously described fabrication recipe.

The optical losses were measured using end-fire coupling method. In the loss measurement setup a 50/125 μm graded-index multimode fiber was used to couple light in and out of the waveguides. An index matching gel was placed between the waveguide and the multimode fiber to reduce reflections. The propagation loss spectra were measured using a halogen lamp and a spectrometer. The losses were determined using the cut-back method. In figure 4 the propagation loss of 40x40 μm^2 multimode waveguide is given as a function of wavelength. SU-8 channels exhibit low losses of ~ 0.5 dB/cm in the spectral windows from 800 to 1100 nm and also around 1300 nm. In the third telecom window around λ=1550 nm the losses are ~ 3 dB/cm making SU-8 not suitable for applications in that spectral window. The fiber-chip losses are found to be 3 dB, this is a consequence of the mismatch between the numerical aperture of the fiber (0.2) and the waveguide (0.5).

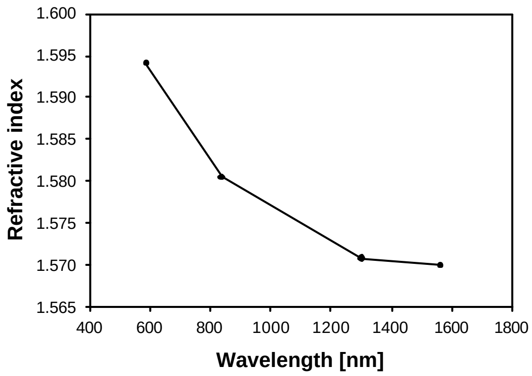

Fig. 3: Refractive index of SU-8 film as a function of wavelength.

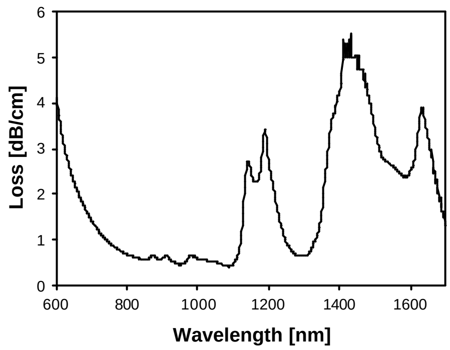

Fig. 4: Loss spectrum of a 40x40 μm^2 multimode SU-8 waveguide.

4. Applications

1xN power splitters

We have realized a 1x2 Y-junction multimode power splitter and 1x2 and 1x3 tapered multimode interference (MMI) based couplers using SU-8 technology. The Y-junction consists of an input waveguide with a cross section of 40x40 μm^2 and two output channels; each starts with an S-bend having bend radius of 32 mm followed by straight channel. The cross sections of the output channels are equal to that of the input waveguide. The MMI couplers consist of 40x40 μm^2 input and output access channels and a tapered coupler region with starting width of 160 μm and a minimum width of 100 and 78 μm for 1x3 and 1x2 couplers, respectively. Detail of the theory and design rules of multimode fiber matched MMI couplers are given in Ref. [5]. Table 2 shows measurements results of excess losses and power imbalance of the different power splitters. Very low power imbalance was obtained, however, excess losses are slightly higher than expected

Device	Imbalance [dB]	Excess loss [dB]
1x3 tapered	0.7	0.5
1x2 tapered	0.5	1.5-2.5
1x2 Y-junction	0.5	0.5

Table 2: performance of 1xN splitters.

NxN star couplers

We have also realized a 4x4 MMI-based coupler and an 8x8 star coupler based on cascaded Y-junctions. The MMI star coupler has 40x40 μm^2 input and output waveguides and a tapered coupler region with initial width of 175 µm and a minimum width of 123 µm. The design of the 8x8 star coupler is identical to that of the symmetrical 8x8 cascaded Y-junctions coupler given in Ref. [6].
Figure 5 shows the excess losses measured for the 4x4 MMI coupler. The result shows that excess losses are very low, even close to the theoretical limit of 6 dB, and the imbalance is 1 dB. There is very little variation in the result when light is launched into the outer (solid circles and triangles) or to the inner input channel 2 (open circles) confirming that the device performance is symmetrical. Results of performance characterizations of the 8x8 star coupler are depicted in figure 6. Due to the symmetrical design only the first 5 input waveguides have been characterized. Power imbalance of ~ 3 dB was obtained and the excess losses deviate ~ 5 dB from the theoretical limit, being 12 dB, in the worst case.

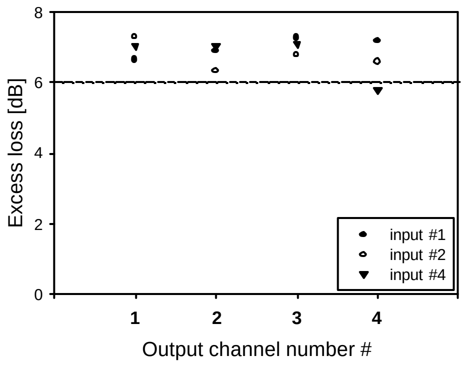

Fig. 5: Excess losses of 4x4 MMI.

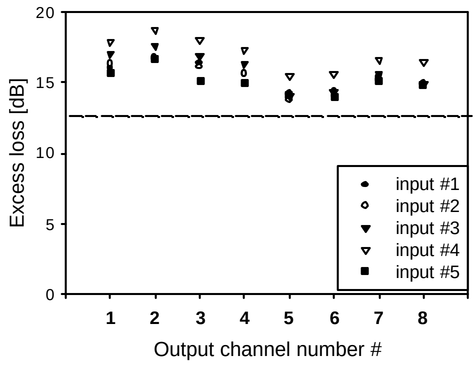

Fig. 6: Excess loss of 8x8 Y-junction based coupler.

5. Conclusions

Large cross sectional multimode waveguides have been successfully realized and characterized using the low-cost SU-8 technology. Optical losses as low as 0.5 dB/cm have been obtained in the wavelength windows around 850 nm and 1300 nm. Good performing multimode fiber matched 1xN splitters and NxN star couplers have been realized.

References

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