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Low-Loss Polymeric Waveguides Having Large Cores Fabricated by Hot Embossing and Micro-contact Printing Techniques

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Abstract: We present simple, low-cost methods for the fabrication of polymeric waveguides that have large core sizes for use as optical interconnects. We have used both hot embossing and micro-contact printing techniques for the fabrication of multimode waveguides using the same materials. Rectangular and large-core (60×60 μm^2) channels were readily prepared when using these methods. The dimensions of the embossed and printed channels were the same as those of the pattern on the original master. The polymeric waveguides that we fabricated with large core sizes exhibited a low propagation loss of 0.1 dB/cm at 850 nm, which indicates that hot embossing and micro-contact printing are suitable techniques for the fabrication of optical waveguides having large-core.

Keywords: polymeric waveguides, hot embossing, micro-contact printing, large-core.

Introduction

Polymeric optical waveguides have attracted considerable attenuation for their possible application as optical components in optical interconnects and optical communication systems. The requirements for optical waveguide include a simple and straightforward fabrication process to be cost effective and low optical loss. Moreover, the optical waveguides require large-cores in order to couple the light from a vertical cavity surface emitting laser (VCSEL) or multimode fibers.[1,2] Polymeric optical waveguides are generally fabricated by photolithography and reactive ion etching process. Processing steps for fabricating polymeric waveguides include spin-coating, the photolithographic patterning of a photoresist to define the waveguide structure and plasma etching to form a channel waveguide.[3,4] This technique has a complicated process, and thus, is not cost effective for mass production. Indeed, this technique is not suitable to define large-core dimension.

A variety of methods for cost effective fabrication, such as UV direct-patterning,[5-7] a laser direct writing,[8,9] hot embossing,[10,11] and molding[12-14] were investigated and reported for multimode polymeric waveguides. A hot embossing, UV direct-patterning and molding techniques are suitable for fabrication of multimode waveguides with the core sizes larger than 50 μm for optical interconnects.

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In this paper, hot embossing and micro-contact printing techniques were used for fabrication of waveguides with a large core for optical interconnects. We present two simple, low-cost methods for fabricating multimode polymeric waveguides with same materials. The optical characteristics of the resulting waveguides are also reported.

Experimental

Materials. A UV-curable epoxy developed by the core material (ZEOM 104, Zen Photonics Co. Ltd.). The material was prepared from the synthesis of formulated epoxy oligomers, various photo-curable monomers and a photoinitiator. The polymethylmethacrylate (PMMA, Ashahi Glass Co. Ltd.) was used the cladding material. The refractive index of the core material was 1.508 and PMMA was 1.498 at the wavelength of 850 nm, respectively. The difference of refractive index (Δn) was 1.2% at 850 nm for multimode waveguide to allow connection with multimode fibers. The polydimethylsiloxane (PDMS, Sylgrad 184, Dow Corning, Midland) was used as the rubber stamp.

Silicon Master.[10,11] Silicon master was produced by a conventional photolithography and deep reactive ion etching (DRIE) process. The etching rate was about 1.2 μm/min and total processing time was about 50 min. The etched silicon master has a rectangular shape of 60 μm wide and 60 μm high. The fabricated silicon master was treated by trichlorodedecylsilane for anti-sticking layer between the master and the embossing material.[15,16] The water contact angles of the silicon master increased from 43 ° to 106 ° after preparing an anti-sticking layer.

Hot Embossing Process.[10,11] The waveguide channel patterns were fabricated by an embossing system (Jenoptik Mikrotechnic, Germany). The 1 mm thick PMMA sheet was placed at the bottom of embossing plate and silicon master was placed above the PMMA sheet. The embossing plate was heated to 150 ºC, above the glass transition temperature of PMMA ($\approx$110 ºC) and the pressure of 0.35 MPa was then applied to the silicon master and PMMA for 100 sec. De-embossing temperature was 85 ºC, and total processing time was about 5 min. The embossed PMMA was used as under cladding to prepare a multimode channel waveguides. The core material was flowed onto the patterned PMMA cladding to form the core of the waveguide. The PMMA over cladding sheet was pressed to complete the waveguide. The waveguide was completed with exposing UV light (100 mW/cm^2) for 1 min.

Micro-contact Printing Process. The schematic diagram of waveguide fabrication by micro-contact technique is illustrated in Figure 1. The silicon master was used as mother master for replication of polydimethylsiloxane (PDMS) stamp by transfer molding technique. The PDMS was supplied in the form of a curing agent (A) and a liquid silicon rubber base (B). We mixed A and B with a ratio of 1/10 and poured the mixture over the original master. After 1 hr of stabilization, the mixture was cured at 90 ºC for 20 min. The cured PDMS rubber does not adhere to the master patterns and is flexible so that it can be easily peeled off from the silicon master. The PDMS stamp had the complementary shape of the patterns of the original silicon master. The replicated PDMS stamp was pressed flat with a pressure during the UV radiation for 1 min. The multimode polymeric waveguides were completed by spin coating PMMA-chlorobenzene solution onto the core and drying the solvent in an oven.

Results and Discussion

The silicon master containing 60 $\times$ 60 μm^2 channel waveguides was used to replicate the patterns to PMMA sheet by the hot embossing method. The embossing parameters such as temperature, pressure, and process time were optimized to fabricate well-defined waveguide structures.[10,11] Figure 2 (a) shows scanning electron microscopy (SEM) images of the resulting embossed PMMA patterns by the hot embossing technique.

In replicating the patterns of the stamp to the UV curable core material, we follow the micro-contact printing process of placing the PDMS stamp on the PMMA sheet. Figure 2 (b) shows the SEM images of resulting printed patterns by micro-contact printing technique.

They show that the dimensions and the shapes of the polymeric optical waveguide channel have been transferred well from the original silicon master. As shown in these pictures,

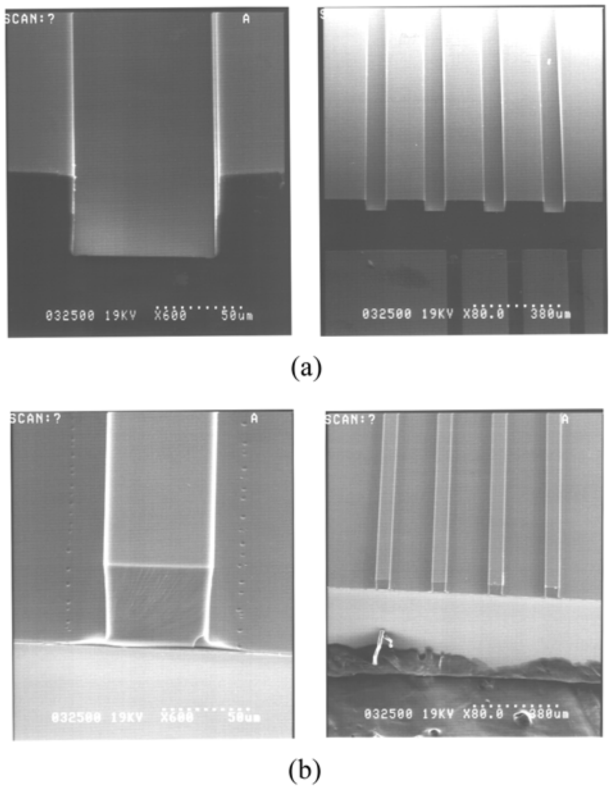


Figure 2. SEM images of waveguide channels obtained by (a) hot embossing technique and (b) micro-contact printing technique.

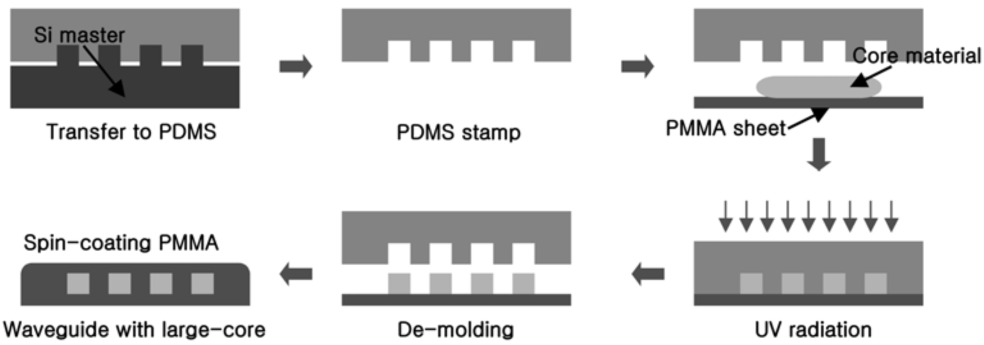
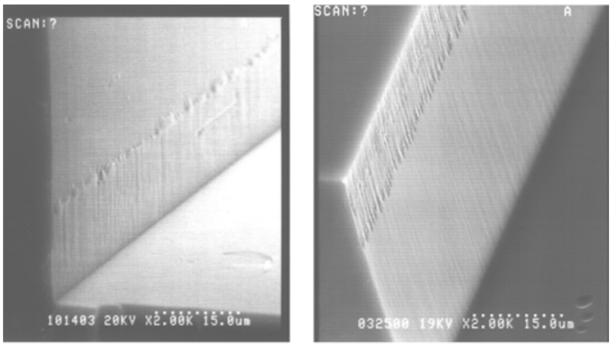


Figure 1. Schematic diagram of fabrication of waveguide by micro-contact printing technique.

the channels show clear rectangular shapes and the dimension of the channel is 60 μm$\times$ 60 μm (horizontal size$\times$ vertical size). The dimension of embossed and printed channel structure was the same as that of the pattern on silicon master indicating transfer of master pattern was successfully achieved by using hot embossing and micro-contact printing techniques.

The residual film shown in the magnified view of Figure 2 (b) must be minimized in the micro-contact printing process. Its thickness is controlled to be less than 1 μm by reducing the amounts of UV curable core material filled in the channel of PDMS stamp. SEM images of sidewall of embossed and printed channels are shown in Figure 3. The sidewall roughness of the embossed channel and the printed channel measured by the atomic force microscope are in the range of 9 and 10 nm (in root mean square), respectively. These values are close to the surface roughness of the original silicon master.



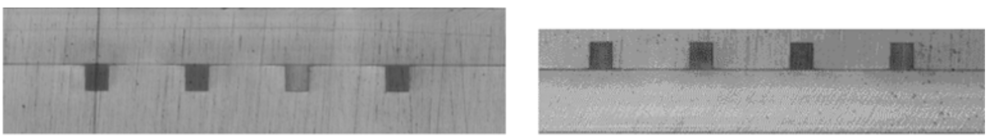
(a) (b)

Figure 3. SEM images of sidewall of channels obtained by (a) hot embossing technique and (b) micro-contact printing technique.

We found that the surface roughness of the channels was strongly affected by that of the original silicon master. The channel fabricated by hot embossing and micro-contact printing techniques is suitable for the use as optical waveguides. The results of these measurements showed high quality of the fabrication process. Thus these replication methods are one of effective methods for patterning of waveguide channels with very smooth surface. Furthermore, these processes have potential for use in mass production of multimode polymeric waveguides with large-core.

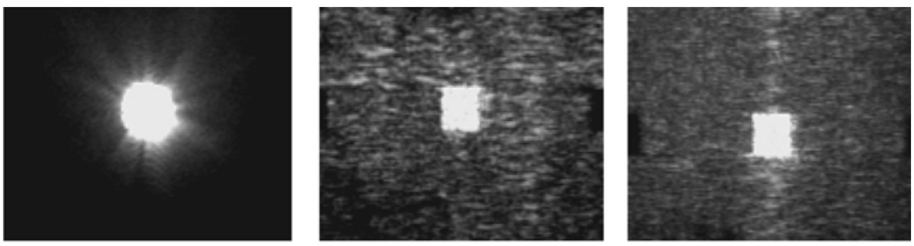
The cross sections of the completed polymeric waveguides are shown in Figure 4. The square cross section was observed by an optical microscopy. The slab was not observed between under and over cladding.

A multimode fiber (with a core diameter of 62.5 μm, GI) is used to launch light into the waveguide to investigate the mode profile and the optical loss. The output mode profiles of the fabricated waveguide at the wavelength of 850 nm are shown in Figure 5. No planar guiding is observed. Propagation loss of the polymeric waveguide was measured by the cut-back method. The propagation loss of waveguides, which were fabricated using hot embossing and micro-contact printing techniques was measured to be 0.12 dB/cm at the wavelength of 850 nm. These multimode polymeric waveguides are suitable for optical devices and planar lightwave circuits. The hot embossing and micro-contact printing techniques can fabricate the large core size waveguides with simple and cost effective.



(a) (b)

Figure 4. Cross sectional view of multimode channel waveguide obtained by (a) hot embossing and (b) micro-contact printing technique.



(a) (b) (c)

Figure 5. Output mode profiles : (a) a multimode fiber, (b) a channel waveguide obtained by hot embossing, and (c) micro-contact printing technique.

Conclusions

Hot embossing and micro-contact printing techniques fabricated the large-core polymeric waveguides with same materials. The channels with smooth surface could be fabricated by hot embossing with a silicon master and the PDMS stamp. The multimode polymeric waveguides had low propagation loss of 0.1 dB/cm at the wavelength of 850 nm. The advantages of these techniques, such as high fidelity and low-cost, make it useful for fabricating polymer-based waveguide devices for short-range networks.

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