Macromolecular Research, Vol. 12, No. 5, pp 437-442 (2004)

Fabrication of Multimode Polymeric Waveguides by Hot Embossing Process: Effect of Sidewall Roughness on Insertion Loss

Keun Byoung Yoon

Optical Interconnection Team, Electronics and Telecommunications Research Institute,
161 Gajeong, Yuseong, Daejeon 305-350, Korea

Received February 13, 2004; Revised July 30, 2004

Abstract: We have fabricated a polymeric waveguide by using a hot embossing technique and have investigated its propagation loss. The replication of waveguide channels through the use of a hot embossing technique is of interest as a single-step process that could deliver surface roughnesses far smaller than the wavelength. We have evaluated experimentally that the sidewall roughness has a dominant effect on insertion losses of the multimode polymeric waveguide. The propagation loss of the waveguide decreased dramatically upon decreasing the sidewall roughness of the channel. We have confirmed that the preparation of waveguides having nanometer-scale sidewall roughness and 0.1 dB/cm propagation loss is possible when using the hot embossing technique.

Keywords: multimode polymeric waveguides, sidewall roughness, insertion loss, hot embossing.

Introduction

The polymeric waveguides have become a subject of interest for use in optical communication and optical interconnection[1] because they can offer such advantages as flexibility and productivity.[2] The polymeric waveguides are attractive for optical interconnections, due to their low cost and simple processing step compared to the silica-based waveguide. Several techniques can be applied to fabricate polymeric waveguides.[3-5] Among them, dry etching methods such as a reactive ion etching (RIE) and an inductively coupled plasma (ICP) are often used because this technique can offer the excellent etching profile.[6] One of the disadvantage of this technique is its complicated process, and thus, not cost effective for mass production. Moreover, they suffer from optical loss because the scattering loss from the defect of sidewall.[7,8]

To overcome these problems, a hot embossing method can be used to fabricate a polymeric waveguide.[9] In this method, waveguide channels are formed by heating a polymer sheet above its glass transition temperature and pressing the polymer sheet with a silicon master, and subsequently, cooling down the polymer below its glass transition temperature.[10-12]

The roughness and the inhomogeneity are inherent in any integrated optics devices.[13] The sidewall roughness of channels predominantly caused by the etching process that is common to most integrated optics process.[14]

The horizontal surfaces are created by the etching process and are smooth within a few nanometers, can be considered as perfectly smooth. On the other hand, the vertical surface (sidewall) created by etching. The smoothness of sidewall relies on the quality of the mask and a deep reactive ion etching (DRIE) condition.[15]

In this paper, a multimode polymeric waveguide was fabricated by means of a hot embossing technique. The waveguide channels are patterned by a silicon master using a hot embossing and characterized with scanning electron microscopy (SEM) and atomic force microscopy (AFM). The waveguides are produced by epoxy core filling and ultraviolet curing process. We present on a study of the effect of the sidewall roughness on insertion loss of waveguide.

Experimental

Materials. A UV curable core material was used as received from Zen Photonics Co. Ltd. This was prepared from the synthesis of formulated acrylate oligomers, various photocurable monomers and photoinitiator. Polymethylmethacrylate (PMMA, Ashahi Glass Co. Ltd.) was used for the cladding material. Refractive index of the core material was 1.508 and that of PMMA was 1.489 at 850 nm.

The fabrication process includes three steps, which are

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*e-mail: kbyoon@etri.re.kr

1598-5032/10/437-06

fabrication of a silicon master, hot embossing process, and waveguide fabrication.

Fabrication of a Silicon Master. The silicon master was fabricated by a conventional photolithography and deep reactive ion etching (DRIE) process. The etching rate was about 1.2~1.6 μm/mim and the total processing time was roughly 28~36 mim. The etched silicon master has rectangular shape of 42 μm wide and 43 μm high. The fabricated silicone master was treated with trichlorododecylsilane for an anti-sticking layer between the master and the embossing material, PMMA.[16] The water contact angles of the silicon master increased from 43° to 106° after treatment of trichlorododecylsilane for an anti-sticking layer.

Hot Embossing Process. The waveguide patterns were fabricated using an embossing system (Jenoptik Mikrotechnic, Germany). The 1 mm thick PMMA sheet was placed at the bottom of a embossing plate, and a silicon master was placed above the PMMA sheet. The embossing was carried out applying heat and pressure. The embossing plate was heated to 150 °C, higher than the glass transition temperature of PMMA ($\approx$110 °C), then 0.35 MPa of pressure was applied to the silicon master and PMMA, with a holding time of 100 sec. The de-embossing temperature 85 °C, and the total processing time was roughly 5 min.

Fabrication of Waveguides. The schematic diagram of the fabrication of waveguide is illustrated in Figure 1. An embossed PMMA (refractive index 1.489 at 850 nm) was used as the under cladding layer to prepare a multimode polymeric waveguide. After preparing the multi mode waveguide patterns on a PMMA sheet by using the hot embossing method, the waveguide patterns filled in with a UV curable core material having a refractive index 1.508 at 850 nm. The PMMA over cladding sheet was then place on the pattern with core materials with pressure. The polymeric waveguide was finally fabricated by exposing UV light (100 mW/cm^2) for 1 min.

Results and Discussion

The waveguide channels were patterned using an embossing system as described in experimental section. The $42\times 43\ \mu m^2$ channel patterned silicon mater was used for replication of patterns to PMMA sheet. The embossing parameter such as temperature, pressure, and process time were optimized to have well defined waveguide structures. We measured the width and height of the embossed PMMA sheet. Figure 2 is shown SEM images of resulting embossed channels.

The result of this measurement showed the clear rectangular shape and a very smooth sidewall. The width and height of the embossed channel on the PMMA were 42 and 43 μm,

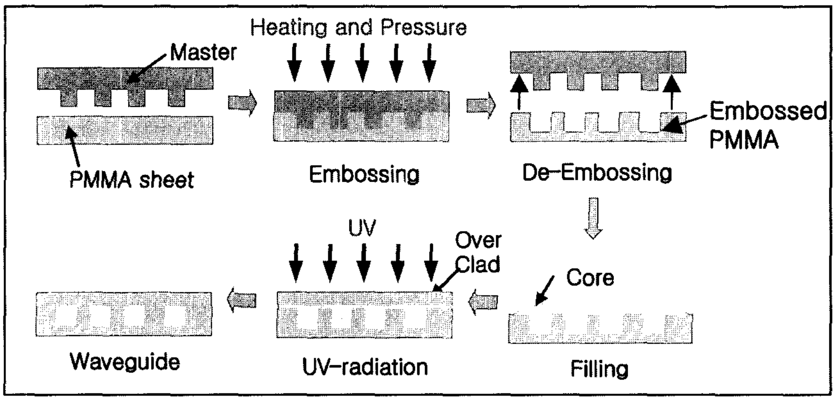


Figure 1. Schematic diagram of fabrication of waveguides by hot embossing process.

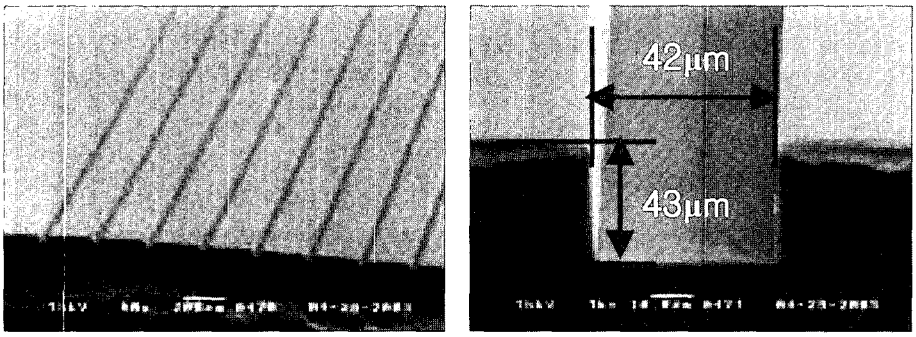


Figure 2. SEM image of cross sectional view of embossed patterns on PMMA.

respectively. The dimension of the embossed structure was same as that of pattern on a silicon master, indicating transfer of master pattern was successfully achieved by using a hot embossing technique.

We used UV curable epoxy for the core, which refractive index was 1.508 at 850 nm. PMMA was used for the cladding of the multimode waveguides. The refractive index of the cladding was 1.489 at 850 nm. The difference of refractive index (Δn) was 1.2% at 850 nm for multimode waveguide to allow connection with multimode fibers.

A UV curable resin was flowed on the patterns. The PMMA over cladding sheet was then placed on the core layer with a pressure. Finally, exposing UV light of 100 mW/cm^2 for 1 min stabilized the waveguide. Cross section of the polymeric waveguides is shown in Figure 3.

As shown in Figure 3, the square cross section was observed by the optical microscopy. Especially, the slab could not observe between under- and over-cladding. From above results, square cross section with smooth sidewall waveguides could be prepared by using a hot embossing technique.

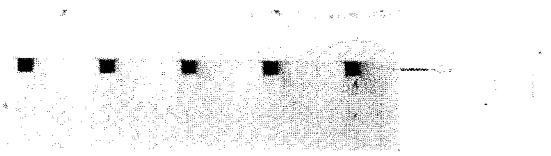
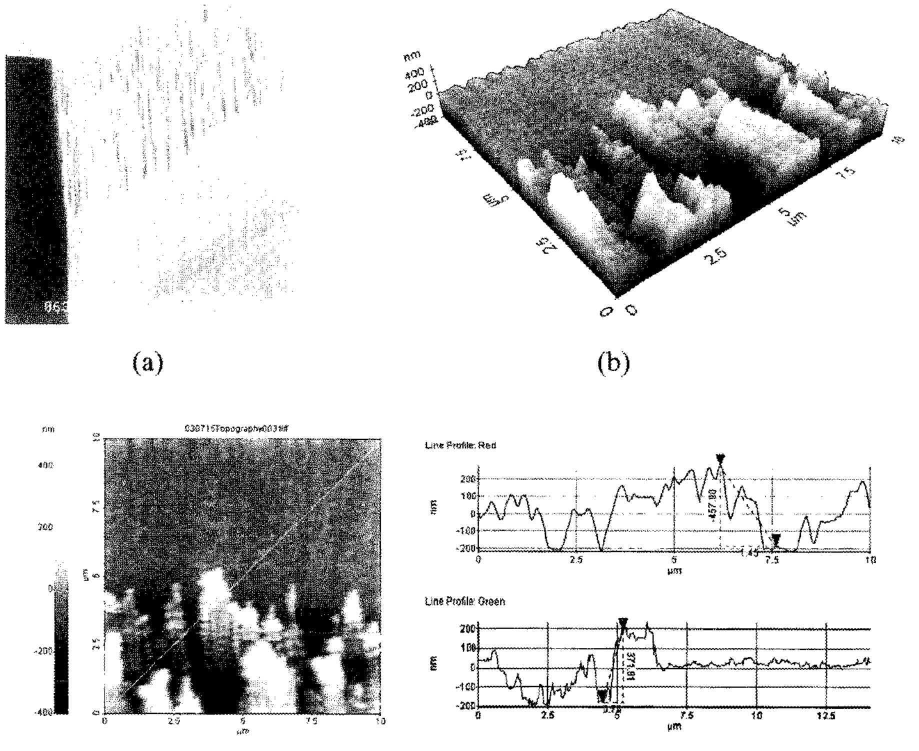


Figure 3. Cross sectional view of multimode waveguides by hot embossing technique.

The deep reactive ion etching (DRIE) is a common processing technique for the fabrication of silicon master for a large core waveguide. The surface roughness is one of the consequences of a DRIE step. Because of the roughness of patterns can affect on optical loss of resulting waveguide due to the scattering, a smooth sidewall should be considered to reduce the optical loss of waveguide.

To confirm the effect of sidewall roughness on optical loss of waveguide, a silicon master was produced at various Si etching conditions. In Figure 4 is shown SEM and AFM images of the sidewall of a silicon master, which is produced by an etch rate of 1.6 μm/min.

As shown in Figure 4, the sidewall of channel was very rough, the root-mean square (rms) roughness and peak-to-valley value were 85 and 450 nm, respectively. The multimode waveguide was produced with this silicon master. The propagation loss of the polymeric waveguide was measured using the cut-back method. A multimode waveguide was butt coupled to a 850 nm wavelength laser light by a GI (Graded Index) multimode fiber (62.5 μm) and the output light from the waveguide was end-fire coupled to a power meter. The propagation loss of this waveguide measured and the result is shown in Figure 5.



(a)

(b)

(c)

Figure 4. (a) SEM and (b and c) AFM images of sidewall of silicon master channel.

The propagation loss of this waveguide was approximately 0.7 dB/cm at 850 nm from the slope of the curve as a function of waveguide length. The coupling loss was about 0.8 dB for the diced end face of the waveguide. The propagation loss of this waveguide was too high for the optical device and a planar lightwave circuits.

In order to smooth the sidewall roughness, the Si etch rate was reduced to 1.2 μm/min. Then H_2/O_2 thermal oxidation at 1,050 °C and subsequent stripping of a silicon oxide with HF was performed.

The sidewall images of this silicon master is shown in Figure 6 and the propagation loss of waveguide, which is produced with this silicon master is shown in Figure 7, respectively.

The sidewall roughness decreased reducing the etch rate and after thermal oxidation process. The values of sidewall roughness and a peak-to-valley were 40 nm (rms) and 270 nm, respectively. The propagation loss of waveguide was

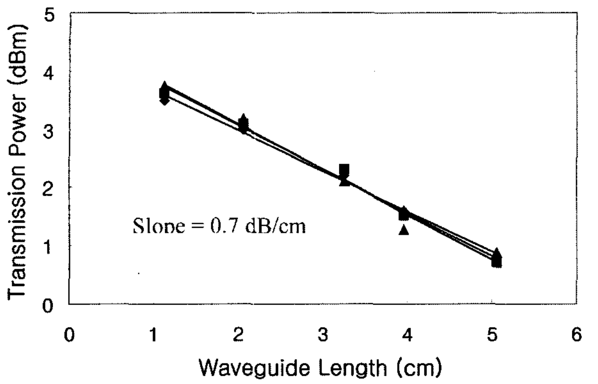


Figure 5. Propagation loss of multimode waveguide, which is produced with silicon master shown in Figure 4.

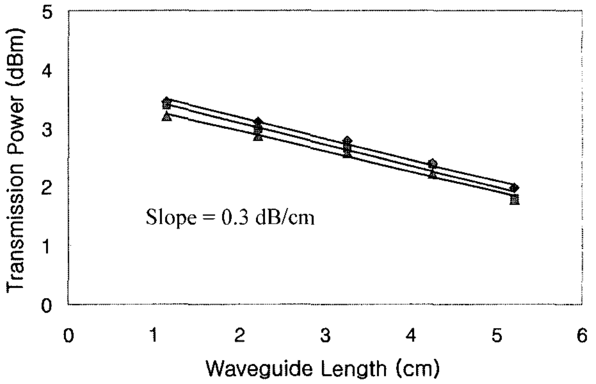


Figure 7. Propagation loss of multimode waveguide, which is produced with silicon master shown in Figure 6.

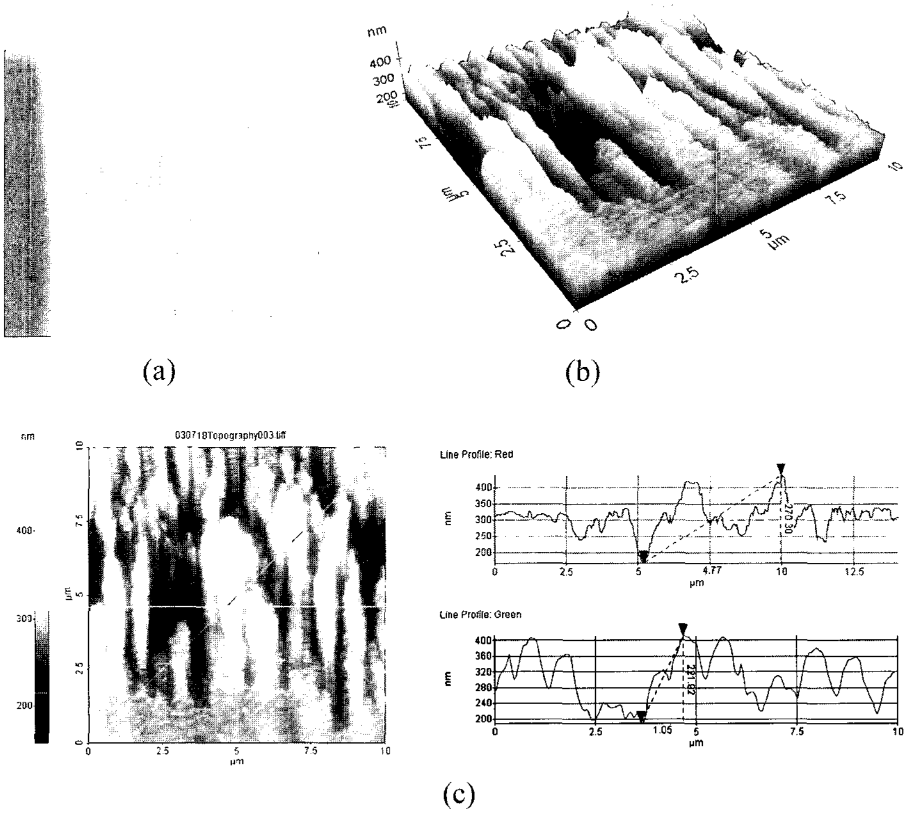


Figure 6. (a) SEM and (b and c) AFM images of sidewall of silicon master channel.

improved to 0.3 dB/cm at 850 nm wavelength.

To improve the sidewall roughness of silicon master, a low frequency bias power introduced in Si etching process and other conditions were same as the previous procedure. The low frequency bias power was 50 W. The resulting silicon master sidewall is shown in Figure 8, and the propagation loss of waveguide is shown in Figure 9, respectively.

As shown in Figure 8, the sidewall roughness decreased to 9 nm (rms) and the value of peak-to-valley dramatically decreased to 45 nm. The propagation loss of waveguide decreased to 0.1 dB/cm at 850 nm with decreasing the sidewall roughness. Thus this hot embossing technique is an effective method for fabricating a waveguide with a very smooth surface.

The sidewall roughness of waveguide channel was predominantly affected to insertion loss. The propagation loss of waveguide dramatically decreased with decreasing sidewall roughness of the channel.

The attenuation of the polymeric waveguides was also investigated. The average attenuation was 1.2 dB for an adjacent 12-channel waveguide, 5.5 cm in length. The uniform attenuation characteristics verified that the polymeric waveguide was successfully produced using a hot embossing process.

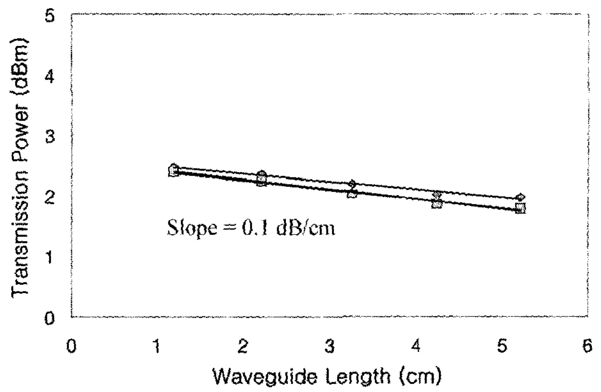
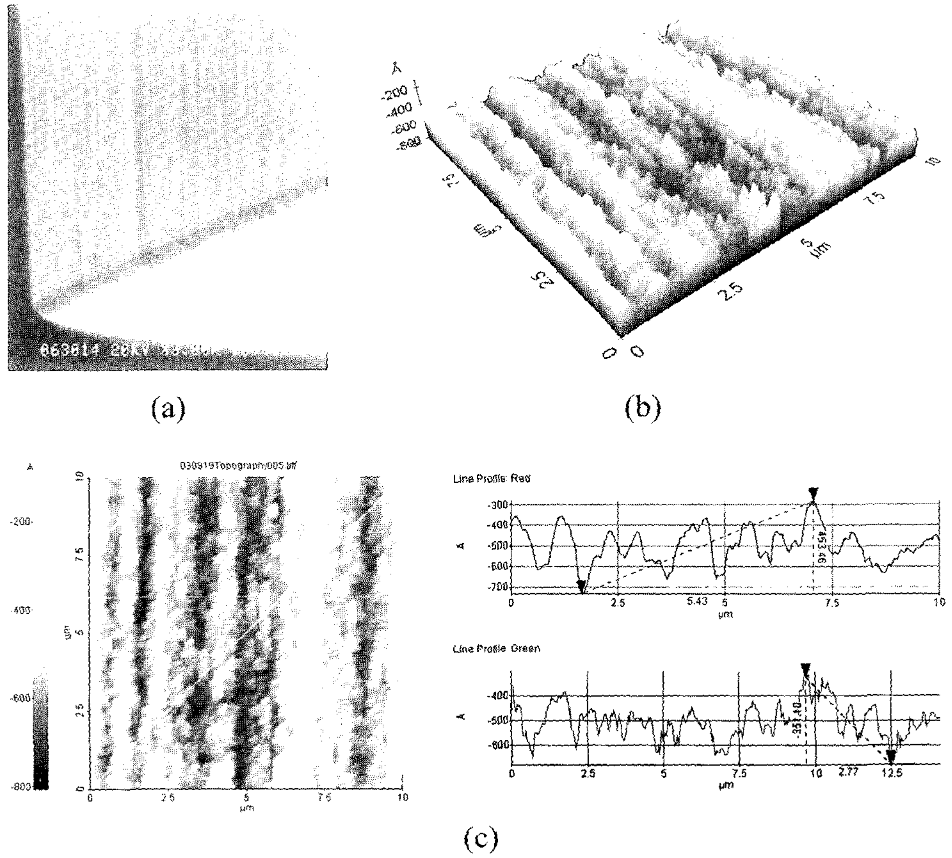


Figure 9. Propagation loss of multimode waveguides, which is produced with silicon master shown in Figure 8.

Conclusions

The polymeric multimode waveguides were fabricated by means of a hot embossing technique. Resulting waveguides exhibited a smooth surface profile and a square cross section of the core. We show that the sidewall roughness of channels dominantly affects the insertion loss of waveguides. The propagation loss of waveguide dramatically decreased with



(a) (b)

(c)

Figure 8. (a) SEM and (b and c) AFM images of sidewall of silicon master channel.

decreasing sidewall roughness of the channel. The propagation loss of fabricated waveguide was measured to be 0.1 dB/cm at 850 nm. Thus, hot embossing process can fabricate the large core size waveguide with simple and cost effective. It can also be applied to fabricate the optical device with low cost.

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