Polymer Planar-Lightwave-Circuit-Type Variable Optical Attenuator Fabricated by Hot Embossing Process

Jin Tae Kim, Choon-Gi Choi, and Hee-Kyung Sung

ABSTRACT—A polymer-based planar-lightwave-circuit-type variable optical attenuator (VOA) was fabricated using a hot embossing process. With an optimized one-step embossing process, forty micro-channels for the guidance of light were defined on a polymer thin film with an accuracy of ± 0.5 μm. The fabricated polymeric thermo-optic VOA shows 30 dB attenuation with 110 mW electrical input power at 1.55 μm. The rise and fall times are less than 5 ms.

Keywords—Polymer planar-lightwave-circuit-type (PLC), variable optical attenuator (VOA).

I. Introduction

Polymer materials for telecommunication component manufacturing have attracted attention because of their satisfactory light-guiding characteristics [1]. Previous studies have shown that the optical transmission losses in polymer can be minimized to about 0.01 dB/cm at 840 nm. In addition, polymer materials have the advantages of a large thermo-optic (TO) coefficient and nonlinear electro-optic coefficients [1]. Those properties enable the development of a TO-based arrayed waveguide grating, a TO-based variable optical attenuator (VOA) with low power consumption, and electro-optical Mach-Zenhder modulators [2]-[4].

Compared to the silica-based waveguides, polymer-based planar lightwave circuit (PLC)-type optical waveguide components can be fabricated by low-cost and high-throughput replication technologies such as injection molding, ultraviolet (UV) embossing, and a hot embossing process [5]-[7]. Among many other alternative fabrication processes, the hot embossing process provides the simultaneous and single-step formation of polymer on various microstructures with high accuracy [8]. It has therefore been considered as an innovative method for a low-cost mass production of polymer micro-electro-mechanical system (MEMS) and micro-opto-electro-mechanical system (MOEMS) devices [9], [10].

In this paper, we fabricated a polymeric TO-VOA using a hot embossing process. Precise polymer micro-channels for the guidance of light were embossed in a single step by an optimized hot embossing process and were characterized with scanning electron microscopy (SEM) and an interferometer. The characterizations of the fabricated polymeric VOA were investigated according to the applied voltage control. The optical properties are also reported.

II. Fabrication and Characterizations

A schematic of the VOA proposed by Noh et al. [2] was used for fabricating the PLC-type VOA as shown in Fig. 1. Single-mode waveguide channels of 7 μm × 7 μm, taper structures, and 7 μm × 40 μm multi-mode waveguide channels were designed. When the voltage is applied to the electrode, the refractive index under the heater changes due to the TO effect; then, the propagation light is partially reflected. As the applied electrical power increases, the amount of reflected light increases, which leads to larger optical power attenuation. To give a maximum attenuation, the length, the width, the angle, and the thickness of the heater were optimized to be about 2,000 μm, 7 μm, 3°, and 500 Å, respectively. The refractive index difference between the under-clad and the core was designed as 0.5% to yield single-mode light propagation in 7 μm × 7 μm waveguide channels. On the other hand, the refractive index difference between the core and the over-clad was optimized to be 3% to minimize the leakage light, which is

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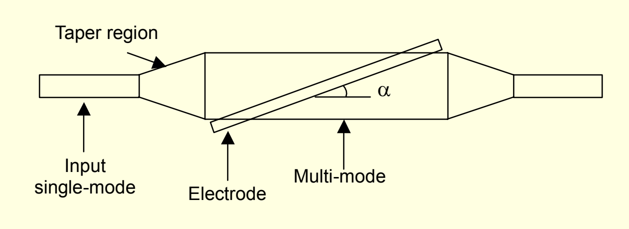

Fig. 1. A schematic layout of the fabricated VOA proposed by Noh et al. [2].

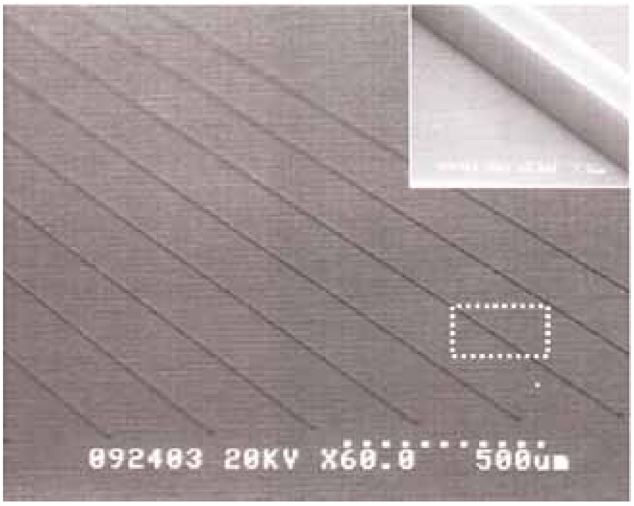

Fig. 2. A silicon mold for embossing polymer waveguide channels.

attributed to the thinness of the over-clad, which is less than 10 μm, enabling low power-consuming heat conduction to the core.

The silicon mold for the embossing of waveguide channels on polymer was fabricated using a deep reactive ion etching (DRIE) process as shown in Fig. 2. Forty straight shims for 7 μm × 7 μm single-mode waveguide channels, taper structures, and 7 μm × 40 μm multi-mode waveguide channels were fabricated. The pitch of each channel is 250 μm, and the length is about 1.5 cm. Because of the accurate etching rate control of the DRIE process, micro shims were obtained with an accuracy of ± 0.5 μm.

The fabricated silicon mold was pretreated with a liquid phase deposition of 1H, 1H, 2H, H-perfluorooctyl-trichlorosilane (Fluorochem, Ltd.) to build a self-assembled monolayer on the mold surface for anti-sticking between the mold and the embossed polymer materials during the hot embossing process. After a 30 min immersion in the trichlorosilane solution at 80°C, the mold was rinsed with anhydrous hexane for 10 min. The water contact angles of the silicon mold increased from 45° to 107°, and the hydrophilic surface changed into a hydrophobic surface.

In order to emboss the polymeric optical device, the poly(methyl methacrylate) (PMMA) of Asahi Glass Co., Ltd., was used as an under-clad. PMMA pellets were dissolved in a chlorobenzene solution and then spin coated on the silicon substrate with the appropriate spin condition. After an optimized convection oven baking, a PMMA thin film of 30 μm thickness was obtained. The refractive index of the PMMA was about 1.4813 at a 1550 nm wavelength as measured with a prism coupler.

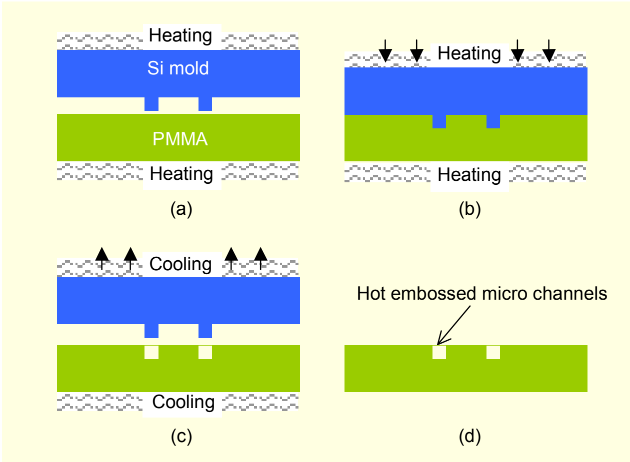

Fig. 3. An illustration of the hot embossing process: (a) a polymer and mold were heated above its glass transition temperature, (b) a mold was pressed into a polymer, (c) after adequate holding time the polymer was cooled down below its glass transition temperature and then the mold was lifted up, (d) well-defined micro channels were obtained.

Using the silicon mold, waveguide channels were embossed in one-step by the hot embossing process as shown in Fig. 3. A polymer is heated above its glass transition temperature, as shown in Fig. 3(a), and a mold master is pressed into it, as shown in Fig. 3(b). After an adequate embossing time (holding time), the polymer is cooled down below its glass transition temperature and then the mold is lifted up, as shown in Fig. 3(c). Finally, hot-embossed microstructures were obtained and are shown in Fig. 3(d). The hot embossing temperature was about 150°C, pressure was 0.35 MPa, holding time was 120 s, de-embossing temperature was 85°C, and total processing time was about 8 min.

Figure 4 shows an SEM picture of embossed waveguide channels on a PMMA thin film. An excellent quality of the embossed structure is a criterion for optical waveguides, and this result directly related to both the surface roughness and the dimensional tolerances of the fabricated microstructures. The sidewall roughness of the waveguide channel was about 20 nm (root mean square) using a WYKO interferometer. The accuracy of the hot-embossed structures was below ± 0.5 μm.

In the VOA fabrication step, the embossed channels are filled with the core material and then covered with an over-clad material. To ensure a good wetting of the core material during

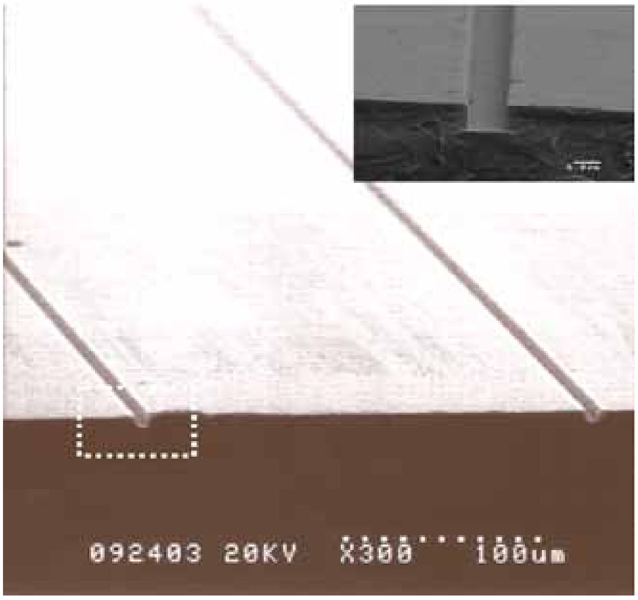

Fig. 4. SEM pictures of hot-embossed waveguide channels on a spin-coated PMMA thin film.

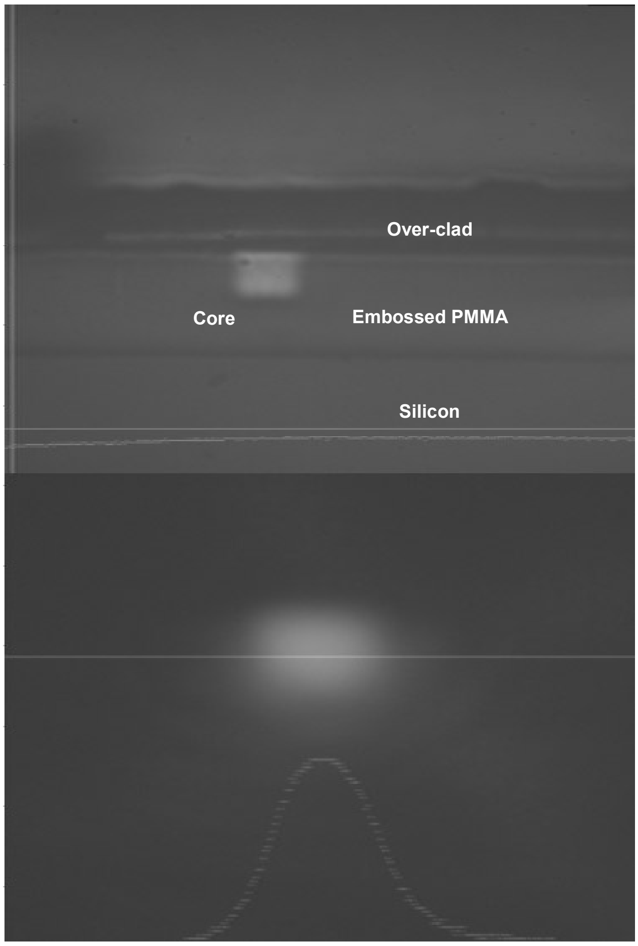

Fig. 5. A cross-sectional view of a fabricated polymer waveguide and a near-field pattern at a wavelength of 1.55 μm.

filling, the embossed under-clad PMMA was pretreated with O_2 plasma before being filled with the core material. After an O_2 plasma treatment, the water contact angle decreased from 75° to 36°. The surface characteristics of the under-clad PMMA films changed from a hydrophobic state into a hydrophilic state.

UV-curable optical adhesives from Zenphotonics Co., Ltd. were used as core materials. Since the refractive index (*n*) of the embossed PMMA was 1.4813, the embossed channels were filled with WIR30-106, whose refractive index is 1.4887. Then, the core material was cured with a 365 nm UV light for 10 min in N_2 atmosphere. After the core material curing, an over-clad ZPU12-450 (n = 1.45) was spin coated and then cured under the same conditions as the core. The practical refractive index difference between the under-clad and the core is 0.5%, and that of the over-clad and the core material is about 2.7%. Finally, the gold electrodes for TO effect were sputtered using a photolithography process.

Figure 5 shows the cross-sectional views of the single-mode output part of a fabricated polymeric VOA and a near field pattern. The images indicate that the guided light is well confined to the core and that the waveguides have good propagation characteristics. The propagation loss for the straight single-mode waveguide was 0.83 dB/cm using the cut-back method. This optical propagation loss, which is slight compared to that of the slab waveguide (about 0.5 dB/cm), can be attributed to the scattering that resulted from the dust particles in the channel. The average insertion loss was less than 2 dB, which is attributed to the high Fresnel loss caused by the large difference in the refractive index between the fiber and the polymer material.

Figure 6 shows the measured attenuation characteristics according to the applied electrical power. The results indicate that the required electrical power to achieve 30 dB attenuation is about 110 mW. This result shows very high attenuation at

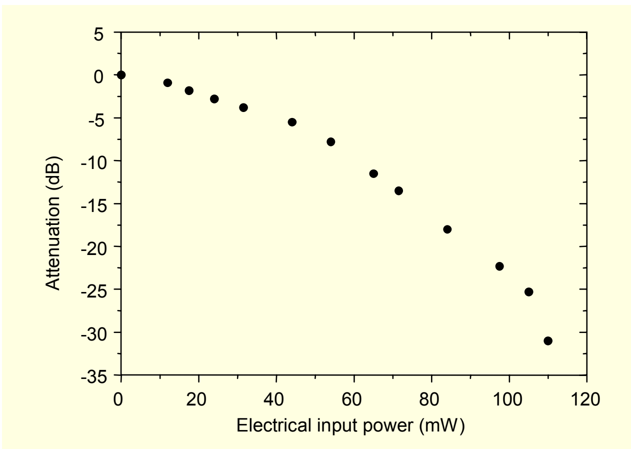

Fig. 6. Measured optical power attenuation according to applied electrical input power.

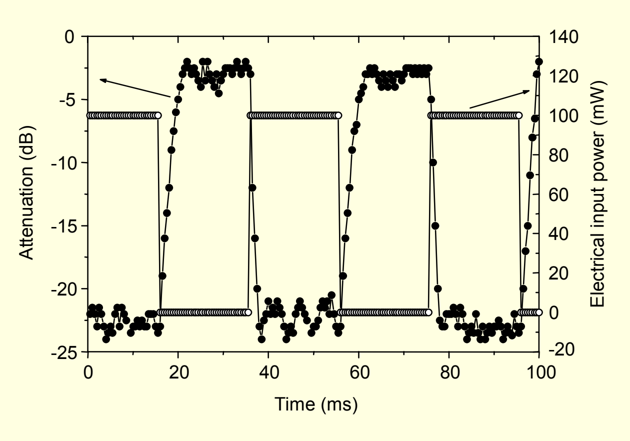

Fig. 7. Rise and fall time characteristics according to time.

low electrical power consumption. Compared to this, the previous study showed a 30 dB attenuation with only an 80 mW input power [2]. In polarization dependence, this shows about 0.2 and 1 dB at 0 and 10 dB attenuations, respectively. In the case of 30 dB attenuation, the polarization dependence was measured to be about 2.8 dB. The rise and fall times are measured to be less than 5 ms as shown in Fig. 7.

III. Conclusion

A polymeric thermo-optic VOA was successfully fabricated through a hot embossing process. The fabricated device exhibits a well-defined single-mode light propagation profile and 30 dB attenuation with only a 110 mW electrical power. The rise and fall times are less than 5 ms.

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