Fabrication of polymeric optical waveguides Using simple method

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ABSTRACT

Simple fabrication techniques of polymeric optical waveguides and waveguide elements toward low insertion loss are demonstrated. Serially-grafted waveguides with active layer such as electro-optic polymer and passive layer such as transparent polymer was fabricated using softlithography as well as photo-bleaching. Single-mode waveguide was fabricated using light-induced self-written (LISW) optical waveguide. For large core optical waveguide, replication technology is adopted for the formation of a platform with a fiber guide.

Keywords: Polymer optical waveguide, Softlithography, Photo-bleaching, Replication technology, Hot-emboss technique, Light-induced self-written waveguide, Serially grafted electrooptic polymer waveguide

1. Introduction

Information society where massive bandwidth required needs the use of optical network systems as well as optical components. Optical networks are very expensive compared to cupper wire system and wireless system. When we want to use optical network system in the home or in the office, optical components and materials which play an important role for transmitting and processing optical signals should be inexpensive. Effective approach to reduce this cost is the use of polymer optical circuits. Optical circuit based on waveguides is the most desirable and the waveguides can be fabricated using either glass or polymer materials. Planar lightwave circuits (PLC) are usually constructed by silica glass and made using photolithography and dry etching techniques. Although PLC components are already commercially available, the fabrication still needs high cost.

Optical device fabrication method of polymer optical waveguides are very simple and cost effective. Polymers are also easy to functionalize where high speed optical switching and signal modulation can be attained. The use of soft-lithography shown below instead of standard photolithography and dry etching technologies is attractive because inexpensive optical device can be realized. Polymerization or decomposition using multi-photon absorption of materials is also a good method for optical waveguide fabrication. Direct waveguide patterning can be done using this method. Laser induced self-writing technology of optical waveguide is also very simple and attractive. Using these processes, we can fabricate and interconnect multiple optical devices at once.

Monolithically integration of passive waveguide with active devices on a single substrate is possible using polymer materials. If the entire structure is on one circuits, the manufacturing, packaging, and assembly costs are reduced dramatically.

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In this paper, recent progress of our research on fabrication techniques of the polymer optical waveguide toward next generation FTTH systems is described. Figure 1 shows a concept of our fabrication technology. It is necessary to reduce waveguide propagation loss, fiber coupling loss and connection loss between two waveguides. For the waveguides with smaller core size, light-induces self-written (LISW) waveguide is realized in order to realize a self-alignment between the waveguide and the fiber. While, the larger core optical waveguide are produced using hot-emboss technique. Moreover, serially grafted passive and electrooptic (EO) polymer waveguide structure is also fabricated based on soft-lithography, photolithography and spin-coating.

Simple techniques for polymer waveguide fabrication

The key for the construction of

next generation FTTH networks

- **Light-induced self-writing method**
- **Hot-embossing technique**
- **Soft-lithography (with photolithography)**
- **Two-photon excited polymerization**
- **Photo-bleaching**

Fig.1. Meaning of the waveguide fabrication toward FTTH systems

2. Single-mode light-induced self-written waveguide

First, single-mode propagation was realized at 1310 nm using the LISW polymeric optical waveguide. There are two obstacles to achieve single-mode waveguide fabrication that needed to be overcome.

(1) A polymerised waveguide core with a diameter of ~10 μm easily bends in the liquid cladding just after core formation.

(2) In order to realize the single-mode condition at 1310 nm the core size and the refractive indices of the core and the cladding should be precisely controlled.

Therefore, we adopted a “pre-UV” treatment before the core formation to increase the viscosity of the resin mixture, and we controlled the ratio of the mixture of the two polymerising resins to satisfy the single-mode condition at the telecoms wavelengths.

The material used in this experiment was a mixed solution of two photopolymerizing resins with different refractive indices. Resin A (used for the higher refractive index core) was an epoxy acrylate monomer incorporating a photoinitiator, which was photosensitive at 488 nm, while resin B (for the lower index material) was an oxetane-type monomer that was not sensitive at 488 nm. The mixing ratio of resin A to resin B was changed as part of our study. Figure 2 shows the process flow for single-mode LISW optical waveguide fabrication. A single-mode optical fiber (Step-Index type) was inserted into the mixed solution. The core diameter and cladding diameter of the fiber were 9.5 μm and 125 μm, respectively. The core was then formed by selective photopolymerization of the higher refractive index monomer (A) by irradiation with an Ar^+ laser (λ= 488nm) through the fiber. We used an irradiation power of ~20 mW and an irradiation time of less than 1 sec.

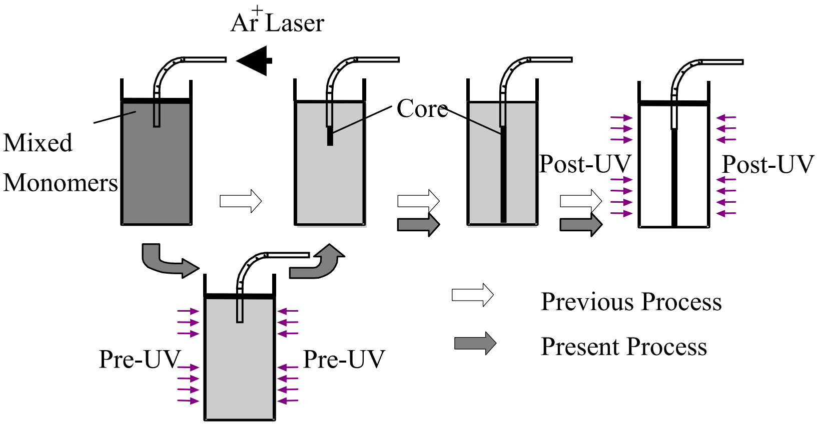
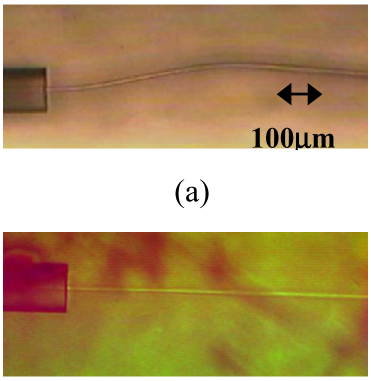


Fig.2. Process flow LISW waveguide fabrication



(a)

(b)

Fig.3. Core formation (a) without pre-UV and (b) with pre-UV

A solid optical waveguide core with almost the same core size and which was several mm in length was formed in the liquid cladding by the ”self-trapping-effect”. The waveguide core was formed from the center of the fiber tip without any deviation. The cladding region was then completely hardened by irradiating with light from a UV lamp (365 nm) from the circumference, and so a self-aligned optical waveguide was fabricated, which was connected to the original fiber.

The main problem with this type of single-mode LISW waveguide is that the thin waveguide core easily bends in the “liquid” resin mixture after the core is prepared by the similar process. In order to solve this problem, we tried performing the UV exposure with the UV lamp in advance of the core formation process to increase the viscosity of the resin mixture. We called this partial hardening process the “pre-UV treatment”. Figure 3 shows photographs of actual fabricated waveguide cores prior to the post-UV process (a) without the pre-UV treatment and (b) after the pre-UV treatment was implemented. The conditions used for the pre-UV treatment were as follows: the UV irradiation power was ~2 mW/cm^2 and the irradiation time was 7 sec. By comparing the two photographs it was confirmed that a straight LISW waveguide could be successfully realized by utilizing the pre-UV treatment in the process. Furthermore, the pre-UV treatment also furnished two other advantages: (1) the index difference between the core and the cladding was effectively reduced, leading to the relaxation of the single-mode propagation condition, and (2) since less energy was required for the core formation, a longer waveguide was grown.

Other further problem is that the single-mode condition should be satisfied in the waveguide at 1310 nm. The approach we took was to try to control the ratio of the mixture of the two resins. We fabricated several waveguides using the process flow shown in Fig.2 while changing the ratio of A:B from 6:1 to 9.5:0.5. Straight waveguides similar to those shown in Fig.3 (b) were fabricated for each sample by adopting the pre-UV treatment. Then by launching a laser with a wavelength of 1310 nm into the waveguides through the fiber the near field pattern (NFP) of the output beam was measured using a beam profiler. From the NFP for the waveguide with a mixture ratio of 9.5:0.5 it was confirmed that single-mode propagation was successfully realized in the waveguide. As a comparison, the NFP of another waveguide with a ratio of 9.0:1.0 was also measured, and an NFP that included a higher-mode was observed. The mode conversion that occurred in the waveguide region was caused by the high index difference between the core and the cladding. Moreover, this technology can also be applied to optical interconnections between fibers and waveguides, without recourse to any precise alignment technique, and so we attempted to realize optical interconnection using two single-mode fibers. The fibers were first set on a grooved substrate for approximate alignment. The distance between the fibers was about 150~300 µm. Then a mixture of our two “process” monomers with a ratio of 9.5:0.5 was used to fill in the whole area around the tip of both fibers. A similar process to that mentioned above was performed by launching an Ar^+ laser beam into both fibers. The core was grown simultaneously from both ends and it connected up at around the mid-point between both fiber tips. From the figure, neither misalignment nor any change in the core size were observed, and a low insertion loss of 0.5 dB was measured.

3. Fabrication of serially grafted waveguide

Moreover, EO polymers have been paid a lot of attention because of their high potential for next generation EO modulators and/or switches, and it was reported that high bandwidth, low drive voltage EO modulators were fabricated using a chromophore-shape-controlled EO polymer . However, in general, EO polymer has a large optical loss (more than a few dB/cm), and it is necessary to reduce the total insertion loss for a practical EO device. In our previous study, we fabricated an EO polymer device serially grafted with a passive waveguide composed of a high transparent polymer by means of conventional photolithography and RIE techniques. Here, we propose and demonstrate a simple technique for fabricating a serially grafted EO polymer waveguide.

Figure 4 shows a process flow, and it consists of soft-lithography, photolithography, and spin-coating techniques. A silicone resin stamper was fabricated by conventional photolithography as well as replication. The stamper pattern was replicated by soft-lithography technique; here a microtransfer molding was performed, and an undercladding was produced. Then a transparent UV-curable resin was filled in a groove region of the undercladding and a core with a groove was fabricated by photolithography. An EO polymer solution was spin-coated as the groove region was filled with the material. After removing an excessive EO polymer layer, an overcladding layer was formed. Figure 5 shows a microscopic photograph of the actually fabricated serially grafted EO polymer waveguide. The EO polymer waveguide was successfully formed and physically contacted between two passive polymer waveguides. The connection loss was measured by launching a laser light (1300nm) to the serially grafted waveguide, and the estimated loss was less than 0.1dB/point.

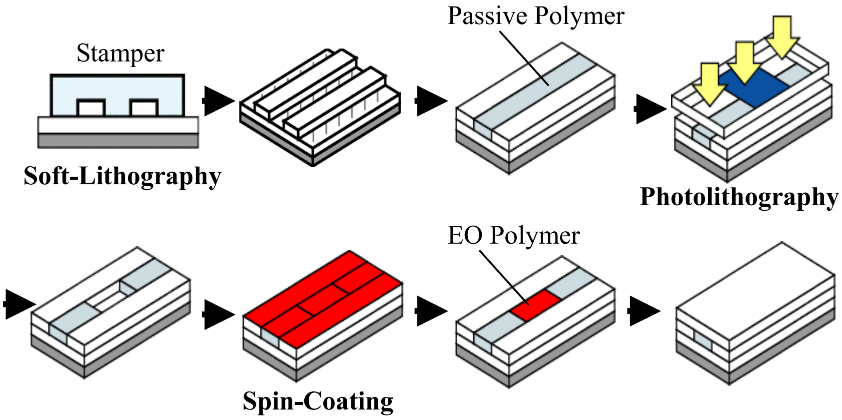


Fig.4. Process flow for serially grafted EO polymer waveguide

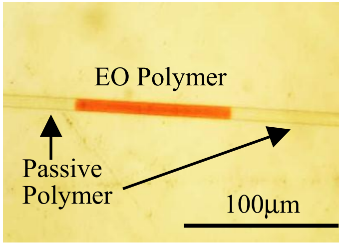


Fig.5. Photograph of serially grafted structure

4. Large core waveguide for POF by hot embossing

The replication process is more effective especially in the large core waveguide fabrication, since a lot of time is necessary for the formation of such a waveguide by the RIE technique. Therefore we attempted to fabricate the waveguide with a core size larger than 100□m using the hot-emboss technique. Moreover, this technique has several advantages over other techniques; (1) Lots of replicas can be manufactured by simply fabricating a mold. (2) A replica with complex pattern (from nanometer- to millimeter-size) can be realized through nanoprint or nanoimprint lithography. (3) When using an elecrooptic polymer both pattern formation and creation of □$^{(2)}$ are realized in only one process.

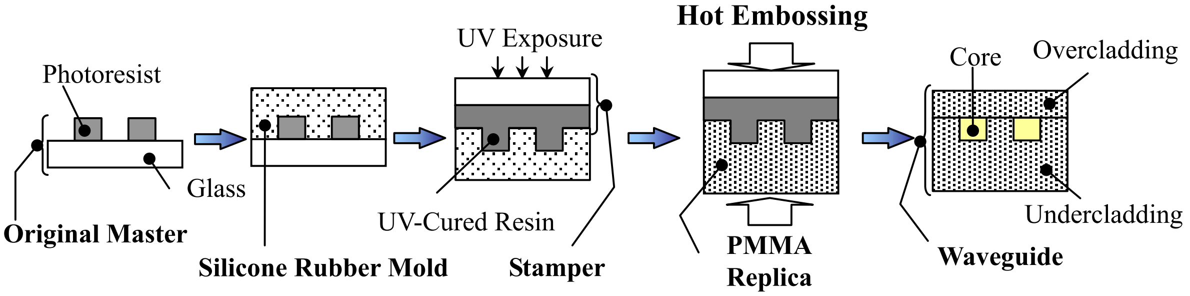
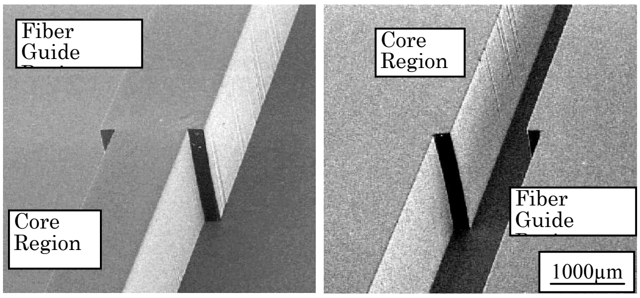


Fig.6. Fabrication process of large core optical waveguide

Large core waveguides with more than 100μm have an advantage; it is easy aligned to POF by passive alignment method using a fiber guide. In our previous paper we presented simple and low-cost method for fabricating large core polymeric optical waveguide by replication technique using a Si original master. However, this master is limited to the straight waveguide formation. Therefore, we propose another simple and low-cost method for fabricating large core waveguides that enables to fabricate waveguides with a variety of patterns by hot embossing. Figure 6 shows the outline of fabrication process. First, a negative-type photoresist original master was fabricated by photolithography. Next, silicone rubber was coated on the master and the pattern was replicated onto the rubber. Then the rubber mold was removed, and a UV-curable resin stamper with high thermal and mechanical stability was fabricated by replication of the rubber mold.

The UV-curable resin stamper was heated at 130~150℃ and a PMMA substrate with 2mm thickness was heated at 130℃. The PMMA replica was fabricated by pressing the stamper with 50~100kgf/cm^2, then the sample was cooled down and the stamper was removed. Optical waveguide was fabricated by dipping a core material (another UV-curable resin) into the groove and by coating a cladding material on it. We have fabricated a series of waveguides with core sizes of 500 μm and 1000 μm. Light propagation was observed by launching a beam from a laser diode (LD) operating at 650 nm, and the estimated propagation loss was 0.2dB/cm for both waveguides. This low value is sufficient as an optical waveguide device for short length network.

It is necessary to reduce not only the propagation loss of the waveguides but also the coupling loss between the waveguide and the POF. In order to realize a low loss POF-to-waveguide connection with passive alignment, a PMMA replica platform was fabricated where the grooves of core region and POF guide parts are connected at both ends of core monolithically. For this purpose, a photoresist original master was fabricated whose shape is shown in Fig. 7 (a). Then we fabricated a PMMA replica with a passive POF-to-waveguide alignment structure {Fig. 7 (b)} through three replication processes as mentioned above. Thus, simple fabrication of a passive POF-to-waveguide alignment structure was achieved. We positioned two POFs into the fiber guide grooves, filled the core material in the core groove, and cured the resin by UV-irradiation. By covering an overcladding material onto the POF and the waveguide core a permanent connection was achieved. Hence, we realized a simple connection of waveguide and POFs. Such a monolithic platform structure for passive alignment could simply be produced by direct photo-patterning using the photoresist which enables a variety of structure unlike Si wet-etching. We also successfully fabricated Y-branch waveguides using the present simple technique.



(a) (b)

Fig.7. Microscopic photographs of (a) original master and (b) PMMA replica with core and fiber guide patterns

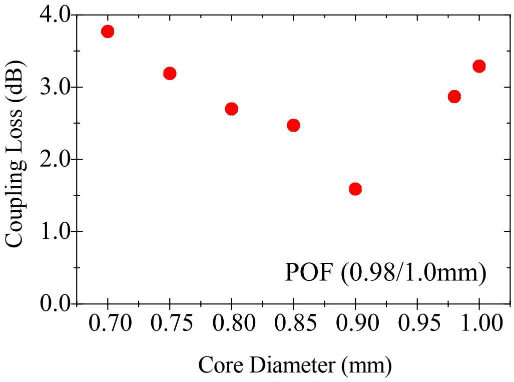


Fig.8. Overall coupling loss vs core diameter (POF→waveguide→POF)

We optimized the coupling loss of POF with 980/1000 µm to the waveguide by changing the waveguide core width of the monolithic platform structure from 700 µm to 1000µm. A series of waveguides attached with two POFs at both ends in one platform was used to measure the overall coupling loss as shown in Fig.8. From the figure it revealed that the overall coupling loss had a minimum value of 1.6 dB at a core width of 900 µm. Such result of optimum waveguide core width was qualitatively supported by theoretical calculation, where the coupling loss is proportional to an overlapping area between cores of waveguide and POF. Therefore, we assured that the optimized core width is 900 µm when we will apply an optical waveguide connected to 980/1000 µm POFs for two-way communications.

5. Conclusion

In conclusion, simple and cost-effective fabrication techniques of polymer optical waveguide toward next generation FTTH systems were presented. For the waveguides with smaller size core, LISW technique was used in order to realize a self-alignment between the waveguide and the fiber. Serially grafted EO polymer waveguide was fabricated based on simple soft-lithography, photolithography and spin-coating techniques. A larger core optical waveguide was fabricated using hot-emboss technique. Simultaneous formation of waveguide groove with fiber guide grooves in one platform based on the hot-emboss technology was also realized. The present techniques, including photo-bleaching and direct patterning, their simple and cost-effective way can be suitably applied for the fabrication of polymer optical waveguide devices.

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