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FABRICATION OF LOW-LOSS WAVEGUIDES USING ORGANIC-INORGANIC HYBRID MATERIALS

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The fabrication of single and multimode waveguides and optical characteristics were investigated. The singlemode waveguide was fabricated by a laser direct writing technique and a multimode waveguide was produced by means of a direct UV patterning technique using organic-inorganic hybrid materials. The fabrication of waveguide channels with these techniques are of interest for simple processes. The resulting single and multimode waveguides exhibited a near rectangular shape and low optical loss. The average propagation losses of these waveguides were 0.07 dB/cm (at 850 nm) and 0.3 dB/cm (at 1310 nm), respectively.

Keywords: Optical waveguides; laser direct writing; index modulation type; direct UV patterning; organic-inorganic hybrid material.

1. Introduction

The polymeric waveguides are attractive for optical integrated circuit device applications because of their low cost and simple processing step compared with silica-based waveguides.[1] Several techniques can be applied to fabricate polymer optical waveguides.[2,3] The dry etching method such as reactive ion etching (RIE) is often used because this technique can offer an excellent etching profile.[4,5] One of the disadvantages of this technique is its complicated processing step, and thus, is not cost effective for mass production. To overcome these problems, UV exposure techniques can be used to fabricate polymeric waveguides. In these techniques, waveguide channels are formed by exposure of UV light in photosensitive polymeric film.[6,7]

There are many publications describing how an organic-inorganic hybrid material can be used to fabricate waveguides.[8–10] Organic polymers offer ease of processibility and toughness and inorganic materials offer superior thermal resistance and compatibility with common inorganic substrates.[8] In general, an organic-inorganic hybrid material exhibits negative resist properties and this material is compatible with the thin-film of electrical and optical interconnection technology.[1,11] This hybrid material is well suited to generated patterned layer with well-defined electrical and optical properties.

In this paper the laser direct writing process and direct UV patterning process can be used to fabricate single and multimode waveguides. The singlemode waveguide was fabricated by a laser direct writing method which has the advantage of allowing rapid and simple processes compared to a conventional dry etching method. The UV patterning method was used for fabrication of waveguide with large core. The characteristics of optical properties of resulting waveguides are also demonstrated.

2. Experiments

The photosensitive polymeric materials are the organic-inorganic hybrid materials, which are synthesized by the non-hydrolytic sol-gel process. The conventional sol-gel process starts by building up an inorganic network through control by hydrolysis and condensation of organically-modified silanes. However, the organic-inorganic hybrid materials synthesized by the conventional sol-gel process contain some of remaining solvent even after moderate evaporation. Thus, the different characteristic of the non-hydrolytic sol-gel process compared with the conventional hydrolytic sol-gel process is the synthesis of the polysiloxane resin without solvent. To get a crack-free pattern structure and little volume contraction, the organic-inorganic hybrid material synthesized by a non-hydrolytic sol-gel process is suitable for UV exposure applications.[2,8,12]

The singlemode waveguides were fabricated by laser direct writing without photo-mask, etching and development processes. The organic-inorganic hybrid materials were used for fabrication of singlemode waveguides, which have high transparency in the visible to infrared region.[13,14] The waveguide channels were written by a He-Cd laser and were characterized with optical microscopy and atomic force microscopy (AFM).

Figure 1 shows the fabrication process of the index modulation type waveguides. The waveguide channels were patterned by a focused laser beam after a one-step spin coating process on the buffer layer. The silicon oxide was used as a buffer layer that was produced by thermal oxidation. In the next step, resulting waveguide channels were baked at 120°C for 3 hrs.

Direct UV patterning process is schematically represented in Fig. 2.[15] In the direct UV patterning technique, a silicon wafer is covered with a buffer layer (an organic-inorganic hybrid material: refractive index is 1.5280 at 850 nm) of precise thickness of 20 μm by spin coating. After polymerization of this buffer layer, a second organic-inorganic hybrid material layer (core material: refractive index is 1.5433 at 850 nm) with a thickness of 51 μm is spin-coated. The definition of the waveguide structures is realized by UV-polymerization through a mask aligner resulting in waveguide channels. The non-polymerized part in the layer is dissolved with a

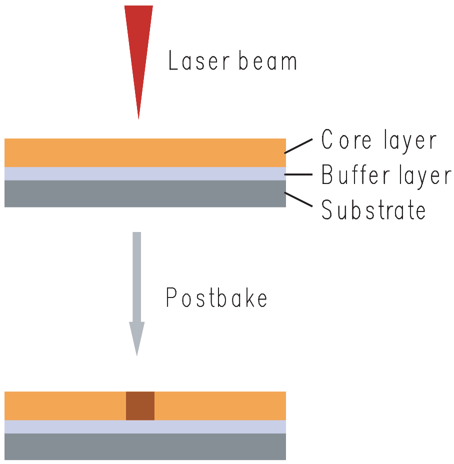


Fig. 1. Schematic diagram of the processes of laser direct writing technique for fabrication of index modulation type singlemode waveguides.

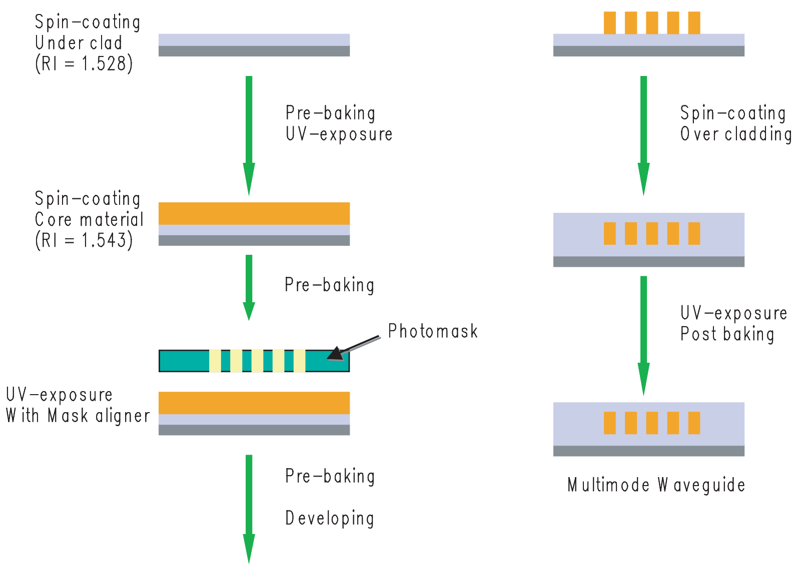


Fig. 2. Schematic diagram of the processes of direct UV patterning technique for fabrication of multimode waveguides.

propylacetate/iso-propylalcohol mixture. In the next step, an upper clad layer is spin-coated and polymerized by UV light.

3. Fabrication of Singlemode Waveguides

The refractive index of organic-inorganic hybrid material films increased after exposure to a laser beam. It has been revealed that polymerization of the organic parts contributes to the increase in the refractive index.[13,14] Therefore, the refractive index of the exposed region is higher than that of the unexposed region, which forms the index modulation type waveguide without etching process. Resulting waveguide channels were baked for stabilization of the organic and inorganic networks. Thus the index modulation type waveguides were finally fabricated.

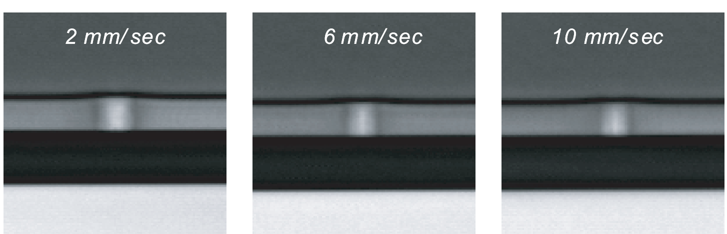
The laser direct writing system consists of a He-Cd laser radiating 325 nm beam, high-resolution computer-controlled translation stages and a video camera that captures the images of the sample on a monitor.

Figures 3(a) and 3(b) show the optical microscope images of cross-sectional views and near-field patterns at a wavelength of 1310 nm. The pattern of waveguide channels were written at various writing speeds to optimize the writing condition.

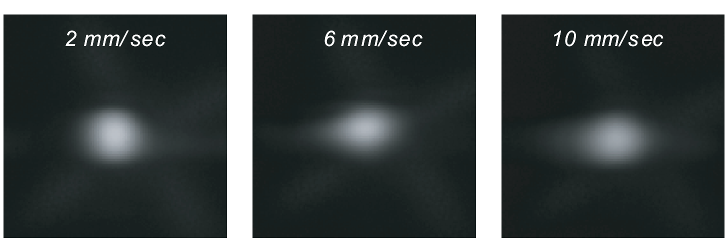
Figure 3 depicts the dependence of the core dimensions and guided mode profiles of singlemode waveguides with various writing speed of 2, 6 and 10 mm/sec, respectively.

The width of the channels decreased from 7 to 5 μm with increasing writing speeds from 2 to 10 mm/sec. The guided mode profile of the channel waveguide produced by high speed was elliptical, whereas that by low speed was circular. Therefore a typical scanning speed used in this work is 2 mm/sec.

The core section of the completed singlemode waveguides was a rectangular shape that resembles the step-like index profile. The core dimension was 7 μm wide and 8 μm high. The refractive index increased form 1.498 to 1.502 after exposure. The difference of the refractive index between the core and cladding was approximately 0.3%.

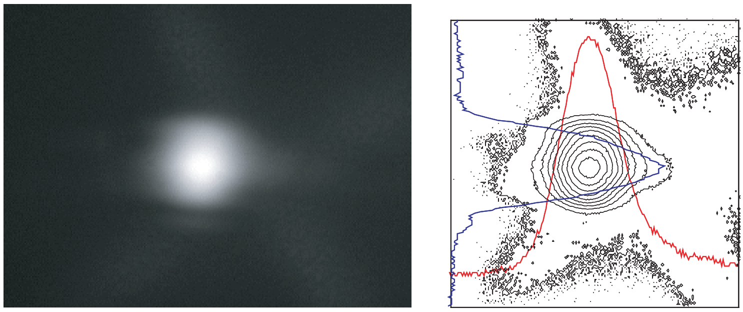


(a)



(b)

Fig. 3. (a) Cross-sectional view, and (b) near-field pattern, of singlemode waveguides.



(a) (b)

Fig. 4. (a) Output near-field pattern, and (b) intensity profile, of singlemode waveguides.

The near-field pattern and intensity profile are shown in Fig. 4. As can be seen in the single lobe of the near-field pattern, this waveguide was singlemode. An almost circular mode profile can be obtained without an over cladding layer. The intensity of the output beam was very uniform.

The surface roughness of channels can cause optical loss of resulting waveguide due to scattering; a smooth surface should be considered to reduce the optical loss.[16] The surface of the waveguide channel was observed by atomic force microscopy (AFM). The AFM image is shown in Fig. 5.

In Fig. 5, the waveguide channel produced by the laser direct writing technique has a very smooth surface and a perfect symmetrical structure. The center of the channel is slightly raised due to the polymerization of organic parts during the exposure. It can be seen that the channels are well defined with no visible defects.

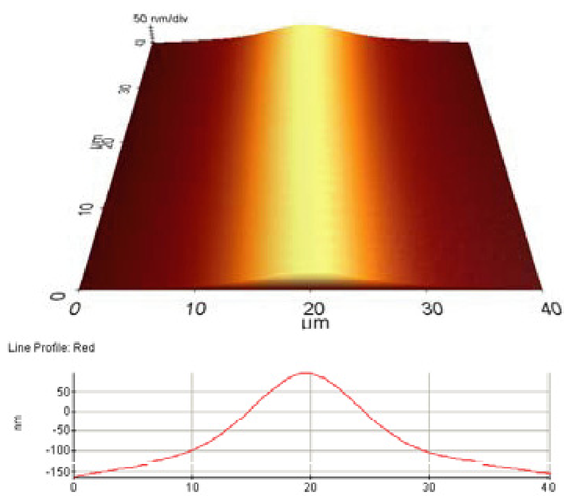


Fig. 5. AFM image of waveguide channel produced by laser direct writing.

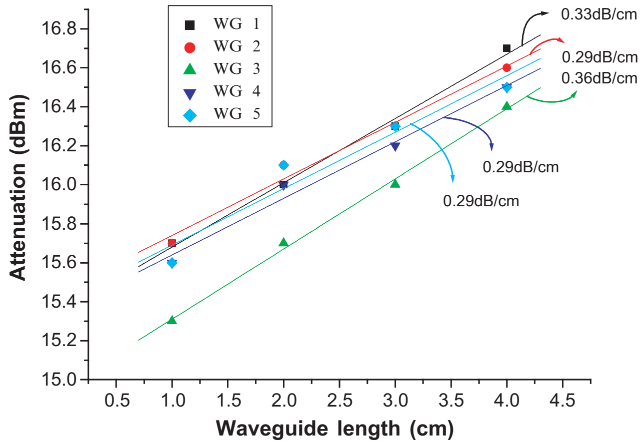


Fig. 6. Propagation loss of index modulation type singlemode waveguides.

Thus this laser direct writing process is one of the effective methods of preparing waveguides with a very smooth surface.

The propagation loss of the waveguides was measured by cutback method using a singlemode fiber as an input tip, a multimode fiber (50 μm GI) as an output tip, and 1310 nm wavelength of laser light source. The results are shown in Fig. 6.

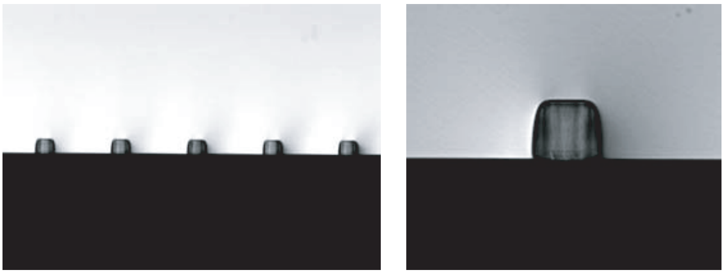
The propagation loss of the singlemode waveguides were approximately 0.3 dB/cm at a wavelength of 1310 nm from the slope of the curve as a function of waveguide length. The coupling loss was about 1.2 dB for the polished end face of the waveguide.

4. Fabrication of Multimode Waveguides

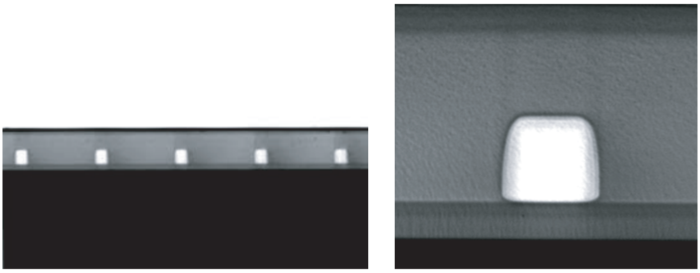
The multimode waveguides were fabricated by the direct UV patterning technique with organic-inorganic hybrid materials. The optical microscopy pictures of waveguide channels after development are shown in Fig. 7(a).

It can be seen that all the channels are well defined with no visible defects, indicating the very high photocontrast for organic-inorganic hybrid materials. The high photocontrast is very important as it permits control of device geometry and allows for fabrication of high-density waveguide arrays for complex structures. Geometrical characterization involved qualitative examination of the structure of the photo-defined devices by optical microscopy. The optical microscopy pictures of channel and covered ridge waveguide are shown in Fig. 7(b).

The mask opening for the exposed channel was 43 μm. The results of these measurements are a good indication of the high quality of the fabrication process. The height of the core is 51 μm, which is correspondent with the thickness of the spin-coated core layer.



(a)



(b)

Fig. 7. (a) Cross-sectional view of channel after developments, and (b) completed multimode waveguide channels.

The optical loss depends not only on the material loss but also very strongly on the roughness of the core-cladding interface.

The surface roughness of the channel's top and side wall after developments are about 2 and 5 nm, respectively. Due to the low shrinkage and solvent-free nature of the organic-inorganic hybrid material, thick films and therefore large-dimension devices have been produced.

The output profile of the multimode waveguides irradiated by a 850 nm laser was investigated and the near-field pattern is shown in Fig. 8.

Fig. 8. Output near-field pattern of multimode waveguides.

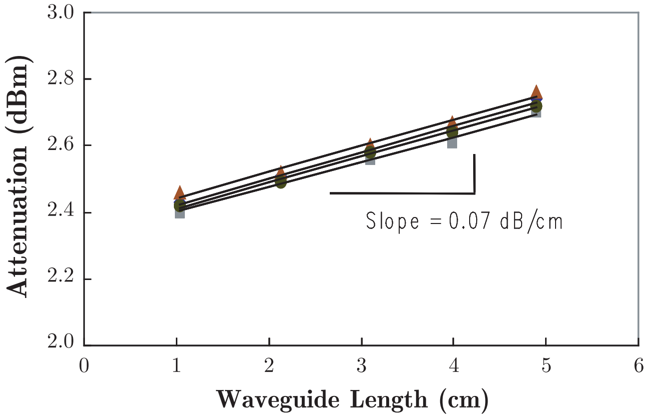


Fig. 9. Propagation loss of multimode waveguide.

The scattering from localized defects was not observed along the 5 cm guide, which demonstrated a highly homogeneous and uniform structure. The output profile of the guide is virtually rectangular and simply reflects the shape of the waveguide cross-section. The propagation loss of the polymeric waveguide was measured using the cut-back method, its value was 0.07 dB/cm at 850 nm as shown in Fig. 9. 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 average attenuation was 2.72 dB for adjacent 12-channel waveguide at a length of 4.9 cm. The uniform attenuation characteristics verified that the multimode waveguides were successfully fabricated.

5. Conclusion

The single and multimode waveguides were fabricated through a laser direct writing and direct UV patterning techniques. The index modulation type waveguides were successfully fabricated with an organic-inorganic hybrid material without photomask, etching and developing process. The resulting waveguides exhibited a smooth surface profile and a square cross-section of the core. The multimode waveguides were produced by means of a direct UV patterning technique. The average propagation losses of these waveguides were 0.07 dB/cm (at 850 nm) and 0.3 dB/cm (at 1310 nm), respectively. Thus, the laser direct writing and direct UV patterning techniques are a simple and promising process for various waveguide structures. These techniques can fabricate single and multimode waveguides in a simple and cost-effective manner. It can also be applied to fabricate optical devices at low cost. The laser direct writing process can fabricate large area optical circuits like optical PCB (printed circuit board).

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