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Influence of Exposure Spectra on Optical Properties of Alicyclic Methacrylate Copolymer Waveguides Fabricated by Deep UV Exposure

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We have investigated the fabrication of waveguides from alicyclic methacrylate copolymer based on refractive index modification by deep UV exposure. To control and optimize the properties of the UV-induced process, the influence of exposure spectra on mode spectra and near-field patterns was studied. Depending on the exposure condition, a single-mode propagation could be achieved at 1550 nm. The waveguide loss was 1.5 dB/cm at 1550 nm. As a first basic waveguide device, we fabricated a symmetrical 1×2 splitter. [DOI: 10.1143/JJAP.45.6654]

KEYWORDS: polymer waveguide, alicyclic methacrylate copolymer, PMMA, refractive index, deep UV exposure, single-mode waveguide

1. Introduction

Owing to the demand for high-speed communication access networks, a major reduction in the cost of optical components is required. Also, the development of novel, cheap, disposable integrated optical sensors for environmental, chemical and biological monitoring will open up new niche markets. Therefore, new technologies are required that are capable of low-cost waveguide fabrication.

Polymer waveguides are not suitable for long-range communication because of their large propagation loss, but they have other merits such as low fabrication cost and flexibility.[1] From a material-science point of view, polymers can easily be combined with other materials. The combination with fluidics and biological substances offers the possibility of building a biosensor with various optical components.

We have already reported a waveguide fabrication technology from poly(methyl methacrylate) (PMMA) by deep UV exposure.[2–4] PMMA is a very common polymer for optical applications and shows a significant increase in refractive index with deep UV exposure.[5] However, compared with other optical polymers, such as polycarbonate (PC), PMMA has a lower refractive index (1.49) and its thermal stability is insufficient [glass transition temperature (T_g), 105 °C]. Polymers which possess a higher refractive index and a higher glass transition temperature are required for practical applications.[6] To overcome the drawbacks of PMMA, an alicyclic ring structure was introduced to the methacrylate polymer to obtain a higher T_g and a lower water absorption.[7] We have investigated alicyclic methacrylate copolymers as a new material for waveguide fabrication by deep UV refractive-index change. We have shown that the carbonyl group of the methacrylate part initiates the photochemical reaction by deep UV exposure, which leads to the modification of the refractive index like PMMA.[8,9] This refractive index modification by deep UV exposure is essential for the waveguide fabrication.

By lithographic techniques, such as standard photomasks (Cr on glass), a local and controllable increase in the refractive index in the exposed areas of the polymer surface has been achieved, generating integrated optical waveguide structures. Since only a thin surface layer of a few micrometers is modified by the deep UV light, only a single homogeneous polymer plate, which serves as the substrate as well as the waveguide, is required; no further etching or development steps are required. The use of a single polymer substrate avoids the large mismatch of the coefficients of thermal expansion (CTE) between polymeric and inorganic materials, which leads to birefringence in the polymer layers and results in temperature sensitive devices. Thus, athermal and low-polarization sensitivity polymer devices can be fabricated by using a single substrate with a coefficient of thermal expansion matching that of the modified surface waveguide layer owing to only marginal structural modification.

In this paper, we report on the recent progress for realizing integrated optical circuits fabricated from alicyclic methacrylate copolymer.

2. Experimental

Alicyclic methacrylate copolymer, OPTOREZ-Series (OZ-1100), was obtained from Hitachi Chemical. This compound contains the tricyclodecyl group. OZ-1100 has better thermal stability (T_g: 130 °C) than PMMA, and in our previous study, the waveguide from OZ-1100 worked well. Therefore, we used this copolymer as a material to improve the fabrication method of polymer waveguides. The details of this material have been described elsewhere.[9] For the material investigation, UV spectra of polymer films spin-coated on quartz glass were measured using a Perkin–Elmer Lambda 2 UV/vis-spectrometer. For spin-coating, the polymers were dissolved in anisole.

First, we fabricated a plane polymer sheet of OZ-1100 by hot embossing, because OZ-1100 is marketed in the form of beads and it was necessary to form a sheet for the waveguide fabrication and refractive index measurements. The hot embossing was performed using HEX03 (Jenoptik) at a temperature of 180 °C and a pressure of 20000 N. The thickness of the polymer sheet was 500 µm. Refractive index measurements were carried out by m-line spectroscopy using a self-made prism coupler arrangement.

For the deep UV modification of refractive index, we used two different setups. The first setup is commercial UV-

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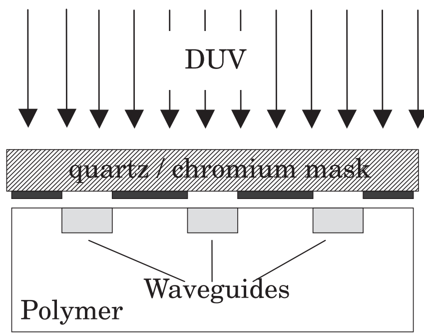

Fig. 1. Scheme of waveguide fabrication.

exposure equipment UVAPRINT CM (Dr. Hönle GmbH): a 100 W/cm mercury xenon arc lamp (F-Lamp, Dr. Hönle GmbH) combined with a cold mirror with reflectance in the range of 220–420 nm. The second setup is a commercial mask aligner (EVG 620, EV Group) with a deep UV configuration. Exposed light intensity was measured using an UV intensity meter (Model 1000, Karl Suss) at 240 nm. The emission spectrums of the light sources were measured with an UV spectrometer (USB2000 Miniature Fiber Optic Spectrometer, Ocean Optics). The exposure was performed under vacuum of 10^{-1} mbar using a rotary vacuum pump to avoid an oxidation reaction during UV exposure.

The structuring of the waveguides was carried out by contact UV exposure using a quartz/chromium mask, as sketched in Fig. 1. The width of the waveguides was 7.5 μm. The UV-exposed area of the polymer surface becomes the core of the waveguide and no further processes such as development are necessary. Therefore, this method is very simple and cost effective.

All transmission experiments were carried out using randomly polarized light.

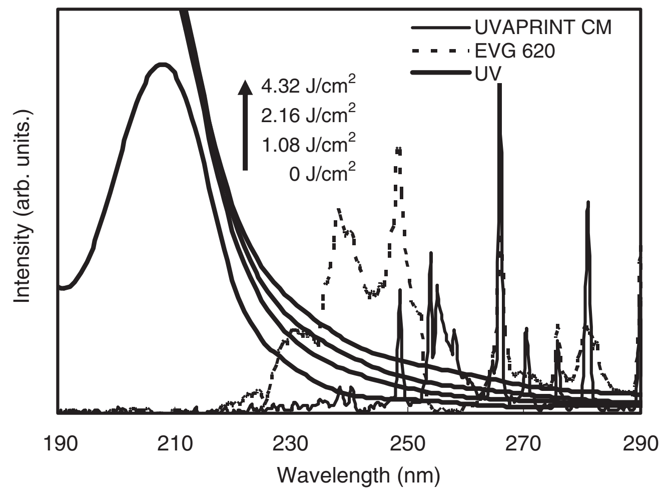

Fig. 2. Emission spectra of light sources (UVAPRINT CM and EVG 620) and UV absorption spectra of OZ-1100 with different exposure doses.

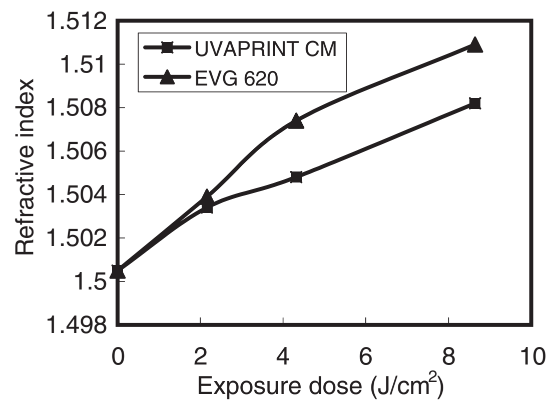

Fig. 3. Effective refractive indexes of OZ-1100 as functions of exposure dose with different UV exposure setups (UVAPRINT CM and EVG 620).

3. Results and Discussion

3.1 *UV exposure conditions for single-mode waveguide fabrication*

To optimize the UV exposure conditions for single-mode waveguide fabrication, we investigated the influence of the light sources. In our previous study, we fabricated a waveguide from OZ-1100, but the waveguide was multi-mode in the vertical direction.[9] To realize a single-mode waveguide, the geometrical accuracy of the waveguide structure is important. The width of the waveguide is determined by the design of the photomask, and the depth of the waveguide is determined by the UV penetration depth. To obtain the desired depth of the waveguide, it is necessary that UV light does not penetrate into the deeper area of the polymer and UV absorption does not occur beyond some micrometers into the polymer surface. Figure 2 shows the emission spectra of the UV-exposure equipment UVAPRINT CM and EVG 620. The EVG 620 has more light intensity in the deep UV region below 240 nm. The UV absorption spectra of OZ-1100 with different exposure doses using the EVG 620 are also shown in Fig. 2. The absorption peak of the polymer becomes larger with increasing UV exposure dose. That is, with increasing UV exposure dose, the deep UV light is absorbed only on the polymer surface and cannot penetrate into the deeper area of the polymer sheet. On the other hand, the UVAPRINT CM spectrum has a higher intensity at wavelengths above 260 nm. The absorbance of OZ-1100 at these wavelengths is still low and light at these wavelengths can penetrate well into the deeper area of the polymer. Therefore, using the UVAPRINT CM, the modification depth of the polymer might be larger than in the case of the exposure using the EVG 620 mask aligner.

Figure 3 shows the effective refractive indexes of OZ-1100 as functions of exposure dose for the two different exposure setups. With increasing exposure dose, the effective refractive indexes increase. Higher effective refractive indexes are obtained with the EVG 620 mask aligner with smaller exposure dose. To the best of our knowledge, the difference in refractive index between the core and the substrate is 0.008.[4] Therefore, the exposure doses used for the waveguide fabrication were determined to be 5 and 8.64 J/cm^2 for the EVG 620 and UVAPRINT CM, respectively.

3.2 *Waveguide characterization*

The waveguides were analyzed by near-field measurements. The near-fields of straight waveguides consisting of OZ-1100 were analyzed depending on the exposure spectra. Figure 4 shows the near-field patterns of a 7.5-μm-wide

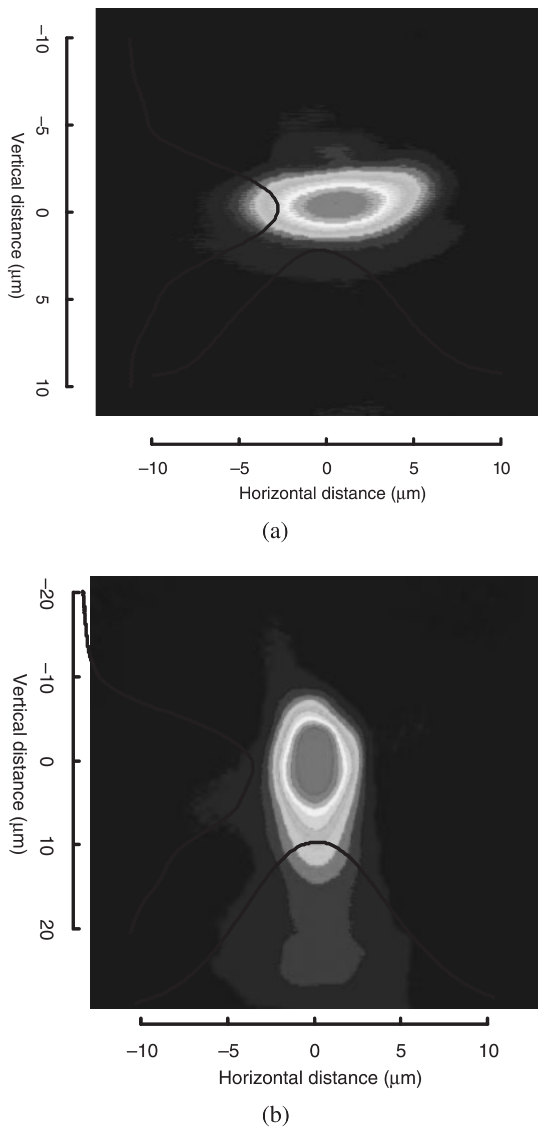

Fig. 4. Near-field photograph of straight waveguides. (a) EVG 620 and (b) UVAPRINT CM.

straight waveguide exposed using the two different exposure setups. The exposure doses were 5 and 8.64 J/cm^2 for the EVG 620 and UVAPRINT CM, respectively. In the horizontal direction, the intensity profiles show no significant difference, but in the vertical direction, a marked difference can be seen. The waveguide exposed with the EVG 620 setup shows an asymmetrical intense single-mode profile. In contrast, the waveguide exposed with the UVAPRINT CM setup is multimode in the vertical direction. As already shown in Fig. 2, the difference in mode field in the vertical direction may arise from the different penetration depths of the UV light.

For an exposure dose of 5 J/cm^2, the attenuation of a waveguide fabricated using the EVG 620 setup was found to be 1.5 dB/cm at 1550 nm. The attenuation of a waveguide fabricated using the UVAPRINT CM was 2.0 dB/cm at 1550 nm.[9] Using the EVG 620 setup, we could improve waveguide loss. All the waveguides show a polarization dependent loss less than 0.15 dB.

As a first basic waveguide device, a symmetrical 1×2 splitter with a branching angle of 1° was fabricated. The device length was 1.5 cm. A microscope photograph of a symmetrical 1×2 splitter with branching angle of 1° is shown in Fig. 5. The spectral insertion loss of the two output ports with a branching angle of 1° is shown in Fig. 6. For comparison, the spectral insertion loss of a straight waveguide is also shown. The excess loss due to the Y-splitter with the branching angle of 1° is in the range of 1.0 dB. The uniformity of the output ports is within the measurement accuracy of 0.1 dB. The wavelength dependence of the insertion loss arises from the material loss in this range due to the absorption loss of the C–H bonds of the polymer.[10]

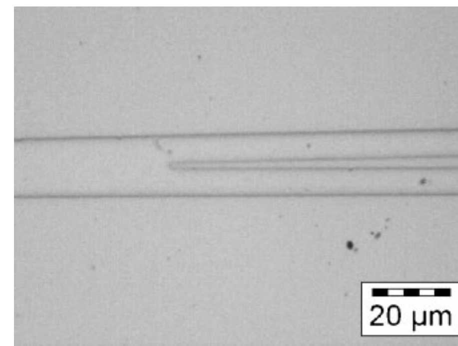

Fig. 5. Microscope photograph of 1×2 splitter with branching angle of 1°.

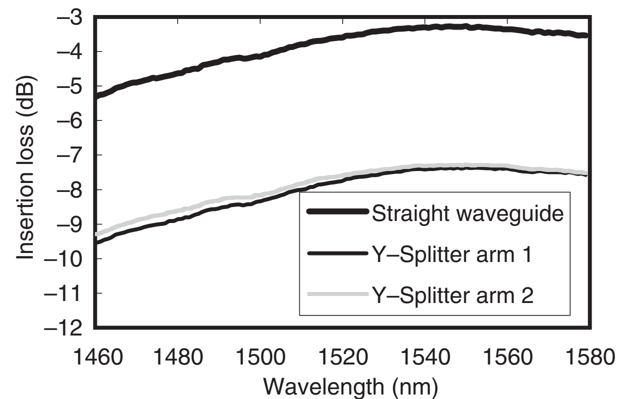

Fig. 6. Measurement result of 1×2 splitter with branching angle of 1°.

4. Conclusions

We investigated waveguide fabrication from alicyclic methacrylate copolymer by deep UV modification of refractive index. The resulting mode spectra and near-field patterns were studied using two different exposure setups. Depending on the exposure spectra, single-mode propagation could be achieved at 1550 nm. The waveguide loss was 1.5 dB/cm at 1550 nm. As a first basic waveguide device, we fabricated a symmetrical 1×2 splitter. Besides short-distance applications in telecommunications, the fabrication process opens up the possibility of new applications in the field of sensor technology.

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