Polymer waveguides from alicyclic methacrylate copolymer 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. By optimizing the UV-exposure process, we were able to obtain single-mode waveguides with a propagation loss of 0.8 dB/cm at 1550 nm, which is due only to material losses in this wavelength range. The loss obtained here is comparable with that of poly(methyl methacrylate) (PMMA) waveguides fabricated by deep-UV exposure. The fabricated waveguide is also single mode at 808 nm, and its propagation loss is 0.6 dB/cm. This alicyclic methacrylate copolymer is a promising material for the fabrication of polymer waveguides by use of deep-UV exposure. © 2007 Optical Society of America

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Polymer waveguides have been investigated vigorously, and many polymer materials have been developed.[1] Polymer waveguide fabrication has mainly been realized using photolithography followed by development and etching. Several steps are required in the process, and sidewall roughness of the waveguide deriving from the fabrication process results in additional waveguide losses. On the other hand, polymer waveguide fabrication by deep-UV exposure is a simple and straightforward method. The refractive index of the UV-exposed polymer surface increases. This UV-exposed area serves as the core of the waveguide. Since a thin surface layer of a few micrometers is modified by the deep-UV light, only a single homogeneous polymer plate that serves as the substrate and waveguide as well is required, and no further etching or development steps are required. Therefore this method is very accurate and cost effective. The use of a single polymer substrate avoids the large mismatch of the coefficients of thermal expansion between polymeric and inorganic materials, which leads to an increase in birefringence in the polymer layers and raises the temperature sensitivity of devices.

Similar methods for the fabrication of polymer waveguides such as refractive-index modification of polymers by ion implantation have been presented.[2–4] Kulisch *et al.* have reported that aliphatic polymers such as poly(methyl methacrylate) (PMMA) and polyvinylalcohol have a larger refractive-index change than aromatic polymers such as polycarbonate and polyimide.[5] Despite several advantages of polymer waveguide fabrication by deep-UV exposure, the polymers that can be used for this process are limited. Usually only PMMA is suitable, because PMMA is a common polymer for optical applications and shows a significant increase of the refractive index on deep-UV exposure.[6] We have already reported a waveguide fabrication technology using PMMA by deep-UV exposure.[7,8] The propagation loss was 0.7 dB/cm at 1550 nm. Compared with other optical polymers, such as polycarbonate, PMMA has a lower refractive index (1.49), and its thermal stability is insufficient regarding the fabrication of telecom devices [glass transition temperature (T_g), 105 °C]. Polymers that possess a higher refractive index and a higher T_g are required for practical applications.[9] To overcome the drawback of PMMA, poly(methyl methacrylimide) (PMMI) (T_g, 160 °C) was investigated.[10,11] But the propagation loss of PMMI waveguides was too large (<2 dB/cm at 1550 nm). New polymers suitable for waveguide fabrication by deep-UV exposure are required.

We have selected alicyclic methacrylate copolymers as a new material for waveguide fabrication by deep-UV refractive-index change. With the introduction of an alicyclic ring structure into the methacrylate polymer, a higher T_g and less water absorption are expected.[12] We have recently 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, similar to what occurs with PMMA.[13] This deep-UV refractive-index modification is essential for waveguide fabrication. Previously fabricated waveguides made from alicyclic methacrylate copolymer had a propagation loss of 1.5 dB/cm at 1550 nm.[14]

In this Letter we report recent progress toward realizing integrated optical circuits from alicyclic methacrylate copolymer and demonstrate propagation losses of 0.8 dB/cm at 1550 nm and 0.6 dB/cm at 808 nm. Alicyclic methacrylate copolymer was obtained from Hitachi Chemical as OPTOREZ-Series (OZ-1100). This compound contains a tricyclodecyl group. OZ-1100 has a better thermal stability (T_g, 130 °C) than PMMA.[13] We fabricated plane OZ-1100

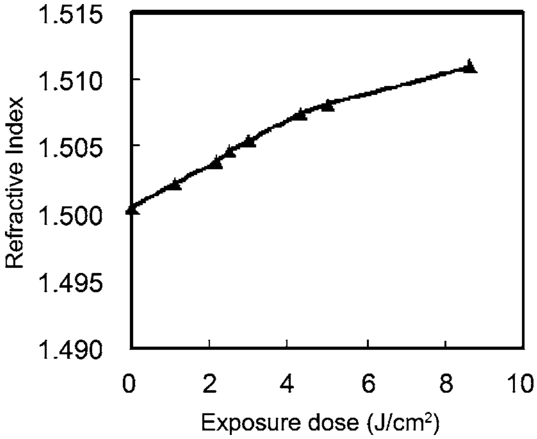

Fig. 1. Effective refractive index of OZ-1100 as a function of exposure dose.

polymer sheets with a thickness of 500 μm from OZ-1100 pellets by hot embossing (HEX03, Jenoptik). Refractive-index measurements were carried out by *m*-line spectroscopy using a self-made prism coupler arrangement.

The structuring of the waveguides was carried out by contact UV exposure using a quartz/chromium mask, and the waveguides were exposed with a commercial mask aligner (EVG 620, EV Group) with a deep-UV configuration. The exposure was performed under vacuum conditions to avoid an oxidation reaction during UV exposure. Samples were baked at 70°C for 4 h after deep-UV exposure.

To optimize the UV-exposure conditions for single-mode waveguide fabrication with low propagation loss, we focused our experiments on the exposure doses. In our previous study, we found we could achieve a single-mode waveguide from OZ-1100 by deep-UV exposure using the EVG 620, but the propagation loss was 1.5 dB/cm at 1550 nm.[14] This loss was much larger than that of PMMA (0.7 dB/cm). Rück *et al.* have reported PMMA waveguide fabrication from PMMA sheets by refractive-index modification using ion implantation.[15] They showed that low ion doses were required for single-mode waveguides with low loss. To improve the propagation loss of the waveguide, we changed the exposure doses. Figure 1 shows the effective refractive index of OZ-1100 with different exposure doses. So far we exposed the OZ-1100 to a dose of 5 J/cm^2, which results in a refractive-index difference between exposed and unexposed areas of 0.008. In a next step, we used an exposure dose of 3 J/cm^2 for the waveguide fabrication. In this case, the difference of the refractive index between exposed and unexposed areas is 0.005. Figure 2 shows a scanning-electron microscope photograph of a straight waveguide from OZ-1100 fabricated by deep-UV exposure with 3 J/cm^2. The width of the waveguide is 7.5 μm. The waveguide surface, being the exposed area, is slightly condensed, forming a small trench (300 nm deep), but the middle of the surface is relatively flat. This trench was shallower than the waveguide exposed with 5 J/cm^2 (530 nm deep).

OZ-1100 waveguides were analyzed by near-field measurements with the LEPAS-11 laser beam profiler (Hamamatsu Photonics) and an IR camera (Micron Viewer Series 7290, Electrophysics). Figure 3 shows the near-field pattern of a 7.5 μm wide straight waveguide exposed with 3 J/cm^2 and measured at 1550 nm. This photograph shows an asymmetrical single-mode profile.

The propagation loss was measured with a lightwave measurement system (Agilent 8164B) and determined by cutback method. Transmission experiments at 1550 nm were carried out using randomly polarized light (Agilent 11896A polarization controller). For the waveguide exposed with 3 J/cm^2, the propagation loss of the waveguides is found to be 0.8 dB/cm at 1550 nm (1.96 dB for a 0.5 cm waveguide, 2.28 dB for a 1 cm waveguide, and 2.73 dB for a 1.5 cm waveguide). The waveguide shows a polarization-dependent loss less than 0.15 dB. By changing the exposure dose to 3 J/cm^2, we could improve the propagation loss of the waveguide made from OZ-1100 considerably, by a factor of nearly 2. This improvement is attributed mainly to the change in the geometry of the waveguide. The waveguide ex-

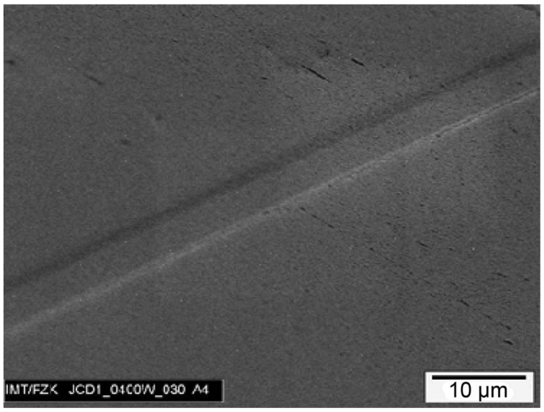

Fig. 2. Scanning-electron microscope photograph of the straight waveguide made from OZ-1100.

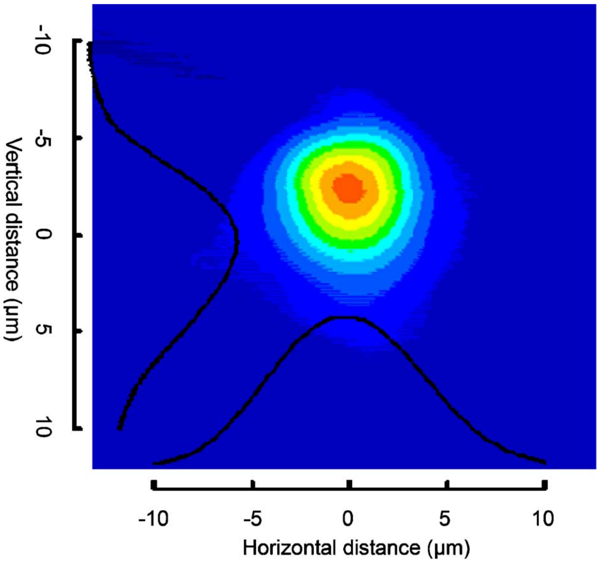

Fig. 3. Near-field photograph of the straight waveguides at 1550 nm.

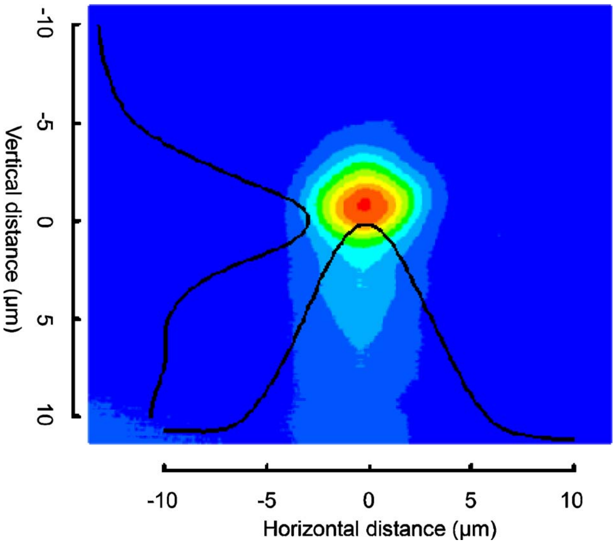

Fig. 4. Near-field photograph of the straight waveguides at 808 nm.

posed with 3 J/cm^2 has a flatter surface than the waveguide exposed with 5 J/cm^2.

Figure 4 shows the near-field pattern of a 7.5 μm wide straight waveguide exposed with 3 J/cm^2 and measured at 808 nm. The DL 100 Diode Laser System (TOPTICA Photonics) was used as a light source. This photograph shows an asymmetrical single-mode profile. For the waveguide exposed with 3 J/cm^2, the propagation loss of the waveguides is found to be 0.6 dB/cm at 808 nm (1.41 dB for a 0.5 cm waveguide, 1.74 dB for a 1 cm waveguide, and 2.05 dB for a 1.5 cm waveguide). This propagation loss at 808 nm is relatively high compared with those of other acrylate polymers. But OZ-1100 contains more C—H bonds than PMMA, and therefore the loss deriving from C—H vibrational overtones at this wavelength is larger.[1,16] These results indicate that a waveguide made from alicyclic methacrylate copolymer can be used for near-IR region sensor applications. We believe that this alicyclic methacrylate copolymer is a promising material for the fabrication of single-mode polymer waveguides by deep-UV exposure. Besides short-distance applications in telecommunication, the fabrication process opens up new applications in the field of sensor technology.

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