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Fabrication of low loss optical waveguides with a novel thermo-optical polymer material

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The newly synthesized polymer, bisphenol A-aldehyde resin (BPA-resin) has many unique thermo-optical characteristics. The polymer has high transparency, relatively high refractive index, low birefringence, and large thermo-optics coefficient at the optical telecommunication wavelengths. Also, the single-mode channel waveguides have been fabricated using BPA-resin polymer. The experimental results show, that the polymer waveguide has a low propagation loss of 0.43 and 0.51 dB/cm at a wavelength of 1.31 and 1.55 μm, respectively, for both TE and TM polarizations. The low polarization dependence loss (PDL) of the waveguide was less than 0.1 dB/cm at above wavelengths, which can be applied in thermal-optical tuned devices.

Keywords: polymeric optical waveguide, thermo-optical polymer, polarization dependence loss, optical telecommunication.

1. Introduction

Polymeric waveguides have attracted a lot of attention in recent years because of their advantages of easy fabrication and low-cost process [1]. So far various polymers have been used as waveguide materials, for example, poly(methylmethacrylate) (PMMA) [2], cholofluorinated polyimides [3], poly(phenylsilsesquioxane) (PPSQ) [4], allied signal optical polymers [5] and fluorinated poly(arylene ethers) (FPAE) [6]. Many kinds of techniques, such as reactive ion etching (RIE) [7], photo-bleaching [8], ion-implantation [2], laser and electron beam direct writing [9], have been exploited to fabricate polymer waveguides. Polymers usually have a relatively low refractive index and large birefringence at the telecommunication wavelengths, which in turn leads to large polarization dependence loss (PDL). In the past, initial efforts were focused on the electro-optic property of polymers. However, for active device applications, large thermal-optic coefficient means reduction in power consumption, and this will further enhance the development of polymeric active devices. Functional polymeric waveguide devices, that have been demonstrated so far, include wavelength filter [6], TM-pass polarizer [8], and thermo -optic switch [10].

In this work, we synthesized a new polymer, BPA-resin, which is a thermo-optical polymer material, and used it to fabricate channel waveguides by photolithography and RIE technique. BPA-resin is expected to have some unique properties, such as a relatively high refractive index, large thermal-optic coefficient, low birefringence and good environmental stability. The experimental results show the novel thermo -optical polymer material is suitable to fabricate a high quality of optical wavegude. Consequently, the polymer waveguides will attract many applications in thermally tuned devices such as thermo-optic switches, which require its response time within the order of milliseconds [11].

2. Experimental results

The molecular structure of BPA-resin is schematically shown in Fig. 1. It was prepared by condensation of 32 g (0.14 mole) of bisphenol A with 33 g (40%, 0.44 mole) of formaldehyde at the presence of 1.8 g (23%) of ammonic aqueous solution. Gentle heating is necessary, and the heating temperature should not exceed 90–95°C. The resulting resin is soluble in alcohol and DMAc, so it is easy to prepare into film. The preparation process has been described in detail in our recent publication [11].

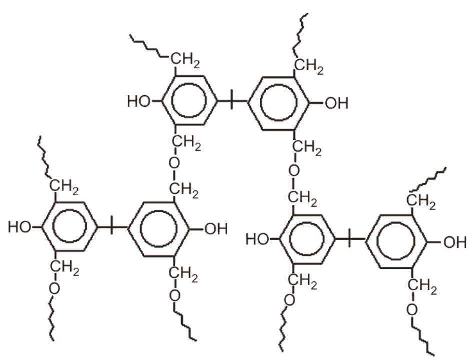


Fig. 1. Chemical structure of BPA-resin molecular.

The absorption spectrum of BPA-resin is shown in Fig. 2, which was measured with a UV/VIS/NIR Spectrometer (Perkin Elmer-Lambda 9) at room temperature. It can be seen that BPA-resin has a strong absorption for wavelength shorter than 400 nm and weak absorption within the ranges of 1110–1250 nm and 1330–1500 nm, respectively. Fortunately, there is no absorption for the communication wavelengths of interest.

In order to get the thermo-optic coefficient of BPA-resin film, it was spin-coated onto a silica wafer followed by thermal curing. The dependence of its refractive

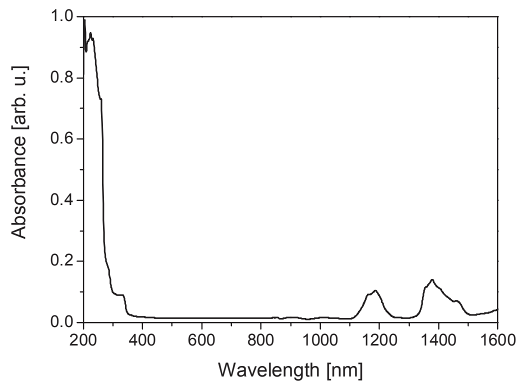


Fig. 2. Linear absorption spectrum of BPA-resin.

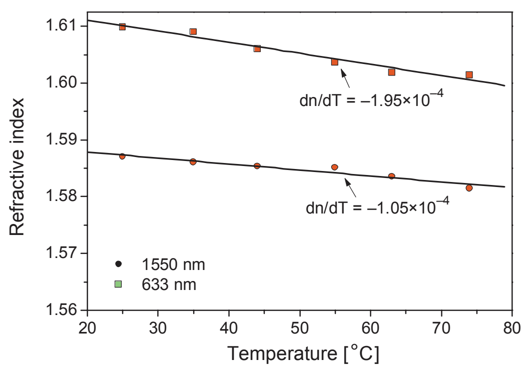


Fig. 3. Temperature dependence of the refractive indices of BPA-resin at the wavelengths $\lambda = 632.8$ nm and $\lambda = 1550$ nm

index on temperature was measured by heating up the sample and monitoring the corresponding change in refractive index using a prism coupler (Metricon 2010) and heat apparatus. Figure 3 shows the variations of the refractive index of BPA-resin film as a function of temperature at the wavelengths $\lambda = 0.633$ μm and $\lambda = 1.55$ μm. The measured value of $\mathrm{d}n/\mathrm{d}T$ is -1×10^{-4}/°C at $\lambda = 1.55$ μm, whose absolute value is by an order of magnitude larger than those of the silica and inorganic glasses (1×10^{-5}/°C) [10], and comparable to those of Allied Signal optical polymers [5] and FPAE [6].

To fabricate single mode waveguides with BPA-resin polymer, Norland Optical Adhesive 61 (NOA61) has been selected as the cladding material because it is stable, and the difference between the refractive index of the cladding and that of the core layers of the waveguide for the TE polarization (Δn_{TE}) is almost the same as that for the TM polarization (Δn_{TM}). This property can be succesfully exploited to satisfy the design requirements of waveguide structures of low PDL. Figure 4 shows the wavelength dependence of the refractive indices of BPA-resin and NOA61. These

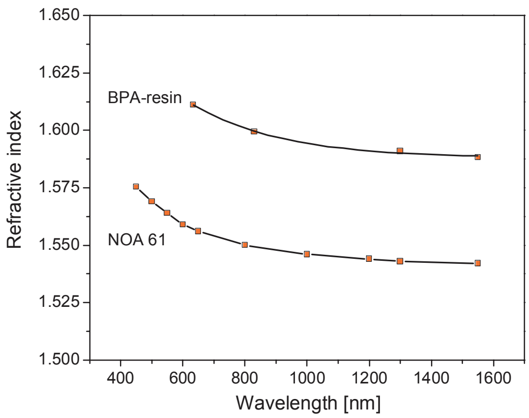
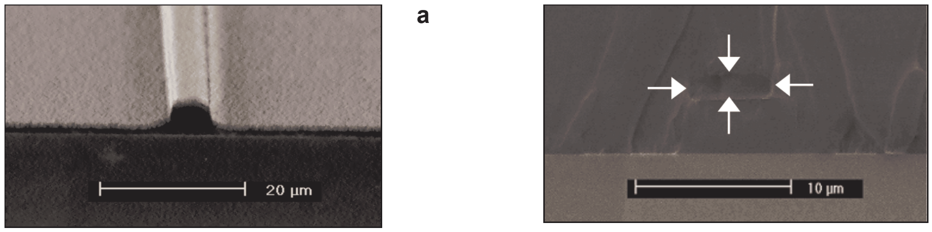


Fig. 4. Refractive indice of BPA-resin and NOA61 as a function of wavelength.

values were measured using planar waveguides and the prism coupling technique. BPA-resin polymer has a relatively high refractive index of 1.59 and there is an index difference $\Delta n = 0.05$ between BPA-resin and NOA61 films at $\lambda = 1.55$ μm, which implies that a thin waveguide layer must be used for the single mode operation. BPA-resin exhibits also a small birefringence, 0.018%, while the index difference between TE and TM mode is 4×10^{-4}. This value is by two orders of magnitude smaller than that of cholofluorinated polyimides [3], one order of magnitude smaller than (PPSQ) [4], and comparable to allied signal optical polymers [5].

The polymeric waveguides were fabricated by spin coating, photolithographic and RIE processes. NOA61 film with 4 μm thickness was initially spin-coated on cleaved silicon substrate as the lower cladding layer, and then cured for 10 min using 350 W UV light ($\lambda = 365$ nm). To further improve the adhesion, the samples were baked at 50°C for 12 hours in a nitrogen-purged furnace. The 2 μm thick BPA-resin polymer was then spin-coated on top of the cured NOA61 film as the core layer of waveguide, and then baked at 50°C for 12 hours to remove the solvent. Photolithographic process was carried out to delineate stripe patterns onto a thin layer of AZ1500 photoresist which was spin-coated on top of the BPA-resin film. The stripe patterns were transferred to BPA-resin by RIE using a mixture of helium and oxygen gases with an optimized ratio of 1:5. The pressure used was 10 mTorr, the power was 120 W, and the etching time was 12 min. Over cladding layers were formed by spin coating another 6 μm thick NOA61 layer on top of the core ridges of BPA-resin. Figure 5**a** shows the scanning electron microscope (SEM) images of the core ridges formed by RIE. The ridge walls have a sharp profile and small wall roughness that imply a better confinement of light in the waveguide and low scattering losses along the waveguide. Figure 5**b** shows the cross section of the waveguide with upper and lower claddings, and the waveguide shape is rectangular of area 6×2 μm^2 which is indicated by the arrows.



b

Fig. 5. SEM images of the cross section of a channel waveguide without upper cladding layer (**a**), and with upper cladding layer (**b**).

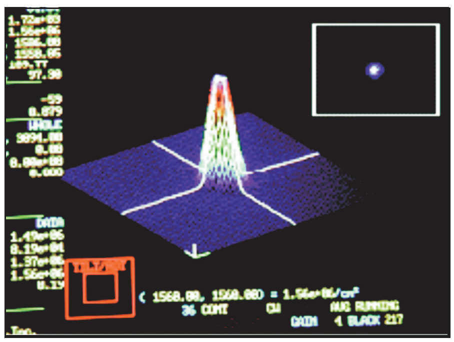


Fig. 6. Measured three-dimensional near-field mode pattern of the channel waveguide at $\lambda = 1.55$ µm by the laser beam analyzer, and the inserted photograph is the mode pattern on the monitor of the CCD camera (Hamamatsu C2741).

The optical characteristics of the waveguides were measured with our planar waveguide test platform. The 1.31 and 1.55 µm stabilized laser diodes were used as light sources, while a 20× object lens for output coupling was applied. Light was coupled into the waveguide through both single-mode fiber and a polarization controller using end-fire technique. The output light intensity was measured with a power meter and recorded by the LBA-100 laser beam analyzer. Figure 6 shows the near-field mode patterns. It is also confirmed that the channel waveguides are of single-mode operation at $\lambda = 1.3$ µm and $\lambda = 1.55$ µm. The propagation loss of the fabricated waveguides was measured by cutback method [12], and a polarizer was added to distinguish the TE and TM modes. Although there is a coupling loss as high as 3 dB between the fiber and waveguide in our experiment, the typical measured values of propagation loss are: 0.43 dB/cm (TE polarization) and 0.35 dB/cm (TM polarization) at $\lambda = 1.31$ µm, 0.51 dB/cm (TE polarization) and 0.45 dB/cm (TM polarization) at $\lambda = 1.55$ µm, respectively. These are determined from the average values of the difference of insertion loss at every waveguide lengths. It is clear that the low propagation losses are due to the good optical merit factor of BPA-resin polymer at these wavelengths. The propagation loss is probably due to the scattering loss caused by irregular boundaries, which vary depending on the fabrication process of the waveguide. It could be reduced with the improvement of fabricating process. According to the above results, the PDL was 0.08 and 0.06 dB/cm at each wavelength, respectively. The PDL is probably caused by the difference in the Δn value for the TE and TM polarizations because the confinements factor depends on the Δn value when the core size is kept constant. Therefore, the low PDL is due to the $\Delta n_{\mathrm{TE}} \approx \Delta n_{\mathrm{TM}}$ for BPA-resin polymer waveguide. It is significantly lower than that of benzocyclobutene (BCB) waveguides [8] being comparable to that of perfluorocyclobutane (PFCB) waveguides [13].

3. Conclusions

Characterization of BPA-resin polymer as an optical waveguide material has been presented. The polymer exhibits high transparency, relatively high refractive index, small birefringence and great thermo-optic coefficient at the optical telecommunication wavelengths. Moreover, the single mode waveguides have been fabricated using BPA-resin polymer and were demonstrated to have low propagation losses and low PDL at $\lambda = 1.31$ μm and $\lambda = 1.55$ μm for both TE and TM polarizations, respectively. Hence, the waveguides fabricated from BPA-resin and NOA 61 could be used as the basic building blocks of low-cost and high-performance thermo-optic devices for practical application.

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