

## Polymer waveguides useful over a very wide wavelength range from the ultraviolet to infrared

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We have designed and fabricated polymer waveguides using the glassy polymers Cytop™ (a fluorinated polyether), PMMA C<sub>6</sub> [poly(methyl methacrylate)], and Cyclotene™ 3022-35 (bisbenzocyclobutane). Since these materials exhibit excellent transparency over a wide wavelength range, and since the refractive index difference of Cytop™ and Cyclotene™ or Cytop™ and PMMA is greater than 0.19, both Cytop™/Cyclotene™/Cytop™ and Cytop™/PMMA/Cytop™ waveguide structures can be employed over a very wide wavelength range from the ultraviolet to the infrared. Efficient waveguiding is achieved for different light sources with 390, 633, 1064, 1310, and 1550 nm wavelengths. © 2000 American Institute of Physics. [S0003-6951(00)01145-1]

A myriad of passive and active guided-wave devices has been successfully demonstrated using polymers. These include high-density linear and curved channel waveguide arrays,<sup>1</sup> electro-optic modulators and modulator arrays,<sup>2</sup> highly multiplexed waveguide holograms for wavelength division demultiplexing and optical interconnects,<sup>3,4</sup> microcavity lasers,<sup>5,6</sup> optical matrix switches,<sup>7</sup> TE–TM mode converters,<sup>8</sup> etc. However, most of these applications make use of the polymer properties in ~600–1550 nm wavelength range. In recent years, great progress has been achieved in the fabrication of blue lasers based on GaN materials.<sup>9</sup> Because of the potential application of blue lasers in optical storage and optical communications, there is increasing interest in studying the integration of semiconductor-based light sources with different wavelengths for the realization of full-color displays and advanced printing applications. While traditional III–V semiconductor materials such as GaAs, InP, and related compounds cannot be used to fabricate waveguides for blue wavelengths due to band-gap limitations, the use of the polymer waveguides for ultraviolet wavelength applications is attractive, but virtually unexplored. It is, therefore, necessary to design, fabricate, and characterize polymer waveguides which can be employed in the blue-light wavelengths for full-color integration. If suitable polymeric materials can be developed for fabricating waveguides operable over a very wide wavelength range from the ultraviolet to the infrared, this will considerably enhance the efficiency and economy of the design and fabrication of such waveguides.

In this letter, we report the design and fabrication of a waveguide geometry in which polymers are used to form both guiding and cladding layers. We show that such waveguides can be employed over a very wide wavelength range, and that such structures are promising for short-

wavelength interconnects as well as for full-color or very wide wavelength integration.

The device structure is shown schematically in Fig. 1 and has a triple-layer stack geometry. The commercially available polymer Cytop™ (a fluorinated polyether) was used for the cladding layers. This polymer has a relatively low refractive index and high optical transparency. In addition, it also has excellent chemical, thermal, electrical, and surface properties. PMMA C<sub>6</sub> [poly(methyl methacrylate)] or Cyclotene™ 3022-35 (bisbenzocyclobutane) having high refractive indices were used as the guiding layer. All three polymer layers were spin coated onto a Si substrate. The spinning speed and concentrations of the polymer solutions were calibrated for the desired film thickness. In our fabrication processes, the spinning conditions were adjusted for a cladding layer thickness of ~3 μm, and guiding layer thickness of ~2 μm. To form uniform films, each layer was

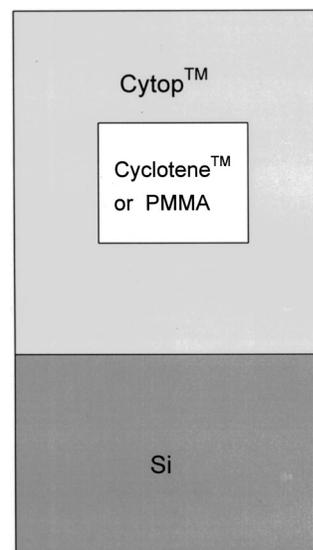


FIG. 1. Schematic cross section of the polymer waveguide.

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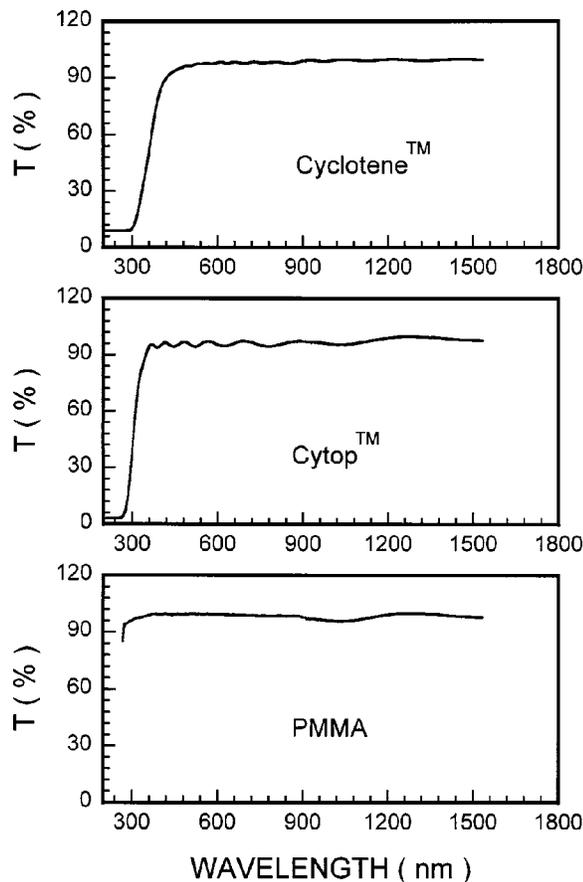


FIG. 2. Room-temperature transmission spectra of the waveguide polymer components, Cyclotene<sup>TM</sup>, Cytop<sup>TM</sup>, and PMMA.

baked in an oven after spin coating. Photolithography and reactive ion etching (RIE) were used for the fabrication of the waveguide. After the channel waveguide patterns were formed by conventional photolithography,  $\text{CF}_4$ , Ar, and  $\text{O}_2$  RIE procedures were carried out to form the waveguide structure. In order to protect the waveguide from moisture, dust, or other physical damage, and to improve the long-term stability, the addition of a cladding layer is essential.

For acceptable waveguiding in a wide wavelength range, the materials of the guiding and cladding layers should be transparent in the desired wavelength ranges, and the refractive-index difference between the guiding and cladding layers should also be large enough to confine most of the light within the guiding layer. Figure 2 shows the transmission spectra of individual Cytop<sup>TM</sup>, Cyclotene<sup>TM</sup>, and PMMA films with thicknesses over  $\sim 1.5$   $\mu\text{m}$ . From 350 to 1550 nm, Cytop<sup>TM</sup> exhibits excellent transparency. PMMA has better transparency in the shorter-wavelength range than Cyclotene<sup>TM</sup>. While, Cyclotene<sup>TM</sup> also exhibits good transparency from 390 to 1550 nm. We have used the following steps to determine the refractive indices of Cytop<sup>TM</sup>, PMMA, and Cyclotene<sup>TM</sup> films as a function of wavelength. First, the refractive indices and thicknesses of the films were accurately measured at a 633 nm wavelength with a prism coupler (Metricon 2010). With the reference data at 633 nm, a Fimetrics F50 advanced thin-film measurement system was then employed to measure the refractive indices of the films as a function of wavelength from 390 to 1700 nm. Specifically, in the Fimetrics F50 measurement, light reflected from

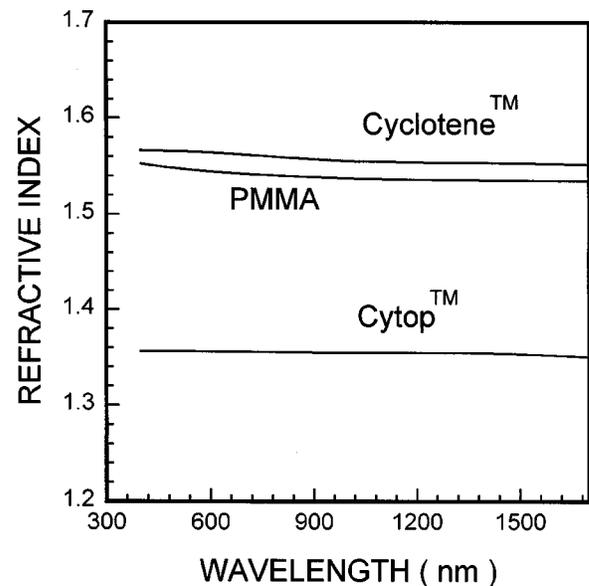


FIG. 3. Wavelength dependence of the refractive indices of Cyclotene<sup>TM</sup>, PMMA, and Cytop<sup>TM</sup>.

the top and bottom interfaces of the films produced characteristic intensity oscillations in the reflective spectra. The results were analyzed with computer simulation routines to calculate the wavelength dependence of refractive indices. The measurement precision is better than 1%, and the results are plotted in Fig. 3.

The refractive-index difference of Cytop<sup>TM</sup> and Cyclotene<sup>TM</sup> is greater than 0.2 in the 400–2200 nm wavelength range. The refractive index of Cyclotene<sup>TM</sup> is larger than that of PMMA, and decreases slightly with increasing wavelength, which is similar to those of Cytop<sup>TM</sup> and PMMA. The refractive-index difference of Cytop<sup>TM</sup> and PMMA remains larger than  $\sim 0.19$  in the 400–2200-nm-wavelength range. All of these data indicate that both Cytop<sup>TM</sup>/Cyclotene<sup>TM</sup>/Cytop<sup>TM</sup> and Cytop<sup>TM</sup>/PMMA/Cytop<sup>TM</sup> geometries are potentially excellent structures from which to fabricate waveguides for use in the very wide wavelength range from the ultraviolet to infrared.

Generally, the method of measuring waveguide loss is to focus light of the desired wavelength directly onto a polished or cleaved input face of a waveguide; then measure the total power transmitted. The measurement is normally repeated for a relatively large number of waveguide samples having different lengths. In our case, since the top cladding layer is Cytop<sup>TM</sup>, which is transparent, it is most convenient to measure the light intensity along the waveguide from the top of the sample. In the present study, a 633 nm light source was directed into the waveguide and a vidicon camera used to take images of the waveguide from the sample top. The change of the image intensity was measured versus the length of the waveguide. The results are shown in Fig. 4 for different waveguide structures A: Cytop<sup>TM</sup>/Cyclotene<sup>TM</sup>/Cytop<sup>TM</sup>, and B: Cytop<sup>TM</sup>/PMMA/Cytop<sup>TM</sup> with a core size of  $2.0 \mu\text{m} \times 5.0 \mu\text{m}$ . The propagation losses of the straight waveguides were determined from Fig. 4 to be 0.51 and 0.65 dB/cm for Cytop<sup>TM</sup>/Cyclotene<sup>TM</sup>/Cytop<sup>TM</sup> and Cytop<sup>TM</sup>/PMMA/Cytop<sup>TM</sup> structures, respectively. To reduce the influence of the nonlinear sensitivity of the vidicon camera on

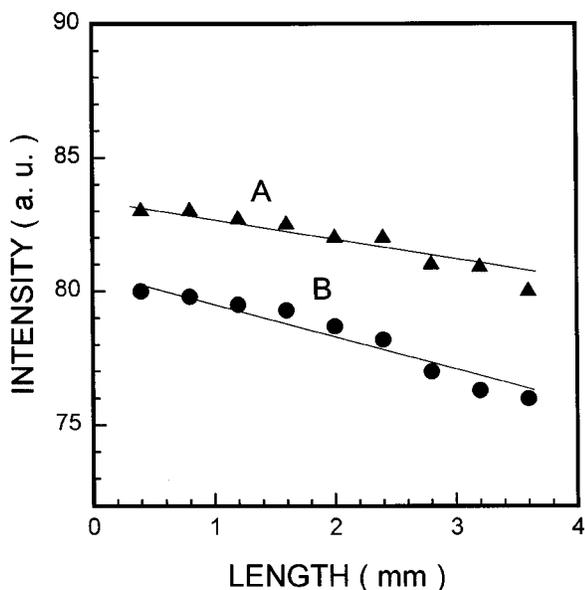


FIG. 4. Measured image intensity as a function of waveguide length for different waveguide structures A: Cytop<sup>TM</sup>/Cyclotene<sup>TM</sup>/Cytop<sup>TM</sup>, and B: Cytop<sup>TM</sup>/PMMA/Cytop<sup>TM</sup>.

the measurement results, the data were only taken over a small range along the waveguide. In that range, the vidicon camera response is linear.

To determine the wavelength dependence of loss, light beams with wavelengths of 390, 633, 1064, 1310, and 1550 nm were coupled through the waveguides, respectively. The input and output powers of the waveguides were measured for different light sources. It is found that the ratio of the output to input power increases with increasing wavelengths. The loss at 390 nm is approximately three times that at 1550 nm. This result shows that the scattering loss probably plays a dominant role in determining the propagation loss of the waveguides. We find that the surface scattering due to sidewall roughness (vertical striations) is the most significant

contribution to the propagation loss in the waveguides.

The refractive-index difference of Cyclotene<sup>TM</sup> and PMMA is about  $\sim 0.02$ . Therefore, it is also possible to fabricate waveguides using PMMA/Cyclotene<sup>TM</sup>/PMMA geometry with a relatively thicker guiding layer.

In summary, the wide transparency wavelength ranges of Cytop<sup>TM</sup>, Cyclotene<sup>TM</sup>, and PMMA, combined the large refractive-index differences between Cytop<sup>TM</sup> and Cyclotene<sup>TM</sup> or Cytop<sup>TM</sup> and PMMA allows the fabrication of Cytop<sup>TM</sup>/Cyclotene<sup>TM</sup>/Cytop<sup>TM</sup> or Cytop<sup>TM</sup>/PMMA/Cytop<sup>TM</sup> waveguide structures, which can be employed over a very wide wavelength range from the ultraviolet to infrared. We have demonstrated the fabrication of the waveguide structures Cytop<sup>TM</sup>/Cyclotene<sup>TM</sup>/Cytop<sup>TM</sup> and Cytop<sup>TM</sup>/PMMA/Cytop<sup>TM</sup> with propagation losses of 0.51 and 0.65 dB/cm at a 633 nm wavelength. This waveguide is, therefore, a good candidate for use in full-color or very wide wavelength optical integration.

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