Low-Loss, Single-Mode, Organic Polymer Waveguides Utilizing Refractive Index Tailoring

Christopher W. Phelps, Timothy S. Barry, Daniel L. Rode, and Robert R. Krchnavek, Member, IEEE

Abstract—Low-loss, single-mode optical waveguides have been fabricated from photopolymerizable acrylic monomers. The material system consists of a low-index cladding resin and a high-index core resin. The two resins are miscible so that precise control over the refractive index can be obtained. This allows the fabrication of single-mode waveguides with specific cross-sectional dimensions. One advantage of this is the ability to fabricate waveguides with high coupling efficiencies to other devices such as optical fiber or semiconductor lasers. The materials adhere to a wide variety of substrates and exhibit average waveguide losses of 0.56 dB/cm at 1300 nm for single-mode waveguides. Details of the fabrication procedure, index of refraction tailoring technique, and waveguide loss data are presented.

Index Terms—Polymers, single-mode, waveguides.

I. INTRODUCTION

Increasing clock speed in integrated circuits (IC’s) has begun to stress chip-to-chip interconnects and has initiated considerable research in the area of optical interconnects. The use of photonics to solve interconnect problems is based on the immense bandwidth available in optical systems for the transmission of information. One promising method for optical interconnection is the channel or ridge waveguide [1]–[6]. The photo-patternable materials discussed in this paper can be processed onto a variety of board materials with the ease of photoresist, yet can be developed in acetone with no requirement for plasma or reactive-ion etching. They are also durable, capable of withstanding the etching steps and temperatures involved in board fabrication, and have low optical losses at wavelengths of interest. In addition, they have the important advantage that the refractive index can be tailored to achieve a specific mode-field diameter thereby maximizing coupling efficiency.

In this paper, we provide details on the fabrication and characterization of the single-mode waveguides optimized for high coupling efficiency to single-mode fiber. The coupling experiments are published elsewhere [7], [13]. [9] who used them to fabricate low-loss multimode optical ridge waveguides. These mixtures consist of resin, diluent, and photoinitiator.1 The two primary resins, Ebecryl 600 and Ebacryl 4883, are a high-index epoxy diacrylate and a low-index aliphatic urethane diacrylate, respectively. A low-viscosity propoxylated glycerol triacrylate, OTA 480, serves as the diluent. Irgacure 184, a highly efficient and nonyellowing phenyl ketone, is the photoinitiator. The nominal mixtures of the monomers, diluent, and photoinitiator as well as the measured refractive indexes, glass transition temperatures (Tg) and maximum temperatures before the onset of decomposition (Tm) are shown in Table I. Note, the formulations in Table I will be slightly modified to fabricate the single-mode waveguides described in this paper. The major differences are an increased diluent (OTA 480) and photoinitiator (Irgacure 184) for the core resin. The diluent has been increased to lower the viscosity which lowers the spin-on thickness of the core resin, consistent with the smaller dimensions of single-mode waveguides. The photoinitiator of the core resin has been increased to counter the effects of oxygen inhibition [10].

The acrylic polymers resulting from these mixtures are highly cross-linked as evidenced by dynamic mechanical analysis [9]. Therefore, when heated above their respective glass transition temperatures, the waveguides maintain their proper shape.

Fig. 1 contains the absorption spectrum of the low-index cladding material (see Table I). The modified, low-viscosity, high-index core material used for the single-mode waveguides has a nearly identical spectrum. These spectra suggest that the bulk acrylic polymer is low-loss in the visible range of the spectrum as well as at 1300 nm. However, at 1550 nm, the absorption increases to approximately 1.5 times the value at 1300 nm.

B. Waveguide Fabrication

To propagate a single mode, further restrictions on the refractive index difference with respect to the physical size (cross-section) of the dielectric waveguide are required. Therefore, the waveguide fabrication must consist of precise control over the physical dimensions as well as precise control over the refractive indexes of the core and cladding layers.

Silicon wafers (75 and 100 mm diameter) were chosen as the substrate material for our waveguide samples. An adhesion promoter, 3-aminopropyltriethoxysilane (3-APS), was spun on 1Ebecryl 600, Ebecryl 4883, and OTA 480 are supplied by Radcure, 131 Revco Rd., N. Augusta, South Carolina 29841. Irgacure 184 is supplied by Ciba-Geigy, Additives Division, 7 Skyline Dr. Hawthorne, New York 10532.

1900 JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 15, NO. 9, SEPTEMBER 1997

Manuscript received July 10, 1996. This work was supported by the Rome Laboratory, Griffiss Air Force Base, Rome, NY. The authors are with the Department of Electrical Engineering, Washington University, St. Louis, MO 63130 USA (E-mail: rrk@ee.wustl.edu).

Publisher Item Identifier S 0733–8724(97)06659-0.
Fig. 1. Absorption spectrum for a bulk sample of the low-index cladding resin shown in Table I. The sample was 8 mm thick, photopolymerized with a 4 min ultraviolet lamp exposure. The core material has a nearly identical spectrum.

Table I

<table>
<thead>
<tr>
<th>Commercial Name</th>
<th>Chemical Name</th>
<th>wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebecryl 600</td>
<td>epoxy diacylate</td>
<td>69.3</td>
</tr>
<tr>
<td>OTA 480</td>
<td>propoxylated glycerol triacrylate</td>
<td>29.7</td>
</tr>
<tr>
<td>Irgacure 184</td>
<td>1-hydroxycyclohexyl phenyl ketone</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Low-Index Resin Formulation for Cladding

Table II

<table>
<thead>
<tr>
<th>Commercial Name</th>
<th>Chemical Name</th>
<th>wt. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebecryl 4883</td>
<td>urethane diacrylate</td>
<td>58.9</td>
</tr>
<tr>
<td>tripropylene glycol diacrylate</td>
<td>10.4</td>
<td></td>
</tr>
<tr>
<td>OTA 480</td>
<td>propoxylated glycerol triacrylate</td>
<td>29.7</td>
</tr>
<tr>
<td>Irgacure 184</td>
<td>1-hydroxycyclohexyl phenyl ketone</td>
<td>1.0</td>
</tr>
</tbody>
</table>

After cleaning to ensure adhesion that would withstand a cellophane-tape pull.

The bottom cladding layer is prepared as follows. After cleaning the silicon substrate and spinning on the 3-APS, the low-index cladding monomer is spun onto the wafer at 2500 rpm for 90 sec. The monomer is then exposed to ultraviolet light using a 1000W HgXe lamp (435 mW/cm²) for approximately 2 min, in a nitrogen ambient. The nitrogen atmosphere prevents an oxygen inhibition reaction from causing slow polymerization in a thin layer (≈1 to 5 μm) at the surface of the monomer [9]. After exposure, the sample is rinsed with acetone to remove any uncured resin.

The core layer is processed in a similar manner. A proximity mask is used to pattern the core layer. To facilitate spinning on a thin (≈7.5 μm) core layer, the diluent (OTA 480) was increased to 50%. In addition, the photoinitiator concentration was increased to 3% to overcome the affects of oxygen inhibition. The modified core resin consisted of (wt.%): Ebecryl 600—47%, OTA 480—50%, Irgacure 184—3%.

Fig. 2. (a) Photomicrograph of the cleaved endface of a ridge waveguide. This structure consists of a bottom polymer cladding layer, a mask-patterned polymer core layer, and an air uppercladding layer. The substrate is silicon. The waveguide is approximately 10 μm across, while the cladding layer is approximately 40 μm thick. (b) Photomicrograph of the cleaved endface of a buried waveguide. This structure consists of a core polymer region surrounded by a polymer cladding region. The dimensions are similar to the ridge waveguide. The photograph was taken while white light was launched into the waveguide.

C. Refractive Index Tailoring

High efficient coupling between waveguides and other devices (lasers, fibers, etc.) requires matching both the physical aperture and the numerical aperture. The physical aperture is controlled by the fabrication process. The numerical aperture is determined by the refractive indexes of the core and cladding materials. The acrylic polymers used in this work demonstrate...
considerable flexibility in this regard due to the fact that their indexes can be tailored over a relatively wide range (1.494–1.549).

Control of the refractive index is simply achieved. The high- and low-index mixtures shown in Table I serve as base mixtures. Nakagawa [8], [9] determined their indexes experimentally to be 1.549 and 1.494 respectively. By combining these two base mixtures together in different proportions, polymers with indexes ranging between 1.549 and 1.494 are obtained. Nakagawa showed experimentally that the relationship between mixing proportion (by weight) and refractive index was linear (see Fig. 3). The significance of this is that we can calculate a range of normalized frequencies, or $V$-numbers, for this material system. Assuming a core radius of 5 $\mu$m and a wavelength of 1300 nm, and further assuming that the minimum reliable $\Delta n$ that can be mixed is 0.002, the range of $V$-numbers in this material system is $1.87 \leq V \leq 0.89$. While this approximation is for a cylindrical fiber, and the actual waveguides are neither cylindrical nor square, this approximate $V$-number can be used to estimate cutoff conditions, mode-field diameter, and bending losses.

### D. Waveguide Loss Measurements

The bulk material absorption spectrum (Fig. 1) gives only an approximate idea of what the optical losses might be in a waveguide, and must be accompanied by a traditional cutback measurement. This technique involves measuring the power transmitted through a waveguide after each of a series of sample cleaves. The resulting data are a measure of power lost as a function of waveguide length. This method was chosen for its reliability and accuracy, even though it results in the destruction of the sample.

For the purposes of this work we investigated waveguide losses at only 1300 nm. The optical source was an unpackaged 1300 nm laser diode focused through a lens onto the core of a single-mode optical fiber. We typically ran the laser diode at 30 mA, producing approximately 2 mW of infrared light in the fiber. Power out of the sample waveguides was measured with a Fotec M200 fiber-optic power meter. The sample was secured on a machined aluminum vacuum chuck, which was mounted on a rotating stage to provide alignment flexibility. We launched light into and collected light from the sample waveguides with single-mode optical fiber held in fiber positioners. The positioners allowed fine adjustment of the pitch and yaw as well as $x$, $y$, and $z$ positions of the fibers. Each fiber endface was polished. To minimize damage to the waveguides, measurements were carried out while keeping the input and output fiber endfaces approximately 5 $\mu$m from the waveguide interface.

Each sample contained several waveguides approximately 6 cm in length, separated by 1 mm. Prior to the initial
measurement, both the input and output ends were cleaved. For each subsequent measurement 8–10 mm was cleaved off the output end while the input end was left untouched. The final sample length was always greater than 1 cm to minimize measuring regions expected to show significant mode stripping if any higher-order modes were coupled into the waveguide. The cleaving procedure involved applying a scratch with a diamond scribe on the edge of the sample, through the polymer layers to the silicon substrate, and then applying tension to the polymer and silicon until it snapped.

III. RESULTS AND DISCUSSION

Cutback measurements were performed on both ridge (air cladding on three sides) and buried waveguides. The results of the cutback measurements are shown in Fig. 4 (ridge waveguides) and Fig. 5 (buried waveguides). The horizontal axis is the length of the waveguide in cm while the vertical axis is the insertion loss in dB. The insertion loss includes coupling losses (Fresnel reflections, alignment errors, physical and numerical aperture differences) and waveguides losses (absorption losses, scattering losses, and any radiation mode stripping). Extrapolating the experimental data to the y-intercept, corresponding to a waveguide length of 0 cm, gives the coupling loss for the measurement. The slope of the experimental data gives the waveguide losses. Fitting the data to a straight line gives both the waveguide losses (slope) and the coupling losses (y-intercept).

The results for the ridge waveguides (Fig. 4) indicate a waveguide loss of 1.56 dB/cm and a coupling loss of 21.6 dB. The enormous coupling loss has been attributed to the quality of the endface. Without a polymer cladding layer on three sides of the waveguide, the ridge waveguides appear to cleave roughly, leaving a damaged waveguide endface. This in turn can significantly increase scattering losses at the coupling interface. Comparing the ridge waveguide data with similar data obtained for the buried waveguides (Fig. 5), we see that the buried waveguides have a coupling loss of 0.74 dB and a waveguide loss of 0.56 dB/cm. The polymer cladding layers on all four sides of the core region produced a well-controlled, smooth endface during cleaving. In comparing the
waveguide losses, we note that the buried waveguides show significantly less loss than the ridge waveguides (0.56 dB/cm versus 1.56 dB/cm). The increase in loss may be due to the ridge waveguides being multimode in the horizontal direction because of the large index difference of the air/core interface ($\Delta n \approx 0.497$). Under multimode operation, higher order modes will concentrate more of their energy at the air/core interface. Surface roughness will scatter energy from these higher order modes into leaky and radiation modes and thus increase the loss. The effect is further increased by the larger $\Delta n$ at these scattering centers. Regarding the coupling losses, this number could be further reduced to less than 0.2 dB by using index matching fluid [11], [13].

A brief analysis of the output of a buried waveguide was conducted in order to determine experimentally the difference in index between the core and cladding, and to verify that the waveguide was operating single-mode. The work was accomplished using an infrared imaging system. Images were collected from just inside the waveguide (ahead of the cleaved endface) and from a ground-glass plate placed at 5 and 10 mm away from the waveguide endface. Fig. 6 comprises grayscale intensity plots at these three positions. If we assume that the square waveguide can be approximated by a circular waveguide, then one can calculate $\Delta n$ from the measured numerical aperture (NA). This measurement indicates that the NA = 0.082 which corresponds to a $\Delta n$ of 0.002—in good agreement with the design value of $\Delta n \approx 0.003$. The cutoff wavelength for this waveguide is calculated to be 1070 nm. The concentration of the high-index resin in the core formulation could be increased to raise $\Delta n$ to 0.003. This would result in a more strongly guiding waveguide and allow for smaller turning radii and exhibit less coupling to other waveguide structures or the surface.

A further analysis of the output of the waveguide is shown in Fig. 7. The image formed on the ground glass plate located 5 mm away from the waveguide endface [Fig. 6(b)], shows a fit to a Gaussian curve. This further suggests the single-mode nature of these waveguides at 1300 nm.

IV. SUMMARY

Using proximity masking and ultraviolet laser scanning, we have fabricated low-loss single-mode waveguides with acrylic polymers. Loss measurements indicate that single-mode, buried waveguides can be fabricated with internal losses less than 0.56 dB/cm at 1300 nm. Measurements are presented confirming that these waveguides are single-mode at that wavelength. Comparison to loss measurements involving ridge waveguides with single-mode dimensions indicate that the presence of a top cladding layer significantly decreases losses due to surface scattering.

The versatility of these commercially available, photo-polymerizable, spin-on polymers hinges on the ability to tailor their indexes of refraction. We have described the tailoring method, and have demonstrated its use in the fabrication of single-mode waveguides which require a difference in index of refraction between the cladding and the core of approximately 0.003. Previous work has also shown that these acrylic polymers are highly cross-linked and suitable for use in a variety of optical interconnect applications [8].

ACKNOWLEDGMENT

The authors would like to thank R. D. Esman at the Naval Research Laboratory and A. Chin at Polaroid for providing laser diodes. The authors would also like to thank Radcure and Ciba-Geigy for supplying polymer materials and D. Crippa of MEMC Electronic Materials for supplying silicon substrates.

REFERENCES

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Daniel L. Rode, photograph and biography not available at the time of publication.

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