The Fabrication and Characterization of Polymer Optical Conductors

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Synopsis

Polymer microstructures were evaluated as thin film optical conductors. The polymer waveguides were fabricated from a photosensitive silicone polymer by selectively crosslinking the polymer with the near-ultraviolet radiation from an argon ion laser. The optical transmittance properties of curved and linear microstructures were characterized using an optical sensing technique. For the curved guides, an exponential decay in the intensity of transmitted light with guide length was observed. The linear guides exhibited an oscillatory relationship between output intensity and length over a range of 2 mm in length. The nature of the results for the linear guides was explained by considering the variations in the refractive index across the polymer microstructure and by comparison with the optical behavior of graded-index glass fibers.

INTRODUCTION

Integrated optics involves the development of thin film optical devices and circuits to enhance and broaden microelectronics technology and to process signals transmitted by glass fibers in optical communication systems. Because of their versatility, ease of processing, and compatibility with existing fabrication techniques, polymers may have wide applications as active or passive optical devices. The compatibility with existing microelectronics fabrication technology means that the polymer microstructures could serve a dual role as resists for electronic circuit fabrication and as optical devices on a single substrate.

Initial work on optical waveguides used sputtered ZnO and vacuum evaporated ZnS films.[1] Later, glass films were developed by Goell,[2] and attention then turned to organic and inorganic polymeric films. Waveguides were fabricated from polyurethane and polyester epoxy films by Harris et al.,[3] Ta_2O_5 films by Hensler et al.,[4] Kodak Photoresist films by Ulrich and Weber,[5] and organosilicon films by Tien et al.[6] Other devices such as directional couplers and dye lasers[8,9] have been developed and demonstrated.

The primary objective of this study was to fabricate and characterize optical conductors based on polysiloxane materials. The polymer microstructures consisted of curved and linear waveguides fabricated by a laser lithographic technique.[10,11] This processing technique, which is adaptable to a wide range of materials, was used to produce geometrically complex microstructures on glass and silicon substrates.

The optical transmittance properties of the waveguides were investigated. A fiber optic sensing method was employed to measure the on-axis intensity of both polymer and glass waveguides.

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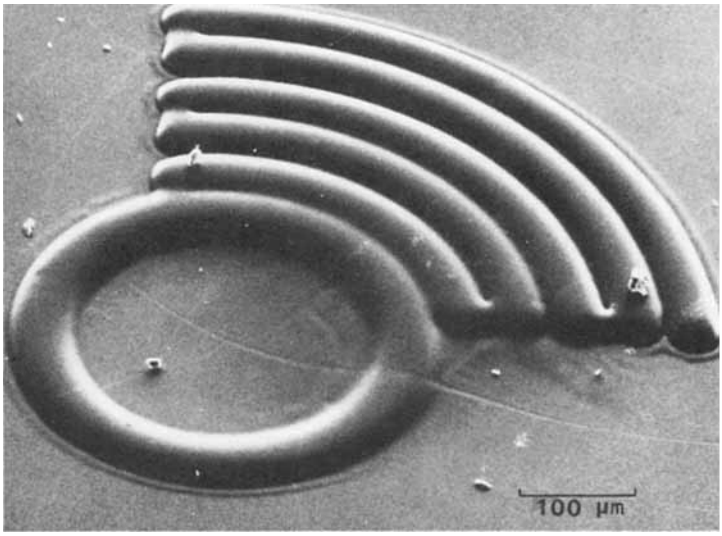

Fig. 1. Polymer microstructure produced by the laser lithography of a silicone polymer.

EXPERIMENTAL

Fabrication. Polymer microstructures were prepared from a photocrosslinkable silicone polymer supplied by the Dow Corning Corporation, Midland, Mich. The polymer was a two-part system consisting of a mercapto-functional siloxane copolymer and a vinyl-functional siloxane fluid. Benzophenone was used as the photosensitizer.

Glass and silicon wafers were employed as substrates for device fabrication. Prior to metalization, the wafers underwent a rigorous cleaning procedure.[7] Aluminum was vapor deposited onto the substrates, and a thin film of the polymer solution was then spun onto the metallized wafer. The substrate was inserted into the laser lithography system,[10] exposed to the 351.1–363.8 nm band from an argon ion laser for 2.5–5 ms, developed with hexane, and etched in an

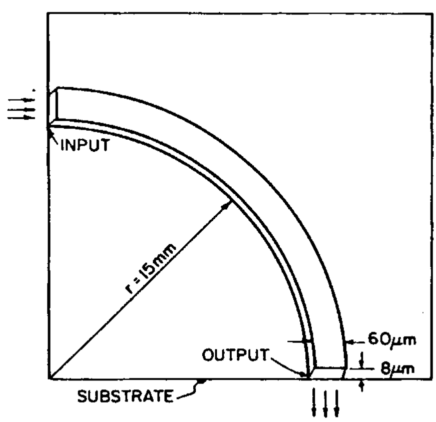

Fig. 2. Diagram of curved optical waveguide.

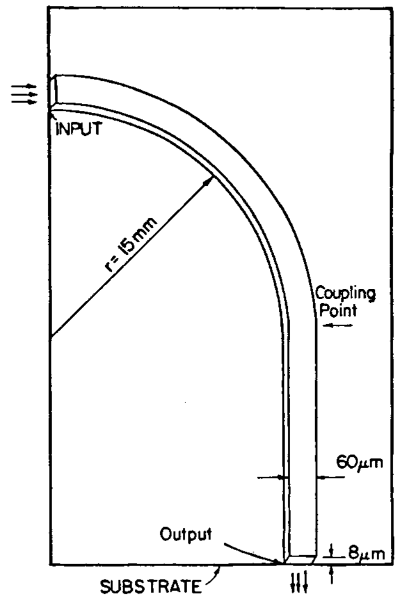

Fig. 3. Diagram of linear optical waveguide. The curved section acts as a coupler to the linear guide.

acid bath. Structure dimensions were 3–60 μm in width, 5–8 μm in thickness, and 3 cm in length. An example of the complex microstructure that can be prepared with the technology is illustrated in Figure 1.

The curved and linear waveguides prepared by this technique are shown schematically in Figures 2 and 3. Sets of curved waveguides of varying widths and radii of curvature were fabricated on the substrates whereas the linear guides consisted of linear microstructures connected to curvilinear guides. The width for all the guides on any given substrate was constant at 50 or 60 μm. These exceptionally broad structures were fabricated by making multiple passes with the laser beam.

Characterization of Optical Transmittance. The polymeric microdevices were characterized by determining the absorption spectra in the visible range, the refractive indices, and the transmission losses as optical conductors. The absorption and refractive index measurements were performed on bulk samples for various degrees of crosslinking or exposure times. Transmission losses were evaluated by measuring the intensity of light as a function of the length of the device using a photodiode or a photomultiplier.

Curved waveguides were characterized for their optical transmittance with 632 nm light from a HeNe laser. Light from the source was coupled into the device with a microscope lens, and the output intensity was detected with a photodiode. Data on the output intensities were collected for guides of different lengths on a given substrate. Knowing the guide lengths and the output intensities, the transmission losses per unit length could be determined for guides of various widths.

Linear guides, shown in Figure 3, were also characterized by measuring the on-axis intensity as a function of the device length by successively cleaving the guide. Two new ideas were tried here. First, light was coupled directly into the

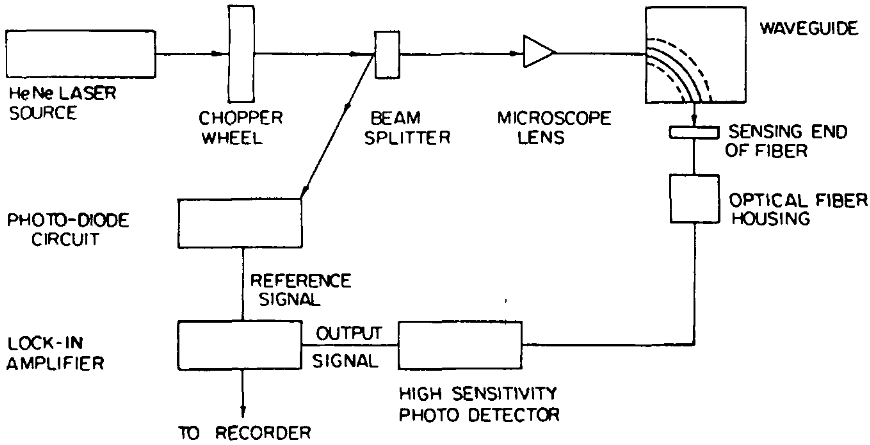

Fig. 4. Loss determination apparatus employing fiber optic sensing.

linear device using a curved waveguide. This was done to demonstrate the feasibility of direct coupling and also to minimize the amount of scattered light entering the detector directly from the source.

Second, the techniques of fiber optic sensing was employed to measure the on-axis intensity of the waveguide. The experimental apparatus is shown in Figure 4. The optical fiber was scanned across the guide output in the plane of the substrate; the light intensity sensed by the fiber was transmitted to a high sensitivity photodetector whose output was fed to a lock-in amplifier. The lock-in amplifier had two inputs, a reference signal from the photodiode and the signal from the high sensitivity detector. The lock-in amplifier selectively amplified only those parts of the detector signal synchronous with the reference

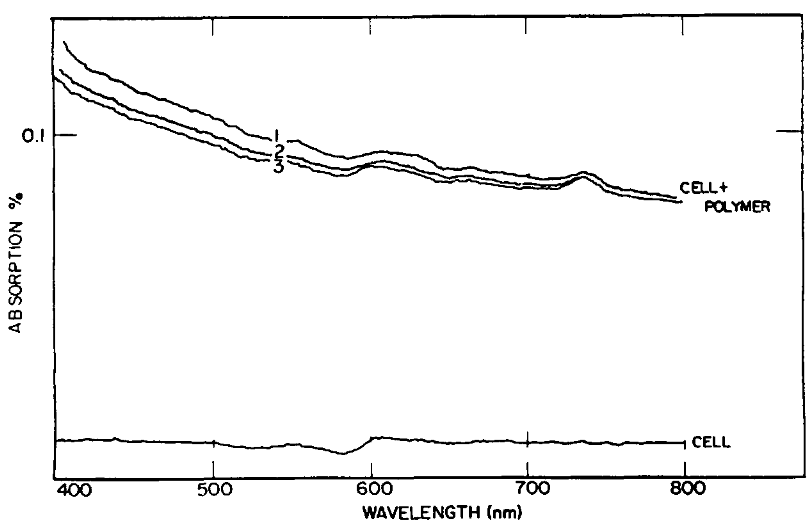

Fig. 5. Absorption spectra of bulk polymer samples: (1) uncrosslinked; (2) exposure for 3 min; (3) exposure for 5 min.

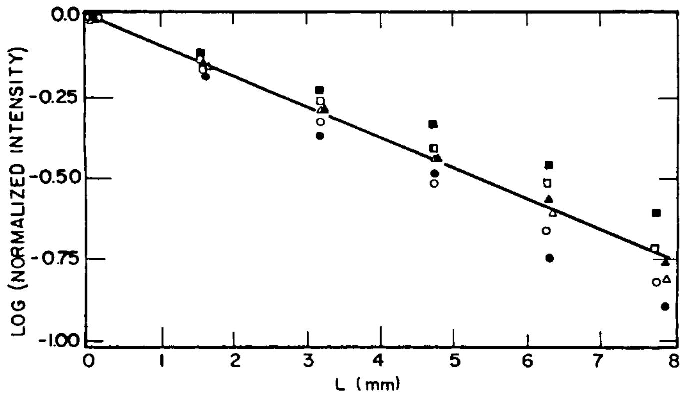

Fig. 6. Optical transmission data for curved polymer waveguides with 632 nm radiation: (△, ▲, ■) guides width, 50 μm; (●, ○, □) guide width 60 μm. The line represents the data fitted to eq. (2).

signal. This greatly reduced the effect of stray light on the measurements. The intensity sensed by the fiber as a function of position was recorded on the chart recorder. The intensity at any axial point was then found by measuring the height of the peak produced on the recorder output.

The optical properties of the linear guides were investigated with 632 nm radiation from a HeNe laser and with white light. An unclad graded-index glass fiber (Corning Glass Works, No. 2560D) was also characterized for the on-axis transmission losses using coherent (632 nm) and incoherent (white light) illumination to demonstrate the reliability of the new sensing technique.

RESULTS AND DISCUSSION

The absorption spectra of the bulk polymer system for different exposure times over a wavelength range of 400–800 nm are shown in Figure 5. The data indicate relatively low absorption losses in the polymer.

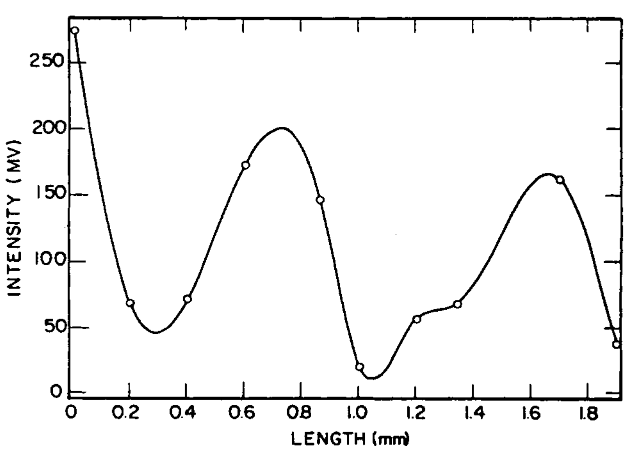

Fig. 7. Optical transmission data for a linear polymer guide characterized with 632 nm radiation.

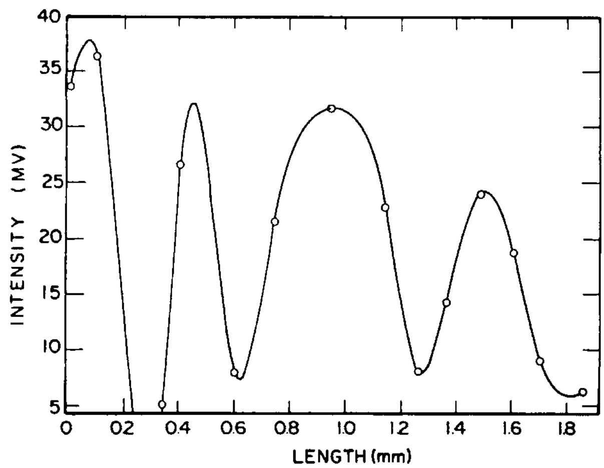

Fig. 8. Optical transmission data for a linear polymer guide characterized with white light.

For the curved waveguides, transmittance measurements were conducted on six sets of waveguides. Each set consisted of six waveguides of constant width with lengths ranging from approximately 1.5 to 2.3 cm on a single substrate. In order to account for differences in the input intensities between substrates, the data were normalized by defining the normalized intensity, NI, as the ratio of the output intensity of the guide to the output intensity of the shortest guide on that particular substrate and the length, L, as the difference between the length of the guide and the length of the shortest guide on the substrate. Figure 6 is a plot of log (normalized intensity) versus L for six different substrates.

The data indicate an exponential decay in intensity with length. An equation of the form[12,13]

$$I = I_0 \exp(-2xl) \quad (1)$$

or, in terms of the normalized parameters,

$$\mathrm{NI} = \exp(-2xL) \quad (2)$$

describes the results, where I and I_0 are the output and the input intensities, l is the length of the guide, and x is the amplitude decay constant. The average value of the amplitude decay constant for the polymer guides was 0.05 mm^{-1}, with an overall correlation coefficient using eq. (2) of 0.99. The very high values of the amplitude decay constants observed in the curved guides agree with those reported on other polymers, such as polyurethane,[3] Kodak Photoresist,[5,14] and organosilicon polymers,[6] and indicate significant losses caused by irregularities at the surfaces of the guide.

The data obtained for linear waveguides indicate an oscillatory dependence of intensity on guide length. Figure 7 is a plot of output intensity vs. guide length in which the length of the guide was changed by cutting the guide with a sharp edge.[7] A similar pattern was observed with incoherent illumination as shown in Figure 8. The curves drawn through the data were generated using a cubic spline interpolation technique.

In the case of linear guides, measurements were made on a single guide. This was done to avoid accounting for the efficiency of coupling at the junction of the

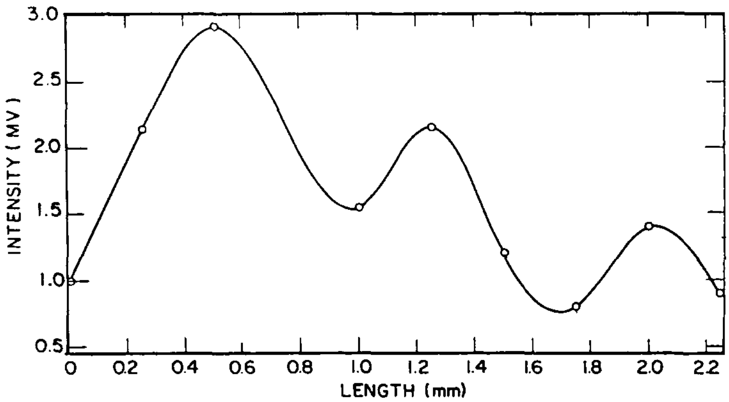

Fig. 9. Optical transmission data for a graded-index glass fiber characterized with 632 nm radiation.

curved and linear guides for the different devices. Also, with the use of the fiber optic sensing technique, it was possible to make measurements at any point on the waveguide. This was not possible with the photodiodes, where the output intensity could only be sensed at the edge of the substrate.

On-axis intensity data collected on graded-index glass fibers are shown in Figures 9 and 10. For coherent illumination, an average spacing of 0.7 mm between peaks was observed, which agrees very well with the experimental and the theoretical results reported by Feit et al.[15]

The oscillatory nature of the results for the linear guides can be explained by considering the effect of a gradation in refractive index in the polymer waveguide. The refractive index of the polymer changes with the degree of crosslinking ranging from 1.415 for the uncrosslinked material to 1.419 for the highly crosslinked material, as shown in Figure 11. In the polymer waveguide, the crosslinking density varies due to the developing process, in which the polymers must gel to become insoluble, and because of overwriting in fabricating the relatively broad structures. Hence, the refractive index varies across the microstructure.

In graded-index guides, periodic focusing and defocusing of the propagating wave front occurs, because of the gradation in index in the guide across the wave

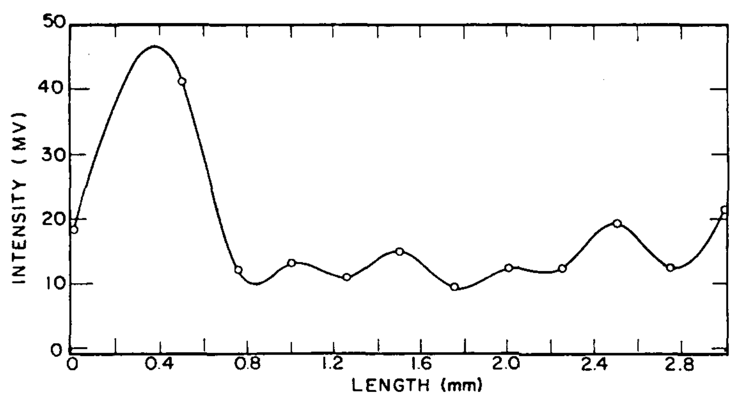

Fig. 10. Optical transmission data for a graded-index glass fiber characterized with white light.

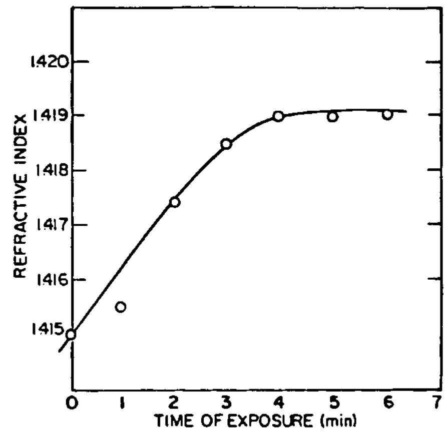

Fig. 11. Refractive index vs. time of exposure for bulk polymer films.

front,[15] as shown in Figures 9 and 10 for the glass fiber and Figures 7 and 8 for the linear guide. In the extreme case for the linear guide, a step-wave pattern may occur in the refractive index. This could not only lead to periodic focusing and defocusing but also to interference patterns. The various modes propagating in the regions of constant refractive index can interfere destructively.[16] This explains the lack of periodicity in the peak separation for linear guides.

Since the bulk absorption of the polymer is small for relatively short guides, the transmission losses can be attributed to scattering of light at the polymer–air interfaces due to surface roughness.[17] The polymer microstructure exhibits a corrugated upper surface, resulting from the overwriting with the laser beam, and nonuniformities and irregularities at the edges of the structure. The developing process also leads to increased losses due to swelling and induced surface roughness.[5]

CONCLUSIONS

Using the technique of laser lithography, geometrically complex microstructures can be fabricated from polymeric materials. These microstructures are capable of guiding light by virtue of their higher refractive indices in comparison with the surrounding media.

For curved waveguides, 50–60 μm wide and 8 μm thick, an average loss of 0.05 mm^{-1} was obtained, whereas, for linear guides, an oscillatory dependence of intensity on guide length was observed.

A new technique employing fiber optic sensing to measure the on-axis intensity of light transmittance in optical waveguides has been developed. The feasibility of using polymeric microstructures to directly couple light into another device has also been demonstrated. The technique has proved to be a reliable means of acquiring data on on-axis intensity as a function of position for both polymeric and glass waveguides.

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