Polymer microstructure waveguides on alumina and beryllium oxide substrates for optical inteconnection

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(Received 5 September 1989; accepted for publication 12 December 1989)

We report the first high quality optical waveguides (loss < 1 dB/cm) on alumina and beryllium oxide substrates. The tunability of the polymer guiding layer refractive index is provided through a recently developed wet processing technique. This procedure changes the waveguide propagation loss from larger than 40 dB/cm to less than 1 dB/cm. Since alumina (Al_2O_3) and beryllium oxide (BeO) are the major substrates for hybrid mode microwave integrated circuits (HMMICs), realization of such waveguides is useful for optical interconnection and signal processing for HMMIC.

Since the initiation of integrated optics in the early 1970s, guided wave optical devices, including waveguides,[1] modulators,[2,3] and lenses,[4,5] have been intensively studied. Because of the requirements for high fan-out, high speed, and immunity from microwave interference, signal processing and computing using protons instead of electrons has attracted a great deal of attention. Especially cases in which electrical interconnection has met its limitations in modulation speed and fan-out capability, optical interconnection is an outstanding candidate to solve problems. To make possible various optical interconnection architectures, there is a fundamental need for an optical waveguide which is integrable with various electronic and optoelectronic devices and systems. Optical waveguides on such surfaces as glass, $LiNbO_3$, and GaAs substrates represent the best results among the various substrates tested. Waveguide fabrication methods vary from substrate to substrate. Ion exchange, metal indiffusion, and molecular beam epitaxy are some of the most well known. However, these methods are subject to strict limitations.

We report a novel way to provide excellent microstructure optical waveguides on GaAs, $LiNbO_3$, glass, and aluminum.[6] Our experimental results show that the waveguide fabrication method is universal and is capable of producing very high quality waveguides. We investigated the feasibility of forming polymer waveguides on alumina (Al_2O_3) and beryllium oxide (BeO) substrates. It is well known that Al_2O_3 and BeO thin-film substrates are the most promising materials for hybrid mode microwave integrated circuits. They are the leaders for hybrid applications in either their polycrystalline forms or as single crystals. A tremendous amount of optical research has been concentrated on GaAs substrates, mainly for monolithic optoelectronic microwave integrated circuits (MOMICs), while no effort had been made to investigate the possibility of building optical circuits on microwave ceramic substrates such as Al_2O_3 and BeO. One of the major reasons is that these substrates are opaque within the visible and near-infrared optical wavelengths. As a result, they are too absorptive to be optical waveguide substrates unless new techniques can be developed to eliminate this problem.

To the best of the authors' knowledge, our research has produced the first high quality polymer waveguides on Al_2O_3 and BeO substrates. The surface of these substrates was first polished to optical quality. A liquid solution of pure water and polymer material, photolime gelatin, was coated on top of the substrates. The polymer film thickness which forms can be varied from submicron to $\sim 100\,\mu m$ by changing either the ratio of water and photo-lime gelatin or the spin speed of film coating. It was proven that the gelatin film prepared in such a way shows a step index.[6] Due to the absorption of the substrates, the optical waveguides formed were very lossy. Figure 1 shows a photograph of the lossy guide whose loss level was estimated to be more than 40 dB/cm. A waveguide like this has no possible application. Its high propagation loss was due to the strong interaction between the evanescent wave of the guided light and the substrates. A sizeable portion of the zigzag wave was absorbed by the substrates once it impacted the substrate/polymer interface. The only way to reduce this loss is to minimize the overlap between the evanescent tail of the guided wave and the substrates.

A guiding layer refractive index tuning method was developed to meet this purpose. The basic concept of this index tuning method is shown in Table I. The polymer film was first hardened by a fixer solution. The hardened film was then soaked in pure water for a few minutes so it would swell. Finally, the polymer film was dehydrated through wet and

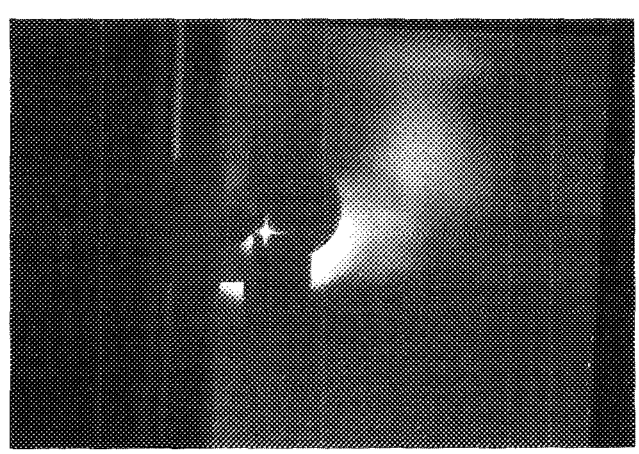

FIG. 1. High loss polymer gelatin waveguide on alumina substrate (> 40 dB/cm).

TABLE I. Refractive index profile tuning method.

Immerse inWater
↓
Immerse in 25% Alcohol Bath
↓
Immerse in 50% Alcohol Bath
↓
Immerse in 75% Alcohol Bath
↓
Immerse in 100% Alcohol Bath
↓
Immerse in 100% Alcohol Bath
↓
Hot Bath at 70°C in 100% Alcohol

dry processing. The mass density of the polymer thin film was perturbed by this process. According to the Lorentz–Lorentz equation,[7] the index of refraction, n, of a material is given by

$$n = \left(1 + 4\pi \frac{N_i r_i}{1 - 4\pi N_i r_i/3}\right)^{1/2}, \tag{1}$$

where r_i is a constant which characterizes the response of the ith type molecules to an applied field and N_i is the average number of ith type molecules per unit volume. This is proportional to the density of the substance. Summation over i is assumed in Eq. (1).

The swelling and dehydration processes changed the mass density of the polymer thin film. As a result, the refractive index of the polymer thin film was disturbed. The inverse Wentzel–Kramers–Brillouin (IWKB) method[8,9] was used in determining the refractive index profile. The WKB approximation reduces the solution of the eigenvalue problem, by application of boundary conditions at the guide surface, to the solution of the equation

$$\int_0^{x_m} [n^2(x) - N\mathrm{eff}_m^2]^{1/2} dx = \frac{4m-1}{8} \quad m = 1,2,..., \tag{2}$$

where x_m is defined by $N(x_m) = N\mathrm{eff}_m$. The integration is along the depth direction (x) of the polymer film. We also let $x = 0$ and $N\mathrm{eff} = N_0$. This treatment is good because the effective index of the zeroth-order mode of a waveguide with many modes is very close to the surface index. The polymer refractive index profile after the index tuning process is shown in Fig. 2. A nearly Gaussian refractive index profile with higher surface index is observed on the alumina substrate. A similar result has been obtained on BeO substrate. With a guiding layer profile like this, the overlap between the evanescent wave and the substrates is drastically reduced. An excellent waveguide is thus observed. The photographs for both substrates, i.e., Al_2O_3 and BeO, are shown in Fig. 3. The propagation loss measurement based on the two prism method shows that the propagation loss is lower than 1 dB/cm. Further experimental results indicate that a guiding

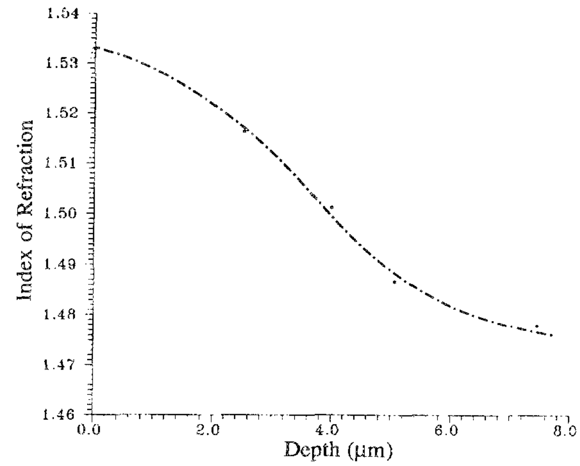

FIG. 2. Refractive index profile of polymer gelatin after tuning.

layer index from nearly linear to nearly Gaussian can be successfully achieved by choosing different time durations for each refractive index tuning procedure shown in Table I. Depending upon the optical parameters of the substrates (optical transparency, index of refraction, and conductivity), we can choose the optimal index tuning process to minimize the propagation loss of the polymer waveguide. For example, on alumina substrate, a tuning method is needed to

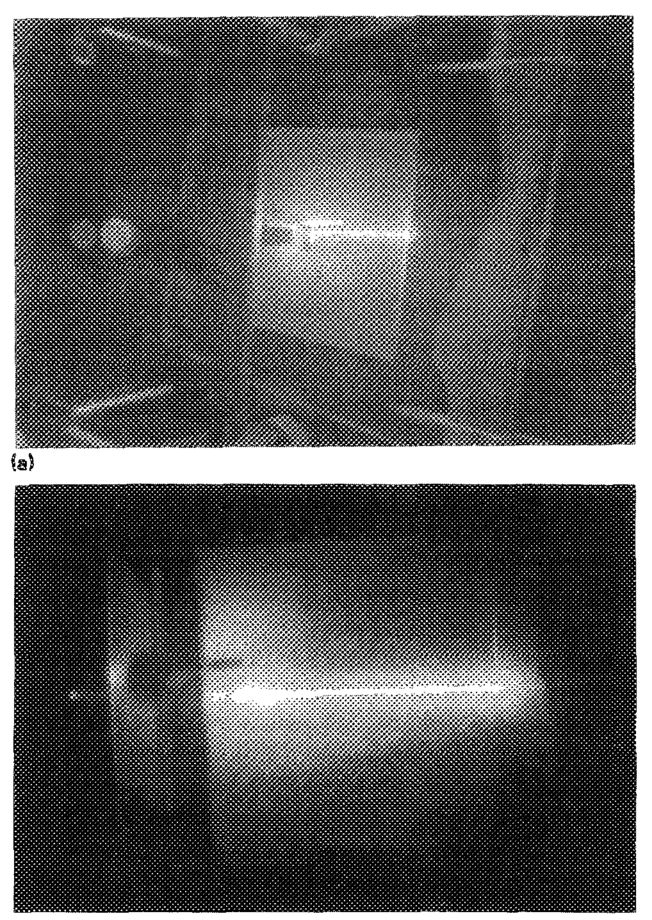

FIG. 3. Low loss polymer gelatin waveguides on (a) Al_2O_3 and (b) BeO substrates (< 1 dB/cm) after profile tuning.

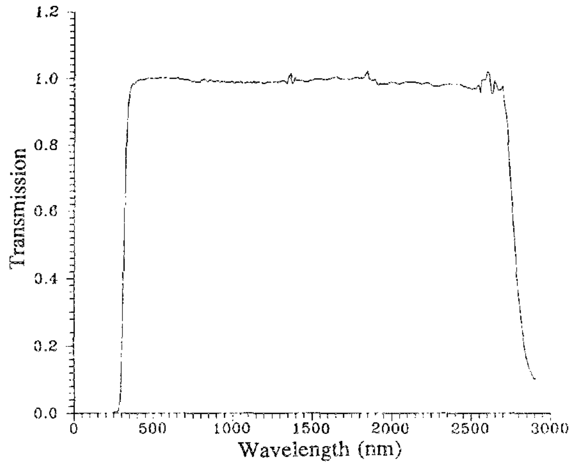

FIG. 4. Optical transparency of polymer gelatin thin film (10 μm).

create a "buffer layer" and to upgrade the optical waveguide quality. The index profile shown in Fig. 2 is nearly Gaussian and is capable of changing the waveguide propagation loss from larger than 40 dB/cm (Fig. 1) to less than 1 dB/cm (Fig. 3).

The optical transparency of the polymer photolime gelatin was further evaluated. Optical wavelengths from 250 to 2900 nm were used to appraise the optical transparency of the polymer thin film. The outcome obtained by a spectrophotometer is shown in Fig. 4. Fresnel reflection is excluded in this figure. Excellent optical transparency is shown for a wide span of optical wavelengths.

The wide range of optical transparency of the polymer thin film opens a myriad of practical applications. Due to the limitation of conventional microwave integrated circuits, such as fanout capability, modulation speed, electronmigration, and electromagnetic interference, interconnections and signal processing using photons (bosons) instead of electrons (fermions) are widely agreed as promising alternatives for next generation communication systems.[10] The polymer waveguides we report on alumina and beryllium oxide substrates provide a new avenue to access optical interconnection, signal processing, and computing on hybrid mode microwave integrated circuits.

The integrability of the polymer waveguide with dicromated gelatin (DCG) holographic optical elements has been successfully achieved.[6] Accordingly, the application of polymer waveguides for intrachip and intraboard optical interconnections on hybrid mode microwave integrated circuits is a valuable scenario to pursue.

This research project is currently sponsored by Strategic Defense Initiative Organization (contract No. DASG60-89-C-0053).

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