Integration of holographic optical elements with polymer gelatin waveguides on GaAs, $LiNbO_3$, glass, and aluminum

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We have observed waveguiding in thin films of polymer gelatin on GaAs, $LiNbO_3$, glass, and aluminum substrates. A graded-index profile can be induced in the gelatin layer and tuned by wet processing. This makes it possible to form waveguides on any smooth surface. Locally sensitizing the gelatin waveguide with ammonium dichromate allows us to integrate single and multiplexed gratings on the same substrate to perform various functions for optical interconnects and signal processing. A waveguide grating coupler that converts free-space TEM_{00} laser light to a two-dimensional spherical guided wave with 50° angle of divergence has also been demonstrated. An optical clock distribution network on wafer-scale integrated circuits is feasible with this new technology.

Research on integrated optics is a far-reaching effort to apply thin-film technology to optical circuits and devices and to accomplish better and more-economical optical systems. One of the major building blocks required to fulfill the above scheme is a good-quality optical waveguide that can receive and propagate optical signals with minimum loss and yet be integrated with various passive and active devices on different substrates. The difficulty in building such good-quality optical waveguides on various electro-optic (EO) crystals is one of the major reasons that integrated-optic devices are fabricated primarily on $LiNbO_3$ and III–V heterostructure.[1,2] For example, strontium barium niobate (SBN) has an EO coefficient r_{33} that is more than one order of magnitude higher than that of $LiNbO_3$. However, the tremendous propagation losses of SBN:60 waveguides[3] make it impractical to build any passive or active devices on this substrate. Sputtering methods offer another means to make waveguides on different substrates. However, the complications intrinsic to multilayer depositions, the relatively high propagation losses, and the difficulty of combining sputtered films with other integrated-optic devices such as lenses and gratings make it an undesirable choice. Materials that can be placed on different EO substrates and form good-quality waveguides and be integrated with other integrated-optic devices are necessary to solve this problem.

In this Letter we report an innovative way to form low-loss optical waveguides using polymer gelatin on different substrates, including insulators, semiconductors, and conductors. The original motivation for building gelatin waveguides is derived from our research with holographic recording emulsions such as dichromated gelatin (DCG). The importance of DCG as a holographic material lies in its ability to record phase holograms by modulating the refractive index with values greater than 0.1.[4] High-efficiency holographic optical elements based on DCG have been reported by various groups.[5,6] Integration of such devices in the thin-film format is useful. However, DCG itself, owing to the presence of the photosensitizer ammonium dichromate, has serious in-plane scattering loss (>10 dB/cm), which makes the formation of waveguides in conjunction with other integrated-optic devices impractical.

In this Letter we describe good-quality waveguides (loss of <1 dB/cm) formed from pure gelatin (photolimed bone gelatin), i.e., gelatin without ammonium dichromate. Pure gelatin solutions with various water-to-gelatin ratios were spun on top of soda-lime glass ($N = 1.512$ at 632.8 nm). When gelatin first goes into aqueous solution the molecules exist as single chains encircled by water molecules. On standing at temperatures below 30°C, solutions containing more than 1% gelatin become rigid through natural cross linking and exhibit rubberlike mechanical properties. In this research optical waveguides were thus formed. The waveguiding properties were examined through the prism-coupling method. The measured effective indices for TE and TM guided waves were the same (to 0.0001 accuracy) for each sample. This implies that no birefringence exists in the gelatin layer. The guiding layer index profiles of multimode gelatin waveguides were determined by the inverse Wentzel–Kramers–Brillouin (IWKB) method commonly used in integrated optics.[7,8] The graded-index profile of a multimode waveguide can be accurately determined by the IWKB methods. Step indices can also be determined through this method with a small deviation at the turning point.[9] The calculated index profile of sample D1, made of 15 g of gelatin (photo-limed bone gelatin) and 100 cm^3 of water and spun at 100 rpm, is given in Fig. 1, curve A. The depth of the step-index profile is equal to the film thickness. The measured surface refractive index of various samples with different water-to-gelatin ratios is shown in Fig. 2. Surface refractive index variation from 1.522 to 1.543 was observed. The data of Fig. 2 were determined by the zeroth-order mode of the corresponding multimode waveguide (total number of modes >10). Since the guiding layer has a step index, the zeroth-order mode effective index is almost equal to the surface index. The plotted index profiles of the various gelatin wave-

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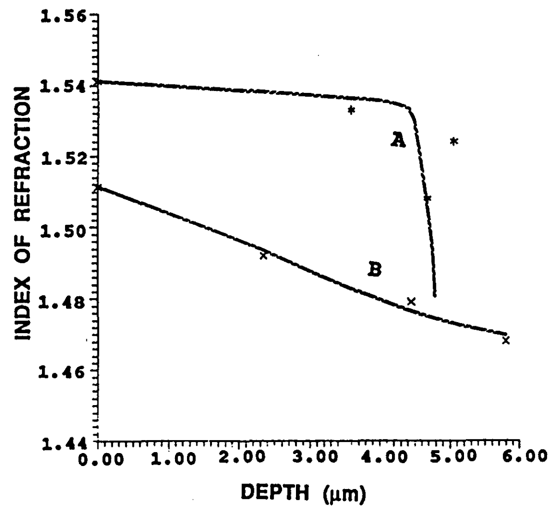

Fig. 1. Index profile of gelatin waveguide D1. Curve A, before wet processing; curve B, after wet processing.

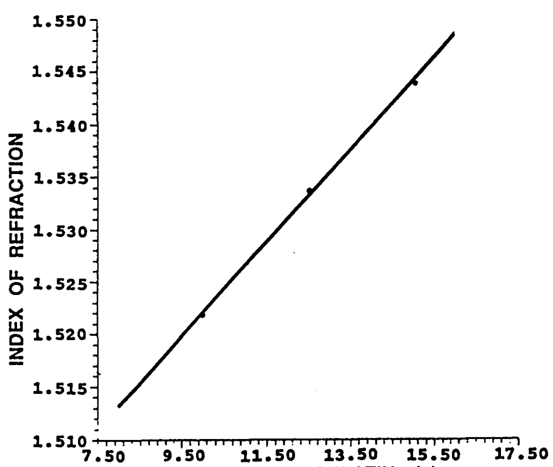

Fig. 2. Refractive indices of gelatin layer at 632.8 nm as a function of gelatin weight in 100 cm^3 of water solution before wet processing.

guides before wet processing, a method associated with DCG hologram fabrication,[10] demonstrate that the gelatin layer forms a step-index layer and that the index of refraction increases as the gelatin ratio increases.

A wet processing method associated with DCG hologram fabrication was done immediately after the above experiment. The gelatin layer was made to swell in water and then was dehydrated with isopropyl alcohol.[10] Waveguide parameters were measured again. The propagation loss measured by the two-prism method[11] gave us a propagation loss of less than 1 dB/cm on various substrates. The waveguide loss remained low (<1 dB/cm) after wet processing. The index profiles were shifted to a graded index with lower surface index than the initial film. Profiles ranging from approximately linear to approximately Gaussian can be produced by choosing different wet processing procedures. The result for sample D1 after wet processing is shown in Fig. 1, curve B. The same tendency, i.e., a decrease in the surface index and a change in the index profile from a step-index to a graded-index distribution, was consistently observed in all samples measured. This index distribution is similar to that of a graded-index fiber. The lower-index portion of the gelatin layer functions as a cladding layer for the formation of the waveguide. The basic material used for waveguide fabrication has extreme temperature stability. The initial results indicate that the optical parameters such as transparency and optical density will remain unaffected even if the temperature variation ranges from −180°C (liquid nitrogen) to 160°C for several hours and to 200°C for tens of minutes.[12] The change of index of refraction of DCG as a function of temperature (dn/dT) from 80°C to 200°C was measured to be $2.7 \times 10^{-4}/°C$.[12] These data were derived by assuming no thickness change within these temperatures. The rubberlike mechanical property is relatively sensitive to moisture. Therefore the humidity control is important to provide good-quality waveguides.

The results described above imply that waveguides with mode indices lower than the substrate index can be constructed. For example, sample D1 has three modes with mode indices lower than the substrate index 1.512 (Fig. 1). With an index profile like this, waveguide structures can be formed on any smooth surface regardless of its index of refraction and conductivity. We have spun gelatin layers on $LiNbO_3$, GaAs, and aluminum substrates. Figure 3 shows waveguiding in graded-index waveguides made by this process in glass, $LiNbO_3$, GaAs, and aluminum substrates. Graded-index profiles after wet processing have been confirmed on $LiNbO_3$, GaAs, and aluminum substrates. The index profiles determined by the IWKB method on these substrates are similar to glass. The general shape of the gelatin layer after wet processing is shown in Fig. 4. Profiles ranging from approximately linear to approximately Gaussian can be produced by choosing different wet processing procedures.

Integrated holographic optical elements such as lenses, grating couplers, and multiplexed gratings can be fabricated on gelatin waveguides by locally sensitiz-

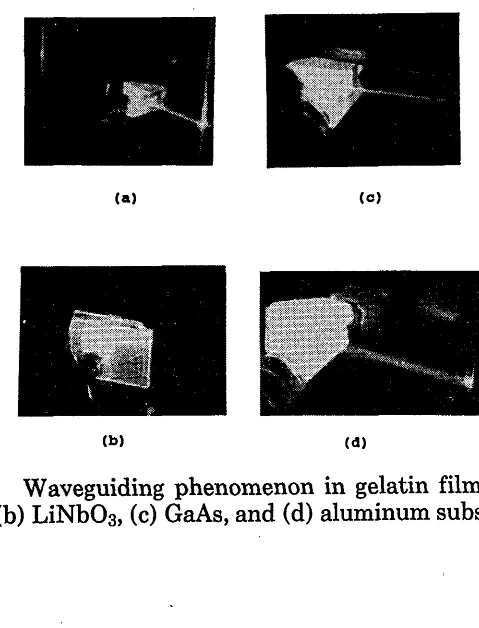

Fig. 3. Waveguiding phenomenon in gelatin films on (a) glass, (b) $LiNbO_3$, (c) GaAs, and (d) aluminum substrates.

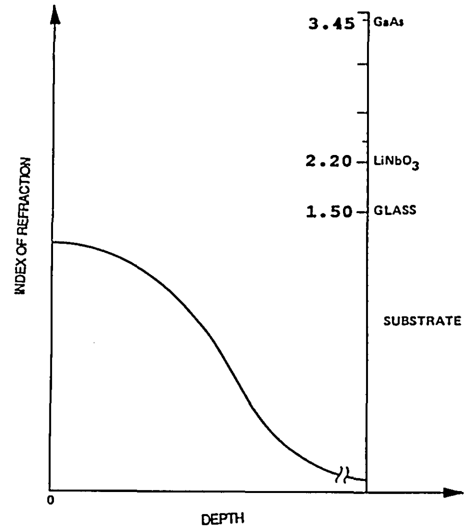

Fig. 4. General shape of the gelatin index distribution after wet processing.

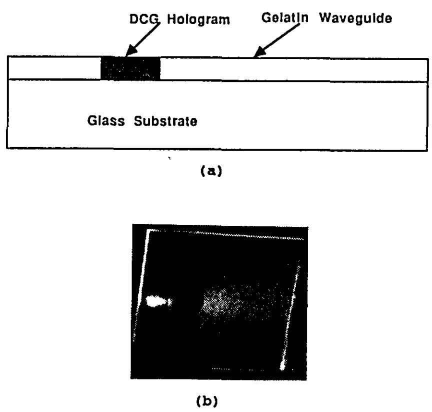

Fig. 5. Coupling of 488-nm TEM_{00} free-space laser radiation into a two-dimensional spherical wave with a 50° beam divergence in a gelatin waveguide. (a) Cross section of the device, (b) real photograph of the grating coupler.

ing the gelatin layer with ammonium dichromate. A grating coupler that converts free-space TEM_{00} laser light to a two-dimensional spherical guided wave with a 50° angle of divergence was demonstrated. Figure 5(a) is a side view of the device; Fig. 5(b) is a photograph of the waveguide coupling. An optical clock distribution network on wafer-scale integrated circuits is feasible with this new technology. The grating was designed at 488 nm with a 45° coupling angle. We analyzed the coupling efficiency of various grating structures using coupled-mode theory.[13] Several structures, including various surface relief and phase gratings that share different portions of the waveguide cross section, were analyzed. The results show that maximum coupling efficiency is obtained with the grating structure's having the same cross section as the planar waveguide. The grating couplers introduced here exactly meet this requirement. Although our experiment was carried out with a glass substrate, this result is transferable to any substrate, such as Si or GaAs, owing to the exclusive characteristics of the index profile of the gelatin waveguide after wet processing. Therefore this new type of polymer gelatin waveguide, with the desired locally sensitized areas for grating devices, can be integrated with various active and passive guided-wave devices.

Because only a few select materials can be grown on III–V and II–IV compounds, owing to the strict limitation of lattice matching, locally sensitized gelatin waveguides may provide an economical and reliable means of forming high-quality waveguides. In addition, their ability to form various multiplexed grating structures for optical interconnects, computing, and signal-processing functions on different substrate materials is an attractive side benefit. Further results of these applications will be presented in the future publications. Since DCG holograms provide a large index modulation (>0.1), a large number of multiplexed gratings can be simultaneously recorded on the same locally sensitized area. A high optical fan-out capability on $LiNbO_3$ and GaAs is provided using this new technology while the highest grating efficiency is maintained. Furthermore, gelatin waveguides on GaAs and aluminum can also be used as active devices by employing the evanescent EO effect.

In summary, we report what is to our knowledge the first polymer gelatin waveguide capable of being fabricated on a multitude of different kinds of substrates, including insulators, semiconductors, and conductors, owing to the exclusive index profile introduced after wet processing. Waveguiding on GaAs, $LiNbO_3$, glass, and aluminum has been experimentally demonstrated. Further experiments have shown that by locally sensitizing the waveguide with photosensitive material (ammonium dichromate), multiplexed holographic grating (not described here) could be formed. Because of the simplicity of fabrication and the excellent optical properties, further deployment of polymer gelatin waveguides on various active and passive devices and systems appears attractive.

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