

A STUDY OF OPTICAL WAVEGUIDES

By

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ABSTRACT

A planar optical waveguide has been produced by immersion a microscope slide (sodium rich) in molten KNO_3 . The resulting K^+ profile is due to an ion-exchange with Na^+ . The higher atomic number of K^+ increases the index of refraction at the surface and therefore allows for the propagation of light by alternate total internal reflections. Methods for observing the K^+ profile and measuring the refractive index are discussed, as well as the difficulties involved. Also, suggestions for future experiments and characterizing techniques are given.

INTRODUCTION

Recently, considerable attention has been given to glass waveguides due to their compatability with optical fibers, ease of fabrication, and low cost [1,2]. Ultimately, it is desired to reliably and inexpensively produce Integrated Optical Circuits (IOC's). These circuits offer low power consumption, wide bandwidths, immunity to electromagnetic interference, electrical isolation, and high data security [3]. It is the goal of this particular study to examine the feasibility of producing and characterizing planar optical waveguides as an initial step towards fabricating IOC's.

Before any experimental results can be interpreted or fully acknowledged, it is important that one understands the basic properties involved in guided light. A detailed analysis is not necessary at this point, although detailed information is readily available on this subject.

A condition that must be satisfied for light to propagate through a waveguide is that of total internal reflection. As shown in Figure 1, in order to have total internal reflection, n_2 must be greater than n_1 , where n_2 is the index of refraction of the wave guide and n_1 is that of the surrounding medium.

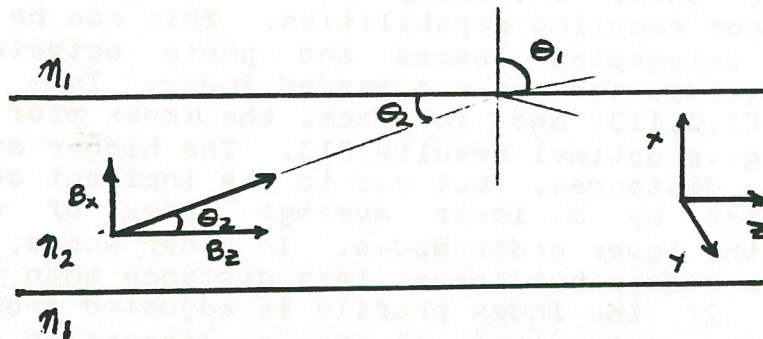


Figure 1. Snell's law and components of the propagation vector.

Since $n_1 \sin \theta_1 = n_2 \sin \theta_2$, [4]

there is total internal reflection if θ_1 equals 90° , so that there will be no refracted ray.

Consider a plane wave directed into the face an optical waveguide. Figure 1 shows a cross-sectional view of this situation. The plane wave can be described as a family of rays perpendicular to the wave front. Certain families of rays can interfere constructively with each other, and create a standing wave in the transverse (x) direction. The component of propagation in the z-direction is given by

$$B_z = n_2 k \cos \theta_2$$

since

$$k = 2\pi/\lambda_0$$

and

$$\lambda = \lambda_0/n_2$$

where k is the wave number, λ_0 is the wavelength of light in a vacuum and λ is the wavelength of light in the medium of n_2 .

The component in the x-direction,

$$B_x = n_2 k \sin \theta_2$$

determines whether or not constructive, destructive or random interference will occur. Only certain angles will allow for propagation down the z-axis [4,5,6]. These angles correspond to modes, an important concept used in describing the characteristics of a waveguide. Another important concept is that of the evanescent field, or the field that extends outside the boundaries of the waveguide. It is this field that allows

coupling to other waveguides, and can be used to determine index profiles and the number of allowable modes in a given waveguide [6,7]. The more modes there are, the more dispersion there will be. Recently much work is being done with single-mode waveguides [8,9,10]. The problem with these types of guides are their extremely small numerical apertures, resulting in poor coupling capabilities. This can be overcome by utilizing integrated lasers and photo detectors or by producing waveguides that have a graded index. This has been demonstrated [1,2,11] and in fact, the index profile can be controlled to give optimal results [1]. The higher order modes travel longer distances, but due to the incident angle, they will be effected by a lower average index of refraction compared to the lower order modes. In other words, the lower order modes are slower but travel less distance than the higher order modes. If the index profile is adjusted properly, all the modes can travel together, minimizing dispersion effects.

EXPERIMENTAL

A microscope slide was used as the substrate for an optical waveguide. These slides are made from sodium compounds and therefore have an abundance of Na^+ ions available. When placed in molten AgNO_3 or KNO_3 , an exchange of ions takes place, and the Ag^+ or K^+ ions are effectively diffused into the substrate. The higher atomic number of K^+ (or Ag^+) relative to Na^+ means that an area of diffused K^+ ions will have a greater optical density than that of Na^+ . Therefore, an index profile is expected; being gaussian or erf-like [2] with the highest index at the surface of the diffused area.

It was decided that KNO_3 , due to being inexpensive, would be used as the ion source. A suitable container was needed to contain the molten KNO_3 and the glass slide at approximately 385°C . A quartz tube furnace was used as a heat source. A thick walled pyrex dish was tested to see if it could hold up to the temperature extremes, which it did. KNO_3 crystals were piled into the dish, covering two small (75mm X 25mm) glass slides. One of these was masked with a bar type pattern of gold to see if it would be an effective barrier to the K^+ ion diffusion (this slide will be referred to as the masked waveguide, and the unaltered slide will be referred to as the planar waveguide). The dish was then placed in the furnace and heated for three days at a temperature of about 380°C (It was difficult taking the dish out of the oven without cracking it. It is unexplained as to why it did not crack earlier when a trial run was made and the pull rates were the same.)

It was earlier determined [1] that the diffused profiles could be observed by viewing an edge profile of the sample in an SEM using backscattered electrons. The backscattered intensity will be greater for those regions where high atomic number atoms are prevalent. So, a small sample (1.5cm X 1.5cm)

was cut out of each slide, (in order to obtain a cross-sectional profile), using a diamond scribe and epoxied to an undiffused sample, which serves as a reference for the relative intensity profiles throughout the entire sample. See Figure 2. The desired edge was polished with fine jeweler's powder to minimize surface defects. The entire mount was then coated with carbon to prevent surface charging in the SEM.

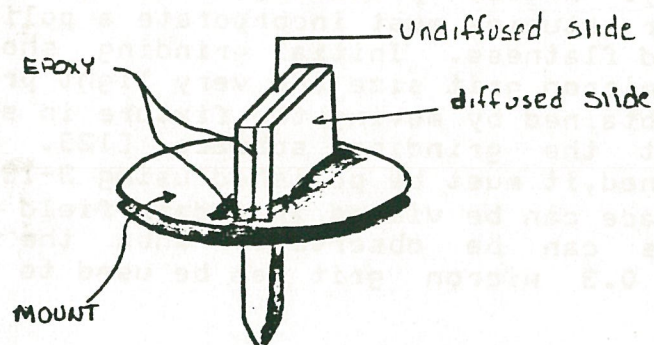


Figure 2. Waveguide sample mount for SEM.

RESULTS/DISCUSSION

The profiles in the masked waveguide could be seen with the un-aided eye even after the gold was stripped away. The diffused areas were visible in much the same way that different indices of refraction in air cause "heat waves" over hot pavement. Shining a HeNe laser through the top of the slide and perpendicular to the bar pattern (Figure 3), the profiles of the diffused areas could easily be observed on a white background.

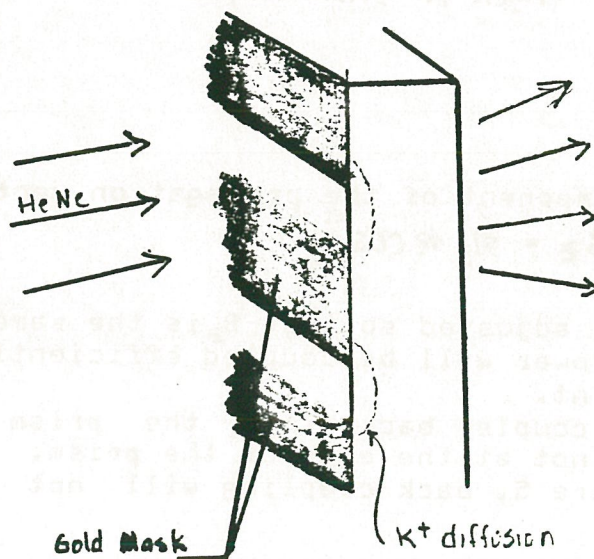


Figure 3. Gold bar pattern over glass substrate

There were a lot of defects noticed, perhaps due to the poor quality of the glass. These defects looked like bubbles, generally of the same size, and seemed higher in concentration in the processed slides than unprocessed slides. The diffused areas were severely broken up in some spots, the cause of which is unknown. Perhaps agitation during diffusion would help.

The diffusion profile of the planar waveguide could not be observed in the SEM. It is suspected that the surface was not polished properly. A good polishing technique is essential [4,12]. Further studies must incorporate a polishing fixture for stability and flatness. Initial grinding should be with wet paper of 50 micron grit size and very light pressure. Best results can be obtained by moving the fixture in small figure-8 patterns against the grinding surface [12]. After an even surface is obtained, it must be polished using 3-13 micron grit size. The surface can be viewed in a dark field microscope so that all defects can be observed. When the defects are polished away, 0.3 micron grit can be used to obtain a high gloss surface.

Further studies could be done on planar wave guides by utilizing a prism coupler for exciting any selected mode of propagation [7]. The set-up should be similar to that of Figure 4.

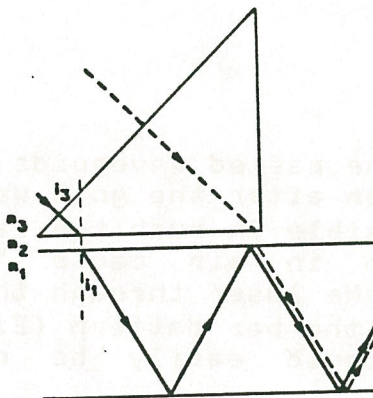


Figure 4. Prism Coupler

The horizontal component of the propagation vector in the prism is given by

$$B_z = n_3 k \cos i_3$$

The angle i_3 can be adjusted so that B_z is the same as that of the waveguide mode. Power will be coupled efficiently into the waveguide at this point.

This power will couple back into the prism providing the incident ray is not at the edge of the prism. If the incoming ray is as in figure 5, back coupling will not occur and the

energy will travel down the waveguide, where it cannot be as readily observed. The back coupling can be used to expose a piece of film so that quantitative analyses can be made. The entire procedure is described in more detail by P.K. Tein [7].

Techniques for measuring the index profile of the masked waveguides (recall Figure 3) can be classified as either transverse or longitudinal methods [4]. Transverse methods are set-up as in Figure 3, where the incident light is perpendicular to the axis of the waveguide. From this, either the backscattered pattern or the far-field scattered pattern can be analyzed. This requires the use of a computerized data acquisition system because of the complex relationship between intensity distribution and index profile [8,9].

The longitudinal method requires the illumination of the front face, or a cross-section of the waveguide. The refracted-ray technique is often used in this situation. That is, the rays that are not trapped by the waveguide are examined, not those that are bound. The necessary calculations involved are not as cumbersome as those of other methods.

A more practical approach to determining the index profile is possible, and depends on either the use of backscattered electrons in an SEM, or a knowledge of the diffusivity constant for the ion/substrate combination. The procedure is as follows: Obtain about ten high quality glass slides and measure the index of refraction of a few, average them and call it n_s . An absolute index profile can be obtained as a function of time if the slides are placed in a diffusing solution and taken out at various times (say t_1 - t_{10}) but left in the high temperature furnace. The residual surface solution must be removed somehow so as to eliminate the source of ions. At $t=t_{10}$, all of the slides are withdrawn and their respective surface indices measured. The slide that was in solution the entire time must be observed using the backscattered electron approach mentioned earlier. The point of this is to find a relationship between the index as a function of time and relate it to the index as a function of distance (it is assumed that there is a linear relationship between the backscattered intensity profile and the index profile [11,13]). From this data, the diffusivity of the ion can be found and compared to published results.

After these techniques are reasonably well established, it may be desirable to produce and characterize thin film waveguides. Then the fabrication of devices similar to those in Figures 5 and 6 may prove feasible:

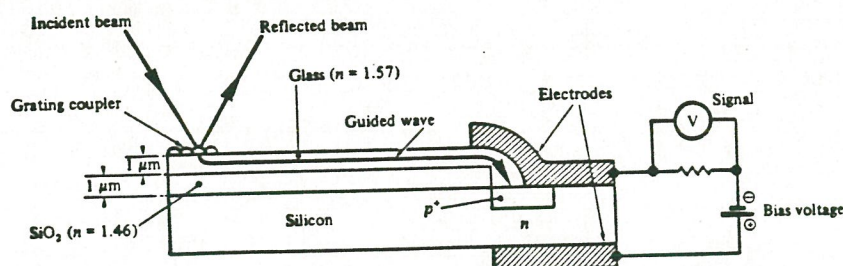


Figure 5. An integrated optical photodetector fabricated on a silicon substrate

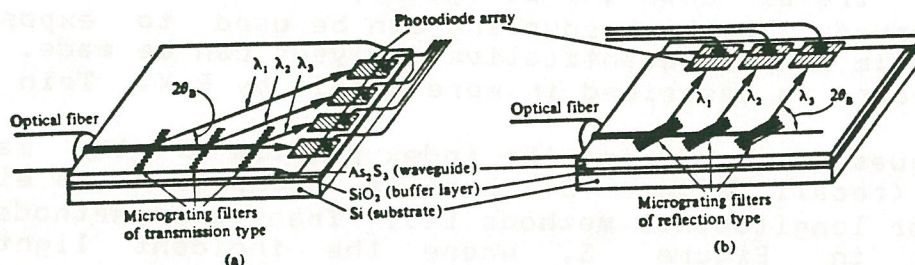


FIG. 6 Monolithic integrated optical wavelength demultiplexers fabricated with micrograting filters and a Schottky barrier photodiode array on a silicon substrate: (a) using transmission gratings; (b) using reflection gratings

CONCLUSION

A few reasonable methods have been described for characterizing waveguides. Suggestions for future processing techniques include the use of better quality glass, AgNO₃ as an Ag⁺ ion source due to its high polarizability, and agitation during diffusion. Also, it is important to study the effects of an electric field on the index profile and how it influences the transmission characteristics of the waveguide. The next step is to attempt similar processing and measuring techniques for CVD films.

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