Effect of annealing on diffused channel waveguides

Ramakant Srivastava, Huo Zhenguang, and Ramu V. Ramaswamy

H. Zhenguang is with Changchun Institute of Physics, Changchun, China; the other authors are with University of Florida, Department of Electrical Engineering, Gainesville, Florida 32611-4961.

Received 1 September 1989.
0003-6935/90/030330-02$02.00/0.

Mode size measurements of the Ag^+–Na^+ ion-exchanged channel waveguides in BK7 glass show a square root dependence on the annealing time in contrast to the linear variation predicted in the literature.

Diffusion of cations is often used to fabricate 2-D (channel) waveguides with graded index profiles. Furthermore, glass waveguides fabricated by ion exchange or ion implantation methods are sometimes subjected to a postbake (annealing) process which modifies the index profile and propagation characteristics of the waveguide. By careful choice of annealing parameters (temperature and time), propagation losses can be reduced,[1] and the mode field distribution can be tailored to minimize the fiber–waveguide coupling losses.[1,2] There have been published reports of the numerical simulation of the annealing,[2,3] and it has been predicted that the mode size increases almost linearly with the annealing time. To the best of our knowledge, no quantitative measurements of the mode size have yet been reported showing the dependence on the annealing parameters. The objective of this paper is to report results of such measurements in Ag^+–Na^+ ion-exchanged waveguides. We observe the mode size to increase in proportion to the square root of the annealing time. We determine the effective diffusion coefficient from our data, compare it with that of the planar waveguides, and explain the differences.

A series of surface waveguides of varying widths were fabricated by immersing BK7 glass substrates in a melt consisting of 33% KNO_3 + 67% $NaNO_3$ + 2.5×10^{-3} $AgNO_3$. The presence of potassium in the melt is necessary to prevent outdiffusion of the K^+ ions present in the glass.[1] The Ag^+–Na^+ ion exchange occurring in this glass system has been characterized in detail and reported elsewhere.[1] Low loss waveguides were then subjected to an annealing schedule where the guides were maintained at 380°C in a furnace and the mode size and fiber-guide insertion losses at a wavelength of 1.3 μm were measured for several annealing times using the characterization procedure described in Ref. 4.

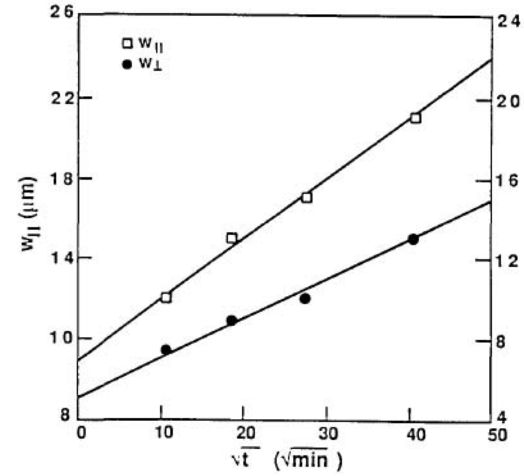

Fig. 1. Variation of mode size with annealing time. Mask width $W_m = 4.5$ μm.

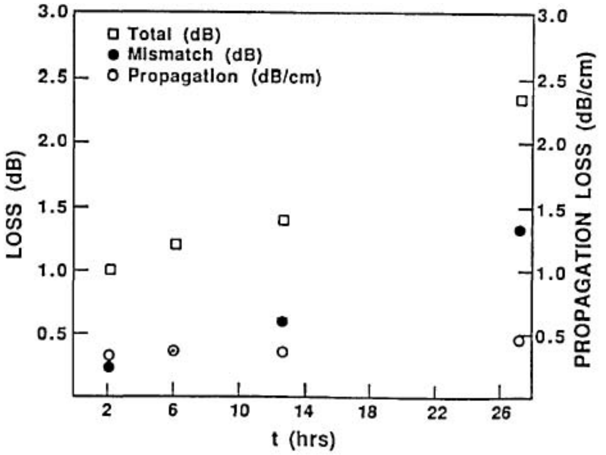

Fig. 2. Variation of loss with annealing time. $W_m = 4.5$ μm.

The mode size data are shown in Fig. 1 for a waveguide fabricated with mask opening $W_m = 4.5$ μm. $W_\parallel$ and $W_\perp$ represent the $1/e$ field widths parallel and perpendicular to the substrate plane, respectively. The solid straight lines are the least-squares fit to the data. Notice that, unlike the predictions in Ref. 2, both $W_\parallel$ and $W_\perp$ increase at different rates in our waveguides. We can write the two straight lines as

$$W_\parallel = W_\parallel^0 + 2\sqrt{D_e^\parallel t},$$

$$W_\perp = W_\perp^0 + \sqrt{D_e^\perp t},$$

where the D_e terms may be interpreted to represent the respective effective diffusion coefficients. The factor of 2 in the second term in the expression for $W_\parallel$ has been introduced to account for the diffusion on each side of the mask opening.

Table I. Values of Effective Diffusion Coefficients for Various Channel Waveguides

	W_m 3.0 μm	W_m 3.5 μm	W_m 4.5 μm	Average	Planar
$D_e^{\parallel}$ (μm^2/min)	0.0235	0.0227	0.0229	0.023	0.078
$D_e^{\perp}$ (μm^2/min)	0.0237	0.0192	0.0370	0.027	0.078

In the case of $W_{\perp}$, on the other hand, the diffusion is directed only in the depth direction, and the position of the index maximum is clamped at the substrate surface.

Table I shows the values of $D_e^{\parallel}$ and $D_e^{\perp}$ for W_m = 3.0, 3.5, and 4.5 μm. The two values are very nearly equal indicating an isotropic diffusion during annealing. In comparison, a value of 0.08 μm^2/min was measured in the planar waveguides fabricated from a similar melt at 380°C. This reduction in D_e in the annealed waveguides is caused by the continual reduction in the interdiffusion coefficient of the silver ions as a result of the reduced concentration of silver in the glass caused by the expansion of the guide cross section. The results in Fig. 1 have been simulated and are reported elsewhere.[5]

Figure 2 shows the loss data for W_m = 4.5 μm. The total throughput loss is made of Fresnel, mode-mismatch, and propagation losses. The mode-mismatch loss was determined by calculating the overlap integral between the measured fiber and waveguide mode-field profiles. The Fresnel loss (0.18 dB) occurred only at the waveguide output end since the fiber–waveguide throughput was maximized by adjusting the fiber-guide gap to give peak Fabry-Perot transmission. The results of Fig. 2 show that the propagation loss is almost unaffected by the annealing. The total insertion loss increases as a result of increased mode-mismatch between the fiber and waveguide. Similar results have been obtained for other mask widths.

In conclusion, we have shown that the mode size of the Ag^+–Na^+ ion-exchanged channel waveguides varies as the square root of the annealing time, and the linear time dependence reported in Ref. 2 is not universal. The data have been used to derive a value of the effective diffusion coefficient for the annealing process.

This work was supported by AFOSR grant 88-0199 and the DARPA Initiative at the University of Florida under Navy contract MDA 972-85-J-1006.

References

1. H. Zhenguang, R. Srivastava, and R. V. Ramaswamy, "Low-Loss Small-Mode Passive Waveguides and Near-Adiabatic Tapers in BK7 Glass," IEEE/OSA J. Lightwave Technol. **7**, 1590–1596 (1989).
2. J. Albert and G. L. Yip, "Insertion Loss Reduction Between Single-Mode Fibers and Diffused Channel Waveguides," Appl. Opt. **27**, 4837–4843 (1988).
3. R. G. Walker, C. D. W. Wilkinson, and J. A. H. Wilkinson, "Integrated Optical Waveguiding Structures Made by Silver Ion-Exchange in Glass. 1: The Propagation Characteristics of Stripe Ion-Exchanged Waveguides: a Theoretical and Experimental Investigation," Appl. Opt. **22**, 1923–1928 (1983).
4. P. G. Suchoski and R. V. Ramaswamy, "Minimum Mode-Size Low-Loss Ti: $LiNbO_3$ Channel Waveguides for Efficient Modulator Application at 1.3 μm," IEEE/OSA J. Quantum Electron. **QE-23,** 1673–1679 (1987).
5. H. C. Cheng and R. V. Ramaswamy, "Simulation of Tapered Transitions in Ion-Exchanged Channel Waveguides," Appl. Opt., to be published.