

Characterization of planar optical waveguides by K⁺-ion exchange in glass

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Mode indices measurements for both the TE and TM modes have been made on planar waveguides by K⁺-ion exchange in soda-lime glass substrates. These were directed toward establishing formulas for evaluating the effective guide depth and diffusion constant for both the TE and the TM modes, given the diffusion temperature and time. The corresponding surface-index change can also be determined.

Recently, there has been much interest in low-loss ion-exchanged waveguides.¹⁻⁵ Such waveguides not only provide the correct guide thickness and refractive index for applications in integrated optical circuits but are also inexpensive and relatively simple to fabricate. The K⁺-ion exchange in glass, in particular, provides an ideal technique for fabricating passive low-loss single-mode planar optical waveguide devices since it yields a small index increase.⁶⁻⁸ In order to design the K⁺-ion-exchange devices and theoretically analyze their performance features, the properties of the K⁺-ion-exchanged planar waveguides, e.g., the surface index change and the effective guide depth for both the TE and TM modes, must be known. Stewart *et al.*² carried out a detailed study to characterize the planar waveguides by Ag⁺-ion exchange in soda-lime glass substrates. However, a similar treatment for the K⁺-ion-exchanged slab waveguides is still lacking. Although some investigators⁴ have attempted to determine the appropriate index profile for such waveguides, formulas for calculating the effective diffusion constant D_e and the guide depth d , given the diffusion temperature T and time t , are still not available. Furthermore, it has also been noted that, hitherto, work on the characterization of the planar ion-exchanged waveguides was directed mainly toward the TE modes. Less attention has been paid to the TM modes, which do not lead to the same waveguide parameters, as will be seen below. In this Letter, we report our experimental results on the characterization of the K⁺-ion-exchanged planar waveguides in soda-lime glass for both the TE and the TM modes. In particular, we establish the formulas for D_e and d in the same manner as was done for the silver nitrate (AgNO₃) melt.² Such information would facilitate the characterizations of K⁺-ion-exchanged devices, such as branch waveguide and directional coupler devices, which use thin-film channel waveguides as basic structures.

For AgNO₃, Stewart *et al.* found a linear relationship between d and $t^{1/2}$, as given by

$$d = \sqrt{D_e t}, \tag{1}$$

where t is the diffusion time in seconds and D_e has been defined as the effective diffusion constant. Further,

they also found that the dependence of D_e on the inverse temperature $1/T$ was given by the exponential relation

$$D_e = C_1 \exp(-C_2/T) \text{ m}^2 \text{ sec}^{-1}. \tag{2}$$

Hence, from Eqs. (1) and (2),

$$d = (60C_1)^{1/2} \times 10^6 t^{1/2} \exp(-C_2/2T) \mu\text{m}, \tag{3}$$

where t is in minutes and T is in kelvins. C_1 and C_2 are constants. It was intuitively thought that for ion-exchanged waveguides employing soda-lime glass substrates and a potassium nitrate (KNO₃) melt, relations similar to Eqs. (1)–(3) should hold. Our task was, therefore, to determine C_1 and C_2 experimentally for KNO₃ since they do not appear to be available yet. The importance of establishing such relations for KNO₃ is that, given (T, t) of such a waveguide, one can establish

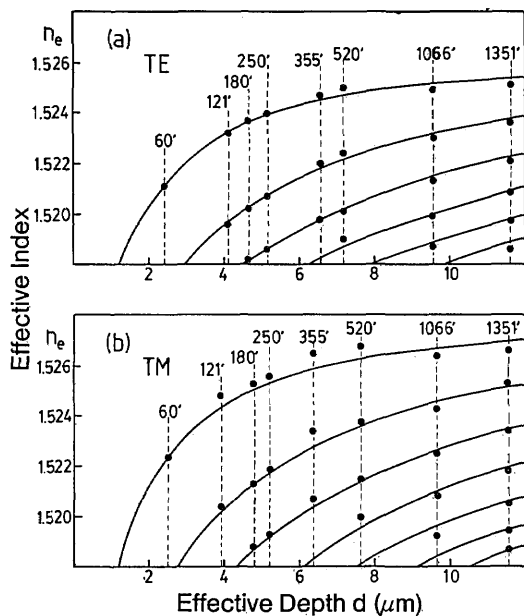


Fig. 1. Theoretical dispersion curves (Gaussian profile) of the guided modes compared with measured mode indices for samples prepared at 400°C (diffusion times in minutes). (a) TE modes. (b) TM modes.

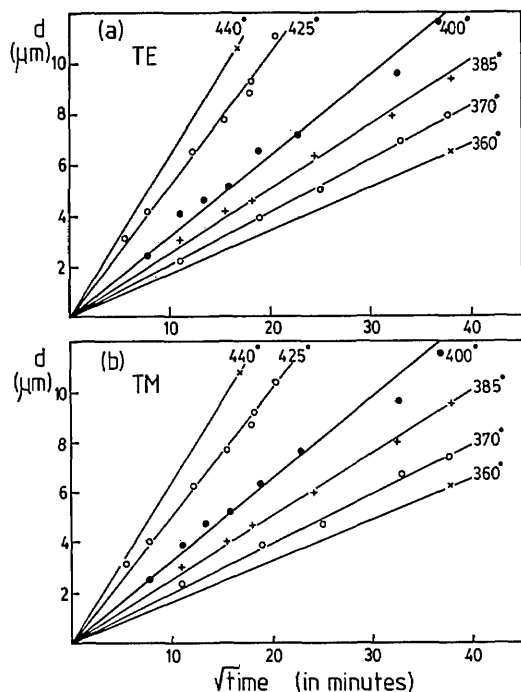


Fig. 2. Effective guide depth d versus the square root of the diffusion time (temperatures in degrees C). (a) TE modes. (b) TM modes.

the waveguide's important parameters quickly without the need for further measurements.

To fabricate the diffused planar waveguides, the soda-lime glass microscope slides were immersed in molten KNO_3 at different temperatures and for different time durations. The melt temperatures ranged from 360 to 440°C, whereas the diffusion times ranged from 30 min to 24 h. The effective indices of the guided modes in each sample were obtained by measuring the synchronous angles with a prism coupler (flint glass, $n_p = 1.785$).⁹ However, in our measuring scheme an output prism was not used. Instead, the light coupled into the diffused thin layer was allowed to propagate to the end face of the slide, where it was focused, through two lenses, onto a photodetector connected to an analog voltmeter. This scheme yielded an accuracy of $\pm 1'$ in the measured synchronous angle θ_i , corresponding to an accuracy of $\pm 1 \times 10^{-4}$ in the measured effective index n_e . The refractive index of the soda-lime glass slides used was determined separately to be $n_b = 1.518 \pm 5 \times 10^{-4}$.

Assuming a Gaussian index distribution in the diffused waveguide $n(\bar{x}) = n_b + \Delta n_s \exp(-\bar{x}^2)$, $\Delta n_s = n_s$

$-n_b$, and $\bar{x} = x/d$, where n_s is the surface index and d is the effective guide depth such that $n(d) = n_b + \Delta n_s/e$, the well-known WKB dispersion relation for the guided modes [Eq. (2.1) of Ref. 2] was used. This relation can be expressed as

$$d = \frac{(m + 3/4)\pi}{k_0 \int_0^{\bar{x}_t} [n^2(\bar{x}) - n_e^2]^{1/2} d\bar{x}}, \quad m = 0, 1, 2, \dots \quad (4)$$

where \bar{x}_t is the normalized turning point and n_e is the effective mode index. The phase shift on reflection at the glass-air interface has been taken to be $-\pi$ for both TE and TM modes. Equation (4) involves two unknowns, n_s and d . Thus, given any pair of measured mode indices for a waveguide, one can eliminate d by using Eq. (4) and determine n_s by a root-search technique in the resulting equation. After this, n_s can be substituted into Eq. (4) to obtain d . Applying this procedure repeatedly to all the possible pairs of the mode indices for a particular waveguide sample, one can determine the average values of n_s and d of that sample.

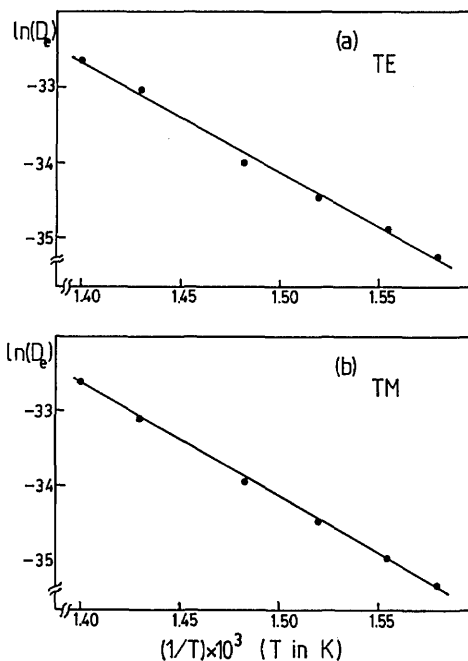


Fig. 3. The relation between $\log_e D_e$ (diffusion constant) and the inverse diffusion temperature $1/T$.

Table 1. Measured Surface Index Change Δn_s and Effective Diffusion Constants D_e at Different Temperatures^a

Temp. (°C)	Δn_s^{TE} ($\times 10^{-3}$)	Δn_s^{TM} ($\times 10^{-3}$)	D_e^{TE} (m ² /sec) ($\times 10^{-16}$)	D_e^{TM} (m ² /sec) ($\times 10^{-16}$)
360	9.2 ± 0.3	11.3 ± 0.3	4.91	4.53
370	9.1 ± 0.5	10.7 ± 0.4	7.18	6.50
385	8.8 ± 0.2	10.8 ± 0.4	10.82	10.61
400	8.7 ± 0.3	10.5 ± 0.5	17.14	18.02
425	8.7 ± 0.3	10.4 ± 0.4	45.21	42.16
440	8.4 ± 0.5	10.0 ± 0.6	66.78	68.81

^a All the readings must be multiplied by the factor indicated to yield the actual values.

Table 2. Comparisons of Measured TE-Mode Indices with Theoretical Ones for Sample Prepared with $T = 385^\circ\text{C}$ and $t = 24$ h

m	n_e (Meas.)	n_e (Theor.)			
		Gaussian ^a	Δ^b	Second-Order Poly. ^c	Δ^b
0	1.5251	1.5251	0	1.5250	1×10^{-4}
1	1.5229	1.5230	1×10^{-4}	1.5229	0
2	1.5212	1.5212	0	1.5213	1×10^{-4}
3	1.5198	1.5198	0	1.5198	0
4	1.5185	1.5186	1×10^{-4}	1.5185	0

^a $n_s = 1.5267$, $d = 9 \mu\text{m}$.

^b $\Delta = |n_e(\text{meas.}) - n_e(\text{theor.})|$.

^c Second-order polynomial function, $n(x) = n_s - (n_s - n_b)[(x/d) + b(x/d)^2]$. $n_s = 1.5276$, $d = 14.6 \mu\text{m}$, $b = 1.16 \times 10^{-6}$.

The value of the surface index n_s has been observed to be affected only by the diffusion temperature and is independent of the diffusion time.³ Our own observations have confirmed this. For each temperature chosen, we prepared waveguide samples with different diffusion times and obtained the average value of n_s for all the samples. This value of n_s was then used to compute the theoretical dispersion curves from the WKB dispersion relation. In Fig. 1, the theoretical dispersion curves for the TE and the TM modes in the samples prepared at 400°C are presented together with the experimentally measured data. The agreement seems good. The difference between the measured mode index and the theoretical one was calculated for each of the 167 measured mode indices, and the average of this difference was found to be $|n_e(\text{meas.}) - n_e(\text{theor.})|_{\text{av.}} = (1.6 \pm 1.2) \times 10^{-4}$, with the largest single deviation being 6×10^{-4} .

The measured data of d versus \sqrt{t} are presented in Fig. 2(a) for the TE modes and in Fig. 2(b) for the TM modes. These plots again clearly establish a linear relation between d and \sqrt{t} for KNO_3 . Table 1 summarizes results of our measurements and values of D_e obtained from Eq. (1) and Fig. 2. Results in Table 1 were then used to plot $\log_e D_e$ versus $(1/T)$ in Fig. 3, whence, with the help of a linear-regression method,^{10,11} we determined $C_1^{\text{TE}} = 7.82 \times 10^{-6} \text{ m}^2/\text{sec}$, $C_2^{\text{TE}} = 1.489 \times 10^4 \text{ K}$ and $C_1^{\text{TM}} = 1.604 \times 10^{-5} \text{ m}^2/\text{sec}$, $C_2^{\text{TM}} = 1.54 \times 10^4 \text{ K}$, respectively. To characterize a slab waveguide with (T, t) given, its effective guide depth can be obtained by using Eq. (3). The value of n_s can be obtained by referring to Table 1 if T is one of the temperatures studied. Otherwise, n_s can be determined by interpolation. Anisotropy in ion-exchanged waveguides as suggested by the differences in C_1^{TE} , C_1^{TM} and C_2^{TE} , C_2^{TM} was also observed previously.^{4,12} It is caused by induced stresses in the glass owing to the replacement of sodium ions by potassium ions, which are of a different size. An explanation based on diffusion theory is beyond the scope of this Letter.

In this Letter, we have used a Gaussian function to approximate the refractive-index profile, although in two previous papers^{2,4} it was found that the second-order polynomial function gives a better fit, i.e., the least $|n_e(\text{meas.}) - n_e(\text{theor.})|$ values. We have made comparisons between the Gaussian fit and the second-order polynomial one for one sample prepared with $T = 385^\circ$ and $t = 24$ h. The results are shown in Table 2. The three parameters (n_s , d , b) were obtained by using an optimization procedure.¹¹ Table 2 shows that the two

approximate index profiles yield comparable results. Since the Gaussian function approximation requires the determination of only two parameters (n_s , d) instead of three (n_s , d , b), it is more convenient to use. Hence the Gaussian index profile was chosen.

Our experimental results have verified that the linear relation between d and $t^{1/2}$ in Eq. (1) and the exponential relation between D_e and $1/T$ in Eq. (2) also hold true for the K^+ -ion-exchanged waveguides in soda-lime glass for both the TE and the TM polarization. The constants D_e , C_1 , and C_2 have also been determined. The pair of parameters (n_s , d) can thus be easily determined to provide sufficient input data for designing and characterizing K^+ -ion-exchanged planar waveguide devices involving slab and channel waveguides as the basic structures. The established formulas are valid for the ranges of the diffusion temperatures from 360 to 440°C and times from 30 min to 24 h. These ranges are believed to cover most of the practical fabrication conditions under which the K^+ -ion-exchanged waveguides and devices are to be made.

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References

1. T. G. Giallorenzi, E. J. West, R. Kirk, R. Ginther, and R. A. Andrews, *Appl. Opt.* **12**, 1240 (1973).
2. G. Stewart, C. A. Miller, P. J. R. Laybourn, C. D. W. Wilkinson, and R. M. De LaRue, *IEEE J. Quantum Electron.* **QE-13**, 192 (1977).
3. G. H. Chartier, P. Jaussaud, and A. D. de Oliveira, *Electron. Lett.* **14**, 132 (1978).
4. J. Finak, H. Jerominek, Z. Opilski, and K. Wojjala, *Opt. Appl.* **12**, 11 (1982).
5. E. T. Aksenov, A. V. Kukherev, A. A. Lipovskii, and A. V. Pavlenko, *Sov. Phys. Tech. Phys.* **27**, 1472 (1982).
6. T. Findakly and B. Chen, *Appl. Phys. Lett.* **40**, 549 (1982).
7. G. L. Yip and J. Finak, *Opt. Lett.* **9**, 423 (1984).
8. K. Honda, E. M. Garmire, and K. E. Wilson, *IEEE J. Lightwave Technol.* **LT-2**, 714 (1984).
9. P. K. Tien and R. Ulrich, *J. Opt. Soc. Am.* **60**, 1325 (1970).
10. S. S. Kuo, *Computer Application of Numerical Methods* (Addison-Wesley, Reading, Mass., 1972), p. 254.
11. M. J. Box, *Comput. J.* **9**, 67 (1966).
12. R. H. Doremus, "Ion exchange," in *Ion Exchange*, J. A. Marinsky, ed. (Dekker, New York, 1969), Vol. 2, pp. 1-42.