Modal Characterization of Planar Waveguide Formed by Ag\(^+\)/Na\(^+\) Ion Exchange in Soda Lime Glass

Ahmad Marzuki, Seran Daton Gregorius
Department of Physics, Sebelas Maret University, Surakarta 57126, Indonesia

*E-mail: amarzuki@mipa.uns.ac.id

Abstract. Modal characterization carried out reported in this paper was aimed determining the refractive index and thickness profile of Ag\(^+\)/Na\(^+\) Ion Exchanged planar waveguides formed in Soda Lime Glass. Modal characterization was carried out using prism coupling technique and applied to all waveguides fabricated at temperature of 240 °C, 260 °C and 280 °C and processed for different duration. It was shown that the number of modes tends to increase with the increase of both temperature and duration of ion exchange process.

Keywords: Waveguide, Planar waveguide, Ion exchange planar waveguide, refractive index profile, prism coupling characterization.

1. Introduction
An optical planar waveguide is designed structurally to guide light through a particular path within small region just below the surface. Optical planar waveguides are developed for many applications, such as optical sensing [1, 2], optical amplifiers [3, 4], optical splitter [5] and integrated optics [6, 7].

Various techniques for planar waveguide fabrication have been developed [8]. Among them, ion exchanged planar waveguide is of interest since this method provides cheap and easy mass production. In order to design these devices to meet the technological requirement, better understanding on controlling parameter process fabrication is required. For this purpose, several research on ion exchange planar waveguide have been reported [9, 10, 11].

There are two type of planar waveguide: step index planar waveguide and graded index planar waveguide. Step index planar waveguide has abrupt change in index of refraction, i.e., the abrupt change from high refractive index corresponding to the guiding layer to a lower refractive index which corresponds to its surrounding transparent materials. For a given step index planar waveguide, its refractive index profile can be simply determined using optical microscope or scanning electron microscopy. The boundary between them can be clearly seen. In graded index planar waveguide, however, distinct boundary does not exist. Refractive index changes gradually from a point with the highest refractive index to that of the lowest refractive index corresponding to the refractive index of substrate. Consequently, simple refractive index profiling by applying optical microscopy cannot be done. Considering that formation of waveguiding layer by ion exchange is a complex restructuration process involving not only two main atomic ions, such as Ag\(^-\) and Na\(^+\) ions in Ag\(^+\)/Na\(^+\) ions exchange, refractive index profile cannot also be resumed from individual
atomic profiling. Other change in concentration profile involving other components of glass matrix do occur, although is not as significant as the main exchanged ions [12, 13].

In this work, we present planar waveguides formed by Ag⁺/Na⁺ ions exchange. Modal characterizations were performed to derive the refractive index profiles of the samples as function of temperature and duration of the ion exchange process. For this purpose, prism coupling method was applied.

2. Experiment
Commercial soda lime glass from Sail Brand was used as substrate. Glass was cut for the size of 10 mm x 15 mm. Ion exchange process was carried out by immersing the glass into a molten salt of 100 mol% of AgNO₃ at three different constant temperatures: 240°C, 260°C and 280°C; each processed for 15, 60, 135, 240, 375, 540 and 735 minutes.

Refractive index of the samples, before and after ion exchange, were measured using ABBE Refractometer using light source generated from red LED. Modal characterization was carried out by applying prism coupling method. Figure 1 is the experimental setup. Light from He-Ne laser was launched to the base of the prism sitting at the centre of spectrometer. the spectrometer table was then rotated such that the incident angle formed by laser light at the base of prism is gradually change. Whenever strong coupling occurs, spot light with dark line at its centre is formed. The number of modes for a given planar waveguide can be obtained from the number of this occurrence.

3. Results and Discussion
Table 1 shows the change in refractive index and numerical aperture of all ion exchanged glasses treated at different processing time and temperature. Refractive index of all glass surfaces after ion exchange process are increased indicating that Ag⁺ ions diffuse into the glass to substitute the light ions already exist in the glass. Since the main components of the glass are SiO₂ (69 – 74 %), CaO (5 -14 %) and Na₂O (10 -16%); the most probable ion exchanged with Ag⁺ ions is Na⁺ ions. Na⁺ ion is lighter and therefore is more mobile than the heavier components Si⁴⁺ and Ca²⁺. In addition, Na⁺ ion is weakly bonded to the glass structure and therefore less energy required to break its binding to other ions. The refractive index increase appearing after Ag⁺/Na⁺ ion exchange process is because Ag⁺ ion possesses higher ionic polarizability (2.4 Å³) compared to that of Na⁺ (0.41 Å³) [10, 14, 15, 16]. For all processing temperature, the refractive index change increases for processing time up to 240 minutes and fluctuates at around 0.06 for processing time longer than 240 minutes.
Table 1. Refractive index change Ag⁺/Na⁺ ion exchanged planar waveguide processed at different time and temperature.

| Temperature (°C) | Time (minute) | Refractive index Before (n₁) | Refractive index After (n₂) | Refractive index change (Δn = n₂ - n₁) | Numerical Aperture (NA) |
|------------------|--------------|-------------------------------|-----------------------------|----------------------------------------|------------------------|
| 240              | 15           | 1.528                         | 1.532                       | 0.004                                  | 0.11                   |
|                  | 60           | 1.528                         | 1.533                       | 0.005                                  | 0.12                   |
|                  | 135          | 1.530                         | 1.536                       | 0.006                                  | 0.14                   |
|                  | 240          | 1.525                         | 1.533                       | 0.008                                  | 0.16                   |
|                  | 375          | 1.528                         | 1.534                       | 0.006                                  | 0.14                   |
|                  | 540          | 1.528                         | 1.535                       | 0.007                                  | 0.15                   |
|                  | 735          | 1.530                         | 1.536                       | 0.006                                  | 0.14                   |
| 260              | 15           | 1.525                         | 1.529                       | 0.004                                  | 0.11                   |
|                  | 60           | 1.525                         | 1.530                       | 0.005                                  | 0.12                   |
|                  | 135          | 1.525                         | 1.5315                      | 0.0065                                 | 0.14                   |
|                  | 240          | 1.525                         | 1.532                       | 0.007                                  | 0.15                   |
|                  | 375          | 1.525                         | 1.530                       | 0.005                                  | 0.12                   |
|                  | 540          | 1.525                         | 1.532                       | 0.007                                  | 0.15                   |
|                  | 735          | 1.525                         | 1.531                       | 0.006                                  | 0.14                   |
| 280              | 15           | 1.522                         | 1.527                       | 0.005                                  | 0.12                   |
|                  | 60           | 1.522                         | 1.528                       | 0.006                                  | 0.14                   |
|                  | 135          | 1.522                         | 1.529                       | 0.007                                  | 0.15                   |
|                  | 240          | 1.522                         | 1.5275                      | 0.0055                                 | 0.13                   |
|                  | 375          | 1.522                         | 1.528                       | 0.006                                  | 0.14                   |
|                  | 540          | 1.522                         | 1.528                       | 0.006                                  | 0.14                   |
|                  | 735          | 1.522                         | 1.527                       | 0.005                                  | 0.12                   |

Figure 2 shows the typical change of the spot light appearance observed on the screen in prism coupling experiment (figure 1). Strong coupling of light into the waveguide occur only at a particular synchronism angles (θₘ-1). In Figure 2, spot light pattern indicating the occurring of strong coupling is shown by the pattern (b). If the incident angle (θ) is gradually changed, there might be several θₘ-1 with i, equals 1, 2, 3, 4, etc., is the number of mode present for each waveguide. If the light intensity corresponding to the appearance of θₘ-1 is represented by a point at “0” and spot with no line is represented by a point at “1” [17], a series of “V” shape pattern can be drawn (intensity Vs incident angle) as shown in Figure 3. Number of modes for each waveguide is shown by the number of valley (lower dot for each “V” shape) and the results...
are tabulated in Table 2. As seen, the number of modes increases with the increase of the processing time. Since the number of modes \( M \) at a given wavelength \( \lambda_0 \) is related to the numerical aperture (NA) and effective diffusion depth \( d \) as given by:

\[
M = 2 \frac{d}{\lambda_0} NA
\]

(1)

Where

\[
NA = \sqrt{n_{co}^2 - n_{cl}^2}
\]

(2)

Here, \( n_{co} \) and \( n_{cl} \) are refractive index of core (the surface of the waveguide) and substrate, respectively.

\(\text{Figure 3. Mode patterns of Ag}^{+}/\text{Na}^{+} \text{ion exchanged planar waveguide as function of the processing times taken from simple prism coupling experiment as described above for the processing temperature; (a) 240}^\circ\text{C, (b) 260}^\circ\text{C, (c) 280}^\circ\text{C.}\)

Figure 4 is the effective diffusion depth calculated based on Tables (1) and (2). For a given processing temperature, it can be seen that the effective depth increases with the increase of the square root of the processing time, which is easily understood since \( d = 2\sqrt{Dt} \) with \( D \) is diffusion coefficient whose value depends on temperature as expressed by:

\[
D = D_0 \exp \left( -\frac{\Delta H}{kT} \right)
\]

(3)

where \( \Delta H \) is activation energy and \( k \) is Boltzmann constant.
Table 2. Number of mode of Ag⁺/Na⁺ ion exchanged planar waveguide possessed at different time and temperature.

| Processing time (minutes) | Number of modes for processing temperature |
|---------------------------|-------------------------------------------|
|                           | T = 240°C | T = 260°C | T = 280°C |
| 15                        | 2         | 3         | 4         |
| 60                        | 4         | 7         | 8         |
| 135                       | 7         | 10        | 12        |
| 240                       | 10        | 13        | 14        |
| 375                       | 10        | 14        | 17        |
| 540                       | 13        | 19        | 19        |
| 735                       | 15        | 21        | 20        |

Figure 4. Effective diffusion depth at processing temperature 240°C, 260°C and 280°C as function of $t^{1/2}$ (square root of processing time)

Using refractive index data (Table 1) and equation (1) and (2), refractive index profiles of the samples can then be calculated from equation:

$$n(x) = \Delta n \text{erfc} \left( \frac{x}{d} \right) + n_s$$

where $n_s$ is refractive index of the substrate and the results are shown in Figure 5. For all samples treated at a constant temperature (Figure 5-a, 5-b, 5-c), the waveguiding depth increases with the increase of the processing time. In addition, the gradient concentration decreases with increasing the processing time, which is a direct consequence of the third law of thermodynamics relates movement of particles towards a new equilibrium concentration.
4. Conclusions
Ag+/Na+ ion exchanged planar waveguides have been fabricated and characterized utilizing prism coupling technique. It has been shown that the number of modes increases with the increase of both processing time and temperature. Combining both the data of refractive index change and the number of modes, the refractive index profile of each waveguide has also been drawn.

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