Diffusion processes for planar waveguides fabrication in soda-lime glasses

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Abstract. This paper reports about the fabrication of planar waveguides made of the ion-exchanged technique on a soda-lime glass. The process of the ion-exchanged from molten salt AgNO₃+KNO₃. Fabrication is conducted at 70 mol% of KNO₃ and 30 mol% of an AgNO₃ melt takes place for the realization of planar waveguides. The duration of ion-exchanged has been varied in the range of 25-900 minutes at the temperature of 315°C and 350°C to diffusion processes. The purpose of our experiments is especially to study the effect temperature and duration of the ion-exchange process to the main parameters used to characterized optical waveguides. The refractive index change, the number of modes waveguides, and diffusion depth had been investigated. The m-lines spectroscopy with standard prism-coupling technique at 632.8 nm was used to measure the number of modes and depth of waveguides. Refractive index was measured with refractometer ABBE. The Ocean Optics USB4000 Spectrometer is used to obtain absorption spectra. The values of penetration depth from glass surface increased with increasing ion-exchange temperature and time.

1. Introduction
Planar waveguide is a device that has a geometric shape structure which light are guided only on one dimension. Fabrication of planar waveguides using thin transparent glass with refractive index on the substrate, or that is between two layers of substrate. There are several planar waveguide fabrication techniques that researchers often use such as sputtering, chemical vapor deposition (CVD), sol gel coating, ion-exchange, and ion implantation [1]. Among these techniques, an ion-exchange method is the most popular technique for fabricating planar waveguides. The ion-exchange method is based ion displacement on a glass substrate with different ions in a molten salt bath. Some materials are used for integrated optical fabrication such as glass, dielectrics, organic materials, semiconductors, silica based materials [2]. For obtaining optical waveguides, glass is an excellent material as a planar substrate in which to fabricate waveguides. Due to its compatibility with optical fibers in material properties, the fabrication process are very simple and low cost [3]. In this paper, the planar waveguides of soda-lime glass are prepared by silver ions from AgNO₃ and potassium ions from KNO₃ has been used to produce localized variations in refractive index. The diffusion processes of waveguides fabricated at different temperatures and varying time of diffusion. Planar waveguides are characterized by their optical properties. There are absorption spectra, a number of modes, refractive index change, and penetration depth.
2. Experimental
The fabrication of planar waveguides involved the sample preparations and diffusion processes. The soda-lime glass was chosen due to its high optical homogeneity, specifically the nitrate salts. Ions from the glass diffused out of the sample, while ions from the source diffused into the sample. Moreover, the transition temperature of the glass was also higher than the temperature required for the ion-exchange processes [4].

2.1. Sample preparation
The substrates used a commercially sail brand microscope slide which has dimensions 76.2 mm × 25.4 mm × 1 mm. The chemical composition of the glass was specified (wt.%) SiO$_2$ 73.1%, Na$_2$O 13.8%, CaO 8.6%, MgO 4.0%, SO$_3$ 0.3%, Al$_2$O$_3$ 0.1%, and Fe$_2$O$_3$ 0.1%. The glass surface was cut into dimensions of 20 mm x 20 mm. After that, cleaning was realized using ethanol and aquades in an ultrasonic cleaner for 15 minutes to remove any contaminants.

2.2. Diffusion processes
The first crucible containing 30% mol AgNO$_3$ and 70% mol KNO$_3$ were used as starting materials. The temperature of the treatment 315°C and 350°C was set using an electric furnace. Diffusion processes were carried out for the time intervals duration ranging from 25 to 900 minutes. In the crucible Ag$^+/K^+$ ions were driven into the glass substrate from the mixed salt bath. After diffusion processes, the glasses were pulled out of the salt mixture in a crucible and put at room temperature. Furthermore glass substrate washed using ethanol liquid and aquades by cleaning in an ultrasonic cleaner for 15 minutes to remove any residues from the surface and dried in the air. Finally the glass changed to transparent and orange caused by this process continues for different varying time of diffusion into the soda-lime glass.

2.3. Characterization methods
The characterization obtained to determine the optical properties of the waveguide and the practical use of this component in integrated optical circuits (IOC). The ion-exchanged planar waveguides were characterized by the absorption spectra, refractive index profile and a number of wave modes. The absorption by Ocean Optics USB4000 Spectrometer. The refractive index is one of the most important properties of an optical waveguide. Refractive index profile obtained using a refractometer ABBE. The m-line with standard prism-coupling technique at 632.8 nm has been used for the measurement of the penetration depth of waveguide glass [5].

2.3.1. Number of modes measurements
Measurements number of wave modes were made by the m-line spectroscopy technique. The incident on a prism whose refractive index ($n_i$) as the core material higher than substrate index ($n_s$) and cover film index ($n_c$) as cladding. The polarization of the laser controlled by a polarizer.

![Figure 1. Schematic of the prism coupling method with in m-line.](image)
Figure 1 shows schematic of the experimental prism set-up used to modes planar waveguides obtained. Experimental set-up He-Ne laser, a polarizer, a prism, planar waveguide, and substrate [6]. The light source of He-Ne laser with wavelength 632.8 nm is passed through a polarizer with prism is placed on a spectrometer rotation stage [7]. Then light enters into the prism and will be refracted first into a substrate and reflected. A prism which has the refractive index \( n_p \) higher than the refractive index substrate materials \( n_s \), or cover material \( n_c \) [8]. Finally the excitation of guided modes is realized throughout the evanescent waves created in the air gap between the prism and guiding layer on the black screen.

3. Results and Discussion

The dependence of the planar waveguide parameters of different diffusion process temperatures and varying time of diffusion were illustrated in table 1.

**Table 1.** Characterization of planar waveguides fabricated in molten salt with varying time and temperature diffusion.

| Waveguides | Temperature of the process (°C) | Time of diffusion (s) | Number of modes | Refractive index change | Penetration depth (m) |
|------------|---------------------------------|-----------------------|-----------------|------------------------|-----------------------|
| Sample Ag/K 1 | 315 | 25 | 6 | \( 2 \times 10^{-3} \) | 24.30 |
| Sample Ag/K 2 | 100 | 8 | 2 \times 10^{-3} | 32.40 |
| Sample Ag/K 3 | 225 | 11 | 3 \times 10^{-3} | 381. |
| Sample Ag/K 4 | 400 | 13 | 2 \times 10^{-3} | 52.66 |
| Sample Ag/K 5 | 625 | 16 | 5 \times 10^{-3} | 332.50 |
| Sample Ag/K 6 | 900 | 17 | 5 \times 10^{-3} | 353.28 |
| Sample Ag/K 1 | 350 | 25 | 6 | 2 \times 10^{-3} | 24.30 |
| Sample Ag/K 2 | 100 | 8 | 3 \times 10^{-3} | 26.53 |
| Sample Ag/K 3 | 225 | 10 | 3 \times 10^{-3} | 33.16 |
| Sample Ag/K 4 | 400 | 12 | 3 \times 10^{-3} | 311.82 |
| Sample Ag/K 5 | 625 | 15 | 4 \times 10^{-3} | 389.78 |
| Sample Ag/K 6 | 900 | 20 | 4 \times 10^{-3} | 519.71 |

Table 1 reports that the values of penetration depth from glass surface increased with increasing ion-exchange temperature and time at wavelength 632.8 nm. The number of modes obtained was higher than refractive index of the glass on the same wavelength.

**Figure 2.** The refractive index in a different time and temperature 315°C diffusion of Ag⁺/K⁻–Na⁺ ions.

**Figure 3.** The refractive index in a different time and temperature 350°C diffusion of Ag⁺/K⁺–Na⁺ ions.
Figure 2 shows the refractive index for six planar waveguides where the points represent refractive index profile of the planar waveguide calculated made the number of wave modes. The value of the refractive index glass waveguide by ion-exchange at 315°C for 25–900 minutes. The waveguide depths from glass surface increased with increasing ion-exchange time. The \( n_{surf} \) of the waveguides were 1.522–1.525. Refractive index change from glass substrate index was 0.002–0.005. Figure 3 shows the refractive index profiles planar waveguide using ion-exchanged at 350°C for 25–900 minutes. The \( n_{surf} \) of the waveguides was 1.522–1.524. Refractive index changed from glass substrate index were 0.002–0.005. Planar waveguide at temperature 315°C had higher refractive index than planar waveguide for 350°C at the same wavelength. Where indicate the number of wave modes obtained for each waveguide as well as the refractive index changed \( \Delta n \).

3.1. UV-Vis Spectrophotometer

The Ocean Optics USB4000 Spectrometer was used to obtain absorption spectra between 200 and 1100 nm. Experiments were performed in the wavelength range 350–600 nm, with a resolution 5.5 μm.

![Figure 4](image1.png)  
**Figure 4.** The absorption spectra of planar waveguide produced in soda-lime glass in different time and temperature 315°C diffusion of Ag⁺/K⁺–Na⁺ ions.

![Figure 5](image2.png)  
**Figure 5.** The absorption spectra of planar waveguide produced in soda-lime glass in different time and temperature 350°C diffusion of Ag⁺/K⁺–Na⁺ ions.

Figure 4 shows the absorption spectra in the UV and visible spectral regions of all exchanged soda-lime glass planar waveguide Ag⁺/K⁺–Na⁺ ion exchanged glasses processed within the time of diffusion range of 25 to 900 minutes at temperature 315°C. Figure 5 shows the absorption spectra in the UV and visible spectral regions of all exchanged soda-lime glass planar waveguide Ag⁺/K⁺–Na⁺ ion exchanged glasses processed within the time of diffusion range of 25 to 900 minutes at temperature 350°C.

3.2. Diffusion parameters

The approximate the planar waveguide index profile by the function \( n(x) \), where erfc is the complementary error function [9].

\[
n(x) = n_{sub} + (n_{surf} - n_{sub}) \text{erfc}(x/d) \\
= n_{sub} + \Delta n \text{erfc}(x/d) \\
\]

(1)

Where \( x \) is the penetration depth from the surface of glass substrate, \( n_{sub} \) is the refractive index of glass substrate, \( n_{surf} \) is the refractive index of glass surface, \( \Delta n \) is the refractive index change at the surface of the substrate, and \( d \) is the penetration depth of the planar waveguide [10]. \( d \) is used as a representative penetration depth to calculate the diffusion parameters of Ag⁺/K⁺–Na⁺ ions in the planar waveguide, since the gradual refractive index change of the planar waveguide with the penetration...
depth makes the determination of waveguide difficult. $d$ could be given by the following equation that described the diffusion process:

$$d = M\pi/k (n_{\text{surf}} - n_{\text{sub}})^{-1/2}$$

(2)

where $M$ is number of modes, and $k$ is $2\pi/\lambda$.

4. Conclusion

The planar waveguide has been successfully fabricated on soda-lime glass substrate by Ag$^+/K^-\text{–Na}^+$ ion-exchange under various conditions. Glass samples are colored slightly, so a decrease was recorded in the visible region absorption for all of the varying time diffusion. The optical properties waveguide is already characterized. Based on the experiment obtained the planar waveguides of the soda-lime glass have been able to fabricated by Ag$^+/K^-\text{–Na}^+$ ion-exchange at temperatures 315°C and 350°C for 25–900 minutes. $M$-line spectroscopy also uses determination of the refractive index and penetration depth. The refractive index change give the value of different diffusion process temperatures and varying time of diffusion. This shows that $n_{\text{surf}}$ and refractive index change is the independent of the diffusion process temperatures and time of diffusion.

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