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EXPERIMENTAL AND THEORETICAL INVESTIGATION OF THE ION-MASKING EFFECT IN PLANAR OPTICAL WAVEGUIDES FABRICATED BY THE DOUBLE-ION EXCHANGE TECHNIQUE IN GLASS SUBSTRATES

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ABSTRACT:

Previous works have shown that, using two consecutive ion-exchange processes with two different ions, it is possible to fabricate, in the same planar optical waveguide, two different regions having different effective refractive indices. In this paper we present a quantitative experimental and theoretical study of the double-ion exchange process. It is shown that an ion-exchange process with one species of ions halts a subsequent exchange process with another different ion. The refractive index profile of the resulting waveguide is derived from the measured values of the propagation constants of the guided modes using an inverse scattering method. We demonstrated that a third-order polynomial provides a good enough description of the measured refractive index profile; the different parameters involved in the double-ion exchange process can then be deduced by comparison with an infinite power series solution.

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ABSTRACT:

Previous works have shown that, using two consecutive ion-exchange processes with two different ions, it is possible to fabricate, in the same planar optical waveguide, two different regions having different effective refractive indices. In this paper we present a quantitative experimental and theoretical study of the double-ion exchange process. It is shown that an ion-exchange process with one species of ions halts a subsequent exchange process with another different ion. The refractive index profile of the resulting waveguide is derived from the measured values of the propagation constants of the guided modes using an inverse scattering method. We demonstrated that a third-order polynomial provides a good enough description of the measured refractive index profile; the different parameters involved in the double-ion exchange process can then be deduced by comparison with an infinite power series solution.

Introduction:

Glass waveguides are suitable candidates for a class of passive integrated optical components such as star and acccess couplers, beam splitters, power combiners, ring resonators etc.. The use of glass as he building block for such components is attractive for reasons such s low loss, compatibility with commercial fibre interfacing, and otential low cost. The ion-exchange method is the most powerful echnique because of its simplicity and flexibility in choosing the umerical aperture and dimensions of the waveguides. Many investigators ave reported results on the ion-exchange properties of glass in binary olten salt media[1-4].

Chartier et. al.[5] have experimented with a double-ion exchange n the same glass substrate, firstly with potassium at 390°C, and ubsequently with silver at 225°C (using a pure melt of $AgNO_3$) or at 15°C (using dilute melt of 5% molar $AgNO_3$ in $NaNO_3$). They found that a hallow exchange of potassium into a soda-lime glass slows the ubsequent exchange of silver, by a significant amount in the dilute elt, and almost to a standstill in pure silver nitrate. They claimed at this effect may be due to the reduced self-diffision coefficient f potassium at the lower silver exchange temperatures. The value of e effective diffusion coefficient D_e of the K^+/Na^+ exchange is two to ree orders of magnitude lower than the corresponding value for the g^+/Na^+ exchange. As a small self-diffusion coefficient will dominate y exchange process[1], it is presumably the slow diffusion of otassium which is regulating the silver exchange into a previously otassium-exchanged substrate, the potassium exchanged areas at the urface of the waveguide act as a mask for a next silver exchange.

In this paper we present a quantitative experimental verification f this masking effect in the case of double-ion exchanged waveguides.

We also demonstrate that the refractive index distribution resulting from such a process can be described by a third-order polynomial rather than by a second-order one[4]. A comparison between the infinite power series solution of the diffusion equation and the third-order polynomial enables us to calculate the depth parameter and the effective diffusion coefficient involved in the double-ion exchange process.

1- Experimental verification of the ion-masking effect:

We performed two sets of experiments. In the first one, a microscope glass slide was immersed in a molten bath of KNO_3 at 370°C for 24 hours, the resulting waveguide has the refractive index profile $n(x)$ shown in curve (1) of figure 1. Then we immersed the same glass slide in a dilute melt of 2.5% molar $AgNO_3$ in $NaNO_3$ at 380°C for one hour. The resulting waveguide has the refractive index profile shown in curve (2) of figure 1.

On the other hand, a second glass slide is immersed in a dilute melt of 2.5% molar $AgNO_3$ at 380°C for one hour, and the resulting waveguide has the refractive index profile shown in curve(3) offigure 1. These profiles are calculated from the measured values of the propagation constants of the guided TE modes using the well known inverse WKB method[6]. A comparison between curves (3) and (2) shows that, for the same depth x below the surface of the waveguide, the refractive index of the double-ion exchanged waveguide (curve(2)) isless than the refractive index of the single-ion silver exchanged waveguide (curve (3)).

Since the refractive index profile $n(x)$ is proportional to the Ag^+ ion concentration [4] in the waveguide, we can conclude that the silver concentration in a previously potassium-exchanged waveguide is less than the silver concentration in a previously unexchanged (blanked) glass slide. This means that the potassium ion halts a subsequent exchange process of the silver ion; as if potassium ions masked the exchange with silver ions.

This masking effect is verified experimentally, at higher temperature; because we repeated the previously described procedure at 425°C. Curves (2) and (3) of figure 2 represent the results at this temperature.

Recently, the authors[8] published the results of an experimental integrated optical demultiplexer fabricated by the double-ion exchange technique in a glass substrate.

2- Theoretical analysis:

It is well known that the ion exchange process is governed by the following partial differential equation[4],[7]:

$$\frac{\partial C_i}{\partial t} = \frac{\partial}{\partial x} \left(D \frac{\partial C_i}{\partial x} \right) \qquad \text{-------------------------------}(1)$$

where C_i is the concentration of the ion at adepth x (from the surface of the glass slide) and t is the instant at which we calculate C_i. The parameter D is called the "diffusion coefficient" and it is a fuction of the concentration C_i. The solution of (1) can be expressed as an infinite power series[4] in the form:

$$C_i(x,t)=C_o[1 - a(x/d) - b(x/d)^2 + c(x/d)^3 + \ldots\ldots] \qquad \text{--------}(2)$$

where C_o is the ion-concentration at the surface, a, b and c are constants which depend on the relative concentrations and self diffusion coefficients of the species of ions involved in the exchange process[4], since such a process involves at least two types of ions. The "depth parameter" d is related to the diffusion coefficient of the ion D and the time t by the following relation[4] :

$d=2\sqrt{Dt}$ ----------------------------------(3)

Stewart et.al.[4] found that a second-order polynomial is an excellent approximation to the solution of (1) for a single-ion exchange process. Assuming that the refractive index profile is proportional to the concentration C_i of the ion (Ag^+ in a silver-exchanged waveguide), we can write this profile n(x) in the form:

$n(x) = n_s - \Delta n_s[(x/d) + g(x/d)^2]$ -------------------(4)

where n_s is the refractive index at the surface of the waveguide, and Δn_s is the differnce between n_s and the refractive index of the substrate, and g is a constant.

From figures 1 and 2 we see that the refractive index profiles of glass waveguides fabricated by the Ag^+ ion-exchange in a previously potassium-exchanged glass slide - curves (2) in figures 1 and 2- still have the main characteristics corresponding to a silver-exchanged glass waveguides. So we tried a second-order polynomial approximation for describing the refractive index profile of the double-ion exchanged waveguides in the form n(x) :

$n(x) = a_o + a_1x + a_2x^2$ -----------------------(5)

ere the a's are unknwon coefficients to be determined by fitting to e measured profile using the method of the least squares[9]. We tained an unsatisfactory result, so we had to try a third-order olynomial of the form:

$$n(x) = a_o + a_1 x + a_2 x^2 + a_3 x^3 \quad \text{-----------------------(6)}$$

where $a_o = 1.5856$, $a_1 = -0.00295$, $a_2 = -0.000332$ and $a_3 = 0.000146$.

ith these values, the third-order polynomial gives an excellent greement with the measured profile of curve (2) of figure 2. In our xperiments the substrate refractive index n_o is equal to 1.507 at the e-Ne laser wavelength 0.6328 μm.

quation (6) allows us to calculate the thickness "τ" of the waveguide ince $n(\tau) = n_o = n_s - \Delta n_s$, where $\Delta n_s = a_o - n_o = 0.0795$ since $n_s = n(0) = a_o$.

ubstituting in (6) for the a's we obtain:

$$n(\tau) = a_o + a_1 \tau + a_2 \tau^2 + a_3 \tau^3 \quad \text{-----------------------(7)}$$

hich is a third-order equation in τ, and can be solved for the aveguide thickness: τ = 20 μm. As stated before, since there is a roportionality between the concentration of the Ag$^+$ ion and the local ncrease in the refractive index of the glass slide, we can write the nfinite power series solution (2) for the refractive index profile[4] s follows:

$$n(x) = n_s - \Delta n_s [(x/d) + B(x/d)^2 + C(x/d)^3 + \dots] \quad \text{----(8)}$$

here B and C are constants, and "d" is the depth parameter defined by quation (3). Now, from (8) and (6) it is possible to get:

$$a_1 = -\frac{\Delta n_s}{d} \quad , \quad a_2 = -\frac{\Delta n_s}{d^2} B \quad , \quad a_3 = -\frac{\Delta n_s}{d^3} C \quad \text{----------------(9)}$$

From (9) we obtain the depth parameter "d"$=-\Delta n_s/a_1=$ 25.4 μm. Using $d=2(Dt)^{1/2}$, with $t=60$ minutes in our experiment, we calculate the effective diffusion constant of Ag^+ ion in the double-ion exchange process: $D=2.69\ \mu m^2/sec$ similarly we determine the other coefficients, B and C, of the infinite power series solution $B=1.67$ and $C=-1.47$.

3- Conclusion:

We presented in this paper an experimental and theoretical investigation of planar optical waveguides fabricated by the double-ion exchange technique in glass substrates. We used two consecutive ion-exchange processes: a K^+ ion-exchange followed by an Ag^+ one. The masking effect of the K^+ ion is verified experimentally at two different temperatures: 380°C and 425°C. The refractive index profile of the resulting waveguide can be described accurately by a third-order polynomial. A comparison between the coefficients of this polynomial and those of the truncated infinite-power series solution of the diffusion equation allows us to calculate the main parameters of the double-ion exchange process: the depth parameter "d" and hence the effective diffusion coefficient D of the Ag^+ ion.

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Figure Captions

Figure 1 : Double ion exchange at 380°C:

Curve (1) : K$^+$ exchange at 370°C for 24 hours.

Curve (2) : K$^+$ exchange at 370°C for 24 hours, followed by Ag at 380°C for one hour.

Curve (3) : Ag$^+$ exchange at 380°C for one hour.

Figure 1 : Double ion exchange at 425°C:

Curve (1) : K$^+$ exchange at 370°C for 24 hours.

Curve (2) : K$^+$ exchange at 370°C for 24 hours, followed by Ag at 425°C for one hour.

Curve (3) : Ag$^+$ exchange at 425°C for one hour.

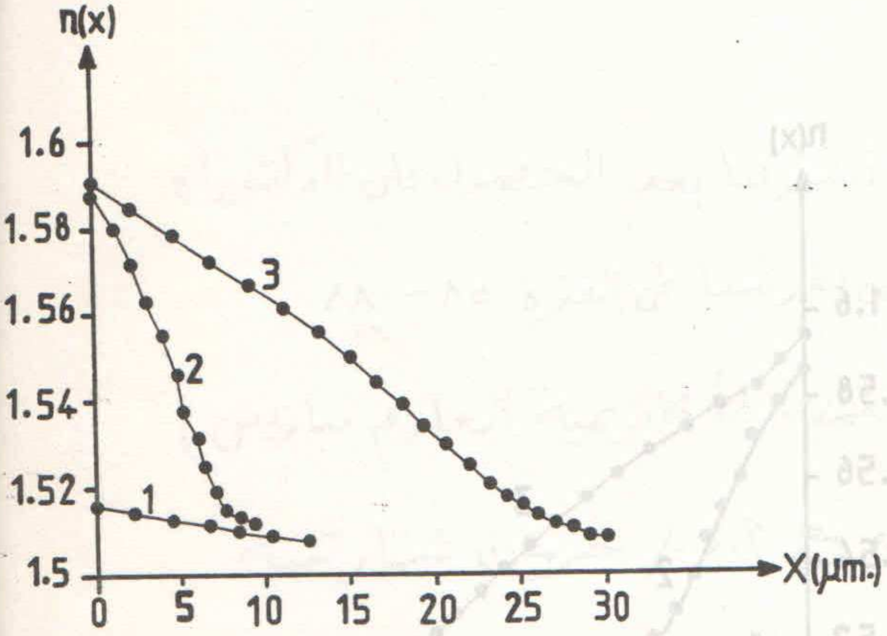

Fig.1

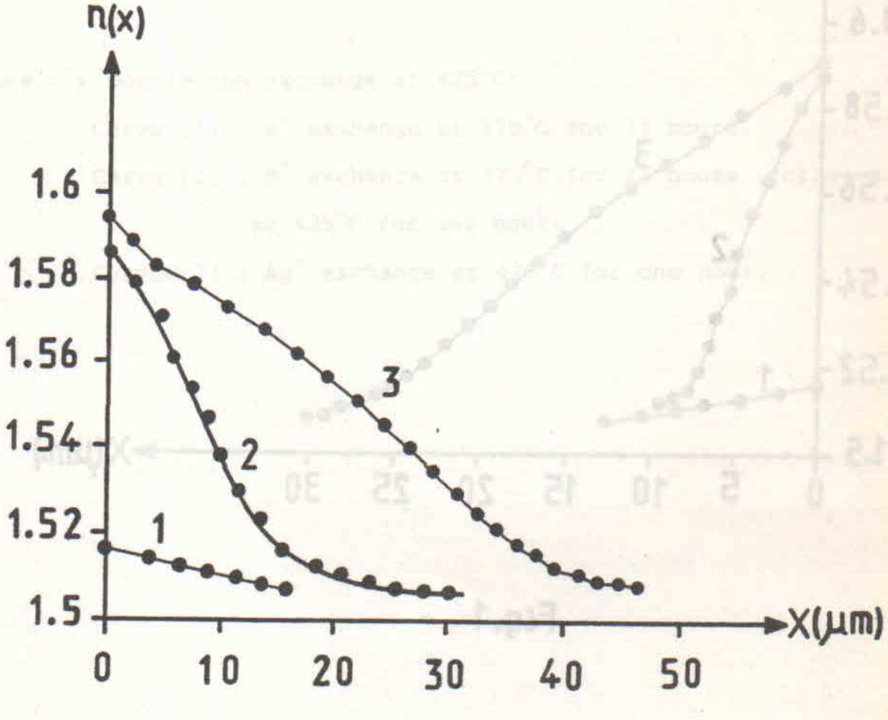

Fig. 2