

Determination of the refractive-index profile of Ag^+ ion-exchanged optical waveguides using M-lines spectroscopy

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In an optical waveguide for the same parameters of the refractive index, the number of the modes is smaller and the normalized fundamental electric field is localized on a smaller depth and therefore producing a better mode confinement (smaller mode profile dimensions) for complementary error function in comparison with the Gaussian or exponential profile. Also, the number of the modes, the waveguide depth and the value of the maximum refractive index reached close to the waveguide-air interface are increased with the diffusion time, the temperature and the concentration of the AgNO_3 in NaNO_3 for some planar optical waveguides obtained by Ag^+ ion-exchange in soda lime glass which are investigated by using m-lines spectroscopy.

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1. Introduction

In the last years many theoretical and experimental papers using several methods dealt with the determination of the refractive index profile because its knowledge plays an important role in the characterization of optical waveguides (i.e. bandwidth, spot size, single-mode propagation conditions, etc.) [1-8].

In a previous paper [9] we report some theoretical results on the evaluation of the propagation constants in an optical wave guide obtained in glass by double ion exchange (Ag^+).

In this paper we present the determination of the refractive index profile of some planar optical waveguides obtained by Ag^+ ion-exchange in soda-lime glass using m-lines spectroscopy [6].

2. Theoretical considerations

By using the prism-coupling method of the light into an optical waveguide the effective refractive index N_m of the m th mode can be determined using the relation [6]:

$$N_m = n_p \sin \left[\sin^{-1} \left(\frac{\sin \theta_m}{n_p} \right) + A \right] \quad (1)$$

where n_p and A are the refractive index and the base angle of the prism, respectively. The output light from the waveguide obtained using a second prism forms a multiple pattern, which is called m-lines. Each line corresponds to a guided mode in the waveguide. The angles θ_m between these m-lines and the normal to the prism can be measured by using a telescope mounted on a goniometer.

The WKB (Wentzel, Kramers, Brillouin) method [6] is an approximate method for solving the wave equation for the graded refractive index profile of an ion-exchanged slab waveguides. If the effective refractive indices of the

waveguide are known, the index profile can be determined. In the case of an index distribution

$$n(x) = \begin{cases} n_c, & x < 0 \\ n(x), & x > 0 \end{cases} \quad (2)$$

for which $n(x) \gg n_c$, based on the WKB method one obtained the following equation [6]:

$$\frac{2\pi}{\lambda} \int_0^{x_m} \sqrt{n^2(x) - N_m^2} dx - m\pi - \frac{\pi}{4} - \arctan(T_m) = 0, \quad m = 0, 1, 2, \dots, M-1, \quad (3)$$

where

$$T_m = \sqrt{\frac{N_m^2 - 1}{(n_s + \Delta n)^2 - N_m^2}}, \quad (4)$$

x_m is defined by the relation $N_m = n(x_m)$, n_s is the refractive index of the substrate, $\Delta n = n(0) - n_s$ is the maximum index change, λ is the wavelength and M represents the number of modes. If $n(x)$ is a function characterized by k parameters,

$$n(x) = f(p_1, p_2, p_3, \dots, p_k, x) \quad (5)$$

the parameters $p_1, p_2, p_3, \dots, p_k$ can be determined by fitting the measured refractive indices in Eq. (3).

The shape of the refractive index profile for waveguides obtained by diffusion techniques are modeled by exponential [9], Gaussian or complementary error functions [10]. Fig. 1 shows a comparison of the refractive index $n(x) = n_s + \Delta n \times f(x/d)$ and the normalized electric field (TE_0 mode) of complementary error function ($f(x/d) = \text{erfc}(x/d)$), Gaussian ($f(x/d) = \exp(-x^2/d^2)$) and exponential profiles ($f(x/d) = \exp(-x/d)$) versus the depth x for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. Fig. 2 shows the effective index N_m as a function of the mode order m , the refractive index $n(x)$ versus the depth x , the values for $n(x_1(m)) = N_m$ and an electric field (TE_3 mode) as a function of the depth x for the error-function profile (4 modes) for a waveguide with

$\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. Fig. 3 shows the effective index N_m as a function of the mode order m , the refractive index $n(x)$ versus the depth x , the values for $n(x_t(m)) = N_m$ and an electric field (TE_4 mode) as a function of the depth x for the Gaussian profile (5 modes) for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. Fig. 4 shows the effective index N_m as a function of the mode order m , the refractive index $n(x)$ versus the depth x , the values for $n(x_t(m)) = N_m$ and an electric field (TE_6 mode) as a function of the depth x for the exponential profile (7 modes) for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. Table 1 show the exact and WKB values of the effective refractive indices N_m and normalized propagation constants b_m for the TE_m - modes of complementary error function, Gaussian, and exponential profiles for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. An interesting physical point can be inferred from this data. The number of the modes is different (smaller for complementary error function) for the same parameters of the waveguide but with a different refractive index profile. Also, the refractive index and the normalized fundamental electric field for a complementary error function are localized on a smaller depth (and therefore producing a better mode confinement) in comparison with the Gaussian or exponential profile.

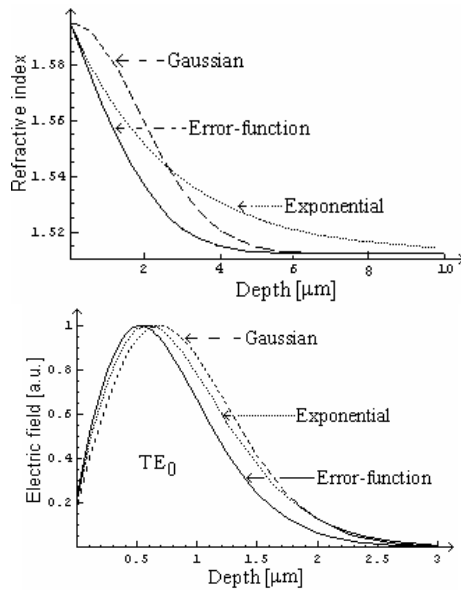


Fig. 1. The refractive index $n(x) = n_s + \Delta n \times f(x/d)$ and the normalized electric field (TE_0 mode) of complementary error function ($f(x/d) = \text{erfc}(x/d)$), Gaussian ($f(x/d) = \exp(-x^2/d^2)$), and exponential profiles ($f(x/d) = \exp(-x/d)$) versus the depth x for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$.

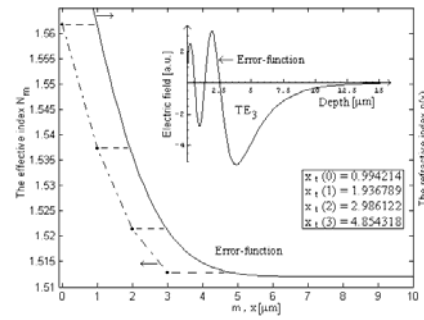


Fig. 2. Error-function profile (4 modes). The effective index N_m as a function of the mode order m and the refractive index $n(x)$ versus the depth x for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. The inset show the electric field as a function of the depth x for the mode TE_3 and the values for $n(x_t(m)) = N_m$, $x_t(m) = d \times \text{Ierfc}((N_m - n_s) / \Delta n)$ where Ierfc gives the inverse complementary error function.

For waveguides fabricated by ion-exchange, the index profile can be determined using the complementary error function:

$$n(x) = n_s + \Delta n \times \text{erfc}\left(\frac{x}{d}\right) \quad (6)$$

where

$$d = 2\sqrt{Dt} \quad (7)$$

represents the waveguide depth, $D \sim \exp(-8.933 \times 10^4 / RT) \text{ m}^2/\text{s}$ [6] is the diffusion coefficient, t is the diffusion time, and

$$\text{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^\infty \exp(-\alpha^2) d\alpha. \quad (8)$$

The refractive index profile of ion-exchange waveguides is thus characterized by the maximum index change, Δn and the waveguide depth, d .

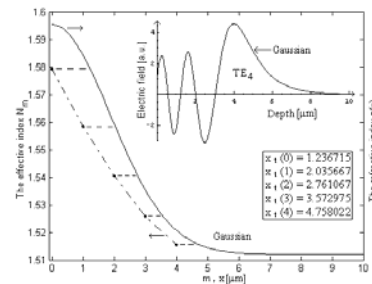


Fig. 3. Gaussian profile (5 modes). The effective index N_m as a function of the mode order m and the refractive index $n(x)$ versus the depth x for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. The inset show the electric field as a function of the depth x for the mode TE_4 and the values for $n(x_t(m)) = N_m$, $x_t(m) = d \times \sqrt{-\ln((N_m - n_s) / \Delta n)}$ where $\ln$ signifies the natural logarithm.

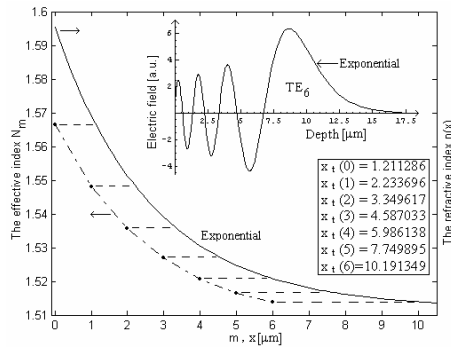


Fig. 4. Exponential profile (7 modes). The effective index N_m as a function of the mode order m and the refractive index $n(x)$ versus the depth x for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$. The inset show the electric field as a function of the depth x for the mode TE_6 and the values for $n(x_t(m)) = N_m$, $x_t(m) = -d \times \ln((N_m - n_s) / \Delta n)$ where $\ln$ gives the natural logarithm.

3. Waveguide fabrication and experimental setup

In our experiments we used four optical waveguides obtained by Ag^+ ion-exchange in soda-lime glass ($n_s = 1.5125$): waveguide 1: with AgNO_3 having the concentration 0.1% in NaNO_3 , diffusion time $t = 60$ min and the temperature 330°C ; waveguide 2: with AgNO_3 having the concentration 0.5% in NaNO_3 , diffusion time $t = 15$ min, and the temperature 380°C ; waveguide 3: with AgNO_3 having the concentration 0.5% in NaNO_3 , diffusion time $t = 30$ min and the temperature 330°C ; waveguide 4: with AgNO_3 having the concentration 0.5 % in NaNO_3 , diffusion time $t = 60$ min and the temperature 380°C . The experimental set up used to determine the effective refractive index for the waveguide mentioned above using m-lines method is presented in Fig. 5.

Table 1. The exact and WKB values of the effective refractive indices N_m and normalized propagation constants b_m for the TE_m -modes of complementary error function, Gaussian, and exponential profiles for a waveguide with $\lambda = 0.6328 \mu\text{m}$, $n_s = 1.512$, $\Delta n = 0.0833$, $d = 2.66 \mu\text{m}$.

TE_m -modes	Complementary error function $f(x/d) = \text{erfc}(x/d)$ $N_m(\text{Exact})$ $N_m(\text{WKB})$ $b_m(\text{Exact})$	Gaussian profile $f(x/d) = \exp(-x^2/d^2)$ $N_m(\text{Exact})$ $N_m(\text{WKB})$ $b_m(\text{Exact})$	Exponential profile $f(x/d) = \exp(-x/d)$ $N_m(\text{Exact})$ $N_m(\text{WKB})$ $b_m(\text{Exact})$
TE_0	1.561738 1.561887 0.590647	1.579107 1.578985 0.801414	1.566648 1.566821 0.649987
TE_1	1.537252 1.537236 0.297477	1.558376 1.558279 0.550117	1.547971 1.548013 0.425245
TE_2	1.521361 1.521309 0.109700	1.540361 1.540269 0.334444	1.535646 1.535663 0.278419
TE_3	1.512821 1.512759 0.009595	1.525711 1.525621 0.160910	1.526850 1.526958 0.175526
TE_4		1.515397 1.515311 0.039733	1.520776 1.520780 0.102828
TE_5			1.516522 1.516524 0.052904
TE_6			1.513806 1.513808 0.021115

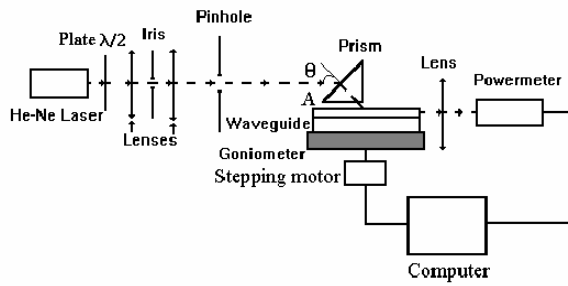


Fig. 5. The experimental set up of the prism coupling method.

The light emitted by a He-Ne laser having the wavelength $\lambda = 0.6328 \mu\text{m}$ was coupled into the waveguide mounted on a goniometer using a prism having the refractive index $n_p = 1.62205$ and the angle $A = 59.285^\circ$. The maximum of the m-lines were registered using a power meter and the corresponding values of the incident angles (θ_m) at which the guided modes are excited into the waveguide were acquired by a computer which also controls the stepping motor of the goniometer.

4. Numerical results and discussion

For the same parameters of the refractive index in an optical waveguide, the number of the modes is smaller and the normalized fundamental electric field is localized on a smaller depth and therefore producing a better mode confinement (smaller mode profile dimensions) for complementary error function in comparison with the Gaussian or exponential profile (Fig. 1).

By using the experimental arrangement presented in Fig. 5 we measured the incidence angles (θ_m) at which the guided modes are excited into the planar optical waveguide and from Eq. (1) we calculated the effective refractive indices. The incident angles (θ_m) and the corresponding effective refractive indices corresponding to the two polarizations, TE and TM, respectively are presented in Fig. 6. The number of the modes and the value of the effective refractive indices N_m for both TE and TM polarization are increased with the diffusion time, the temperature and the concentration of the AgNO_3 in NaNO_3 in the planar optical waveguides obtained by Ag^+ ion-exchange in soda lime glass.

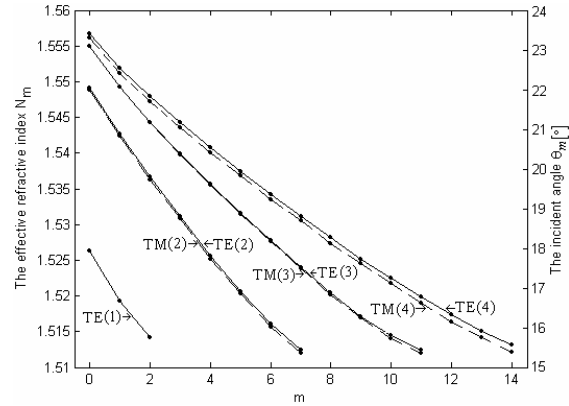


Fig. 6. The incident angles θ_m obtained from m-lines measurement and the corresponding effective refractive indices N_m for both TE and TM polarization for the waveguide (1) with AgNO_3 having the concentration 0.1% in NaNO_3 , diffusion time $t = 60\text{min}$ and the temperature 330°C ($D = 0.0022\mu\text{m}^2/\text{s}$ [6]), for the waveguide (2) with AgNO_3 having the concentration 0.5% in NaNO_3 , diffusion time $t = 15\text{ min}$ and the temperature 380°C ($D = 0.0085\mu\text{m}^2/\text{s}$ [6]), for the waveguide (3) with AgNO_3 having the concentration 0.5% in NaNO_3 , diffusion time $t = 30\text{min}$ and the temperature 330°C and for the waveguide (4) with AgNO_3 having the concentration 0.5% in NaNO_3 , diffusion time $t = 60\text{ min}$ and the temperature 380°C .

Based on the model outlined in the Section 2 and the values of the effective refractive indices measured by m-line spectroscopy method presented in the Section 3 we determined the refractive index profile by least-squares fitting of a set of measured effective indexes. The effective index N_m as a function of the mode order m , the refractive index profile and the normalized electric field in TE_0 polarization for the waveguide 1 are presented in Fig. 7. Also in Fig. 8 we show the wave function (normalized to a maximum value of 1) for TE_1 and TE_2 modes as a function of the depth x for the waveguide 1. From the refractive index profile the maximum index change, Δn and the waveguide (penetration) depth, d can be determined. Fig. 9 shows the refractive index $n(x)$ versus the depth x for the waveguides 1 - 4. The fitted parameters are $\Delta n = 0.025$, $d = 4.357635 \mu\text{m}$ for the waveguide 1, $\Delta n = 0.05$, $d = 6.738616 \mu\text{m}$ for the waveguide 2, $\Delta n = 0.056606$, $d = 7 \mu\text{m}$ for the waveguide 3, and $\Delta n = 0.058767$, $d = 7 \mu\text{m}$ for the waveguide 4. These results correspond to the best fitted for the recovery of graded index profile of the fundamental electric field (TE_0).

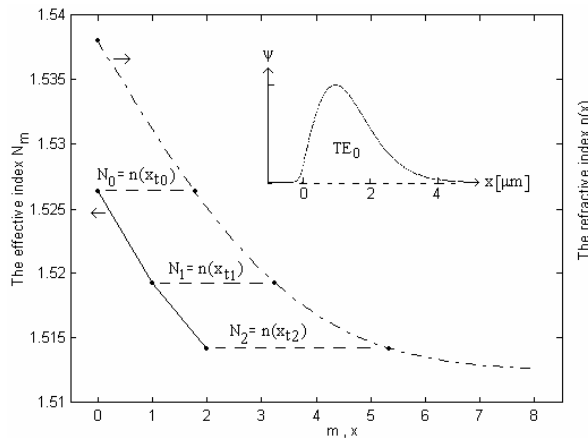


Fig. 7. The effective index N_m as a function of the mode order m and the refractive index $n(x)$ versus the depth x for the waveguide 1. The inset is the fundamental electric field (normalized to a maximum value of 1) as a function of the depth x . The fitted parameters are $n(0) = 1.5375$, $n_s = 1.5125$, $\Delta n = 0.025$, $d = 4.478643 \mu\text{m}$.

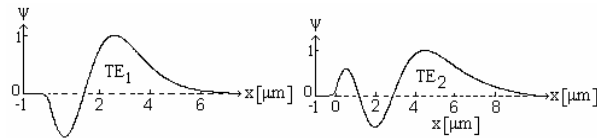


Fig. 8. The wave function (normalized to a maximum value of 1) for TE_1 and TE_2 modes as a function of the depth x for the waveguide 1.

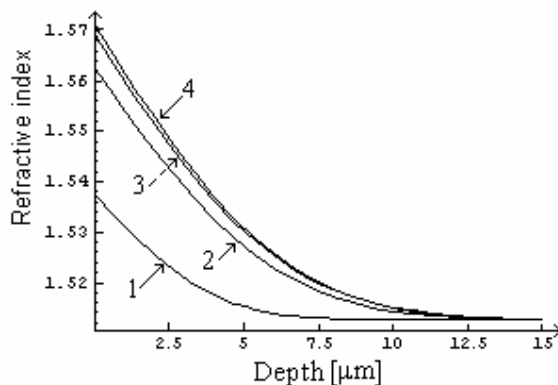


Fig. 9. The refractive index $n(x)$ versus the depth x for the waveguides 1 - 4. The fitted parameters are $\Delta n = 0.025$, $d = 4.357635 \mu\text{m}$ for the waveguide 1, $\Delta n = 0.05$, $d = 6.738616 \mu\text{m}$ for the waveguide 2, $\Delta n = 0.056606$, $d = 7 \mu\text{m}$ for the waveguide 3, and $\Delta n = 0.058767$, $d = 7 \mu\text{m}$ for the waveguide 4.

The number of the modes, the waveguide depth and the value of the maximum refractive index reached close to the waveguide-air interface are increased with the diffusion time, the temperature (the diffusion coefficient increases exponentially with the inverse of the temperature) and the concentration of the AgNO_3 in NaNO_3 in some planar optical waveguides obtained by Ag^+ ion-exchange in soda lime glass which are investigated by using m-lines spectroscopy.

The obtained experimental results are in good agreement with the theoretical ones and can be used in the design of new optical integrated circuits.

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