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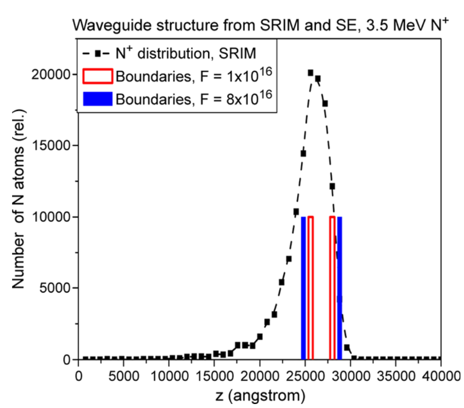

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Abstract: We report on the fabrication and characterization of planar waveguides in an Er-doped tungsten-tellurite glass by implantation of 3.5 MeV N^+ ions. Implantations were carried out in a wide fluence range of $1 \cdot 10^{16} \div 8 \cdot 10^{16}$ ions/cm^2. Waveguides were characterized by m-line spectroscopy and spectroscopic ellipsometry. Irradiation-induced refractive index modulation saturated around a fluence of $8 \cdot 10^{16}$ ions/cm^2. Waveguides operating at 1550 nm were obtained in that material using 3.5 MeV N^+ ion implantation.

Index Terms: Integrated optics, planar waveguide, ellipsometry, m-line spectroscopy.

1. Introduction

Ion beam techniques are among the best methods for optical waveguide fabrication in crystalline and amorphous materials. The first report on waveguide fabrication in fused silica using proton beam was published by Schineller *et al.* in 1968 [1]. An important monograph of this field was written by Townsend *et al.* [2]. A detailed review of ion-implanted waveguides in optical materials has recently been published by Chen *et al.* [3].

Tellurite glasses have gained a widespread attention because of their potential as hosts of rare-earth elements for the development of fiber and integrated optic amplifiers and lasers covering all main telecommunication bands [4]–[6]. Er^{3+}-doped tellurite glasses in particular are very attractive materials for the fabrication of broadband amplifiers in wavelength division multiplexing (WDM) around 1.55 μm, as they exhibit large stimulated cross sections and broad emission bandwidth. Furthermore, tellurite glasses have low process temperature and nonlinear properties. Fabrication and optical properties of bulk and planar waveguides obtained in such materials have been extensively studied [7]–[9]. Only a few papers over the past few years reported on the possibility to fabricate channel waveguides in these activated glassy materials by means of femtosecond laser writing [10] and reactive ion etching (RIE) process in pure TeO_2 thin films [11], [12]. In spite of the relevant advancements in performance achieved by these approaches, still significant problems persist toward the full exploitation of this material. In fact, RIE still lacks the necessary quality output to allow the fabrication of waveguides fully embedded in the glass, which would enable more flexibility in the optimization of the waveguides and of the pumping schemes. On the other hand, laser writing does not induce high index contrast between waveguide and substrate, which would permit a better field confinement and, consequently, a more efficient performance of the device.

Research interest in the field of Er^{3+}-doped tellurite materials is still going on, with the aim of discovering the best combination of tellurite glass formulation and fabrication process in order to reduce the cost and increase the performance of the devices so obtained. In this context, ion implantation presents some unique advantages compared with other fabrication methods. It proved to be a universal technique for producing waveguides in many optical materials and has good controllability and reproducibility [3].

We have recently reported fabrication of channel waveguides in an Er-doped tungsten-tellurite (Er:Te) glass via implantation of MeV N^+ ions [13]. Based on our experiences with the 2-D waveguide structures, we carried out a systematic study of the implantation parameters for planar waveguides, in order to better understand the nature of the guiding structure and realize waveguide operation in the 1550-nm telecommunication band. We increased the ion energy from the 1.5-MeV value used in those experiments to 3.5 MeV to achieve this goal by obtaining a broader guiding layer. N^+ ions implantation has already been long demonstrated as a means to fabricate low loss waveguides in other materials, hence our choice for the tests described in this paper [14], [15]. Moreover, we decided to use N^+ ions for the fabrication of the waveguides because of two reasons: on the one hand ion mass in the accelerator was limited by ion mass energy selector magnet. On the other hand, the higher the atomic mass the bigger the ion-solid interaction. If compared with He ions, in the case of N, we expected three times bigger electronic stopping and more than ten times bigger nuclear stopping in the MeV energy range. In fact, we succeeded in achieving the same refractive index modulation in a Pyrex glass with N^+ ions of a dose of one order of magnitude lower than with He^+ ions of the same energy [16].

2. Waveguide Fabrication

The composition of the glass developed for our experiments was 60 TeO_2-25 WO_3- 15 Na_2O-0.5 Er_2O_3 (mol. %) with a density of 5.75 g/cm^3. We fabricated planar waveguides in the Er:Te glass samples via implantation of N^+ ions with 3.5-MeV energies. Irradiations were carried out with a collimated beam from a Van de Graaff accelerator at the Research Institute for Particle and Nuclear Physics, Budapest, Hungary, with normal incidence on the glass samples. Lateral homogeneity of the irradiation was assured by defocusing the ion beam with a magnetic quadrupole and by scanning the sample under a 2 mm $\times$ 2 mm beam. Useful size of the implanted waveguides was 6 mm $\times$ 6 mm. Irradiation was carried out at fluences of 1, 2, 4, and 8 $\cdot$ 10^{16} ions/cm^2.

3. SRIM Simulations and Ellipsometric Measurements

Structure of the ion implanted planar waveguides is determined mainly by the energy and fluence of the implanted ions. Distribution of the implanted ions or that of the collision events along the depth of the implanted sample can serve as a rough estimation of the refractive index profile of the implanted waveguide. We used SRIM 2008 code (Stopping and Range of Ions in Matter) [17] to simulate the fabrication of the waveguides. Full-cascade SRIM simulations were performed to estimate the ion and damage depth distributions in the target. Maximum of the distribution of the implanted N^+ ions was 2.5 μm below the surface of the Er:Te glass sample in case of 3.5-MeV ion energy, with a longitudinal straggling of 0.5 μm. Maximum of the collision events (vacancy production) distribution roughly coincides with that of the ion distribution, but it extends considerably toward sample surface.

The ion-implanted waveguides were measured with a WOOLLAM M-2000DI spectroscopic ellipsometer ($\lambda = 193{-}1690$ nm). A three-layer optical model was applied in the evaluation of the

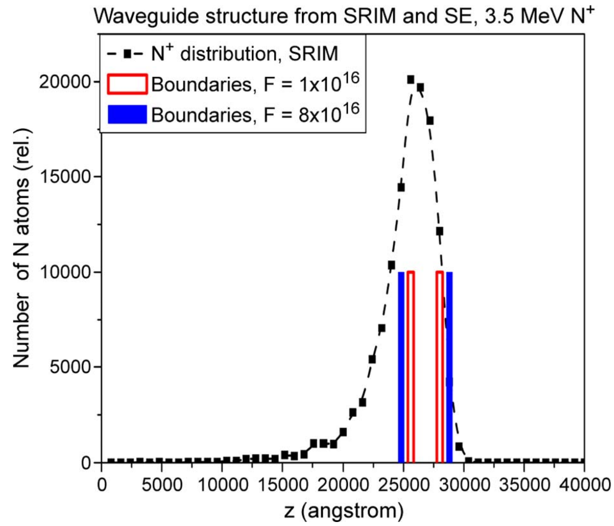

Fig. 1. SRIM simulation and SE fit of the waveguide structure.

spectroscopic ellipsometry (SE) data. The first layer, which is adjacent to the substrate, represents the stopping region. The second layer is the region that the implanted ions traverse before they stop. The third layer is a surface roughness film taken into account on basis of effective medium approximation [18]. Dielectric functions of the first and second layers were described by the Cauchy dispersion relation. Parameters of the Cauchy dispersion relations and layer thicknesses were considered as free parameters. We applied the evaluation software WVASE32 created by J. A. Woolam, Inc. [19] for the analysis of the spectroellipsometric data. The evaluation yielded 7.9 $\pm$ 0.1 nm for the thickness of the surface roughness layer and 2.019 $\pm$ 0.001 for the refractive index of the nonimplanted glass substrate at $\lambda = 635$ nm.

A graphical comparison of implanted N^+ distribution obtained by SRIM and barrier layer boundaries obtained by SE is shown in Fig. 1. Center of the barrier layer is slightly beyond the projected range, while its width increases with the implanted fluence, as expected.

4. M-line Spectroscopic Measurements

For the characterization of the planar waveguides implanted in the tungsten-tellurite glass, we used a semiautomatic m-line spectroscopic instrument ("COMPASSO"), which was developed at IFAC. Accuracy of the instrument is generally $\pm 1 \cdot 10^{-4}$ and $\pm 4 \cdot 10^{-4}$ on the effective refractive index and bulk refractive index, respectively. In the case of the N^+-implanted planar waveguides in the Er:Te glass, due to the lower contrast in the measurement, the accuracy was lower: about $\pm 5 \cdot 10^{-4}$ and $\pm 1 \cdot 10^{-3}$, respectively.

Due to the high refractive index of the bulk glass (around 2.0 at 635 nm), we used a rutile prism to couple the light in the irradiated regions. Table 1 summarizes the values obtained from the m-line measurements performed at 635 and 1550 nm. Each value is an average of three measurements. Bulk refractive index was $2.041 \pm 1 \cdot 10^{-3}$. We observed modes with effective refractive index below the corresponding value of the bulk refractive index, a clear indication of leaky modes.

Fabrication of the Er:Te glass waveguides with 3.5-MeV energy N^+ ions resulted in waveguides able to support modes also at 1550 nm wavelength. We present here two examples of the results obtained. The m-line spectrum (reflected relative intensity versus effective refractive index) with five TE modes for the highest implanted fluence, $8 \cdot 10^{16}$ ions/cm^2, measured at 635 nm, is presented in Fig. 2(a). Proof that the same waveguide supports modes at 1550 nm is shown in Fig. 2(b).

To analyze how the implantation parameters influence the characteristics of the waveguides, we have carried out numerical fits based on the m-lines measurements. The model upon which the numerical fit was based was rather simple but effective: The waveguide has been considered a

TABLE 1

Effective refractive indices (average values) versus ion fluence measured at 635 and 1550 nm for Er:Te glass. Error of the refractive indices is $\pm 5 \cdot 10^{-4}$

Fluence ($\cdot 10^{16}$ ions/cm^2)	Mode	Effective refractive index at 635 nm	Effective refractive index at 1550 nm
1	TE0	2.0186	1.9528
	TE1	2.0089	
	TE2	1.9920	
	TE3		
2	TE0	2.0197	1.9549
	TE1	2.0097	
	TE2	1.9928	
	TE3	1.9674	
4	TE0	2.0207	1.9571
	TE1	2.0097	
	TE2	1.9925	
	TE3	1.9668	
8	TE0	2.0213	1.9543
	TE1	2.0076	
	TE2	1.9860	
	TE3	1.9564	

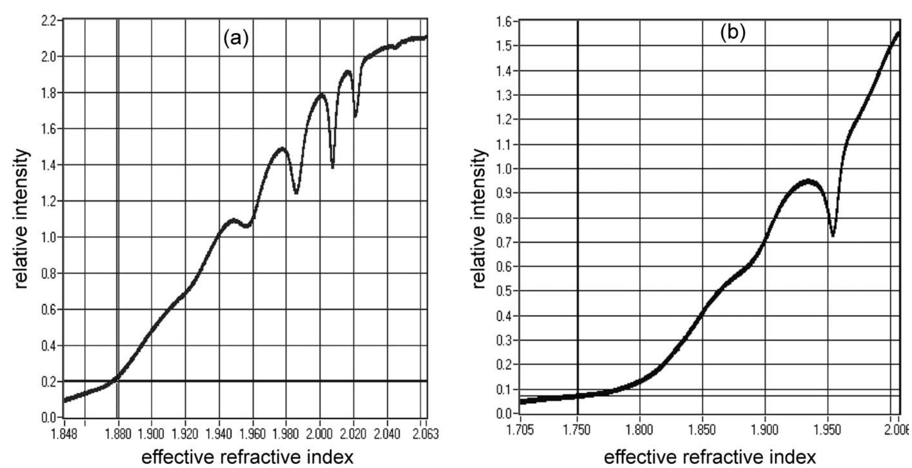

Fig. 2. M-line spectra of waveguide. Fluence = $8 \cdot 10^{16}$ ions/cm^2, E = 3.5 MeV. (a) At 635 nm and (b) at 1550 nm.

three layer step structure and the leaky nature of the waveguide has been neglected, using the barrier layer as the substrate of the waveguide. Indeed, to justify the latter assumption it must be stressed that, though propagation losses are obviously strongly influenced by how well the mode is confined by the leaky structure or, in other terms, how well the leaky structure resembles a truly confined mode, values of the effective indices are much less dependent from this factor, and the approximation can be applied to the numerical fit used to assess only the physical characteristics of the structure.

The availability of data at several wavelengths (635, 980, 1310, and 1550 nm) has allowed us to obtain a more accurate and flexible data processing. Actually, assuming a Sellmeier-like law to account for chromatic dispersion for all layers:

$$n^2 = 1 + \frac{\lambda^2}{A\lambda^2 + B} \tag{1}$$

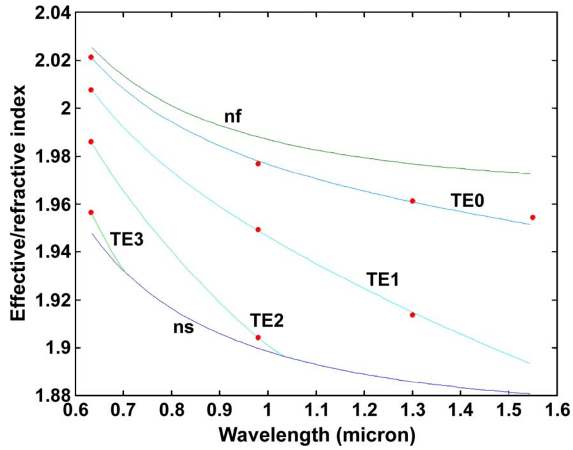

Fig. 3. Reconstruction of the refractive index of the guiding and barrier layers as a function of the wavelength. Sample irradiated with $8 \cdot 10^{16}$ ions/cm^2 Calculated effective indices of the modes are also shown.

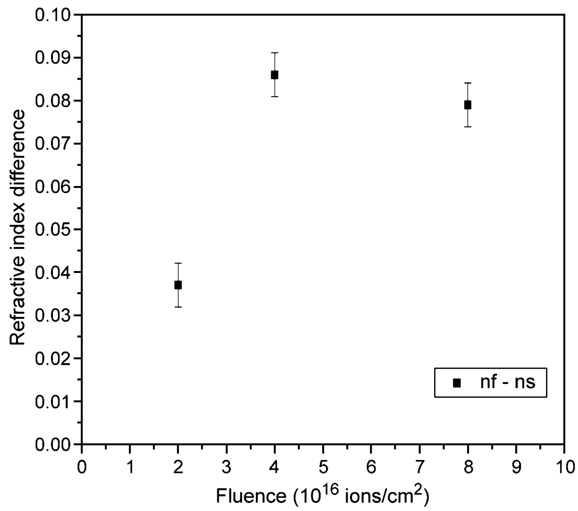

Fig. 4. Refractive index difference of the guiding and barrier layers versus fluence at 635 nm.

and using it in the fit process, it was possible to obtain the thickness of the guiding layer and the parameters A and B for the guiding and the barrier layers in a broad wavelength range.

As shown in Fig. 3 for the sample irradiated with $8 \cdot 10^{16}$ ions/cm^2, the fit process allowed us to model through the A and B parameters the wavelength dependent refractive index of both the guiding (nf) and barrier layers (ns) by means of the A and B parameters and (1). Moreover, the effective indices of the modes were calculated with the values of the numerical regression results and the same assumptions used in the fit process. The agreement between the experimental data (dots in Fig. 3) and the calculated effective indices is very good. Thickness of the guiding layer was assessed to be 2.2 μm, in agreement with SRIM simulations [17].

Fig. 4 shows how the difference of the refractive indices of the guiding and barrier layers is affected by the fluence, as obtained by the same fit procedure at 635 nm. The guiding layer index shows a slight increase with higher fluences, whereas the barrier layer exhibits a saturating larger decrease; combination of both effects produces the guiding properties of the structure.

5. Discussion and Conclusion

In conclusion, planar waveguides were fabricated by irradiation with 3.5 MeV N^+ ions in a rare-earth-doped tellurite glass. Fluences of the implanted ions ranged from $1 \cdot 10^{16}$ to $8 \cdot 10^{16}$ ions/cm^2. The experimental results and modeling reported here demonstrate the optical barrier nature of the waveguide due to the nuclear interactions among the bombarding and target ions. Therefore, light is confined in the layer comprised between the end of range or optical barrier (of lower refractive index) and the surface of the glass. Nevertheless, with an increase of the ion fluence, we observed an increase of effective indices of the leaky modes toward the bulk refractive index value. This seems to partially justify the assumption, formulated in a previous work [13], for which some ionization phenomenon along the path of the nitrogen ions induces a positive refractive index change ($\Delta n > 0$) locally in the region between the surface of the glass and the end of range. All samples supported guided modes from 635 nm to 1550 nm. Saturation of the refractive index change occurred in the $5 \cdot 10^{16} \div 10^{17}$ ions/cm^2 range of the implanted fluence. The fact that these waveguides supported propagation also in the 1.55 μm band envisages their application in the telecom field to the fabrication of integrated optical amplifiers capable of exploiting the good spectroscopic properties offered by using tellurite glasses as hosts for the rare earth dopants.

Refractive indices of the barrier and guiding layers and the thickness of the guiding layer have also been characterized using the effective indices of the waveguide modes. These measurements have evidenced that the waveguides obtained by ion implantation exhibit a large refractive index contrast ($\Delta n \cong 0.09$), which will enable the fabrication of waveguides with small field size, provided the barrier formation process is optimized.

Agreement with the experimental data and thickness assessment by SRIM modeling and ellipsometric measurements was good. Next steps will include the fabrication of channel waveguides with optimized irradiation and structural parameters based on the results of the characterization described in this paper.

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