Single - and double energy swift and slow heavy ion irradiated optical waveguides in Er: Tungstene-Tellurite glass and BGO for telecom applications

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OUTLINE

1. **Motivation**
2. **Design and fabrication of the waveguides**
3. **Spectroscopic ellipsometry**
4. **M-line spectroscopy**
5. **Conclusion and Outlook**

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1. Motivation

- **Er^{3+}- doped tungsten-tellurite glasses - 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.**
- **$Bi_4Ge_3O_{12}$ (eultine type BGO) - well known scintillator material, also a rare-earth host material, photorefractive waveguides produced in it only using light ions in the past. Recently: MeV N^+ ions and swift O^{5+} and C^{5+} ions, too*.**
- **$Bi_{12}GeO_{20}$ (sillenite type BGO) - high photoconductivity and photorefractive sensitivity in the visible and NIR – good candidate for real-time holography and optical phase conjugation, photorefractive waveguides produced in it only using light ions. No previous attempts of ion beam fabrication of waveguides in it.**

***J. Yang, et al, Appl. Optics , 50, 6678 (2011)**

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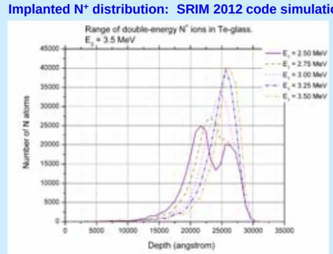
2. Design and fabrication of the waveguides

2.1 SRIM calculations

2.1.1 Single- and double energy N^+ ion irradiation in Er: Tungstene-Tellurite glass

Mechanism of waveguide formation : Reduced refr. index barrier layer around stopping range (dominant nuclear interaction)*

Implanted N^+ distribution: SRIM 2012 code simulation



*** I. Bányász, et al, IEEE Photonics Journal, 4, 721-7 (2012)**

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Fig. 1 Algebraic sum of the pairs of calculated N^+ distributions along the sample depth.

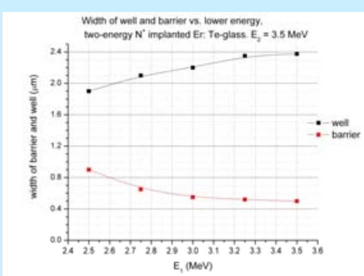

Fig. 2 Widths (at half maximum of the N^+ distribution) of well and barrier layers *vs.* lower energy of N^+ irradiation. Higher energy is kept constant at 3.5 MeV.

Irradiation conditions (at Wigner Research Centre, Budapest)
Energy combinations: 3.5 MeV, 3.5 + 3.0 MeV and 3.5 + 2.5 MeV
Total irradiadiaton fluences: $10^{15} < F < 10^{17}$ ions/cm^2

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2.1.2 Single- and double-energy N^+ ion irradiation in eulityne ($Bi_4Ge_3O_{12}$) and sillenite ($Bi_{12}GeO_{20}$) type Bismuth Germanate crystals

Mechanism of waveguide formation : Reduced refr. index barrier layer around stopping range (dominant nuclear interaction) *.

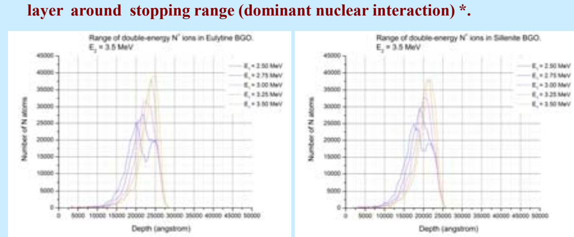

Fig. 3 Double –energy N^+ distributions along the sample depth in eulytine (left) and sillenite (right) type BGO crystals.

***I. Bányász, et al, NIM-B, 286, 80–84 (2012).**

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Irradiation conditions (at Wigner Research Centre, Budapest)
Energy combinations: 3.5 MeV, 3.5 + 3.25 MeV and 3.5 + 2.75 MeV
Total irradiadiaton fluences: $10^{15} < F < 10^{17}$ ions/cm^2

2.1.3 Waveguide fabrication via irradiation of sillenite ($Bi_{12}GeO_{20}$) type Bismuth Germanate crystals with 25 MeV C^{5+} ions

Mechanism of waveguide formation : A reduced refr. index amorphous barrier layer is created around the maximum of the electronic stopping power , $S_e(z)$. Its thickness is controlled by the irradiated (low or ultralow) fluence (use of the electronic interaction) *.

Irradiation conditions (at CMAM, UAM, Madrid)
Energy : 25 MeV
Angles of incidence: 60˚ and 70˚.
Total irradiadiaton fluences: $10^{13} < F < 10^{15}$ ions/cm^2

*J. Olivares, et al, Appl. Phys. Lett., 86, 183501 (2005)

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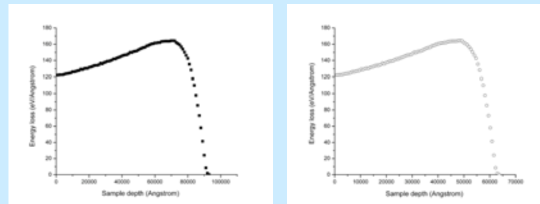

Fig. 4 SRIM calculation of $S_e(z)$ for 25 MeV C^{5+} with corrections for angle of incidence of 60 ˚ (left) and 70˚ (right) in sillenite type BGO crystal.

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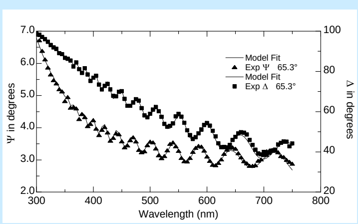
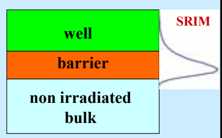
3. Spectroscopic ellipsometry

Spectroscopic ellipsometer used: WOOLLAM M-2000DI.





Optical model: 2-layer Cauchy dispersion

Fig. 5 Measured and simulated ellipsometric spectra of a waveguide in an Er:Te glass, obtained with 1.5 MeV N^+ ions at a fluence of 4 x 10^{16} ions/cm^2.

ψ = relative intensity change at reflection
Δ= relative phase change at reflection

$$\rho = tg\,\Psi\, e^{i\Delta}$$

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3.1 Results for Er:Te glass

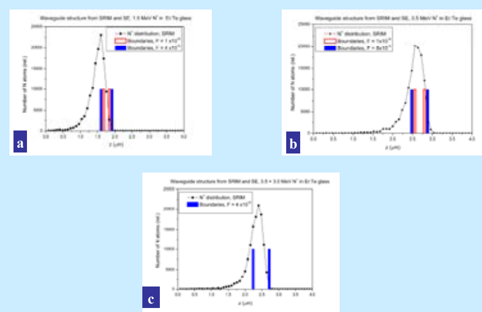

Fig. 6 SRIM simulation and SE fit of the waveguide structure in Er: Te glass at various irradiation energies and fluences: **a)** E = 1.5 MeV, fluences are 1 ·10^{16} and 4 ·10^{16}. **b)** E = 3.5 MeV, fluences are 1 ·10^{16} and 8 ·10^{16} ions/cm^2. **c)** E = 3.5 MeV + 3.0 MeV, fluence is 4 ·10^{16} ions/cm^2.

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3.2 Results for Eulytine and Sillenite type BGO

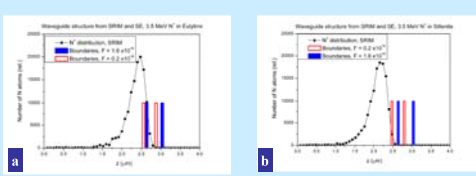

Fig. 7 SRIM simulation and SE fit of the waveguide structure in BGO and CaF_2 with 3.5 N^+ irradiation at various fluences: **a)** Eulytine, fluences are 0.2 ·10^{16} and 1.6 ·10^{16}. **b)** Sillenite, fluences are 0.2 ·10^{16} and 1.6 ·10^{16} ions/cm^2..

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4. M-line spectroscopy

COMPASSO, a semi-automatic m-line spectroscopic instrument, developed at IFAC, was used for the characterization of the planar waveguides implanted in the samples, except of the 25 MeV C^{5+} irradiated sillenite type BGO.

With COMPASSO, multi-wavelength m-line spectroscopy was perfumed at the following wavelengths:

635, 980, 1310 and 1550 nm.

Accuracy of the instrument is generally ±1·10^{-4} and ±4·10^{-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 ±5·10^{-4} and ±1·10^{-3} respectively. Due to the high refractive index of the bulk Er: Te glass (around 2.0 at 635 nm), and even higher of the sillenite BGO (about 2.55 at 635 nm) we used special rutile prisms to couple the light in the irradiated regions. **All the measurements presented here were performed in TE configuration**.

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4.1 Results for Er:Te glass

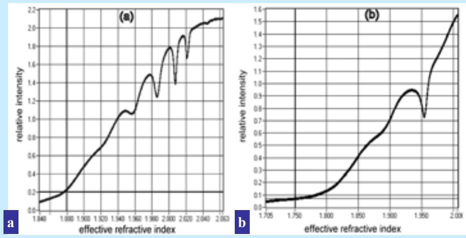

Fig. 8 M-line spectra of a waveguide in Er: Te glass. Fluence = $8 \cdot 10^{16}$ ions/cm^2, E =3.5 MeV. (a) at 635 nm and (b) at 1550 nm.

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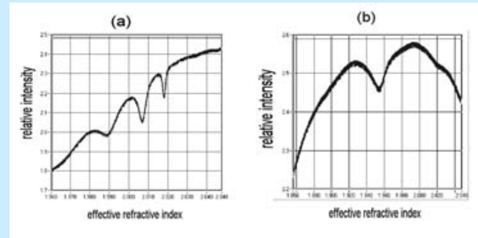

Fig. 9 M-line spectra of a waveguide in Er: Te glass, with double energy N^+ ions at 3.5 MeV and 3.0 MeV, taken at 635 nm (a) and 1550 nm (b).

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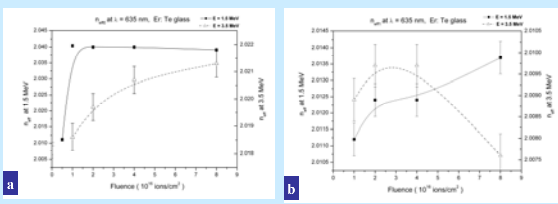

Fig. 10 Effective refractive indices of the **a)** fundamental and **b)** first modes *vs.* fluence at λ = 635 nm for 1.5 MeV N^+(full squares) and 3.5 MeV N^+ (open triangles), Er: Te glass. Note the different abscissas for the two curves.

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4.2 Results for Eulytine and Sillenite type BGO

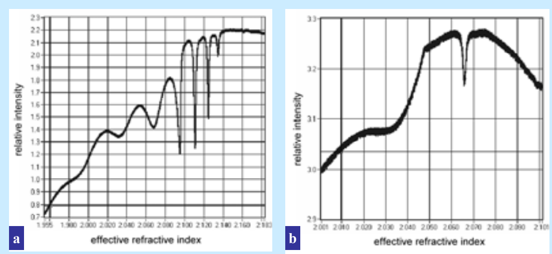

Fig. 11 M-line spectra of waveguide in Eulytine BGO. **a)** N^+ Fluence = $1.6 \cdot 10^{16}$ ions/cm^2, E =3.5 MeV. at 635 nm and **b)** at 1550 nm.

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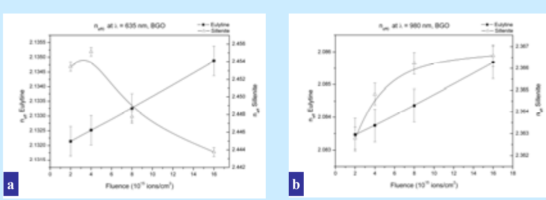

Fig. 12 Effective refractive indices at **a) 635 nm** and **b) 980 nm** of the fundamental mode *vs.* fluence for **Eulytine** (full squares) and **Sillenite** (open triangles) type BGO, irradiated with 3.5 MeV N^+. Note the different abscissas for the two curves in both graphs.

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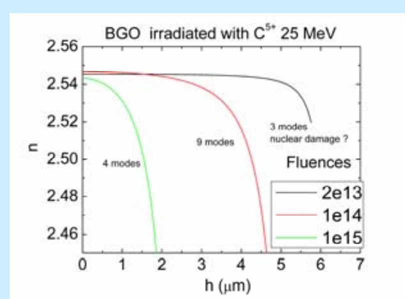

Fig. 13 Calculated refractive index profile of the waveguides in Silenite type BGO irradiated with 25 MeV C^{5+} ions. Angle of incidence was 60°.

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5. Conclusion and outlook

Working barrier-type slab waveguides in Er: tungsten-tellurite glass, and in Eulytine and Sillenite type BGO fabricated by 2.5 – 3.5 MeV **N⁺** and 25 MeV C^{5+} ion irradiation, **up to λ = 1550 nm.**

Double-energy **N⁺** ion irradiation in in Er: tungsten-tellurite glass to suppress leaky modes and reduce propagation loss thanks to a thicker barrier layer.

A new method for waveguide characterization, making use of the multiwavelength m-line measurements has been developed (not discussed here) and is being improved by Dr. Stefano Pelli.

Propagation loss measurements in new single- and double N⁺ ion irradiated planar waveguides of increased lateral dimensions are under way.

Annealing experiments with all the availabe ion beam irradiated waveguides are under way.

Refinement of spectroscopic ellipsometric model needed.

Special thanks to: Prof. M. Bettinelli and A. Speghini of the University of Verona for the Er:Te glass samples, to Mr. R. Calzolai of IFAC, Sesto Fiorentino and Mr. Gy. Matók of the Wigner research centre for polishing the glass and crystal samples.

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Thank you!

Preguntas

問題

и замечания

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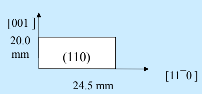
The materials

Composition of the **Er: tungsten - tellurite glass**: 60 TeO_2 – 25 WO_3 – 15 Na_2O – 0.5 Er_2O_5 (mol%)

$Bi_4Ge_3O_{12}$ (eulytine type)
Thickness = 1 mm

$Bi_{12}GeO_{20}$ (sillenite type)
of the same orientation and thickness, but 14.0 mm x 21.5 mm.



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Waveguide Characterization

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, 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.

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

The fitting 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 the above equation.

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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. 14**) and the calculated effective indices is very good. Thickness of the guiding layer was assessed to be 2.2 m, in agreement with SRIM simulations.

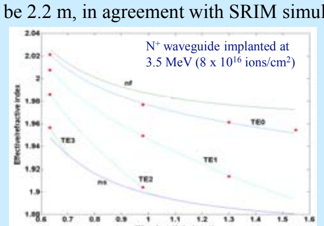

Fig. 14 Reconstruction of the refractive index of the guiding and barrier layers as a function of the wavelength. Sample irradiated with 8 $\cdot 10^{16}$ ions/cm² . Calculated effective indices of the modes are also shown.

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