Photorefractive effect and optical damage thresholds in z-cut swift heavy ion irradiation $LiNbO_3$ waveguides.

M. Jubera, A. García-Cabañes and M. Carrascosa.
Dpto. de Física de Materiales
Universidad Autónoma de Madrid
Madrid, Spain.
mariano.jubera@uam.es

J. Olivares[1] and F. Luedtke[2]
CMAM and Instituto de Óptica[1], Institute of Physics[2]
Universidad Autónoma de Madrid and CSIC[1], University of Bonn[2]
Madrid, Spain[1]; Bonn, Germany[2]

Abstract: We have investigated the photorefractive effect and the corresponding optical damage thresholds of novel $LiNbO_3$ waveguides fabricated by swift-ion irradiation. TE- and TM-mode operation has been characterized and the influence of the beam propagation length analysed. The results are briefly discussed and compared with some data from other type of $LiNbO_3$ waveguides.

I. INTRODUCTION

Photorefractive optical damage is a main drawback for high power photonic devices based on $LiNbO_3$ crystals and waveguides. Thus, a great effort has been devoted to characterize and reduce it. Particular attention has been paid to waveguide configurations because the long propagation lengths and the high intensities reached increase optical damage effects. Most experiments have been performed in Ti-undiffused and PE waveguides whereas the information is scarcer for ion implanted waveguides [1].

Recently, a new method to produce nonlinear $LiNbO_3$ optical waveguides by swift ion irradiation has been reported [2]. It involves irradiation of the substrate with swift-heavy ions (SHI), such as F at 20 MeV, whose electronic stopping power reaches a maximum value inside the crystal instead of on the surface. As a very low fluence ($1\text{-}4\times10^{14}$ cm^{-2}) is sufficient, the fabrication time is reduced by about three orders of magnitude in comparison with similar guides prepared by conventional implantation. The guides, at difference with proton-exchanged (PE) waveguides, support ordinarily and extraordinarily polarized modes showing in both cases step-like, high-jump index profiles (Δn_e=0.1, Δn_o=0.2). Furthermore, good nonlinear and electroptical coefficients have been reported [2,3]. Very recently, using high temperature annealing treatments (350-375 ºC) propagation losses have been reduced under 0.5 dB/cm [4], so that SHI waveguides become very competitive for photonic applications. However, photorefractive optical damage effects have been studied only preliminarily and using non-optimized waveguides with high propagation losses of 1-5 dB/cm [3]. Moreover, those data were taken from a *X*-cut configuration although Z-cut geometries, are usually preferred for efficient non linear applications.

The aim of this work is to address a detailed investigation of photorefractive optical damage of Z-cut $LiNbO_3$ planar waveguides using two complementary approaches: *i)* determination of optical damage thresholds, i.e. maximum light intensity supported by the waveguide without distortion and *ii)* measurements of the corresponding light induced refractive index changes responsible for the beam damage. TE- and TM-mode operation will be characterized and the influence of the propagation length analysed. The results are briefly discussed and compared with some data from other type of $LiNbO_3$ waveguides.

II. EXPERIMENTAL DETAILS.

Planar waveguides have been fabricated by swift ion irradiation (F-20 MeV) on *z*-cut congruent $LiNbO_3$ substrates in the 5 MV Tandem Accelerator at University Autónoma of Madrid. Propagation losses were measured obtaining values below 0.5 dB/cm for both polarizations.

A standard single-beam method using in- and out-coupling rutile prism-couplers, as described in Ref. [5] was used to determine optical damage thresholds (ODT) for two optical different path lengths l of 4 and 16 mm. The optical damage threshold is defined by the in-coupled intensity I_{in} inside the guide at which the out-coupled intensity I_{out} is no longer proportional to I_{in}. In turn, a Mach-Zehnder interferometer is used for the quantitative measurement of light-induced index changes [6]. Optical damage is induced by light of 532 nm wavelength and probed with red light of 633 nm wavelength.

III. RESULTS AND DISCUSSION.

The light-induced refractive index change generated by the TE fundamental mode at λ=532 nm as a function of the light beam intensity inside the waveguide I_{in} has been measured using the Mach-Zehnder technique. Both TE (n_o) and TM (n_e) polarized probe beams at λ=630 nm have been used and the corresponding results are shown in Fig. 1. The obtained curves $\Delta n(I)$ follows the typical shape reported for α-phase proton exchanged waveguides in [6] and successfully explained through a two-centre model in [7]. Then these data can be considered a further confirmation of the validity of that model for the photorefractive effect in $LiNbO_3$ waveguides. At each intensity, Δn for the TM mode is larger than that for TE and, the relation is roughly consistent with the rate $n_e^3 r_{33}/n_o^3 r_{13}=2.8$ (where r_{33} and r_{13} are the corresponding electrooptic coefficients). This indicates that, as expected, these differences arise from the electrooptic effect. The maximum refractive index change is 2.5×10^{-4} and 10^{-4} for TM (n_e) and TE (n_o) modes. Moreover, Δn_e coincides roughly with the values measured for soft proton exchanged waveguides ($2x10^4$) [6]. Finally, when optical damage is induced by TM instead of TE modes, very similar curves to those of Fig. 1 have been obtained reaching the same Δn saturating values.

Optical damage thresholds have been measured for TE and TM modes and two propagation lengths l. The results for l=16 mm are illustrated in Fig. 2. The ODT values are ~40 and ~100 W/cm^2 for *TM* and *TE* laser beam propagation respectively. The lower intensity threshold for TM modes is consistent with the higher photorefractive index change exhibit in Fig. 1. For l=4 mm the intensity threshold shifts to higher light intensities for both polarizations (roughly a factor 6). This result shows the key role played by the propagation length in the ODT although it is rarely considered.

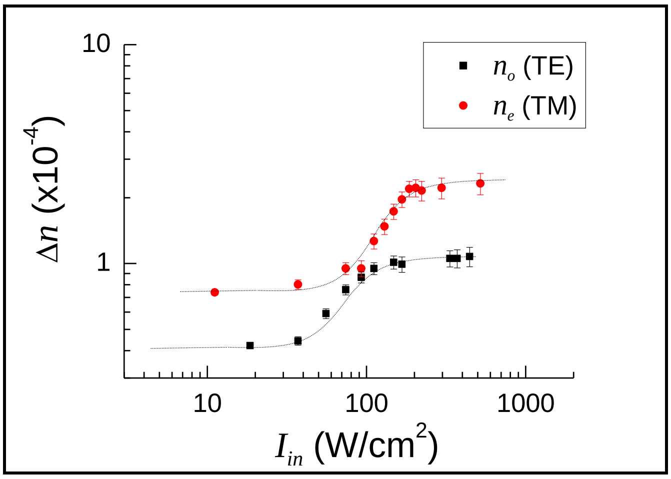

Figure1. Logarithmic plot of the photorefractive index change Δn_e (circles) and Δn_o (squares) versus the light intensity I inside the waveguide.

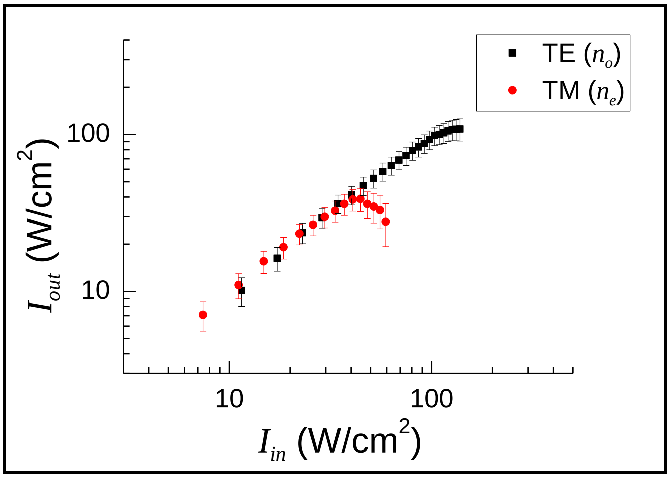

Figure 2. Logarithmic plot of the output intensity I_{out} versus input intensity I_{in} inside the waveguide for TE (squares) and TM propagating fundamental modes (rhombus)

In summary, the photorefractive effect of SHI $LiNbO_3$ waveguides has been characterized finding an intensity response in accordance with the recently reported two-center charge transport model [7]. In addition, the optical damage thresholds for TE and TM polarizations have been determined obtaining values that decrease with the propagation length and that are roughly similar to those of PE waveguides.

ACKNOWLEDGMENT

This work was supported by MICIN, MAT2008-06794-C03 and MAT2011-28379-C03-01.

REFERENCES

[1] D. Kip and M. Wesner, “Photrefractive waveguides,“ in Phtorefractive Materials and their applications I: Fundamental phenomena (Springer Berlín, 2006)

[2] J. Olivares, G. García, A. García-Navarro, F. Agulló-López, O. Caballero and A. García-Cabañes, “Generation of high-confinement step-like optical waveguides in LiNbO3 by swift heavy ion-beam irradiation,” Appl. Phys. Lett. **86**, 183501 (2005).

[3] J.Villarroel, M. Carrascosa, A. García-Cabañes, O. Caballero, M. Crespillo and J. Olivares, “Photorefractive response and optical damage of lithium niobate optical waveguides produced by swift-heavy ion irradiatio”, Appl. Phys. B **95**, 429-433 (2009)

[4] M. Jubera, J. Villarroel, A. García-Cabañes, M. Carrascosa, J. Olivares, F. Agullo-López, A. Méndez and J. B. Ramiro, “Analysis and optimization of propagation losses in $LiNbO_3$ optical waveguides produced by swift heavy-ion irradiation”, Appl. Phys. B, 10.10007/S00340-012-4897-9, (2012), in press.

[5] O. Caballero-Calero, A. Alcázar, A. García-Cabañes, J. M. Cabrera and M. Carrascosa, “Optical damage in x-cut proton exchanged $LiNbO_3$ planar waveguides,” J. Appl. Phys. **100**, 093103 (2006).

[6] F. Luedtke, J. Villarroel, A. García-Cabañes, K. Buse and M. Carrascosa, “Correlation between photorefractive index changes and optical damage thresholds in z-cut proton-exchanged-$LiNbO_3$ waveguides,” Opt. Express **17**, 658 (2009).

[7] J. Villarroel, J. Carnicero, F. Ludtke ,M. Carrascosa, A. García-Cabañes, J. M. Cabrera, A. Alcazar and B. Ramiro, “Analysis of photorefractive optical damage in lithium niobate: Aplication to planar waveguides”; Opt. Express **18**, 20852-20861 (2010).