# Recent achievements in $LiNbO_3$ waveguides fabricated by swift heavy ion irradiation


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***Abstract*— Optical waveguides having some unique characteritics can be fabricated in Lithium niobate using high energy heavy ions. High optical confinement or very thick optical waveguides can be obtained using moderate ($10^{14}$ cm$^{-2}$) or even ultralow ($10^{11}$ cm$^{-2}$) fluences. The method has also been applied to other crystals of photonic interest. We present a review of the recent achievements obtained.**



***Lithium niobate, nonlinear optical waveguides, ion irradiation, nanostructures, nanotracks***


## I. INTRODUCTION

Recently, novel methods for waveguide fabrication have been proposed and tested [1-3] for $LiNbO_3$ substrates, that use heavy-mass ions at energies in the range 5-50 MeV, that require much shorter irradiation fluences ($10^{12}$ - $10^{15}$ cm$^{-2}$) than in standard ion implantation. In these methods the crystal amorphization is produced by electronic excitation processes and not elastic collision mechanisms and/or implantation of foreign atoms. The involved physical mechanisms are not yet sufficiently known and intense activity is now devoted to their clarification [4-7]. At variance with light ion implantation these methods rely on the electronic energy deposition (stopping power) and the subsequent relaxation of the excitation into structural defects. The fabricated waveguides present several relevant advantages over those fabricated by conventional low energy light ion implantation [8-9]. For example, they have step-like and high-jump index profiles (~0.2 and ~0.1 for ordinary and extraordinary refractive indexes respectively) and thick easily controllable amorphous layers that allow for supporting highly confined propagation modes. Since a low irradiation fluence is sufficient ($\approx 10^{14}$ cm$^{-2}$) to produce the waveguides, the fabrication time may be reduced up to two orders of magnitude in comparison with the implantation case. Moreover, good nonlinear optical and photorefractive properties have been already reported [1,3]. In fact, novel microring optical resonators have been recently achieved [10].

The purpose of this paper is to report on our new recent achievements and results concerning the potential and promising properties of those novel waveguides.

## II. CONTROL AND OPTIMIZATION OF PROPAGATION LOSSES

Preliminary reported values for propagation losses (PL) yielded values ranging between 1-10 dB/cm [1], which was still high for many applications. In order to reduce PL a systematic study has been carried out for the SHI waveguides looking for an optimized response. Suitable post-irradiation annealing treatments reaching higher temperatures than those previously used, i.e. T~300 ºC, were implemented. We have demonstrated the feasibility of markedly reducing optical losses when annealing treatments in the range (300-375 ºC) are applied. Values under 0.5 dB/cm for both polarizations have been achieved as listed in Table I

Table I: Values of the propagation losses (PL) measured in a planar waveguide fabricated by fluorine ions at 20 MeV and a fluence of $4\times10^{14}$ cm$^{-2}$, after two annealing treatments indicated in the Table. $n_o$ and $n_e$ indicate ordinary and extraordinary polarizations, respectively.

| ***T* (ºC)** | ***Time* (h)** | ***PL-$n_o$* (dB/cm)** | ***PL-$n_e$* (dB/cm)** |
|---|---|---|---|
| 350 | 1 | 0.3 | 1.5 |
| 375 | 0.25 | <0.3 | 0.5 |

Good quality planar waveguides have been obtained in congruent LiNbO3 substrates as well as on those doped with Mg. This doping is shown to enhance the optical damage resistivity of the material and it may be particularly useful for high power NLO applications

## III. CHANNELLED WAVEGUIDES

In addition to planar waveguides channeled waveguides have also been produced. A two step procedure has been followed. First, planar waveguides were fabricated by soft proton exchange. Then, $SiO_2$ or aluminium stripped masks were photo-litographically made on top of the waveguide. Finally, in order to obtain the channel waveguides the samples were irradiated with Br ions at 12 MeV. The masks stop the ions and preserve the waveguide previously recorded structure in the protected region. In the areas free of masks, the ion irradiation produces an amorphous layer of 2-3 μm thick with an isotropic refractive index around 2.10 (for $\lambda$ = 633 nm) lower than the refractive index of the previous waveguide. In Fig.1 a microphotograph of the $LiNbO_3$ surface is shown where two channel waveguides of 12 μm and 20 μm wide can be distinguished.

## IV. THICK WAVEGUIDES FOR IR APPLICATIONS

Using higher energy ions, thicker waveguides can be achieved with potential application in the medium infrared. Heavy mass ions, Kr and Xe, having energies of 809 MeV and 1.43 GeV, respectively, were used to produce planar optical waveguides, using fluences as low as $2x10^{11}$ at/cm$^2$. The irradiations were performed [11] on Z-cut samples at GANIL (Caen, France) and GSI (Darmstadt, Germany). The waveguides had a thickness of 40-50 μm, a refractve index jump of up to 0.04 and propagate both TE and TM polarizations.

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