Proton-exchanged $LiNbO_3$ waveguides for photonic applications

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ABSTRACT
This talk shall provide an overview of the current activity on integrated $LiNbO_3$ devices based on proton-exchange techniques at the ORC. We shall present the technology and the experimental results obtained so far on slab waveguides in 2D Nonlinear Photonic Crystals and on channel waveguides in Periodically Poled Lithium Niobate and discuss perspective applications for all-optical signal processing in ultra-fast fibre telecom systems.

Keywords: Lithium Niobate, Nonlinear Optics, Integrated Optics, All-optical devices

1. INTRODUCTION

Lithium niobate ($LiNbO_3$) has become a very attractive material for integrated optical applications because of its excellent electro-optical, acousto-optical and nonlinear optical properties.

The fabrication of waveguides in $LiNbO_3$ and $LiTaO_3$ crystals by means of proton exchange (PE) dates back to 1982 [1] and since then extensive work has been carried out on its many possible implementations. The PE process has proven to be a simple and effective method of fabricating low-loss waveguides in $LiNbO_3$ crystals that has the advantage, with respect to the Ti-indiffusion method [2], of a much higher photorefractive damage threshold [3] and much lower process temperatures.

Lithium Niobate ($LiNbO_3$) waveguides are already widely used in many functional electro-optic and acousto-optic waveguide devices. In more recent years, they have also been emerging as the most promising candidates for the development of all-optical devices based on quadratic nonlinearities, due to substantial technological advances in ferroelectric domain micro-structuring (the "poling" technology) that provided an effective way to implement the Quasi-Phase-Matching (QPM) principle [4].

Progress in waveguide and poling technologies has increased the efficiency of quadratic ($\chi^{(2)}$) interactions in $LiNbO_3$ by more than a factor of 10^4 since the initial demonstrations of blue and green light generation [5]. Nowadays, the best nonlinear optical devices in $LiNbO_3$ [6, 7] have reached efficiencies in excess of 3000 % W^{-1} or 100 % $W^{-1}cm^{-2}$. The variety of applications of $\chi^{(2)}$ devices has also increased: Periodically Poled $LiNbO_3$ (PPLN) waveguides can not only provide coherent sources ranging from the ultraviolet [8] through to the mid-infrared [9] but also signal processing devices for optical communications [10].

Our work at the ORC has focused on the development of a research activity on proton-exchanged waveguides, aiming at the realisation of novel functional nonlinear devices in $LiNbO_3$. Our main target is the development of devices for all-optical signal processing in fibre telecom systems, although numerous applications can also be envisaged in other fields such as spectroscopy, fundamental nonlinear optics, ultrafast optics and quantum optics.

2. THE TECHNOLOGY

Integrated nonlinear optical devices in $LiNbO_3$ rely heavily on cutting-edge technologies for micro-structuring and engineering the linear and nonlinear properties of the material. Their fabrication process needs to meet more and more stringent tolerances and demanding specifications as the complexity and functionality of the devices grows. Two basic technologies are fundamental for our work:

- ferroelectric domain micro-structuring through *electric field periodic-poling*, a well-developed area of research within the ORC [11]
- waveguide fabrication by *proton-exchange* (in its multiple variations, including post-exchange annealing and Reverse Proton Exchange (RPE) [12]).

2.1 Electric field poling

Nowadays, the electric field poling is a well-known and consolidated technique for achieving QPM in $LiNbO_3$. By applying an electrical field exceeding the coercive value (~21 kV/mm, i.e. ~10.5 kV for our 500μm–thick

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crystals) though patterned electrodes, 1 or 2D arrays of ferroelectric domains of alternating polarity can be “written” in the crystal with the desired periodicity (normally > few microns). The technique we currently employ for poling features greater than 4 μm involves photolithographic patterning though standard photoresist on the –z face, followed by the application of high voltages in a current-controlled poling process, through a conductive gel which is in direct contact with the crystal surface in the photoresist openings [11].

Although the poling technology has reached a relative high maturity, good uniformities in large-area (cm^2) 2D patterns and good control over the domain size with submicron scale accuracy require special care and expertise. The pictures below show some of the structures we poled for recent experiments:

- an Hexagonally Poled $LiNbO_3$ (HexLN) sample (total patterned area = 20 mm x 8 mm) designed for guided-wave quadratic interactions around 1.54 μm (poling period = 14.4 μm instead of the 18 μm required by the same interaction in the bulk).
- the first 2D quasi-crystal, poled according to a Penrose-tiling pattern (each pattern = 20 mm x 1 mm), used in Second Harmonic Generation (SHG) experiments at 1.536 μm [13];
- PPLN patterns designed to be combined with multiple channel waveguides for quadratic experiments at telecom wavelengths (Bands with different periods: 14.5-16.5μm, 26 mm long).

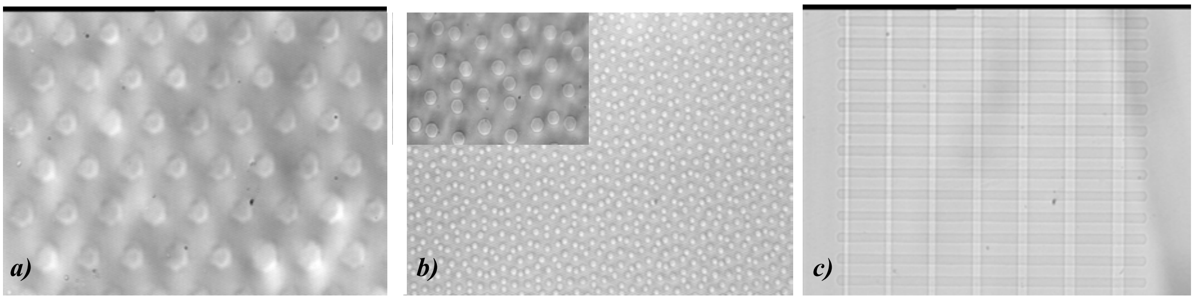

Figure 1. *a)* a 2D nonlinear photonic crystal: Hexagonally poled $LiNbO_3$ with a period of 14.4 μm; *b)* a 2D nonlinear photonic quasi-crystal: hexagonal domains arranged according to a Penrose tiling pattern with an average period of 19.3 μm; *c)* a 15μm-period PPLN band with several channel waveguides;

2.2 Proton-exchanged waveguides

Proton-exchange has long been used to fabricate waveguides in $LiNbO_3$ [1]. Among its many implementations, those that have proven most effective so far for nonlinear optical applications involve Proton Exchange (PE) in diluted melts [14] or in benzoic acid followed by thermal annealing (APE=Annealed Proton-Exchange) [15], for *surface waveguides,* and APE followed by a Reverse Proton Exchange [12], for *buried waveguides*. We have chosen to concentrate our efforts mainly on the latter technique, which only in recent times has been successfully used for quadratic interactions [6, 16], yielding the highest normalised efficiencies to date for $\chi^{(2)}$ interactions in the telecom band [6].

The waveguide fabrication process is sketched in Fig. 2. It consists of an initial PE carried out at around 160 °C which produces a relatively deep (≥ 1μm) step-index waveguide, followed by an annealing at ~ 330 °C that turns it into a deeper graded index surface waveguide. Finally a last RPE step, carried out in a Li-rich mixture of salts ($LiNO_3$, $NaNO_3$, KNO_3), yields the desired buried waveguide (for extraordinarily polarised light only, i.e. TM modes in z-cut substrates). For the fabrication of waveguide channels, the same PE-anneal-RPE sequence is performed through a photolithographically defined mask that allows the exchanges to take place only in selected portions of the crystal surface.

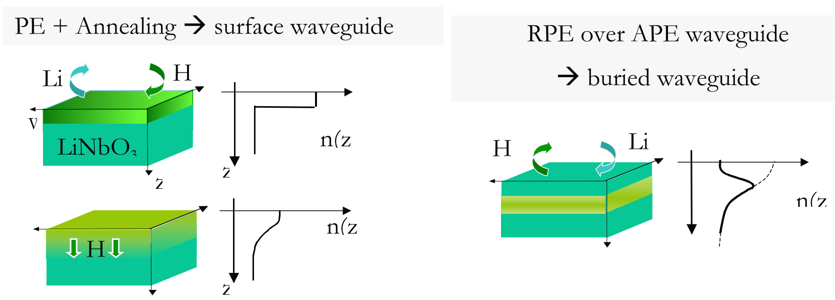

Figure 2. Sketch of the three-step fabrication process for buried RPE waveguides in $LiNbO_3$

2.3 Novel technological solutions

Despite their relative maturity, the poling and PE technologies can still provide novel research activities. For instance, as an alternative to common practice for PE waveguides, it is interesting to reverse the usual sequence of poling + waveguide fabrication. This could potentially reduce waveguide losses and inhomogeneities (which can result from surface contamination or degradation sometimes associated to the poling step), although at the expense of increased complexity in the poling process. The feasibility of this solution with traditional voltage-controlled poling has been demonstrated over RPE waveguides [16] and we have also further tested it by performing "surface polings" on APE slabs [17].

Another idea we have been exploring combines proton-exchange and UV laser writing to create guiding channels within buried (RPE) and surface (APE) slab waveguides, a method that has the appeal of employing a one-step maskless process and could in principle be applied to the direct-writing of arbitrary optical circuits. In a first series of experiments we were able to obtain good confinement at telecom wavelengths [18]. Fig. 3 reports specific results obtained by UV writing on two slab waveguides made under the following conditions:

- APE slab: (*PE in pure benzoic acid: 159^{o}C, 15 hours) + (Annealing: 325 ^{o}C, 26 hours)*
- RPE slab: *(PE: 158^{o}C, 31 hours) + (Annealing: 325 ^{o}C, 8.5 hours) + (RPE: 330 ^{o}C, 10.5 hours)*

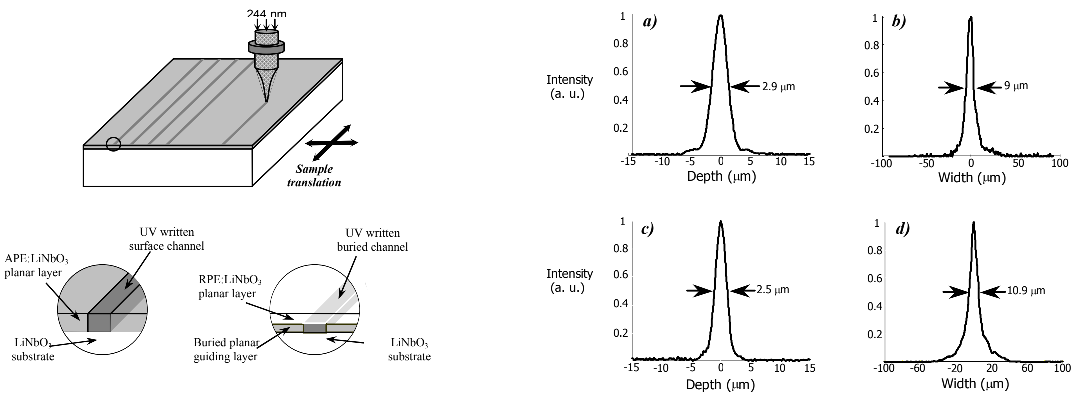

Figure 3. *Left:* sketch of the UV writing of guiding channels in surface (APE) and buried (RPE) slabs; *Right:* near field intensity distribution of the light guided at 1550 nm by channels written in: *a)-b)* an APE sample: vertical and lateral intensity distributions for a channel written at a speed of 800 mm/min; *c)-d)* an RPE sample: vertical and lateral intensity distributions for a channel written at a speed of 50 mm/min. In both cases the UV writing power and beam spot size were 40 mW and 7μm, respectively.

3. GUIDED-WAVE QUADRATIC INTERACTIONS

Our experimental work on nonlinear guided-wave optical interactions has been following two main directions: on one side we concentrated on the combination of slab waveguides with 2D nonlinear photonic crystals [19], while on the other we developed a parallel activity on PPLN channels.

3.1 Slab waveguides in Nonlinear Photonic Crystals (NPC)

Quadratic planar waveguides in NPC's hold promise for increasing the conversion efficiencies by one order of magnitude with respect to the bulk [20], due to the transverse 1D field confinement, while still preserving all the degrees of freedom of the 2D NPC structure.

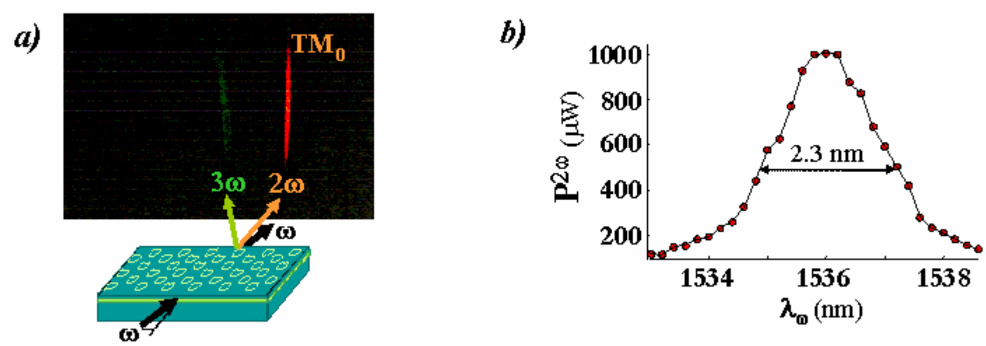

Figure 4. *a)* Sketch of the NPC buried slab structure and image of the red and green TM_0 mode outputs. Wavelength tuning curve for SHG from a 15 mm long slab waveguide in HexLN (period = 14.4μm).

So far by using planar waveguides made by annealed and reverse proton exchange on HexLN we have reached internal efficiencies of the order of 0.05 % $W^{-1}cm^{-1}$ (for a 15 mm long sample and a beam size of 100µm in the "free" transverse direction) [21]. These results could still in principle be improved and to this aim we are currently working at a joint optimisation of the HexLN and of the waveguide fabrication, as well as at the experimental conditions (optimised spatial shaping of the input beams and wavelength tuning instead of temperature tuning in SHG).

3.2 Channel waveguides in PPLN

In developing the process for channel waveguides in PPLN samples (fig.1c) we have been following the guidelines set by previous results obtained on buried PPLN waveguides, made by the RPE technique [6, 16]. Work is under way to further improve our fabrication process, nevertheless, some of the waveguides we produced so far are already efficient enough (normalised efficiency ~ 60% $W^{-1}cm^{-2}$) to be tested in more sophisticated experimental set-ups, such as all optical samplers or correlators based on $\chi^{(2)}$ interactions [22].

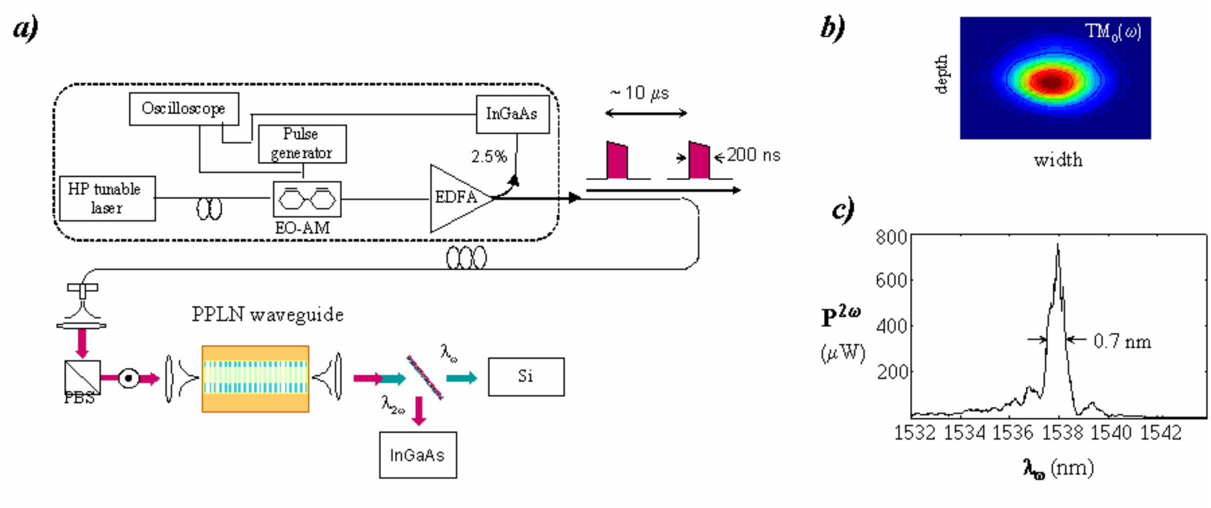

Figure 5. *a)* Experimental setup used in the nonlinear characterisation of the PPLN channels; *b)* Intensity distribution of the TM_0 mode at 1550 nm at the output of a buried channel (width = 8 µm); *c)* SHG tuning curve of a 26mm long, 6µm wide waveguide (PPLN period = 15µm, average input (external) power ~ 30 mW).

4. CONCLUSIONS

We provided an overview on the ongoing work on proton-exchanged $LiNbO_3$ waveguides at the ORC and discussed the most relevant experimental results we have got so far in the implementation of quadratic interactions in (1D and 2D) guided-wave configurations. This work is targeting devices based on quadratic nonlinearities for all-optical signal processing in fibre telecom systems. Efficient integrated nonlinear optical frequency mixers in $LiNbO_3$ could serve as optical wavelength converters, spectral inverters, or gated mixers for wavelength and time-division multiplexed systems and would play a key role in the development of transparent all-optical networks.

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