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Surface hexagonally poled lithium niobate waveguides

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Abstract

We report on surface hexagonally poled lithium niobate for two-dimensional non-linear interactions in optical waveguide structures. A method for surface inversion of ferroelectric domains has been applied for the fabrication of a hexagonal two-dimensional periodic domain structure with a period of 7.6 μm on an annealed proton exchanged lithium niobate waveguide. This periodic pattern is suitable for quasi-phase-matched second harmonic generation at the fundamental wavelength of 1.06 μm by means of the first order (G_{10}) reciprocal lattice vector.

Keywords: lithium niobate waveguides, ferroelectric domain engineering, frequency conversion

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As the area of nonlinear optics continues to expand and new applications appear there is a constant demand for more efficient miniaturized devices. Lithium niobate ($LiNbO_3$) is a nonlinear optical material that contributes significantly in this area due to its numerous useful properties. Lithium niobate waveguide structures are commonly used in the telecom industry for high speed optical switching but research is increasingly associated with the expansion of its use in frequency conversion and higher harmonic frequency generation.

The development of ferroelectric domain engineering allows direct access to the largest nonlinear coefficient d_{33} via highly efficient quasi phase matched (QPM) harmonic generation by periodic domain inverted structures in both bulk and waveguide format [1,2]. Furthermore, expansion of periodically poled $LiNbO_3$ structures into two-dimensional (2-D) geometries has been successfully demonstrated for both single and cascaded nonlinear interactions on the same sample [3] in bulk hexagonally poled lithium niobate (HexLN). Application of 2-D poled structures in waveguide geometries is expected however to enhance the efficiency of such devices mainly due to the tight waveguide mode confinement.

The possibility of expanding the operation of these 2-D inverted domain structures to shorter wavelengths would also be useful but the limitations of conventional electric field poling become apparent when fabrication of the short period inverted domain structures, which are required for short wavelength frequency conversion applications, is attempted. Using a technique therefore of surface domain inversion would be suitable for such short period waveguide applications due to its capability for poling short period structures and its compatibility with waveguide geometries. By inverting the ferroelectric domains in a few μm thick layer only the aspect ratio domain instability problem is overcome and short period poled structures are feasible.

To date, inverted one dimensional domain structures with a period of order ~1 μm have been achieved [4]. Here we demonstrate the application of the surface poling technique for the fabrication of a short period 2-D hexagonally poled nonlinear lattice on an annealed proton exchanged lithium niobate planar optical waveguide.

Full details of the surface poling technique are given in [4]. Briefly, however, the method is based on the observation that the area below a photoresist patterned sample will maintain its domain orientation upon "overpoling" of the whole area due to compensating trapped charges in the interface between the photoresist and the lithium niobate surface.

The amount of charge which is required to domain invert an area A is : $Q=2\times A\times P_s$, where Q is the calculated charge, and P_s is the spontaneous polarization of lithium niobate (0.72 μC/mm^2). An additional external empirical factor (EF) is also usually taken into account in conventional poling, to correct for variations in supplier dependent material stoichiometry, precise values of thickness across the sample and specific electrical characteristics of the power supply itself. An *EF* value exceeding unity is often used to achieve the desired high quality periodic domain patterning, resulting in a modified calculated Q value of $2\times A\times P_s\times EF$

Furthermore, the *EF* factor determines the state of the sample after poling. Specifically for values lower than 1 the sample becomes *underpoled*, where only a portion of the patterned area is successfully domain inverted, while for values far greater than 1 it becomes *overpoled* where the sample appears uniformly poled regardless of any initial photoresist patterning. It is this technique of overpoling that allows the fabrication of such small period gratings that are compatible with the waveguide geometries used here.

A surface planar waveguide compatible with the poling technology, was fabricated on a z-cut sample of congruent $LiNbO_3$ by the Annealed Proton Exchange (APE) technique[5]. We used a first exchange at 160^0C in pure benzoic acid to create a shallow (0.2 μm deep) proton-rich surface layer, followed by an annealing of few hours at 330^0C in air to diffuse the protons into the substrate (to a depth of ~ 2.2 μm) and at least partially heal the crystal damage (and loss of nonlinearity) induced by the first proton-exchange step. The waveguide fabrication steps (with the corresponding extraordinary refractive index profiles) are outlined in figure 1.

The period of the pattern, defined as the distance between the centers of two neighboring hexagonal patterns along the x-direction of the crystal, was 7.6 μm. The pattern is carefully arranged so that one of the edges of the hexagonal pattern is aligned along the y-axis following the symmetry of the crystal. The hexagonal pattern was photolithographically transferred onto the photoresist covered –z face of the waveguide sample and was subsequently overpoled with an *EF* of 8.

In order to assess the quality of the poled structure another test sample of lithium niobate, without the waveguide, was patterned and poled with identical conditions to the previous one. Brief etching of the test sample revealed the surface inverted hexagonal structure, which is shown in the scanning electron microscopy (SEM) picture presented in figure 2. The SEM picture of figure 2 shows a low magnification view of the poled area where the uniformity of poling over large areas can be seen.

The optical waveguide structure was designed to support only the fundamental mode at the wavelength of λ=1.064 μm. QPM second harmonic generation experiments were used to characterize the poled waveguide structure.

For the QPM second harmonic generation experiment a diode pumped $Nd:YVO_4$ laser (λ=1.064 μm) was used as the source of the fundamental wave. The polarization of the laser beam was rotated using a half wave plate in order to excite a TM mode in the waveguide and it was focused by a microscope objective on the polished x face of the waveguide. In order to tune the device into phase matching condition but also to avoid possible photorefractive damage induced by the second harmonic radiation, the sample was mounted on a heating element, which was driven by a feedback stabilized power supply for temperature stability between the values 20° C to 150° C. The output end face of the waveguide was imaged on a CCD detector by a second microscope objective and was analyzed by commercial beam analysis software. Finally a colored glass filter was placed between the output objective and the camera to separate the second harmonic from the fundamental radiation. The transmission of the filter at the second harmonic wavelength (λ=532 nm) was 75%.

The sample was temperature tuned in order to achieve QPM conditions, and the temperature-tuning curve that was obtained is shown in figure 3. The peak of the QPM tuning curve is located at 105.5° C and the FWHM of the curve is of order 3.5°C. The internal efficiency of the QPM second harmonic generation process is 0.145 % /Wcm^2.

From the images of the waveguide mode profiles which are shown in figure 4 for both the fundamental wavelength (figure 4 top) and the second harmonic (figure 4 bottom) it is obvious that the generated second harmonic wave propagates as the TM_1 mode of the waveguide structure.

As the HexLN mask was originally designed for phase matching the *bulk collinear* SHG process from 1.064 μm with the G_{10} vector, and the interaction with the TM_1 waveguide mode at 532 nm appears to be closer to the bulk phase matching condition than the one involving the TM_0 mode. Besides, the waveguide fabrication process induces a damaged crystal layer which reduces dramatically the nonlinearity near the surface of the sample (in the originally proton-exchanged layer), as is shown in figure 1 thus resulting in poor overlap between the TM_0 modes for the fundamental and second harmonic wavelengths.

The problem of the surface damaged crystal layer can be overcome by the use of a "soft" proton exchange process [6] for the waveguide fabrication. Application of poled structures onto such waveguide structures, together with optimization of the HexLN period for waveguide interactions, is expected to increase the efficiency of the process and to allow better mode control for the second harmonic wave.

In conclusion, we have demonstrated the implementation of the surface poling technique for successful periodic poling of 2-D hexagonal short period structures onto lithium niobate waveguides. Initial results of QPM second harmonic generation show the potential for efficient 2-D QPM nonlinear interactions in lithium niobate waveguides.

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Figure captions

Figure 1 Outline of the fabrication steps for the annealed proton exchange planar waveguide on z-cut lithium niobate.

Figure 2 Scanning electron microscopy pictures of a briefly etched surface hexagonally poled lithium niobate sample. The inset drawing shows the orientation of the pattern with respect to the crystallographic axes.

Figure 3 Temperature-tuning curve of the second harmonic signal.

Figure 4 Images of the waveguide mode profiles of the fundamental wave (top image) and the second harmonic (bottom).

Figure 1, Busacca *et al.*

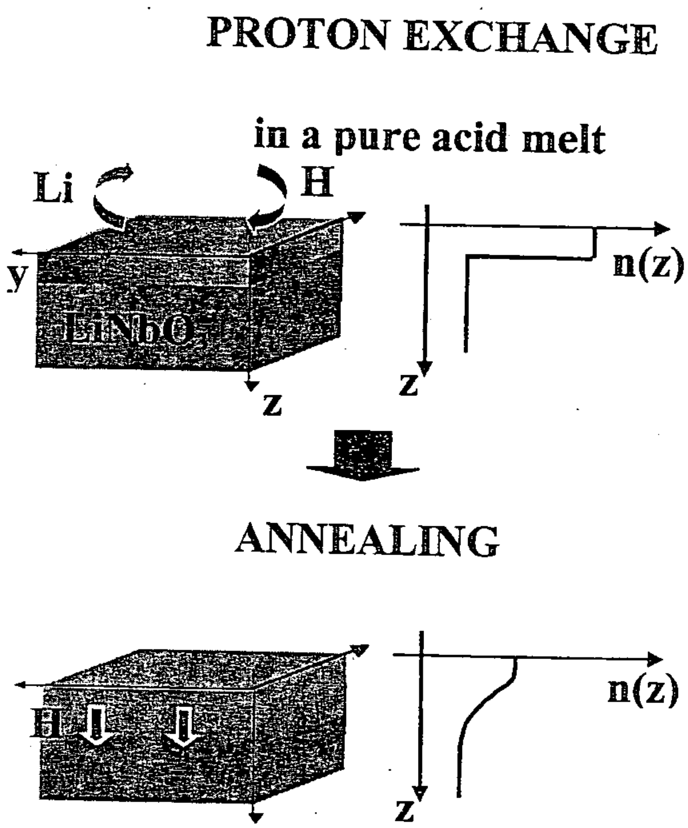

Figure 2, Busacca *et al.*

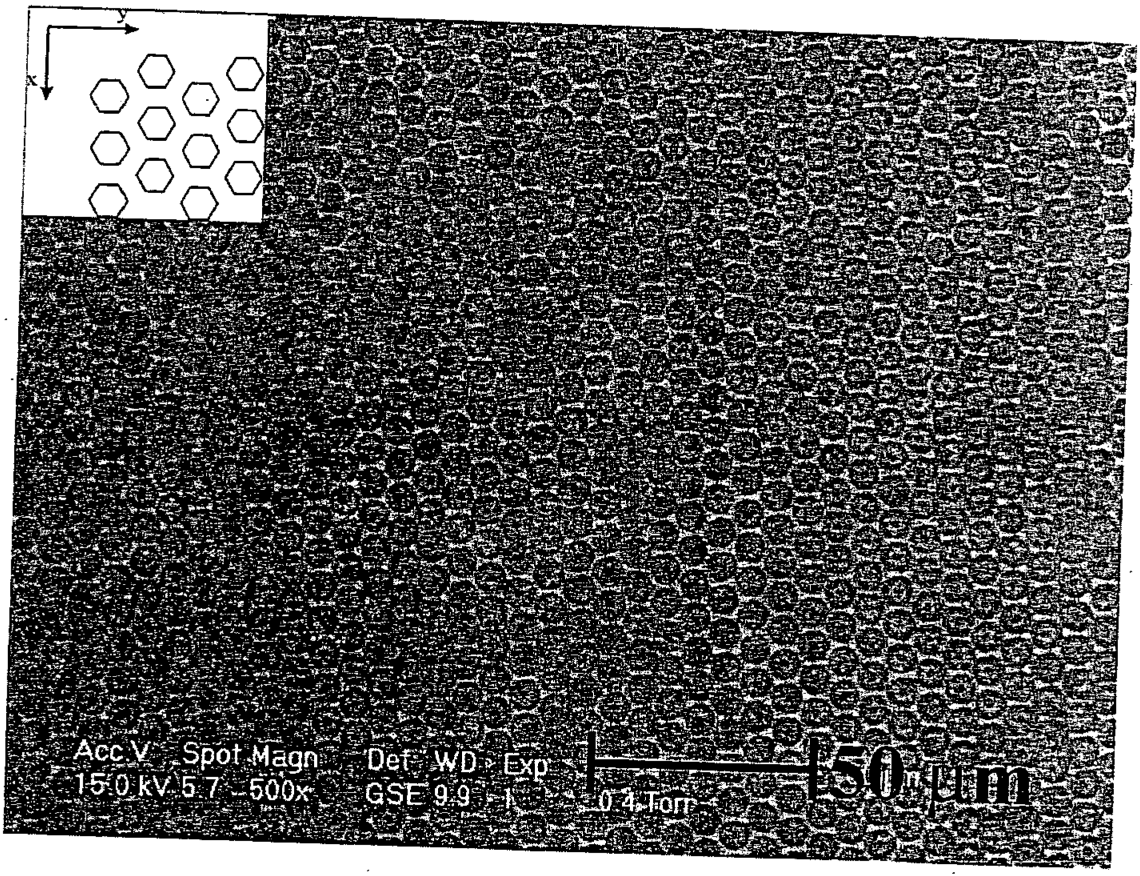

Figure 3, Busacca *et al.*

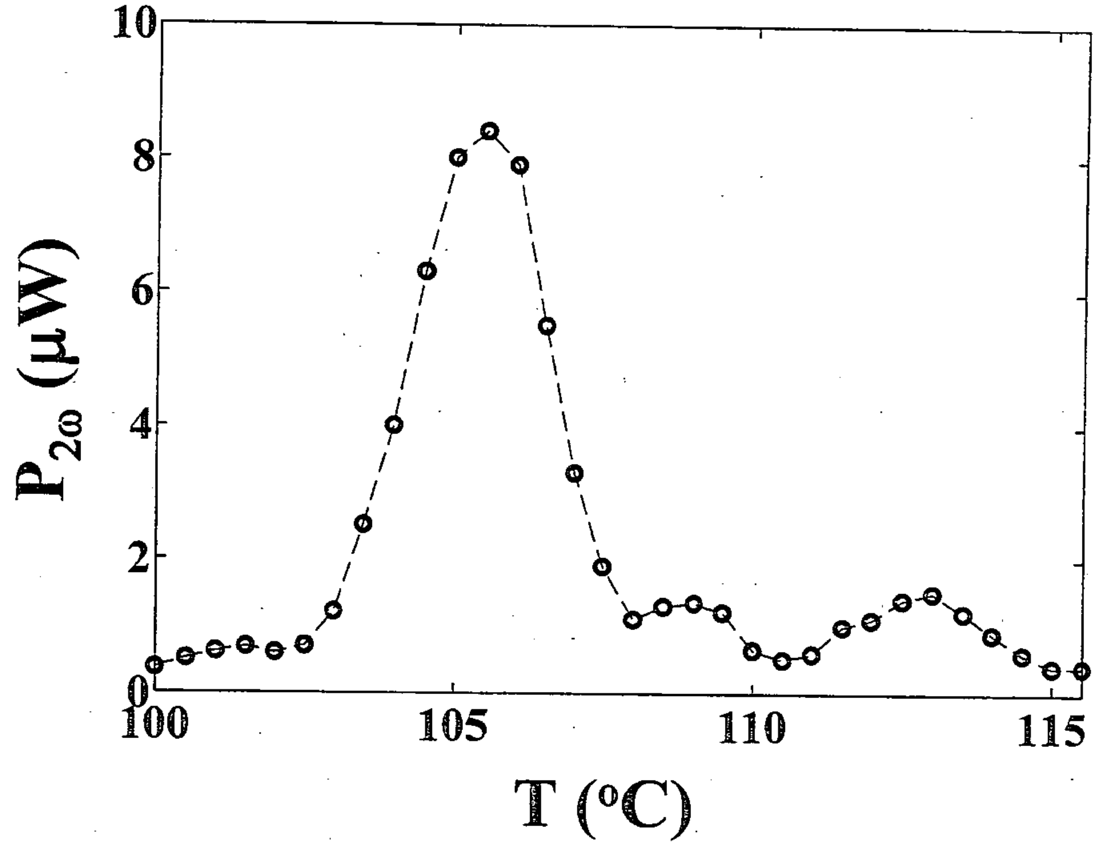

Figure 4, Busacca *et al.*