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# Second Harmonic Generation
# in Hexagonally Poled Lithium Niobate slab waveguides

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**Abstract:** Slab nonlinear waveguides have been fabricated by annealed and reverse proton-exchange in Hexagonally Poled Lithium Niobate (HexLN). The technology allowed the first demonstration of guided-wave quadratic interactions in 2D nonlinear photonic crystals.

*Introduction:* Unique spatio-spectral features make 2D nonlinear quadratic photonic crystals [1] a thriving research subject. The extension of the electric field poling technology of $LiNbO_3$ to bi-dimensional patterns allowed the fabrication of the first Nonlinear Photonic Crystals (NPCs) [2] in which both second and higher order harmonic generation [2-3] as well as simultaneous wavelength interchange of telecom signals [4] have been demonstrated. All those experiments were performed in bulk NPCs and suffered from relatively low conversion efficiencies. Quadratic planar waveguides in NPCs hold promise for increasing the conversion efficiencies by one order of magnitude with respect to the bulk, due to the transverse 1D field confinement, while still preserving all the degrees of freedom of the 2D NPC structure.

In this paper we present the first demonstration of quadratic interactions in a *planar waveguide* in a NPC, made by an annealed and reverse proton exchange on HexLN (Hexagonally Poled $LiNbO_3$) samples.

*Fabrication:* The HexLN crystals were fabricated in 500μm–thick *z*–cut $LiNbO_3$ by standard photolithography and electric field poling via liquid electrodes at room temperature [5]. The resulting nonlinear 2D grating (period $\Lambda$ = 18.05 μm) and its orientation with respect to the crystallographic axes of $LiNbO_3$ are shown in Fig. 1.

The planar buried waveguides were fabricated after the poling via a sequence of proton exchange, annealing and reverse proton exchange [6]. The initial proton exchange (PE), performed at 160°C, yielded a 1 μm–deep proton–rich layer on top of the crystal, corresponding to a high refractive index planar waveguide for the extraordinary polarization. Subsequent annealing at 330°C relaxed the constraints associated with the PE step and at the same time created a deeper, graded-index waveguide. Finally, reverse proton exchange (RPE) at 330°C in an eutectic melt of $LiNO_3$, $KNO_3$ and $NaNO_3$ re-created a $Li^+$ rich film at the surface of the annealed PE waveguide. The process conditions were chosen so as to obtain a nonlinearity–preserving buried planar waveguide, single–moded ($TM_0$) at wavelengths around 1.53 μm. The waveguide end faces were polished parallel to the *y* axis.

*Experiments:* The quadratic response of the slab HexLN waveguides was studied by employing a pulsed source at 1.536 μm, delivering square 5 ns pulses with adjustable repetition rates (1 – 500 kHz) and peak powers (up to 2 kW) [3]. In order to avoid photorefractive effects, the HexLN waveguide was maintained at temperatures above 100°C. The infrared light was coupled into the buried waveguide with an efficiency of 36 % through the sequence of a cylindrical lens and a microscope objective. By rotating the sample we could adjust the pump incidence angle to explore the angular response of the HexLN waveguide.

The HexLN pattern was originally designed for *bulk* Second Harmonic Generation (SHG) from a pump at 1.536 μm propagating along the $x$ axis, quasi-phase-matched through the $G_{10}$ Reciprocal Lattice Vector (RLV) at 120°C. Nevertheless, we could use it also for SHG in the slab waveguides, by letting the fundamental beam propagate off the $x$ axis and taking advantage of the availability of multiple RLVs in the $x$-$y$ plane.

For an operating temperature of 147.5°C, we observed the guided-wave $TM_0(\omega)\rightarrow TM_0(2\omega)$ SHG at relatively high incidence angles [corresponding to an internal propagation angle $\theta_{\omega x} \sim 6^\circ$ between the fundamental wave and the symmetry axis ($x$) of the HexLN], and the $TM_0(\omega)\rightarrow TM_1(2\omega)$ SHG at lower angles ($\theta_{\omega x} \sim 3^\circ$). The two SHG processes were phase–matched via the $G_{11}$ and the $G_{10}$ RLVs, respectively. The latter yielded the best SHG efficiencies (essentially due to the lower non-collinearity and RLV order).

The SHG temperature tuning curves had the Gaussian shape typical of HexLN (Fig.2)[3].

In order to evaluate the intrinsic efficiency for the $TM_0(\omega)\rightarrow TM_1(2\omega)$ interaction, we optimised the incidence angle and the temperature and then measured the evolution of the external SH average power versus the input pump power at low conversion efficiencies (asterisks in Fig. 3). We then fitted the experimental data, accounting for coupling losses and for the pulsed regime, by using standard coupling mode equations (with no spatial walk-off and propagation losses) in a quasi-stationary approximation, the nonlinear coupling coefficient being the only adjustable parameter. Through the fit (shown as a solid line in Fig. 3) we estimated the intrinsic quadratic efficiency to be $\eta_{nor} = 0.05\%\ W^{-1}cm^{-2}$, a value which compares well with the prediction for a fully nonlinearity-preserving waveguide:

$$\eta_{nor} = \omega^2 \left( \frac{3}{\pi^2} d_{33}^2 \right) \frac{2\mu_0 c}{N_{eff}^{\omega\;2} N_{eff}^{2\omega}} \cdot \frac{\int E_\omega^2(z)\, E_{2\omega}(z) dz}{\left( \int E_\omega^2(z)\, dz \right)^2 \int E_{2\omega}(z) dz} \cdot \frac{1}{w} = 0.09\% \mathrm{W}^{-1}\mathrm{cm}^{-2},$$

obtained for $d_{33}$ = 27 pm/V, $w$=100μm (average beam width along $y$), with the effective indices ($N_{eff}$) and mode profiles in depth [$E(z)$] calculated for the following refractive index profile :

$$n(z) = n_{LiNbO3} + \begin{cases} \Delta n \cdot exp\left[ (z - z_0)^2 / z_1 \right] & \text{for } z \geq z_0 \\ \Delta n \cdot exp\left[ (z - z_0)^2 / z_2^2 \right] & \text{for } z < z_0 \end{cases}$$

with $z_0$=1.6μm, $z_1$=1.3μm, $z_2$=1.3μm, Δn(1536nm)=0.022, Δn(768nm)=0.028 and $n_{LiNbO3}$ given by Sellmeier equations. At lower repetition rates (2 kHz) we reached internal conversion efficiencies as high as 46 % and also observed crystal damage associated to the generation of green light (third harmonic generation).

We expect that by using the same RPE waveguides in combination with a grating pattern specially designed to phase-match the $TM_0(\omega) \rightarrow TM_0(2\omega)$ SHG via $G_{10}$ we could increase the quadratic efficiencies in HexLN by one order of magnitude and approach the theoretical value of $\eta_{nor}$ = 2.7% $W^{-1}cm^{-2}$.

*Conclusions:* We have fabricated the first planar waveguides in a nonlinear photonic crystals and explored their quadratic response by studying experimentally the SHG from a 1.536 μm pulsed pump. The SHG to the $TM_1$ mode yielded the highest efficiency showing good agreement with predictions. We expect a one-order of magnitude increase of the SHG efficiency to be achieved through an optimisation of the HexLN period to fit the waveguide dispersion. This would allow full exploitation of the capabilities of NPCs for both telecommunication and fundamental physics.

# *References*


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*Figure captions*

**Fig.1:** Microscope images of the unetched HexLN structure taken after the poling.

**Fig. 2:** Temperature tuning curve measured at 100 kHz, for the $TM_0(\omega) \rightarrow TM_1(2\omega)$ SHG.

**Fig. 3:** Measured average second harmonic ($TM_1$) output power as a function of the average infrared input power (asterisks). The solid line is the numerical fit obtained from coupled mode equations with $\eta_{nor} = 0.05\% W^{-1} cm^{-2}$, as discussed in the text.

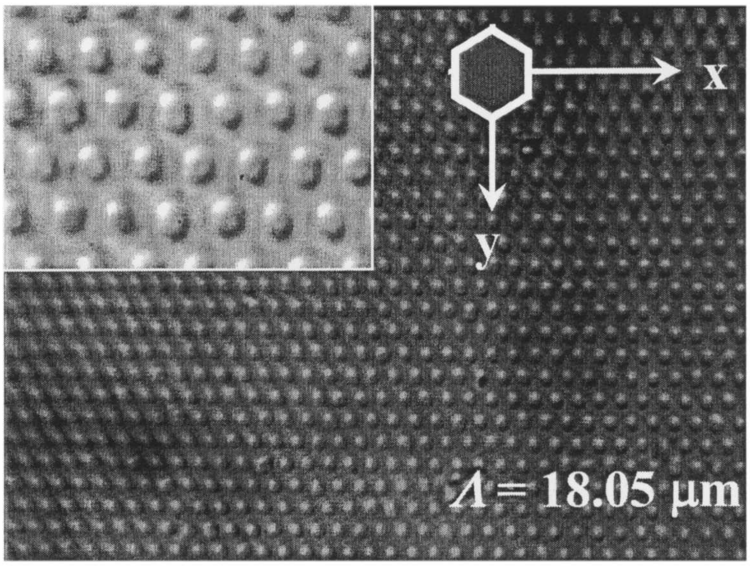


*Figure 1*

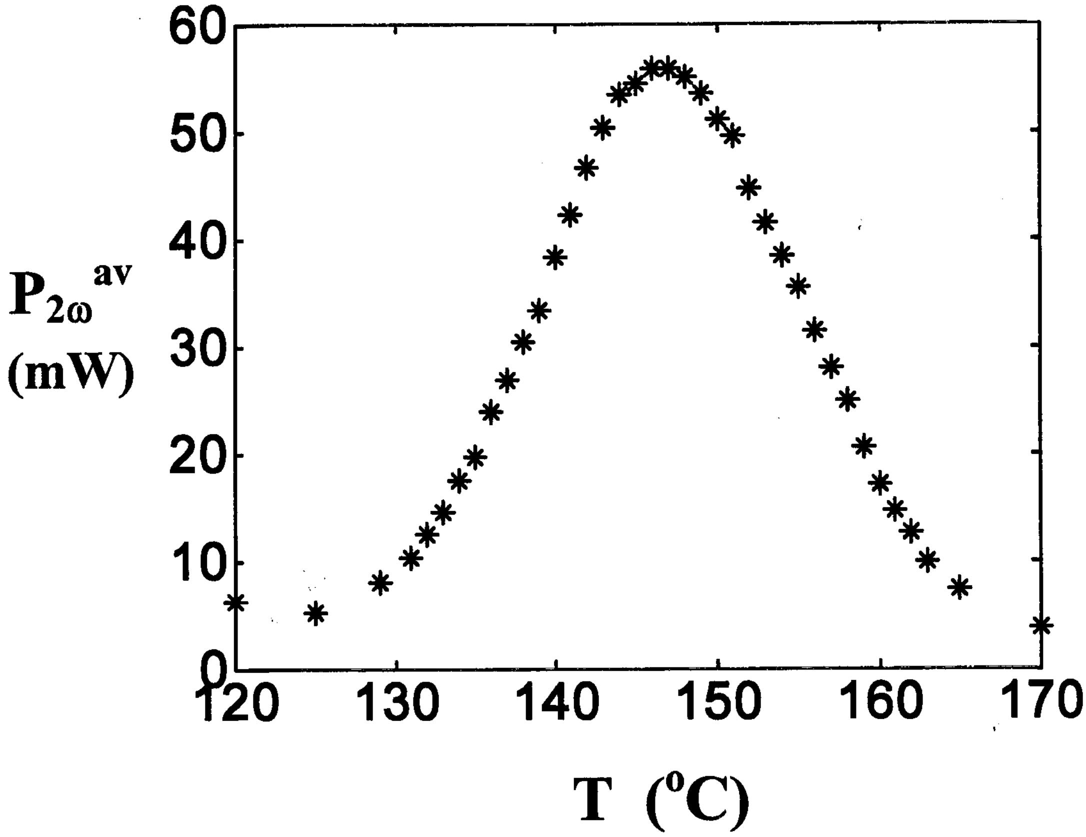


*Figure 2*

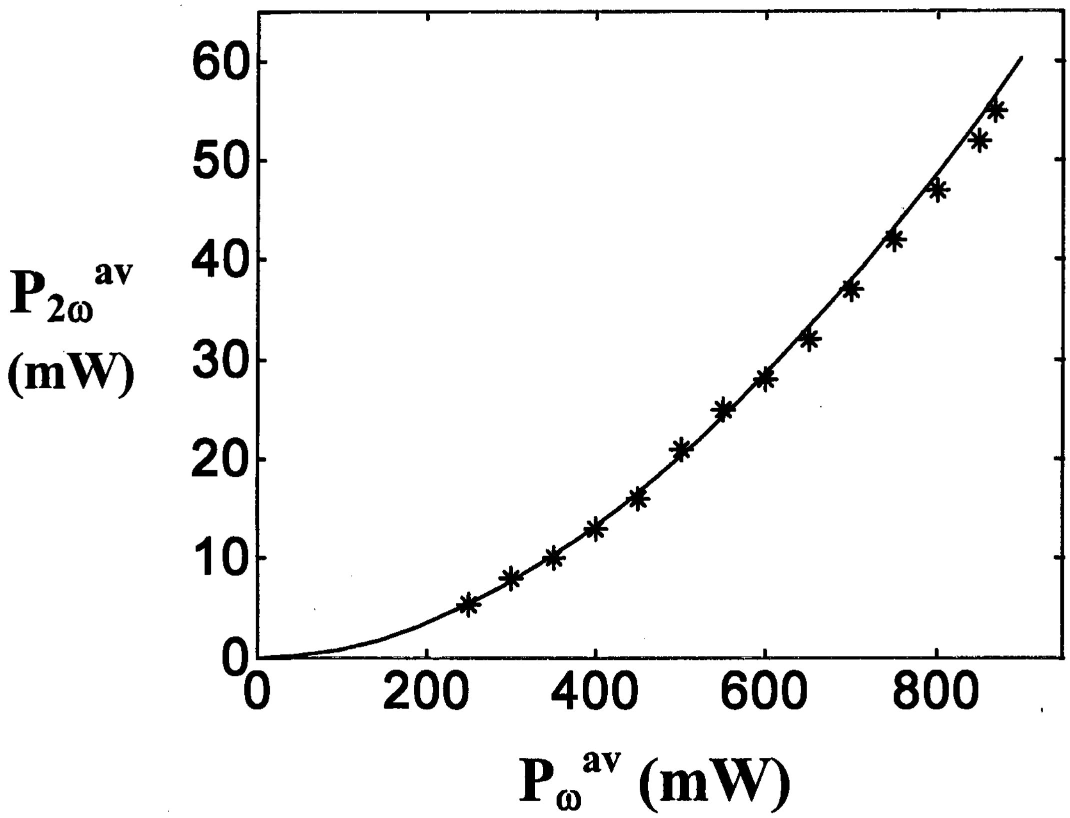


*Figure 3*