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# SHG in PPLN waveguides with stitching errors

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## RÉSUMÉ

Imperfections of the periodic material impact the performances of Quasi Phase Matched devices. Our numerical study allows predicting the impact of stitching errors on the nonlinear interactions in waveguides using domains induced by e-beam writing in Lithium Niobate and explaining the observed experimental results.

**MOTS-CLEFS :** *Nonlinear Integrated optics, Quasi Phase Matching, Second Harmonic Generation, Periodically Poled Lithium Niobate*

## 1. INTRODUCTION

Periodically poled nonlinear ferroelectric crystals are widely used to produce photonic devices such as frequency converters. Lithium Niobate (LN), which offers large electro-optical and nonlinear coefficients [1] and the ability to combine periodical poling and low-loss waveguides fabrication is one of the most popular [2]. Second Harmonic Generation (SHG) in Periodically Poled Lithium Niobate (PPLN) waveguides fabricated by proton exchange has been the object of previous studies [3], [4] for coherent single frequency pumping. We have presented a detailed study of periodic domain formation by e-beam irradiation of congruent LN (CLN) [5] containing waveguides produced by the Soft proton Exchange (SPE) process [6]. Using this technique we have produced PPLN channel SPE waveguides with a PPLN section length, which is an integral multiple of 1.5mm, the maximum length obtainable without moving the sample. SHG experiments were done using a TUNICS T100S-HP tunable laser with a fiber amplifier delivering 100mW within the wavelength range 1535-1570 nm. For 1.5 mm-long periodically poled structures, we obtained up to 48%/W.cm<sup>2</sup> normalized nonlinear conversion efficiency at the Quasi-Phase Matching (QPM) wavelength. Longer domain patterns, obtained by joining up to four 1.5mm long periodically poled sections present several finite stitching errors [5].

Within the reversible SHG mechanism, it is expected that a stitching error corresponding to a phase shift of the order of  $\pi$  will yield to a severely reduced conversion efficiency especially if this error appears in the middle of the grating, as the conversion taking place in the second segment is opposite in phase with what has been created in the first one [7], [8]. Studying SHG in PPLN structures with a tunable laser allowed us to explore the spectral domain around the QPM wavelength, and the originality of our study is to experimentally and numerically show that the stitching errors not only reduce the SH response at QPM resonance, but split the SH spectrum into two or more lateral peaks while keeping the total conversion (integral of the spectrum) and coherence (width of the individual peaks) [9] unchanged.

The influence of a phase shift appearing in the middle of the PPLN grating has been numerically studied as a function of its amplitude and we show that it splits the SH spectrum into two peaks whose position and width at half maximum depends not only on the poling period, the total length of the grating, and the waveguide parameters, but also on the amplitude of the defect.

Recording the SHG tuning curves in waveguides with several stitching errors, we obtained several multiple humped spectra depending on the value of the different phase shift linking the “perfect” PPLN segments. In the numerical model we have considered the dynamics when the finite stitching

errors prevail over the distributed imperfections of the sample which have already been studied [10]-[13], and show that this calculation taking into account only the stitching errors can predict the main modification of the SHG spectra and therefore could also be used to explain the results obtained on devices produced by other techniques such as e-field poling where the nonlinear grating is also affected by important errors, such as domains merging or missing domains.

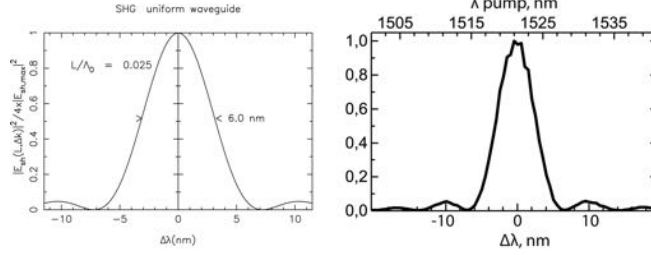


Figure 1. SHG tuning curves: (Left) Numerical SH spectrum for the regular PP waveguide of dimensionless length  $L/\Lambda_0 = 0.025$ , normalized to its maximum  $0.25 \times |E_{sh,max}|^2 = 6.25 \times 10^{-4} |E_{pump}|^2$ , as a function of the pump wavelength detuning with respect to QPM  $\Delta\lambda = \lambda_p - \lambda_{QPM}$  in nm. The sinc<sup>2</sup> spectrum presents a principal single peak, the first lateral small peaks located out 10.4 nm left and right to the central peak at  $\Delta\lambda = 0$ . The spectral width measures 6 nm. (Right) Experimental SH spectrum for the regular waveguide of  $L = 1.5$  mm length as function of  $\Delta\lambda = \lambda_p - \lambda_{QPM}$  in nm. The sinc<sup>2</sup> spectrum presents a principal single peak of 6 nm spectral width. The first lateral small peaks are located out 10 nm left and right to the central peak at  $\Delta\lambda = 0$ .

## 2. SHG DYNAMICAL EQUATIONS

The SHG process, assuming the slowly varying envelope approximation, is governed by the coupled mode equations in the periodically poled waveguides possibly presenting stitching errors:

$$(\partial_t + v_F \partial_x + \gamma_F + i\beta_F \partial_{tt}) \mathbf{A}_F = i\kappa_F \mathbf{A}_F^* \mathbf{A}_{SH} \exp(i\Delta K x) \exp[i\delta\Phi_m(x_m)] \quad (1)$$

$$(\partial_t + v_{SH} \partial_x + \gamma_{SH} + i\beta_{SH} \partial_{tt}) \mathbf{A}_{SH} = i\kappa_{SH} \mathbf{A}_F^2 \exp(-i\Delta K x) \exp[i\delta\Phi_m(x_m)] \quad (2)$$

where  $\mathbf{A}_F$  and  $\mathbf{A}_{SH}$  are the field amplitudes ( $\mathbf{A}_j = \sqrt{n_j \ell \omega_j} \mathbf{E}_j$ ,  $j = F, SH$ ) at  $\lambda_F$  and  $\lambda_{SH}$  ( $F =$  fundamental,  $SH =$  second harmonic) respectively;  $\delta\Phi_m(x_m) = \sum_{m=1}^N \delta\sigma_m(x_m)$  ( $m = 1, N$ ) are the  $N$  integral phase-shifts due to the eventual stitchings where the phase-shifts  $\delta\sigma_m(x_m)$  ( $m = 1, N$ ) =  $\delta\Phi_m(x_m) - \delta\Phi_{m-1}(x_{m-1})$  (with  $\delta\Phi_0(x_0) = 0$ ) link the regular PPLN waveguide pieces;  $\kappa_F = [2\pi\omega_F^2 / (k_F c^2)] v_F \chi^{(2)}(\omega; 2\omega, -\omega)$  and  $\kappa_{SH} = [4\pi\omega_{SH}^2 / (k_{SH} c^2)] v_{SH} \chi^{(2)}(2\omega; \omega, \omega)$  are the nonlinear coupling constants and the wave vector mismatch between the fundamental and SH is

$$\Delta K = 2\pi[2(n_{SH} - n_F) / \lambda_F - 1 / \Lambda_G] \quad (3)$$

where  $2\pi/\Lambda_G$  is the PP grating period,  $\beta_F, \beta_{SH}$  the dispersion coefficients and  $\gamma_F, \gamma_{SH}$  the damping coefficients (here we will consider a lossless and dispersionless SHG process).

If the difference between  $v_F$  and  $v_{SH}$  can be neglected for the nonlinear medium with a given length  $L$  and in the parametric approximation (intensity of the pump field  $\mathbf{A}_P = \mathbf{A}_F$  remaining much higher than the intensity of the second-harmonic field  $\mathbf{A}_{SH}$ ) we may set  $v_F = v_{SH} = v_p$  and  $|A_F|^2 = |A_p|^2 = const$  in (1)(2) to derive in the retarded frame of reference with  $x' = x$  and  $\tau = t - x/v_p$  the intensity equation of the second-harmonic

$$I_{SH}(L) \propto \kappa_{SH}^2 I_p^2 \left( \frac{\sin(\frac{\Delta K L}{2})}{\frac{\Delta K L}{2}} \right)^2 L^2, \quad (4)$$

where  $I_p$  is the intensity of the pump field. Fig. 1(left) shows the spectral behaviour issued from the simulation of Eqs. (1) and (2) for a nonlinear dimensionless length  $L/\Lambda_0 = 0.025$  corresponding to a 1.5 mm uniformly PP length. The characteristic length being  $\Lambda_0 = 2v_F / (\kappa_F A_F(0))$  and  $|A_F(0)| = [I_F^0 (\text{MW/cm}^2) / 0.2838]^{1/2}$ . The principal single peak has a FWHM of 6.0 nm. The first adjacent low peaks are at 10.1 nm. The experimental spectrum for the uniform waveguide of 1.5 mm length corresponding to the numerical  $L/\Lambda_0 = 0.025$  of Fig. 1(left) is shown in Fig. 1(right). The SH spectrum presents a single peak that coincides with the sinc<sup>2</sup> theoretical prediction and allows determining  $\lambda_{QPM}$  corresponding to a particular association waveguide width and PPLN period. The measured conversion efficiency reaches up to 36%/( $\text{W}\cdot\text{cm}^2$ ). The experimental spectral

efficiency of a single stitched PPLN waveguide is plotted in Fig. 2(left) and fits quite well to the numerical spectrum we obtained for a stitching phase shift of  $7\pi/6$  [Fig. 2(right)]. In both cases the spectral separation between the two peaks is 5.5 nm, but this best fit is obtained for a stitching phase shift which almost correspond to the one measured on the domains structure. We remark that this error, not only nearly annihilates the amplitude at QPM as expected, but also dramatically modifies the shape of all the SH spectrum.

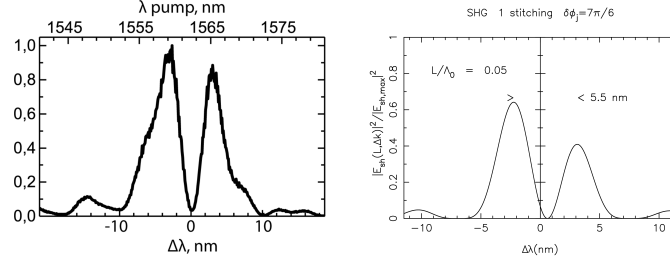


Figure 2. SHG tuning curves: (Left) Spectral efficiency for the experimental 1-stitching sample as function of the pump wavelength detuning with respect to QPM  $\Delta\lambda = \lambda_p - \lambda_{QPM}$  in nm. The length of the PP section measures  $L \simeq 2 \times 1.5$  mm.  $\lambda_{QPM}$  is deduced from the SHG spectra of a waveguide of the same width crossing a single 1.5 mm long PP section of the same period. The spectral separation between the two peaks measures 6.0 nm. (Right) Numerical SH spectrum for the 1-time stitched PP waveguide of phase shift  $7\pi/6$  as a function of  $\Delta\lambda = \lambda_p - \lambda_{QPM}$  in nm for a normalized length  $L/\Lambda_0 = 0.05$ . The spectral separation between the two peaks measures 5.5 nm.

### 3. CONCLUSIONS

In this paper we studied numerically and experimentally the influence of one or a few well localized important errors in the periodic organization of the domains of a Quasi Phase Matched waveguide on its SHG spectrum. We have shown, that these errors modify the efficiency and the shape of the SHG spectrum. The maximum of the SHG signal does no longer correspond to the QPM wavelength, which is a very important point to keep in mind when observing an experimental spectrum.

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