Second harmonic generation in nonlinear photonic crystals (PPLN 2D)optical waveguides

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***Abstract*— In this work, we report the investigation of second harmonic generation in nonlinear photonic crystals optical waveguides. The influence of waveguide parameters is studied and the conversion efficiency is compared to that of bulk samples.**

***Keywords*- optics nonlinear; Quasi Phase Matching (QPM); second harmonic generation (SHG); Polarized poled lithium niobate (PPLN).**

I. INTRODUCTION

Recently, the utilization of nonlinear photonic crystals (NLPC) has allowed the development of new laser sources based on nonlinear conversion of the already existing diode laser. The interest of NLPC comes from the fact that several quasi-phase matching (QPM) scheme are possible using different reciprocal vectors [1].

In particular, using integrated optics can also increase the conversion efficiency thanks to light confinement within the waveguide. Stat-of-the-art shows that SHG conversion efficiency in waveguide can be three times higher compared to the bulk 2DPPLN [2].

In this paper, we report the study of SHG in NLPC optical waveguide. Here we are interested in the influence of different parameters such as effective refractive indices, modal dispersion, and the overlap integral. Besides, we repport the experimental results of SHG characterization of PPLN 2D in Bulk and waveguide.

II. SHG IN BULK

In reference [1], Berger has defined the nonlinear photonic crystals (NLPC) in two dimensions as structure having a quasi-periodic two dimensional (2D) special distribution of $\chi^{(2)}$ whilst the susceptibility $\chi^{(1)}$ is linear and homogenous in the crystal.

The purpose of the second harmonic generation is to product new sources at different wavelength, to do that it's important to achieve high conversion efficiency.

The general theory of second harmonic conversion efficiency is available in [3]. Note that in an ideal phase matching scheme and without the pump depletion, the SH power can be written as:

$$p_{SH}(L) = \left| \int_0^L \frac{dA_{SH}(z)}{dz} dz \right|^2 = (\omega_{SH} k_{SH} d_{eff})^2 L^2 P_{FF}^2 = \eta_{nor} L^2 P_{FF}^2 \quad (1)$$

The conversion efficiency is then given as:

$$\eta_{nor} = \frac{8\pi^2 d_{eff}^2 I_\omega}{\lambda_{FF}{}^2 n_{FF}^2 n_{SH} \varepsilon_0 c} \quad (2)$$

However, in the case of pump depletion, one can write (SHG power is very high):

$$\eta_0 = \frac{P_{SH}(L)}{P_{FF}} = \tanh^2 \sqrt{\eta_{nor} P_{FF}} L \quad (3)$$

The intrinsic conversion efficiency η_{nor} is usually expressed in $\%.W^{-1}.cm^{-2}$.

A. Quasi phase matching (QPM)

Quasi-phase matching (QPM) is a technique used to enhance nonlinear wave interactions, realized to achieve the phase matching in ferroelectrics crystals where the sign of the nonlinear coefficient is periodically inverted at every coherent length [4]. The first experience reported on the fabrication of the NLPC 2D was presented in [5] achieving a conversion efficiency > 60%.

In case of the QPM –SHG process, for a given temperature and incident angle, efficient SHG can only occur at a single wavelength that fulfils the momentum conservation condition:

$$2k_{1\omega} + K_{mn} = k_{2\omega} \quad (4)$$

Where $k_{i\omega}$ are the wave vectors at the fundamental and second harmonic frequencies, respectively.

$K_{mn} = 2\pi / \Lambda(m+n)$ is the reciprocal lattice vector.

In reference [6], the spatial distribution of $\chi^{(2)}$ in the 2D QPM configuration is represented in five types of periodic two-dimensional nonlinear structures: hexagonal, square, rectangular, centred rectangular and oblique.

Indeed, several vectors of the reciprocal lattice can intervene to realize the phase matching, thus several phase matching conditions can be satisfied as represented in figure 1 below.

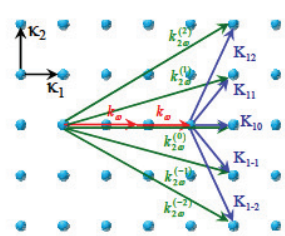

Figure.1 The schematic geometrical reciprocal lattice for SHG interaction [2].

By using the nonlinear Bragg's law [1], we can predict the walk-off angles of each reciprocal lattice vector (RLV) according to the temperature.
Several studies have been presented in literature for SHG in bulk:

QPM SHG has been demonstrated at wavelengths ranging from 325 nm in UV [7] to 5.25 µm in mid-IR [8]. up to 42% for CW 532-nm generation [9], 86% with ns pulses at 768 nm [10], also there is many works in case of 2D configuration, in [11] the presented work achieve 50% of efficiency, in [12]the first telecommunication application of NLPCs was demonstrated, and a orthorhombic structure was proposed in [13].

III. SHG IN WAVEGUIDE

Waveguide interactions are important in some applications because they have efficiencies of several orders of magnitude larger than those in bulk media [14]. In optical waveguide various modes can propagate at various phase velocities thus, characterized by their effective indices Nm (m: the order of the guided mode). Under these conditions, a new degree of freedom exist using phase matching by modal dispersion [15].

The mathematical theory of waveguide interactions is quite similar to that for plane waves, but with an effective area for relating the power to an effective intensity that depends on the overlap integral of the interacting waveguide modes [16]. The scaling of the mixing efficiency for undepleted-pump SHG then goes as:

$$\frac{p_{SH}}{p_{FF}} = \eta_{nor} L^2 P_{FF} \tag{5}$$

Where:

$$\eta_{nor} = \frac{8\pi^2 d_{eff}^2 I_\omega}{\lambda_{FF}{}^2 n_{mFF}^2 n_{mSH} \varepsilon_0 c} \cdot \frac{1}{S_{ovl}} \tag{6}$$

s_{ovl} the effective overlap area

One of the most interesting things about SHG in waveguide configuration is that the Gaussian beam diffraction problem can be overcome by guided-wave configuration. In such configuration, the high optical density power is confined, thus, increasing the interaction along the waveguide length.

The coupled-mode equations describing the evolution of the fundamental and the second harmonic waves inside a waveguide are formally given by:

$$\begin{aligned} \frac{dA_{FF}(z)}{dz} &= 2i\omega_{FF} k d A_{FF}^{*}(z) A_{SH}(z) \exp(i\Delta\beta z) \\ \frac{dA_{SH}(z)}{dz} &= i\omega_{SH} k d A_{FF}^{2}(z) \exp(-i\Delta\beta z) \end{aligned} \tag{7}$$

Where:

$$k = \sqrt{\frac{2\mu_0}{N_{eff,FF}^2 N_{eff,SH} c}} \sqrt{\frac{1}{s_{ovl}}} \tag{8}$$

There are two main differences in the above equations compared to coupled-mode equations describing the evolution of fundamental and second harmonic waves in bulk: Bulk material wave vector mismatch Δk is replaced by the waveguide wave vector mismatch:

$$\Delta\beta = \beta_{SH}^{(m)} - 2\beta_{FF}^{(n)} \tag{9}$$

where m denotes the mode indices, $\beta_j^{(m)} = \frac{\omega_j}{c} N_{eff,m}$ is the propagation wave vector of mode m with frequency ω_j inside the waveguide, with $N_{eff,m}$ being the effective refractive index of the propagating mode.

From (7) this condition is called phase-matching and corresponds to:

$$\Delta\beta = \frac{4\omega_{FF}}{c} (N_{eff,SH}^{(n)} - N_{eff,FF}^{(m)}) \tag{10}$$

However, $N_{eff,SH}^{(n)} \neq N_{eff,FF}^{(m)}$ due to chromatic dispersion in most materials and waveguides, including lithium niobate.

Therefore, we define the coherence length by l_c as the length in which the power generated increase due to the destructive interference between the beams generated at a point of crystal:

$$l_c = \frac{\pi}{\Delta\beta} = \frac{\lambda}{4[N_{eff,SH} - N_{eff,FF}]} \tag{11}$$

A. Overlap integral

The calculation of the effective area overlap in a waveguide takes into account the EM field distribution between the possible fundamental and SHG transversal modes. This factor is a concept specific to waveguides. It can be described as being a space integral of the product of the fundamental power normalized by the distribution of the electric field through the nonlinear area of the guide. An important value of this integral is its high conversion efficiency [15].

$$S_{ovl} = \frac{\int \left|H_{y,SH}{}^{(m)}\right|^2 dx.dy \left(\int \left|H_{y,FF}{}^{(n)}\right|^2 dx.dy\right)^2}{\left(\int \left|H_{y,SH}{}^{(m)}\right|^2 \left|H_{y,FF}{}^{(n)}\right| dx.dy\right)^2} \tag{12}$$

The effective overlap area must be optimised; its value should be close to 1.

B. Phase matching by modal dispersion

An effective SHG must obey to the condition $\Delta\beta'_p = 0$
In multimodal waveguide, the effective indices take a value between the refractive index of the waveguide, and the highest refractive index of the surrounding layers. However, it should be noted that the conversion efficiency is very different according to the considered interaction due to the integration overlap. It is known that interactions between odd and even modes are highly disadvantaged. In addition,

the losses (tunnelling losses) increase significantly with the propagation mode number. Moreover, the modal dispersion can cause multiple phase matching conditions. From $\Delta\beta'_p = 0$, we get:

$$N^{(n)}_{eff,SH} = N^{(m)}_{eff,FF} + \frac{\lambda}{2\Lambda} p \qquad (13)$$

P: entire

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Here we present preliminary experimental results of the characterization of PPLN 2D in Bulk and waveguide

We took a sample of 2D PPLN with a square lattice and a period of $\Lambda = 6.92$ µm as presented in figure 2.

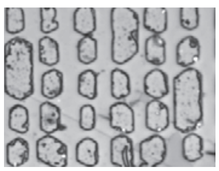

Figure 2. Microscopic image of a periodically polarized lithium niobate crystal showing the inversion domains of the polarization 2D

Characterization results are presented in figures 3((a) in Bulk, (b) in waveguide) using a pump power at 1064 nm with repetition rate equal to 10 Hz.

Experimental results show that the RLV appear by increasing the temperature. Figure 3 shows the RLV results of G10, G11 and G-11 at 80° in Bulk and 60° in waveguide.

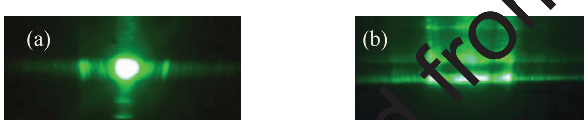

Figure 3. Far-field SHG images observed in PPLN 2D, (a) for the bulk configuration and (b) wavelength.

V. CONCLUSION

In this paper we reported the study of second harmonic generation in waveguide and Bulk 2D.

We presented the experimental results of the characterization of PPLN 2D in Bulk and waveguide at different temperature.

In future work, we will experimentally investigate the influence of different parameters as effective refractive indices, modal dispersion, and overlap integration to generate SHG in waveguide.

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