Ridge optical waveguide curved in a KTiOPO4 single crystal for triple photon generation: preliminary characterization by birefringence phase-matched third-harmonic generation

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Ridge optical waveguide curved in a $KTiOPO_4$ single crystal for triple photon generation: preliminary characterization by birefringence phase-matched third-harmonic generation

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Abstract. Ridge waveguides carved in bulk nonlinear crystals such as $KTiOPO_4$ (KTP) are used to reach a strong confinement of electromagnetic waves with large second-order or third-order non-linearity. We report on our recent experiments where we show the possibility to shape the birefringence phase-matching (BPM) conditions for direct Third-Harmonic Generation (THG: $\omega + \omega + \omega \rightarrow 3\omega$) in micrometric KTP ridge waveguides by acting on their transverse dimensions. The real goal of this preliminary study is to design quantum optical experiments based on Triple Photons Generation (TPG: $3\omega \rightarrow \omega + \omega + \omega$) that is the reverse process of THG, thus exhibiting the same BPM conditions.

The aim of this study is to design and characterize through direct Third-Harmonic Generation (THG) ridge waveguides that have been curved in $KTiOPO_4$ (KTP) for Triple Photon Generation (TPG) [1]. Because the transverse finite dimension of the ridge waveguide influences the effective indices of the crystal, a first step has been to model the wavelength dispersion of the effective indices as a function of the transverse dimension *d* of a squared-transverse-section ridge. From these data, it has been possible to calculate the birefringence phase-matching (BPM) conditions of THG or TPG. Figure 1 shows the BPM fundamental wavelength λ_ω calculated as a function of *d*. Then, in order to reach BPM at λ_ω = 1596nm, which is the Third-Harmonic of 532 nm, it is necessary to design a guide with d = 6.2µm.

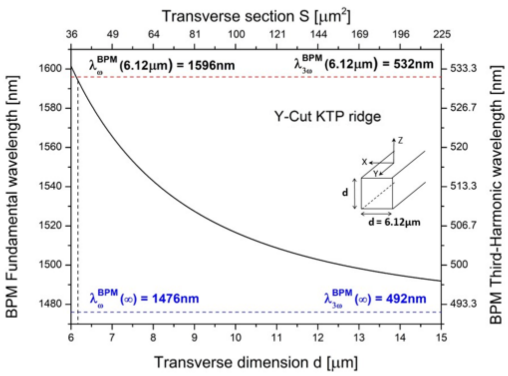

Fig.1 BPM conditions for THG as a function of the transverse dimension of the KTP ridge waveguide.

The ridge waveguide has been elaborated using a diamond blade technic [2] in a bulk crystal provided by Cristal Laser SA. From scanning electron micrcoscopy (SEM) measurements, the transverse section *S* is found to be non-constant over the 8.6 mm length along the propagation axis. Consequently, the longitudinal gradient of transverse section of the KTP ridge will induce a longitudinal gradient of the phase-matching conditions. The average square section is found at d_{avg} = 6.17 µm.

Following this step, the experimental investigation of the THG in the ridge waveguide was performed using a tunable optical parametric generator pump beam with a pulse duration of 15 ps at a repetition rate of 10 Hz. In order to achieve the BPM, the polarization of the incoming pump is precisely adjusted. Figure 2 shows the THG intensity measured as a function of the fundamental wavelength and compared with the calculation in the case of a perfectly uniform 8,6-mm-long square ridge with a square transverse dimension d = 6.17µm.

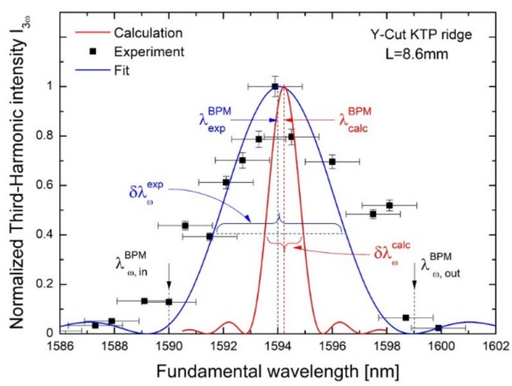

Fig.2 Normalized intensity of the generated TH signal as a function of the Fundamental wavelength.

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The blue curve is a *sinc*^{2} fit of the experimental data. The red curve corresponds to the calculation for a ridge with a uniform longitudinal section. As a consequence of the prismatic shape of the waveguide, the experimental full width at 0.405 of the BPM peak (blue curve) is enlarged by a factor of three compared to calculation (red curve). This difference is used to deduce an effective interaction length $L_{eff} = L.(\frac{\delta\lambda_\omega^{exp}}{\delta\lambda_\omega^{calc}}) = 2.7mm$, where $L = 8.6mm$ is the geometrical length of the KTP ridge. This effective length is about 1/3 smaller than the geometrical length because of the longitudinal phase-mismatch gradient between the nonlinear polarization and the generated Third-Harmonic (TH) wave.

Figure 3 shows the TH energy measured at the exit of the KTP ridge as a function of the incoming Fundamental energy. The energy conversion efficiency reaches up to 3.4% for a Fundamental energy as low as 2 µJ. The experimental data are compared to calculations that have been performed in the Undepleted Pump Approximation (UPA).

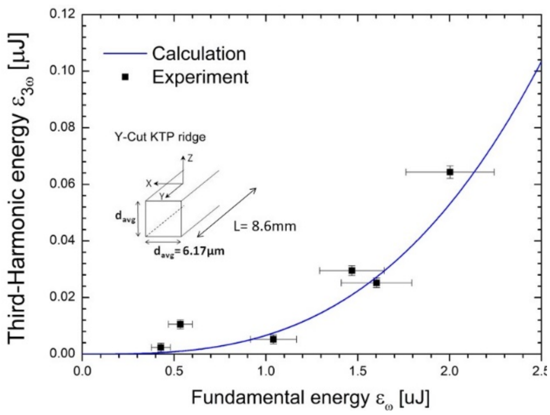

Fig.3. Measured Third-Harmonic energy (black square) at the exit of the crystal as a function of the Fundamental energy at the entrance. Calculated energy (blue curve) without any adjusting parameter.

In the UPA, we established that the TH energy is given by:

$$\varepsilon_{3\omega}(L_{eff}) = \frac{103}{3\pi^3\sqrt{3}}\frac{\mu_0}{\varepsilon_0}\frac{\left(T_\omega^z\right)^2 T_\omega^x T_{3\omega}^x}{\left(\tau_\omega W_\omega^2\right)^2}\frac{\Omega^2}{n_{eff,\omega}^x\left(n_{eff,3\omega}^z\right)^2}\Gamma^2\left[\varepsilon_\omega(0)\right]^3 \quad (1)$$

where $T_{\omega,3\omega}^{x,z}$ are the Fresnel transmission coefficients, W_ω is the 1/e^2 mode radius, $\varepsilon_\omega(0)$ is the Fundamental incident energy and Ω and Γ are parameters involving the effective length L_{eff} and the propagation loss coefficients β at ω and 3ω. We assumed that the losses mainly come from the presence of the gold layer below the silica buffer layer. The numerical values of the parameters of Eq. (1) that have been used are given in Table 1.

The theoretical prediction of the energy conversion efficiency (blue curve in Fig. 3) matches perfectly the experimental results without any fitting parameters.

Table 1. Parameters used in the calculation of the generated Third-Harmonic energy.

	ω	3ω
λ [nm]	1594	531.3
$\chi_{16}^{(3)}$ [m^{2}V^{-2}]	-	8.05 10^{-22}
τ [ps]	15	-
W [µm]	2.5	-
T^z	0.92	-
T^x	0.93	0.92
β [cm^{-1}]	0.3	0.1
n^x	1.7205	1.7780
n^z	1.8067	-

The THG conversion efficiency can be further optimized by improving the waveguide cross section uniformity and by decreasing the propagation losses for example by increasing the thickness of the silica layer at the bottom of the ridge waveguide from 0.6 to 2 µm.

This study of BPM THG (ω + ω + ω → 3ω) is a first step toward an optimal design of BPM TPG (3ω → ω + ω + ω) experiments in KTP ridge waveguide. Actually, TPG and THG are reverse processes, thus exhibiting the same BPM conditions. Our quantum model shows that about 100 triplets per second at λ_ω = 1596 nm could be generated in a 5cm-long-KTP ridge waveguide when pumped with a laser beam of 5 W at $\lambda_{3\omega}$ = 532 nm in the CW regime [1]. These preliminary results pave the way for new quantum optics experiments involving triplet states.

References

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