# Third-Harmonic Generation at 1594 nm in a KTP Ridge Optical Waveguide

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**Abstract:** We achieved birefringence phase-matched Third-Harmonic Generation at 1594 nm in a $KTiOPO_4$ single crystal ridge optical waveguide. The energy conversion efficiency reached 3.4% for a pump energy as low as 2 µJ over a pulse duration of 15 ps. Strong agreements between theory and experiments for phase-matching and conversion efficiency were obtained.

## 1. Introduction

The achievement of the direct Third-Harmonic Generation (THG: $\omega + \omega + \omega \rightarrow 3\omega$) in the framework of guided optics is a current challenge of photonics, where the wavelength of the Fundamental beam must often range in the telecom domain. Ridges optical waveguides carved in quasi phase-matched (QPM) periodically-poled $LiNbO_3$ (PPLN) [1] and $KTiOPO_4$ (PPKTP) [2], or in birefringence phase-matched (BPM) $KTiOPO_4$ (KTP) single crystals [3] have shown strong potentialities in the case of Second-Harmonic Generation (SHG: $\omega + \omega \rightarrow 2\omega$). We report here on the first experiments where we show the ability of such a technology for performing direct THG in a KTP single crystal, with the target of reaching BPM for the conversion $\lambda_\omega = 1596$ nm $\rightarrow \lambda_{3\omega} = 532$ nm.

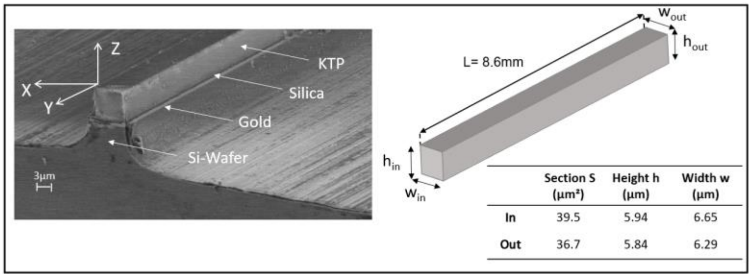
## 2. Design and fabrication of the optical waveguide

We considered ridges with squared-transverse-section, where $d$ is the side of the square. Starting from the dispersion equations of the refractive indices of bulk KTP crystal, we were able to calculate the dispersion equations of the three principal effective indices of the waveguide as a function of $d$ in any direction of propagation of the crystal. From these data, we found that it was possible to achieve BPM in the telecom range by propagating the waves in the $y$-axis of KTP, the Fundamental BPM wavelength $\lambda_\omega^{BPM}$ being given as a function of $d$ by the following relation:

$$\lambda_\omega^{BPM}(d) = \lambda_\omega^{BPM}(\infty) + \rho d^{-\alpha} \tag{1}$$

with $\lambda_\omega^{BPM}(\infty) = 1476$ nm, $\rho = 5945$ and $\alpha = 2.144$.

From Eqs. (1), it comes that the ridge transverse dimension has to be $d = 6.12\mu m$ in order to get with $\lambda_\omega^{BPM}$ = 1596 nm. In a following step, the corresponding ridge waveguide has been elaborated using a diamond blade technic in a bulk crystal provided by Cristal Laser SA. The measured transverse section $S$ is found to be non-constant over the 8.6 mm length along the propagation axis, as shown in Fig. 1.



| | Section S (µm²) | Height h (µm) | Width w (µm) |
|---|---|---|---|
| **In** | 39.5 | 5.94 | 6.65 |
| **Out** | 36.7 | 5.84 | 6.29 |

Fig. 1. Left: MEB image of the ridge waveguide. ($x$, $y$, $z$) is the dielectric frame of KTP. Right: Schematic view of the geometrical prismatic shape of the waveguide and dimensions of the in and out faces.

The average transverse dimension of the fabricated waveguide is very close to the 6.12 µm that was targeted, *i.e.*: $d_{avg} = \sqrt{(S_{in} + S_{out})/2} = 6.17\mu m$. The corresponding BPM Fundamental wavelength calculated from Eq. (1) is $\lambda_{\omega}^{BPM} = 1594.2nm$, which is very close to the 1596 nm that are targeted.

## 3. Optical measurements

We used a tunable Optical Parametric Generator as the fundamental beam, with a pulse duration of 15ps and a repetition rate of 10Hz. It is injected in the waveguide using a x20 microscope objective (MO). The generated Third-Harmonic (TH) beam is collected by a x40 MO placed at the exit of the waveguide.

The TH energy measured as a function of the fundamental wavelength allowed us to determine that $\lambda_{\omega}^{BPM}$ = 1594 nm, which is very close to the 1594.2 nm predicted by our model.

Figure 2 shows the generated TH energy measured as a function of the fundamental incident energy. The energy conversion efficiency reaches up to 3.4% for a fundamental energy as low as 2 µJ. We compared these experimental data with a calculation performed in the undepleted pump approximation. We considered evanescent wave losses calculated at 10% cm$^{-1}$ and 30% cm$^{-1}$ for the fundamental and TH wavelengths respectively, and an effective interaction length of 2.7 mm measured from the spectral acceptance and allowed us to take into account the gradient of the transverse section of the waveguide along its axis. Figure 2 shows the perfect agreement between measurements and calculations, and that without any fitting parameters.

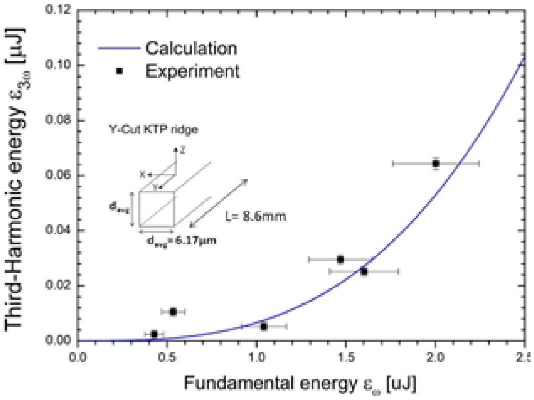


Fig. 2. Measured Third-Harmonic energy (in black) at the exit of the crystal as a function of the Fundamental energy at the entrance. Calculated energy (in blue) without any adjusting parameter.

## 4. Conclusion

In summary, we fabricated a 8.6-mm-long ridge waveguide based on a single KTP crystal allowing THG to be phase-matched at 1594 nm. We obtained an energy conversion efficiency of 3.4% for a fundamental energy of 2 µJ in the picosecond regime. The THG conversion efficiency can be mostly optimized by decreasing the losses, which will be done by increasing the thickness of the silica layer between the gold film and the KTP crystal.

The full agreement between calculation and measurement validates our calculation of effective indices as well as the notion of effective interaction length for the modeling of the effect of the prismatic shape of the ridge.

The fabrication of samples with a 2-µm-thick Silica layer is in progress with the target to decrease the propagation losses so that it is expected to reach a THG energy conversion efficiency up to 50% from our calculations.

## 5. References

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