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# The influence of bulk frequency doubling crystals on two-photon transition in rubidium

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**Abstract**

An excellent candidate for a high-quality portable frequency standard at the telecommunication region is the $5S_{1/2}$ (F = 3) –$5D_{5/2}$ (F = 5) two-photon transition of rubidium (85) at 778 nm. The interrogation of the two-photon transition needs efficient second harmonic conversion of a laser at 1556 nm. In the present work, a comparison is made between the conversion efficiencies of bulk and waveguide periodically polled lithium niobate (PPLN) crystals. In order to acquire the optimum operating conditions, the frequency doubled power is measured as a function of crystal temperature and laser wavelength. The conversion efficiency of the bulk PPLN crystal is found to be smaller than that of the waveguide PPLN for input powers less than 150 mW.

**Keywords:** Frequency doubling; Bulk PPLN; Waveguide PPLN; Rubidium.

## 1. Introduction

An increasing solicitation for an absolute optical frequency standard in the telecommunication c-band about 1.5 μm has motivated many scientists to seek reference candidates to obtain this goal. Among these candidates is a two-photon transition of rubidium at 778 nm [1].

In order to interrogate the two-photon transition of Rb, the fundamental frequency should be firstly doubled in a waveguide PPLN crystal or a bulk; i.e., the PPLN will form an integral part of the optical metrology source for this study. Accordingly, a full characterization of these kinds of frequency doublers is crucial for use in nonlinear spectroscopy [2].

Quasi-phase matching (QPM) allows efficient Second harmonic generation (SHG) with less stringent conditions on the crystal length and beam coupling conditions. The QPM can be introduced by applying periodic poling in a non-linear ferroelectric crystal such as lithium niobate ($LiNbO_3$). On the other hand, it is possible to generate efficient frequency conversion with much lower input light power [3].

Light diffracts as it propagates along the crystal and limits the conversion efficiency of the bulk PPLN crystal. By tightly confining the light along the crystal by what is called waveguide structure, high optical intensities can be maintained over a considerable distance to improve the conversion efficiency by two to three orders of magnitude as compared to bulk crystals [4], see Fig 1. Therefore, it is possible to generate efficient frequency conversion with much lower input light power.

In this present study, bulk and waveguide PPLN crystals doped with 5% MgO are applied to produce frequency doubled light. The conversion efficiencies of both crystals are acquired and compared by measuring the frequency doubled powers with respect to the fundamental powers. In order to achieve the optimum operating conditions, the frequency doubled power is also measured as a function of the laser wavelength and the PPLN crystal temperature.

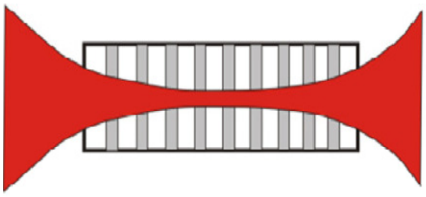

Fig 1 - Structure of bulk PPLN.

### 1. Second harmonic generation (SHG)

In order to obtain frequency doubling in a nonlinear crystal, the energy conservation and the phase matching conditions between the propagating waves must be satisfied. In SHG process, the energy conservation condition is satisfied when the input frequency equals exactly twice the output frequency ($\omega_1 = 2\omega_2$). In the case of quasi-phase matching in periodically poled nonlinear crystals with period of ($\Lambda$), the mismatch wave vector $\Delta k$ is given by the following equation [5]:

$$\Delta k = \frac{n_e(\lambda_1, T)}{\lambda_1} - \frac{2n_e(\lambda_2, T)}{\lambda_2} - \frac{1}{\Lambda} \qquad (1)$$

Where $n_e$ ($\lambda$, T) is the crystal extraordinary refractive index at temperature (T) and $\lambda_1$, $\lambda_2$ are the wavelengths of the fundamental and the second harmonic waves, respectively. Ideally, the mismatch wave vector should be zero, hence the above equation becomes:

$$\frac{1}{\Lambda} = \frac{n_e(\lambda_1, T)}{\lambda_1} - \frac{2n_e(\lambda_2, T)}{\lambda_2} \qquad (2)$$

The extraordinary refractive index ($n_e$ ($\lambda$, T)) can be described by wavelength and temperature dependent Sellmeier equation as follows, where f = (T − 24.5 °C) (T + 570.82) [6]:

$$n_e^2 = a_1 + b_1 f + \frac{a_2 + b_2 f}{\lambda^2 - (a_3 + b_3 f)^2} + \frac{a_4 + b_4 f}{\lambda^2 - a_5^2} - a_6 \lambda^2 \qquad (3)$$

Eqs. (2) and (3) are used to find the suitable period of the crystal at the fundamental wavelength $\lambda_1$= 1556 nm and its second harmonic at $\lambda_2$= 778 nm at temperature of around 49 °C. The crystal period which matches this wavelength is found to be $\Lambda$= 19.49 µm. Temperature applied to the crystal causes thermal expansion of the poling period, which can be described by the following equation [7]:

$$\Lambda(T) = \Lambda[1 + ((T - 19\ {}^\circ C) + \beta(T - 19\ {}^\circ C)^2] \qquad (4)$$

Where $\alpha = -1.54 \times 10^{-5}\ K^{-1}$, $\beta = -5.3 \times 10^{-9}\ K^{-2}$. Therefore, the temperature corrected crystal period ($\Lambda$ (T) = 19.5 µm).

## 2. Experiment

Firstly, a DFB diode laser was applied as a light source (EM4 Inc., wavelength: 1555–1559 nm, line width: 3 MHz. In order to adjust the laser wavelength to match exactly the desired two-photon transition of rubidium at 1556.2 nm, tuning maps were produced to account for the diode laser tunability as a function of its operating parameters namely, injection current and temperature. Obviously, different combinations of injection current and laser temperature would lead to the identical preferred Rb two-photon transition amongst them, and as an example, injection current of 285 mA and a temperature of 27.4 °C. The highest power of the laser, which is 80 mW, is not adequate for the nonlinear interaction in the PPLN crystal. Accordingly, an erbium doped fiber amplifier (EDFA) is applied to fortify the laser power to reach approximately 700 mW.

Fig 2 shows the system applied to evaluate the SHG conversion efficiency and the power dependence on the temperature of PPLN bulk crystal. The system consists of the DFB laser, Erbium doped fiber amplifier (Pritel, FA30, maximum power: 1 W, gain 30 dB), polarization controller (Thorlabs, FPC560), PPLN bulk crystal (HCPho-tonics, poling period: 19.5–21.3 µm, length: 25 mm) and powermeter (calibrated).

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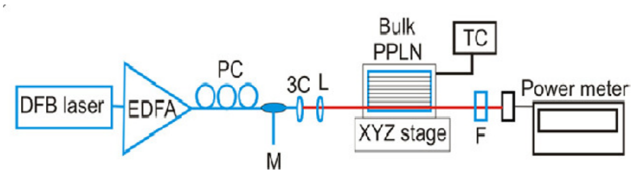

Fig 2 - The system applied to evaluate the dependence of SHG power on temperature of bulk PPLN.

## 3. Results

The power readings arerecorded while the temperature of the crystal is tuned from 43 to 57 °C. Fig 3 shows the measured curve, which reached a peak at 50.4 °C. The setup is then applied to measure the ratio of the input power to the output power, which is conversion efficiency. The SHG light power is measured while enhancing the fundamental pump power.

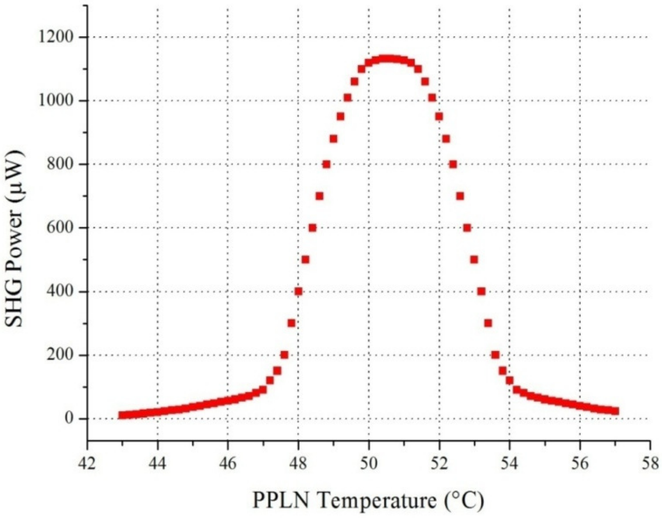

Fig 3- SHG power dependence on PPLN temperature ($P_{pump}$= 400 mW, λ = 1556.2 nm).

In Fig 4, the relation between SHG and fundamental light powers is not linear. This indicates that for superior pump power the SHG efficiency (PSHG/P pump) is anticipated to be better for superior pump powers. The curve denotes a conversion efficiency of 0.5% at 700 mW of input light power. By tuning the laser wavelength in steps of about 0.02 nm, the influence of the wavelength on the SHG power is measured. Fig 5 shows that peak SHG power is acquired at a wavelength of approximately 1556.2 nm. This shows that the temperature of the crystal is well adjusted to acquire SHG peak power at the needed wavelength.

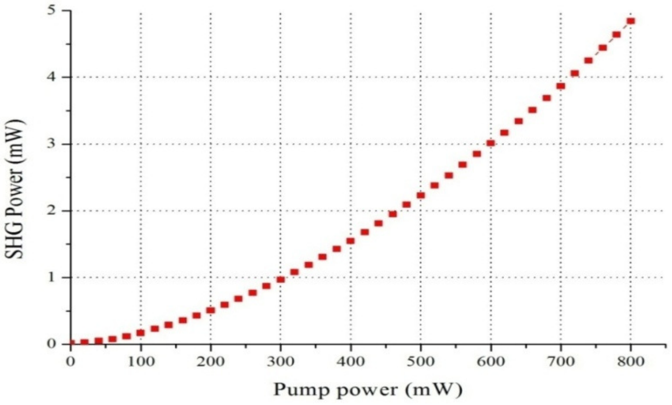

Fig 4- SHG power dependence on bulk PPLN pump power (λ = 1556.2 nm, T = 50.4 °C).

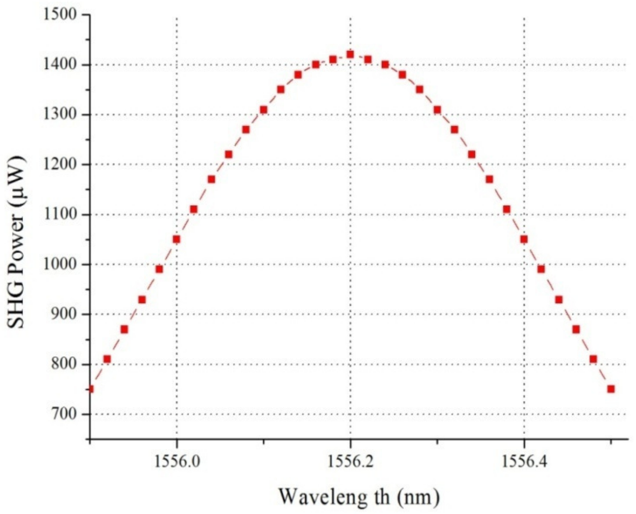

Fig 5- SHG power dependence on wavelength of bulk PPLN ($P_{pump}$= 400 mW, T = 50.4 °C).

## 4. Conclusion

Bulk PPLN:MgO crystals are applied to produce frequency doubled light at 778 nm from the fundamental light at1556 nm.

The efficiency of the frequency conversion of the bulk crystal reaches only 0.5% at 700 mW pump power and only 0.1% at 150 mW. This conversion efficiency exceeds by around two orders of magnitudes that of the bulk PPLN crystal at the same input power. The peak SHG power is acquired at a wavelength of approximately 1556.2 nm. This shows that the temperature of the crystal is well adjusted to acquire SHG peak power at the needed wavelength. The relation between SHG and fundamental light powers is not linear. The SHG power decreases to 50% to approximately ±2.2 °C in the bulk crystal and ±1.2 °C for waveguide crystal. The produced second harmonic light from crystals is applied to investigate the two-photon transition in a natural rubidium cell.

## References

[1] A.J. Olson, E.J. Carlson, S.K. Mayer, Two-photon spectroscopy of rubidium using a grating-feedback diode laser, Am. J. Phys., 74 (2006) 218.

[2] N. Chiodo, F. DuBurck, J. Hrabina, Y. Candela, J.P. Waller, O. Acef, CW frequency doubling of 1029 nm radiation using single pass bulk and waveguide PPLN crystals, Opt. Commun., 311 (2013) 239–244.

[3] G.I. Stegeman, R.H. Stolen, Waveguides and fibers for nonlinear optics, JOSA B 6(4) (1989) 652–662.

[4] G.I. Stegeman, R.H. Stolen, Waveguides and fibers for nonlinear optics, JOSA B 6(4) (1989) 652–662.

[5] O. Paul, A. Quosig, T. Bauer, M. Nittmann, J. Bartschke, G. Anstett, J.A. L'huillier,Temperature-dependent Sellmeier equation in the MIR for the extraordinaryrefractive index of 5% MgO doped congruent LiNbO3, Appl. Phys. B 86 (2007)111.

[6] L.H. Deng, X.M. Gao, Z.S. Cao, W.D. Chen, Y.Q. Yuan, W.J. Zhang, Z.B. Gong,Improvement to Sellmeier equation for periodically poled LiNbO3crystalusing mid-infrared difference-frequency generation, Opt. Commun. 268 (2006)110–114.

[7] D.H. Jundt, Temperature-dependent Sellmeier equation for the index of refrac-tion, ne, in congruent lithium niobate, Opt. Lett. 22 (1997).