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Investigation of waveguide frequency doubling crystals for interrogation of a 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.

2. Second harmonic generation (SHG)

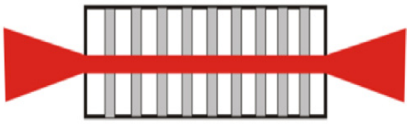

Fig 1 - Structure of waveguide PPLN.

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 (Λ), the mismatch wave vector Δk 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 (λ, T) is the crystal extraordinary refractive index at temperature (T) and λ_1, λ_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 (λ, 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 λ_1= 1556 nm and its second harmonic at λ_2= 778 nm at temperature of around 49 °C. The crystal period which matches this wavelength is found to be Λ= 19.49 μm. Temperature applied to the crystal causes thermal expansion of the poling period, which can be described by the following equation [7]:

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

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

3. 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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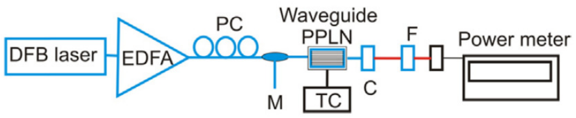

Fig 2 - The system applied to evaluate the dependence of SHG power on temperature of bulk PPLN.

4. Results

To compare the efficiency of SHG in waveguide against that of bulk PPLN crystals, the setup is applied. A measurement is performed for the optical power of SHG light at various temperatures, pump powers and laser wavelengths. The setup is used first to study the temperature influence on SHG power from the waveguide PPLN crystal. The basic wavelength is selected to be 1556.24 nm and the output power of the optical amplifier is retained at 100 mW. The power readings are entered while the temperature is tuned between 42 and 48.5 °C. As shown Fig 3, the highest SHG power is acquired at 46.9 °C, which decreases to 50% of its value at ±1 °C around this temperature. The setup is applied to measure the conversion efficiency of the waveguide PPLN crystal. The frequency power doubled light is measured while raising the input power. According to the manufacturer specification it is feasible to enhancement of the input power to only 150 mW to elude crystal damage. Fig 4 denotes the relation between both pump and SHG powers. At this the highest accepted pump-power value of 150 mW, we manipulated to acquire a second harmonic output laser power of nearly 17 mW.

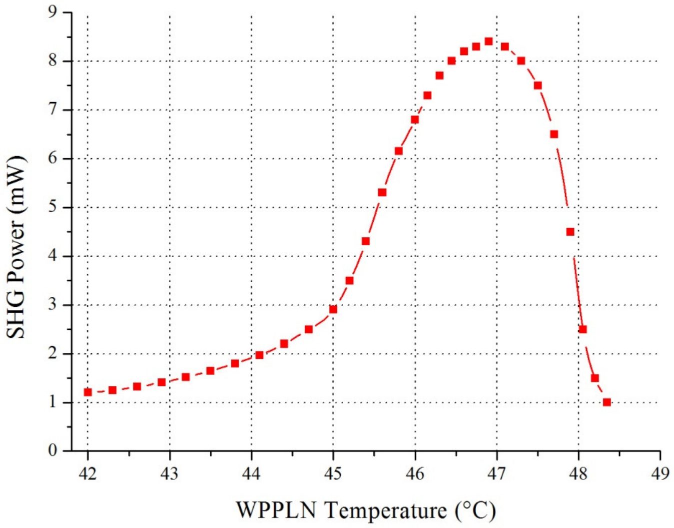

Fig 3- SHG power dependence on temperature of waveguide PPLN (Ppump= 100 mW, λ= 1556.24 nm).

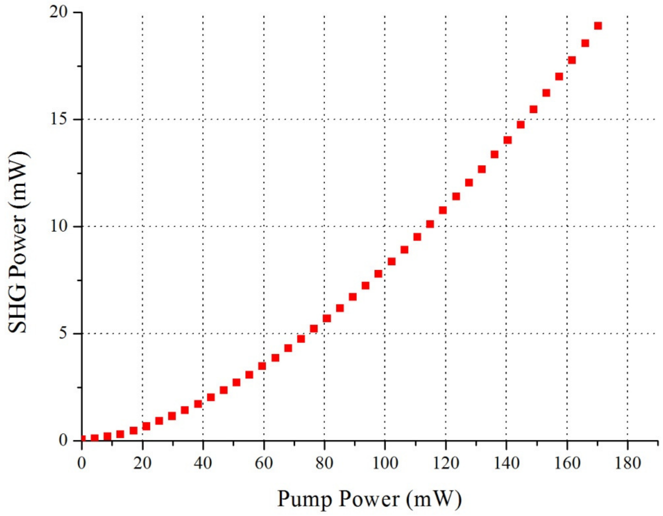

Fig 4- SHG power dependence on pump power of waveguide PPLN (λ= 1556.24 nm, T = 46.7 °C).

The influence of the wavelength on the SHG power of the waveguide PPLN crystal is considered by tuning laser wavelength in steps of approximately 0.02 nm. Fig 5 illustrates peak SHG power is acquired at a wavelength of approximately 1556.24 nm. It shows almost the identical characteristics, in which the SHG powers decreased to 50% at approximately ±0.2 nm away from peak.

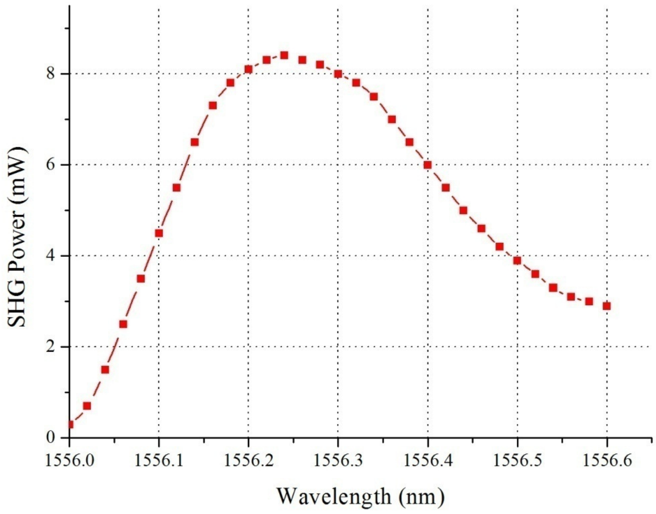

Fig 3- SHG power dependence on wavelength of waveguide PPLN (P_{in}= 1 mW, T = 46.7 °C).

Conclusion

Waveguide PPLN: MgO crystals are applied to produce frequency doubled light at 778 nm from the fundamental light at 1556 nm. The efficiency of the waveguide crystal reaches approximately 11% at the same pump power. This efficiency exceeds by around two orders of magnitudes that of the bulk PPLN crystal at the identical input power. The SHG output powers from crystals are evaluated as a function of laser wavelength. The highest SHG power is acquired at 46.9 °C, which decreases to 50% of its value**.** It was illustrated peak SHG power is acquired at a wavelength of approximately 1556.24 nm**.** 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.

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