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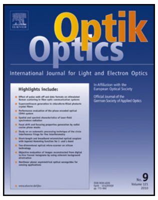

Investigation of bulk and waveguide frequency doubling crystals for interrogation of a two-photon transition in rubidium

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ABSTRACT

The $5S_{1/2}$ ($F=3$)–$5D_{5/2}$ ($F=5$) two-photon transition of rubidium (85) at 778 nm is an excellent candidate for a high-quality portable frequency standard at the telecommunication region. The interrogation of the two-photon transition requires efficient second harmonic conversion of a laser at 1556 nm. In this work, a comparison is made between the conversion efficiencies of bulk and waveguide periodically polled lithium niobate (PPLN) crystals. Both crystals are doped with 5% from MgO and used to generate frequency doubled light at 778 nm from a fundamental light source operating at 1556 nm. In order to obtain the optimum operating conditions, the frequency doubled power is measured as a function of laser wavelength and crystal temperature. The conversion efficiency of the waveguide PPLN is found to be around two orders of magnitudes larger than that of the bulk PPLN crystal for input powers less than 150 mW. At the end, the generated second harmonic light from both crystals are used to interrogate the two-photon transition in a natural rubidium gas cell. A comparison is made between the fluorescence spectrums resulting from the two-photon transition using second harmonic generated powers from both crystals.

1. Introduction

An increasing demand for an absolute optical frequency standard in the telecommunication c-band around 1.5 μm has motivated many researchers to look for reference candidates to achieve this goal. Among these candidates is a two-photon transition of rubidium at 778 nm [1], where one can phase-lock the second harmonic of the 1556 nm laser to the ^{85}Rb transition $5S_{1/2}$ ($F=3$)–$5D_{5/2}$ ($F=5$). The main advantage of this approach is that it provides us with two highly stable wavelengths; the one lying in the edge of the visible spectrum is serviceable in length metrology applications while the fundamental wavelength offers an ideal reference for optical telecommunication industry or other fiber-related measurement/metrology. In order to interrogate the two-photon transition of Rb, the fundamental frequency should be firstly doubled in a bulk or a waveguide PPLN crystal; i.e., the PPLN will form an integral part of the optical metrology source for this experiment. Therefore, a full characterization of these types of frequency doublers is crucial for use in nonlinear spectroscopy [2]. Quasi-phase matching (QPM) allows efficient SHG with less stringent conditions on the crystal length and beam coupling conditions. QPM also compensates the phase-velocity mismatching between the interacting waves [3]. The QPM can be introduced by applying periodic poling in a non-linear ferroelectric crystal such as lithium niobate ($LiNbO_3$).

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 work, bulk and waveguide PPLN crystals doped with 5% MgO are used to generate frequency doubled light. The conversion efficiencies of both crystals are obtained and compared by measuring the frequency doubled powers with respect to the fundamental powers. In order to find the optimum operating conditions, the frequency doubled power is also measured as a function of the laser wavelength and the PPLN crystal temperature.

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Fig. 1. Structure of PPLN crystal (a) bulk PPLN and (b) waveguide PPLN.

2. 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 (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 $n_e(\lambda, T)$ 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 ($n_e(\lambda, T)$) can be described by wavelength and temperature dependent Sellmeier equation as follows [6,7]:

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

where $f = (T - 24.5\,^\circ\mathrm{C})(T + 570.82)$, the values of a_i and b_i are shown in the following table:

$a_1 = 5.5336$	$a_2 = 0.100473$	$a_3 = 0.20692$	$a_4 = 100$	$a_5 = 11.34927$
$a_6 = 1.5334 \times 10^{-2}$	$b_1 = 4.629 \times 10^{-7}$	$b_2 = 3.862 \times 10^{-8}$	$b_3 = -0.89 \times 10^{-8}$	$b_4 = 2.657 \times 10^{-5}$

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 $\Lambda = 19.49\ \mu$m. Temperature applied to the crystal causes thermal expansion of the poling period, which can be described by the following equation [6]

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

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

3. Experiment

3.1. Laser characterization

In the initial phase of the experiment, a DFB diode laser was used as a light source (EM4 Inc., wavelength: 1555.5–1558 nm, line width: 3 MHz. In order to adjust the laser wavelength to match exactly the desired two-photon transition of rubidium at 1556.21 nm, tuning maps were generated to account for the diode laser tunability as a function of its operating parameters namely, temperature and injection current as depicted in Fig. 2. Obviously, different combinations of laser temperature and injection current would lead to the same preferred Rb two-photon transition amongst them, and as an example, a temperature of 27.4 °C and injection current of 285 mA.

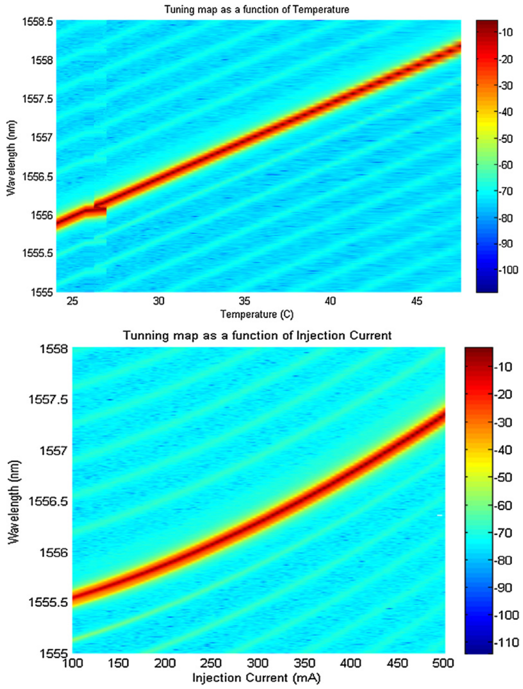

Fig. 2. Top: laser tuning map as a function of temperature and bottom: as a function of injection current.

The DFB laser spectral line-width $\Delta\nu_{\mathrm{Laser}} = 3$ MHz while the two-photon transition spectral line-width $\Delta\nu_{\mathrm{Trans}} = 300$ kHz. For frequency locking purposes, the line-width of the 1556 nm DFB diode laser has to be less than the $\Delta\nu_{\mathrm{Trans}}$ value (approximately a few tens of kiloHertz). Therefore, to be able to resolve the narrowly spaced hyperfine excited states, we need to use a laser with a narrower spectral line-width. However, the specification of the DFB laser should be sufficient to investigate the performance of the frequency conversion.

3.2. SHG in bulk PPLN crystal

Fig. 3 shows the system used to investigate the SHG conversion efficiency and the power dependence on the wavelength and 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), triplet collimator (Thorlabs, TC06APC-1550), PPLN bulk crystal (HCPhotonics, poling period: 19.5–21.3 μm, length: 25 mm) and power meter (Newport, 1830C-818UV detector, calibrated), F: achromatic mirror (passes 778 nm and blocks 1556 nm).

The maximum power of the laser, which is 80 mW, is not sufficient for the nonlinear interaction in the PPLN crystal. Therefore, an erbium doped fiber amplifier (EDFA) is used to amplify the laser power to reach around 700 mW. As discussed in Section 2, the frequency conversion will take place only when the phase matching condition is satisfied between the fundamental and the second harmonic waves. Hence, the polarization of both waves should be the

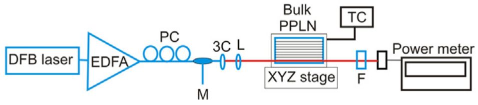

Fig. 3. The system used to investigate the dependence of SHG power on wavelength and temperature of bulk PPLN. M, monitor port (1%); EDFA, erbium doped fiber amplifier; PC, polarization controller, 3C, triplet collimator; TC, temperature controller; L, lens; F, achromatic mirror.