Generation of blue light at 426 nm by frequency doubling with a monolithic periodically poled $KTiOPO_4$

Xue Deng,[1] Jing Zhang,[1,2] Yuchi Zhang,[1,2] Gang Li,[1] and Tiancai Zhang[1,*]

[1]*State Key Laboratory of Quantum Optics and Quantum Optics Devices, and Institute of Opto-Electronics, Shanxi University, Taiyuan 030006, Shanxi Province, China*

[2]*College of Physics and Electronics Engineering, Shanxi University, Taiyuan 030006, Shanxi Province, China*

**tczhang@sxu.edu.cn*

Abstract: Continuous-wave (cw) blue laser generation at 426 nm by frequency doubling with a monolithic periodically poled KTP (PPKTP) cavity is reported in this paper. Without any free mirrors, the standing-wave cavity solely consists of a monolithic PPKTP crystal, and both ends of which are spherically polished and mirror-coated. An output power of 158 mW is obtained when the pump power is 350 mW. The conversion efficiency is 45%. The dependence of the conversion efficiency on the temperature and the incident fundamental power has been discussed. Such a system is integrally stable and compact for long-time operation under temperature control. The system is much more stable than the usual servo lock system for external cavity doubling.

OCIS codes: (190.2620) Harmonic generation and mixing; (140.4780) Optical resonators.

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1. Introduction

Frequency doubling of near-infrared light by nonlinear process, such as the external cavity doubling, is an important method to obtain blue laser which has been widely used in many fields, such as optical measurement [1], information storage and readout [2,3], nonlinear optics [4,5], quantum optics [6,7], quantum information [6,8] and other fundamental studies in quantum physics. Those wavelengths exactly corresponding to the transitions of the alkalis are significant as they provide various important quantum resources by optical parametric down conversion for the research of light-atom interaction [9,10], precision measurement [11] and information storage [12,13]. The optical parametric oscillator (OPO) is a common device for non-classical light generation [4,11,13–15], whose pump beam is usually from a frequency doubler. During the past decades, the technique for blue laser generation by frequency doubling has been developed. In 1991, 650 mW of blue light at 430 nm was produced with $KNbO_3$ in a ring optical cavity, and the conversion efficiency was 48% [16]. In 2004, 200 mW of blue light at 461 nm was obtained via frequency-doubled $KNbO_3$ in a semi-monolithic cavity [17]. In 2007, using a PPKTP crystal in a ring cavity, 330 mW blue light at 426 nm was obtained, and the conversion efficiency was 55% [18]. Recently, 680 mW of blue light at 486 nm was obtained with a Brewster cut PPKTP crystal in a ring cavity [19]. Also investigated were the blue light generation by frequency doubling based on ring cavity either by $KNbO_3$ [20] or PPKTP [21], and the conversion efficiencies were 39% and 40%, respectively. In all the above schemes, the elements making up the doubler were separated, which facilitated the beam and cavity alignment and flexibility of cavity length adjustment. However, they also had disadvantages of large internal losses and less long-term stability. A monolithic cavity with simply one crystal provides a new attempt to construct a robust compact doubler with high efficiency and stability [22].

This paper reports for the first time to our knowledge, the frequency doubling with a monolithic PPKTP cavity for blue light generation at 426 nm. A monolithic PPKTP crystal acts as a standing-wave cavity. Both ends of the crystal are spherically-polished (radius of curvature is 20 mm) and mirror-coated. A maximum power of 158 mW of blue light at 426 nm is obtained. Because of the short cavity length and the large free spectral range (FSR) and bandwidth (FSR = 5.2 GHz and the cavity bandwidth is 160 MHz), it is easy to achieve resonance under temperature control for the crystal.

2. Theoretical analysis

The overall conversion efficiency is given by [18, 23]:

$$\sqrt{\eta}=\frac{4T_1\sqrt{E_{\mathrm{NL}}P_1}}{\left[2-\sqrt{1-T_1}\left(2-L-\Gamma\sqrt{\frac{\eta P_1}{E_{\mathrm{NL}}}}\right)\right]} \tag{1}$$

where $\eta = P_2/P_1$ is the overall conversion efficiency, with P_1 the mode-matched fundamental beam power, and P_2 the second harmonic output beam power. Γ represents the nonlinear losses, and can be written as: $\Gamma = E_{\mathrm{NL}} + \Gamma_{\mathrm{abs}}(\mathrm{W}^{-1})$. The first term E_{NL} is the round-trip conversion efficiency, $P_2 = E_{\mathrm{NL}} P_{\mathrm{c}}^2$ (P_{c} is the internal circulating fundamental power), and the second term Γ_{abs} formulates second harmonic (SH) light absorption process inside the crystal: $P_{\mathrm{abs}} = \Gamma_{\mathrm{abs}} P_{\mathrm{c}}^2$. The SH absorption cannot be neglected here, and the absorption coefficient is approximately $\alpha \approx 10\%\mathrm{cm}^{-1}$ at 426 nm [18, 24]. L represents the intra-cavity losses at fundamental wavelength, including absorption and scattering losses inside the crystal and at both ends, and T_1 is the transmission coefficient of the input coupler for fundamental field (here the cavity is single-ended). The optimum T_1 depends on L , Γ and P_1 .

3. Experimental setup

The experimental setup is shown in Fig. 1. The pump beam, provided by a cw single-longitudinal-mode Ti:Sapphire laser which is locked round 852 nm, corresponding to the D2 transition of cesium atoms, passes through an optical isolator (OI), and is split into two parts by a half-wave-plate (HWP) and a polarization beam splitter (PBS). The main part of the beam is mode-cleaned by a single-mode fiber before entering the crystal cavity. The maximum fundamental power of 350 mW is mode-matched into the monolithic PPKTP cavity by lens L1. The HWP before the cavity is used to adjust the polarization of the pump beam.

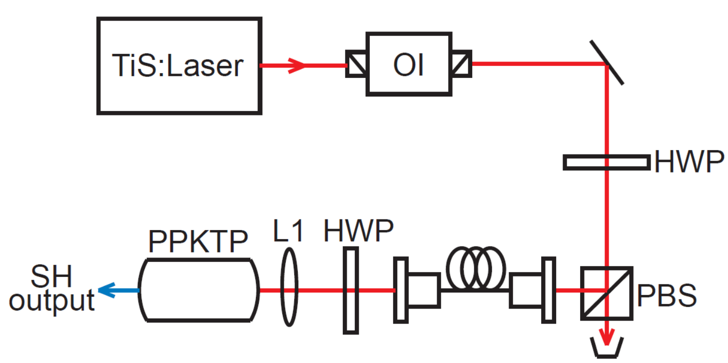

Fig. 1. Experimental setup. OI: isolator; HWP: half-wave plate; PBS: polarizing beam splitter; L1: mode-matching lens, f = 80 mm.

The PPKTP crystal (Raicol crystals) is a type I phase-matching crystal. Its parameters are shown in Fig. 2. Both ends of the crystal are spherically-polished. Based on the coating design, the front facet has a transmittance of 8% for 852 nm and is highly reflective (T<0.1%) for 426 nm, and the rear facet is highly reflective (T<0.1%) for 852 nm and AR coated (T<0.5%) for 426 nm. The crystal is 15 mm long with 2 mm × 1 mm cross-section. The poling period of the crystal is about 4.19 μm. The crystal is placed in a copper-made oven and

#197468 - $15.00 USD Received 11 Sep 2013; revised 12 Oct 2013; accepted 12 Oct 2013; published 22 Oct 2013

is temperature-controlled to the level of millikelvin. According to the parameters, the cavity waist is 51 μm and is located in the center of the crystal. The mode-matching efficiency is about 89%.

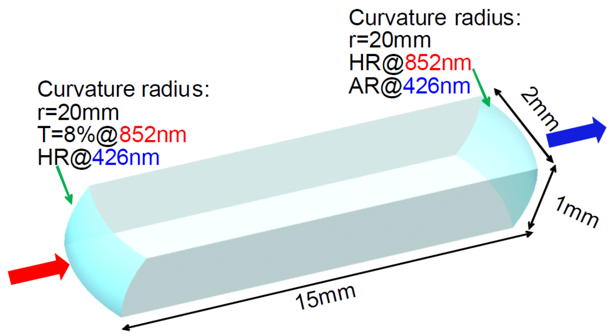

Fig. 2. The monolithic PPKTP crystal.

The PPKTP crystal is quasi-phase-matching crystal and its phase-matching condition is realized by temperature control. Compared to the usual non-monolithic cavity, the temperature should be tuned to achieve phase-matching and maintain the cavity resonance simultaneously. Wide bandwidth of the phase-matching temperature and the cavity bandwidth are thus important to satisfy the conditions. The challenge is to select a proper temperature which keeps the cavity length on resonance while the phase-matching is still fulfilled.

4. Experimental results and discussions

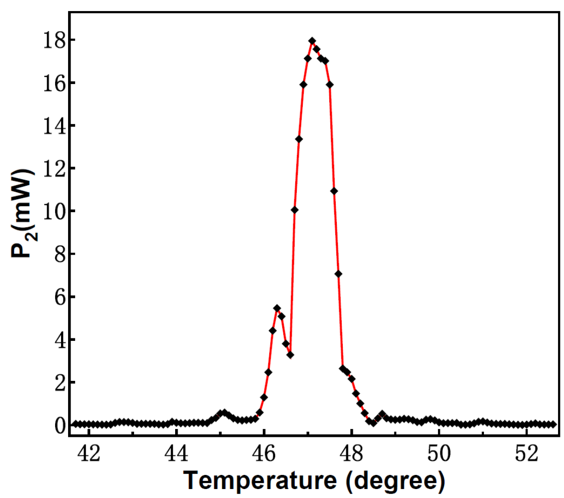

Fig. 3. Output blue power at 426 nm versus temperature. The input fundamental power is 70 mW.

Figure 3 shows the measured doubling power as the temperature is tuning. It can be seen that the best phase matching temperature is at 47.1 ⌡C, and the temperature bandwidth is about 1 ⌡C. The refractive index of the crystal at 852 nm is 1.84. The temperature tuning coefficient of phase matching is around −21GHz/⌡C (corresponding to + 0.052 nm/⌡C). The free spectrum range (FSR) of 5.2GHz measured in terms of temperature is ΔT_{FSR} = 1 ⌡C. Thus, when an appropriate temperature can be selected and controlled with the precision of millikelvin, the cavity resonance and crystal phase-matching can be realized simultaneously.

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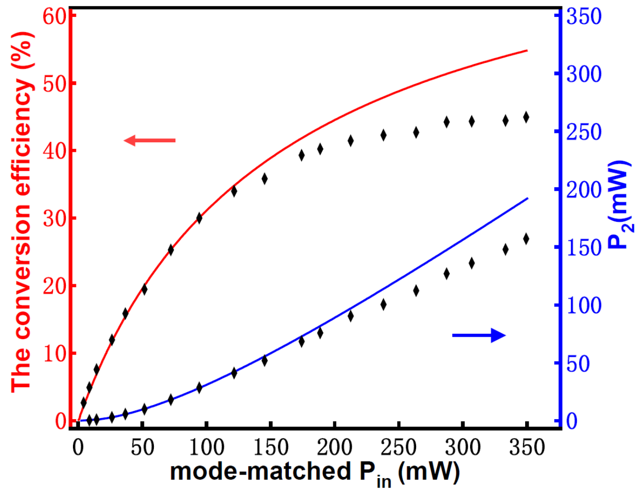

Fig. 4. Total conversion efficiency and second harmonic power versus fundamental power. Solid lines represent the theoretical results based on parameters of the system (E_{NL} = 0.75%W^{-1}, L = 2.9%, Γ_{abs} = 0.08 E_{NL}) and the solid rhombuses are experimental results.

Figure 4 shows the conversion efficiency and the blue power at 426 nm as a function of fundamental power. Solid lines and rhombuses indicate the theoretical and experimental results, respectively. A maximum output power of 158 mW for a mode-matched input power of 350 mW can be obtained, corresponding to the conversion efficiency of 45%.

The conversion efficiency is slightly lower than that of the ring cavity system [18]. It is known that the conversion efficiency is affected by several factors, including the intra-cavity losses, pump power, the coefficient of phase-matching, etc. In our experiment the losses of the crystal are not as expected. The intra-cavity loss L is measured 2.9% [25], which is higher than expected. This could be attributed to those internal defects or imperfections during the manufacturing process. The second reason is the phase-matching condition, which is not perfect, and the inferred E_{NL} is about 0.75%W^{-1}. At a relatively high pump, a deviation was found between the experiment results and theoretical fittings. This may be caused by the thermal effects due to the blue light absorption inside the cavity [24]. However, the above-mentioned problems, which limit the conversion efficiency, can be solved with high quality crystal. The present configuration suggests there is potential to obtain frequency doubling, especially for making a robust and compact frequency doubler.

5. Conclusion

In conclusion, frequency doubling with a monolithic PPKTP cavity has been studied. An output power of 158 mW is obtained for a mode-matched power of 350 mW with a conversion efficiency of 45%. The best phase matching temperature is 47.1 ⌡C. The experimental results are consistent with the theory. In the experiment, the conversion efficiency of monolithic cavity was compared with a separated system and the results were analyzed. It shows that the present monolithic crystal system is feasible in setting up a high-efficiency and long-term running robust doubler without electronic servo locks.

Acknowledgments

The work was supported by the Major State Basic Research Development Program of China (Grant No. 2012CB921601) and the National Natural Science Foundation of China (Grant No. 11125418, 61227902, 61275210, 11204165, 61121064), and the Natural Science Foundation of Shanxi (Grant No. 2013021005-2).