# Frequency doubling with periodically poled $KTiOPO_4$ at the fundamental wave of cesium $D_2$ transition

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We report the continuous wave (CW) second harmonic generation (SHG) with a periodically poled $KTiOPO_4$ (PPKTP) pumped by a diode laser at 852.356 nm, which is exactly resonant on the cesium $D_2$ transition. An output power of 54.4 mW of blue light at 426 nm was obtained at the pump power of 136.4 mW. The conversion efficiency is about 40%. The best matching temperature is 318.3 K. This CW blue light can be used for atomic physics, especially for the generation of nonclassical light at the transition of cesium atom through optical parametric oscillator (OPO).

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The interaction between light field and atoms is a key issue in modern atom-molecular-optics research. With the development of quantum optics and atomic physics, it has been the workhorse of quantum information processing[1]. Nonclassical light field, known as a very important quantum resource, plays an important role in light-atoms interaction, and a lot of quantum phenomena have been investigated, such as nonclassical spectroscopy[2], nonclassical excitation[3−5], atoms-field nonclassical transfer[6], etc.. Mapping the quantum state of light field onto an atomic ensemble is becoming a critical task for quantum information science and ultra-precise measurement[7]. Yet, these experiments require the quantum state of light field which is exactly resonant on the specific atom transition. The usual method of generating nonclassical light is the optical parametric process. Previously, squeezed beams at cesium (Cs) D-line and rubidium D-line by either $KNbO_3$[8] or $KTiOPO_4$ (KTP)[9] have already been generated. The usual way of obtaining the pump beam of optical parametric oscillator (OPO) is to use the frequency-doubled Ti:sapphire laser as pump source[10]. In 1991, with a continuous wave (CW) Ti:sapphire laser, 0.65 W of blue light at 430 nm was obtained at the pump power of 1.35 W with $KNbO_3$[11], the conversion efficiency was about 48%. 500 mW of blue light at 473 nm was reached in 1997[12]. Recently, frequency doubling conversion efficiency as high as 75% was achieved at 922 nm with either periodically poled $KTiOPO_4$ (PPKTP)[13] or semimonolithic $KNbO_3$[14] for strontium atom cooling. At the wavelength of 860 nm, the frequency doubling conversion efficiency of 45% has been obtained with $KNbO_3$[15]. However, there have been relatively few experiments of getting blue beam at 426 nm with PPKTP, which is the frequency doubling of the Cs $D_2$-transition. This even shorter wavelength of CW blue light has many applications in optical communication, biomedical applications, spectroscopy, and neutral atom lithography[16], etc..

In this letter, we report the blue light generation at 426.178 nm by frequency doubling at Cs $D_2$ transition. We have built an optical frequency doubler with PPKTP pumped by a diode laser. The conversion efficiency of about 40% is obtained. This result can help people to generate nonclassical beam at Cs $D_2$ transition and will be very useful for studies on nonclassical field-atoms interaction[17].

Figure 1 shows the experimental setup. A diode laser SDL-TC40 (SDL Inc.) is employed as the pump source. The beam from diode laser passes through an optical isolator (OI) and is split into two parts by a half-wave-plate (HW) and a polarizing beam splitter (PBS). The small part goes to a Fabry-Perot (F-P) cavity for mode monitoring and saturation absorption system of Cs atom while the main part goes to the frequency doubler. The wavelength of the pump beam can be finely tuned to the Cs $D_2$ transition by a piezoelectric transducer (PZT) of SDL-TC40. The maximal pump power just before the frequency doubler is 136.4 mW.

The nonlinear material used in our experiment is quasi-phase-matching (QPM)[18] PPKTP (Raicol crystals)[15]. QPM materials are free of walk-off effect. Compared with $KNbO_3$, the blue-light-induced infrared absorption[19] (BLIIRA) for PPKTP is not a problem, and this crystal has been widely used for frequency doubling and down-conversion[13,15,18].

The frequency doubler is a bow-tie type ring cavity

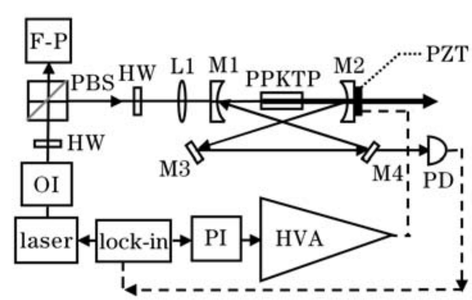


Fig. 1. Experimental setup. HVA: high voltage amplifier; PI: proportion integral circuits; lock-in: lock-in amplifier; PD: photodetector.

 

which consists of two flat mirrors M3 and M4, and two curved mirrors M1 and M2 with curvature radius of 50 mm. There is a PZT on M2 which is used for controlling cavity length. The two flat mirrors are coated high-reflection at 852 nm. One of the curved mirrors is a super-mirror with reflectivity of 99.9992% at 852 nm and transmission of 77.2% at 426 nm. Another curved mirror M1 is the input coupler with transmission of 7.6% at 852 nm. The size of PPKTP crystal is $1 \times 2 \times 10$ (mm) and both sides of the crystal are anti-reflection coated at 852 nm. The crystal is placed at the beam waist between M1 and M2. According to the optimal design, the best radius of beam waist inside the crystal should be around 20 $\mu$m[13,20]. The crystal is placed in a copper-made oven and is temperature-controlled within 0.005 K. The measured nonlinear efficiency of the crystal is $E_{\mathrm{NL}} = 1.4\%$ $\mathrm{W}^{-1}$. The total round trip cavity length is 516 mm and the distance between the two curved mirrors is 58 mm[21]. L1 is a lens with $f = 80$ mm for mode-matching the ring cavity. Since we do not use the mode cleaner[22], the beam profile is not a perfect Gaussian mode and the mode-matching efficiency is about 87%.

The efficiency of frequency doubling is sensitive to temperature. Figure 2 shows the change of blue power when the temperature of crystal is increased from 287 to 370 K (corresponding to the resistance of the thermistor from 16.47 to 0.74 k$\Omega$). The best phase matching temperature is 318.3 K (4.31 k$\Omega$) for 852.356 nm. The period of the PPKTP is 4.15 $\mu$m and the temperature tuning coefficient is around $0.04 - 0.05$ nm/K. Theoretically the phase matching temperature is within $293 - 323$ K[23], which is essentially coincident with actual measured temperature. The temperature bandwidth of the crystal is $\Delta T_{\mathrm{FWHM}} = 1.8$ K.

When detuning the temperature of crystal far away from the best matching temperature and scanning the cavity length by the PZT attached to M2, we have measured the reflection and transmission of the cavity. The total internal loss is then determined, which is $L = 2.65\%$. This loss is mainly caused by the imperfect coating of the crystal and the absorption and dispersion of the intra-cavity mirrors. According to our maximal available input power, the above intra-cavity loss and nonlinear efficiency of the crystal, one can get the best transmission of the input coupler[10], which is about $T_{\mathrm{opt}} = 5.7\%$. The transmission of the input coupler is $T = 7.6\%$ at present time, which is a little higher than $T_{\mathrm{opt}}$.

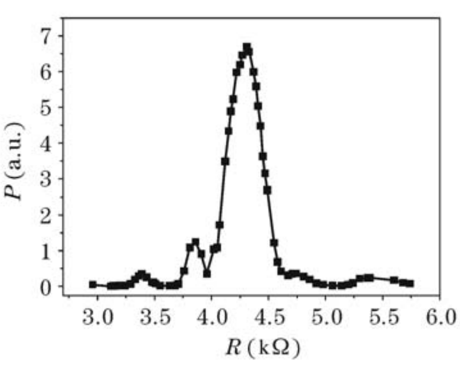


Fig. 2. Output blue power at 426 nm versus the temperature represented by the resistance of thermistor.

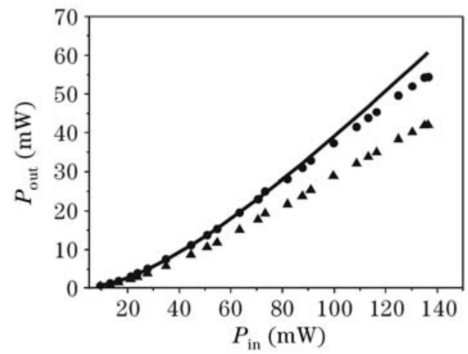


Fig. 3. Output power of doubling blue light versus the 852-nm input power. The triangles are the directly measured power, the dots are the really generated blue light just before M2, and the solid curve is the theoretical result according to the parameters of the system.

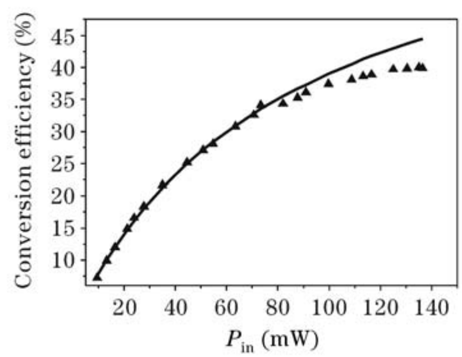


Fig. 4. Conversion efficiency as a function of pump power at 852 nm. The triangles are the measured results and the solid curve is the theoretical result.

The ring cavity is locked to the frequency of the pump beam by frequency modulation locking technique. We have measured the generated blue light passing through the output coupler M2. The measured maximal blue light power at 426 nm is 42 mW, while the pump power is 136.4 mW. Considering the transmission loss of M2 for blue light, the really generated power is 54.4 mW and the corresponding conversion efficiency is $\eta = P_{2\omega}/P_{\omega} = 40\%$. Figure 3 shows the output power of second harmonic generation (SHG) as a function of the pump power. The triangles are the directly measured blue power and the spots are the actual power generated before M2, while the solid curve is the theoretical result according to the cavity loss and the pump power[10]. The fitting is quite good at relatively low pump level. The conversion efficiency as a function of the pump power is shown in Fig. 4. The triangles are the actual conversion efficiency when the transmission loss of M2 is taken into account, the solid curve is the theoretical prediction, they are in good agreement. The discrepancy at relatively high pump level in Figs. 3 and 4 is due to thermal lensing effect caused by the focused waist[13]. This thermal lensing can affect the infrared beam propagation and reduce its mode matching. The total conversion efficiency is then decreased.

In conclusion, we have generated blue light at 426 nm by the frequency doubling with PPKTP using a diode laser as pump source. Maximum blue light of 54.4 mW is obtained and the conversion efficiency is about 40% at the optimal matching temperature of 318.3 K, which agree well with the theoretical results. This blue light can be used for quantum state generation at the Cs $D_2$ transition, laser spectroscopy, and atom lithography, etc.. Higher conversion efficiency and more blue light may be obtained if the intra-cavity loss can be reduced further and Ti:sapphire laser is used as pump source.

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