

CW blue light generation at 429 nm by utilizing second harmonic process with KNbO_3

Hongxiang Lei (雷宏香), Tao Liu (刘涛), Liping Li (李利平),
Shubin Yan (闫树斌), Junmin Wang (王军民), and Tiancai Zhang (张天才)

State Key Laboratory of Quantum Optics and Quantum Optics Devices,
Institute of Opto-Electronics, Shanxi University, Taiyuan 030006

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Continuous-wave blue light at 429 nm from a second harmonic process has been investigated at room temperature with Potassium Niobate (KNbO_3) crystal. Optimum parameters for nonlinear conversion in our designing single-resonant, external ring cavity pumped by the Ti:sapphire laser are established. 39% of maximum overall conversion efficiency is obtained and factors that limit the conversion efficiency is discussed.

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Potassium Niobate (KNbO_3)^[1] has some defects, such as instability and crystal clustering and so on, yet due to its larger nonlinear optical coefficient d_{32} , it is found to be one of the most versatile crystal for second harmonic generation (SHG), sum frequency mixing (SFM), optical parametric oscillation (OPO), and it is widely used for the generation of green-blue light via SHG, tunable near infrared (NIR) light via OPO/OPA. But because of the blue light induced infrared absorption (BLIIRA) and the thermal effect, the conversion efficiency can be limited.

In past years, a substantial amount of work has been done on the blue light generation by frequency doubling pumped with semiconductor diode laser^[2,3], Ti:sapphire laser^[4], nonlinear mixing of diode laser and Nd:YAG laser^[5]. The best conversion efficiency was 80% at 917 nm with the phase-matching temperature around 130 °C^[6] at which BLIIRA is much smaller compared to that in the room temperature^[7,8].

In this paper, we design a single-resonant, external ring cavity as our frequency doubler. A Ti:Sapphire laser with a linewidth of 200 kHz is chosen as the pump source. It operates at 858 nm and corresponding phase-matching temperature for KNbO_3 is around room temperature. 235 mW of blue light at 429 nm is produced from the external cavity with 600 mW of pump power. When the cavity is locked, the output power drops to 137 mW with 565 mW of pump level mostly because of the thermal effect. The results are coincident with the theoretical prediction on our experimental conditions^[4].

We designed a four-mirror ring cavity with an opening angle minimized to about 6° in order to avoid optical aberrations (see dotted box of Fig. 1). It consists of two plane mirrors M_1 , M_2 and two curved mirrors M_3 , M_4 both with radius of curvature of 4 cm. A KNbO_3 crystal with length of 7 mm is positioned on the beam waist between M_3 and M_4 . The use of a-cut KNbO_3 allowed non-critical temperature phase-matching of degenerate parametric process. Mirrors are coated for single-resonance at fundamental wave and single-pass for second harmonic beam. M_2 , M_3 and M_4 are total reflection mirrors at 858 nm, and M_1 , M_4 are the input and output couplers, respectively. The temperature of the crystal is well controlled within 0.005 °C, which is checked by

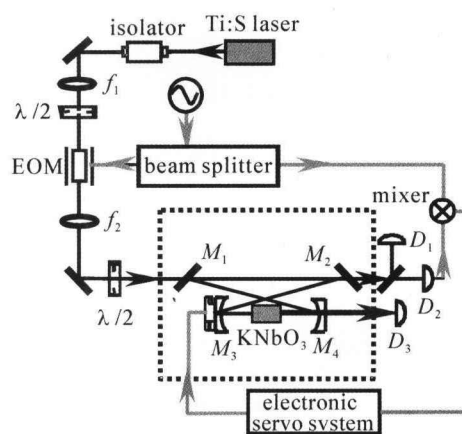


Fig. 1. Schematic of experimental setup.

measuring the resistance of the thermistor within 4 hours.

The first factor we have to consider is the beam size inside the crystal. The length of the crystal determines the optimum size of the waist eventually^[9]

$$l = 2z_0 = \frac{2\pi n\omega_0^2}{\lambda}, \quad (1)$$

where l is the length of crystal, z_0 the Rayleigh length, λ the wavelength of fundamental field, ω_0 the beam waist inside the cavity and n the index of the crystal. With $\lambda=858$ nm, $n = 2.2372$ and $l = 7$ mm, the best waist should be $\omega_0 \approx 20.67$ μm . Here we did not consider the thermal effect and other factors, which may affect the optimal focusing condition^[10]. Actually, the size of beam waist should be smaller. In our experiment, we choose $d_1 = 48.5$ mm and the total cavity length is $d_2 = 360$ mm, then the beam waist is around 20 μm which fulfills Eq. (1), and the waist can be adjusted experimentally by fine changing the distance d_1 .

Another important factor that affects the efficiency of doubling is the input coupler. Suppose T_1 is the transmission of the input coupler. On cavity resonance, we

have the following relation^[3,6]:

$$\frac{P_c}{P_{in}} = \frac{4\alpha T_1}{(T_1 + L + P_c E_{NL})^2}, \quad (2)$$

where P_c is the intracavity circulating fundamental power and P_{in} the input power. L is the residual intracavity roundtrip losses including scattering, absorption of the mirrors and the crystal and also the BLIIRA^[3,7,8]. α is the mode-matching efficiency. E_{NL} is the single-pass nonlinear conversion efficiency and $P_c E_{NL}$ is the nonlinear loss due to the conversion of the fundamental into the second harmonic wave. From Eq. (2), we obtain

$$\gamma = \frac{\beta}{3} \left(\begin{array}{l} \left[1 + \frac{27}{2} \frac{\rho}{\beta^3} \left(1 + \sqrt{1 + \frac{4}{27} \frac{\beta^3}{\rho}} \right) \right]^{\frac{1}{6}} \\ - \left[1 + \frac{27}{2} \frac{\rho}{\beta^3} \left(1 + \sqrt{1 + \frac{4}{27} \frac{\beta^3}{\rho}} \right) \right]^{-\frac{1}{6}} \end{array} \right)^2, \quad (3)$$

where we have defined $\gamma = P_c E_{NL}$, $\beta = T_1 + L$, and $\rho = 4T_1 \alpha P_{in} E_{NL}$. The second harmonic power is now given by

$$P_2 = E_{NL} P_c^2 = \frac{\gamma^2}{E_{NL}}. \quad (4)$$

The overall conversion efficiency

$$\eta = \frac{\beta^2}{9P_{in} E_{NL}}$$

$$\left(\begin{array}{l} \left[1 + \frac{27}{2} \frac{\rho}{\beta^3} \left(1 + \sqrt{1 + \frac{4}{27} \frac{\beta^3}{\rho}} \right) \right]^{\frac{1}{6}} \\ - \left[1 + \frac{27}{2} \frac{\rho}{\beta^3} \left(1 + \sqrt{1 + \frac{4}{27} \frac{\beta^3}{\rho}} \right) \right]^{-\frac{1}{6}} \end{array} \right)^4, \quad (5)$$

Given the available pump power P_{in} , the intracavity extra-losses L and the effective nonlinearity E_{NL} , we can optimize transmission of the input coupler. L and E_{NL} in Eq. (5) can be directly measured in experiment and we have $L = 3.73\%$ (in absence of BLIIRA) and $E_{NL} = 1.0\% \text{ W}^{-1}$. The major contribution to the intracavity roundtrip losses comes from the absorption and scattering of the crystal and the mirrors. Figure 2 shows the theoretical conversion efficiency vs the input coupler transmission at different pump levels based on the Eq. (5) and the actual measured data. For our

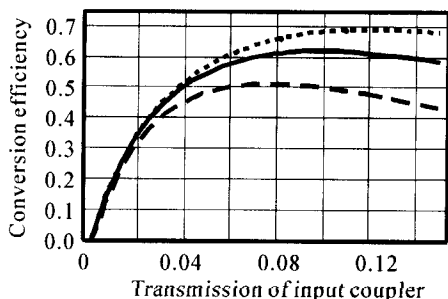


Fig. 2. Theoretical second-harmonic conversion efficiency vs. transmission of the input coupler in different pump power ($P_{in} = 1.0 \text{ W}$ (upper curve), 0.6 W , 0.3 W (lower curve)) based on Eq. (5) where $L = 3.73\%$ and $E_{NL} = 1\%/\text{W}$, $\alpha = 95\%$.

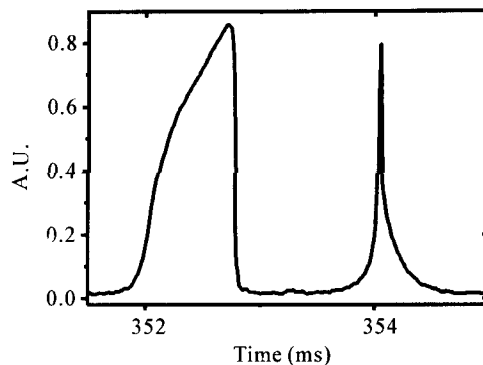


Fig. 3. Fundamental wave at phase-matching temperature with $f_{\text{scanning}} = 80 \text{ Hz}$, $P_{in} = 570 \text{ mW}$.

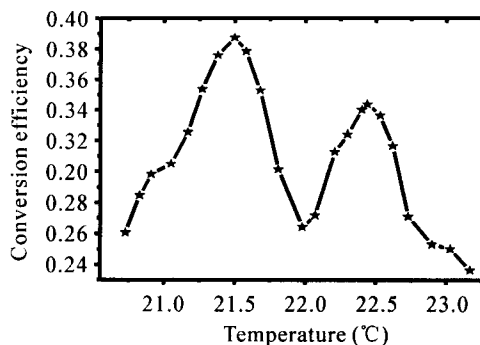


Fig. 4. The overall conversion efficiency vs. temperature in a swept mode.

experiment, the optimum transmission of the input coupler is around 10% with 600 mW of pump power.

The schematics of experimental setup is shown in Fig. 1. An optical isolator is used just after the output from the Ti:sapphire laser to avoid feedback. The beam diameter of the Ti:S laser before lenses is about 2 mm. Two lenses with focal length $f_1 = 1000 \text{ mm}$ and $f_2 = 400 \text{ mm}$ are used for cavity mode-matching. We have been able to get as much as 95% of mode-matching.

When the blue light is generated, BLIIRA will increase the infrared absorption inside the crystal and induce a remarkable thermal effect which is shown by the very asymmetric transmission of fundamental wave (the second harmonic is similar)(see Fig. 3). To reduce the influence of this effect on our optimization process, we can maximize the second harmonic by scanning the cavity quickly while reduce the crystal temperature a little bit to compensate. Figure 4 shows the harmonic output with the pump power of 600 mW as the temperature varies while the cavity is scanned. The corrected maximum overall conversion efficiency is 39%. The measured blue power is 170 mW and the corrected result is 235 mW considering the transmission of the output coupler ($T_{4(\text{blue})} = 78\%$) and 5.5% of the propagation losses for blue light.

The cavity is then locked on the resonance via an FM sideband technique^[11] and the RF signal on the EOM is 17.9 MHz. The blue light output vs. pump power is shown in Fig. 5. The dots are the measured harmonic output when cavity is locked whereas the stars are the result when the cavity is scanned.

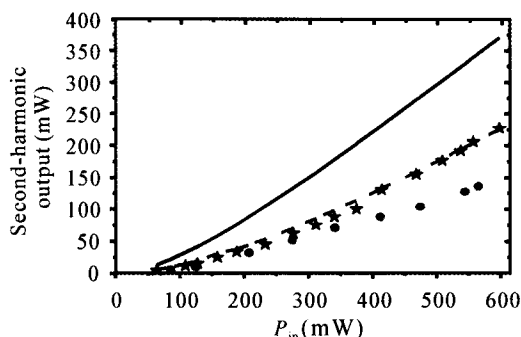


Fig. 5. Second harmonic output vs. pump power. The solid line shows the theoretical prediction in absence of BLIIRA and the dashed-line is the fitting result corrected by 3.4% of BLIRRA; Stars and dots show the measured values in the scanning ($f = 400$ Hz) and locking operations, respectively.

The solid line in Fig. 5 is the theoretical result without BLIIRA. We can see that large discrepancy still exists. The losses include not only the unideal antireflection coating of the potassium niobate, the leakage and scattering from the three total reflection mirrors, but also the nonlinear loss on the crystal suffers in the presence of blue light. This BLIRRA turns out to be the dominating loss at a high pump level and it limits the conversion efficiency eventually. The dashed line in Fig. 5 is the result when we take 3.4% of BLIIRA into account and we can then fit reasonably the obtained results. To reduce the BLIIRA, one may have to increase the temperature at relative longer wavelength. The second problem we have faced is the thermal effect aforementioned (see Fig. 3), especially at high pump level. The induced thermal-lens effect tends to reduce the mode-matching and consequently the coupling efficiency of the pump into the doubling cavity. The thermal-lens effect can affect the size of the beam inside the crystal and this directly reduce the conversion efficiency since the effective nonlinearity depends on the focusing, phase-matching and it also changes the cavity transmission profile and induces the problem of cavity locking. The last but not the least, the quality of the crystal is important. The impurities in the crystal are found to vary substantially from crystal sample to sample. Over $2\% \text{ W}^{-1}$ of effective nonlinearity should be obtainable with better crystal.

We have designed the single-resonant, external ring

cavity for frequency doubling. The whole system is optimized either for the beam size in the crystal or transmission of the input coupler. 39% of overall conversion efficiency from 858 nm to 429 nm is obtained. Steady output about 137 mW of blue light is produced when the cavity is locked with the efforts focused on the mode matching, the design of the cavity and the input coupler. The harmonic beam can be widely used in information science, optical measurement, and fundamental research, such as generation of quantum states, entanglement photon resources.

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