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External Cavity Frequency-Doubler from 858nm to 429nm by Using $KNbO_3$ Crystal

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Abstract

Second harmonic generation from 858nm to 429nm has been investigated at room temperature by using Potassium Niobate ($KNbO_3$) crystal. The optimum parameters for nonlinear conversion in our designing singly resonant, external ring cavity pumped by the Ti:Sapphire laser are established. In addition, we investigate the conversion efficiency over a range of operating conditions. When the cavity is scanned, 170 mW (235mW corrected for losses of the output mirrors) of blue light at 429nm is produced with 600mW of pump power near 858 nm whereas 137 mW is generated with 565 mW of pump when the cavity is locked.

Keywords: Frequency doubling, $KNbO_3$, second harmonic generation(SHG)

1. Introduction

Potassium Niobate ($KNbO_3$) crystal belongs to the orthorhombic group mm2 and it is possible to realize non-critical type-I phase matching in a-cut $KNbO_3$ for the wavelength between 840 nm and 990 nm (corresponding temperature -40 ^{0}C to 210 ^{0}C) with larger nonlinear optical coefficient d_{32}[1]. Because of this property, $KNbO_3$ is found to be one of the most versatile materials for second harmonic generation (SHG), sum frequency mixing (SFM), optical parametric oscillation (OPO), and is widely used for the generation of green-blue light via SHG, tunable near infrared (NIR) light via OPO/OPA.

Here we are more interested in making $KNbO_3$ as a source of blue light, which is supposed to be used for the process of parametric down conversion. In past years, a substantial amount of work has been done on the blue light generation by frequency doubling. For example, frequency doubling at about 429nm by a semiconductor diode laser,[2,3] at 467nm by nonlinear mixing of diode laser and Nd:YAG laser in $KNbO_3$,[4] and at 430nm by cw Ti:Sapphire laser[5] have been accomplished. The best efficiency obtained is 80% at 917 nm with the phase matching temperature around 130 ^{0}C.[6] Due to blue light induced infrared absorption (BLIIRA), the losses are much smaller at such high temperature compared to that at room temperature.[7,8]

In this paper, we design a singly 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 858nm and the phase-matching temperature of $KNbO_3$ is around room temperature accordingly. 235 mW of blue light at 429nm is produced from the external cavity with 600mW 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.[5,9]

2. Experimental design

Let's consider a four-mirror ring cavity with an opening angle minimized to about 6^0 in order to avoid optical aberrations shown in Figure 1. It consists of two plane mirrors M_1, M_2 and two curved mirrors M_3, M_4 with radius of curvature of 4cm. An a-cut $KNbO_3$ crystal with length of 7 mm is placed in the focal position between M_3 and M_4. Mirrors are coated for single-resonance at fundamental wave and single-pass for second harmonic beam. M_2, M_3 and M_4 are totally reflected mirrors at 858nm, and M_1, M_4 are the input and output couplers respectively. The crystal is temperature controlled

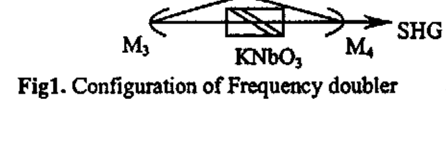

Fig1. Configuration of Frequency doubler

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within 0.005°C.

The size of beam waist is sensitive as the distance between M_3 and M_4 varies. The optimum size of the waist is determined by the length of the crystal. [10]

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

Where $l = 7$ mm is the length of crystal, z_0 is the Reyleigh length. λ is the wavelength of fundamental field. ω_0 is the beam waist inside the cavity. n is the index of the crystal. With $\lambda = 858nm$ and $n = 2.2372$, we know the waist should be $\omega_0 = 20.67\mu m$ given that the thermal effect is neglectable. This waist is a little bit larger than that obtained by Boyd-Kleinmann optimal focusing condition[11]. Figure 2 shows the size of beam waist as the distance d_1 between the two curved mirrors M_3 and M_4 varies. When the distance d_1 is 48.5mm and the total cavity length d_2 is 360 mm, the beam waist is around 20 μm. From Figure 2 we know that the waist can be adjusted experimentally by fine changing the distance d_1.

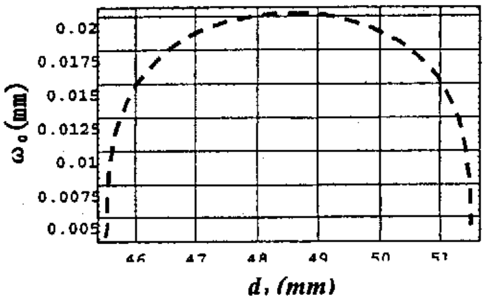

Fig2. Fundamental waist ω_0 vs. the distance d_1.

Another important factor that affects the efficiency of doubling is the input coupler. Suppose T_1 is the transmission of the input coupler and the overall conversion efficiency is η. On resonance, we have the following relation [3,6]:

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

Here P_c is the intracavity circulating fundamental power. P_{in} is the input power. L is the residual intracavity roundtrip losses including scattering, absorption of the mirrors and crystal and also the BLIIRA. 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 equation (2), we can obtain:

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

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

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

Then the overall conversion efficiency η is

$$\eta = \frac{\beta^2}{9 P_{in} E_{NL}}\left(\left[1 + \frac{27}{2}\frac{\rho}{\beta^3}\left(1 + \sqrt{1 + \frac{4}{27}\frac{\beta^3}{\rho}}\right)\right]^{\frac{1}{6}} - \left[1 + \frac{27}{2}\frac{\rho}{\beta^3}\left(1 + \sqrt{1 + \frac{4}{27}\frac{\beta^3}{\rho}}\right)\right]^{-\frac{1}{6}}\right)^4 \tag{5}$$

Given the available pump power P_{in}, the intracavity extra losses L and the nonlinear conversion efficiency E_{NL}, we can optimize transmission of the input coupler in order to get the highest conversion efficiency. In our experiment, L and E_{NL} in equation (5) can be directly measured. Passive losses $L \approx 3.73\%$ (losses of empty cavity is 1.52%) are determined by measuring the finesse of the cavity when the input coupler is replaced by a high reflected mirror. The major contribution to the losses comes from the absorption and diffusion of the crystal and mirrors. E_{NL} is 1.0% W^{-1} which is measured by letting the pump light singly passthrough the crystal in the mode-matched cavity. Fig3 shows the theoretical conversion efficiency vs. the input coupler transmission at different pump levels based on the equation (5) and the actually measured data. For this experiment, the optimum transmission of the input coupler is around 10% with 600 mW of pump power.

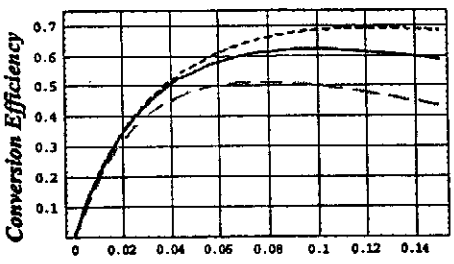

Fig3. Second-harmonic conversion efficiency vs. the transmission of input coupler in different pump power (P_{in}=1.0W(up), 0.6W, 0.3W(down)) based on the experimental data. The plot corresponds to $L = 3.73\%$ and $E_{NL} = 1\%/W$.

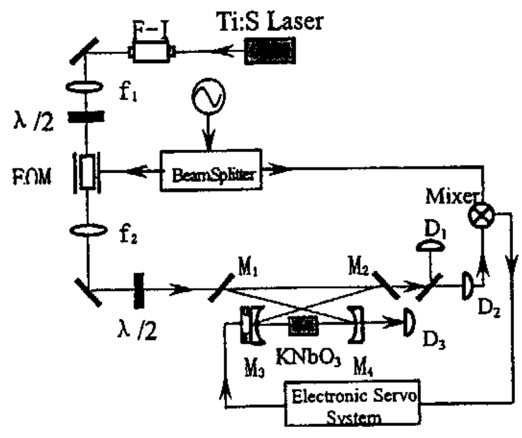

Fig4. Experimental Setup

3.Experiment and results

The whole experimental setup is shown in Fig4. An optical isolator is used just the output from the Ti:Sapphire laser to avoid feedback. Two lenses with focal length f_1=1000mm and f_2=400mm are used to focus the pump beam into the doubling cavity to realize mode-matching. We have been able to get as much as 95% of mode-matching of the laser beam into the TEM_{00} mode of the cavity.

Second harmonic beam is produced as the temperature is set on the phase-matching point. Fig.5 shows the second harmonic output with the pump power of 600mW as the temperature varies while the cavity is scanned to avoid thermal effect of the crystal. The corrected maximum overall conversion efficiency is 39%. The measured blue power is 170mW and the corrected result is 235mW considering the transmission of the output coupler ($T_{4\ (blue)}$ = 78%) and the propagation losses for blue light (about 5.5%). The cavity is then locked to the frequency of the laser via a FM side-band technique[12], and we obtain the stable cw blue light. The result is shown in Fig6. The dots on the figure are the measured harmonic output when cavity is locked while the stars are the result when the cavity is scanned. Due to the thermal effect the power in the case of cavity-locked operation is somewhat lower. The solid line in Fig6 is the theoretical result without BLIRRA.

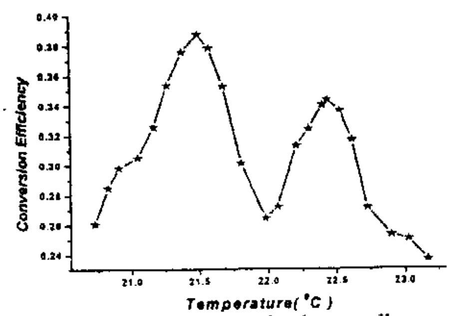

Fig5. In a swept mode, the overall conversion efficiency vs. temperature

From Fig6, we can see that large discrepancy still exists. There may have two reasons. The first is the blue light induced infrared absorption (BLIIRA), which plays an important role as the conversion efficiency increases. The dashed line in Fig6 is the result when we take 3.4% of BLIIRA into account and we can explain reasonably what we have obtained. To reduce the BLIIRA, one may have to increase the temperature at relative longer wavelength. Yet, the mechanism of BLIRRA is not very clear. The second problem we have faced is the thermal effect aforementioned, 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

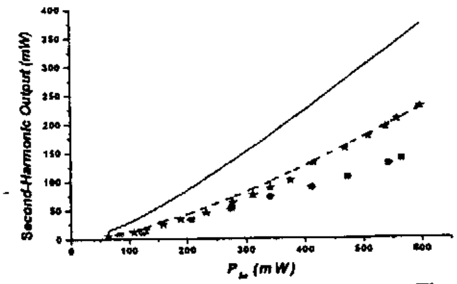

Fig6. Second harmonic output vs. pump. The solid line shows the theoretical prediction in absence of BLIIRA; The dashed-line is the fitting result corrected by 3.4% of BLIRRA; Stars and dots show the measured values in the scanning and cw operations, respectively

cavity. Also the thermal-lens effect can affect the size of the beam inside the crystal and, as we know, this can directly reduce the conversion efficiency. Last but not least, the thermal effect changes the transmission profile and induces the problem of cavity locking as well as the output stability of the total system.

Conclusion

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 858nm to 429nm is obtained. Steady output about 137mW of blue light at 429nm is obtained when the cavity is locked. This harmonic beam can be widely use either in information science, measurement, or fundamental research, such as generation of quantum states, entangled photon sources.

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References

1. P. Günter, P. M. Asbeck, and S. K. Kurtz, "Second-Harmonic Generation with $Ga_{1-x}Al_xAs$ Lasers and $KNbO_3$ Crystals," **Appl.Phys.Lett**, Vol.35, No.6, 461 (1979).
2. W. J. Kozlovsky, W. Lenth, E. E. Latta, A. Moser, G.L.Bona, **Appl. Phys. Lett**, Vol.56, No.23, 2291(1990).
3. P. Lodahl, J. L. Sørensen, E. S. Polzik, **Appl. Phys. B**, Vol.64, 383-386 (1997).
4. M.K.Chun, L.Goldberg, I.N.Duling III, and T.F.Carruthers, in **Digest of Conference on Lasers and Electro-Optics (Optical Society of America, Washington, D.C**, 1990), paper CWE2.
5. E. S. Polzik, H. J. Kimble, **Opt. Lett**, Vol.16, No.18, 1400 (1991).
6. " Nonclassical Light for Atomic Physics and Quantum Teleportation" **Ph. D. thesis** by J. L. Sørensen, Institute of Physics and Astronomy University of Aarhus (1998).
7. H.Mabuchi, E.S.Polzik, H.J.Kimble, **J.Opt.Soc.Am.B**, Vol.11, No.10, 2023 (1994).
8. L.Shiv, J.L. Sørensen, E.S.Polzik, **Opt.Lett**, Vol.20, No.22, 2270 (1995).
9. Lew Goldberg, Myung K. Chun, **Appl. Phys. Lett**, Vol.55, No.3, 218 (1989).
10. "Introduction To Optical Electronics " (Second Edition) by Amnon Yariv , Holt, Rinehart and Winston (1976).
11. G.D.Boyd and D.A.Kleinman, **J. Appl.Phys**, Vol.39, No.8, 3597 (1968).
12. R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, H. Ward, **Appl. Phys. B**, Vol.31, 97(1983).