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Intra-cavity second harmonic generation with Nd:YVO_4/BIBO laser at 542 nm

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Abstract

We report, for the first time, an efficient intra-cavity second-harmonic generation (SHG) at 1084 nm in a nonlinear optical crystal, BiB_3O_6(BIBO) at the direction of $(\theta, \varphi) = (170.1°, 90°)$, performed with a LD end-pumped cw Nd:YVO_4 laser. With 590 mW diode pump power, a continuous-wave (cw) SHG output power of 19 mW at 542 nm yellow–green color has been obtained using a 1.5 mm-thick BIBO crystal. The optical conversion efficiency was 3.22%. It was found that the output wavelength could be 532 nm, 537 nm or 542 nm according to regulating the angle of BIBO.

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Keywords: Second harmonic generation; Phase-matching; Angular bandwidth; Yellow–green light; BIBO crystal

1. Introduction

Diode-pumped solid-sate lasers have facilitated considerable advances in various fields of science and technology. Diode-end-pumped configuration can provide much stronger pump power density than transversely pump structure. Therefore it is possible for cw operation to be achieved at some weak transitions by diode-end-pumped configuration [1–3]. Neodymium-doped YVO_4 has been proved to be an excellent gain medium. The output wavelengths of the research involving Nd:YVO_4 crystals were mostly focused at 1064 nm [4,5], 1342 nm [6] and 914 nm [7]. However, a spectroscopic study with crystal-field analysis [8] has revealed that there are five or six emission bands with the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of a Nd:YVO_4 crystals. Fig. 1 displays the room-temperature fluorescence spectrum for the $^4F_{3/2} \rightarrow {}^4I_{11/2}$ transition of Nd:YVO_4 crystals. It can be seen that one of the Stark components has a central emission wavelength at 1084 nm. To the best of our knowledge, there have been no studies of Nd: YVO4 lasers at 1084 nm.

In the field of nonlinear frequency conversion there are many materials with very excellent linear and nonlinear optical characteristics. Bismuth borate, BiB_3O_6, is a newly developed nonlinear material [9,10] with unique optical properties for frequency conversion in the visible and UV. It combines the advantages of UV transparency and high optical damage threshold, as in BBO and LBO, with enhanced optical nonlinearity [11], as in KTP.

Since the first introduction of BiB_3O_6 [9,10], a number of frequency-conversion experiments have been performed, including internal second-harmonic generation (SHG) of a cw radiation at 1.06 μm [12], single-pass SHG of pulsed laser at 1.06 μm [13], Q-switched internal SHG at 1.06 μm [14], internal frequency-doubling of cw Nd:YAG laser [15,16], photo-induced SHG in partially crystallized BIBO glass [17], efficient SHG of high-repetition-rate femtosecond pulses into the blue using BiB_3O_6 [18], internal

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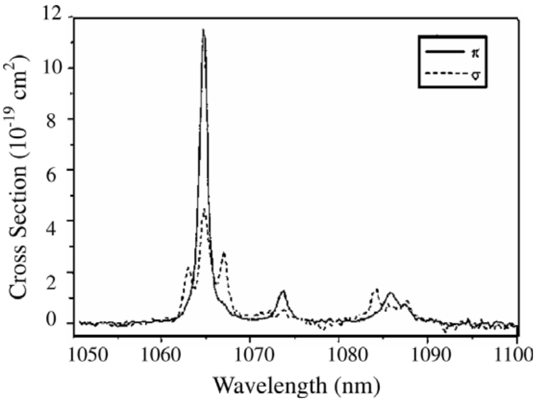

Fig. 1. Stimulated emission cross section for Nd:YVO$_4$.

SHG of cw and quasi-cw Nd:YVO$_4$ laser at 1.34 μm [19], Q-switched SHG of 1342 nm and third-harmonic generation (THG) of 1064 nm Nd:YVO$_4$ laser [20], and the third-order optical phenomenon of a two-photon absorption (TPA) in BIBO crystals [21].

In this paper, we report, for the first time, the results of intra-cavity SHG at 1084 nm in BIBO crystal for the type-I phase-matching (PM) direction of $(\theta, \varphi) = (170.1°, 90°)$, and performed with a LD end-pumped cw Nd:YVO$_4$ laser. The characteristics of intra-cavity second-harmonic generation are also presented in the paper.

2. Experimental procedure

2.1. Phase-matching curve

With the Sellmeier equation of BIBO presented in [10], we calculated the type-I phase-matching directions for SHG and the corresponding effective nonlinear coefficients d_{eff} of BIBO, as shown in [11] Fig. 2. It was found that the maximum value of $d_{\text{eff}} = 2.89$ pm/v appeared at the orientation of $(\theta, \varphi) = (170.1°, 90°)$. Therefore, the BIBO crystal used in the SHG experiment was cut for this direction, with dimensions of $2 \times 2 \times 1.5$ mm^3.

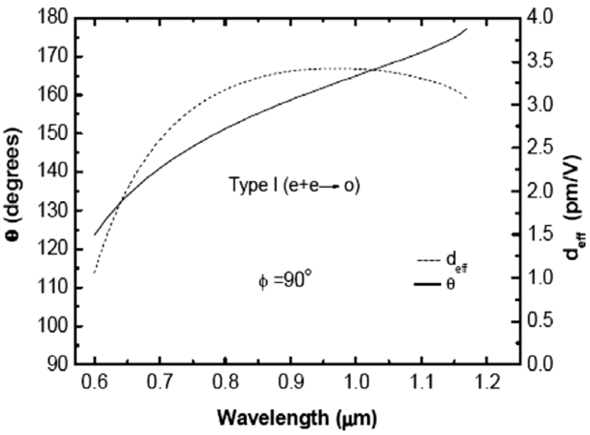

Fig. 2. Phase-matching angle and corresponding magnitude of effective nonlinear coefficient for type-I SHG as a function of fundamental wavelength.

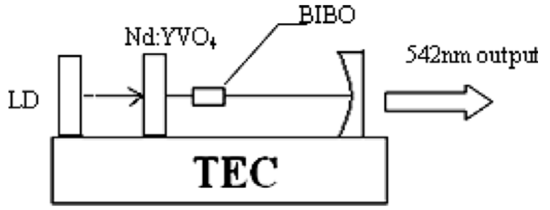

Fig. 3. Schematic of intra-cavity SHG with Nd:YVO$_4$/BIBO lasers on 1084 nm.

2.2. Experimental setup

Fig. 3 is a schematic of intra-cavity SHG with the Nd:YVO$_4$lasers on 1084 nm. Since the stimulated-emission cross section for 1084 nm transition is approximately several times smaller than that for 1064 nm line, we used the specifically cut-direction of BIBO to select the 1084 nm line for SHG. The pump source was a 1 W 808 nm laser diode. The cavity length was approximately 12 mm. The 1.0 at.% doped Nd:YVO$_4$ crystal, with a dimensions of $2 \times 2 \times 1.5$ mm^3, was coated with high transmission ($T > 90\%$) at the pump wavelength (808 nm), high reflectivity(HR) ($R > 99.9\%$) at 1064–1084 nm and 532–542 nm on the entrance face, and high transmission ($T > 99\%$) at 1064–1084 nm and 532–542 nm on the other face. So the pumping surface acted as one of the resonator mirrors. The output mirror, with a radius of curvature of 100 mm, was also coated with high reflectivity (HR) ($R > 99\%$) at 1064–1084 nm, anti-reflectivity (AR) ($T > 90\%$) at 532–542 nm and served as the output coupler for the SHG yellow–green laser. The reflectivity of the output coupler at 1084 nm may be higher than that at 1064 nm. Because the output coupler is a concave mirror, so it is difficult to measure the reflectivity accurately. The BIBO crystal, $2 \times 2 \times 1.5$ mm^3, was cut for type-I phase-matching of second-harmonic generation (SHG) on 1084 nm. To minimize the internal losses caused by the BIBO crystal, it was anti-reflectivity (AR) ($T > 99\%$) coated at 1064–1084 nm and 532–542 nm on both end faces. The laser diode, Nd:YVO$_4$ crystal and the BIBO crystal were all held in a copper block cooled by a thermoelectric cooler. The temperature was maintained at 25 °C during the experiment.

3. Results and discussion

By adjusting the position of the output mirror and TEC carefully, we obtained higher output with TEM$_{00}$ mode. Then we inserted the BIBO crystal, type-I phase-matching, with anti-reflectivity coating at 1064 nm and 532 nm on both end surfaces, into the laser cavity. And three-wavelength laser (532 nm, 537 nm, 542 nm) was observed. The laser output at 532 nm, 542 nm and 537 nm were obtained simultaneously, which resulted from second-harmonic generation (SHG) of 1064 nm and 1084 nm, and sum-frequency generation (SFG) of 1064 nm with 1084 nm, respectively. Fig. 4 is the optical spectrum of the laser monitored by an optical spectrum analyzer (MFS-01) with a resolution of 1.2 nm [22]. During the experiment, we found that the relative output power of each wavelength was very sensitive to the adjustment of the angle of BIBO. It was mainly because that the relative cavity losses were changed in the adjusting procedure. It was impossible that these two wavelengths achieved the maximum output power at the same time. In the proceeding of regulating the angle of BIBO, three different wavelengths would emerge in turns. When regulating BIBO to a certain angle, only the 542 nm yellow–green laser could be observed which was caused by the narrow phase-matching angular bandwidth and appropriate angle regulation. Fig. 5 shows the optical spectrum of 542 nm. The values of the phase-matching angular bandwidth were calculated from the sensitivity of phase-matching, Δk, to the spectral spread and angular divergence of the fundamental using the appropriate Sellmeier equations [10]. The calculation results were 2.32 mrad cm at the frequency-doubling of 1064 nm, 2.66 mrad cm at 1084 nm, 2.50 mrad cm and 2.45 mrad cm at the sum-frequency mixing of 1064 nm and 1084 nm, respectively. According to the Sellmeier equations for BIBO [10], the phase-matching directions were calculated to be (168.9°, 90°), (170.1°, 90°) and (169.5°, 90°), corresponding to the SHG of 1064 nm, 1084 nm, and the SFG of 1064 nm with 1084 nm, respectively. The difference of the theoretical phase-matching values between either two of them was $\Delta\theta = 0.6°$, by simple calculation, it can be converted to 1.57 mrad cm for the length of 1.5 mm, which is smaller than the angular acceptant bandwidth 2.32, 2.66 and 2.50 mrad cm. So the three PM directions were all involved in the range of phase-matching angular bandwidth, three nonlinear-processes of intra-cavity frequency conversion were realized simultaneously, and the three-wavelength radiation was emitted. From the expression of SHG output power:

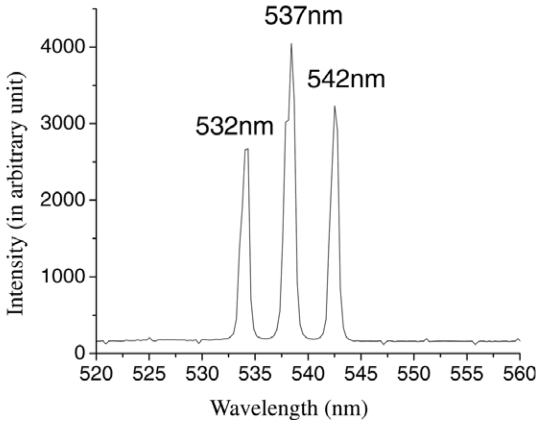

Fig. 4. Principal set-up for the spectrum of three-wavelength laser.

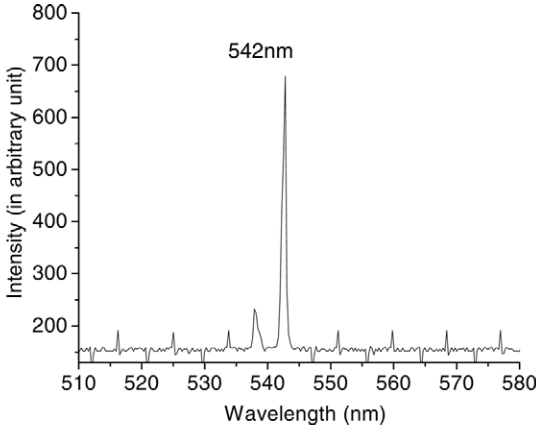

Fig. 5. Spectrum of the double-frequency wave (542 nm).

$$P^{2\omega} = \frac{2\pi}{c}\,\frac{\omega_3^2 d^2 L^2}{n_3 n_1^2}\,\frac{(P^{\omega})^2}{A}\left[\frac{\sin\left(\frac{\Delta kL}{2}\right)}{\frac{\Delta kL}{2}}\right]^2$$

where L is the length of the frequency-doubled crystal, n_1 and n_3 are the refractive indexes of the fundamental and SHG wave in the frequency-doubled crystal, c is the speed of light in vacuum, ω_1 and ω_3 are the frequencies of the fundamental and SHG wave, d is the optical nonlinear coefficient of the crystal, P^{ω} is the power of the fundamental wave, A is the cross section of the beam in the crystal, and the phase mismatch $\Delta k = \mathbf{K}_3 - 2\mathbf{K}_1$, where $\mathbf{K}_1$ and $\mathbf{K}_3$ are the wave vectors for the beam at ω_1 and ω_3.

By adjusting the angle of BIBO, Δk, will changed. The two wavelengths(532 nm, 537 nm) may moved out of the PM angular bandwidth, namely, $\Delta kl < -\pi$, and then the output power at 532 nm and 537 nm will be very small, even could be seen as zero. So the output frequency-doubling must be only 542 nm. A 19 mW cw output was obtained at an incident pump power of 590 mW.

We also measured the output power at 532 nm, 537 nm and 542 nm as a function of the incident pump power by using a monochromator and the optic power meters of Coherent Inc. on 532 nm behind the output mirror. We found that the output power of each wavelength versus the incident pump power was not steady. It could be comprehended that there are two different fundamental wavelengths (1064 nm, 1084 nm) in the cavity, and the two wavelengths lasing competed with each other. When the BIBO has only an effect on SHG of 1084 nm, the output of 542 nm could be seen as the losses of 1084 nm, so that the net gain of 1064 nm will increase relatively. The result of competition is that the intra-cavity power of 1084 nm and the SHG output (542 nm) decreased simultaneously. Correspondingly, the losses of 1084 nm will fall down, while the net gain of 1084 nm will increase, and also the output power begins to rise. Until the net gain of 1064 nm is bigger than that of 1084 nm, the output power of 542 nm will decrease once more. The output power will fluctuate like this again and again.

4. Conclusion

In this paper, we have reported an efficient intra-cavity second-harmonic generation (SHG) at 1084 nm in a nonlinear optical crystal of BIBO, performed with a LD pumped cw Nd:YVO_4 laser. According to rational phase-matching, a cw SHG output power at 542 nm of 19 mW has been obtained with optical conversion efficiency of 3.22% at the incident pump power of 590 mW. Our experiments have shown that the cw simultaneous emission could be chosen through the effective phase-matching when there were two or more spectrally close lines. It will provide a simple and direct way to generate single-wavelength output.

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