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High-stability single-frequency green laser with a wedge Nd:YVO$_4$ as a polarizing beam splitter

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ABSTRACT

The effect of the large power depletion of the fundamental wave in the phase-matched polarization on the stability of the second-harmonic wave output from an intracavity frequency-doubled ring laser is discussed. It has been demonstrated that the instability resulting from the unbalanced power depletion of the fundamental waves can be eliminated by using a wedge laser rod. The function dependence of the wedge angle and the laser power is concluded. An intracavity frequency-doubled ring laser with a wedge Nd:YVO$_4$ laser crystal and a LBO doubler is designed and built. Comparing with similar lasers but without using the wedge laser crystal, the frequency-conversion efficiency, the power stability and the polarization purity of the second-harmonic wave output from the laser with a wedge laser rod are significantly improved. The single-frequency green laser of 6.5 W at 532 nm, with the polarization degree more than 500:1 and the power stability better than ±0.3% for 3 h, was experimentally achieved.

1. Introduction

All-solid-state single-frequency laser is one of the most important light sources with the features of low noise, good beam-quality and long coherent length, which attracted a lot of interest of scientific and technical researchers [1–5]. In some solid lasers the laser crystal is cut in a wedge for different aims such as, to eliminate the etalon effect for improving the tuning property of a tunable laser [6], to be a Brewster window for producing linearly polarized light in isotropic laser medium [7], to gain broad tuning range in the tunable Ti:sapphire lasers [8], or to serve as a prism for forming a ring cavity only with two mirrors [7]. It should be mentioned that there was a patent issued 10 years ago [9], in which a wedge plane of the laser rod was used as a birefringent element for refracting the different wavelengths of light in different directions. In their linear laser cavity another birefringent element, a birefringent filter, was also applied. The two birefringent elements together discriminate between the desired fundamental wavelength and the unwanted wavelengths, so that one polarization of the desired wavelength is refracted in one direction which causes it to lase while certain portions of the unwanted wavelengths are refracted in other directions which cause all polarizations of the unwanted wavelengths to be extinguished. However, in high power CW lasers the birefringent filter is easily warmed up and the temperature instability of the material will result in the change of the refraction indexes for different wavelength which must influence the stability of both polarization and power of the output laser. For obtaining stable laser output the birefringent filter has to be precisely temperature-controlled. In most modern CW solid-lasers ring resonators are utilized to eliminate the spatial hole-burning effect for achieving the single-mode operation of lasers. However, we found that for an intracavity frequency-doubled laser with a ring cavity and a laser rod without the wedge plane, the output of the fundamental wavelength was quite stable before the frequency-doubler was put in. But the stability of the second-harmonic wave output became much worse after the nonlinear doubling crystal was placed into the resonator, especially in the case of high nonlinear conversion efficiency. We consider that is because the losses of the main polarization mode of the fundamental wave satisfying the phase-matching condition are much larger than other polarization modes due to the depletion in frequency-up-conversion that will unavoidably increase the oscillating possibility of other unexpected polarization modes. For solving the problem, we designed a ring laser in which a wedge birefringent laser crystal is utilized as a polarizing beam splitter to suppress the oscillation of unexpected polarization modes and enhance the superiority of the main polarization mode in the mode competition. In the laser system only using the simple wedge design of the laser crystal without adding any other birefringent element, the oscillation of the unexpected polarization modes is totally suppressed and thus the stable second-harmonic output in a certain polarization is obtained.

The development of high-stability watt-level single-frequency green laser is mandatory for many applications. To realize the stable single-frequency operation of solid lasers with ring cavity con-

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figuration, linear polarized lasing in a stationary polarization direction is prerequisite. On the basis of the principle of Brewster plate with full transmission of *P*-polarization and 85% of transmission of *S*-polarization, Martin et al. obtained the linear polarized lasing by inserting a Brewster plate into the ring cavity [10]. Since the Nd:YVO$_4$ is a birefringent laser crystal and the optical gain in the polarization parallel to the *c*-axis (π-polarization)is four times of that in σ-polarization perpendicular to the *c*-axis, lasing will naturally operate in π-polarization direction [11,12]. However, in an intracavity frequency-doubled laser with high conversion efficiency, the nonlinear conversion is the dominant loss for the fundamental wave and thus the loss of the fundamental wave in σ-polarization at non-phase-matched direction is much smaller than that in π-polarization satisfying the phase-matched condition. Thus, the net gain of the laser in π-polarization may be less than that in σ-polarization, so the laser will be possible to oscillate in the non-phase-matched σ-polarization direction due to mode competition. The phenomenon must influence the stability of laser operation and degrade the single-frequency output in a polarization.

In this paper, we analyze the effect of the polarization dependence of the fundamental wave depletion on the stability of the second-harmonic output in an intracavity frequency-doubled ring laser, firstly. For preventing the oscillation of the fundamental wave in non-phase-matched polarization direction, a laser rod with a wedge plane is utilized to be a "mode-selector". By means of a simple theoretical model we conclude the dependence function between the wedge angle of the laser rod and the pump power under the condition of the stable operation. According to the calculated result, the Nd:YVO$_4$ laser crystal with a suitable wedge was manufactured. The wedge facet forms an enough deviation between the transmission directions of π- and σ-polarization, which can efficiently avoid the oscillation of the non-phase-matched σ-polarization mode of the fundamental wave in the laser resonator. Using the designed system, the single-frequency green laser of 6.5 W at 532 nm with the polarization degree of more than 500:1 and a stability of better than ±0.3% for 3 h was experimentally demonstrated.

2. Calculation of wedge angle

The anisotropic positive uniaxial YVO$_4$ crystal exhibits strong birefringence, the refractive indexes of Nd:YVO$_4$ crystal for the ordinary and the extraordinary beams are 1.9573 and 2.1652 for the laser wavelength at 1064 nm, respectively. When a Nd:YVO$_4$ crystal is cut along the *a*-axis, the effective stimulated emission cross section at 1064 nm parallel to the *c*-axis ($\sigma_{\parallel}$) is about four times larger than that perpendicular to the *c*-axis ($\sigma_{\perp}$) [13]. The Nd:YVO$_4$ laser is designed naturally to operate in π-polarization ($\sigma_{\parallel}$) direction. For an intracavity frequency-doubled laser the π-polarization is selected in the phase-matched direction of the nonlinear frequency-doubling crystal placed inside the laser resonator for implementing efficiently the second-harmonic wave generation. So the nonlinear loss of the fundamental wave resulting from the power depletion during frequency-up-conversion only exists in π-polarization radiation.

For an intracavity frequency-doubling laser with a wedge Nd:YVO$_4$ crystal, while the laser propagates from the crystal to air through the wedge facet, the deviation angles of the ordinary light and the extraordinary light are different because their refractivities in the birefringent crystal are not the same, as shown in Fig. 1. For the Nd:YVO$_4$ laser operating in π-polarization direction, the wedge angle will result in the geometry deviation loss for the lasing in σ-polarization, whereas no loss for the lasing in π-polarization. To obtain a long-term stable laser operation in π-polarization, the following equations should be satisfied [14]:

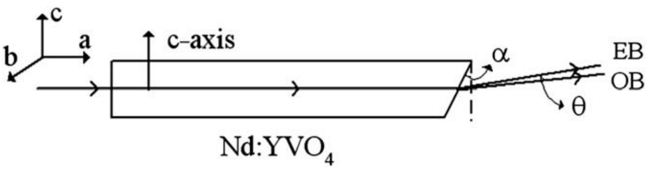

Fig. 1. Schematic diagram of the wedge Nd:YVO$_4$ crystal. OB: ordinary beam, EB: extraordinary beam, α: wedge angle, θ: the angle between the ordinary beam and the extraordinary beam.

$$G_{\pi} = \frac{2g_{\pi}l}{1+\frac{2S}{S_0}} - L - KS = 0 \tag{1}$$

$$G_{\sigma} = \frac{2g_{\sigma}l}{1+\frac{2S}{S_0}} - L - D(\alpha)\frac{2g_{o}l}{1+\frac{2S}{S_0}} < 0 \tag{2}$$

where $G_{\pi}(g_{\pi}l)$ and $G_{\sigma}(g_{\sigma}l)$ are the net gain (small-signal gain) of the extraordinary and ordinary light, respectively; S_0 is the saturation power; S is the circuiting power; L is the round-trip loss, excluding the nonlinear loss and the geometry deviation loss; K is the coefficient of nonlinear conversion, the optimal value K of which is $2L/S_0$ according to Ref. [15]; $D(\alpha)$ is the coefficient of geometry deviation loss, which is relevant to the wedge angle α. $D(\alpha)$ value is calculated with the mode overlap ratio between the π-polarization and σ-polarization. Since $\sigma_{\parallel}$ is about four times larger than $\sigma_{\perp}$, so g_{π} should be also four times of g_{σ}. Solving Eq. (1) we obtain the expression of S/S_0, and then substituting the obtained S/S_0 into Eq. (2) we found the function of the wedge angle (α) vs. the pump power (P_{in}) of the laser which determines the conditions fulfilling inequality Eq. (2). The function drawn with the parameters of our experimental system ($L = 4.72\%$, $g_{e}l = 0.1553P_{in}$, $g_{\sigma}l = 0.0388P_{in}$, $\omega_0 = 300\ \mu\text{m}$) is shown in Fig. 2. The function curve is a boundary above which for a given P_{in} the wedge angles result in larger deviation (θ) between π- and σ-polarization light beams and thus the σ-polarization light is totally suppressed, below which the smaller wedge angles can not make an enough separation of the two polarization light beams and thus the non-phase-matched σ-polarization laser will possibly oscillate in the resonator. When the pump power increases the nonlinear loss of the phase-matched π-polarization light also increases such that we have to use larger wedge angle to suppress the oscillation of π-polarization light. For the pump power of 30 W used in our experiment, we can see from Fig. 2 the minimum wedge angle α to suppress σ-polarization equals to 1.1°.

We cut an end-facet of the Nd:YVO$_4$ crystal in a wedge shape of $\alpha = 1.5°$ (larger than 1.1°) with respect to the *c*-axis of the crystal and made its front facet parallel to the *c*-axis, which is enough to

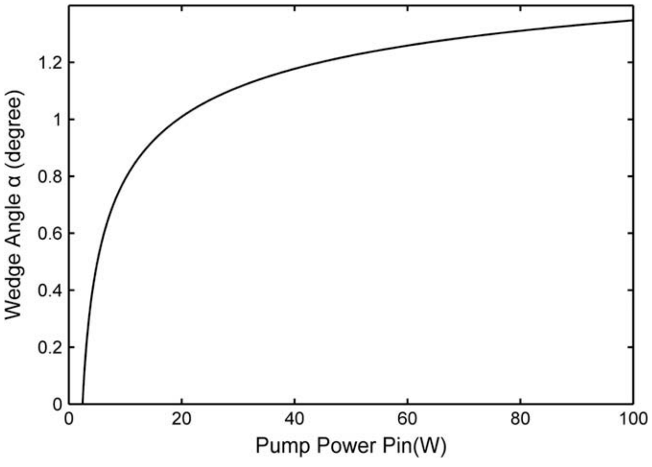

Fig. 2. Phase diagram of the wedge angle α vs. pump power.

suppress the oscillation of unexpected σ-polarization mode and enhance the superiority of the π-polarization mode in the mode competition. Thus the laser will operate stably in the π-polarization and keep the unidirectional state.

3. Experimental setup and results

The configuration of the designed laser is shown in Fig. 3. A composite Nd:YVO$_4$ rod of 15 mm-length (including undoped end cap of 5 mm, Nd-doped part of 10 mm) with a wedge end-facet of $\alpha = 1.5°$, a type-I phase-matching LBO crystal for frequency-doubling, an optical diode consisting of the faraday rotator and half-wave plate for the unidirectional operation of laser (TGG, terbium gallium garnet crystal, is used as the magnetic rotation material of the faraday rotator) and an etalon for the spectral filter were involved in the bow-tie ring resonator. The pump diode laser of 808 nm wavelength with a maximum output power of 30 W was focused into the center of the Nd:YVO$_4$ crystal with a waist spot of 680 μm-diameter to produce a fundamental mode with a waist size of 600 μm, which is in accordance with the requirement of mode-to-pump ratio.

Under the incident pump power of 30 W, a single-frequency TEM$_{00}$ green output laser ($M^2 < 1.2$) of 6.5 W was directly measured with an optical–optical conversion efficiency (CE) of 24.1% accounting for the transmission losses of the pump light (CE equals to 21.7% if the transmission losses are not considered.), whereas the CE of conventional laser with the same design but without using the wedge plane is only 17% [11]. We found that the polarization direction of the fundamental and harmonic wave and the unidirectional state of the laser can be stably maintained for different pump levels from the threshold to 30 W. The power stability of output green laser at 6.5 W was better than ±0.3% for 3 h as shown in Fig. 4, which is superior to ±1.2% of conventional laser [11]. The polarization ratio measured with a Glan prism was higher than 500:1, which is better than 100:1 of conventional laser [11]. The fundamental mode of laser was monitored by a scanning Fabry–Perot interferometer with the free spectral range of 750 MHz. Fig. 5 shows that the laser was in the state of single-frequency operation and the frequency shift of the fundamental mode was

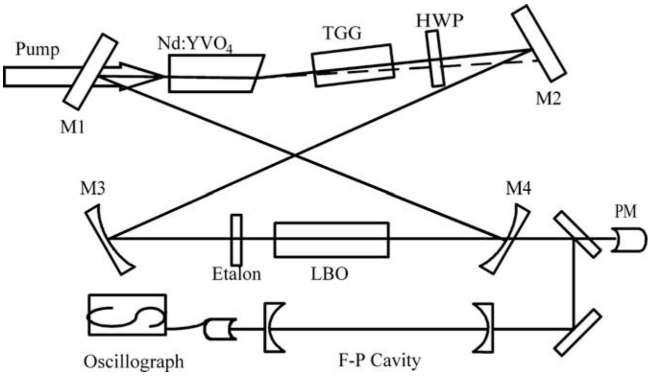

Fig. 3. Experimental schematic of single-frequency green laser using a wedge Nd:YVO$_4$ crystal. HWP: half-wave plate, TGG: terbium gallium garnet, PM: power meter. The solid line: extraordinary beam; the dashed line: ordinary beam, which cannot oscillate in the resonator.

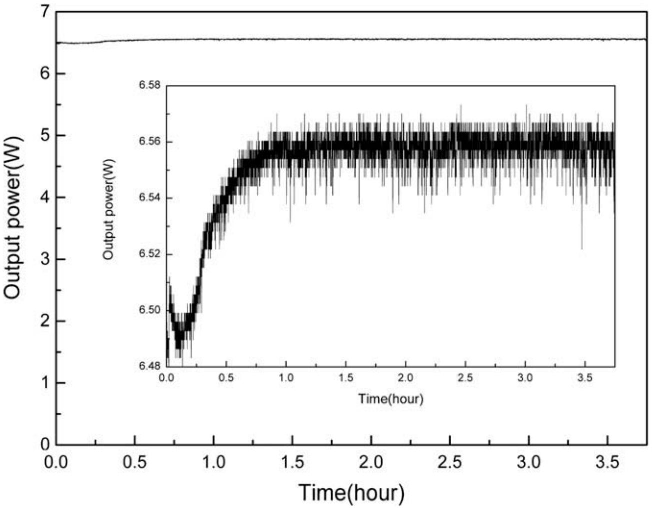

Fig. 4. Power stability of laser within 3 h.

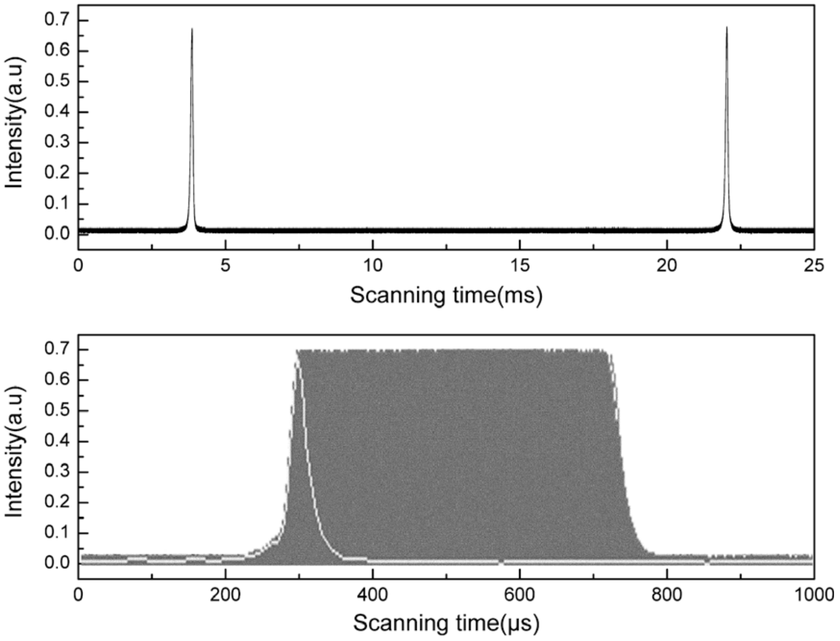

Fig. 5. Frequency shift of the fundamental wave in 1 min.

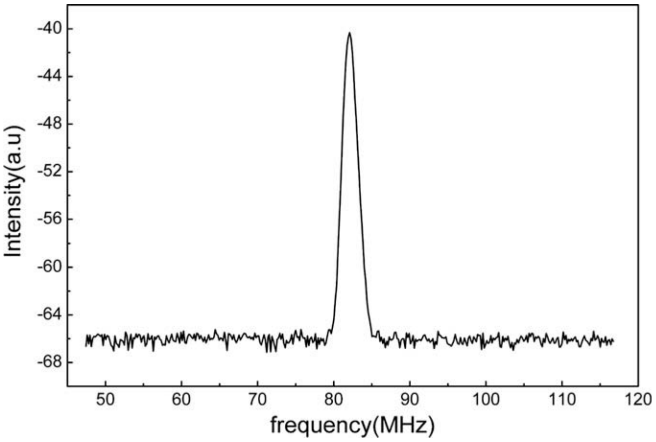

Fig. 6. Measured linewidth of laser.

better than ±10 MHz in 1 min (it can be inferred that the frequency shift of second-harmonic mode was better than ±20 MHz in 1 min). A narrow linewidth of 2.5 MHz was measured by a heterodyne beat signal between the presented laser and a reference laser with linewidth of 150 kHz with a spectrometer of model E4411B (Fig. 6).

4. Conclusion

For the first time to the best of our knowledge, the influence of the unbalanced depletion of the fundamental waves with different polarizations on the stability of the second-harmonic output in an intracavity frequency-doubled laser is discussed. Using a wedge facet of the birefringent laser crystal the oscillating of the unwanted modes in a ring resonator is suppressed. The function dependence between the wedge angle and the pump power is concluded. Based on the calculated result, we designed and built a high power single-frequency green laser by use of the wedge crystal with the wedge angle of 1.5°. The wedge design of the laser crystal not only increased the purity of polarization of the fundamental wave in a desired polarization, but also enhanced the stability of the output power of the second-harmonic wave. By compare with the conventional crystal laser without a wedge facet, we found that the wedge crystal can effectively increase the CE, the stability and the polarization ratio of the laser.

The design of the wedge laser crystal can be applied in other single-frequency laser, which can effectively simplify the complexity of the laser adjusting. The concluded formula for the wedge angle can serve as a useful reference to direct the manufacture of the wedge facet of the laser rod. By further optimizing the parameters of laser systems and increasing the pump power according to the concluded function the second-harmonic output with much higher intensity can be achieved with the presented laser configuration.

Acknowledgments

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References

[1] J.J. Zayhowski, A. Mooradian, Opt. Lett. 14 (1989) 24.
[2] Z. Lin, C. Gao, M. Gao, Y. Zhang, H. Weber, Appl. Phys. B 94 (2009) 81.
[3] Y.F. Chen, T.M. Huang, C.L. Wang, L.J. Lee, S.C. Wang, Opt. Commun. 152 (1998) 319.
[4] T.J. Kane, R.L. Byer, Opt. Lett. 10 (1985) 65.
[5] L.J. Bromley, D.C. Hanna, Opt. Lett. 16 (1991) 378.
[6] Y.H. Zheng, H.D. Lu, Y.M. Li, K.S. Zhang, K.C. Peng, Appl. Phys. B 90 (2008) 485.
[7] G.T. Maker, P.A. Malcolm, A.I. Ferguson, Opt. Lett. 18 (1993) 1813.
[8] Y.H. Cha, K.H. Ko, G. Lim, J.M. Han, H.M. Park, T.S. Kim, D.Y. Jeong, Opt. Express 16 (2008) 4866.
[9] Ping Xie, Single Mode Laser and Method Suitable for Use in Frequency Multiplied, US Patent 5905748, May 18, 1999.
[10] K.I. Martin, W.A. Clarkson, D.C. Hanna, Opt. Lett. 21 (1996) 875.
[11] Y.H. Zheng, H.D. Lu, F.Q. Li, K.S. Zhang, K.C. Peng, Appl. Opt. 46 (2007) 5336.
[12] Y.H. Zheng, H.D. Lu, F.Q. Li, K.S. Zhang, K.C. Peng, Chin. J. Lasers 34 (2007) 739.
[13] E. Wu, H.F. Pan, H.P. Zeng, J. Opt. Soc. Am. B 21 (2004) 1463.
[14] S. Greenstein, M. Rosenbluh, Opt. Commun. 248 (2005) 241.
[15] R.G. Smith, IEEE J. Quantum Electron. 6 (1970) 215.