Stable continuous-wave single-frequency Nd:YAG blue laser at 473 nm considering the influence of the energy-transfer upconversion

Yaoting Wang, Jianli Liu, Qin Liu, Yuanji Li, Kuanshou Zhang*

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

** kuanshou@sxu.edu.cn*

Abstract: We report a continuous-wave (cw) single frequency Nd:YAG blue laser at 473 nm end-pumped by a laser diode. A ring laser resonator was designed, the frequency doubling efficiency and the length of nonlinear crystal were optimized based on the investigation of the influence of the frequency doubling efficiency on the thermal lensing effect induced by energy-transfer upconversion. By intracavity frequency doubling with PPKTP crystal, an output power of 1 W all-solid-state cw blue laser of single-frequency operation was achieved. The stability of the blue output power was better than ± 1.8% in the given four hours.

OCIS codes: (140.3480) Lasers, diode-pumped; (140.3560) Lasers, ring; (140.3515) Lasers, frequency doubled; (140.6810) Thermal effects.

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1. Introduction

The large interest that exists today in compact package blue laser with high power and high efficiency is driven by numerous applications, such as in high-density optical data storage, color displays, medical diagnostics and precision metrology. Especially, continuous-wave (cw) single-frequency blue lasers are attractive owing to the scientific applications including spectroscopy, atom cooling and trapping, quantum optics and quantum information. The blue laser can be generated by frequency doubling of a Ti:sapphire laser. A maximum average output of 3.5W 400nm blue-violet laser was obtained by intracavity frequency-doubling of a Q-switched Ti:sapphire laser [1]. 690mW cw single-frequency 423nm blue laser was reported by intracavity frequency-doubling of a cw Ti:sapphire laser [2]. However, the laser system is complex because the Ti:sapphire laser should be pumped by a high power all-solid-state 532 nm green lasers. Most present work to get compact package blue laser have been concentrated on frequency doubled Nd:YAG 946 nm laser because of Nd:YAG's good optical quality, high thermal conductivity, and large Stark splitting of the ground state [3–5]. A 3.8 W 473 nm blue laser was produced by an intracavity frequency doubling 946 nm Nd:YAG/LBO laser [5], and the fluctuation of the blue output power was 5.0% in the given 30 min. Because of the sum-frequency mixing of different longitudinal modes, correspondingly to be "the green problem", the blue laser tends to noisy. Diode pumped cw frequency doubling Nd:YAG 473 nm laser of single-frequency operation were applied for narrow linewidth and low-noise operation [6–8]. A 500mW cw single-frequency blue laser with high stability was demonstrated by extracavity frequency doubling a Nd:YAG ring laser [6].

However, high power and efficiency 473 nm blue laser is difficult to achieve because of the significant reabsorption loss, the lower stimulated-emission cross section and serious thermal effect on the quasi-three-level lasing transition at 946nm. Several methods had been used to improve the laser performance of Nd:YAG at 946 nm, such as optimizing the length of laser crystal [9], using a composited laser rod [10], and efficiency cooling schemes [11]. Another factor to limit the scaling of the Nd:YAG laser output power is the influence of energy-transfer upconversion (ETU). First, since the ETU reduces the population of the upper laser level, the laser performance is degraded. Second, the presence of ETU will give rise to an extra heat load in the laser crystal, so the thermal effect is much more serious than that of laser crystal without ETU effect. The influence of ETU on threshold, output power, spatial distribution of population-inversion density and fractional thermal loading in Nd:YAG 946 nm laser had been theoretically and experimentally investigated [12–14]. To the authors' knowledge, an investigation of the influence of ETU on the performance of an intracavity frequency doubled Nd:YAG blue laser has not been published previously, especially, the influence of frequency doubling efficiency on the thermal lensing effect induced by ETU.

In this paper, a ring laser resonator was designed and PPKTP was used to build up a diode-end-pumped cw intracavity frequency doubling Nd:YAG blue laser of single frequency operation. The influence of frequency doubling efficiency and incident pump power on the thermal lensing effect induced by ETU and the stable region of ring resonator depend on the thermal focal length of laser medium were theoretical analyzed. Based on the experimental studies of the relations between the output power of cw single frequency blue lasers and the incident pump power at different cavity length, phase-matching temperature and length of PPKTP crystal considering the influence of the thermal focal length induced by ETU, a stable high power cw blue laser of single-frequency was achieved. The measured output power of cw blue laser was 1.01 W with the power stability of better than ± 1.8% in the given four hours.

2. Theoretical analysis

In a high power diode-end-pumped solid-state laser, the thermal lensing effect of laser medium is serious. In order to getting high power and efficiency cw single-frequency 473 nm blue laser, the thermal lensing effect induced by ETU needs to be thoroughly understood.

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If the ETU effect is not considered, the thermal focal length of laser medium in a diode-end-pumped laser can be calculated using [15]

$$f_{th} = \frac{\pi K_c \omega_p^2}{\xi_0 P_p (dn/dt)[1-\exp(-\alpha l)]}, \quad (1)$$

where K_c is the thermal conductivity, ω_p is the pump beam radius, P_p is the incident pump power, *dn/dt* is the thermal-optic coefficient of refractive index, α is the absorption coefficient, l is the laser crystal length and ξ_0 is the fractional thermal loading.

The presence of ETU effects will give rise to an extra heat load in the laser crystal because of multiphonon relaxation from the excited level back to the upper laser level and from the lower-lying level down to the ground state, so the thermal lensing effect is much more serious than that of laser crystal in which there is no ETU effect. If the ETU effect have to be considered, the fractional thermal loading ξ_0 in Eq. (1) should be substituted by ξ that can written as [13]

$$\xi = \xi_0 \frac{N_b}{N_{bnoETU}} + 1 - \frac{N_b}{N_{bnoETU}}, \quad (2)$$

where N_b and N_{bnoETU} are the populations in the upper laser level with and without the ETU effect, respectively, that are given by

$$N_b = \iiint\limits_{\text{crystal}} \frac{2\tau f\, Rr_p + \frac{2c\sigma\tau}{n} f\, N_a^0 \Phi \varphi_0}{1 + \frac{c\sigma\tau}{n} f \Phi \varphi_0 + \left[\left(1 + \frac{c\sigma\tau}{n} f \Phi \varphi_0\right)^2 + 4W\tau^2 \left(Rr_p + \frac{c\sigma}{n} N_a^0 \Phi \varphi_0\right)\right]^{1/2}} dV, \quad (3)$$

and

$$N_{bnoETU} = \iiint\limits_{\text{crystal}} \frac{\tau f\, Rr_p + \frac{c\sigma\tau}{n} f\, N_a^0 \Phi \varphi_0}{1 + \frac{c\sigma\tau}{n} f \Phi \varphi_0} dV, \quad (4)$$

Where, W is the single uperconversion parameter, τ is the lifetime of the upper state, c is the speed of light in vacuum, σ is the stimulated emission cross section, n is the refractive index of the laser medium, N^0_a is the unpumped population density of the lower state, $f = f_a + f_b$, f_a and f_b are the fractional population of the lower and the upper laser levels, respectively, r_p and φ_0 are the spatial distributions of the pump beam and the laser photons, respectively, R is the pumping rate, Φ is the total number of laser photons in the intracavity frequency doubling laser cavity and can be written as

$$\Phi = \frac{2l_c^* P_{out}}{ch\nu_L \eta_{SHG}}, \quad (5)$$

where l_c* is optical path length of the laser cavity, P_{out} is the laser output power, $h\nu_L$ is the laser photon energy, and η_{SHG} is the frequency doubling efficiency. Figure 1 is the calculated thermal focal length of laser medium in a diode-end-pumped intracavity frequency doubling laser using the Eqs. (1-5). It can be seen that the thermal focal length is dependent on the incident pump power and the frequency doubling efficiency, the thermal lensing effect become more serious as the incident pump power and the frequency doubling efficiency increased when the influence of ETU effect is considered. As a comparison, if the influence of ETU effect is not considered, the calculated thermal focal lengths using the Eq. (1) are 63.3 mm, 57.0 mm and 51.8 mm at the incident pump power of 18 W, 20 W and 22 W,

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respectively. The thermal lensing effect is not so serious and is not dependent on the frequency doubling efficiency.

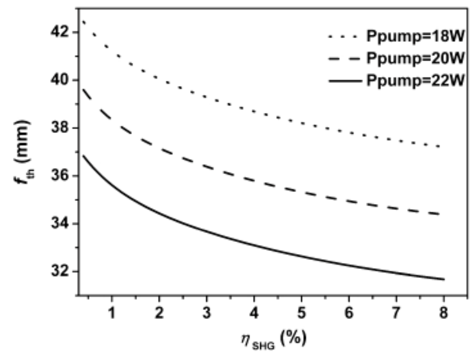

Fig. 1. Dependence of calculated thermal focal length on the incident pump power and the frequency doubling efficiency when the ETU effect is considered.

The thermal focal length of laser medium is a critical factor for the ring laser resonator design. For a given laser cavity, we should know how long the thermal focal length should be when the laser can be stable operation. The ring resonator we designed as shown in Fig. 3 was formed by two plane mirrors (M1, M2) and two plano-concave mirrors (M3, M4). In the three cases that the optical length between M3 and M4 (L1) is 125 mm and the rest optical length (L2) is 220 mm, 240mm and 260mm, respectively, the laser cavity stable condition of A + D was calculated as a function of the thermal focal length using the standard ABCD matrix formalism with the approximation of a thin thermal lens in the middle of the Nd:YAG crystal, as shown in Fig. 2. The cavity stable condition of A + D reaches the critical point of 2 when the thermal focal length is 30 mm, 35mm and 40mm in the case that L2 is 220 mm, 240mm and 260mm, respectively. If the thermal focal length is less than the critical value, the laser cavity will be out of stable region and the laser cannot oscillate. Because thermal lensing effect become more serious as the incident pump power and the frequency doubling efficiency increased when the influence of ETU effect is considered, if we want to get high power blue laser, the short laser cavity length should be used.

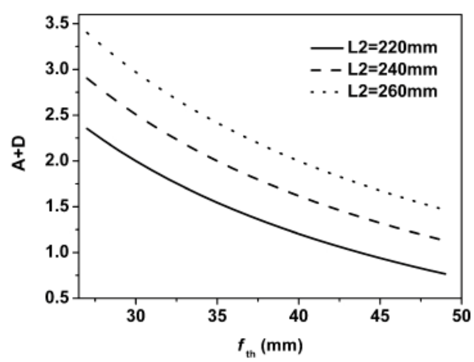

Fig. 2. Dependence of calculated laser cavity stable condition of A + D on the thermal focal length.

3. Experimental setup and results

We built a diode-end-pumped cw single frequency Nd:YAG laser with a ring optical cavity. The experimental setup is schematically depicted in Fig. 3. Because the periodically poled crystals permit access to the highest nonlinear coefficient and avoid any walk-off problems and PPKTP crystal offers the possibility of second-harmonic generation at room temperature, we used PPKTP crystals as the intracavity frequency doubling medium in our experiment.

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Another advantage of the PPKTP is that thicker crystals can be poled because of their lower coercive field.

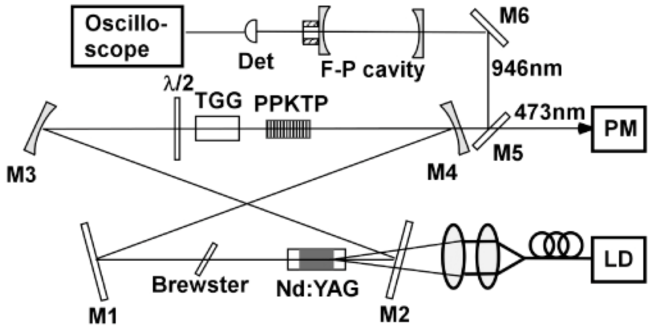

Fig. 3. Experimental setup of the diode-end pumped cw intracavity frequency doubled Nd:YAG blue laser of single frequency operation. LD: fiber-coupled diode laser; PM: power meter; F-P cavity: scanned confocal Fabry-Perot cavity; Det: photodetector.

The pump source is a fiber-coupled diode laser with center wavelength of 808 nm and core diameter of 400 µm. The pump power is coupled into the gain medium with spot size of 400 µm diameter via a multi-lens system. To overcome the thermal effect caused by the deformation of the Nd:YAG crystal faces, a composite Nd:YAG rod was used. The composite Nd:YAG rod has a diameter of 3 mm and a length of 11 mm, which consists of a 5 mm-long 1 at.% Nd-doped part in the middle with two 3 mm-long undoped end caps. Both end faces of the Nd:YAG rod were anti-reflection (AR) coated at 946 nm ($R_{946\ nm} < 0.25\%$) and high-transmission (HT) coated at 808 nm ($T_{808\ nm} > 90\%$). The Nd:YAG rod was tightly wrapped with indium foil for reliable heat transfer and mounted in a copper block, which was temperature controlled by a temperature controller with the accuracy of ± 0.01 °C (Model YG-4S). To reduce the reabsorption loss, the temperature of Nd:YAG rod was controlled at 12 °C. The ring resonator was formed by two plane mirrors (M1, M2) and two plano-concave mirrors (M3, M4). M1 and M2 were high-reflection (HR) coated at 946 nm ($R_{946\ nm} > 99.5\%$) and HT coated at 808 nm and 1064 nm ($T_{808\ nm,\ 1064\ nm} > 90\%$). M3 and M4 were HR coated at 946 nm ($R_{946\ nm} > 99.5\%$) and HT coated at 473 nm ($T_{473\ nm} > 90\%$). The radius of both plano-concave mirrors is 100 mm. A PPKTP crystal with a period of 6.5 µm was inserted into the ring laser cavity between M3 and M4 as the intracavity frequency doubling medium. Both end faces of the PPKTP crystal are AR coated at 946 nm and 473 nm ($R_{946\ nm,\ 473nm} < 0.25\%$). The PPKTP crystal was temperature controlled using a temperature controller with the accuracy of ± 0.005 °C (Model YG-2009B). The temperature of PPKTP was tuned carefully to get maximum blue laser output power in experiment. Using a Brewster plate and an optical diode formed by a half-wavelength plate and a TGG crystal in the resonator, a all-solid-state cw Nd:YAG/PPKTP blue laser of single frequency operation can be obtained.

As indicated in Section 2, the thermal lensing effect become more serious as the incident pump power and the frequency doubling efficiency increased when the influence of ETU effect is considered and we should shorten the cavity length of L2 in the design of ring cavity to get high power blue laser. Because the ring resonator is designed to obtain single frequency laser and several optical elements should be inserted into the cavity, we did our best to optimize the cavity length in the experiment and the best result was 240 mm for L2 and L1 was designed about 125 mm.

In order to get high power blue laser, the intracavity frequency doubling efficiency (η_{SHG}) should be investigated and optimized. As we know, η_{SHG} depends on the cycling power inside cavity that is related to the incident pump power, the phase-mismatch that is related to the controlled temperature of PPKTP crystal, the waist size at the PPKTP crystal (ω_{SHG}) and the length of PPKTP crystal. At first, a PPKTP crystal with the dimensions of 10(length) × 2(width) × 1(thickness) mm^3 was used and the temperature of crystal (phase-mismatch) was changed in the experiment to study the influence of ETU on the blue laser output. The output

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power of cw blue lasers as functions of the incident pump power at difference temperature of PPKTP crystal is shown in Fig. 4.

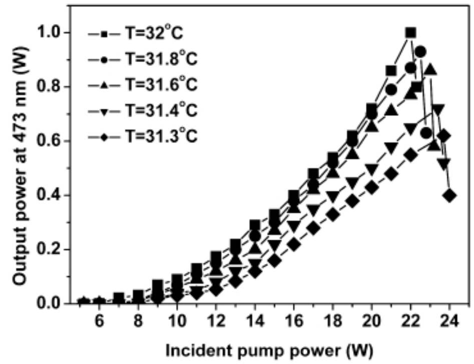

Fig. 4. Output power of cw single frequency blue lasers as functions of the incident pump power at difference temperature of PPKTP crystal.

The incident pump threshold power of laser was 5 W. Considering the absorption efficiency of Nd:YAG crystal for 808 nm pump light is 80%, the absorbed pump threshold power of laser was 4 W. Such high pump threshold is because the ring resonator was designed and several optical elements was inserted into the cavity to obtain single frequency laser, the cavity losses is relative large that was measured of about 3%. The measured maximum cw 473 nm blue laser output power was 1.01W at incident pump power of 22 W and the optimum PPKTP temperature of 32 °C. When the incident pump power was further increased, the laser oscillation rapidly vanished owing to the more serious thermal lensing effect that makes the resonator out of stable region. When the PPKTP temperature was decreased, the maximum incident pump power was increased but the intracavity frequency doubling efficiency was decreased and the cw 473 nm blue laser output power was low. It is proved that the thermal focal length of laser medium is dependent on the frequency doubling efficiency and the thermal lensing effect become more serious as the frequency doubling efficiency increased when the influence of ETU effect is considered.

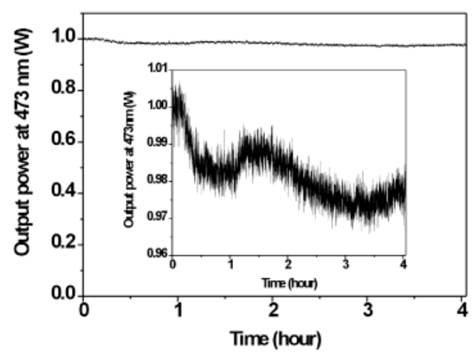

Fig. 5. Output power stability of cw single frequency blue laser.

The blue laser beam quality factor measured using a Beam Propagation Analyzer (Model SPIRICON M^2-200) and M^2 was less than 1.1. The longitudinal mode of the laser was monitored by a scanned confocal Fabry-Perot (F-P) cavity (with free spectral ranges of 750 MHz and fineness of 500) recorded by a digital storage oscilloscope (Agilent Infiniium 54830B). The blue laser was in single-frequency operation and the frequency drift was 50 MHz in 1 minute. The power stability of the blue laser at average output power around 1W was measured by a power meter (*LabMax-TOP*, Coherent) and recorded by a computer as

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shown in Fig. 5. The stability of the blue output power was better than ± 1.8% and no mode hopping was observed in the given four hours.

The second, cavity length between M3 and M4 (L1) was changed (correspondingly the waist size at the PPKTP crystal was changed) in the experiment to study the influence of ETU on the blue laser output. When L1 was 119 mm, 122 mm, 125 mm, 128 mm, and 132 mm (correspondingly ω_{SHG} was 141μm, 137μm, 133 μm, 128 μm and 123 μm), the maximum cw single frequency 473 nm blue laser output power was 420 mW, 860 mW, 1.01W, 900 mW and 800 mW at the maximum incident pump power of 21 W, 23 W, 22 W, 21 W and 20 W, respectively. When the waist size at the PPKTP crystal was smaller, the intracavity frequency doubling efficiency was increased, but the cw single frequency 473 nm blue laser output power of laser is lower because the maximum incident pump power is decreased that indicated the thermal lensing effect induced by ETU becomes more serious. On the other hand, when the waist size at the PPKTP crystal was larger, more pump power could be incident, but the cw single frequency 473 nm blue laser output power of laser is limited by the low intracavity frequency doubling efficiency. The relation between the maximum output power of cw single frequency 473 nm blue lasers and the waist size at the PPKTP crystal is shown in Fig. 6. The squares are the experimental data. The dash line is the theoretical prediction without considering the influence of ETU effect that is not in agreement with the experimental results. The higher output power can be obtained is because the thermal lensing effect is relatively weak when the influence of ETU effect is not considered (as we mentioned in Section 2), and more pump power can be incident in the same ring cavity configuration. The solid line is the theoretical prediction considering the influence the ETU effect that obtains good agreement with the experimental results. It can be seen, if the influence of the ETU effect is considered, the optimum waist size at the PPKTP crystal should be 133 μm (correspondingly L1 should be 125 mm) in the cw single frequency 473 nm blue laser we designed.

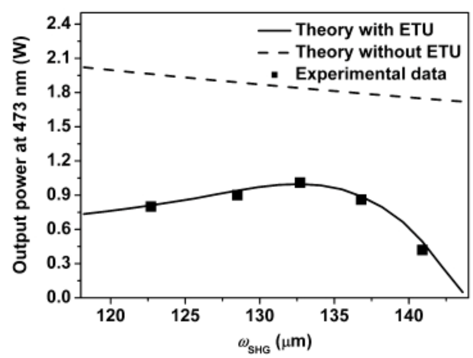

Fig. 6. Relation between the maximum output power of cw single frequency 473 nm blue lasers and the waist size at the PPKTP crystal

The third, other two PPKTP crystals with length of 15 mm and 20 mm used in the experiment to study the influence of ETU on the blue laser output. When the length of PPKTP crystals was 15 mm and 20mm, the maximum cw single frequency 473 nm blue laser output power was 820 mW and 670 mW at the maximum incident pump power of 20 W and 18 W, respectively. Comparing with the experimental results in the first experiment that the PPKTP crystals with length of 10 mm was used, it is clear that the higher intracavity frequency doubling efficiency could be obtained as the longer length of PPKTP was used, but the output power of cw single frequency 473 nm blue laser was limited owing to the maximum incident pump power is decreased that indicated the thermal lensing effect induced by ETU becomes more serious. The relation between the maximum output power of cw single frequency 473 nm blue lasers and the length of the PPKTP crystal is shown in Fig. 7. The squares are the experimental data. The dash line is the theoretical prediction without considering the influence of ETU effect that is not in agreement with the experimental results.

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The higher output power can be obtained using the same length of PPKTP is because the thermal lensing effect is relatively weak when the influence of ETU effect is not considered, and more pump power can be incident. The solid line is the theoretical prediction considering the influence the ETU effect that obtains good agreement with the experimental results. It can be seen, if the influence of the ETU effect is considered, the optimum length of the PPKTP crystal should be 6.7 mm in the cw single frequency 473 nm blue lasers we designed. If the optimum PPKTP crystal is used, the maximum output power of cw single frequency 473 nm blue laser of 1.1 W can be obtained at the incident pump power of 23 W. Unfortunately, we only have three pieces of PPKTP crystal that had used in our experiment and do not have a PPKTP crystal with the length of 6.7 mm.

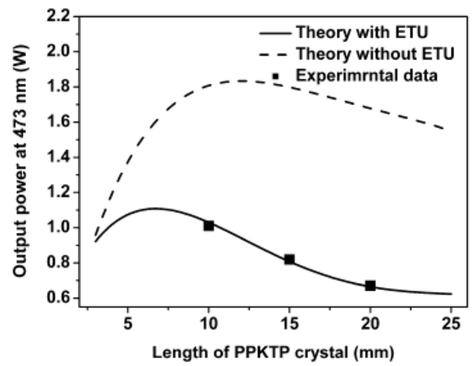

Fig. 7. Relation between the maximum output power of cw single frequency 473 nm blue lasers and the length of the PPKTP crystal

4. Conclusion

We have demonstrated stable cw single-frequency Nd:YAG blue laser at 473 nm. The influence of frequency doubling efficiency on the thermal lensing effect induced by ETU was theoretically and experimentally studied. Considering the influence of the thermal focal length induced by ETU, the ring cavity length, phase-matching temperature and length of PPKTP crystal were experimentally investigated and optimized to get stable high power blue laser. 1 W cw single-frequency blue laser at 473nm was achieved with the power stability of better than ± 1.8% and no mode hopping in the given four hours. The stable cw single-frequency blue laser can be used in the scientific applications and laser-based applications to improve the spectral sensitivity or spatial resolution.

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