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Highly efficient continuous-wave intracavity frequency-doubled Nd:YVO$_4$-LBO laser at 457 nm under diode pumping into the emitting level $^4F_{3/2}$

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Abstract The continuous-wave high efficiency laser emission of Nd:YVO$_4$ at the fundamental wavelength of 914 nm and its 457 nm second harmonic obtained by intracavity frequency doubling with an LBO nonlinear crystal is investigated under pumping by diode laser at 880 nm into emitting level $^4F_{3/2}$. 6.5 W at 457 nm with $M^2 = 1.8$ was obtained from a 5-mm-thick 0.4 at.% Nd:YVO$_4$ laser medium and a 15-mm-long LBO nonlinear crystal in a Z-type cavity for 18.6 W absorbed pump power. An optical-to-optical efficiency with respect to the absorbed pump power was 0.35. Comparative results obtained for the pump with diode laser at 808 nm, into the highly-absorbing level $^4F_{5/2}$, are given in order to prove the advantages of the 880 nm wavelength pumping.

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1 Introduction

Since Fan and Byer introduced the first diode laser pumped 946 nm Nd:YAG laser at room temperature in 1987 [1], lasers operating around 0.9 μm have attracted much attention in the past few years. This is because the laser around 0.9 μm has some unique applications such as water vapor lidars and differential absorption lidars for ozone measurements, and it also can be used as the pump source for the Yb-doped crystals and Yb-doped fibers. The quasi-three-level 0.9 μm continuous-wave laser emission was recently investigated for Nd:YAG [2, 3], Nd:YVO$_4$ [4, 5] and Nd:GdVO$_4$ [5, 6] crystals. The corresponding frequency-doubled blue lasers were also in moderate progress. In 2003, Czeranowsky reported a 2.8 W blue laser output at 473 nm in a diffusion bonded Nd:YAG rod with a BiBO crystal and a Z-type cavity [7]. In 2006, Xue presented a 4.6 W deep-blue laser at 457 nm in a V-type resonator by utilizing a Nd:YVO$_4$ bulk crystal and a LBO crystal as the frequency doubler, with an optical-to-optical efficiency η_{oi} of 0.153 and a beam M^2 factor of 2.5 [8]. In 2007, Lü demonstrated a 6.2 W 456 nm Nd:GdVO$_4$/BiBO laser with $\eta_{oi} \sim 17.2\%$ and $M^2 \sim 2.5$ [9]. In 2009, Zheng reported a 13.2 W 457 nm Nd:YVO$_4$/LBO laser with $\eta_{oi} \sim 34.7\%$, till now the output power of which represents the highest level [10]. In all these papers, pumping is traditionally into the $^4F_{5/2}$ level, this induces a parasitic upper quantum defect between the pump and the emitting laser levels, with negative influence on the laser parameters and on the generation of heat by non-radiative processes. Therefore, the performances are still limited and the full lasing potential is not yet been exploited. A more efficient pumping method was presented recently, which was to pump the Nd^{3+} ions directly into the $^4F_{3/2}$ upper lasing level. This method was used successfully in the case of the four-level 1.06 μm emission of Nd:YAG [11–13], Nd:YVO$_4$ [14, 15] and Nd:GdVO$_4$ [16] crystals. However, only several works on 0.9 μm emission by direct pumping were reported for the quasi-three-level. In 1999, Kellner et al. first reported a 879 nm Ti:Sapphire laser pumped

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Nd:YVO$_4$ laser operating at 915 nm [17]. In 2002, Lupei et al. first reported a 885 nm Ti:Sapphire laser pumped Nd:YAG laser operating at 946 nm [18]. In the same year, a 946 nm continuous-wave Nd:YAG laser pumped by a 885 nm Ti:Sapphire laser was reported, with a slope efficiency of 68.0% [19]. In 2002, the possibility to increase the output performances of lasers that generate visible light and are pumped directly into the emitting level was first discussed [20]. In 2007, for the first time, the pump with diode lasers around 0.88 µm was used to obtain deep-blue light at 0.46 µm by using Nd-vanadate crystals in thin-disk geometry [21]. In 2008, 1.0 W output power of deep-blue light at 457 nm was obtained from an Nd:YVO$_4$/LBO thin-disk laser [22]. In 2009, Gao et al. first reported an end-pumped with diode lasers at 879 nm deep-blue laser at 456 nm from a 912 nm Nd:GdVO$_4$ emitting laser that was intracavity frequency-doubled by LBO and BiBO. The power levels of the blue light were low (i.e. 118 mW from a linear cavity, and 391 mW with a V-type resonator) [23].

In this paper, we report high efficiency continuous-wave emission in Nd:YVO$_4$/LBO at 457 nm under pumping by diode laser at 808 nm in the $^4F_{5/2}$ level and 880 nm directly into the $^4F_{3/2}$ emitting level. Improvement of the blue performances was observed under 880 nm pumping, in spite of a lower absorption at this wavelength: 6.5 W at 457 nm with $M^2 = 1.8$ and $\eta_{oa} = 0.35$ was obtained from a 5 mm-thick 0.4 at.% Nd:YVO$_4$ laser medium and a 15 mm-long LBO nonlinear crystal in a Z-type cavity. Under the same absorbed pump power at 808 nm, the maximum blue emission was 4.3 W, with $\eta_{oa} = 0.23$ and a beam quality of $M^2 = 3.9$.

2 Theoretical analysis

The second-harmonic power $P_{2\omega}$ is determined by the intracavity emission intensity of the active material I_ω and by the characteristics of the doubling crystal

$$P_{2\omega} \propto I_\omega^2 \frac{d_{\text{eff}}^2 l^2}{n_1^2 n_2}, \tag{1}$$

where d_{eff} is the effective nonlinear coefficient along the phase-matching direction, l is the length of the nonlinear crystal, and n_1 and n_2 are the refractive indices at the fundamental and the second-harmonic wavelengths, respectively. Equation (1) can be rewritten by using the slope efficiency for the absorbed pumping power η_{sa} and the absorbed pumping threshold of the intracavity emission at the fundamental frequency ω as

$$P_{2\omega} \propto \eta_{sa}^2 \cdot (P_a - P_{th})^2 \cdot \frac{d_{\text{eff}}^2 l^2}{n_1^2 n_2}. \tag{2}$$

The slope efficiency in the absorbed pump power $\eta_{sa} = 2K_a/(GA)$, where $K_a = \eta_p \eta_u \eta_{qd}^l$ is the global efficiency, i.e. the product of several partial efficiencies of the various steps in the flow of excitation inside the laser crystal, where η_p is the pump level efficiency, η_u is the overlap efficiency for the pump and laser mode volumes, and $\eta_{qd}^l = \lambda_p/\lambda_l$ is the quantum defect ratio between the pump and laser wavelengths, G is the resonator loss, A is the pumped area. Assuming that all the parameters except η_{qd}^l are invariable under the different quantum defect ratios, it can be deduced that we can increase the quantum defect ratio to raise the slope efficiency in the absorbed pump power. The absorbed pumping threshold is $P_{th} = GAI_s/(2\eta_p\eta_u\eta_{qd}^l)$, where I_s is the saturation intensity. Assuming that all the parameters except η_{qd}^l are invariable under the different quantum defect ratios, it can be deduced that we can increase the quantum defect ratio to reduce the absorbed pump power at threshold. According to (2), we can increase the slope efficiency in the absorbed pump power or reduce the absorbed pump power at threshold to improve the second-harmonic power.

In a continuous-wave quasi-three-level laser the fractional thermal loading (the fraction of the pump power that is dissipated as heat) is [18]

$$\eta_h = 1 - \eta_l \eta_p \eta_{qd}^l (1 - \gamma f^l) - (1 - \eta_l)\eta_{qe}\eta_p\eta_{qd}^f (1 - \gamma f^f). \tag{3}$$

In (3), the superscripts f and l of η_{qd} refer to fluorescence and lasing emission, respectively; $\eta_l = (1 - f_{th})\eta_u$ is the laser extraction efficiency well above threshold, where f_{th} is the fraction of population in the emitting level at threshold; the reabsorption correction coefficient γ being dependent on the reabsorption fractions for the emitted laser and luminescence radiation, f^l and f^f, respectively. Under non-lasing η_h is governed by the product of the emission quantum efficiency η_{qe} ($\eta_{qe} = \lambda_p/\lambda_e$, where subscripts p and e represent the pump and lasing beam) and the quantum defect ratio $\eta_{qd}^f = \lambda_p/\lambda_{em}^f$, whereas for efficient lasing emission η_h is determined by $\eta_{qd}^l = \lambda_p/\lambda_{em}^l$. The reduction of heat generated in the laser material under pumping, expressed with the help of the fractional thermal loading η_h, depends on the reabsorption losses that influence the reabsorption correction factors $(1 - \gamma f^l)$ and $(1 - \gamma f^f)$ as well as the laser extraction efficiency via the fraction f_{th}. By strongly restricting these losses, η_h could be much more diminished from the value corresponding to that of 808 nm pumping [19].

3 Experimental setups

A simple plano-concave cavity was employed to generate the fundamental 914 nm laser, as shown in Fig. 1(a). The optical pumping at 880 nm was made with a 400 µm diameter, 0.22 number aperture fiber-coupled diode laser, whereas

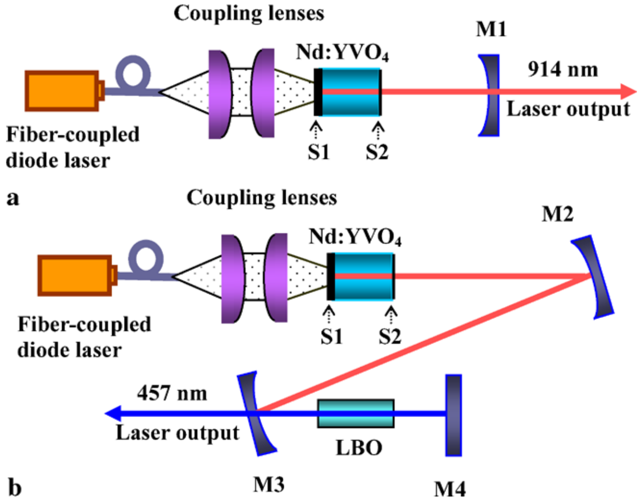

Fig. 1 Schematic diagrams of the experimental setup. (**a**) is for fundamental 914 nm infrared laser and (**b**) is for the frequency-doubled 457 nm blue laser. The distances of S1 to mirror M1, of S1 to mirror M2, of M2 to M3, and of M3 to M4 were 56, 188, 254, and 54 mm, respectively

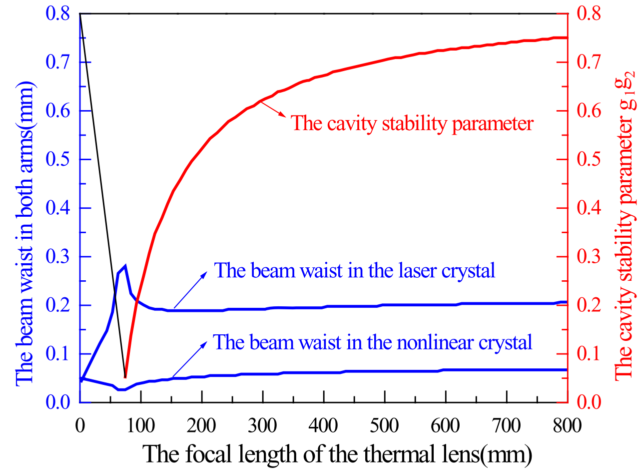

Fig. 2 Beam waist in both arms and the cavity stability parameter versus focal length of the thermal lens respectively

the pumping into $^4F_{5/2}$ level at 808 nm was performed with a diode laser that had the same fiber characteristics. The coupling optics consists of two identical plano-convex lenses with focal lengths of 15 mm that is used to re-image the pump beam into the laser crystal at a ratio of 1:1. The coupling efficiency is 98%. Because the pump intensity is high enough in the pump-spot regions, the first lens must be well adjusted to collimate the pump beam, since it will strongly affect the focal spot. However, the distance between the two lenses can be freely adjusted in experiment. For the aberration, the average pump-spot radius is about 220 μm. A conventional a-cut Nd:YVO$_4$ crystal (0.4 at.% doping level, 5 mm thick) has the pumping side, S1, coated with antireflection (AR) at 808 nm and 880 nm pumping wavelengths, and with high reflectivity (HR) at 914 nm and high transmission at 1064 nm and 1342 nm to suppress the strong parasitical oscillation at there transitions. The opposite side, S2, was AR coated for 914 nm in order to increase the pump beam absorption efficiency, and HR coated for the pumping wavelengths. The crystal was wrapped in indium foil and placed in a copper holder, whose temperature was kept at 15°C, through a thermoelectric cooler. A plano-concave mirror M1 with a curvature-radius of 200 mm was employed, with a transmission of 5% at 914 nm and high transmission ($T > 95\%$) at 1064 nm and 1342 nm to suppress the strong parasitical oscillation at the transitions. The geometric cavity length was about 56 mm.

To realize efficient frequency doubling, a Z-folded cavity was designed, as shown in Fig. 1(b). A Z-type resonator of 396 mm length was designed. This configuration grants an enhanced value ($\eta_u \sim 0.9$) of the laser-to-pump beam overlap efficiency under high-pumping conditions, whereas the laser beam in the Nd:YVO$_4$ crystal and on the output mirror M3 was almost constant over the resonator stability zone. The radiuses of curvature were chosen as 300 mm and 100 mm for M2 and M3, respectively. The 300 mm radius mirror M2 and the plane mirror M4 were HR coated at 457 and 914 nm, whereas the 100 mm radius mirror M3 was HR coated at 914 nm and AR coated at 457 nm. A LBO crystal with dimension of $3 \times 3 \times 15$ mm^3 was employed as the frequency doubler. The crystal was cut for type I critical-phase-matching condition ($\theta = 90°, \phi = 21.7°$ at 300 K; with $d_{\mathrm{eff}} = 0.803$ pm/V) and placed in a copper holder whose temperature was precisely controlled by a thermal electric cooler with 27 ± 0.1°C accuracy. Both facets of the nonlinear crystal were well polished and AR coated at 457 nm and 914 nm. The pump beam of 808 nm or 880 nm was focused into the Nd:YVO$_4$ crystal with a waist-spot radius of around 200 μm. The folded angle (α) was set to be $\sim$7° to reduce the astigmatism. Thus under these conditions, the radius of the laser mode in both arms and the cavity stability parameter $g_1 \cdot g_2$ versus focal length of the thermal lens, respectively, are shown in Fig. 2, which were calculated by the ABCD matrix formalism with the approximation of a thin lens in the middle of the laser crystal. From Fig. 2, we can see that both of the spot radiuses in the laser crystal Nd:YVO$_4$ and the nonlinear crystal LBO are nearly constant within a broad region of the thermal-lens focal length from 100 mm to 800 mm. Therefore, such a cavity is very insensitive to the thermal lens and can stably operate even at high pump level. The radius in the middle of LBO is about 50 μm, which would yield a good frequency doubling efficiency. When the absorbed pump power at 880 nm was 18.6 W, the thermal-lens focus length of the Nd:YVO$_4$ crystal was about 200 mm measured by a method which used the transform circle theory of resonator proposed in [24]. We can see that the Nd:YVO$_4$ laser is still in the stability

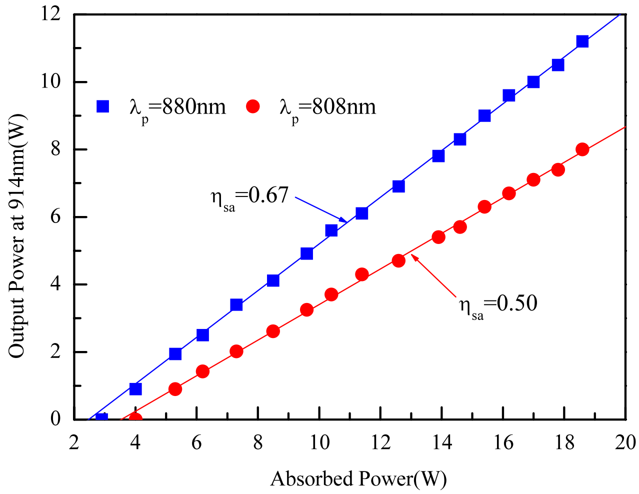

Fig. 3 Output power at 914 nm vs. absorbed pump power

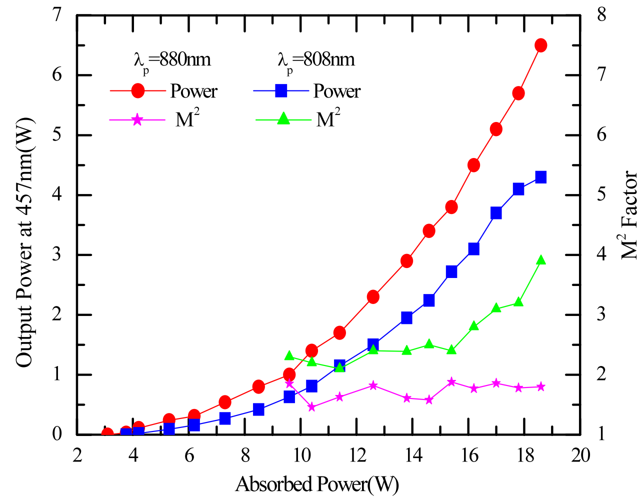

Fig. 4 Output power at 457 nm vs. absorbed pump power

zone when it is operated with the maximum pump power for both pumped wavelength from Fig. 2.

4 Results and discussions

The $Nd:YVO_4$ laser continuous-wave output power at 914 nm versus the absorbed pump power measured is shown in Fig. 3.

Under 808 nm pumping, the maximum output power is 8.0 W with an optical-to-optical efficiency in absorbed power η_{oa} of 0.43. The slope efficiency in absorbed power η_{sa} and the threshold were 0.50 and 4.0 W, respectively, with more than 97% of the pump power absorbed in the laser crystal. When the pumping was done at 880 nm, the maximum output power increased to 11.2 W. The threshold of operation was 2.9 W. Since 81.7% of the 880 nm pump power was absorbed in the $Nd:YVO_4$, the slope efficiency and the optical-to-optical efficiency were 0.67 and 0.50, respectively.

Figure 4 shows the continuous-wave 457 nm power and laser beam M^2 factor as a function of pump power for the 15 mm-long LBO nonlinear crystal. Under 808 nm pumping, the blue power increases quadratically with the pump until 4.1 W of blue laser output: the optical-to-optical efficiency in absorbed power η_{oa} was 0.22. The beam M^2 factor was 3.2. Behind this point the laser output saturates, reaching 4.3 W ($M^2 = 3.9, \eta_{oa} = 0.23$). The strong thermal lens induced in $Nd:YVO_4$ may be responsible for this behavior. The reduction of $Nd:YVO_4$ thermal lens under 808 nm pumping is believed to be responsible for the improvement of the laser beam mode quality and the increased absorbed power where the output power started to saturate. A decreased dependence of the $Nd:YVO_4$ focal length on the absorbed power, such as in the case of 808 nm pumping, will increase the absorbed power at which the resonator is driven out of the stability zone. On the other hand, maximum 6.5 W of output power was obtained under 18.6 W of absorbed pump power (or 23 W of incident pump power) at 880 nm ($\eta_{oa} = 0.35$) and with an M^2 factor of 1.8. The output power kept good quadratic curve and no saturation appearance was observed. Contrast with the 808 nm pumping, direct pumping at 880 nm can increase the output power and improve the beam quality. This resulted from the larger quantum efficiency of ∼8.9% under 880 nm pumping than that of 808 nm pumping. Besides, the optimization of Z-type cavity is also an important contributing factor. Moreover, the expected less heat generation induced by a ∼40% smaller quantum defect ratio in 880 nm pumping than in 808 nm pumping also improves the laser parameters.

The stability of the laser was investigated with a fast photodiode and recorded with a digital storage oscilloscope. The output light showed a quite stable behavior and did not show any large-amplitude fluctuation on the very short time scale. The maximum amplitude of the fluctuation was less than 5.0%. The average stability of the blue laser was also investigated and the time trace of the average output power around the 6.5 W operating point is shown in Fig. 5. The fluctuation of the blue output power was better than 3.0% in the given 30 min.

5 Conclusion

In summary, we first presented a high efficiency direct-pumped $Nd:YVO_4$/LBO laser at 457 nm pumped by a diode laser at 880 nm. A Z-type cavity with length of about 396 mm is optimized to obtain high efficient blue laser. When the absorbed pump power is 18.6 W, the maximum output power, of 6.5 W at 457 nm, has been obtained by using a 15 mm-long LBO crystal. The optical conversion efficiency in absorbed power was 35%. At the output power

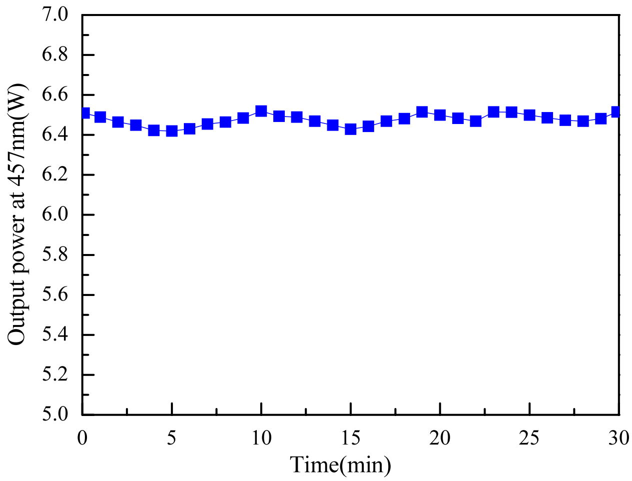

Fig. 5 Stability of the blue output power around the 6.5 W operation point

level of 6.5 W, the output stability is better than 5%. The beam quality M^2 value was equal to 1.8 at the maximum output power. The results of this work demonstrate that diode laser pumping into the emitting level $^4F_{3/2}$ of Nd^{3+} laser crystal is a solution for the construction of efficient lasers and for scaling to high power.

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