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Compact 600 mW blue laser with a composite Nd:YAG

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Abstract

A compact and simple design for an LDA-end-pumped intracavity doubling high-power blue laser with a composite Nd:YAG laser on the $^4F_{3/2}$ to $^4I_{9/2}$ laser transition in a flat-curved cavity is demonstrated. The nonlinear crystal used in the experiment is an LBO crystal cut for phase-matching type I. Through the thermo-lensing effect of the laser crystal at high-pumped power, the optimum mode-matched and efficient intracavity doubling are realized at the same time. The maximum output power at 473 nm was 600 mW when the absorbed, pumped power of 15 W, and the optical-to-optical conversion efficiency is 4%. The stability of blue output power is 3.2% within 2 h.

Keywords: Compact; Composite Nd:YAG; Blue laser

1. Introduction

LD-pumped all-solid-state lasers with intracavity second-harmonic generation are attractive sources for many applications such as display, printing technology, inspection, optical data storage, etc. However, all-solid-state blue laser at 473 nm is in an early stage of development because of the quasi-three-level nature of the $^4F_{3/2}$ to $^4I_{9/2}$ laser transition at 946 nm. Nd:YAG crystal has significant temperature-dependent reabsorption loss at 946 nm because of the lower laser level, that is, the highest level of $^4I_{9/2}$ manifold has a thermal population of 0.007% Nd atoms [1,2]. It is necessary to provide very high pump power density in laser crystal to realize the population inversion at lower laser level. Furthermore, the 946 nm transition must compete with the much stronger $^4F_{3/2}$ to $^4I_{11/2}$ 1064 nm transition because the emission cross section for 946 nm is only 4.5×10^{-20} cm^{-2}, a factor of ten less than for 1064 nm. So, efficiency at 946 nm or its frequency-doubling laser 473 nm at room temperature is very low. To overcome this problem, almost all high-power blue laser pumped by LDA have been reported applying the water-cooling system to remove the heat in laser crystals and reduce the reabsorption [3–6]. Moreover, due to the big pump beam size, generally V- [3] or Z-type [4,7] folded cavities are used in high-power blue laser to ensure the good mode match and the efficient intracavity frequency doubling. These blue lasers are complicated, bulky, high priced and less stable.

In this letter, we report on what is, to our knowledge, the highest output power at 473 nm of an LDA-end-pumped composite Nd:YAG laser rod and intracavity frequency doubling with LBO crystal blue laser in a simple flat-curved cavity [8]. The laser rod is cooled by TEC (thermoelectrically cooled) at 16°C. The maximum output power at 473 nm is 600 mW when the absorbed pumped power is 15 W. The optical-to-optical efficiency is 4% and the stability of blue output power is 3.2% within 2 h. This cavity design approach based on the fact that the thermal-lensing effect in a laser rod can be seen as a thin lens inserted into the cavity and there will be two beam waists in a linear cavity. The laser rod and the doubler can be placed at two separate beam waists. Adjusting the optical components location, the optimum mode match and efficient intracavity frequency doubling can be realized at the same time. This laser is compact and stable. So it is very important to realize the industrialization of the high-power blue laser.

2. Experimental setup

A schematic of a flat-curved cavity blue laser is shown in Fig. 1. The composite Nd:YAG crystal(Onyx Optics, Inc.) had flat, undoped end pieces, each 3 mm long, diffusion bonded to a 3-mm-thick doped inner part. The crystal was α cut, and the Nd concentration was 0.9 at%.

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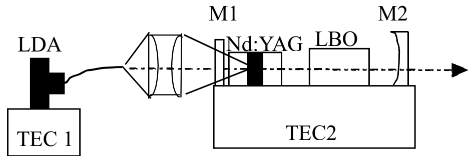

Fig. 1. Scheme of the flat-curved cavity 473 nm blue laser.

The crystal had a dual band antireflection coating at both 946 and 808 nm. The pump source was a fiber-coupled laser diode, with a core diameter of 0.4 mm and a numerical aperture of 0.22. The fiber output was focused into the crystal through a pair of flat–convex mirrors ($T_{808\ \mathrm{nm}} > 99.9\%$) whose focal lengths are 10 mm. The input flat mirror had antireflection coating at the pump wavelength and high-reflection coating at operating wavelength. The output mirror, M2, was a 100 mm radius of curvature concave mirror with high-reflection coating at laser wavelength and antireflection coating at doubling frequency wavelength. The output mirror was also coated at about 40% transmitting at 1064 nm to eliminate parasitic oscillation. The 10-mm-long LBO crystal (Crystech Inc.) had a dual band antireflection coating at both 946 and 473 nm and was oriented for critical type I phase matching at room temperature. The overall cavity length was set at 45 mm. The LDA and cavity were cooled by TEC.

It is very important for quasi-three-level laser operations to remove the heat in laser crystals because the reabsorption loss due to the thermal population of the lower laser level will increase with the temperature rise. Some authors used water-cooled laser crystal to realize the 946 nm operation. This system is very complicated and inconvenient. An alternative method is to use a new laser rod such as a composite laser rod. The concept of combining doped and undoped components for improving thermal conductivity has been applied to solid-state laser rods in diode-end-pumped geometries lately. The composite rod structure can dramatically improve thermal diffusion and reduce temperature rise in an active segment, thermally induced stress, and also other thermal effects [9–11]. The effect of reduction in temperature rise in a pumped active segment is more attractive for high-power quasi-three-level laser operation, for example, the 946 nm oscillation with Nd:YAG crystal, because the temperature-dependent reabsorption loss by the lower laser level increases with temperature. We used a composite Nd:YAG and a simple TEC-cooled system to realize the efficient 946 nm operating.

On the other hand, in order to achieve the optimum mode match the cavity configuration in high-power LDA-end-pumped lasers, the laser mode must be several hundreds micron due to the big pump size. It is extremely difficult to simultaneously realize the efficient intracavity frequency doubling if the laser crystal and the doubler are placed in one cavity. To overcome this problem a number of approaches have been reported, including the use of the V-type, Z-type and ring cavity. These methods suffer from the disadvantage that laser is unstable and very difficult to adjust. In this paper, we describe an alternative cavity design strategy to overcome this problem and make a high-power intracavity frequency doubling laser in a flat-curved cavity realize the optimum mode match and efficient intracavity frequency doubling simultaneity.

3. Theory analysis and experimental result

For a pump beam with Gaussian-like transverse intensity profile, the thermal-lensing effect in a side-cooling cylindrical laser crystal can be replaced by a thin lens. The focal length of the thermal lens is given by [12]

$$f_{\mathrm{th}} = \frac{\pi \cdot K \cdot \omega_{\mathrm{p}}^2}{p_{\mathrm{p}} \cdot \xi \cdot (\mathrm{d}n/\mathrm{d}t)} \cdot \frac{1}{1-\exp(-\alpha \cdot l)},$$

where ω_{p} is the radius of the pump spot, K is the thermal conductivity, α is the absorption coefficient for the pump and ξ is the fraction of absorbed pump power converted to heat, l is the laser crystal length and $\mathrm{d}n/\mathrm{d}T$ is the thermal optical coefficient. A flat-curved cavity will have two subsidiary cavities because of the thermal lens. The first beam waist locates on the input coupler plane mirror and the second locates between the laser crystal and the output coupler plane–curved mirror. This can be seen in Fig. 2. Adjusting the cavity length and the location of the laser crystal and the doubler, the optimum mode match and high efficient intracavity doubling can be realized in a linear cavity.

To illustrate absorbed pump power controlling the focal length of the thermal lens, we compute the focal length with parameters: $\omega_{\mathrm{p}} = 200\ \mu\mathrm{m}$, $K = 0.13\ \mathrm{W/(m\ K)}$, $\alpha = 0.8\ \mathrm{cm}^{-1}$, $\xi = 0.4$, $l = 3$ mm and $\mathrm{d}n/\mathrm{d}T = 7.3 \times 10^{-6}/\mathrm{K}$.

Fig. 3 is the thermal lens focal length in the laser crystal as a function of the absorbed pump power. Fig. 3 shows that with increase of absorbed pumped power, the thermal-lensing effect becomes stronger and the focal length gets shorter. If we choose the absorbed pump power to be 15 W, the focal length is about 40 mm. The round trip ABCD matrix for cavity, as shown in Fig. 2 can be represented as

$$M_{\mathrm{round}} = M_1 \cdot M_{\mathrm{th}} \cdot M_2 \cdot M_0 \cdot M_2 \cdot M_{\mathrm{th}} \cdot M_1 \cdot M_i,$$

where

$$M_i = \begin{bmatrix} 1 & 0 \\ -2/\rho_1 & 1 \end{bmatrix}, \quad M_1 = \begin{bmatrix} 1 & l_1 + \dfrac{l_{\mathrm{rod}}/2}{n_{\mathrm{rod}}} \\ 0 & 1 \end{bmatrix},$$

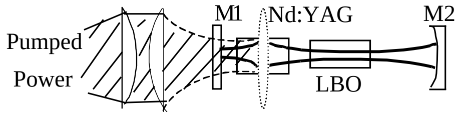

Fig. 2. Schematic of the flat-curved cavity with the thermo-lens.

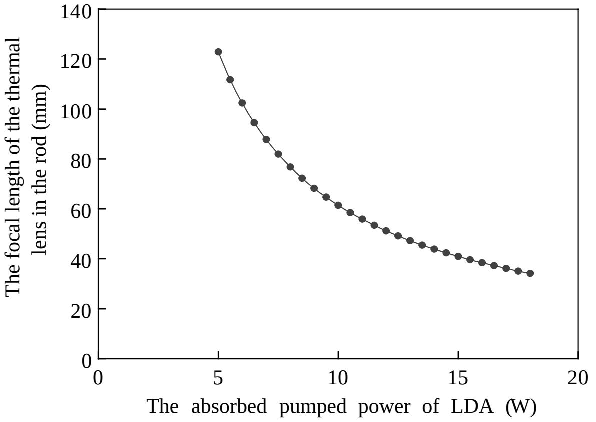

Fig. 3. The focal length of the thermal lens in gain medium via the absorption pumped power of LDA.

$$M_2 = \begin{bmatrix} 1 & l_2 + \dfrac{l_{\text{rod}}/2}{n_{\text{rod}}} + \dfrac{l_{\text{LBO}}}{n_{\text{LBO}}} \\ 0 & 1 \end{bmatrix},$$

$$M_{\text{th}} = \begin{bmatrix} 1 & 0 \\ -1/f_{\text{th}} & 1 \end{bmatrix}, \quad M_0 = \begin{bmatrix} 1 & 0 \\ -2/\rho_2 & 1 \end{bmatrix},$$

where l_1 and l_2 are the air spaces between the M1 or M2 and the laser rod, respectively, l_{rod} and n_{rod} are the length and refractive index of the laser rod, l_{LBO} and n_{LBO} are the length and refractive index of the doubler LBO crystal, and ρ_1 and ρ_2 are the radii of the input coupler mirror M1 and output coupler mirror M2. Here, $l_1 = 1$ mm, $l_{\text{rod}} = 9$ mm, $n_{\text{rod}} = 1.83$, $l_{\text{LBO}} = 10$ mm, $n_{\text{LBO}} = 1.63$, $f_{\text{th}} = 40$ mm, $\rho_1 = \infty$ and $\rho_2 = 100$ mm. Through computer calculation, the appropriate parameter of l_2 is found to be 35 mm. Here the laser mode in the laser crystal is 314 μm and the second beam waist (the location of the doubler) is 74 μm in diameter. Experimental data of output power with the absorbed pump power or current of LDA variation in this blue laser are shown in Fig. 4.

The measurements were carried out in the absorbed pump power range from 2 to 15 W. The pump power threshold is 5 W and is very much lower than that of the V- or Z-type cavity intracavity doubling blue laser [13]. The maximum output power at 473 nm is 600 mW with the absorbed pump power 15 W and the optical-to-optical conversion efficiency is 4%. The optical-to-optical conversion efficiency is lower in the absorbed pump power range from 5 to 12 W compared to that is from 12 to 15 W. This is explained by the fact that we designed the cavity configuration based on $f_{\text{th}} = 40$ mm. When the pump power was lower than 15 W the focal length would be longer than 40 mm and that resulted in the decrease in the laser mode in the laser crystal and mode mismatch. The theory data of the laser mode and the second beam waist under the absorbed pump power variation are shown in Fig. 5.

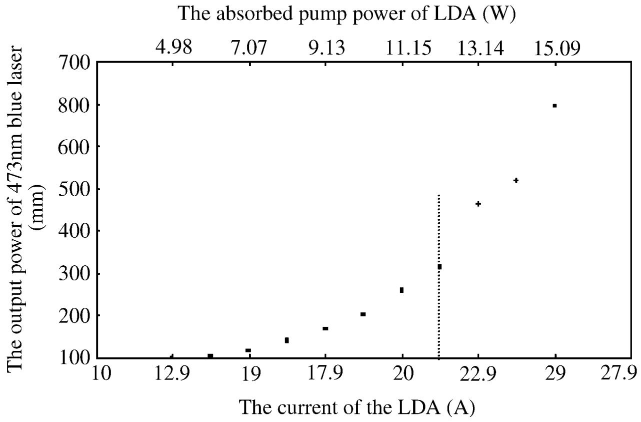

Fig. 4. The output power of 473 nm via the current of LDA and the absorbed pump power.

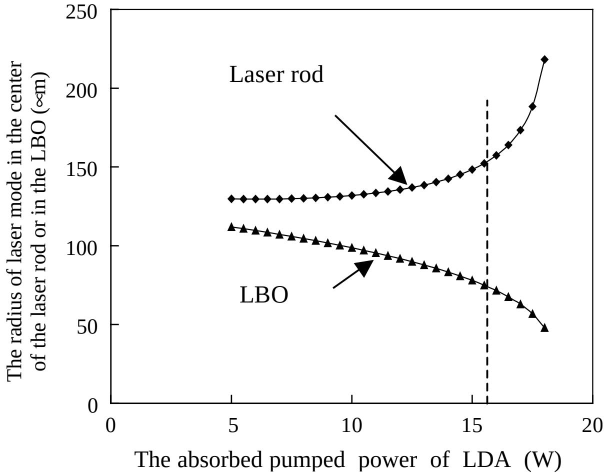

Fig. 5. The laser mode and the second beam waist via the absorbed pump power.

The laser mode in laser crystal increases with the pump power rise and the second beam waist decreases with the pump power rise. These two factors lead to the higher pump power absorption efficiency in laser crystals and higher power intensity in the doubler too. These two points account for the optical-to-optical conversion efficiency increase. Certainly, this increase is somewhat attributable to the saturation of the reabsorption.

The beam shape of LDA pumped flat-curved cavity blue laser is shown in Fig. 6. It is clear that the beam was TEM00 mode and coincident with what we modeled in theory.

4. Conclusion

A simple design of LDA-end-pumped high-power intracavity doubling 473 nm blue laser in a flat-curved cavity is reported. The temperature of the LDA and the laser crystal are controlled by TEC. By considering the thermal-lensing

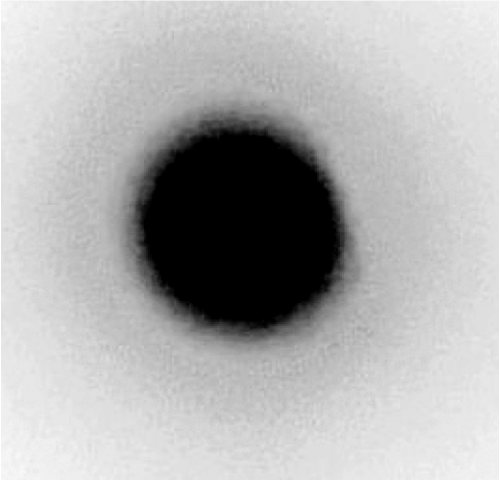

Fig. 6. Beam shape of phase-matching I LBO 473 nm blue laser.

effect in laser crystal, the mode match and efficient intracavity doubling are achieved at the same time in high-power flat-curved cavity blue laser. The maximum output power of 473 nm blue laser is 600 mW when the pump power is 15 W. The optical-to-optical conversion efficiency is 4%. The stability of blue output power is 3.2% within 2 h. The laser is simple in structure, and high in stability. So it is in favor of the realization of high-power 473 nm blue laser products.

Acknowledgements

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