Diode-end-pumped passively Q-switched blue laser with Nd:YAG/YAG/Cr⁴⁺:YAG/YAG composite crystal

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Abstract

For obtaining efficient passively Q-switched laser at 473 nm, an Nd:YAG/YAG/Cr⁴⁺:YAG/YAG composite crystal and a coupled cavity were employed to reduce the thermal lens effect and enable the laser system operating on high pumped power. In our experiment, the maximum average output power of 0.81 W was obtained with the repetition rate of 28.5 kHz and the pulse width of 104 ns at the pumped power of 9.79 W, corresponding to an optical-to-optical conversion efficiency of 8.27%.

Keywords

Solid-state; Diode-pumped laser; Passively Q-switched; Quasi-three-level laser

1. Introduction

Since it was demonstrated by Fan and Byer for the first time in 1987 [1], the diode-pumped quasi-three-level Nd:YAG laser at 946 nm and its frequency doubling laser at 473 nm have achieved great development. Though the laser at 946 nm not only operates with a very small stimulated emission cross section compared to that at 1.06 μm , but also suffers a significant reabsorption loss for the thermal population in the lower level at room temperature, the watt level 473 nm blue laser has been obtained successfully.

In 2006, Chen et al. had achieved a continuous wave (CW) 473 nm blue laser with a maximum average output power of 3.8 W by intracavity frequency doubling of a 946 nm Nd:YAG laser with the LBO crystal [2]. In 2013, Deyra et al. reported an actively Q-switched (AQ) Nd:YAG laser at 473 nm, whose average output power reached 3W [3]. However, all these are CW or AQ lasers. In contrast, the average output power of passively Q-switched 473 nm laser is relatively low [4, 5]. This is because the saturable absorber in the passively Q-switched laser system would introduce an extra loss and aggravate the thermal lens effect.

To accelerate the heat transferring and reduce the thermal lens effect, the un-doped YAG crystals were bonded to each end face of the gain medium (Nd:YAG), which have been used in the laser in many previous researches [2, 6, 7]. Besides, Nd:YAG crystal, Cr^{4+} :YAG and un-doped YAG crystal also can be bonded together for a compact design and achieving multi-functions. This kind of composite crystal has already been used to set up the laser system at 1064 nm, 532 nm and 266 nm [8-11]. Those above have demonstrated that the composite crystals have an excellent performance of optimizing the laser system. On the other side, an appropriate cavity design also can compensate the thermal lens and make the laser system working stably at the high pumped power. Moreover, as there is a blue region absorption band (400 nm - 500 nm) of Cr^{4+} :YAG crystal, it will make a great loss of 473 nm blue laser while travelling through the Cr^{4+} :YAG crystal. Thus, preventing the 473 nm blue laser from passing through the Cr^{4+} :YAG crystal by inserting a mirror with a suitable coating would make a great sense to improve the output laser.

In this paper, an Nd:YAG/YAG/Cr⁴⁺:YAG/YAG composite crystal and a coupled cavity were used to realize a passively Q-switched 473 nm blue laser. The maximum average output power of 0.81 W was obtained with the repetition rate of 28.5 kHz and the pulse width of 104 ns at the pumped power of 9.79 W, corresponding to an optical-to-optical conversion efficiency of 8.27%.

2. Experimental Setup

Firstly, the focal lengths of thermal lens of the Nd:YAG/YAG/Cr⁴⁺:YAG/YAG composite crystal were measured and shown in Fig. 1. When the pumped power increased from 4.4 W to 9 W, the focal length decreased from 188 mm to 51 mm. The absolute value of the slope is ~30. That means, even the un-doped YAG crystals were added for accelerating the heat transferring, the focal length of thermal lens was still sensitive to the pumped power. This is very unfavorable for the system operating. Thus, the compensation of thermal lens effect must be considered during the designing of cavity configuration.

Fig. 1. The focal lengths of thermal lens in an Nd:YAG/YAG/Cr⁴⁺:YAG/YAG composite crystal with respect to the pumped power.

The experimental arrangement is shown in Fig. 2. The composite laser crystal with a total length of 12.5 mm comprises a 1.0 at. % Nd³⁺-doped Nd:YAG crystal, a Cr⁴⁺:YAG crystal

with an initial transmission of 95% and two un-doped YAG crystals. The dimensions of Nd:YAG, Cr⁴⁺:YAG and the YAG are 4×4×8 mm³, 4×4×0.5 mm³ and 4×4×2 mm³ respectively. Since the absorption of pumped light on the Cr⁴⁺:YAG was more serious than that on Nd:YAG, the two un-doped YAG crystals were bonded to each faces of the Cr⁴⁺:YAG crystal for better heat transferring. Moreover, the composite crystal was wrapped with the indium foil and kept stationary in a copper block and its temperature was maintained at 12 °C. The two end faces of the composite crystal are HT coated at 808 nm (98.2%) and 946 nm (99.5%). The pumped source was a fiber-coupled laser diode (LD) at 808 nm with a core diameter of 100 μm and the N. A. of 0.22. A 1:3 imaging lens system was used to reimage the pumped beam into the laser crystal. The input plane mirror M1 was high reflective (HR) coated at 946 nm (R>99.5%) and high transmitting (HT) coated at 808 nm (T=98%), 1064 nm (T=98%) and 1341 nm (T=98%). The plane-concave output coupler M3 with the radius of curvature of 150 mm, which can compensate the thermal lens and make a smaller beam focused to the LBO crystal. It was HR coated at 946 nm (R=99.5%), HT coated at 1064 nm (T=98%) and 1341 nm (T=98%), and anti-reflective (AR) coated at 473 nm (T=99.5%). Besides, owing to the small walk-off angle and the wide spectral and angular acceptance bandwidths, a type I phase matching ($\theta = 90^\circ$, $\phi = 19.4^\circ$) LBO crystal with the size of 3×3×10 mm³ was taken as the nonlinear crystal for frequency doubling at 473 nm. It was HT coated at 946 nm and 473 nm and maintained the temperature at 20 °C by using a TEC cooling temperature control system.

Fig. 2. Schematic of the passively Q-switched 473 nm laser system.

Furthermore, with HR coating of 473 nm and HT coating of 946 nm, the plane mirror M2 between the composite crystal and LBO crystal could prevent the 473 nm blue laser from entering the composite crystal. That would help to improve the output performance without too many losses. The distance from M1 to the end side of composite crystal (L1) was approximately 14 mm. The distance from the end side of composite crystal to the output coupler M3 (L2) was set to be adjustable.

Based on the ABCD matrix theory, the stability parameters of the resonant cavity with a variation of L2 (the distance from the end side of composite crystal to the output coupler M3) were calculated while the focal length of thermal lens equaled 50 mm and L1 (distance from M1 to the end side of composite crystal) was set to be 14 mm, which shown as Fig. 3 (a). The calculation result indicated that there were two stable regions (20 mm - 45 mm and 140 mm – 198 mm) when L2 changed from 20 mm to 200 mm. In Fig. 3 (b) and 3 (c), the value of L2 was set to be 30 mm and 160 mm which were in these two stable region respectively, and the stability parameters of these two resonant cavities were calculated with a variation of the focal lengths of thermal lens in a range from 0 mm to 275 mm, including the range we measured (51 mm - 188 mm). As we can see that if using a short cavity structure, the cavity becomes unstable when the focal length of thermal lens was shorter than 30 mm, shown in Fig. 3 (b). On the contrary, if

using a long cavity structure, the cavity becomes unstable until the focal length of thermal lens is longer than 160 mm, shown in Fig. 3 (c). Since the focal length of the thermal lens decreases with the increasing power, employing a long cavity structure helps the passively Q-switched system to stably operate at high pumped power. In view of that mentioned above, we set L2 to be 161 mm and the total length of the cavity was 175 mm approximately. A graphic model of the laser beam radius in the experimental cavity is depicted in Fig. 4.

Fig. 3. The stability parameters of a resonant cavity with a variation of L2 while the focal length of thermal lens equaled 50 mm (a). The stability parameters of a resonant cavity while L2 was set to be 30 mm (b) and a resonant cavity while L2 was set to be 160 mm (c) with a variation of the focal lengths of thermal lens respectively.

Fig. 4. The laser beam radius inside the cavity in the longitudinal direction while the focal length of thermal lens was set to be 50 mm

3. Result and analysis

As shown in Fig. 5, the average output power of the laser at 473 nm is positive correlated with the pumped power. At the pumped power of 9.79 W, a maximum average output power of 0.81 W was obtained, corresponding to an optical-to-optical

conversion efficiency of 8.27%. This benefited much from the plane mirror M2, which was inserted to prevent the 473 nm laser passing through the composite crystal and improved the output performance. When the mirror M2 was taken away, there was no output laser detected because of serious losses. Nevertheless, the average output power was not of good linearity. This is because the emission cross-section of Nd:YAG at 946 nm is relative small and the output performance is very sensitive to the cavity parameters. Thus, when the focal length of the thermal lens changes with the increasing pumped power, the output performance changes with it.

Fig. 5. Average output power of the passively Q-switched 473 nm laser versus the pumped power.

Fig.6. Pulse width and repetition rate of the 473 nm laser, with respect to the pumped power.

According to Fig. 6, the pulse repetition rate increases significantly with increasing the pumped power and reaches approximately 28.6 kHz at the pumped power of 9.79 W, and the pulse width fluctuates in a relatively large range around 100 ns varied with the pumped power. Fig. 7 shows a train of the 473 nm output laser pulses and a single pulse profile with the width of 103.9 ns at a pumped power of 9.79 W. However, there is an unavoidable variation of output pulses in the system, which disturb the precise measurements of repetition rate and pulse width.

Fig. 7. A train of the 473 nm output laser pulses (a) and pulse profile with the width of 103.9 ns (b) at a pumped power of 9.79 W.

Possible reasons for these variation were analyzed as follows. First, because the temperature fluctuation is unavoidable, the focal length of the thermal lens cannot be kept stable at a certain pumped power. When the thermal lens changed, the size of pumped light spot on the saturable absorber changed. It means the system needs different time to bleach the saturable absorber as well, which would lead to different pulse widths and repetition rates [12]. Second, since the spot size of the pumped laser in the composite laser rod is larger than that of fundamental laser, it tended to multi-modes operation at high pump power. The competition between the fundamental mode and high transverse mode might lead to fluctuation of output power at high pumped power [13]. Though these instabilities are unavoidable as instincts of passively Q-switched system, we can reduce the pulse fluctuations effectively by using a suitable cavity structure and maintaining the laser system operation in the fundamental mode. In addition, improving the precision of temperature control system is also helpful.

Pulse width mainly depends on the property of the gain medium, the initial transmission of the saturable absorber and the round-trip time of the cavity [14]. Thus, the pulse width reaches ~100 ns in our experiment due to the relative long cavity structure and long round-trip time. A lower initial transmission of the saturable absorber

can narrow the pulse width. However, lower initial transmission of the saturable absorber means higher losses for the laser system and harder to generate laser in a quasi-three-level system. In general, the balance between the pulse width and the losses is an important issue that should be investigated for the further study.

4. Conclusion

By using a composite crystal to accelerate the heat transferring, sandwiching the plane mirror M2 in the cavity to reduce the losses of blue laser and employing a relative long cavity structure to enable the system operating at high pumped power, an efficient passively Q-switched blue laser at 473 nm was realized. Under a pumped power of 9.79 W, a maximum average output power of 0.81 W was obtained with the repetition rate of 28.5 kHz and the pulse width of 104 ns, corresponding to an optical-to-optical conversion efficiency of 8.27%.

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