Efficient corner-pumped Nd:YAG/YAG composite slab laser*

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(Received 21 September 2009; revised manuscript received 18 November 2009)

A corner-pumped type is a new pumping type in the diode-pumped all-solid-state lasers, which has the advantages of high pump efficiency and favourable pump uniformity. A highly efficient corner-pumped Nd:YAG/YAG composite slab laser is demonstrated in this paper. The maximal continuous-wave output power of the 1064 nm laser is up to 18.57 W with a slope efficiency and an optical-to-optical conversion efficiency of 44.9% and 39.8%, respectively. Inserting an acousto-optic Q-switch in the cavity, the highest average output power of the quasi-continuous wave 1064 nm laser of 6.73 W is obtained at a repetition rate of 9.26 kHz. The experimental results show that a corner-pumped type is a kind of feasible schedules in the design of diode-pumped all-solid-state lasers with low or medium output powers.

Keywords: corner-pumped, Nd:YAG crystal, continuous wave, acousto-optic Q-switch
PACC: 4260B, 4260D, 4260F

1. Introduction

Laser-diode-pumped all-solid-state lasers are applied in a variety of fields, due to their merits: high efficiency, long life-span, high stability, small volume and high beam quality. With the development of the semiconductor laser technologies, the performances of the single laser diode and laser diode array are greatly improved, which make all-solid-state lasers stand on the leading position in many fields, such as industrial field, military field, space field and so on. Since the 1990s, laser-diode-pumped slab lasers have been the study focus in the world, which are considered as one of the most efficient approaches to generating the lasers with high output powers and high beam qualities.[1−5] In the recent years, based on the traditional slab lasers, the researchers have developed some novel slab lasers.[6−8]

A corner-pumped type is a new diode-pumped type for slab lasers, which was first presented by our research group.[8,9] The principle of the corner-pumped method is simple and practical. The slab is chamfered at one corner; therefore, one plane at the corner is formed, from which the pump light is coupled into the slab. The multi-pass absorption is realized by the total internal reflection of the pump light in the slab, which enhances the absorption path and benefits the extraction of the energy of the pump light. The corner-pumped method can offer a simple pump structure, high pump efficiency and uniformly high pump power density. Furthermore, combined with the thermal-bonding technique, a composite slab with centre doped and two sides undoped may result in higher pump power density, better pump uniformity and mode matching because the absorption region of the pump light is confined in the central area of the slab.

A corner-pumped method for high-power quasi-three-level lasers has been reported in the recent years.[9−12] We have realized continuous-wave (CW) operation with 1 kW output power and 42.8% slope efficiency from a corner-pumped composite Yb:YAG/YAG slab laser.[10] However, its disadvantages are obvious, such as low beam quality, serious astigmatism and difficulties in generating the fundamental mode output, which limit its application fields. At present, all-solid-state lasers with low or medium output powers have broader application prospects. The diode-end-pumped Nd:YAG/Nd:YVO_4 lasers have made great progress, whose advantages include high beam quality and high conversion efficiency.[13−16] However, their disadvantages are the high cost and the difficulty in enhancing the output power. The recent reports on diode-side-pumped Nd:YAG lasers are also familiar.[17−19] The primary merits of the lasers are

*Project supported by the Postdoctoral Science Foundation, China (Grant No 20090450370).
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easiness to generate high output powers, and their demerits are low conversion efficiencies, high costs, and inferior beam qualities. The corner-pumped type, as a new diode-pumped type, has not only the merits that the end-pumped type possesses, but also the merits that the side-pumped type possesses. Therefore, it is very important to carry out the study of high efficient all-solid-state lasers with low or medium output powers by using the corner-pumped method.

Nd:YAG and Nd:YVO_4 crystals are popularly used in the all-solid-state lasers.[20,21] The merits of Nd:YAG crystals are good thermo mechanical performances. The merits of Nd:YVO_4 crystals are large efficient stimulated emitting cross sections and polarized outputs, which can remove the effects resulting from the thermo birefringence. As for the corner-pumped type, the doping content and efficient stimulated emitting cross section of the laser crystal can be permitted to be relatively low because of the long absorption path. Compared with Nd:YVO_4 crystals, Nd:YAG crystals, as the laser media, are more appropriate in the all-solid-state lasers with low or medium output powers with employing the corner-pumped method.

2. Corner-pumped Nd:YAG/YAG composite slab CW 1064 nm laser

2.1. Experimental setup

First, a corner-pumped Nd:YAG/YAG composite slab CW laser emitted at 1064 nm is studied. A simple linear two-mirror cavity configuration used in the experiment is shown in Fig. 1.

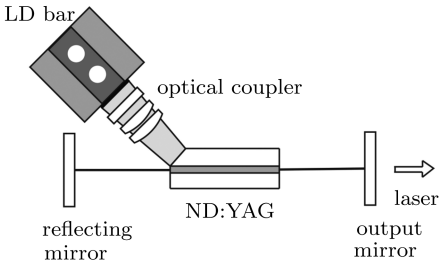


Fig. 1. Experimental setup of a corner-pumped CW Nd:YAG/YAG slab 1064 nm laser.

The detailed size of the composite slab is illustrated in Fig. 2. The slab is of a diffusion-bonded composite crystal of undoped YAG and 1.0 at.% Nd:YAG. The Nd:YAG crystal is 1 mm in thickness, 1 mm in width, and 17 mm in length. Two pieces of 1 mm×3.5 mm×17 mm undoped YAG are thermally bonded to each face (1 mm×17 mm) of Nd:YAG crystal. After bonding, the slab is polished and one corner of the slab is chamfered with a chamfered angle of 45°, thereby forming a 5 mm×1 mm face, through which the pump light is incident into the slab. In the corner-pumped configuration, bonding at the two edges is necessary to produce a higher pump efficiency. In a nonbonded slab, about 50% of pump light is wasted on the two edges, because energy stored in the edges cannot be extracted, whereas there is no such loss in the dual-edge bonded slab.

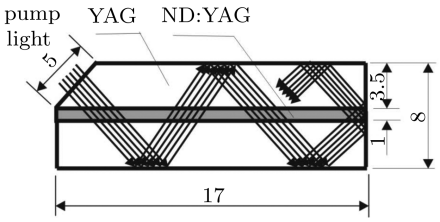


Fig. 2. Pump light (simplified into a plane wave) transmission in the composite slab fulfilling the total internal reflection condition and maximum absorption efficiency.

The cavity length is 22 mm. A LD bar with a maximum 808 nm output power of 50 W is used in the experiment. The light-emitting area of the LD bar is 10 mm×0.7 mm with a certain angle of divergence. The optical coupler system is employed to shape the pump light. The reflecting coupler is a plane mirror with a high reflectivity coating at 1064 nm ($R > 99\%$) and the output coupler is also a plane mirror with a partial transmission at 1064 nm ($T = 30\%$). In order to obtain a high output power, the cavity length should be as short as possible for reducing the strong thermal effect under a high pumping power condition.

2.2. Experimental results

The curve for the output power versus pumping power is shown in Fig. 3. A highest output power is obtained to be 18.57 W with a slope efficiency of 44.9% and an optical-to-optical conversion efficiency of 39.8%. As is known from Fig. 3, the output power is not saturated with the increase of the pumping power. If we continue to increase the pumping power, it is possible to obtain a higher output power and a higher conversion efficiency. The short-term instability of the output power at a pumping power of 45.2 W is measured and the result is shown in Fig. 4. We record an

output power every one minute, and in a time period of fifteen minutes, the instability of the output power can be obtained from the following formula:

$$\Delta P/\overline{P} = \sqrt{\frac{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^2}{n-1}} \cdot \frac{1}{\overline{P}} \approx 0.38\%, \ (n = 15). \quad (1)$$

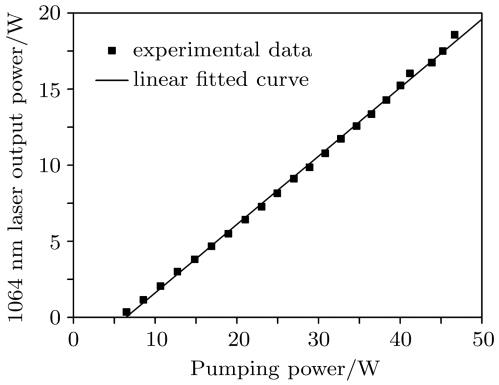


Fig. 3. Output power of CW 1064 nm laser versus pumping power.

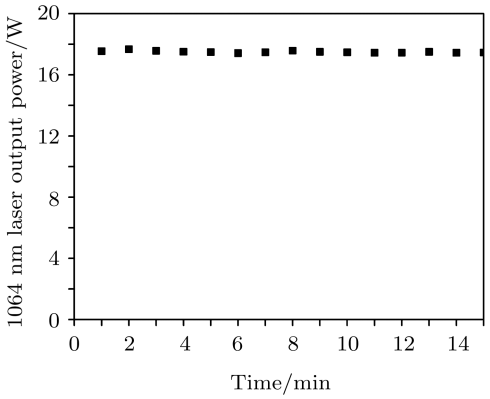


Fig. 4. Short-term instability of 1064 nm laser output power at a pumping power of 45.2 W.

The measured result indicates that the output power of the CW 1064 nm laser is very stable.

The beam quality factor M^2 is measured by a Spiricon M^2-200 beam propagation analyzer. Figure 5 shows the propagation behaviour of the output beam at an output power of 17.5 W, and the measured beam propagation factors are $M_x^2 = 10.18$, and $M_y^2 = 2.75$. The far-field output beam facula is shown in Fig. 6. Because the simple linear short cavity is employed, the laser operates with a multi-mode output at high pumping powers and the corresponding output beam quality is not favourable. In the y direction, which is the direction of the slab thickness, the thermal-lens effect is reduced with the decrease of the pumping power and the beam quality becomes better and better. Table 1 shows the measured beam propagation factors at different output powers.

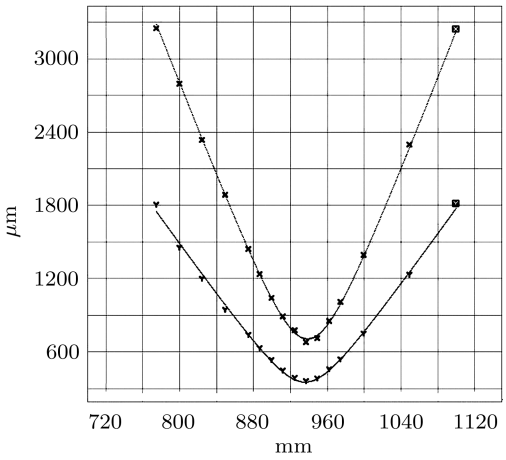


Fig. 5. Propagation behaviour of output beam at an output power of 17.5 W.

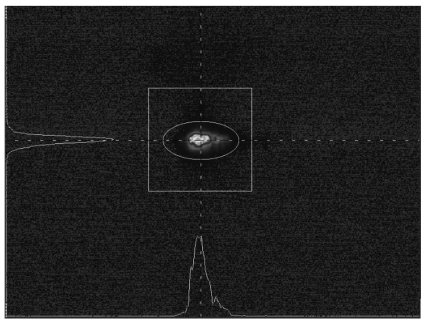


Fig. 6. Far-field output beam facula.

Table 1. Beam propagation factors at different output powers.

pumping current/A	output power/W	M_x^2	M_y^2
58	17.5	10.18	2.75
50	14.28	7.71	2.44
40	9.86	3.89	2.22
30	5.49	4.04	1.71

In order to suppress the generation of high-order modes of the 1064 nm laser at high pumping powers, we extend the cavity length to 110 mm. Figure 7 shows the relation between the pumping power and the output power. When the pumping power is up to 46.6 W, the output power goes up to 13.06 W with a slope efficiency being 39.7% and an optical-to-optical conversion efficiency being 28%. The beam quality M^2 factors are measured at different output powers, and the results are shown in Table 2. At an output power of 9.64 W, the beam quality M^2 factors are $M_x^2 = 2.69$, $M_y^2 = 1.6$, and the corresponding beam propagation behaviour is shown in Fig. 8. With the decrease of the pumping power, the 1064 nm laser

beam quality becomes better and better. In the y direction, the laser can remain the fundamental mode output.

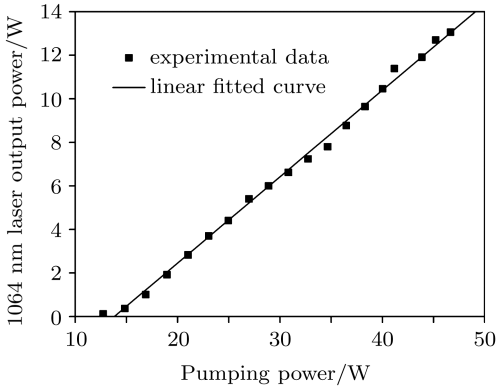


Fig. 7. Output power of CW 1064 nm laser versus pumping power.

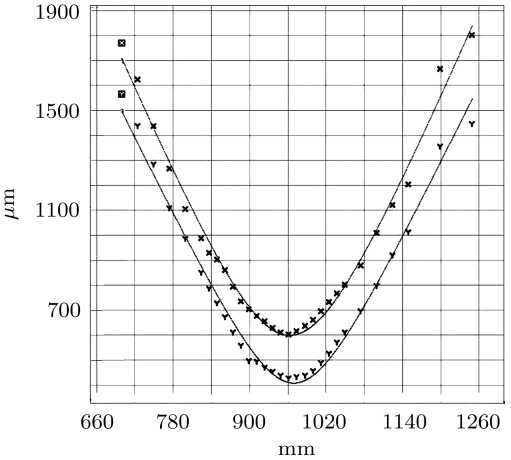


Fig. 8. Propagation behaviours of output beam at an output power of 9.64 W.

Table 2. Beam propagation factors at different output powers.

pumping current/A	output power/W	M_x^2	M_y^2
50A	9.64 W	2.69	1.6
40A	6 W	2.3	1.51
30A	1.92 W	1.97	1.19

3. Corner-pumped Nd:YAG/YAG composite slab acousto-optic (AO) Q-switch 1064 nm laser

In order to increase the peak power of the 1064 nm laser, we insert an AO Q-switch into the cavity. The AO Q-switch is driven at a 40 MHz working frequency with a 7.0 W electric power.

The cavity length is still 110 mm. Figure 9 shows the experimental layout of the corner-pumped Nd:YAG/YAG composite slab quasi-continuous wave (QCW) 1064 nm laser. The pumping source, the optical couplers, the Nd:YAG/YAG composite slab, the reflecting mirror and output mirror are not changed.

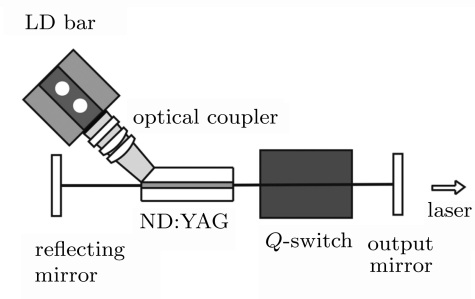


Fig. 9. Experimental setup of a corner-pumped QCW Nd:YAG/YAG slab 1064 nm laser.

Figure 10 shows the 1064 nm laser QCW output power as a function of pumping power at a repetition rate of 9.26 kHz. A maximum average output power of 6.73 W is obtained at a pumping power of 9 W. The corresponding optical-to-optical conversion efficiency and the slope efficiency are 17.3% and 21%, respectively. When the average output power is 4.67 W, the pulse width is 14.90 ns and the peak power is high up to 33.8 kW. The pulse widths of the 1064 nm laser at different pumping powers are measured, and the measured results are shown in Fig. 11. With the increase of the pumping power, the pulse width of the 1064 nm laser decreases while its peak power increases step by step.

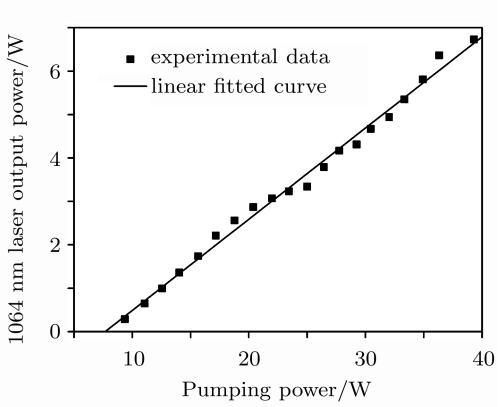


Fig. 10. Output power of QCW 1064 nm laser versus pumping power at a repetition rate of 9.26 kHz.

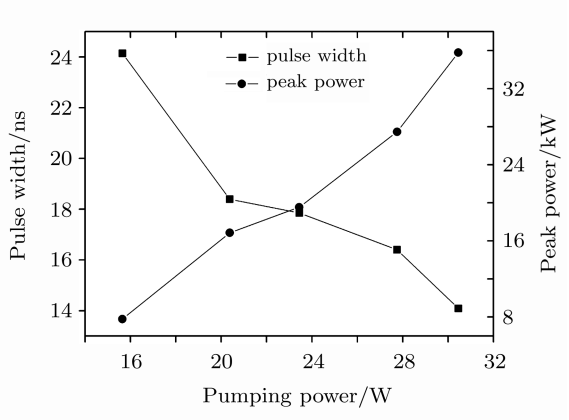


Fig. 11. Curves for pulse width and peak power versus pumping power.

4. Conclusion

In summary, a novel pumping method for the all-solid-state slab lasers with low or medium output powers is demonstrated. Compared with other pumping types, the corner-pumped type has unique merits not only for the high-average-power Yb:YAG/YAG slab lasers, but also for the Nd:YAG/YAG slab lasers with low or medium output powers. A highly efficient corner-pumped Nd:YAG/YAG composite slab CW 1064 nm laser is reported. The maximal output power is up to 18.57 W with a slope efficiency and an optical-to-optical conversion efficiency of 44.9% and 39.8%, respectively. The short-term instability of the output power at a pumping power of 45.2 W is less than 0.38%. Inserting an AO Q-switch into the cavity, a highest average output power of 6.73 W is obtained at a repetition rate of 9.26 kHz. At an average output power of 4.67 W, the pulse width and the peak power of 1064 nm laser are 14.90 ns and 33.8 kW, respectively. The above experimental results indicate that the corner-pumped type is a kind of feasible scheme in the design of diode-pumped all-solid-state lasers with low or medium output powers.

Next, we plan to adopt some useful ways for improving the laser system performances. First, a high-transmission coating at 808 nm will be coated on the incident corner face of the slab. Second, a cylindrical output coupler and a spherical high-reflector mirror will comprise a concave-plane resonator in the thickness direction and a concave-convex resonator in the width direction. The hybrid cavity will be employed to improve the output beam propagation quality. Third, the two or multi corners pumped Nd:YAG/YAG composite slab laser is under design, which has a better pump uniformity and higher pump efficiency. Finally, two or multi Nd:YAG/YAG composite slabs will be used and placed perpendicularly in the cavity so as to gain a higher output power and decrease a thermal-lens effect.

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