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High-power and high optical conversion efficiency diode-end-pumped laser with multi-segmented Nd:YAG/Nd:YVO_4*

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A novel flat–flat resonator consisting of two crystals (Nd:YAG + Nd:YVO_4) is established for power scaling in a diode-end-pumped solid-state laser. We systematically compare laser characteristics between multi-segmented (Nd:YAG + Nd:YVO_4) and conventional composite (Nd:YAG + Nd:YAG) crystals to demonstrate the feasibility of spectral line matching for output power scale-up in end-pumped lasers. A maximum continuous-wave output power of 79.2 W is reported at 1064 nm, with $M_x^2 = 4.82$, $M_y^2 = 5.48$, and a pumping power of 136 W in the multi-segmented crystals (Nd:YAG + Nd:YVO_4). Compared to conventional composite crystals (Nd:YAG + Nd:YAG), the optical-optical conversion efficiency of multi-segmented crystals (Nd:YAG + Nd:YVO_4) from 808 nm to 1064 nm is enhanced from 30% to 58.8%, while the laser output sensitivity as affected by the diode-laser temperature is reduced from 55% to 9%.

Keywords: diode-pumped solid-state laser, multi-segmented crystals (Nd:YAG + Nd:YVO_4), spectral line matching, diode-laser temperature

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1. Introduction

The diode end-pumped solid-state laser (DPSSL) features high efficiency, compact structure, and good beam quality. It is commonly utilized in industrial, medical, information, and military fields.[1–7] Optical efficiency is a key factor in any DPSSL. Generally speaking, there are two main conditions for scaling DPSSL efficiency, i.e., a laser gain material that is able to sustain high pump power while exhibiting high gain and a limited thermal lensing effect,[8,9] and a pump scheme with excellent overlap between the pump emission spectrum and laser gain material absorption spectrum.[10,11]

Nd:YAG crystal is generally considered to be the optimal choice for the high power pumped laser-diode (LD) due to its favorable thermal, optical, and mechanical properties. Kracht *et al.*[12] obtained a continuous-wave (CW) output power of 407 W with an optical conversion efficiency of 54% under a maximum pump power of 750 W in an end-pumped composite rod Nd:YAG laser. Nd:YAG has a narrow absorption bandwidth, while LD has a broad emission linewidth. The mismatch between them renders the Nd:YAG unable to completely absorb the excess power of LD. Nd:YVO_4 material comes with significant advantages compared to Nd:YAG crystal including high gain, broad absorption bandwidth around 808 nm, and a large stimulated emission cross section. In 2008, Li *el al.* obtained a 13.3 W CW output and an optical conversion efficiency of 57.8% under 23 W pump power using a grown-together YVO_4/Nd:YVO_4 composite rod.[13] Unfortunately, the relatively poor thermal and mechanical characteristics of Nd:YVO_4 restrict pump and laser power, degrade the beam quality, and may damage the crystal.[14,15]

In this study, we built a novel multi-segmented crystals system consisting of two parts: Nd:YAG and Nd:YVO_4. In the laser resonant cavity, a segment of Nd:YVO_4 crystal is placed at the end of the Nd:YAG. During the pumping process, Nd:YAG absorbs all of the pump energy coinciding with its absorption spectrum. The remaining pump energy beyond the said Nd:YAG absorption spectrum can be absorbed completely by Nd:YVO_4. The two crystals can be perfectly matched around the pump wavelength of 808 nm, which can greatly improve the laser efficiency compared to the setups described above. We also built a compact linear cavity for comparison against multi-segmented (Nd:YAG + Nd:YVO_4) and conventional composite (Nd:YAG + Nd:YAG) crystals in regards to the laser performance during CW operation and the sensibility to diode temperature. Our results show that the laser with multi-segmented crystals outperforms the conventional composite crystals. The former system also maintains a high optical conversion efficiency due to the close overlap between the LD emission spectrum and the absorption spectrum of the laser gain material.

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2. Materials and methods

2.1. Theoretical background

The matching degree between the crystal absorption spectra and LD emission line is the key to improving the optical conversion efficiency. Table 1 shows the optical parameters among Nd:YAG, Nd:YVO_4, and LD.[16] The absorption peak of Nd:YAG is 808.3 nm and its absorption bandwidth (10 dB level) is only 2.5 nm. For the high power coupling fiber LD (DILAS 240 W), however, the emission linewidth (10 dB level) at 808 nm is 8 nm. This wavelength mismatch prevents a large amount of pump power from being absorbed. Nd:YVO_4 has a broader absorption line (10 dB level), about 15.7 nm at 808 nm, which far exceeds the LD's emission linewidth.

Table 1 also shows the emission lines of Nd:YVO_4 and Nd:YAG overlapping at 1064 nm. The central emission peak of Nd:YVO_4 is at 1064.3 nm and the linewidth is 0.8 nm, while the central emission peak of Nd:YAG is 1064.4 nm and linewidth is 0.45 nm. The two crystals can be perfectly matched around the pump wavelength of 808 nm and converted to the desired laser at a common wavelength.

Table 2 shows the thermal properties of Nd:YVO_4 and Nd:YAG. Nd:YVO_4 has only half the thermal conductivity of Nd:YAG, which makes the latter generally well-suited to high LD power end-pumped experiments. However, due to its narrow spectrum, Nd:YAG cannot fully absorb the given pump power and leads to poor optical conversion efficiency. To broaden the absorption spectrum and enhance the thermal properties of the system, we placed a Nd:YVO_4 crystal at the rear of the Nd:YAG to absorb the excess pump power. Combining the advantages of these two crystals markedly improved the efficiency of the laser, as discussed in detail below.

Table 1. Optical parameters of Nd:YAG, Nd:YVO_4, and LD.

Property	Nd:YAG	Nd:YVO_4	LD
Peak absorption wavelength/nm	808.3	808.5	–
Absorption bandwidth (10 dB level)/nm	2.5	15.7	–
Central emission wavelength/nm	1064.4	1064.3	808
Emission linewidth (10 dB level)/nm	0.45	0.8	8

Table 2. Thermal properties of Nd:YAG and Nd:YVO_4.

Property	Nd:YAG (300 K)	Nd:YVO_4 (300 K)
Thermal conductivity/$W\cdot m^{-1}\cdot K^{-1}$	14	$\parallel c$-axis: 5.23 $\perp c$-axis: 5.10
Thermal expansion/10^{-6} K^{-1}	7.5	$a_{a-\mathrm{axis}} = 4.43$ $a_{c-\mathrm{axis}} = 11.37$
Thermal optical coefficient/K^{-1}	$\mathrm{d}n_o/\mathrm{d}T = 7.3\times10^{-6}$	$\mathrm{d}n_o/\mathrm{d}T = 8.5\times10^{-6}$ $\mathrm{d}n_e/\mathrm{d}T = 2.9\times10^{-6}$

2.2. Experimental setup

The experimental setup we used to compare the laser performance of multi-segmented and conventional composite crystals is shown in Fig. 1(a). We prepared three types of laser gain materials as sketched in Figs. 1(b)–1(d); the crystal rods used in these experiments are detailed in Table 3. The Nd:YVO_4 was cut along the *a* axis.

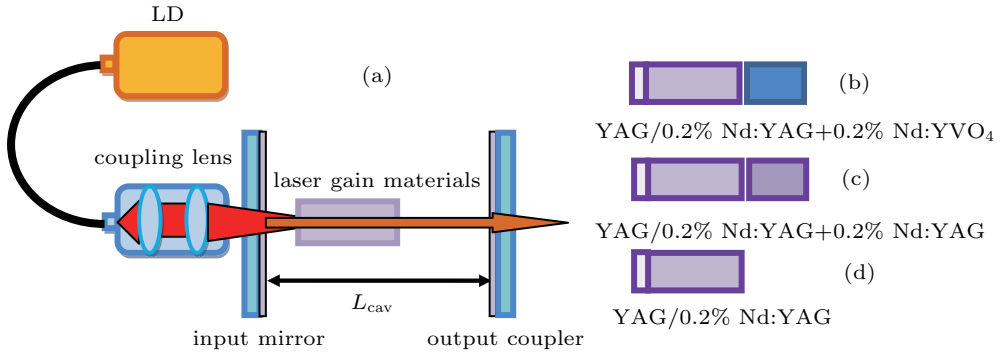


Fig. 1. (a) Comparison between multi-segmented and conventional composite crystals; schematic configurations for (b) YAG/0.2% Nd:YAG + 0.2% Nd:YVO_4, (c) YAG/0.2% + 0.2% Nd:YAG, and (d) YAG/0.2% Nd:YAG crystals.

Table 3. Crystal rods used in experiments.

Crystal rods	Total dimensions /mm×mm×mm	Undoped rod length/mm	Nd^{3+}(Nd:YAG) concentration/at.%	Nd^{3+}(Nd:YVO_4) concentration/at.%	Distance/mm
YAG/Nd:YAG + Nd:YVO_4	3×3×42 + 3×3×16	2	0.2	0.2	1
YAG/Nd:YAG + Nd:YAG	3×3×42 + 3×3×16	2	0.2 + 0.2	–	1
YAG/Nd:YAG	3×3×42	2	0.2	–	–

We built a 180-mm long laser cavity using two plano-plano mirrors. The flat input mirror was coated for high transmission at 808 nm on the pump surface, anti-reflection coated at 808 nm, and high reflection coated at 1064 nm on the other surface. A flat mirror with a transmissivity of 35% at 1064 nm was served as the output coupler. A fiber-coupled LD (DILAS Inc.) with center wavelength at 808 nm was used as the pumping source, which has a top-hat intensity distribution and emission linewidth of 8 nm. The fiber we used had a numerical aperture of 0.22 μm and core diameter of 400 μm. The LD pump light imaged a spot 1.8 mm in diameter into the crystal rod through two convex lenses with a coupling efficiency of 95%. All laser crystals were wrapped with indium foil and mounted in water-cooled copper heat sinks at 18 °C.

2.3. Measurement setup

Several diagnostic instruments were set up to measure various parameters throughout the experiment as illustrated in Fig. 2. The output beam from the laser was first separated from the transmitted pump beam by a dichroic mirror highly reflective for 1064 nm laser light and highly transmissive for 808 nm pump light. The 1064 nm laser light was then reflected off a 98% partial reflector on a power meter, which measured the average output power of the laser. The transmitted 2% 1064 nm light was reflected off a 98% partial reflector and relayed to a beam characterization (M^2 measurement) device (Thorlabs).

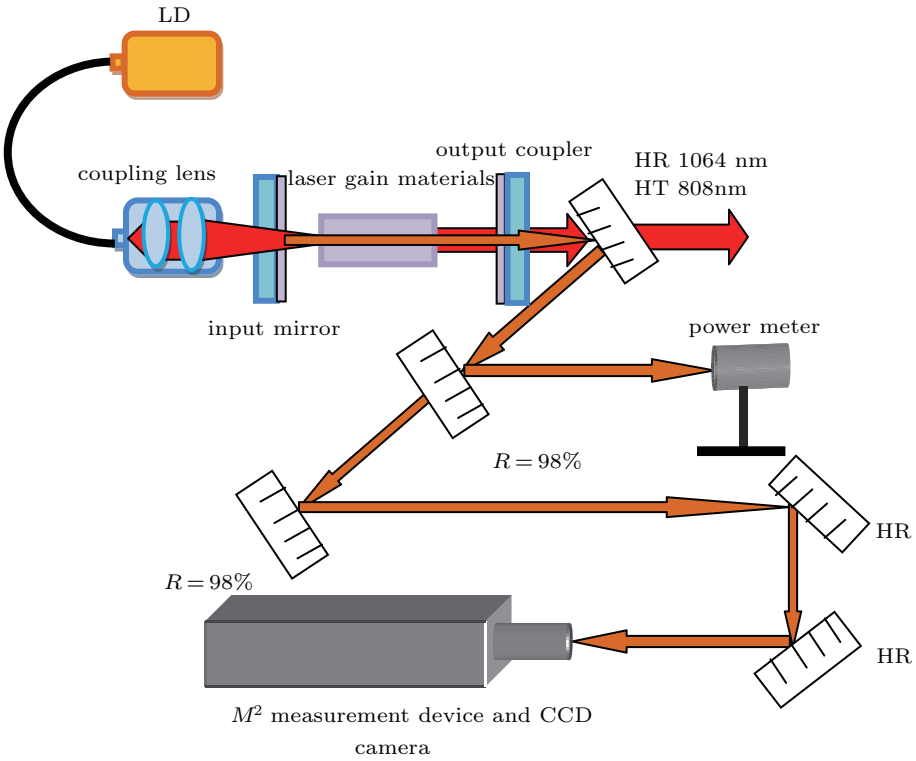


Fig. 2. Diagnostic setup.

3. Experimental results and discussion

Figure 3 shows the dependence of output power at 1064 nm on incident pump power at 808 nm for different laser crystals. The maximum output power was 43.6 W for the YAG/0.2% Nd:YAG crystal under an incident pump power of 126.2 W, corresponding to an optical conversion efficiency of 34.5%. The conventional composite crystals, when another gain medium of the same doping concentration (0.2% Nd:YAG) was placed behind YAG/0.2% Nd:YAG, yielded an output power almost equal to that of the single crystal (YAG/0.2% Nd:YAG). This is because the pump power inside the Nd:YAG absorption bandwidth was completely absorbed by the first crystal (YAG/0.2% Nd:YAG), so no more pump power could be absorbed by the rear crystal (0.2% Nd:YAG). For the multi-segmented crystals (YAG/0.2% Nd:YAG + 0.2% Nd:YVO_4), the maximum output power reached 79.2 W under an incident pump power of 136 W. The corresponding optical conversion efficiency obtained with this novel multi-segmented crystal was significantly enhanced to 58.2%. Our results altogether indicate that a Nd:YVO_4 crystal placed at the end of Nd:YAG indeed has a high optical conversion efficiency. Due to the broad absorption bandwidth, Nd:YVO_4 can absorb the remaining power beyond the Nd:YAG absorption bandwidth to markedly enhance the laser optical conversion efficiency.

Table 4 shows the M_x^2 (beam quality factor along the x-axis) and M_y^2 (beam quality factor along the y-axis) for each test case under an identical output power of 38.6 W. The laser beam quality, as mentioned above, was measured with an automatic beam characterization device (Thorlabs), and the results and the 2-D laser intensity distributions are shown in Fig. 4. The M_x^2 (M_y^2) values of Nd:YAG (0.2%) + Nd:YAG (0.2%) and Nd:YAG (0.2%) + Nd:YVO_4 (0.2%) were 3.73 (4.21) and 2.22 (2.45), respectively. In other words, the beam quality of the Nd:YAG (0.2%) + Nd:YVO_4 (0.2%) multi-segmented crystals exceeded the others at the same output power.

Next we define the relationship between the output power and the LD temperature (22 °C to 32 °C) for different laser crystals, as shown in Fig. 5(a). Figure 5(b) shows the volatility rate of the output power versus LD temperature for different laser crystals. The output performance obtained from the YAG/0.2% Nd:YAG + 0.2% Nd:YVO_4 crystals showed a broader temperature tolerance than YAG/0.2% Nd:YAG + 0.2% Nd:YAG crystals; the maximum volatilities were 9% and 55% for the YAG/0.2% Nd:YAG + 0.2% Nd:YVO_4 and YAG/0.2% Nd:YAG + 0.2% Nd:YAG crystals, respectively.

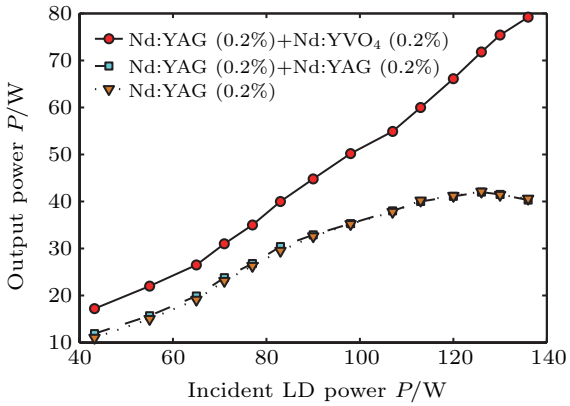


Fig. 3. Output power with respect to incident LD power for different laser crystals.

Table 4. M^2 at output power of 38.6 W.

	Nd:YAG (0.2%)	Nd:YAG (0.2%) + Nd:YAG (0.2%)	Nd:YAG (0.2%) + Nd:YVO_4 (0.2%)
M_x^2	3.93	3.73	2.22
M_y^2	4.45	4.21	2.45

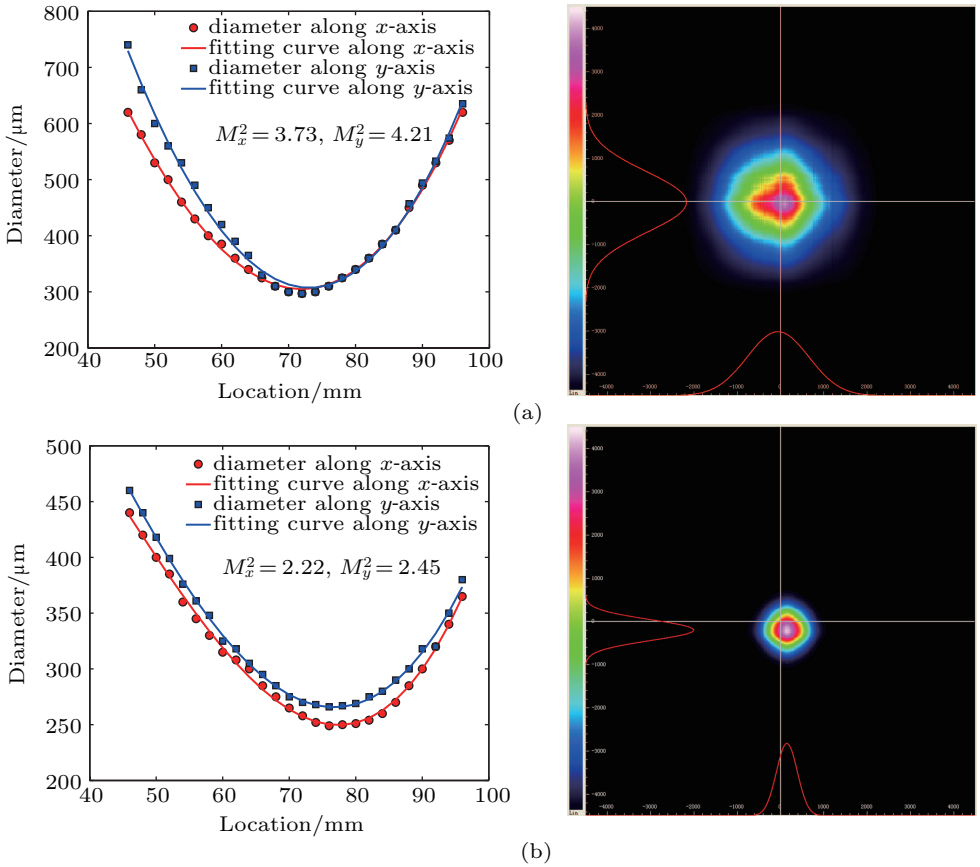


Fig. 4. M^2 in (a) conventional composite crystals (Nd:YAG (0.2%) + Nd:YAG (0.2%), and (b) multi-segmented crystals (Nd:YAG (0.2%) + Nd:YVO_4 (0.2%)).

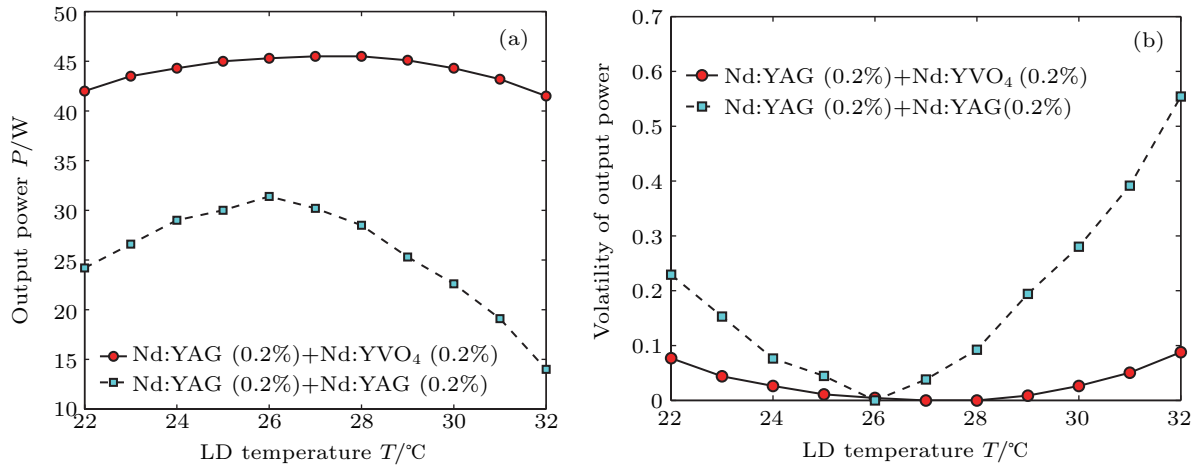


Fig. 5. (color online) (a) Output power and (b) volatility rate versus LD temperature for different laser crystals.

Table 5. Characteristics of output at incident LD power of 136 W.

	Nd:YAG (0.2%)	Nd:YAG (0.2%) +Nd:YAG (0.2%)	Nd:YAG (0.2%) +Nd:YVO$_4$ (0.2%)
Maximum incident LD power P/W	136	136	136
Output power P/W	40.9	40.8	79.2
M_x^2	4.95	5.03	4.82
M_y^2	5.58	5.65	5.48
Optical efficiency	30%	30%	58.8%
Maximum output power volatility rate affected by LD temperature	–	55%	9%

Table 5 shows the output performance at an incident LD power of 136 W for different laser systems. Our results altogether indicate that the multi-segmented crystals (YAG/0.2% Nd:YAG + 0.2% Nd:YVO$_4$) can be used to establish a reliable, efficient, and high-power diode-end-pumped laser system.

4. Conclusion

The laser properties of multiple segments with different crystals (YAG/0.2% Nd:YAG + 0.2% Nd:YVO$_4$) under LD direct pumping were investigated in this study. By comparison against a conventional system, we demonstrated the feasibility of multi-segmented crystals for power scaling in end-pumped solid-state lasers. The beam quality of multi-segmented crystals (YAG/0.2% Nd:YAG + 0.2% Nd:YVO$_4$) is better than the others at the same output power. We obtained a maximum continuous-wave output power of 79.2 W at 1064 nm, with $M_x^2 = 4.82$ and $M_y^2 = 5.48$ at a pumping power of 136 W, corresponding to an optical conversion efficiency of 58.8%. We also successfully reduced the laser output sensitivity as affected by diode-laser temperature from 55% to 9% using the proposed system compared to the conventional system.

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