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Ultrahigh-efficiency 4-J, 10-Hz, Nd:YAG quasi-continuous-wave active mirror oscillator

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Abstract We have demonstrated an ultrahigh-efficiency joule-class quasi-continuous-wave diode-pumped Nd:YAG active mirror oscillator that adopts a pumping scheme without any optical coupling elements and a direct cooling method. A maximum output energy of 4.1 J with the pulse width of 260 µs at the repetition rate of 10 Hz is obtained from a planar–planar cavity that contains four large-aperture slabs, corresponding to an optical-to-optical efficiency of 50.6 % and a slope efficiency of 61.1 %.

1 Introduction

Quasi-continuous-wave (QCW) solid-state lasers with high energy and high efficiency have played important and critical roles in manufacturing applications such as laser welding, laser cutting, and laser drilling [1–4], which requires the laser source with the pulse width of tens to hundreds of microseconds.

Considerable rod-based high-energy QCW solid-state lasers with the single-pulse energy of multi-joules have been well designed and realized. For example, Furuta et al. [5] reported a Nd:YAG rod master oscillator power amplifier (MOPA) system with a pulse energy of about 4 J and a pulse width of 400 µs. Yang et al. [6] demonstrated a diode-pumped Nd:YAG rod-based MOPA system with six amplifier stages, which delivered a pulse energy of 5.1 J with a pulse width of 230 µs and an optical-to-optical efficiency of 38.5 %. In recent years, high-energy QCW slab laser has drawn more and more attentions [7–10], since the power scaling capability of the rod laser is limited by severe thermal lens effects. Single-pulse energy of 6.1 J with the optical conversion efficiency of 36.5 % [8], 10.9 J with the optical efficiency of 43.6 % [9], and 20.5 J with the optical efficiency of 30 % [10] was, respectively, generated from the state-of-the-art face-pumped zigzag Nd:YAG slab laser configuration. However, since the zigzag slab concept has great aspect ratio of the gain medium (width/thickness) and suffers from different thermal lensing between zigzag and non-zigzag directions, the output beam profile from zigzag slab laser always has quite different sizes along the two orthogonal directions [9, 11, 12].

In this article, we report a high-efficiency QCW joule-class Nd:YAG slab laser with the active mirror configuration, in which the laser beam experiences round-trip energy extraction for every single passage through the gain medium. The active mirror configuration [13–15] has an obvious advantage that the thermal gradient barely exists within the laser transverse mode during the amplification process since the heat removal is realized along the slab thickness, which ensures the size symmetry of the beam profile. Besides, a high level of small signal gain can be achieved in the active mirror structure due to its double-pass nature, which is beneficial for highly efficient operation and power scaling. A maximum output pulse energy of 4.1 J at the repetition rate of 10 Hz is produced from the Nd:YAG active mirror resonator that includes four pieces of slab under the total pump energy of 8.1 J, corresponding to an optical-to-optical efficiency as high as 50.6 % and a slope efficiency of 61.1 %. By adopting a pumping scheme that contains laser diode arrays (LDAs) without any optical

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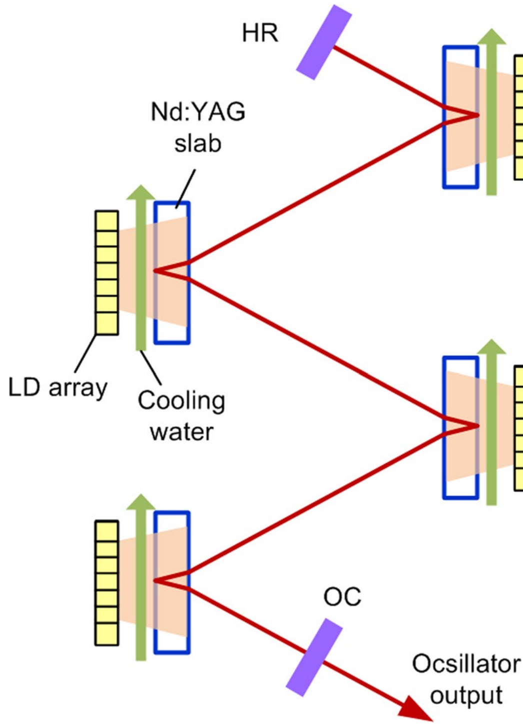


Fig. 1 Schematic diagram of the diode-pumped water-cooled Nd:YAG active mirror oscillator

coupling components, and using a direct cooling method that the heat is carried away by rapidly flowing liquid, the large-aperture active mirror system enjoys the features of high efficiency, high stability, and compact structure.

2 Experimental setup

The experimental setup of the large-aperture diode-pumped Nd:YAG active mirror oscillator directly cooled by the liquid is depicted in Fig. 1. Four Nd:YAG slabs were adopted as the gain medium with the doping concentration of 0.6 at.%. The dimension of each slab was 30 × 20 × 8 mm^3, while a clear aperture size of 20 × 14 mm^2 was used for the passage of both the pump and laser lights. Each Nd:YAG slab was elastically mounted by a flexible supporter that had tiny grooves, to ensure free expansion of the slab under high-temperature gradient, the validity of which was successfully confirmed in our previous 3-kW continuous-wave Nd:YAG multi-slab experiment [16]. The pure water as the liquid coolant rapidly flew through the narrow channel of 1-mm gap between the window and one large surface of the slab, with the flow rate of 5 m/s and an average heat transfer coefficient of 5×10^4 W/(m^2K).

Each slab was pumped by a LDA that was located at a distance of 5 mm from the pump surface of the slab.

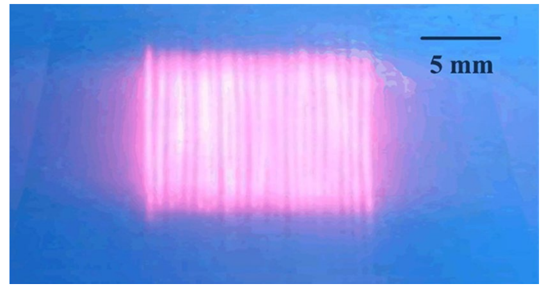


Fig. 2 Pump profile of the LDA measured at the emitting surface

The LDA, consisting of 30 laser diode bars, emitted a peak output power of 7.2 kW with an emitting area of 12.5 × 10 mm^2 at the wavelength of 808 nm at the coolant temperature of 25 °C. The maximum peak intensity at the pump surface was 4 kW/cm^2. Each bar of the LDA was collimated in fast axis by a microlens, corresponding to a fast-axis divergence angle of 5° and a slow-axis divergence angle of 8°. Figure 2 illustrates the measured pump distribution of the LDA at the emitting surface, showing a rectangular profile with the intensity modulation. The pump light of the LDA passed through the water channel and illuminated on the cooling surface of the slab, while a coating that was anti-reflection (AR) at 1064 nm and high reflection (HR) at 808 nm was deposited on the other large surface of the slab (the incidence surface for the laser light) so that the unabsorbed pump power in the first pass could be reflected back and reabsorbed. By employing the pumping scheme without any optical coupling optics, the laser head structure could be made simplified and compact. In addition, the thermal effects induced by the light absorption of pump coupling components would be avoided, and the pump absorption efficiency was obviously enhanced, which was measured in the experiment as 96 % while the loss of 4 % was mainly due to the absorption of the water layer.

A planar–planar cavity was used for the oscillator, with both arm lengths as 300 mm and the transmission of the output mirror as 40 %. The laser light entered the uncooled large surface of the slab at the incidence angle of 45°, reflected at the cooling surface that was HR coated at 1064 nm and AR coated at 808 nm relatively to water, and was coupled out through a second refraction of the uncooled surface. Thus, the laser light experienced a double-pass energy extraction within the gain region in the active mirror scheme.

3 Experimental results and discussion

The thermal effect of the slab under the maximum pump energy was simulated with the finite element method by a commercially available software Ansys. The simulated temperature distribution at the pump repetition rate of 10 Hz was given in Fig. 3, showing the maximum temperature of 31.9 °C with low thermal gradient. Besides, the maximum stress within the slab was calculated as 35 MPa, which was much smaller than the rupture stress of Nd:YAG (130–260 MPa).

The measured dependence of the oscillator output on the total pump energy at the repetition rate from 10 to 50 Hz was depicted in Fig. 4. The output energy was measured by a calibrated multi-joule-level energy meter, with the measurement uncertainty within 3 %. Under the total pump energy of 8.1 J with the pump duration of 280 μs, a maximum output energy of 4.1 J was obtained at 10 Hz, corresponding to an ultrahigh optical-to-optical efficiency of 50.6 % and a slope efficiency of 61.1 %. The pump energy threshold for the operation at 10 Hz is 0.4 J. In the experiment, the laser beam size was estimated as 14 × 20 mm^2 at the slab. It can be seen in Fig. 4 that the output energy drops as the repetition rate increases, since the thermal lensing becomes stronger at higher repetition rates.

To figure out how the thermal lensing affects the output energy in detail, the induced thermal lens of a single slab under pumping was examined by directing a seed beam through the slab in an active mirror manner. Figure 5 compares the thermal focal lengths measured under different

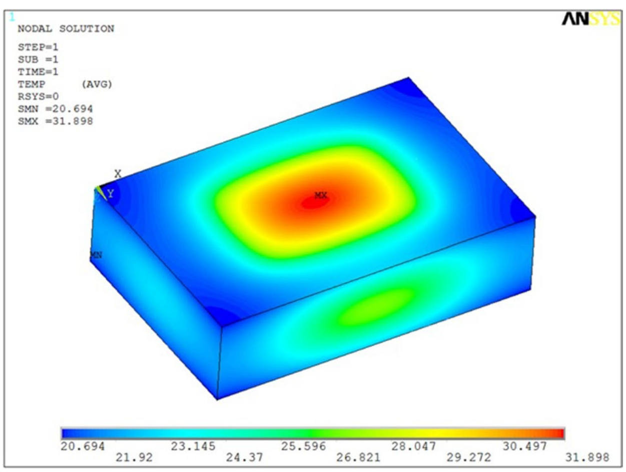


Fig. 3 Simulated temperature distribution of the slab

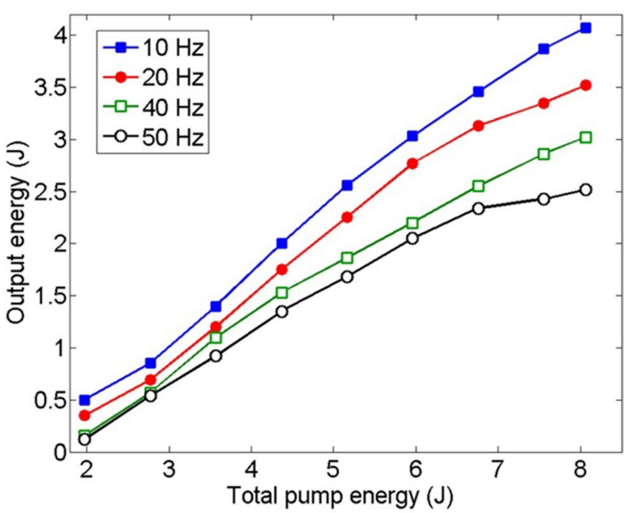


Fig. 4 Oscillator output energy versus the pump energy for different repetition rate

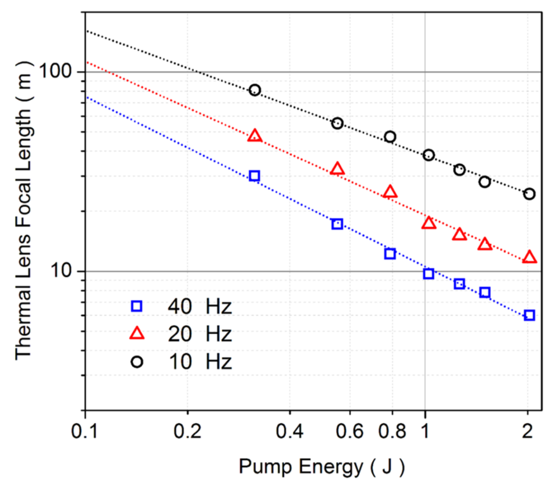


Fig. 5 Thermal focal length versus the pump energy for different repetition rate

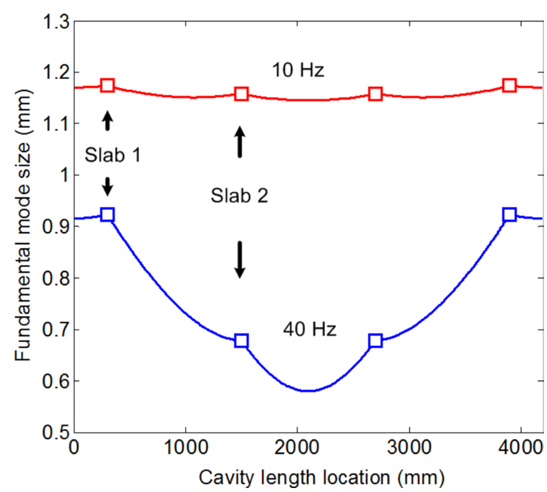


Fig. 6 Beam radius of the fundamental mode along the cavity length

pump energies and repetition rates, in which the dotted lines are fitting curves of the experimental data. It is shown that the focal length decreases dramatically as the pump energy increases. The thermal focal length for a single slab under full pump load is 24.4 m at 10 Hz, 11.6 m at 20 Hz, and 6.0 m at 40 Hz, respectively, from which we can deduce that the combined thermal lens of all four slabs in our setup can reach a thermal focal length of 1–2 m at 40 Hz.

With the measured thermal focal lengths, the beam size of fundamental mode within the resonator at different locations along the cavity length can thus be calculated with the cavity theory [17], by assuming each gain medium as a thin thermal lens. Figure 6 shows the fundamental mode radius for the cases of 10 and 40 Hz, in which the square and triangle signs mark the mode sizes at each slab location. Since the cavity is symmetric, we focus on the variation in mode sizes of slab 1 and slab 2 (as defined in Fig. 6). The ratio of the calculated fundamental mode size of slab 2 to slab 1 is 0.99 at 10 Hz which drops to 0.73 at 40 Hz, and the ratio would hold almost the same for the multi-mode beam oscillating in the cavity. As a result, one can expect that at 40-Hz operation, the beam size at the location of slab 2 of the stably oscillating beam would be about 27 % smaller than the slab clear aperture, leaving a considerable portion of pump energy unextracted, while at 10-Hz operation the beam size is almost identical at slab 1 and slab 2, and thus, both slabs can realize good mode matching between the laser beam and the pump distribution. This well explains the experimental phenomenon that the oscillator output energy obviously drops as the repetition rate increases.

Furthermore, to investigate the stability performance of the joule-class active mirror resonator, the temporal evolution of the output energy was measured for 60 min at the output energy of 4.1 J at 10 Hz, as shown in Fig. 7, indicating a good amplitude stability with the root mean square (RMS) stability of 1.8 %.

Figure 8 demonstrates the near-field profile of the output beam at 10 Hz. The spot size of the near-field pattern was measured as 7.4 × 7.1 (mm), while the beam parameter products were estimated as 8.8 and 8.5 mm mrad in horizontal and vertical directions, respectively, by means of knife-edge measurements. The pulse repetition frequency and temporal profile of the Nd:YAG active mirror oscillator were measured by a digital oscilloscope with 4-GHz bandwidth. Figure 9a shows the pulse train with the repetition rate of 10 Hz, which is in accordance with the frequency of the driving power of LDA. The temporal profile of single pulse is shown in Fig. 9b, indicating the output pulse width of 260 μs.

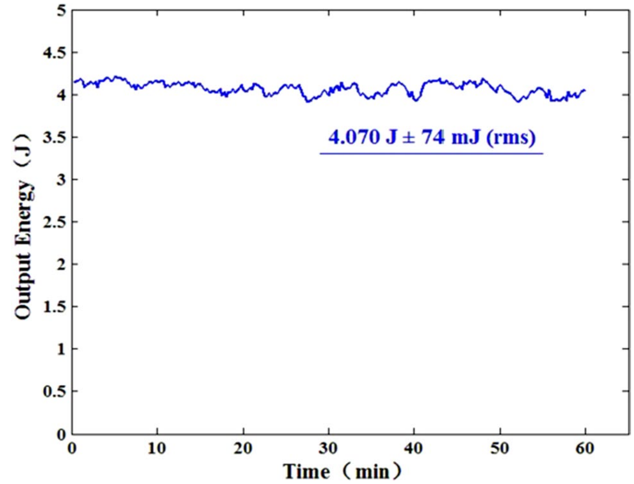


Fig. 7 Temporal evolution of the output energy at 10 Hz

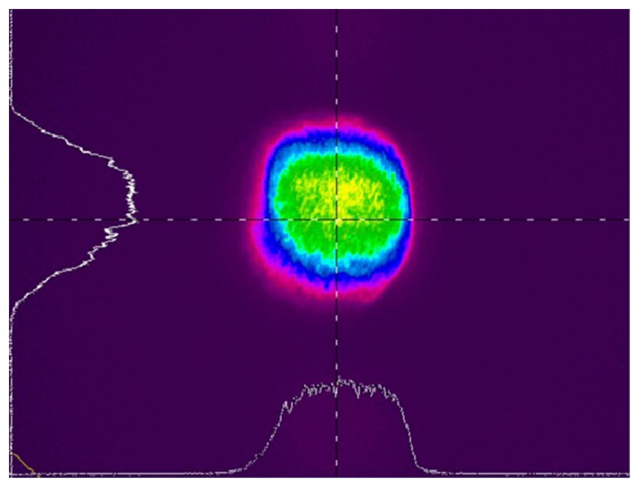
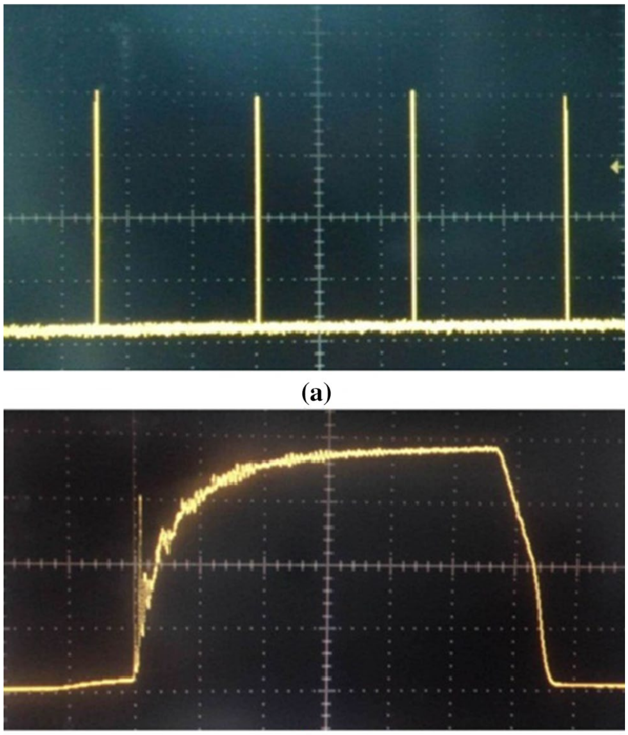


Fig. 8 Near-field profile of the laser output

4 Conclusion

In summary, we have reported a high-efficiency joule-class QCW diode-pumped Nd:YAG active mirror oscillator that adopts a pumping scheme without any optical components as well as a direct cooling method. A maximum output energy of 4.1 J with the pulse width of 260 μs at the repetition rate of 10 Hz is obtained, corresponding to an optical-to-optical efficiency of 50.6 % and a slope efficiency of 61.1 %. Higher output energy can be achieved by increasing the injected pump power, the slab transverse size, and the number of slabs within the cavity, while the careful optimization of mode matching between the laser mode and the pump profile is needed.



(a)

(b)

Fig. 9 Oscilloscope trace of the laser pulse from the oscillator at 10 Hz: **a** pulse train (40 ms/div); **b** single pulse (40 μs/div)

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