A Simple and Efficient Diode-pumped Nd∶YAG Master-oscillator Power-amplifier Laser System with 2.35 J/100 Hz Output*

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Abstract: A simple and efficient diode-pumped Nd∶YAG master-oscillator power-amplifier (MOPA) system is introduced. The master oscillator provides a pulse energy of 1.13 J at a repetition rate of 100 Hz. The maximum pulse energy of the MOPA system is 2.35 J, and the corresponding total optical-to-optical efficiency is 39%. The experimental results are well agreed to the theoretical calculation.

Key words: Nd∶YAG rod; MOPA system; Laser-diode side-pumped

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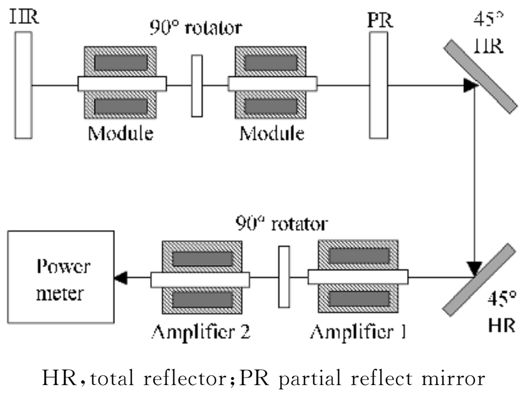
0 Introduction

Diode-pumped solid-state laser operation with a high energy, a high power and a good beam quality is broadly applied in the fields of industry and military due to its high efficiency, reliability, compactness and long operation lifetime[1-3]. For a diode-pumped solid-state laser, the mainly limiting factor for obtaining the laser operation with good beam quality and high output power from a oscillator is the thermal-optics-effect, which is caused by the temperature gradients on the active medium that can make the laser beam quality degenerate[4-5]. In addition, the high intracavity power intensity often damages the intracavity optics. The master-oscillator power-amplifier (MOPA) laser system can avoid the two disadvantages, so it is a common method to obtain laser operation with a high energy, a high average output power and a good beam quality[6-10]. A MOPA laser system with 8.75 J per pulse (1.064 μm) at a repetition rate of 100 Hz was presented and its total optical-to-optical efficiency was not given[9]. However, costly active medium of Nd∶YAG slab geometry in complicated multi-pass amplifier arrangement was used in the system, which makes the laser inconvenient in the application. A MOPA laser system in the rod geometry was reported that delivered 1.25 J per pulse at a repetition rate of 20 Hz in double-pass amplifier arrangement with a total optical-to-optical efficiency 28%[6].

In this paper, a compact, simple and efficient diode-pumped Nd∶YAG MOPA laser system that consists of one total reflector, one coupling output mirror, two 90° quartz rotators and four side-pumped rod geometry pump modules is reported. The master oscillator outputs 1.13 J per pulse with a pulse duration of 236 μs and a beam quality of $M^2 \approx 20$ at 100 Hz. After the amplification system, pulse energy of 2.35 J is obtained, and the corresponding total optical-to-optical efficiency is 39%. The experimental results have a well agreement with the theoretical calculation.

1 Experiment setup

The schematic of the simple MOPA laser system is shown in Fig. 1. The master oscillator is a symmetrically flat-flat resonator, which is composed of two side-pumped rod geometry pump modules, a flat total reflector, a flat output couple mirror with a reflectivity of 50% and one 90° rotators , and the laser cavity length is 400 mm.



HR, total reflector; PR partial reflect mirror

Fig. 1　Schematics of the MOPA system

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The 90° rotators placed between the two rods can effectively compensate for the thermally induced birefringence by changing the polarization states (radial and tangential ones)[10]. The power-amplifier includes two side-pumped rod geometry pump modules placed in a linear arrangement and one 90° rotators arranged between the two pump modules. All the end surface of Nd∶YAG rods are coated with antireflecting film to lower the reflection loss on the end surfaces of Nd∶YAG rod.

Fig. 2 illustrates the schematic of the pump module. Five two-dimensional (2D) laser-diode (LD) arrays symmetrically surround the Nd∶YAG rod (7 mm in diameter, 88 mm in length, with 0.7% Nd^{3+} doping concentration). Each 2D LD array comprises four rows, each row containing five 1 cm long linear quasi-cw LD bars arranged along the slow axes of the bar. The slow axes of the bar is arranged parallel to the axes of Nd∶YAG rod, and the light from the bars is directly coupled into the Nd∶YAG rod without the aid of the intervening lens. At a repetition rate of 100 Hz, each pump module is capable of outputting 1.5 J in a 250 μs pulse at 100 Hz. To increase the absorption efficiency, five polished brass reflectors coated with gold also surround symmetrically the Nd∶YAG rod to reflect unabsorbed pump light into the Nd∶YAG rod again. The distance between the LD bars and the side surface of the Nd∶YAG rod is optimized by use of our ray-tracing code, so that a uniform gain distribution at the cross-section of the Nd∶YAG rod and a high absorption efficiency can be obtained at the same time. Fig. 3 shows the simulated gain distribution at the cross-section of a Nd∶YAG rod with 4.5 mm distance between the LD bars and the side surface of the Nd∶YAG rod. The temperature of cooling water for each pump module is experimentally optimized to realize optimum spectral match between the central emission wavelength of the pump module and absorption band of Nd∶YAG crystal for 1.5 J pump pulse energy at 100 Hz. The small-signal gain G_0 is measured to be 29.

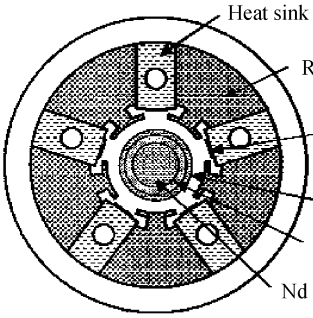

Fig. 2 Schematics of the diode-pumped pump module

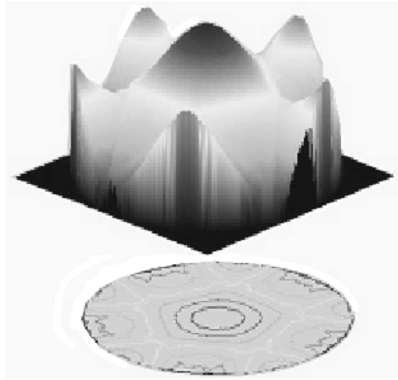

Fig. 3 Calculated pump light distribution in the cross section of a 7 mm-diameter Nd∶YAG rod

2 Results and discussions

The output pulse energy after the master oscillator at a repetition rate of 100 Hz is measured, as the Fig. 4 shown. The maximum output pulse energy at 1 064 nm is 1.13 J with a beam quality of $M^2 \approx 20$ and a pulse duration of 236 μs for a total pump pulse energy of 3 J. The slop efficiency is 49.5%. The diameter of laser beam from the master oscillator is about 6.3 mm. The output pulse energy after the master oscillator, the Amplifier 1 and the Amplifier 2 at different repetition rates is measured for 1.5 J pump pulse energy on each pump module, as the Fig. 5 shown. The maximum output pulse energy for the MOPA system is 2.35 J with a beam quality of $M^2 \approx 25$ at 100 Hz, corresponding to a total optical-to-optical efficiency of 39%. It can be observed from the Fig. 5 that the output pulse energy increases with the repetition rate, which is because the central emission wave of each pump module is more approaching to the absorption band of Nd∶YAG crystal at 808.5 nm as the pump repetition rate increases, since the cooling temperature of each pump module is set at a constant value that is optimum for a pump pulse energy of 1.5 J at a repetition rate of 100 Hz. As mentioned in the paragraph 4, the temperature of the cooling water for each pump module is optimized for 1.5 J pump pulse energy at 100 Hz, so the central emission wavelength of the pump module is under 808.5 nm for a pump pulse repetition rate of under 100 Hz. While the pump pulse repetition rate increasing from 10 Hz to 100 Hz, the temperature of LD bar in the pump module increase also, which will result in the central emission wavelength of the pump module more approaching to 808.5 nm and the absorption efficiency of pump module increasing. When the repetition rate increases to 100 Hz, the optimum match between the central emission wavelength of the pump module and the absorption band of Nd∶YAG crystal is realized, hence the maximum output pulse energy at 1 064 nm for the MOPA system also can be achieved.

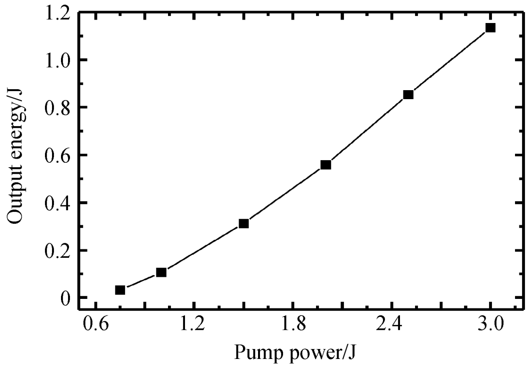

Fig. 4　Output pulse energy from the master oscillator dependence on the pump energy

To fully characterize the output to input signal energy for the amplification system, we calculate the output pulse energy from Amplifier 1 and Amplifier 2. Because the duration of laser pulse is approximately equal to the lifetime of Nd∶YAG (230 μs), the pulse energy from one amplifier stage is approximately expressed as[11]

$$E_{out}=I_{out}\cdot s\cdot t \tag{1}$$

$$I_{out}=I_{in}\cdot G \tag{2}$$

$$\frac{I_{in}}{I_s}=\frac{\ln\left(\frac{G_0}{G}\right)}{G-1} \tag{3}$$

In the above expression, I_{out} is the output laser intensity of the amplifier; I_{in} is the input laser intensity; t is the laser pulse duration; s is the area of laser beam; G is the energy gain for a light pass through a amplifier and I_s (2.89 kW/cm^2) is saturation intensity of Nd∶YAG. By the equation 1～3, the output energy from Amplifier 1 and Amplifier 2 at different repetition rate are calculated, which are shown in Fig. 5, respectively. As the Fig. 5

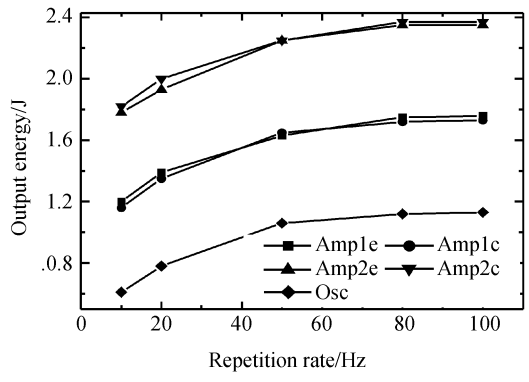

Fig. 5　The output energy at the different repetition rate

shows, Osc: measured pulse energy from the master-oscillator; Amp1e, measured output pulse energy from the Amplifier 1; Amp1c, calculated pulse energy from Amplifier 1; Amp2e, measured pulse energy from Amplifier 2; Amp2c, calculated pulse energy from Amplifier 2. The calculated results have a well agreement with the experimental results. The energy stored in the upper laser level of active medium in one pulse and the extraction efficiency are given by

$$E_{st}=\frac{g_0\cdot h\cdot \nu_{21}\cdot t_p\cdot V}{\sigma_{21}} \tag{4}$$

$$\eta_{ex}=\frac{E_{out}-E_{in}}{E_{st}} \tag{5}$$

$$g_0=\frac{\ln(G_0)}{L} \tag{6}$$

where t_p is the duration of pump pulse; h is Plank's constant; ν_{21} is the frequency of laser beam; E_{in} is the input pulse energy; σ_{21} (2.8×10^{-19} cm^2) is the effective stimulated-emission cross section of Nd∶YAG crystal; g_0 is the small signal gain coefficient; L is the length of active medium (5.8 cm); V is the total volume of active medium (4.46 cm^3), E_{st} is the energy stored in the upper laser level. By the equation 4～6, extraction efficiency for the amplification system is calculated to be 86%.

To evaluate the application of this MOPA system on drilling or cutting, the laser beam is focused on a 1 mm-thickness steel plate by use of a lens with a 200 mm focal length. A ϕ1.4 mm hole is penetrated in one second.

3　Conclusions

In summary, a simple and efficient MOPA laser system consisting of four Nd∶YAG pump modules, two flat mirrors and two 90° quartz rotators is demonstrated. The MOPA system outputs 2.35 J per pulse with a pulse duration of 236 μs at 100 Hz, and the corresponding optical-to-optical efficiency is 39%. There is a well agreement between the theoretical calculation and experiment data. In one second, the laser beam from the MOPA system is able to penetrate a 1 mm thicks steel coupon.

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高效率激光二极管泵浦 100 Hz 3.5 J Nd∶YAG MOPA 激光器

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摘 要:研制了结构简单、高效率激光二极管泵浦Nd∶YAGMOPA激光器.振荡级输出单脉冲能量1.13 J,重复频率为100 HZ.MOPA系统输出最大单脉冲能量2.35 J,光-光转换效率为39%.实验结果和理论计算符合较好.

关键词:Nd∶YAG棒;MOPA系统;激光二极管侧面泵浦

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