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RESEARCH ARTICLE

Slab Yb:YAG pulse amplifier with high amplification gain and signal-to-noise ratio

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Abstract This study experimentally investigated a Yb:YAG pulse laser amplifier with a high amplification gain and a high signal-to-noise ratio (SNR). The highest amplification gain of 172 and highest pulse energy of 131 mJ were obtained with the highest SNR of 24.9 dB from a volume gain of 10 mm × 10 mm × 1 mm. The output beam quality values of $M_x^2 = 1.91$ in the slow axis and $M_y^2 = 1.58$ in the fast axis were also achieved.

Keywords laser amplifiers, ytterbium lasers, diode-pumped lasers, signal-to-noise ratio (SNR)

1 Introduction

A telescope optical cavity with a concave curved mirror and a convex curved mirror has been applied in laser amplifiers for more than ten years because of its ability to fold the amplified laser beam and expand the amplified beam size after each round trip in the cavity to maintain the moderately amplified laser energy density; these qualities protect the coating film of the optical components [1–3]. Laser diode (LD) arrays have been widely utilized to pump Yb:YAG amplifiers because of their high output power per bar and emitting a wavelength of 940 nm, which suitably fits the absorption band of the Yb:YAG gain medium [4,5]. Many researchers have studied laser pulse amplifiers in theory and experiments, and a few of them have studied the output characteristics of pulse amplifiers as a function of the input pulse energy [6,7]. However, a study on the LD-pumped pulse laser amplifier with a high amplification gain and a high signal-to-noise ratio (SNR) (i.e., the ratio of the amplified pulse energy to the amplified spontaneous emission (ASE) noise energy) has yet to be reported.

The high amplification gain of a pulse laser amplifier can generally be achieved by increasing the pumping pulse energy density or gain length; however, a high pumping pulse energy density and a long gain length often lead to a high ASE noise energy. The forward traveling part of this energy type degrades the output quality of the laser pulse amplifiers, whereas the backward traveling part can be injected into the signal laser cavity to cause a stability problem of the signal laser output.

This study adopted the structure of a LD end-pumped Yb:YAG slab pulse laser amplifier with a multiple folded cavity to experimentally achieve the high amplification gain of the laser pulse with the high ratio of the amplified pulse energy to the ASE noise energy. The experiments obtained an amplification gain of 172 and amplified pulse energy of 131 mJ, as well as SNR of 24.9 dB from a gain medium volume of 10 mm in width, 10 mm in length, and 1 mm in height. The obtained beam quality was $M_x^2 = 1.91$ in the slow axis direction and $M_y^2 = 1.58$ in the fast axis direction of the slab Yb:YAG crystal.

2 Experimental methods

A multiple folded optical cavity was utilized to match a LD end-pumped slab Yb:YAG crystal with a size of 10 mm × 10 mm × 1 mm and obtain high amplification gain. The multiple folded cavity plays the role of folding the beam and expanding its geometric size to maintain the moderately amplified beam energy density to obtain a high amplification gain.

The structure of the Yb:YAG pulse amplifier is illustrated in Fig. 1. The multiple folded cavity consists of a concave mirror M2 and a convex mirror M5, whose curvature radius were R_1 = 320 mm and R_2 = 140 mm, respectively, with a high reflection coating at 1030 nm. The distance between the two folding curved mirrors was L = 90 mm. Two plane dichroic mirrors (M3 and M4) placed at 45° to the pump light were used to couple the pump light

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and fold the optical cavity. Hence, they were coated for high transmission at 940 nm and high reflection at 1030 nm.

The dual end-pumping configuration was applied in the experiments. The pump sources were two LD arrays, each with four bars and deliver an output peak power of 1200 W. The center wavelength was fixed at approximately 940 nm for Yb:YAG by maintaining the temperature of the cooling water at 23°C. The homogenization system of the pump light was the same as that utilized in Ref. [8]. The pumping peak power was 960 W after the homogenization system with 80% efficiency. A homogenous line pump light inside the Yb:YAG gain medium was obtained after the homogenization system. The dimensions of the pumping line were approximately 10 mm (x) × 0.4 mm (y). A quarter-wave plate with the Polarizer Rotation Mount (Beijing Huawei Haorun Instruments Co., Ltd) and a polarizer were set at the input end of the pulse amplifier, which was utilized to adjust the linear polarized input energy of a signal pulse laser. The input signal pulse laser originates from the LD pulse end-pumped Q-switch Yb:YAG slab laser with a beam quality of $M^2 = 1.55$ in the slow axis and $M^2 = 1.40$ in the fast axis as shown in Ref. [8]. The input beam size of the amplifier was 0.49 mm in width (x-direction). The input signal pulse laser was injected just after the end of the pump pulse light with a DG535 Digital Delay and Pulse Generator (Stanford Research System, Inc.). The output beam size of the amplifier after seven paths was folded in the Yb:YAG gain medium was 5.85 mm in width. The mirrors M1 and M6 were placed at 45° to guide the input and output beams of the pulse laser amplifier. The pulse energy of the amplifier in the experiments was measured by a LE-3B laser energy meter (Beijing Physcience Opto-Electronics Co., Ltd).

The Yb:YAG dimensions were 10 mm in width × 1 mm in height × 10 mm in length with 2.5-at.% doping concentration. The two large area surfaces (10 mm × 10 mm) were coated with gold and were tightly mounted with water-cooled copper heat sinks. Only the two surfaces (10 mm × 1 mm) were polished and coated to pass the pump light (940 nm) and the laser beam (1030 nm). The cooling water temperature for the Yb:YAG gain medium was at 24°C.

3 Results and discussion

The increase in the pumping pulse duration theoretically increases the storage energy of the gain medium and lowers the storage efficiency (i.e., the ratio of the stored

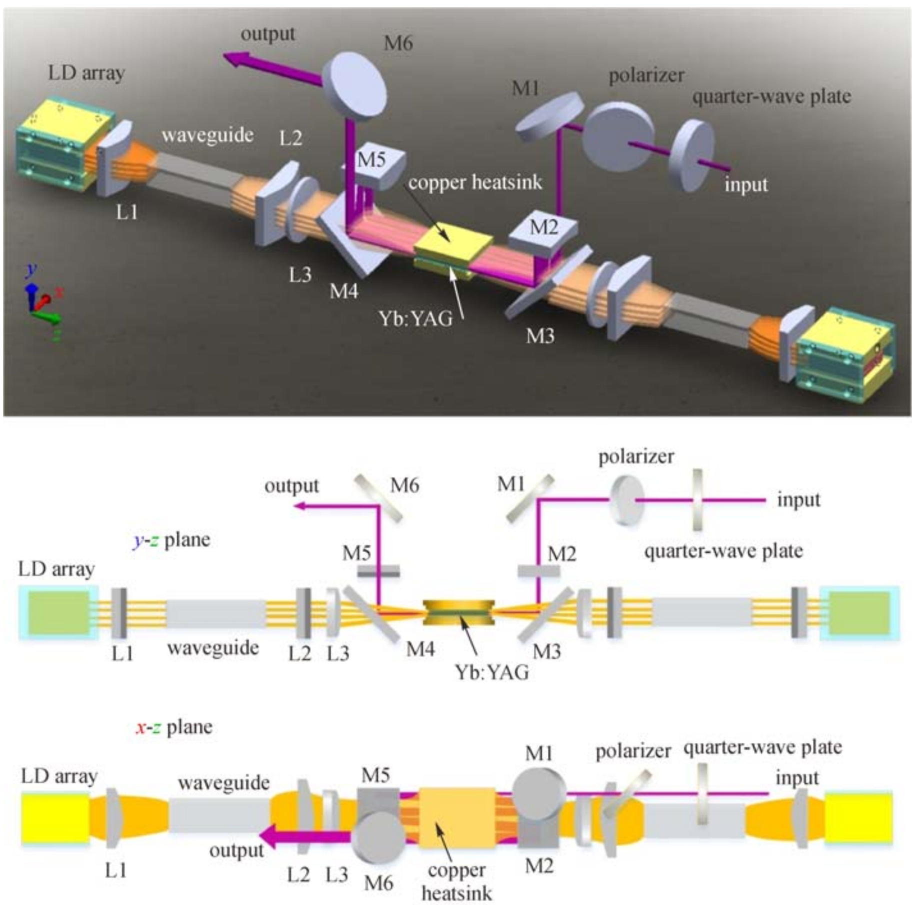

Fig. 1 Experiment setup of the LD end-pumped Yb:YAG pulse laser amplifier

energy of the upper laser level after the pumping process to the total input pump energy) for the specified pumping power intensity in the pulse laser amplifier, as shown in Fig. 2. τ_p is the pumping pulse duration, and τ_{21} is the lifetime of the upper laser level of the gain medium in the said figure. Although the long pumping pulse duration can provide more pumping energy, it produces a more spontaneous emission that lowers the storage efficiency. This scenario indicates a balance between the high amplification gain and ASE noise energy with the selection of the pumping pulse duration. Figure 2 also shows that the higher pumping peak power intensity (Ip) can provide a higher storage energy and a higher storage efficiency of the upper laser level.

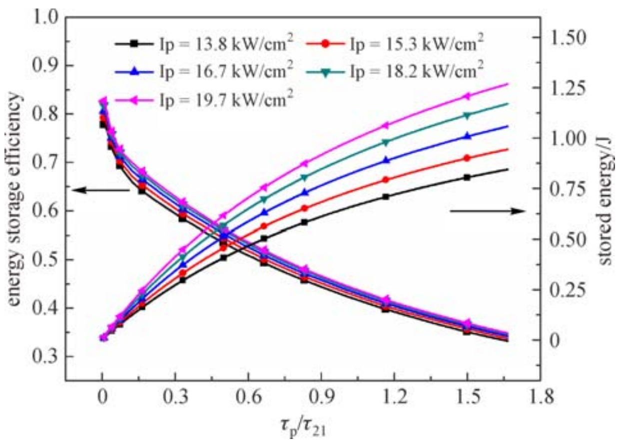

Fig. 2 Energy storage efficiency and stored energy versus the ratio of the pumping pulse duration to the lifetime of the upper laser level

When the high pumping peak power intensity provides the higher storage efficiency and energy, it also produces the higher ASE noise energy that decreases the ratio of the laser pulse energy to ASE noise energy (SNR). Experimental results are shown in Fig. 3 where the ASE noise energy was measured by blocking the input pulse, whereas the pumping pulse was maintained. The said figure shows that the ASE noise energy increases in a small slope for the pumping pulse time duration τ_p for the small pumping power intensity. However, the ASE noise energy increases in a small slope at the beginning and then increases in a sharp slope for the high pumping power intensity. The ASE noise energy for the pumping peak power intensity of 19.7 kW/cm^2 was 6.8 mJ at the time ratio of 1 and the sharp slope starts at approximately the time ratio of 0.46, at which the ASE noise energy was 0.42 mJ. These results indicate that the high ratio of the amplified pulse energy to the ASE noise energy can be obtained by selecting the time ratio at the proper point of the curve slope (i.e., by selecting the proper pulse pumping time duration to achieve the high ratio of the amplified pulse energy to the ASE noise energy (SNR) for the high pumping peak power intensity). Unlike

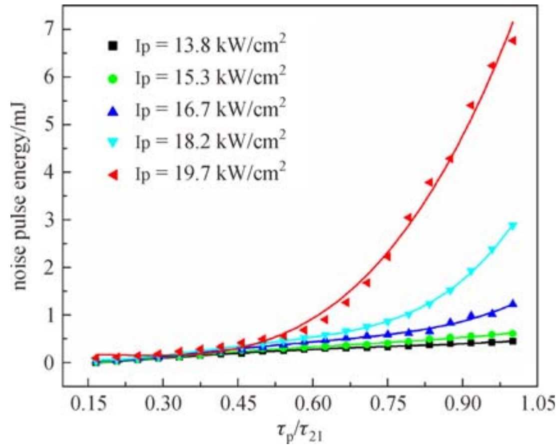

Fig. 3 ASE noise pulse energy versus the ratio of the pumping pulse duration to the lifetime of the upper energy level for different pumping peak power intensity

many research papers that do not consider the pumping pulse time duration [9–11], Fig. 3 provides an experimental method that selects the pumping duration to obtain low ASE noise energy.

Although the high pumping power intensity can increase the output pulse energy and the amplification gain, a higher ASE noise energy can be produced. Therefore, the proper time ratio needs to be selected. The experimental results of the amplified output pulse energy, the ASE noise energy, the amplification gain, and the ratio of the amplified pulse energy to the ASE noise energy (SNR) against the time ratio for the different input signal energy are shown in Figs. 4 and 5, in which the operating repetition rate was fixed at 5 Hz, the input pulse width is 13.4 ns, and the pumping power intensity is 19.7 kW/cm^2.

In Figs. 4 and 5, the time ratio of the pumping pulse time duration to the lifetime of the upper energy is selected below the time ratio of 0.46 for the low ASE noise energy, as concluded from Fig. 3. The output pulse energy rises with the increase in the input pulse energy for a different

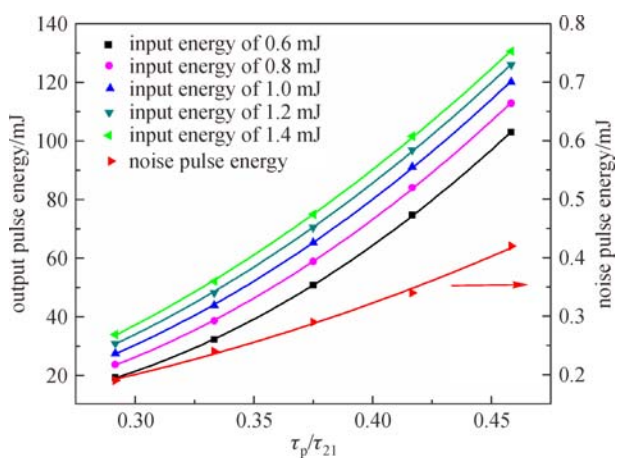

Fig. 4 Output and ASE noise pulse energies versus the ratio of the pumping pulse duration to the lifetime of the upper laser level

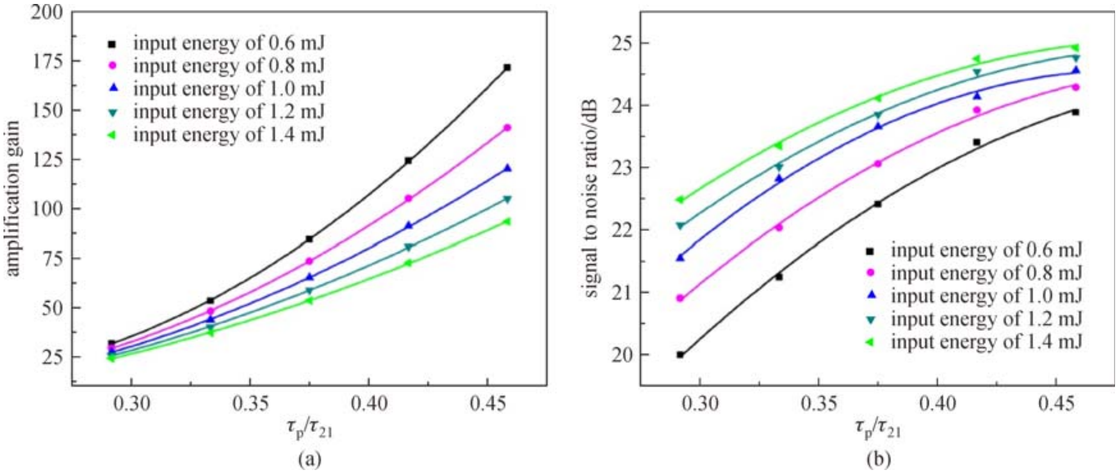

Fig. 5 Amplification gain (a) and the ratio of the amplified pulse energy to the ASE noise energy (b) versus the ratio of the pumping pulse duration to the life time of the upper laser level

time ratio; the growing slope of the ASE noise energy is smaller than that of the amplified pulse energy for a time ratio below 0.46, as shown in Fig. 4. The energy extraction of the laser amplifier increases with the enhancement of the input pulse energy [12].

From Fig. 5, the amplification gain rises with an increase in the time ratio at a sharp slope for a different input pulse energy, and the ratio of the amplified pulse energy to the ASE noise energy (SNR) increases at a small slope and tends toward saturation as the time ratio nears the value of 0.46. This condition is because of the execrable increase in the ASE noise pulse energy when the time ratio exceeds 0.46 as shown in Fig. 3.

In Figs. 4 and 5, the experimental results showed that the highest amplification gain of 172 was obtained with the input pulse energy of 0.6 mJ; the ratio of the amplified energy to the ASE noise energy (SNR) is 23.8 dB. The highest amplified energy of 131 mJ was obtained with the input pulse energy of 1.4 mJ, and the ratio of the amplified energy to the ASE noise energy (SNR) is 24.9 dB.

The far-field intensity distribution of the output beam of the pulse laser amplifier is shown in Fig. 6, which was

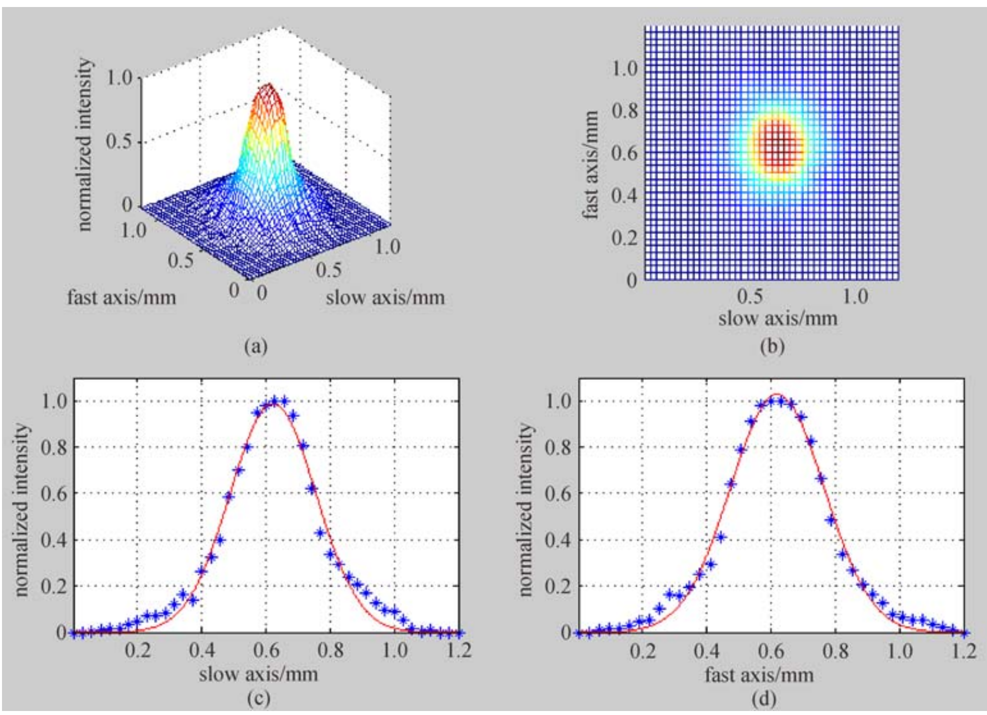

Fig. 6 (a) Far-field intensity distributions of the laser amplifier output; (b) beam transverse profile; (c) intensity distribution in slow axis: experimental data (*) and Gaussian fitting (red curve); (d) intensity distribution in fast axis: experimental data (*) and Gaussian fitting (red curve)

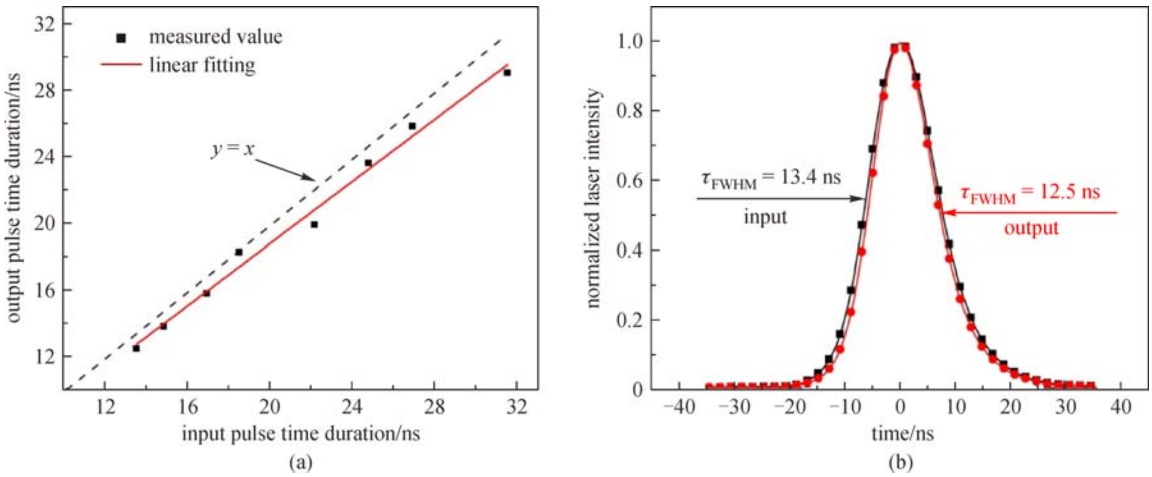

Fig. 7 (a) Output pulse width versus input pulse width; (b) pulse waveform of the input pulse and the output pulses. τ_{FWHM} denotes the full width at half maximum

obtained at the focal point by the cylindrical lens of 150 mm focal length. The far-field intensity distributions of the output beam of the pulse laser amplifier are not well-fitted with the Gaussian fundamental mode, compared with that of the input signal pulse laser with $M_x^2 = 1.55$ in the slow-axis direction and $M_y^2 = 1.40$ in the fast-axis direction of the slab Yb:YAG crystal in Ref. [8]. The output beam quality of the amplifier is $M_x^2 = 1.91$ and $M_y^2 = 1.58$. The beam quality of the output signal pulse laser was not better than the input because of the thermal effects of the gain medium Yb:YAG.

The output pulse width of the pulse laser amplifier as a function of the input pulse width is illustrated in Fig. 7. The output pulse width was compressed by the Yb:YAG pulse amplifier, in which the input pulse time duration was 13.4 ns.

4 Conclusions

In this paper, a LD end pumped slab Yb:YAG laser amplifier with high amplification gain and high SNR was studied. Experimental results showed that by properly selecting the time ratio of the pumping pulse time duration to the lifetime of the upper laser level, the ASE noise energy under the high pumping power intensity can be controlled at a lower level, and the high ratio of the amplified laser pulse energy to the ASE noise energy (SNR) can be achieved. In the experiments, the time ratio was selected at 0.46 for the slow-growing slope of the ASE noise energy. The highest amplification gain of 172 was obtained with the input pulse energy of 0.6 mJ, and the highest amplified energy of 131 mJ was obtained with the input pulse energy of 1.4 mJ. The ratio of the amplified energy to the ASE noise energy (SNR) was 23.8 and 24.9 dB, respectively. In the experiments, the output beam quality of the amplifier is $M_x^2 = 1.91$ in the slow-axis direction and $M_y^2 = 1.58$ in the fast-axis direction of the slab Yb:YAG crystal.

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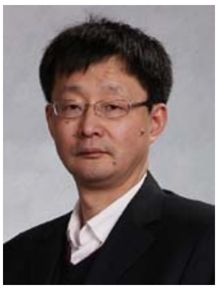

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