High-power picosecond regenerative amplifier based on CW diode side-pumped Nd:YAG with high beam quality

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A compact high-power picosecond regenerative amplifier based on continuous wave (CW) diode side-pumped Nd:YAG is demonstrated. Average power of 8.8 W is achieved at a repetition rate of 5 kHz at a wavelength of 1 064 nm with a pulse duration of 28 ps, corresponding to a pulse energy of 1.76 mJ and a peak power of 62.9 MW. The beam quality is close to the diffraction limit with $M_x^2 = 1.24$, $M_y^2 = 1.03$. To the best of our knowledge, this is the highest pulse energy obtained from a CW diode pumped Nd:YAG picosecond regenerative amplifier.

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Ultra-short laser pulses are powerful tools for micro-machining with high precision. The interaction time between the radiation and the material is so short that thermal damage to the work piece can be strongly reduced or completely avoided[1−5]. Combining high quality and almost melt-free processing, femtosecond laser pulses based on Ti: Sapphire have been widely investigated in recent years[6−8]. However, Ti: sapphire laser systems, which are usually pumped by frequency-doubled diode-pumped solid-state lasers, cannot be conveniently pumped with economic and compact diodes lasers. Chirped pulse amplification (CPA) is also required, making the system more complex and more expensive. Moreover, the processing speed is also far from adequate for industrial requirements. These disadvantages retard their acceptance by industrial end users. Recent investigations have demonstrated pulses with durations in the picosecond regime to be well suited for precise micro-machining without reducing the quality. Nejadmalayeri *et al.* demonstrated that 1.0-ps pulses yield to the best quality for ultrafast laser waveguide writing in lithium niobate[9]. Dausinger reported a pulse duration near 5–10 ps to be optimal for the micro-machining of metals[10]. Raciukatis *et al.* showed that, even for a 60-ps pulse, high quality processing of silicon is possible[11]. Ostendorf *et al.* argued that picosecond lasers with a high repetition rate could be a leading technology in high-quality cutting in good heat-conducting materials[12].

In contrast to Ti:sapphire femtosecond lasers, picosecond lasers based on neodymium-doped crystals offer many advantages, including direct diode pumping, compact scales, high average power output, and high repetition rate. Moreover, because the pulse durations are in the picosecond regime, CPA is not required. Several picosecond regenerative amplifiers (RA) have been demonstrated in recent years. Siebold *et al.* demonstrated an end-pumped Nd:YVO$_4$ RA with 5.3-W average output power at a pulse repetition rate of 40-kHz pulse duration of 19 ps[13]. Kleinbauer *et al.* reported an end-pumped Nd:YVO$_4$ RA providing laser pulses with a pulse duration of 10.2 ps at a repetition rate of 20-kHz and average output power of 10.8 W[14]. Recently, Luhrmann *et al.* demonstrated an end-pumped Nd:YVO$_4$ RA producing up to 33.7-W output power with a repetition rate of 20 kHz and an adjustable pulse duration between 217 ps and 1 ns[15].

In this letter, we attempt to set up a picosecond RA with a more compact scale and much lower cost. Based on the special RA cavity design, the pulse picker is not required, leading to an extremely cost-effective system. In our system, diode-side pumping is adopted instead of diode-end pumping to achieve a more compact scale. Average power of 8.8 W is demonstrated at a repetition rate of 5 kHz with a wavelength of 1 064 nm, corresponding to a pulse energy of 1.76 mJ. To the best of our knowledge, this is the highest pulse energy obtained from a continuous wave (CW) diode-pumped Nd:YAG picosecond RA.

A pulse picker in a RA laser system, which usually consists of a polarizer and a Pockels cell (PC), is used to lower the frequency of the seeding pulses and prevent a second pulse trapped in the RA cavity during the amplification stage. However, the absence of a pulse picker is possible. The electro-optical switch in the RA cavity can be used to lower the frequency of the seeding pulses because the dumping frequency is exactly the frequency we desire. Furthermore, by manipulating a RA cavity length shorter than that of the oscillator, the second pulse always arrives at the RA cavity after the first one leaves. As a result, there would be only one pulse trapped in the RA cavity during the amplification stage. Pulse picker-free RA designs have already beenused in thin-disk RA lasers[16]. The only challenge is that without a pulse-picker, the unwanted seeding pulses will also experience a round trip through the gain medium during the pump stage, leading to a reduction of the stored energy in the gain medium.

As we know, the energy stored in the upper laser level is extracted at the time of the pulse arrival. The output fluence after a round trip through the gain medium E_{out} (when $E_{\text{in}} << E_{\text{s}}$) and the energy extraction efficiency during the pump stage η_{E} are defined as[17]

$$E_{\text{out}} = E_{\text{in}} \times \exp(g_0 l) \times \exp(g_0 l), \tag{1}$$

$$\eta_{\text{E}} = \frac{(E_{\text{out}} - E_{\text{in}})}{g_0 l E_{\text{s}}} \times N, \tag{2}$$

where g_0 is the small signal gain coefficient, l is the length of the gain medium, E_s is the saturation fluence defined by $E_s = \frac{hv}{\sigma}$, h is Planck's constant, v is the lasing frequency, σ is the stimulated emission cross-section of the laser medium, and $g_0 l E_s$ is the stored energy in the upper laser level[17]. E_{in} is the input fluence, and N is the total number of pulses experiencing a round trip though the gain medium during one pump stage. As the pump stage is much longer than the amplification stage, N is defined by $N = \frac{F_o}{F_d}$, where F_o is the frequency of the pulses from the oscillator, and F_d is the dumping frequency of the RA. In our RA laser system, the gain medium is a side-pumped Nd:YAG crystal. g_0 is measured 0.11 in our system, with $l = 6.4$ cm. Other parameters are given as follows: $h = 6.63 \times 10^{-34}$ J·s, $v = 2.8 \times 10^{14}$ Hz, $\sigma = 2.8 \times 10^{-19}$ cm^2, $E_s = 0.66$ J/cm^2, $F_o = 100 \times 10^6$ Hz, and $F_d = 5 \times 10^3$ Hz[17]. Figure 1 gives the extraction efficiency η_E versus the input fluence E_{in} during the pump stage. According to our computation, η_E is less than 5% when E_{in} is below 380 nJ/cm^2. Therefore, in a relatively low single-pass gain medium-based RA, the absence of a pulse picker has little effect on the whole system.

A schematic view of the experimental setup is depicted in Fig. 2. The master oscillator is a home-made diode-pumped Nd:YVO$_4$ passively mode-locked laser. It generates a pulse train with apulse duration of 9.3 ps at a repetition rate of 100 MHz; its maximum output power is 500 mW. The seeding pulse train is directly injected into the RA cavity using the thin film polarizer (TFP2). A 6.4-cm-long, 3-mm-diameter Nd:YAG operates as the gain medium. Combined with a $\lambda/4$ wave plate, one barium boron oxide (BBO) PC with a clear aperture of 4 mm is used to switch the pulses. The 1.1-m-long RA cavity is shorter than the oscillator cavity length, effectively preventing a second pulse trapped during the amplification stage. The input pulse energy at the Nd:YAG is 2.8 nJ, with E_{in}= 53 nJ/cm^2. A fast photodiode is used to monitor the intracavity signal through the leakage light after M$_2$.

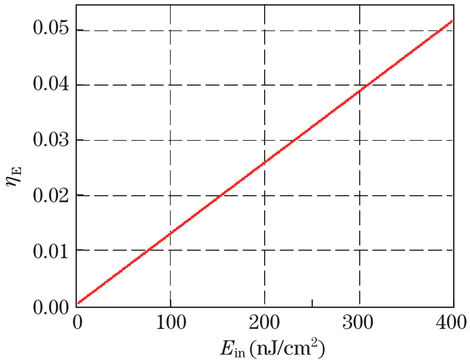

Fig. 1. Extraction efficiency in a time period η_E versus input fluence E_{in}.

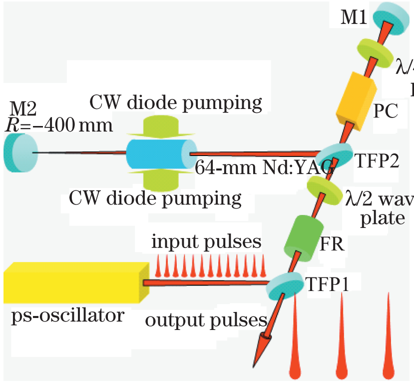

Fig. 2. Sketch of the experimental setup. FR: Faraday rotator.

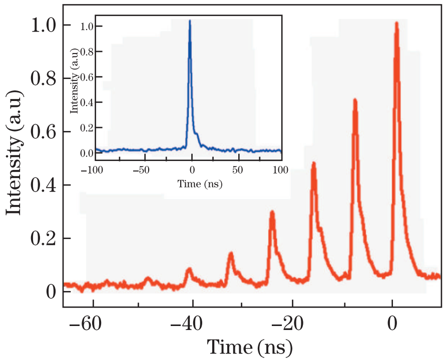

Fig. 3. Intracavity signal of the RA. The inset shows the trace of the amplified output pulse.

Figure 3 shows the intracavity signal of the RA. The recorded pulses are temporally spaced by the cavity round-trip time of 7.3 ns. The pulse energy grows until the gain becomes equal to the resonator losses. The saturated pulse is then dumped out of the RA cavity. The buildup time required to reach the peak pulse energy in our system is 285 ns, corresponding to 39 round trips. However, only 8 of them can be observed in Fig. 3, which also proves that the energy extraction is very

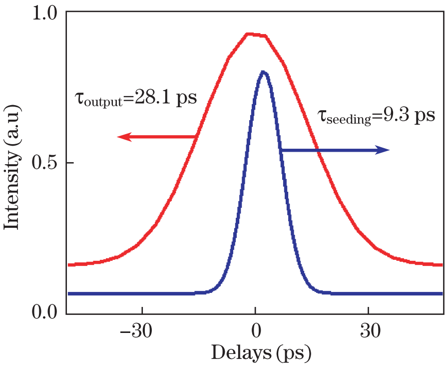

Fig. 4. Autocorrelation of the seeding pulses and output pulses.

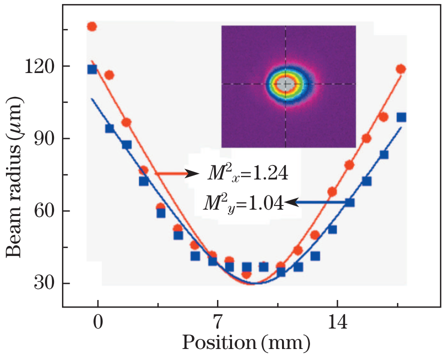

Fig. 5. Camera-based measurement of the beam quality. The inset is the transverse beam profile.

small at the beginning of the amplification stage. The output pulse is shown in the inset in Fig. 3. The system generates a clean output pulse without noticeable pre- or post-pulses. A clean output pulse is also ensured by locating TP2 between the Nd:YAG and the PC, effectively avoiding the unwanted coupling of substantial power to the output due to the thermally induced birefringence. Pulse duration is also measured with a second harmonic auto-correlator, as shown in Fig. 4. Due to the limited bandwidth of the Nd:YAG, the output pulse width is broadened to 28 ps, unlike the oscillator that has a pulse width of 9.3 ps.

Diode-side pumping is adopted in our laser system to achieve a more compact scale and higher power output because the pumping zone is much larger than that in end-pumping. However, diode-side-pumped laser systems always suffer from poor beam quality due to thermally induced deviation from the uniform pump distribution. To overcome this shortcoming, a thermal compensating plane-convex RA cavity design is used in our system, ensuring a uniform gain zone in the laser rode[18]. The transverse beam profile measured with a charge-coupled device (CCD) camera is shown in the insert in Fig. 5, indicating a perfect TEM_{00} mode (TEM is the transverse electric and magnetic field). The result is close to the diffraction limit, giving a beam quality of $M_x^2 = 1.24$, $M_y^2 = 1.03$ in both directions perpendicular to the axis of propagation.

In conclusion, a compact and high-energy picosecond regenerative amplifier based on CW diode side-pumped Nd:YAG with high beam quality is demonstrated. An average power of 8.8 W is demonstrated at a repetition rate of 5 kHz and wavelength of 1 064 nm with a pulse duration of 28 ps, corresponding to a pulse energy of 1.76 mJ and peak power of 62.9 MW. With a thermal compensating plane-convex resonator design, the beam quality is close to the diffraction limit. We believe that this compact and cost-effective picosecond laser system is applicable in micro-machining applications.

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