Laser diode end-pumped Nd:YVO_4 regenerative amplifier for picosecond pulses*

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A diode dual-end-pumped Nd:YVO_4 regenerative amplifier is reported. The influence of the cavity stability on the performance of the regenerative amplifier is studied. The experimental results match well with the analysis at high pump power. The mode locking seed pulses with 15 ps pulse width and 10 nJ single pulse energy at 86 MHz are amplified up to 4.7 mJ at 1 kHz, corresponding to the maximum amplification about 0.5×10^6, by our regenerative amplifier. And an average power of 4.7 W is obtained at the repetition rate from 1 kHz to 10 kHz.

Keywords: regenerative amplifier, cavity stability, picosecond mode locking pulse

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1. Introduction

In recent years, ultra-short pulses with high peak power and high energy have been widely used in many research fields[1] and have played an important role in high-intensity physics.[2] Generally speaking, either the pulse energy or the peak power of the picosecond pulses directly generated from a solid mode-locked laser is low. Therefore, it is necessary for the mode-locked pulses to be amplified by an amplifier to get higher peak power and higher energy. The regenerative amplification is an ideal choice for its high amplification, and low gain media could be used.[2,3]

With a regenerative amplifier, Duling and Sizer obtained an amplified pulse energy of ∼1 mJ in 100 ps with a pulse repetition frequency (PRF) of ∼ 1 kHz in 1986.[4] In 1987, Bado *et al.* amplified 37 ps mode-locked pulse to 2.5 mJ with a continuous-wave (CW) pumped Nd:YLF regenerative amplifier operating at the repetition rate of 500 Hz.[5] In 1988, Postlewaite *et al.* obtained 85 ps duration pulses of 1.1 mJ at 1064 nm and 675 pJ at 552 nm at PRF up to 2 kHz using an Nd:YAG regenerative amplifier with a new high voltage driver employing VFET's. In 2001, Yang and Walker presented an efficient ultrafast regenerate amplifier that increased the energy of a laser pulse from 300 pJ to 6 mJ and produced an average power as large as 9 W in TEM_{00} spatial mode at the repetition rate range from 10 Hz to 1 kHz.[6] In 2004, 5.3 W average output power at a pulse repetition rate of 40 kHz was achieved with a diode end-pumped Nd:YVO_4 regenerative amplifier by Siebold *et al.*, and the maximum output pulse energy was 350 μJ.[7] In 2004, 0.5 mJ pulse energy with 53 MW peak power at 12 Hz to 20 Hz was achieved by Kleinbauer *et al.*[8] In 2005, Kleinbauer *et al.* obtained 13 W output with 65 μJ pulse energy at 200 kHz with an Nd:$GdVO_4$ regenerative amplifier.[9]

In this paper, we report a dual-end pumped Nd:YVO_4 regenerative amplifier. The influence of the position and the thermal effect of the gain medium on the stability of the amplification cavity is analyzed. And the influence of the cavity stability on the performance of the amplification is studied. The best roundtrip that the amplified seed pulses experience in the cavity is calculated. In the experiment, 4.7 mJ pulse energy is achieved with a pulse repetition rate of 1 kHz. And the regenerative amplifier can operate at the repetition rate from 1 kHz to 10 kHz, with a maximum amplification about 0.5×10^6.

2. Experimental setup

The experimental setup is shown in Fig. 1. The seed oscillator was a diode-pumped Nd:YVO_4 laser, CW mode locked with a semiconductor saturable absorber mirror (SESAM). The output pulse of the seed oscillator was 15 ps in pulse width with a high repetition rate of 86 MHz.[10] TFP1 and TFP2 were both polarizers. A Faraday rotator and a $\lambda/2$ wave plate (HWP) were placed between the two polarizers. The above optical elements together made up the optical isolator and the amplified pulses output from TFP1. QWP and the BBO Pockels-cell (PC) made up the *Q*-switch system, which realized the selection of the seed pulses. By setting the duration time of the electric voltage applied on the BBO Pockels-cell, the roundtrip for the chosen pulse going through the cavity could be decided.[8] The aperture of the BBO Pockels-cell was 3 mm × 3 mm, and the $\lambda/4$ voltage was 4000 V. When no

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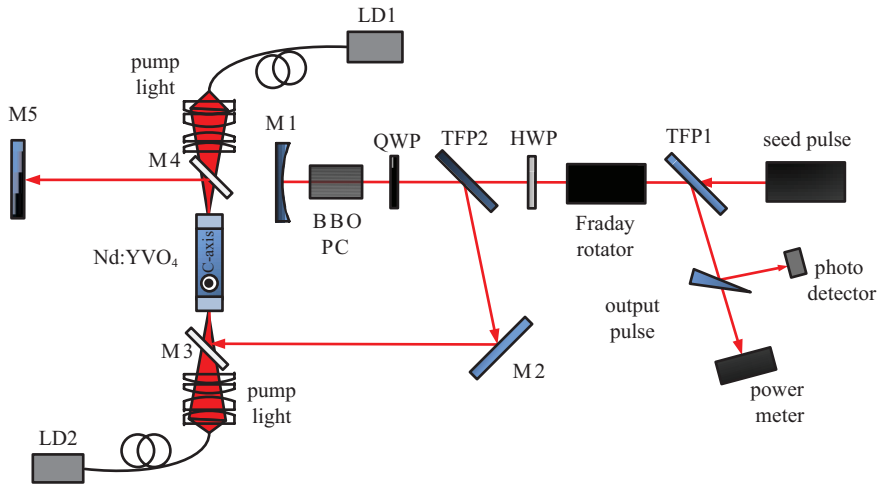


Fig. 1. (color online) Experimental setup of the regenerative amplifier.

voltage was applied on the Q-switch, the horizontal polarized seed went through the amplification cavity for two times and then output from TFP1. When a quarter-wave voltage was applied on the Q-switch, the pulse in the amplification cavity would be locked in the cavity and amplified ceaselessly until the voltage was removed. And then a giant pulse would be achieved. During the duration of the quarter-wave voltage, other seed pulses in the cavity could not come into the amplification cavity.

An a-cut 0.3 at.% doped Nd:YVO_4 crystal was used as the gain medium of the amplifier. The Nd:YVO_4 crystal had a dimension of 3 mm$\times$ 3 mm$\times$16 mm with two undoped 3 mm $\times$ 3 mm $\times$ 2 mm YVO_4 caps placed at each end to reduce the thermal gradients and the mechanical stress. The two ends of the Nd:YVO_4 crystal were dichroic anti-reflection (AR) coated at 1064 nm and 808 nm with transmissivity higher than 99.9% and 98%, respectively. The composite Nd:YVO_4 laser crystal was wrapped in 0.2 mm indium foil and placed in copper heat sinks with water cooling. The pump was from both sides with fiber-coupled diode lasers at 808 nm. The coupling fiber of the laser diode (LD) module had a numerical aperture of 0.22 and a core diameter of 400 μm. An aberration free lens group was used to image the pump beam from the fiber into the Nd:YVO_4 crystal, and the magnification of the coupling system was 1:2. The exact spot radius of the pump beam in the crystal was around 0.5 mm.[11] M1 was a high-reflection (HR) spherical mirror at 1064 nm with a curvature radius of 3 m. M2 and M5 were HR plane mirrors at 1064 nm. M3 and M4 were dichroic plane mirrors that were HR coated at 1064 nm and AR coated at 808 nm with transmissivity more than 99.9% and reflectivity higher than 98% for lasers at the incident angle of 45°, respectively. The optical length in the amplification cavity from M1 to M5 was decided by the equation

$$\frac{c}{2}(t_Q + t_w) \le L \le c\Delta T, \tag{1}$$

where t_Q is the jitter time of the Q-switch, t_w is the pulse width of the seed, and ΔT is the interval between two seed pulses. Since t_Q is about 4 ns, t_w is 15 ps, and ΔT is 11.6 ns, the cavity length should be about 1.4 m.

3. Thermal effects and stability of the regenerative amplifier

3.1. Thermal effects

An end pumped rod gain medium in a laser acts as a thin lens.[12] And the thermal lens focal length of the end pumped rod, when the profile of the pump beam looks like a top-hat, can be expressed as[13]

$$f(r) = \frac{2\pi K_c \omega_p^2}{P_p r \eta_{abs} \eta (dn/dt)}, \quad r \le \omega_p, \tag{2}$$

$$f(r) = \frac{2\pi K_c r^2}{P_p r \eta_{abs} \eta (dn/dt)}, \quad r > \omega_p, \tag{3}$$

where K_c is the thermal conductivity of the laser material, ω_p is the radius of the pump beam, P_p is the incident pump power, $\eta_{abs} = 1 - \exp(\alpha L)$ (α is the absorption coefficient, L is the length of the crystal) is the fraction of pump power absorbed in the laser rod, η is the transmission coefficient of M3 and M4, dn/dT is the change of the refractive index with temperature, and γ is the fraction of absorbed pump power dissipated as heat. From Eqs. (2) and (3), we can see that the focal length has the same value in the region of $r \le \omega_p$, and is proportional to r^2 in the region of $r > \omega_p$.

As described in Section 2, the size of our composite Nd:YVO_4 crystal is 3 mm $\times$ 3 mm $\times$ 20 mm, and the spot size in the crystal is smaller than the cross-section,[11] so we can regard the crystal as a rod and use Eqs. (2) and (3) to estimate the thermal lens focal length. It should be noted that the focal

length caused by thermally induced stress and thermal deformation of the rod is neglected in our paper. The parameters in Eqs. (2) and (3) are listed in Table. 1.

Table 1. Parameters in Eqs. (2) and (3).

Parameter	Value
K_c	||c: 5.5 W/m/K; ⊥c: 5.1 W/m/K
dn/dT	$dn_o/dT = 8.5 \times 10^{-6}$ K^{-1};
	$dn_e/dT = 2.9 \times 10^{-6}$ K^{-1};
α	5 cm^{-1}@808 nm
L	1.6 cm
ω_p	0.5 mm
γ	0.24
η_{abs}	99.99%
η	98%

3.2. Cavity stability

As an independent laser cavity, the performance of the regenerative amplifier is studied in this section. The structure of the cavity is shown in Fig. 2, where L_1, L_2, R_1, and R_2 are invariant after the cavity is set up. However, the focal length f of the convex lens, which represents the thermal lens of the pumped gain medium, varies with the pump power. Through experiment, we find that making R_1 to be 3 m and R_2 to be ∞ would suppress the diffraction loss of the seed beam perfectly.

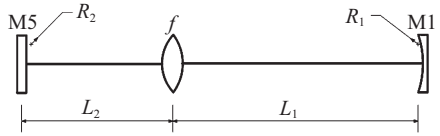


Fig. 2. The equivalent cavity of the regenerative amplification cavity.

With the help of Eq. (2) and the theory about the stability of a laser resonator,[14] we calculate the beam waist size on the gain medium (ω_3) with different values of L_1 and L_2. The results are shown in Fig. 3. The blue line corresponds to the condition of $L_1 = 800$ mm and $L_2 = 600$ mm, the red line corresponds to the condition of $L_1 = 1000$ mm and $L_2 = 400$ mm, and the green line corresponds to the condition of $L_1 = 1200$ mm and $L_2 = 200$ mm. From Fig. 3, we can see that with the increase of L_1/L_2, the interval between the two stable zones becomes large and the width of each zone becomes narrower. In our experiment, we choose the condition of $L_1 = 1000$ mm and $L_2 = 400$ mm to obtain a relatively high pump power and a relatively wide pump power range. Under the condition of $R_1 = 3000$ mm, $R_2 = \infty$, $L_1 = 1000$ mm, and $L_2 = 400$ mm, the waist sizes on M1 (ω_1), M5 (ω_2), and the gain medium (ω_3) corresponding to different pump power are plotted in Fig. 4. The two stability zones are 0–12 W and 26–44 W.

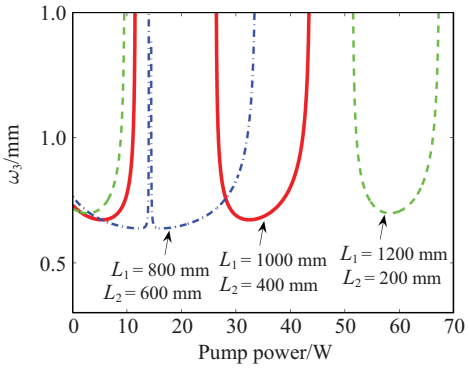


Fig. 3. (color online) Beam waist size on the gain medium ω_3 with different values of L_1 and L_2.

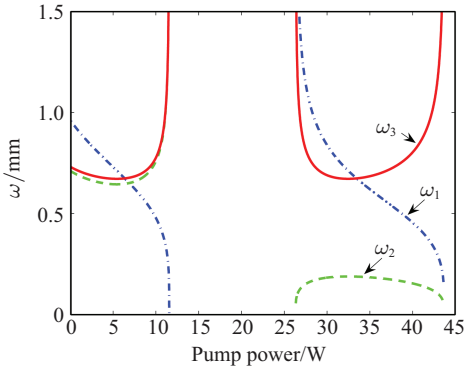


Fig. 4. (color online) Beam waist sizes on M1 (ω_1), M5 (ω_2), and the gain medium (ω_3) corresponding to different pump power under the condition of $R_1 = 3000$ mm, $R_2 = \infty$, $L_1 = 1000$ mm, and $L_2 = 400$ mm.

4. Experimental results and discussion

4.1. Output of the regenerative amplification cavity

Firstly, we test the property of the cavity without the Pockels-cell. The pump power ranges from 6 W to 52 W, the corresponding output power is plotted in Fig. 5. From Fig. 5, we can see that the output power obviously decreases in the pump power ranges from 14 W to 25 W and above 45 W. It is consistent with the theoretical analysis in Fig. 4 very well. Under the 45 W pump power, 8.5 W max average output power is obtained with 20% optical-to-optical conversion efficiency. And in stability zone 2, the slope efficiency is 41.7%. The long cavity and the inserting of the TFP2 and the QWP increase the loss factor and then lead to a relatively low optical-to-optical efficiency.

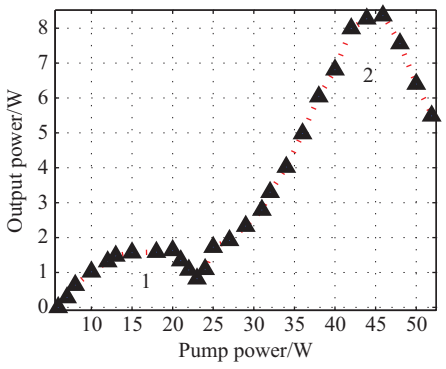


Fig. 5. (color online) Relationship between the output power and the pump power of the regenerative cavity.

4.2. Regenerative amplification results

After the above study of the cavity, we insert the Pockels-cell into the cavity. The mode-locked seed pulse is also injected into the cavity. The power, pulse width, and repetition rate of the seed are 0.9 W, 15 ps, and 86 MHz, respectively, corresponding to a pulse energy of 10 nJ and a peak power of 0.7 kW. The high voltage switch can offer a voltage from 1 kV to 6 kV with a duration of 10–1000 ns at the repetition rate from 1 kHz to 10 kHz. A photodiode is placed at the back of the end mirror M5 for detecting the leakage through M5 to monitor the build-up of the amplified pulse during each trip inside the cavity. The oscilloscope traces detected by the photodiode are shown in Fig. 6. From Fig. 6, we can see that the power of the amplified pulse experiences an up and down process without cavity dumping. It means that we should make the cavity dump at the right time to get the amplified pulse with the highest pulse energy.

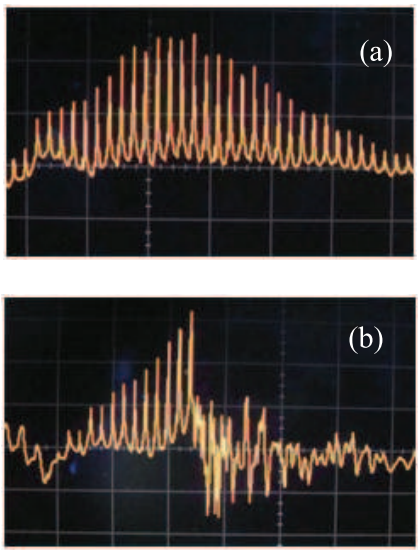


Fig. 6. (color online) Oscilloscope traces detected by the photodiode at the back of M5: (a) without cavity dumping, (b) with cavity dumping.

To find the best k (k represents the roundtrips the pulse traveled in the regenerative cavity), we study the relationship between the pulse energy density and the roundtrips with different small signal gain G_0. The results are shown in Fig. 7, from which we can see that with the increase of G_0, the best k becomes smaller. When G_0 varies from 1.5 to 6, the best k decreases from about 45 down to about 10.

The theoretical value of the small signal gain G_0 corresponding to the pump power for our experimental setup is shown in Fig. 8. The value of G_0 approximately linearly rises from 1.82 at 15 W pump power to 6.1 at 45 W.

From Figs. 7 and 8, we can obtain the theoretically best roundtrips at different pump power. And the best roundtrips of the amplified pulse corresponding to different pumping power in both theory and experiment are shown in Fig. 9. By comparing the experimental results with the theoretical analysis, we

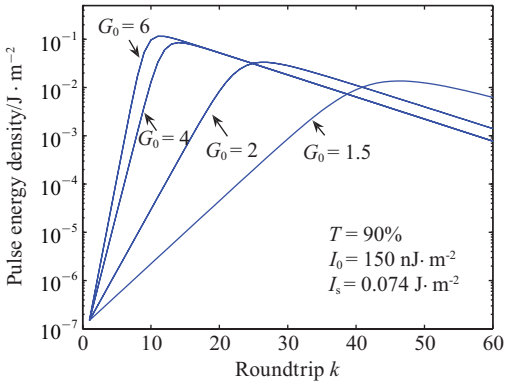


Fig. 7. (color online) The influence of the varying roundtrip k on the pulse energy density with different G_0.

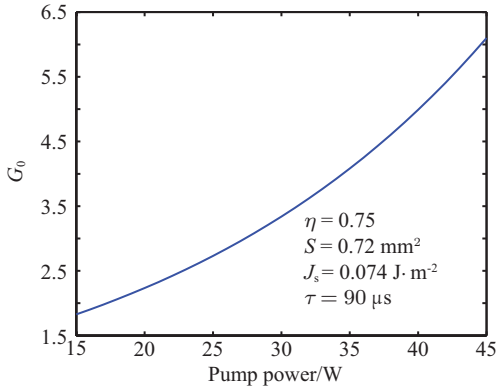


Fig. 8. (color online) The variation of the small signal G_0 with different pump power.

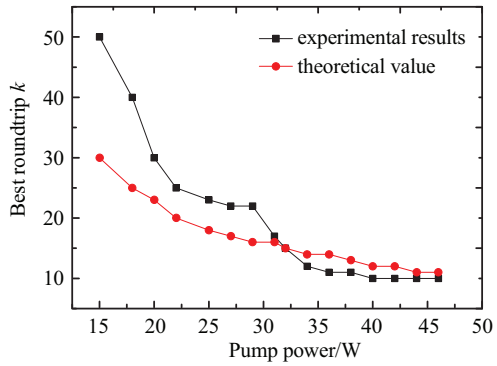


Fig. 9. (color online) The best roundtrips k corresponding to different pumping power P_p.

can see that the two agree with each other well at high pump power, while not that well at low pump power. It may be due to that the real gain coefficient G is lower than the theoretical value at low pump power. From the experimental results, we can see that the best roundtrip k in the unstable zone (from 25 W to 30 W) is lower than the theoretical value by a higher degree. The influence of the unstable zone on the average output power can be seen more clearly in Fig. 10, in which the relationship between the increased average output power and the pump power is shown. Comparing Fig. 10 with Fig. 5, one may see that the range of the unstable zone has a little shift to the high power. It is mainly caused by the insert of

the Pockels-cell. At the total pump power of 45 W, we get the highest average output power of 5.3 W. Considering 0.6 W (it is smaller than 0.9 W of the seed pulse due to the losses in the optical isolator and other optical elements, and it is not amplified as it does not pass through the gain medium) initial power of the unamplified seed, we get the increased output power of 4.7 W at the repetition rate of 10 kHz. We tune the repetition rate from 1 kHz to 10 kHz, and find that there is basically no variation on the average output power. So we get the pulse energy ranging from 0.47 mJ to 4.7 mJ. Comparing it with the seed pulse energy of 10 nJ, we obtain an amplification ranging from 0.47×10^5 to 0.47×10^6.

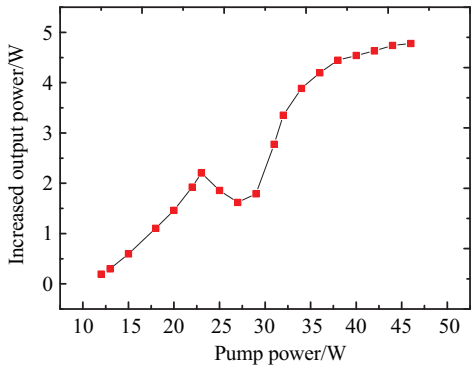


Fig. 10. (color online) The increased power versus the pump power P_p at 10 kHz.

The final output of pulses at the repetition rate of 10 kHz and one single pulse are shown in Figs. 11(a) and 11(b), respectively. The amplified pulse is detected by the photodiode after an attenuation of 1000 times by neutral density filters. From the figures, we can see that there is a high contrast ratio of the pulses. The unamplified seed pulses have little influence on the amplified pulses.

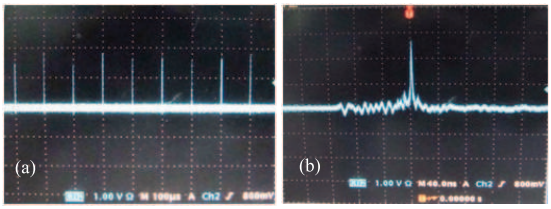


Fig. 11. (color online) The oscilloscope traces of the amplified pulses attenuated for 1000 times: (a) the oscilloscope trace of the pulses at 10 kHz, (b) the oscilloscope trace of one of the pulses.

4.3. Discussion

We now explain why the 5.3 W output seems not that high for the small signal gain coefficient $G_0 = 6$ under the pump power of 45 W. It is mainly caused by two factors. Firstly, the divergence angle of the seed is a little large. Though we have used a concave mirror ($R = -3$ m) to compensate for it, there are still some parts of the beam which can not pass through the relatively long gain medium. This leads to some loss of the seed energy. Secondly, the waist radius of the pump beam is about 0.5 mm, which is smaller than the seed beam radius on the gain medium. The mode radius ratio between the seed beam and the pump beam is relatively large, so the edge of the seed beam can not obtain enough amplification. The two factors should be considered in the future to obtain higher pulse energy and higher output power.

5. Conclusion

A regenerative amplifier with a dual-end-pumped Nd:YVO_4 crystal as the gain medium was demonstrated. The traditional pulse picker was omitted in our design, and relatively ideal results were obtained. The influence of the position and the thermal effects of the gain medium on the stability of the regenerative amplification cavity was analyzed. The influence of the stability of the regenerative amplification cavity on the performance of the amplification was also analyzed, which was seldom studied in the previous articles. The best roundtrip the amplified seed pulses experiencing in the cavity was calculated. The results matched well with the theoretical calculation. The regenerative amplifier we designed could increase the average power of the seed pulse by 4.7 W under the pump power of 45 W at a repetition rate from 1 kHz to 10 kHz. It could amplify the picosecond mode-locked pulses from 10 nJ to 0.47–4.7 mJ at 1–10 kHz, respectively. The max amplification of single pulse was up to 0.5×10^6.

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