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Non-Pulse-Leakage 100-kHz Level, High Beam Quality Industrial Grade Nd:YVO_4 Picosecond Amplifier

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Abstract: A non-pulse-leakage optical fiber pumped 100-kHz level high beam quality Nd:YVO_4 picosecond amplifier has been developed. An 80 MHz, 11.5 ps mode-locked picosecond laser is used as the seed with single pulse energy of 1 nJ. By harnessing the double β-BaB_2O_4 (BBO) crystal Pockels cells in both the pulse picker and regenerative amplifier, the seed pulse leakage of the output is suppressed effectively with an adjustable repetition rate from 200 to 500 kHz. Through one stage traveling-wave amplifier, a maximum output power of 24.5 W is generated corresponding to the injected regenerative amplified power of 9.73 W at 500 kHz. The output pulse duration is 16.9 ps, and the beam quality factor M^2 is measured to be 1.25 with near-field roundness higher than 99% at the full output power.

Keywords: regenerative amplifier; double-crystal Pockels cell; 100-kHz; non-pulse-leakage

1. Introduction

Over the past decade, there has been significant development of high power ultrashort pulse lasers with high repetition rate [1–3], with applications including nonlinear optical frequency conversion, precise material processing, satellite ranging, and high-intensity physics [4–7]. Specifically, in ultrashort lasers in the order of picoseconds, their pulse width is smaller than the electron-phonon coupling time of most materials, heat conduction can be decreased substantially during the process of interaction. This decrease is beneficial to fine processing, biological medicine, and historical relic cleaning [8–11]. Currently, mode-locking is the main approach to obtain the pulse width around ~10 ps. However, the pulse energy of the directly generated mode-locked lasers is very low such that it restricts their applications. To solve this problem, different types of laser amplifiers are utilized, in which a regenerative amplifier is considered to be the most effective method for strong amplification of the mode-locked pulses [1,2,12,13]. In most cases, increasing the repetition rate and power can improve the efficiency of laser processing and laser ranging. Therefore, it is not only necessary to increase the single pulse energy but also the repetition rate of the current regenerative amplified lasers. Determined by the parameters of Pockels cell and regenerative cavity, repetition rates from hundreds to mega-Hz have been obtained with output power up to 100 watts. For instance, $Nd:YVO_4$ picosecond regenerative amplifiers with a repetition rate up to 850 kHz have been demonstrated [14,15]; other broadband gain materials such as $Yb:CaF_2$, Yb:CAlGO, $Yb:YVO_4$, and $Nd:LuVO_4$ show up to 1.43 MHz repetition rate [16–18]. Currently, Bergmann et al. [19] reported the record high repetition rate of 2 MHz for a picosecond regenerative amplifier in Yb:YAG. In general, when the repetition rate is up to 100 kHz, it is very difficult for the Pockels cell to realize the fast and complete switching due to the limitations of high voltage driving supply. This will lead to the leakage of the directly amplified seed pulses in the output that not only introduce optical noise but also increase unnecessary pump power consumption. Especially after traveling-wave amplification, the existence of pulse leakage will further reduce the master-slave pulse ratio of the output and influence the performance of the laser system in applications. For example, in nonmetallic brittle materials processing (viz. artificial crystal, ceramics, and solar panels), the amplified leaking pulses easily cause breakage of the samples because of the excessive heat load; meanwhile, the presence of leaked pulses also results in the reduction of accuracy in laser satellite ranging and laser communication due to the introduction of stray signals. Therefore, it is necessary to eliminate the pulse leakage of regenerative amplifiers used in some specific industrial areas.

$Nd:YVO_4$ crystals as a gain material with sufficient gain bandwidth and a high emission cross section are widely adopted in end-pumping picosecond regenerative amplifiers. Nowadays, fiber coupled high-power laser diode (LD) are an appropriate pumping source for the regenerative amplifier due to their highly compact size and relatively low cost. The pumping of $Nd:YVO_4$ with 888 nm LD induces less thermal stress gradient along the crystal compared with 808 nm that makes it possible for long time operation of the laser with higher stability [20,21]. Table 1 presents the physical parameters of $Nd:YVO_4$ crystal pumped by 808 nm and 888 nm wavelengths [22,23]. As the data show, the lower fractional thermal loading in 888 nm pump compared with 808 nm wavelength results in the heat reduction and optical efficiency growth. Although the absorption coefficient of 808 nm is higher compared to 888 nm wavelength, it shows different values between the two crystallographic axes that result in the varying and irreproducible absorption if without the polarization controlling of pump light. The lower pump absorption efficiency can be optimized by using a longer crystal for high output power that allows the heat load to be spread in a larger volume, thus minimizing stress and thermal gradient [24]. Additionally, the 888 nm wavelength shows a higher absorption band width than 808 nm, which decreases the sensitivity to the shift in the pump wavelength.

Table 1. Comparison of $Nd:YVO_4$ pumped by 808 nm and 888 nm.

Wavelength (nm)	Output Wavelength (nm)	Fractional Thermal Loading	Absorption Coefficient (cm^{-1})	Absorption Band Width (nm)
808	1064	0.241	10 (*a*-axis) 37 (*c*-axis)	0.8
888	1064	0.173	1.5 (*a*- & *c*-axis)	3

In this study, we demonstrate a highly stable and high power industrial grade picosecond $Nd:YVO_4$ amplifier with the adjustable repetition rate from 200 to 500 kHz. A combination of an 888 nm optical fiber pumped $Nd:YVO_4$ regenerative and a traveling-wave amplifiers have been utilized. To eliminate the leakage of the regenerative amplifier in high repetition rate operation, double BBO crystal Pockels cells are adopted as one switch to improve the responsivity of the switching. The maximum output power of 24.5 W is obtained at 500 kHz with the pulse width of 16.9 ps, corresponding to the pulse energy and the peak power of 0.05 mJ and 2.9 MW, respectively. The beam quality factor M^2 is measured to be 1.25 at the full power operation. When operated at 200 kHz, the maximum pulse energy of 0.11 mJ and the maximum peak power of 6.5 MW is obtained. Our measurements show that this method effectively realizes the suppression of leakage and improves the purity of the regenerative amplified pulses.

2. Experimental Principle and Setup

Q-switch is the core component of the regenerative amplifier that is used in the pulse picker for mode-locked sequence. To date, both acousto- and electro-optic switches have been used to realize the pulse selection function in regenerative amplifiers [19,25,26]. However, due to the slow switching speed (with rise time up to 100 nanoseconds) and limited diffraction efficiency (usually less than 90%), the acousto-optic switch is difficult to generate regenerative pulses without the leakage of mode-locked seed. In contrast to the acousto-optic switch, the electro-optic switch has faster switching speed (rise time <10 ns) and excellent switching effect, which is widely adopted in regenerative amplifiers. Nowadays, the commonly used electro-optic crystals include β-BaB_2O_4 (BBO), KH_2PO_4 (KDP), KD_2PO_4 (KD * P), $RbTiOPO_4$ (RTP), and $LiNbO_3$ (Lithium niobate) etc. To meet different experimental conditions (such as half- or quarter-wavelength voltage, acceptable input beam diameter, and available crystal size), both longitudinal and transverse electrode configuration Pockels cells are manufactured. However, so far there is not one kind of electro-optic crystal or configuration the can provide a general solution under different operating wavelengths, repetition rates, spot diameters, and output powers. At present, BBO crystal Pockels cells with minimal piezoelectric ringing and low acoustic noise, have emerged in high repetition rate (>100 kHz) pulse picking applications [14–17,19]. Nevertheless, with the increase of repetition rate, it is difficult to realize fast switching within the effective duty cycle due to the long fall time of the high voltage.

To solve the problem, double BBO crystal Pockels cell is adopted in our experiment to reduce the load of the high voltage driving supply by reducing the quarter-wavelength voltage. The value of the quarter-wavelength voltage $V_{\lambda/4}$ of BBO crystal is given by [27,28]:

$$V_{\lambda/4} = \frac{\lambda d}{4 n_0^3 d_{22} L} \tag{1}$$

where laser wavelength λ = 1064 nm, the crystal section thickness d = 3 mm, the refractive index of the crystal n_0 = 1.66, the effective electro-optic coefficient d_{22} = 2.2 pm/V, and the crystal length L = 40 mm. The calculated value of the quarter-wavelength voltage is just 2000 V, which is almost half that of the previous reports. The lower quarter-wavelength voltage of Pockels cell means faster switching speed, and makes it possible for higher repetition rate operation.

The experimental setup of the picosecond amplifier is shown in Figure 1, which consists of a picosecond seed source, two optical isolators, a BBO pulse picker, a regenerative amplifier, and one stage traveling-wave amplifier.

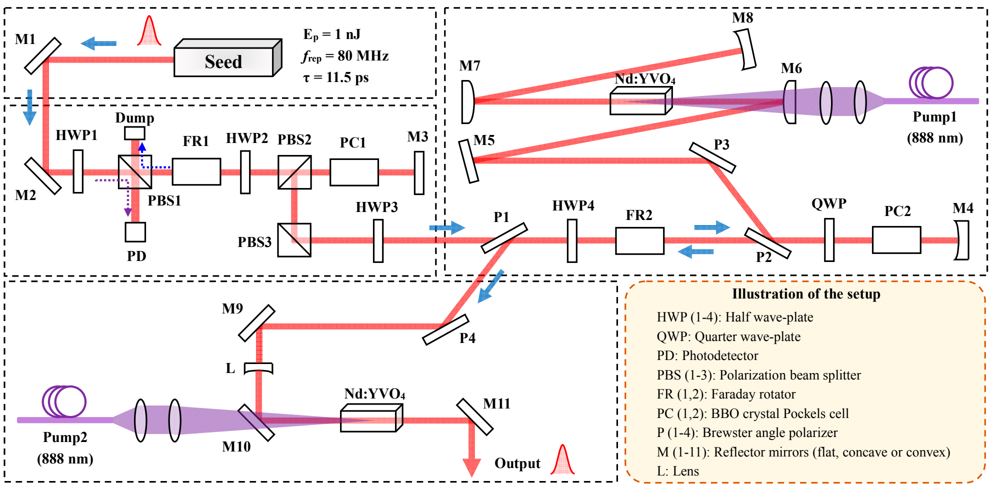

Figure 1. Diagram of the non-leakage 100-kHz $Nd:YVO_4$ picosecond regenerative amplifier. The inset is the illustration of the setup.

In the present system, the amplifier is seeded with a self-developed semiconductor saturable absorption mirror (SESAM) mode-locked oscillator capable of generating 11.5 ps pulses at a repetition rate of 80 MHz with a single pulse energy of 1 nJ. Picosecond pulse sequence from the seed is injected into the pulse picker through two high-reflection mirrors, M1 and M2. The function of the pulse picker is to select the desired repetition rate for regenerative amplifier by eliminating the pulse leakage of the seed sequence. The half-wave plate HWP1 is set to let most of the seed light to *p*-polarization and the rest *s*-polarization reflected into the photodetector (PD) as feedback signal. After passing through the first stage optical isolator composed of a polarization beam splitter PBS1, a Faraday rotator FR1, and a HWP2, the seed enters into the double BBO crystal Pockels cell PC1 (PCB3S-1342; EKSMA Optics, Vilnius, Lithuania). The size of the two BBO crystals are $3 \times 3 \times 20$ mm^3. The distance between the PC1 and M3 is 0.8 m, corresponding to a round-trip time about 5.3 ns. Without voltage of the PC1, the reflected seed from the M3 will pass through the PBS2 and FR1, then enter into the dump. While with a quarter-wavelength voltage of the PC1, the pulse sequence with a specified range of repetition rate can be selected with polarization changed to *s*-polarization after double-passing through PC1 and then output by the PBS2. The switching time of the two Pockels cells in our setup is adjustable from 25 to 200 ns with a rising and falling time about 5 ns. The switch time of the PC1 is set to be 20 ns. With the polarization changed to *p*-polarization by HWP3, the selected pulses enter into the regenerative amplifier. The second optical isolator formed by a Brewster angle polarizer P1, HWP4, and FR2 is placed in front of the regenerative amplifier which is used to output the regenerative amplified pulse.

The laser pulse with *p*-polarization is injected into the regenerative amplifier by the P2. The length of the whole cavity is 1.8 m, corresponding to a cavity round-trip time of 12 ns. The gain medium is 0.5 at. % doped Nd:YVO_4 with a size of $3 \times 3 \times 20$ mm^3 and double-end-wedged cut at 2°. Both sides of the Nd:YVO_4 have anti-reflective (AR) coating at the 1064 nm and 888 nm wavelength. A 50 W, 888 nm fiber-coupled laser diode with a numerical aperture of 0.22 and a diameter of 400 μm is used as the pump source. The coupling ratio of the pump beam is 1:3 into the Nd:YVO_4 crystal. M4 and M8 are two concave mirrors with R = −2000 mm; M4 and M7 are two 1064 nm high-reflection (HR) convex mirrors with R = 1500 mm in which M4 is also 888 nm AR coated. Reflected by an end mirror M4, the seed beam double passes the quarter-wave plate (HWP) and reflects through P2 with *s*-polarization. Then the PC2 inside the cavity is switched on with a quarter-wavelength voltage and the seed laser continues to make round trips in the regenerative cavity with *s*-polarization until the PC2 is switched off. The regenerative amplified pulses are reflected by P1 with *s*-polarization, and then enter into the traveling-wave amplifier.

To further amplify the output power, one stage traveling-wave Nd:YVO_4 amplifier is adopted. A Nd:YVO_4 crystal with the dimensions of $4 \times 4 \times 30$ mm^3 is selected as gain medium with 0.5 at. % Nd^{3+}-doped and at a 2° angle. The pumping source of the traveling-wave amplifier has the same parameters as the regenerative amplifier with a coupling ratio of 1:4. L is a concave lens with f = −360 mm used to compensate the thermal lens effect of the Nd:YVO_4 crystal. M10 and M11 are two 888 nm AR & 1064 nm HR coated 45° plane mirror. The single-pass amplified pulse is output from the M11.

3. Experimental Results and Discussion

In our experiment, we tested the leakage of the regenerative amplifier by monitoring the output power with the PC2 turning on and off. At the maximum pump power of 50 W, the output power of the regenerative amplifier increases with the Pockels cells switching time, however, the leakage appears when the PC2 switching time more than 69 ns. For example, with the switching time of 79 ns, the leakage reached 2 W when the maximum regenerative amplified power was about 18 W at 500 kHz. Accordingly, in order to obtain maximum power regenerative output without leakage, the switching time of Pockels cells is set to be 68 ns, corresponding to the five round trips in the regenerative cavity. The pump power of the regenerative amplifier is set to be 50 W because higher power may result in the self-excited oscillation between the M4 and M8. Next, improvement of the leakage and self-excited oscillation threshold to increase the output power of regenerative amplifier will be studied, including the optimization of cavity design and Pockels cell structure (e.g., employing bidirectional voltage switching power supply to achieve a faster and more thorough switch [29]).

The injected pulse energy into the regenerative amplifier was about 1 nJ, and the output pulse energy saturated with the increase number of round trips in the cavity. Figure 2a,b illustrates the dependence of the output power and pulse energy of the regenerative and final amplifier output on the repetition rate from 200 to 500 kHz, respectively. At the same pump power, the out power of the regenerative amplifier increases with the repetition rate, while the single pulse energy decreases, which is shown in Figure 2a. At 500 kHz, maximum regenerative amplified power of 9.73 W was obtained corresponding to the pulse energy of 0.02 mJ. After passing through the traveling-wave amplifier, the maximum output power of the laser system was 24.5 W at 500 kHz, corresponding to the peak power of 2.9 MW; while the maximum output pulse energy obtained was 0.11 mJ at 200 kHz, corresponding to the peak power of 6.5 MW. No leakage occurred when the repetition rate continuously adjusting from 200 to 500 kHz with the measured root-mean-square-error (RMSE) of output power less than 0.04%.

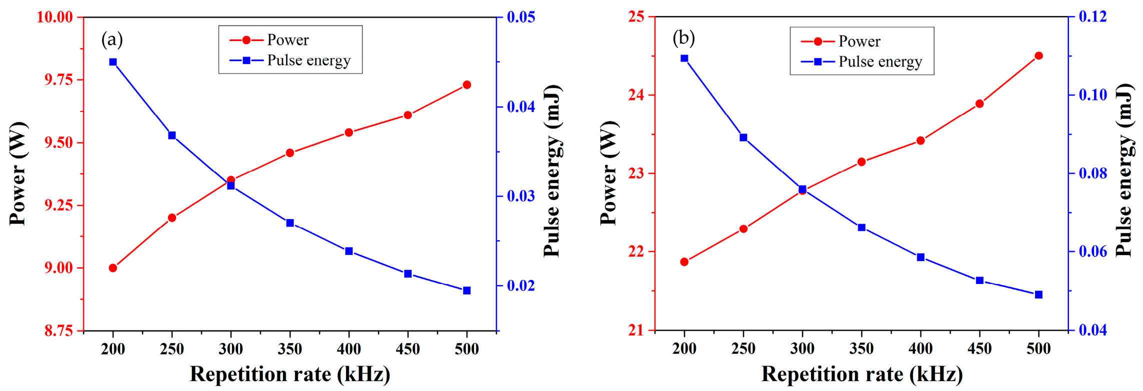

Figure 2. Average output power and pulse energy of the amplifier in dependence on the repetition rate of (**a**) regenerative amplifier output; and (**b**) final amplifier output.

The amplified pulses are monitored using a photodiode. At 500 kHz, oscilloscope trace of the output pulse train with 4 µs/div and single pulse with 10 ns/div are illustrated in Figure 3, respectively. We can observe that the amplifier generates very clean output pulses without any noticeable pulse fluctuation or stray signal.

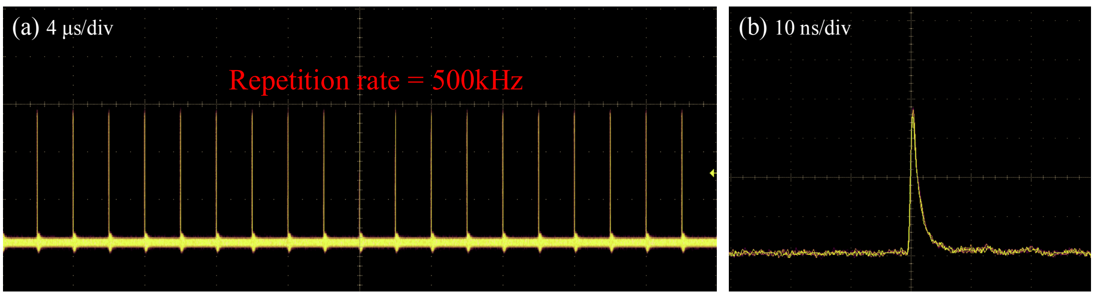

Figure 3. Oscilloscope trace of the regenerative amplified pulse train (**a**) 4 µs/div; and (**b**) 10 ns/div.

Figure 4a shows the autocorrelation trace of the amplified pulses with the measured width of 16.9 ps at a repetition rate of 500 Hz. The pulse width of the output was slightly broadened compared with that of the seed pulses 11.5 ps, which is mainly caused by the gain narrowing [30,31]. The measured beam quality factor M^2 and near-field beam intensity profile are shown in Figure 4b.

The M^2 measured were 1.27 and 1.22 for the horizontal and vertical axes of the output, respectively. The roundness of the near-field intensity distribution is higher than 99%.

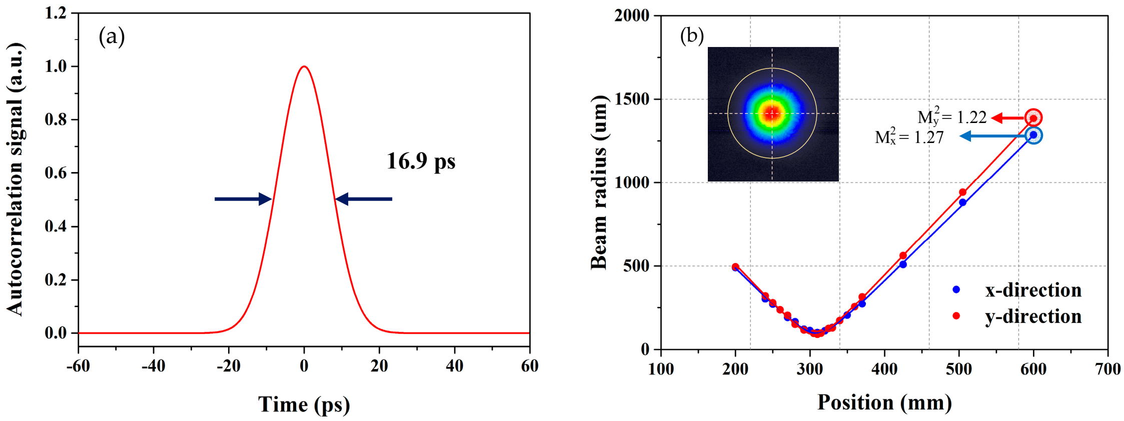

Figure 4. Measured (**a**) autocorrelation trace (Gaussian fitting) for the amplified pulse; and (**b**) beam quality factor M^2 (insert: near-field beam intensity distribution).

4. Conclusions

In conclusion, we have demonstrated a non-pulse-leakage high power industrial grade Nd:YVO_4 picosecond amplifier. Two double BBO crystal Pockels cells were used in the pulse picker and regenerative amplifier, respectively. This design successfully suppresses the appetence of pulse leakage in the regenerative amplifier that improved the purity of the output pulses, which makes it possible for the regenerative amplifier to operate stably at the repetition rate of 100-kHz level with lower high voltage driving supply. A maximum power of 24.5 W was obtained at 500 kHz, and a maximum single pulse energy 0.11 mJ was obtained at 200 kHz. High beam quality output is obtained with M^2 about 1.25 and the roundness of near-field distribution up to 99%. The output pulse width measured to be 16.9 ps with the RMSE of the output is less than 0.04%. Our work offers a new approach to generate high quality (in both time domain and space domain) 100-kHz level repetition rate continuous adjustable picosecond regenerative amplified output. This solution can be made possible with high efficiency and high precision processing for nonmetallic brittle materials, as well as low noise space communication.

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Author Contributions: We confirm that all authors contributed substantially to the reported work. Zhenao Bai was the originator of the idea of this study and conceived most of the experiments; Zhenxu Bai performed the experiments and wrote the manuscript under the supervision of Zhenao Bai and Zhongwei Fan; Zhijun Kang, Fuqiang Lian, and Weiran Lin participated in the research design and analyzed the data; Zhongwei Fan supervised the research and provided the facilities. All the authors discussed and interpreted the results. All the authors read the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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