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Article

Optical Fiber Pumped High Repetition Rate and High Power Nd:YVO_4 Picosecond Regenerative Amplifier

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Abstract: We report a stable optical fiber pumped Nd:YVO_4 all solid state regenerative amplifier with all fiber picosecond laser as seed source. 888 nm Yb optical fiber lasers was chosen as pump source to reduce quantum defect for improved thermal performance. At the repetition rate of 99.6 kHz, maximum power of 19.63 W with 36 ps pulse duration were achieved when seeded by a 150 mW picosecond oscillator. The wavelength delivered was 1064.07 nm with spectral width of 0.14 nm.

Keywords: picosecond laser; all solid state; high repetition rate; regenerative amplifier

1. Introduction

Picosecond lasers with compact structure, lightweight and high stability are in demand for a number of applications, such as laser satellite ranging (SLR), precision machining, biology, spectroscopy, and military science [1–5]. All fiber picosecond laser has the characteristics of miniaturization and lightweight, however, the peak power of all fiber laser operating in the picosecond regime is limited to the nano-Joule level due to the strong nonlinear effect in high peak power operation. In order to generate stable high peak power regenerative amplifier output, a good way is to combine the fiber picosecond seed source with all solid state regenerative amplification technology [6–8].

In order to obtain high peak power regenerative amplified output at high repetition rate, we need to improve the injected pumping power as well as the pump absorption efficiency. At present, 808 nm wavelength is the most widely used pumping source of Nd:YVO_4 crystal for the highest absorption peaks around 810 nm. However, due to the poor thermal and mechanical properties of Nd:YVO_4, a large temperature gradient will be generated inside the crystal at high power pumping. For example, the heat capacity and conductivity of Nd:YAG are 0.59 J/(g·K) and 0.13 W/(cm·K), respectively; however, as for Nd:YVO_4 are corresponding to 0.79 J/(g·K) and 0.06 W/(cm·K). High local stress can even cause the damage of crystal, which limits the increase of pumping power [9–12]. In addition, the Nd:YVO_4 absorption cross section for π and σ polarizations differ by a factor of 3.7 at 808 nm. That is to say, for an ***a***-axis cutting Nd:YVO_4 crystal, the optical absorption coefficient in 808 nm has great difference along the two orthogonal axis. Although Nd:YVO_4 crystal has lower absorption efficiency with 888 nm (0.15/mm along ***a***- & ***c***-axis) than that of 808 nm (1.0/mm and 3.7/mm, respectively), we can also improve absorption efficiency by increasing the crystal length or Nd-doping concentration. The increase of the crystal length means the increase of the heat dissipation area and the decrease of the thermal effect. Compared with 0.8 nm absorption band in 808 nm pumping, Nd:YVO_4 absorption band in 888 nm pumping is 3 nm which is not sensitive to the fluctuation of the wavelength jitter. Therefore, 808 nm pumped Nd:YVO_4 regenerative amplifier is able to achieve stable output in the case of high pumping power at high repetition rate.

In this paper, we develop a high power and high repetition rate all solid state Nd:YVO_4 picosecond regenerative amplifier by using all optical fiber picosecond laser as seed source and 888 nm laser as pumping source. The regenerative amplifier is operating at 99.6 kHz delivering up to 19.63 W output power with pulse duration 39 ps, central wavelength 1064.07 nm and spectral width 0.14 nm. To our best knowledge, this is the highest power has been generated from an optical fiber end pumped all solid-state picosecond regenerative amplifier at ~100 kHz repetition rates.

2. Experimental Section

Design scheme of the regenerative amplifier is shown in Figure 1. It consists of a fiber seed, an optical splitter, an optical isolator and a regenerative amplifier. After passing through the beam collimator and optical isolation, the seed pulses are derived into two parts. One part enter into the photodetector (PD) as the clock signal, the other part inject into the regenerative amplifier.

The seed we chose is a commercial mode-locked all fiber oscillator that produces 150 mW at repetition rate 46.8 MHz. The pulse duration of the seed pulses is 20 ps with a central wavelength of 1064.06 nm and spectral width 0.2 nm. The optical splitter is composed of a half wave plate and a polarized beam splitter (PBS). By adjusting the half wave plate, we can control the seed power injected into the regenerative amplifier and PD. After adjustment, 100 mW power is injected into the regenerative amplifier, and the rest of the 50 mW entered into the PD. Optical isolator consists of a polarizer, a half wave plate and a Faraday (FR) that just allows the light transmission in the direction of injection. Regenerative amplifier is composed of a polarizer, a quarter wave plate, an electro-optic Q-switch, a gain medium, a pumping source and many total reflection mirrors. The total length of the cavity is about 2200 mm.

Inside the regenerative amplifier, the $Nd:YVO_4$ crystal is end pumped by 888 nm continuous wave (CW) laser. The 0.5-at. % $Nd:YVO_4$ crystal has dimensions of 3 × 3 × 20 mm^3 with 2° wedge angle in one end. To improve the cooling efficiency, $Nd:YVO_4$ crystal is welded on heat sink that cooled in both ***x***- and ***y***- directions. Used as a pulse picker, Pockels cell (PC) consists of two BBO crystals with single crystal size of 3 × 3 × 20 mm^3. PC is operated with quarter-wave voltage. The rise and fall times of the PC driver are about 6 ns. The chirp of $Nd:YVO_4$ and BBO crystals is about 1–2 ps. M1 and M5 are two plano-concave high reflectance (HR) mirrors with R = −2000 mm. M2 and M4 are two plane-convex HR mirrors with R = 1500 mm to compensate the thermal focal length of the medium. M3 is a 45° plane mirror coated with antireflection at 888 nm and highly reflective at 1064 nm. The pump source is an 888nm semiconductor fiber coupling module with maximum output power 100 W. Output fiber core diameter is 400 μm, and the pump beam is coupled into the crystal by a 1:4 coupling lens telescope.

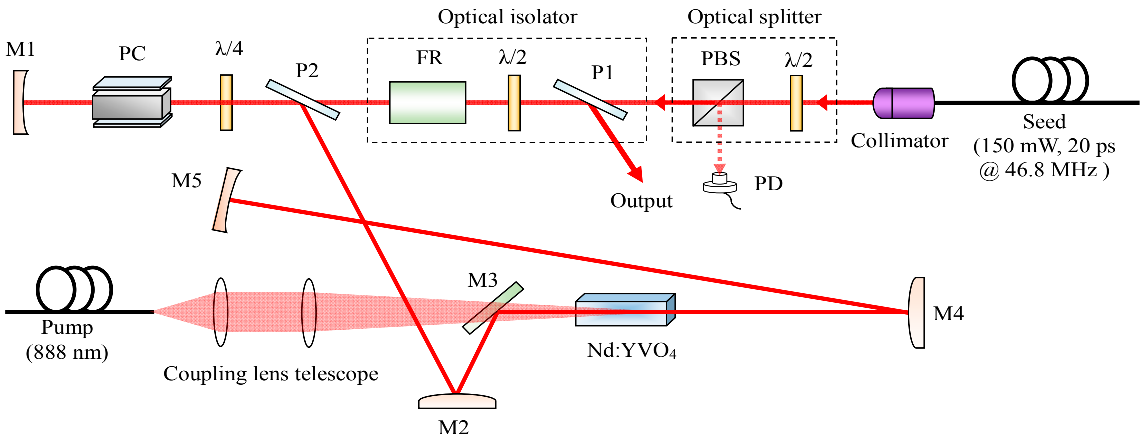

Figure 1. Design scheme of the fiber laser pumped regenerative amplifier.

3. Results and Discussion

When the absorbed pump power is 73.8 W, maximum regenerative amplified output power 19.6 W was generated at 99.6 kHz in center wavelength of 1064.06 nm and spectral width of 0.14 nm. Here, the un-picked seed pulses are amplified to 150 mW when switching off the high voltage of the PC. The pump source spectrum is shifted to the long wavelength with the increase of the power. As shown in Figure 2, the central wavelength of the pump source is 887.66 nm with spectral width of 1.84 nm when operating at 73.8 W.

The curve of output power varies with pump absorbed power is shown in Figure 3. It can be seen from the figure that the output power increases gradually with the increase of the pump power. The highest output power achieved is 19.6W while the absorbed power of medium is 73.8 W.

As shown in Figure 4, different regenerative amplification time corresponding to different output pulse energy. The output energy is relatively stable, about 196 μJ, when the regeneration amplification time ranges from 180 ns to 225 ns.

The stable pulse train, unstable multi-period pulse train trace and a single pulse profile of the regenerative amplified output are shown in Figure 5 (a–c), respectively. Stable pulse train is obtained with the regenerative amplification time of 195 ns at repetition rate of 99.6 kHz, as shown in Figure 5 (a). As the regenerative amplification time continues to increase, along with the phenomenon of multi-period, the output pulse train becomes no longer stable with repetition rate jitter from about 20 kHz to 50 kHz, as illustrated in Figure 5 (b).

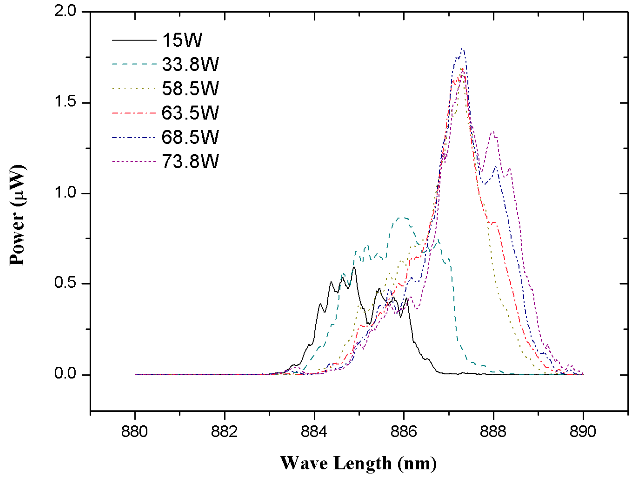

Figure 2. The spectral intensity distribution as a function of absorbed pump power.

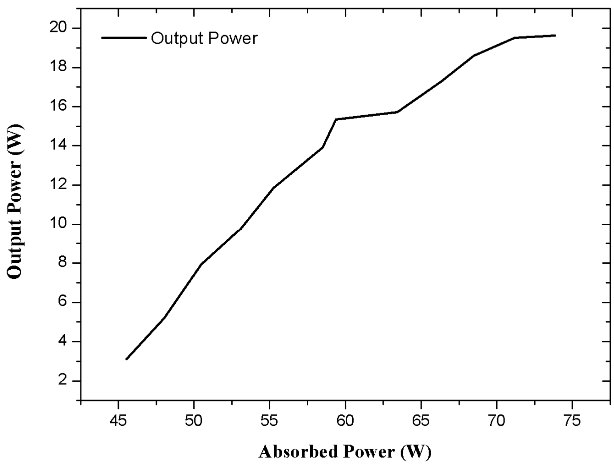

Figure 3. The output power as a function of absorbed power in operation.

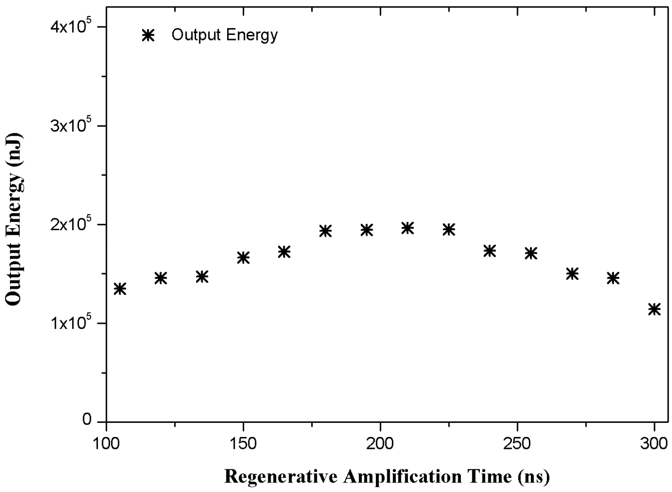

Figure 4. The output energy as a function of regeneration amplification time in operation.

Figure 5. Oscilloscope traces of (**a**) the pulse train at 195 ns regeneration amplification time; (**b**) the pulse train of unstable multi-period phenomenon; (**c**) a single pulse shape at 195 ns regeneration amplification time.

After regenerative regeneration, spectrum distribution of the injected seed is slightly changed, as depicted in Figure 6. Solid line is the spectral intensity distribution curve of seed source with center wavelength 1064.06 nm and the spectral width 0.2 nm. Broken line is corresponding to the regenerative amplified output spectral intensity with center wavelength 1064.07 nm and spectral width 0.14 nm. Results shows that gain narrowing tends to compress the optical spectrum.

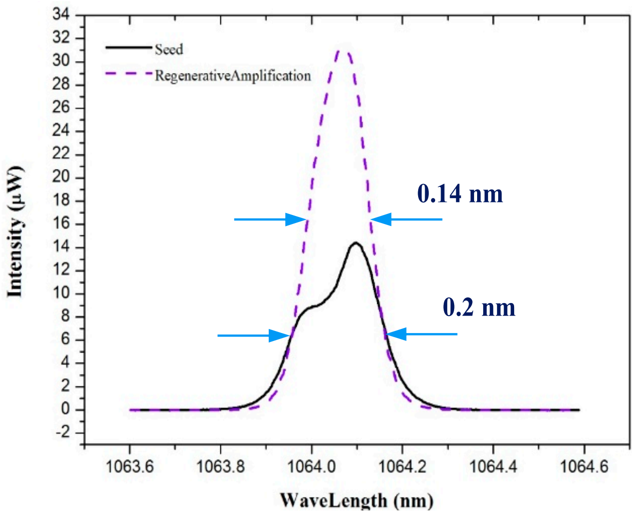

Figure 6. Spectral intensity distribution of the injected seed (solid line) and regenerative amplified output (broken line).

The autocorrelation signal shows that the output pulse duration is 36 ps, as illustrated in Figure 7. Compared with the pulse duration 20 ps of the injected picosecond seed source, the output pulse duration is broadened widely. According to the Fourier transform limited pulse, time-bandwidth product (TBWP) must be equal to or greater than the constant κ[13,14]:

$$\Delta t \cdot \Delta \nu \geq \kappa \tag{1}$$

where Δt is the full width at half maximum (FWHM) of pulse envelope intensity, $\Delta \nu$ is the FWHM of Fourier transform spectroscopy. The TBWP for a Gauss pulse is $\kappa = 2\ln 2/\pi = 0.441$. The TBWP of the fiber picosecond seed source is 1.06, and the regenerative amplified output pulse TBWP is 1.34.

In our experiment, on the one hand, the reason for pulse duration being broader is gain narrowing, and the other is chirp phenomenon.

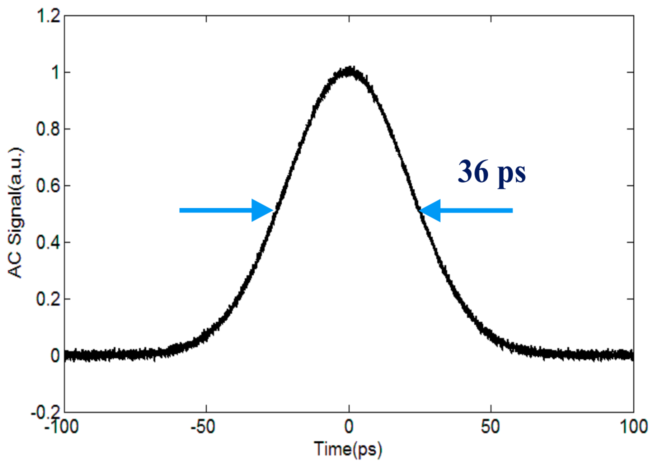

Figure 7. Autocorrelation signal of pulse output from the regenerative amplifier.

Figure 8 represents the beam characteristics of the output, which indicates nearly diffraction limited beam quality. The result giving a beam quality of $M_x^2 = 1.20$, $M_y^2 = 1.19$ in both directions perpendicular to the axis of propagation. The beam diameter in ***x*** direction is 1.5 mm and ***y*** direction is 1.3 mm. The slight deviation of the two direction of the spot is caused by the 2° wedge angle of the crystal.

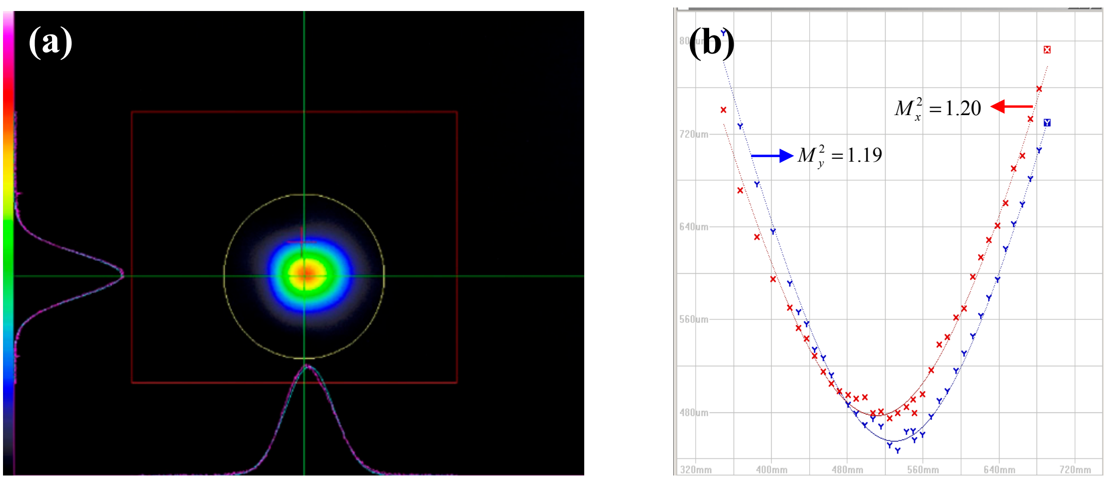

Figure 8. Measured beam characteristics of (**a**) profile of the output with ***x*** direction 1.5 mm and ***y*** direction 1.3mm; (**b**) M^2 with $M_x^2 = 1.20$ and $M_y^2 = 1.19$.

4. Conclusions

In summary, we have demonstrated an optical fiber end pumped high average power and high repetition rate picosecond regenerative amplifier. To reduce the radial temperature gradient of Nd:YVO_4 crystal, 888 nm pumping source is adopted. The influence of different regeneration time on the output waveform, as well as the spectrum distribution of the injected seed and regenerative amplified output are studied. We achieved 19.63 W regenerative amplified output power at 99.6 kHz for 73.8 W pump power when the injected seed power is 150 mW. The output pulse duration was 36 ps in central wavelength 1064.07 nm and spectral width 0.14 nm. Close to the diffraction limit output is obtained with beam quality factors of $M_x^2 = 1.20$ and $M_y^2 = 1.19$. This work offers a new approach to generate high power regenerative amplifier, which is able to deliver sub-millijoule energies regenerative amplified pulses at up to ~100 kHz repetition rates.

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Author Contributions

Zhenao Bai made the study design and performed the experiment, as well as the manuscript writing. Zhongwei Fan provided the ideas and facilities. Zhenxu Bai participated in research plan development and revised the manuscript. Fuqiang Lian, Zhijun Kang and Weiran Lin contributed to the data analysis and results discussion. All authors have contributed to the manuscript and have approved the final version.

Conflicts of Interest

The authors declare no conflict of interest.

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