

High repetition rate picosecond large-mode-area Yb-doped fiber amplifier with mode-locking Nd:YVO₄ laser as seed source

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We demonstrate a diode-pumped master-oscillator/fiber-amplifier (MOFA) system consisting of a passively SESAM mode-locking Nd:YVO₄ laser and a Yb-doped large-mode-area fiber amplifier, which generates total average power of 24.4 W at 1064 nm center wavelength, 91.5 MHz repetition rate, and 21.9 ps pulse duration. Power scaling limitations that arise from nonlinear distortions such as self-phase-modulation (SPM) and stimulated Raman scattering (SRS) have not been observed during the whole experiments.

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Picosecond or femtosecond pulsed laser sources are preferred for a wide variety of multiphoton microscopy techniques, such as two-photon-excited fluorescence, second-harmonic generation, coherent anti-Stokes Raman scattering, and stimulated Raman scattering. Laser systems based on fiber lasers and amplifiers are an attractive technology for compact, robust, and reliable ultrashort-pulse sources^[1–4]. Compared with conventional bulk solid-state lasers, their main performance advantages result from the combination of beam confinement and the excellent heat dissipation that is due to the large surface area-active volume ratio. High efficiencies and high output powers are readily achieved without any thermo-optical problems, even without additional external cooling. Rare-earth-doped fibers can provide high gain, permitting the amplification of short-pulse radiation with high optical efficiencies^[5–7]. One main challenge in achieving high average power from a fiber-based ultrashort-pulse system is the nonlinear effects, which are caused by the high peak power of the ultrashort-pulse laser, the small size of the fiber core and the required length for pump-light absorption^[8]. In picosecond pulsed fiber master-oscillator/power-amplifier (MOPA) systems operated at repetition rates below ~100 MHz, nonlinear effects such as self-phase-modulation (SPM) and stimulated Raman scattering (SRS) arising in the core of the fiber have restricted the average powers obtained. Therefore in order to improve the output power of picosecond fiber amplifiers, not only the absorption efficiency should be high enough for shortening the fiber length, but the active core diameter must be large for decreasing the power density. Usually, the large-mode-area (LMA) fiber should be chosen. Output powers in excess of 300 W have previously been demonstrated from a LMA Yb-doped-fiber amplifier using a 1060 nm gain-switched laser diode delivering 20 ps pulses at GHz repetition rates as a seed laser^[9,10]. By using the polarization maintaining (PM) LMA fiber as the gain medium

of the amplifier, Yb-doped fiber MOPA producing μJ pulses tunable in duration from 1 to 21 ps was reported by Chen *et al.* in 2010^[11]. An average output power as much as 97 W at a repetition rate of 47 MHz, corresponding to a peak power as high as 200 kW was obtained by Limpert *et al.* in 2005^[12]. From the results reported recently, we can know that the ultrashort pulsed lasers have developed fleetly owing to the LMA fiber origination.

In this letter, through a mode-locking Nd:YVO₄/SESAM oscillator as seed source, a diode-pumped ytterbium-doped fiber amplifier that delivers average output powers of 24.4 W at a repetition rate of 91.5 MHz and a pulse duration of 21.9 ps is reported. Accordingly, the pulse energy was 266 μJ and the peak power was 12 kW. The polarization stability is maintained with PM fiber. Using a LMA fiber and 975 nm pumping to minimize the absorption length enabled these high energy pulses to be generated without excessive nonlinear broadening due to self-phase-modulation (SPM) and stimulated Raman scattering (SRS).

As a picosecond seed source, a passively mode-locking Nd:YVO₄ oscillator was applied. The laser runned at an 91.5 MHz repetition rate, producing pulses as short as 20 ps at 1064 nm and an average power of 902 mW. The experimental setup of the seed source was shown in Fig. 1. The pump power came from the high-brightness fiber-coupled laser diode at 808 nm, which provided an output power of 15 W. The fiber had a core diameter

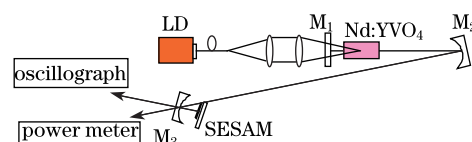


Fig. 1. Experimental setup of 1064-nm Nd:YVO₄/SESAM mode locking laser.

of 400 μm and a numerical aperture (NA) of 0.22. The pump laser at 808 nm was focused into the crystal by a coupling system with the coupling efficiency of 85%. The a-cut Nd:YVO₄ used in our experiment was wedged and the dimension of 3×3×8 (mm). Both sides of the Nd:YVO₄ were coated with an antireflective (AR) film at 808 nm and 1064 nm. To reduce the thermal load, the crystal with the low Nd³⁺-doping concentration of 0.27 at.-% was chosen, was wrapped by indium foil and packed inside a copper holder and was cooled by 20 °C circulating water. M₁ was a flat mirror AR coated at 808 nm and HR coated at 1064 nm, while M₃ was a concave mirror with the radius of curvature $R=100$ mm used as the output coupler with $T=4\%$ at 1064 nm. M₂ was a concave mirror with HR coated at 1064 nm, with the radius of curvature $R=500$ mm. To achieve the stable continuous-wave (CW) mode-locking operation, we designed the radii of the beam spot on SESAM was 30~40 μm , which can ensure the high enough power density for CW mode-locking operation. The SESAM was based on a multilayer GaAs-AlAs Bragg mirror, which had a intensity absorption of 2 %, modulation depth of 1.2 %, saturation fluence of 70 $\mu\text{J}/\text{cm}^2$, damage threshold of 800 MW/cm², and relaxation time of about 500 fs.

In a stable CW mode-locking operation, we achieved the dual output power of 902 mW at the pump power of 12.9 W. The output power of the seed laser with the 808 nm pump power was shown in Fig. 2. From the results shown in Fig. 2, the output power increased with the pump power at 808 nm. For protecting the SESAM from breakage due to the high power density, the maximum pump power was not injected. Figure 3 gave the temporal behavior of the picosecond pulse observed through the oscilloscope (Tektronix TDS 3052B 500 MHz). The measured autocorrelation trace was presented in Fig. 4 with an autocorrelation width of 2.32 ns. From the results

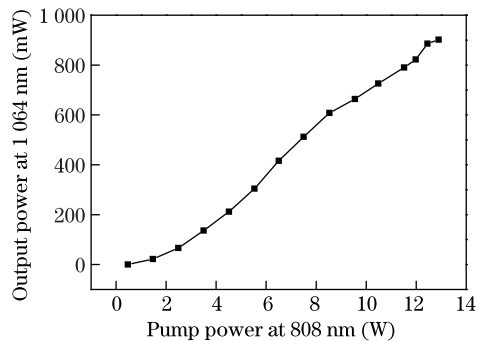


Fig. 2. Output power of the 1064-nm mode-locking Nd:YVO₄ laser versus the 808-nm pump power.



Fig. 3. Temporal behavior of the 1064-nm ps pulsed seed source.

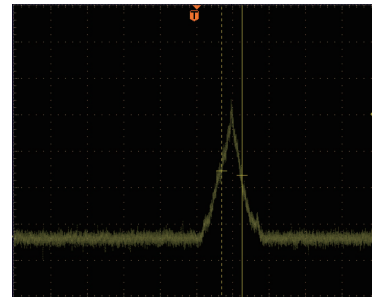


Fig. 4. Measured autocorrelation trace of the 1064-nm ps pulsed seed source.

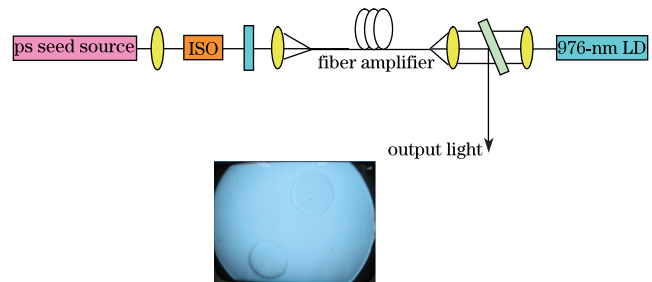


Fig. 5. Experimental setup of Yb-doped double-clad-fiber amplifier and the photo of the fiber cross section.

we have measured, it can be concluded that the pulse duration is 20 ps ($\tau=2.32 \text{ ns} \times 0.707 \times 12.5 \text{ ps/ns}$). The pulse repetition rate of 91.5 MHz, and the linewidth of 1.3 nm at the 1064 nm has been achieved. The seed laser we used for the subsequent amplifier system had the power of merely 350 mW in order to avoiding the damage of SESAM under long time operation.

The experimental setup of the fiber amplifier and the cross section of the fiber is given in Fig. 5. The seed was launched into the Yb-doped fiber through two lenses. To isolate the oscillator from the amplifier we used a bulk Faraday isolator. By means of the rotation of a half-wave plate between the isolator and the fiber, the polarization orientation between the seed light and the PM Yb-doped fiber kept identical. A mirror coated with AR film at 976 nm and HR film at 1064 nm was used to couple out the amplified light from the amplifier. The fiber amplifier was designed to amplify an average power of 350 mW at a wavelength of 1064 nm to several tens of watts while keeping nonlinearities as low as possible. It was essentially to use short fibers with a large core diameter and high absorption coefficient for the pump light. The fiber amplifier was constructed by use of a double-clad Yb-doped large-mode-area fiber, as shown in the iconograph of Fig. 5. The fiber core had a diameter of 30 μm . The inner cladding had a diameter of 250 μm with NA of 0.46. A fiber-coupled diode laser emitting at 976 nm with the fiber core of 400 μm was used as the pump source of the fiber amplifier. The pump light absorption at this wavelength was as high as 9 dB/m. Both fiber ends were polished at angle of 8° to suppress seeding of amplified spontaneous emission (ASE). Approximately 0.3 W average power of picosecond pulses was launched into the gain fiber. In our experiments, two different length fibers of 2 and 3 m were used as the gain media, respectively. The output characteristics of the amplifier were shown in Fig. 6.

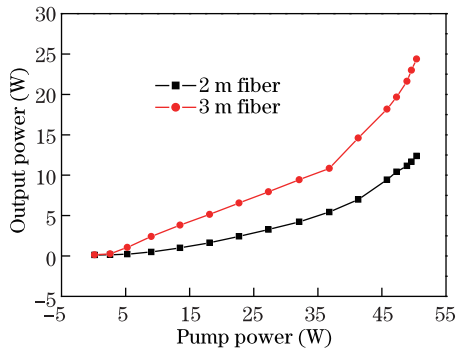


Fig. 6. Output power of the 1064-nm Yb-doped fiber amplifier with different fiber lengths of 2 and 3 m, respectively.

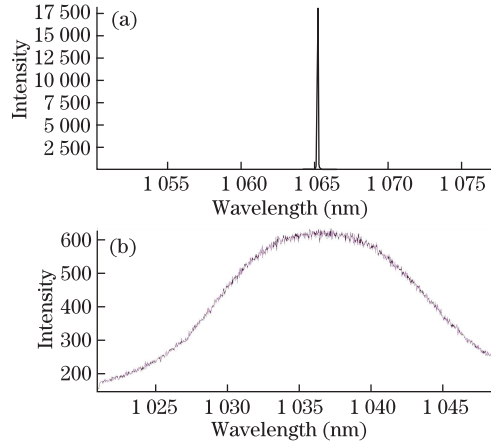


Fig. 7. (a) Spectrogram of the 1064-nm Yb-doped fiber amplifier and (b) ASE spectrogram around 1035 nm.

At a launched pump power of 50 W, the average output power of 24.4 and 12.3 W were obtained by using the 3- and 2-m fiber, corresponding to slope efficiency of 48% and 24%, respectively. The pulse energy was 266 μJ and the peak power was 12 kW at the average output power of 24.4 W and no damage of the end facet of the fiber amplifier was observed. In our experiments, the 2-m Yb-doped fiber was so short that it couldn't absorb the enough pump power, so the output power was lower compared to that of the 3-m Yb-doped fiber. Since the Yb-doped fibers operated at high inversion densities had their gain maximum at 1030 nm, and the gain at 1064 nm was substantially weaker. If the wavelength of the seed source were replaced with 1040 nm (Yb:YAG laser), the slope efficiency would be higher. From the results given in Fig. 6, we can conclude that the output power of the amplifier was limited by the pump power and the amplifier had not achieved the saturation. If the pump power were improved, the higher output power of the amplifier would be yielded. The pulse duration of the amplifier was also measured. We found that the pulse duration of the amplifier was 21.9 ps, which was extended in some sort compared to the seed source. It might owe to the normal chirp from the seed source and the pulse duration would be extended resulting from the normal dispersion of the gain fiber and isolator.

We also observed the spectrum from the amplifier and found that the center wavelength was also 1064 nm with the linewidth of 1.3 nm just as shown in Fig. 7, which was still useful for applications requiring a high spectral brightness, high peak powers and short pulses at the

same time (such as frequency conversion). There was ASE around 1035 nm, however, which was much weaker compared to the amplifier light. An ASE-signal ratio of more than 30 dB was generated. However, to remove all remaining ASE centered at 1035 nm, an interference band pass filter can be employed, which was also made for further power amplified^[13]. It is our next task. At the same time, we also inspected the spectrum at 1116 nm, which was the characteristic line caused by the SRS effect. As a result, no spectrum at this situation was observed. Therefore, we can conclude that no SPM and SRS nonlinear effects were generated. It mostly resulted from the short length LMA fiber used in the experiment, which can increase the threshold of the nonlinear effects.

In conclusion, picosecond pulsed 1064-nm Yb-doped PM LMA fiber amplifier with a mode locking Nd:YVO₄ laser as the seed source is demonstrated. Two kinds of fibers with different lengths are studied in our experiments. An average output power of 24.4 W is yielded with the fiber length of 3 m. The pulse width is 21.9 ps with the pulse repetition frequency of 91.5 MHz. The peak power of the fiber laser is 12 kW. There is no gain saturation and roll over in efficiency of the amplifier during the experiments.

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