# Low-repetition rate, nanosecond, high-power pulse amplifier system based on Yb-doped rod-type fiber

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We report a nanosecond-pulse amplification system based on an Yb-doped, 100-$\mu$m core, rod-type photonic crystal fiber. Up to 10 W of average power with pulse energy of 1 mJ and peak power of 450 kW is obtained at the repetition rate of 10 kHz. The high-power nanosecond pulse has a good pulse shape and spectral characteristics. The usage of rod-type fibers provides a novel structure for nanosecond pulse amplification.

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With the development of laser pulse amplification techniques, high-power, short-pulse laser has been obtained from laser amplifiers. In a short-pulse fiber laser amplification system constituted with conventional gain optical fiber, the peak power is usually limited by the accumulation of nonlinear effects (NLEs) in the conventional gain optical fiber. A new type of fiber called rod-type fiber can reportedly overcome this disadvantage. This type of fiber usually has a very large core diameter ranging from 70 to 120 $\mu$m. Therefore, the effective mode field area is large enough to greatly reduce NLEs and obtain high output power. Moreover, the photonic crystal fiber (PCF) structure ensures that the laser transverse mode is strictly single mode (SM). Given these advantages, rod-type fibers have been used in many optical fiber laser systems in recent years. High-power, continuous-wave (CW) fiber lasers based on rod-type fibers have been developed, which have higher stability and simpler structure compared with that of traditional fiber lasers[1,2]. Rod-type fibers are used to generate high-energy short-laser pulses. High energy pulses with ultra-short duration are obtained in mode-locked oscillators[3], which is based on dissipative soliton generation technique[4,5], and coherently combined fiber laser systems[6]. The most important application of rod-type fibers is chirped pulse amplification (CPA). Rod-type fibers have been used in many CPA systems and in the amplification of picosecond optical pulses, which is a great advantage[7−10]. The pulses obtained from these systems show excellent pulse shape and negligible NLEs. Thus far, few studies on rod-type fiber as a gain medium for generating nanosecond pulses have been reported.

Nanosecond pulses with high beam quality and high pulse energy are widely applied in scientific research and industrial machining, such as material precision processing, remote sensing, laser infrared radar, and nonlinear frequency conversion. To obtain high-power nanosecond pulses, many seed sources with varied fiber amplifiers have been devised[11−15]. Brooks *et al.* reported a nanosecond pulse master oscillator power amplifier (MOPA) source configured with three-stage fiber amplifiers[11]. In their system, two conventional gain optical fibers are used as preamplifiers, and a rod-type fiber is used as the main-amplifier. This system was seeded by a passively $Q$-switched neodymium-doped lanthanum scandium borate microchip laser[16]. However, the pulse shape obtained was not satisfactory, and the filter they used for amplified spontaneous emission (ASE) rejection complicates the system.

In this letter, we describe a two-stage master osoillator power amplifier (MOPA) system seeded by a single longitudinal mode directly modulated laser diode (SLMDM-LD), which is very different from the $Q$-switched laser. The repetition rate ranges from 10 kHz to 1 MHz. The seed duration, which ranges from 800 ps to 10 ns, is tunable. The seed used has 2.2-ns duration and 8-mW output power at the repetition rate of 10 kHz. The center wavelength is 1 064 nm. The seed laser is directly coupled into an Yb-doped large mode area (LMA) double-cladding fiber used as a preamplifier. The all-fiber structure is retained through the direct fiber splicing of the preamplifier and seeder. Finally, an Yb-doped PCF rod-type fiber is used as the main amplifier. A pulse train with high average power is obtained by rod-type fiber amplification. The average output power is up to 10 W and has a pulse energy of 1 mJ, corresponding to a peak power of 450 kW at 2.2 ns duration. The pulse shape and beam quality are simultaneously detected. No more filters are used during the amplification of the system.

The MOPA (shown in Fig. 1) is configured with a two-stage fiber amplifier seeded by a SLMDM-LD. The SLMDM-LD is a compound cavity laser diode (LD) with a Fabry–Perot cavity LD used as intra-cavity and a fiber Bragg grating (FBG) used as outside cavity. In this letter, the FBG is used for mode selection. Furthermore, the FBG can achieve single longitudinal mode operation in the outside cavity. Directly modulated by the electrical pulse signal, the output optical pulse from the SLMDM-LD is tuned to 2.2-ns duration, 10-kHz repetition rate, 1 064-nm wavelength center, and 8-mw average power.

To retain an all-fiber structure and avoid energy loss

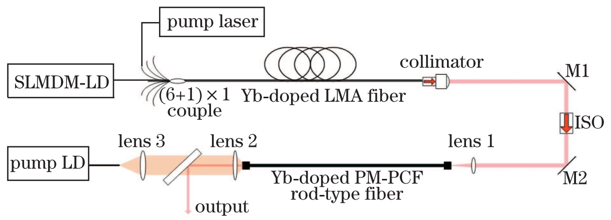

Fig. 1. Configuration of the two-stage fiber MOPA.

in spatial coupling, the seeder is directly coupled into a 4-m-long Yb-doped LMA double-cladding fiber by a (6+1)×1 optical coupler. The LMA fiber (NA=0.06, 30 $\mu$m core diameter) used as the preamplifier is a YDF-30/250-HI-VIIILMA fiber produced by Nufern.

Given the low seed power, a significant gain is generated by the rod-type fiber when the seed is directly amplified by the rod-type fiber without any preamplifier. The large gain, which is pumped by a high power LD, cannot be completely utilized. The plane end of the rod-type fiber forms a resonator cavity, and ASE self-oscillation results from the redundant gain. Therefore, the seed pulse must be pre-amplified with sufficient energy. However, if the peak power of the seeder is excessively preamplified, NLEs obviously increase in this LMA fiber. Therefore, the pump power of this stage must be carefully chosen. The output pulse spectrum of the entire system is detected during the variation in the pump power that is used for the LMA fiber. Initially, ASE can be observed when we increase the pump power from 0 W and disappears when the pump power is approximately 3 W. If the pump power is continuously increased, NLEs can be observed. Finally, an LD with a 2.8-W output power is used as the pump in this stage so that the pulse can be amplified without ASE and NLEs. Therefore, no filters are required. At the end of the preamplifier, the LMA fiber is coupled with a collimator. Then, the pulse propagates in space and passes through a spatial optic isolator (ISO), which is used to ensure that the light unidirectionally propagates and protects the seeder. The output power after the ISO is 302 mW without ASE and distinct NLEs such as stimulated Raman scattering (SRS).

Finally, the pulse is coupled into an 80-cm-long Yb-doped polarization-maintaining (PM) PCF rod-type fiber that is used as the main amplifier by lens 1. The coupling efficiency of the pulses in the rod-type fiber through lens 1 is approximately 70%. This rod-type fiber is a DC-285/100-PM-Yb-ROD Yb-doped PCF fiber produced by NKT Photonics A/S. This fiber has more than 4 500 $\mu m^2$ of effective mode-field area. Moreover, the cladding pump has high absorption efficiency (30 dB/m at 976 nm). The core of this fiber is $SiO_2$ and doped with Yb-ion, so it has the same group velocity dispersion and nonlinear refractive index ($n_2$) as the common gain fibers. Therefore, this structure can effectively weaken the NLEs. The core diameter/pure silica pump cladding of this fiber is 100 $\mu$m/1.7 mm. The special PCF structure also results in a core numerical aperture (NA) of 0.02 at 1 060 nm so that the pulse transverse mode is maintained in SM. The outer cladding is free-air clad. This stage is backward pumped by a tunable high-power LD (0 to 200 W) at 976 m with a pigtail fiber of 200-$\mu$m core diameter. To check whether the rod-type fiber could cause NLEs or ASE, the spectrum needs to be measured when the pump power changes from 25 to 75 W in the high-power LD. Few ASE and NLEs have been observed. However, self-oscillation forms when the pump power is higher than 75 W. Therefore, the maximum pump power of this stage is limited to 74.6 W. At this pump level, only a dichroic filter is used for the output at the end of the system. No filters are used for filtering ASE and SRS in this system, which simplifies the structure.

The output power linearly increases with pump power. The spectrum of the maximum power output pulse is detected using an AQ-6315A optical spectrum analyzer (OSA) produced by the YOKO Gate company. The pulse shape and pulse train are detected using a 6 GHz digital storage oscilloscope equipped with a 45-GHz fiber-coupled photodiode detector. Beam radii are also detected by a charge-coupled device (CCD) at the minimum output power and maximum output power.

Figure 2 shows the average output power of the system versus the pump power supplied by the high-power LD. The maximum output pulse power is 10.4 W with 1-mJ energy at the repetition rate of 10 kHz. The maximum output pulse power is only limited by self-oscillation. The input signal laser power is approximately 330 mW, so this rod-type fiber amplifier exhibits a 30-fold gain at this pump level.

The pulse temporal profile and pulse train are shown in Fig. 3. A nearly smooth pulse shape with pulse duration of 2.2 ns and repetition rate of 10 kHz is obtained. The slight jitter on the top of the pulse is caused by the laser seeder characteristics. No obvious pulse breakup is observed, as shown in Fig. 3. However, more significant NLEs are observed for picosecond pulses than nanosecond pulses. Determining whether the rod-type fiber or the seed pulse itself reduced the NLEs is difficult. Therefore, the spectrum profiles of the amplified pulses are simultaneously detected.

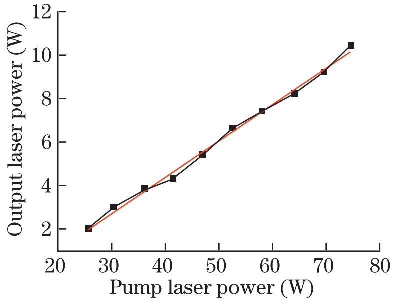

Fig. 2. (Color online) Output power of the rod-type fiber amplifier versus the pump power of the LD. Black line indicates the experimental data. Red line indicates the linearly fitted curve.

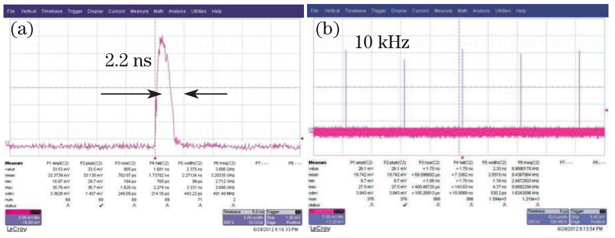

Fig. 3. (a) Pulse temporal profile and (b) pulse train.

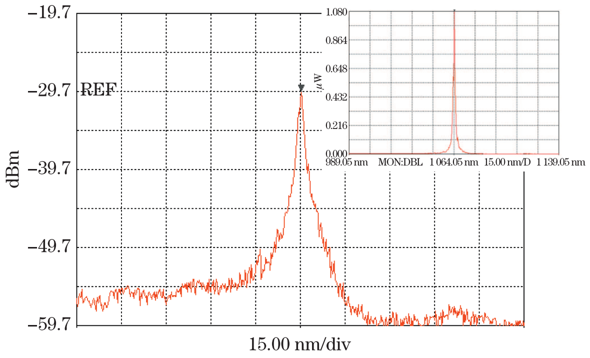

Fig. 4. Spectrum profile of the maximum output pulse power.

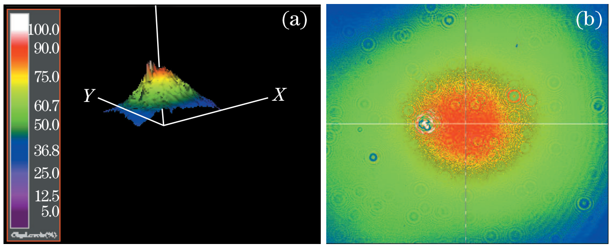

Fig. 5. Near-field image of the output pulse beam at minimum power. (a) 3D profile; (b) 2D profile.

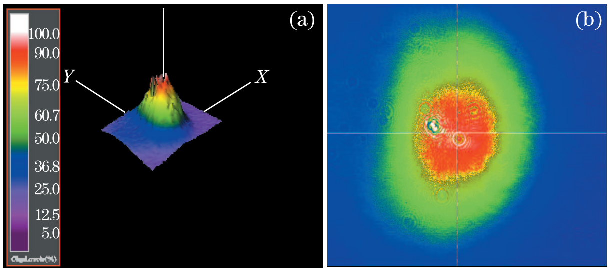

Fig. 6. Near-field image of output pulse beam at maximum power. (a) 3D profile; (b) 2D profile.

Figure 4 shows the spectrum profile at logarithmic scale and recorded at maximum power. The linear scale is inserted at the top-right corner. The spectrum is obtained by directing the output beam toward the OSA without passing through any intermediate. The spectrum width of the output pulse is approximately 3 nm, and the spectrum profile is similar to that of the seed pulse. Figure 4 shows the ASE located 25 dB below the signal and near the 1 030-nm wavelength. SRS is also observed, which is the spectral gain peak located 27 dB below the signal near the 1 100-nm wavelength. This spectral profile proves that a high-energy laser pulse with few ASE and SPM can be obtained using a rod-type fiber amplifier.

Figures 5 and 6 show the near-field images at the maximum output pulse energy and minimum output pulse energy detected by CCD, respectively. The laser transverse mode of the output beam is strictly SM. Although the rod-type fiber has a very large effective mode-field area, a high beam quality can be maintained by the PCF structure. Given this structure, a high-energy nanosecond pulse is obtained under SM.

This result shows the powerful function of the rod-type fiber in a nanosecond laser pulse amplification field. The nanosecond laser pulse energy can be further improved.

In conclusion, we demonstrate a main amplifier of a two-stage MOPA system based on a large-core PCF rod-type fiber. The MOPA generates 3-nm spectrum width pulses with 2.2-ns duration, 10.4 W average output power, 1-mJ energy, and 450-kW peak power at 10-kHz repetition rate. Given that no filters are used, the structure is simplified and an all-fiber structure is achieved through the direct coupling of the seeder and preamplifier. The powerful amplification capability of the rod-type fiber greatly improves the energy of the nanosecond pulse. The NLEs at the high-output energy level are greatly weakened by the large effective mode-field area of this fiber. Moreover, a high beam quality is maintained by the special PCF structure. Therefore, the usage of rod-type fibers can provide a novel structure for nanosecond pulse amplification.

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