

255 W picosecond MOPA laser based on self-made Yb-doped very-large-mode-area photonic crystal fiber

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We report on the amplification of high-average-power and high-efficiency picosecond pulses in a self-made very-large-mode-area Yb-doped photonic crystal fiber (PCF). The PCF with a core diameter of 105 μm and a core numerical aperture of 0.05 is prepared by the sol-gel method combined with the powder sintering technique. The fiber amplification system produces the highest average power of 255 W at a 10 MHz repetition rate with a 21 ps pulse duration corresponding to a peak power of 1.2 MW. This result exemplifies the high-average-power and high-peak-power potential of this specifically designed fiber.

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Although continuous Yb-doped fiber lasers have achieved a relatively high power output, ultrashort pulse amplification is still constrained both by nonlinear effects and energy extraction efficiency^[1-3]. For the sake of mitigating nonlinear effects such as self-phase modulation (SPM), stimulated Raman scattering (SRS), and four-wave mixing (FWM), it is necessary to expand the effective mode field area (MFD) and reduce the fiber length. Increasing the doping concentration can significantly raise pump absorption efficiency so that the fiber length is shortened. Moreover, a larger MFD would increase the damage threshold of the fiber facets, which limit the maximum extractable pulse energy of the fiber^[4]. However, due to manufacturing tolerances, there are obstructions to operate step-index double-cladding fibers near the diffraction limit with core diameters exceeding 25 μm . Recently, exceptional performances in terms of average power and pulse energy have been demonstrated in both master oscillator power amplification (MOPA) and chirp pulse amplification (CPA) systems using very-large-mode-area (VLMA) (MFD > 50 μm) air-clad photonic crystal fibers (PCFs)^[5-9]. In 2012, a 26 mJ quality-*Q*-switched sub-60 ns fiber laser system is enabled by a large-pitch rod-type PCF with a core diameter of 135 μm , which revealed further power-scaling of ultrashort pulses. Two years later, based on a similar large-pitch rod-type PCF, an average power of 2 kW is demonstrated by amplifying a broadband mode-locked fiber with a 150 ps duration and a 20 MHz repetition. However, the research of high power MOPA systems are focused on pulses of the nanosecond (ns) and sub-ns regime, the power scaling of picosecond fiber lasers with simultaneous high-average-power and high-peak-power is limited.

In this Letter, we demonstrate a Yb-doped picosecond MOPA system based on an SESAM mode-locked oscillator with a pulse width of 21 ps at a repetition rate of 10 MHz and a self-made VLMA PCF. Owing to the modified sol-gel method combined with the high temperature sintering technique^[9], the concentrations, homogeneity, and distribution of the dopants are improved; the PCF is fabricated with core diameter of $\sim 105 \mu\text{m}$ and a core numerical aperture (NA) of 0.05. An average power of 255 W at 1030 nm is generated with a maximum peak power of 1.18 MW and a slope efficiency of 77%. Due to the excellent characteristics of the PCF, amplified spontaneous emission (ASE) and nonlinearity is significantly released.

The modified sol-gel method is developed to prepare Yb/Al/F-doped core silica glass as described in Ref. [9]. Through improvement and optimization, the core rod is extended to a diameter of 5 mm and a length of 80 mm with 5500 pm Yb³⁺ ions and a homogeneity of 5×10^{-4} . Moreover, the introduction of fluorine lowers the refractive index of core area of the PCF, thus a lower NA is obtained. The PCFs are fabricated using the standard stack and draw technique at a drawing temperature of 2000°C. Figure 1 shows the optical structure of the PCF, consisting of a 105 μm diameter (corner to corner) Yb-doped hexagonal core, 375 μm diameter pump cladding, and an outer cladding diameter of $\sim 670 \mu\text{m}$. The design parameter ratio of a 3 μm air-hole diameter (d) and a 25 μm inter-hole spacing (Λ) describes the photonic crystal microstructure, and the core NA is ~ 0.05 (at 1030 nm). The 10 μm outer cladding silica bridges lead to an NA of 0.46 at 976 nm, allowing for a high-efficient launch of the multimode pump laser into the PCF. The measured pump absorption coefficient is as high as 24 dB/m at 976 nm.

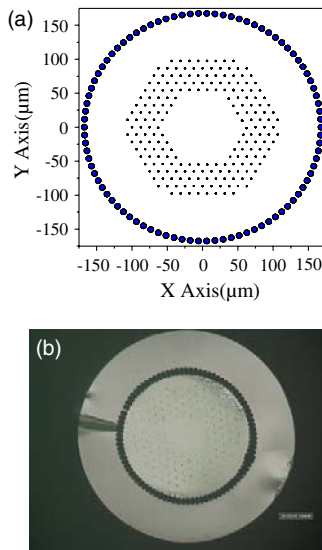


Fig. 1. Schematic cross section of (a) designed and (b) fabricated PCF microstructure, air-cladding, and cladding sides.

The MOPA-based fiber laser system configuration is depicted in Fig. 2, and is comprised of a master oscillator followed by multi-stage preamplifiers and a free-spaced PCF power amplifier. The master oscillator is based on an SESAM mode-locked fiber laser operated at ~ 1030 nm with a 1 nm spectrum full width at half-maximum (FWHM), generating 21 ps with a repetition rate of 10.26 MHz^[10,11]. The seed pulses are transmitted through two-stage Yb-doped fiber amplifiers pumped by 976 nm fiber-coupled diodes. The first amplification stage uses a step-index single-mode double-cladding fiber (10/125 μm , $\text{NA} \sim 0.07$), which is pumped through a fused combiner. The first stage is spliced to the second stage and features a free-space backward end-pumped 3 m-long flexible polarizing double-cladding PCF with a 40/200 μm core/inner cladding diameter, a core NA of 0.03 and a 10 dB/m pump absorption at 976 nm. The fiber output facet is spliced to an anti-reflection-coated endcap for optical damage avoidance and suppression of the Fresnel reflection. In order to optimize the spectra of the preamplifiers, a spatial bandpass filter is placed between the spatial

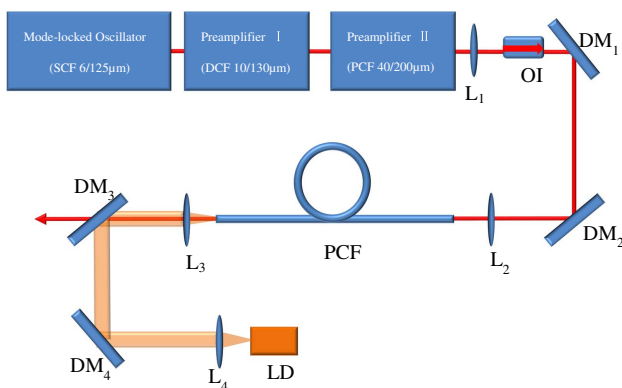


Fig. 2. Experimental setup of the MOPA system. L, lens; OI, optical isolator; DM, dichroic mirror; LD, laser diode.

isolator and the power amplification stage, and the band-pass range of the filter is 1030 ± 5 nm. Finally, the signal is launched to the self-made VLMA PCF. The optimum length of the PCF in the final stage is ~ 115 cm, and the output end of fiber is cleaved to approximately 6° in order to suppress the ASE. Each end of the fiber is held in 20 cm-long water-cooled V-shape grooves mounted on five axis positioning stages. The power amplification stage is also backward end-pumped by a set of three fiber-coupled diodes at 976 nm, and combined to a common delivery fiber (400/440 μm , $\text{NA} \sim 0.22$) which could provide a maximum power of 500 W. The signal and pump are transmitted between the segments by pairs of broadband-coated aspheric lenses and 45° dichroic mirrors. After amplification, the output signal is analyzed by a powermeter, spectrum analyzer, oscilloscope, and autocorrelator.

Figure 3 shows the output pulses profile and the spectrum of the mode-locked oscillator measured by the autocorrelator (APE Pulsecheck SM1200), oscilloscope (LECRYO WR62Xi) with a fast, wideband photodetector, and a spectrum analyzer (Yokogawa AQ6370D). The measured pulses are with FWHM of 21 ps and a repetition rate of 10.26 MHz as shown in Fig. 3(a) and 3(b). The center wavelength of seed is 1030.7 nm and the optical signal-to-noise ratio (OSNR) is ~ 40 dB. The 100 mW average output power from the seed is amplified to 30 W after the two-stage preamplifiers. The corresponding high resolution (0.2 nm) optical spectra with an FWHM of 1 nm and an OSNR of 15 dB are shown in Fig. 3(c). The ASE around 1040 nm becomes stronger after the preamplifiers mainly due to a high gain and the short length of the fibers. Under the estimated peak power over 110 kW after the preamplifiers, the SPM leads to serious spectral broadening. In order to suppress the influences of the ASE and the SPM to the main amplifier, a space bandpass filter transmitting the wavelength range from 1025 to 1035 nm is inserted between DM1 and DM2. The filtered power is ~ 20 W with an OSNR of 40 dB, shown in Fig. 3(c).

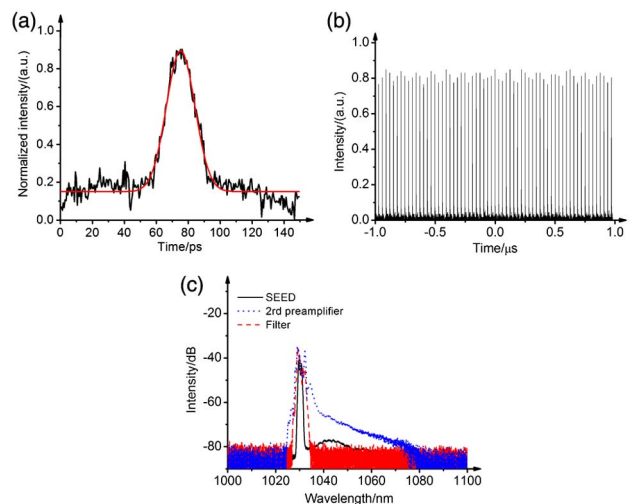


Fig. 3. (a) Pulse profile of the seed. (b) Output pulse sequences of the seed. (c) Output spectra of various amplification stages.

The output signal power as a function of the launched pump power in the final stage amplifier is shown in Fig. 4 (the black line is the measured data, and the red dot is the estimated). The maximum power of 255 W is obtained with a pump power of 408 W, corresponding to the estimated peak power of 1.18 MW and the pulse energy of 25 μ J. The slope efficiency and extraction efficiency are measured to be $\sim 77\%$ and $\sim 58\%$, respectively. Further, the average power scaling is limited by the damage threshold of the fiber end-facets. Since this kind of PCF is integrated with air holes, it is significant to optimizing the polishing process of the facets, and ensuring that there is no humidity or particles adhering to them. In our experimental system, both ends of the fiber facets are not in contact with the water-cooling blocks; the temperature of the dirty fiber output end-facet would soar at an amplified signal power over 80 W, while the clean fiber facet's temperature remains below 100°C even at the maximum output power. Further improvements to decrease the peak intensity on the end-facets can be obtained by expanding the beam through using a spliced endcap^[12]. Through collapsing, cleaving, and fusion splicing facets with CO₂-laser device, the damage threshold would increase by several orders of magnitude.

The maximum peak power and pulse energy scaling of the picosecond direct amplification system is ultimately limited by the power density in the core, whose extreme increase leads to the onset of nonlinearities, such as SRS and SPM. There are several means to improve nonlinear effects thresholds in fiber lasers^[13]; in this system, the length including the active and passive fibers of all amplification stages are minimized, and the large mode area of the PCF is significant to reduce the power density in the final stage. The spectrum at the maximum output power is depicted in Fig. 5(a) (blue solid line); the measured OSNR is recorded to be 35 dB. Furthermore, ASE has started to appear at ~ 1040 nm for output powers beyond 25 μ J. However, the power contained in ASE is not significant and most power remains in the signal wavelength at ~ 1030 nm. Thanks to the large mode area and short length of the PCF, the threshold of the SRS is estimated to be ~ 1.2 MW^[14], which is slightly higher than the maximum peak power of 1.18 MW; thus the SRS at ~ 1080 nm is well mitigated from the system. Due to high

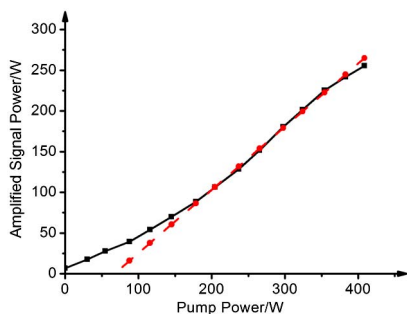


Fig. 4. Amplified average output power versus pump power in the final stage.

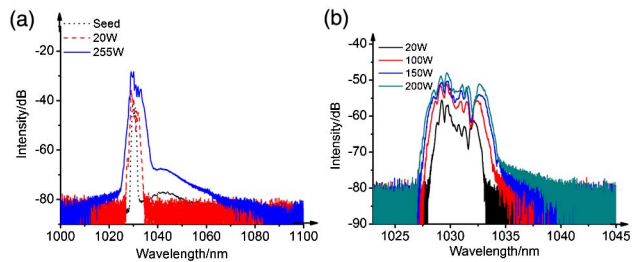


Fig. 5. Output spectra of the system.

peak powers propagating in the core area, SPM still induces spectral broadening; we estimate a total nonlinear phase-shift of 23.9 radians at maximum pulse peak power, and the 20 dB linewidth of the spectrum is broadened from ~ 2.62 nm of seed to ~ 7.5 nm at a 255 W output power. At a lower average power, the effect of SPM is not significant compared to the seed spectrum depicted in Fig. 5(a). Therefore, when the peak power exceeds the SPM threshold of 7.76 kW, the spectral bandwidth broadening is becoming prominent and induces characteristic sidebands on either wavelength sides as shown in Fig. 5(b).

In conclusion, a VLMA PCF-based MOPA system amplifying 21 ps pulses to an average output power of 255 W at 1030 nm is demonstrated. The self-made Yb-doped PCF is prepared by the modified sol-gel method combined with the high temperature sintering technique. The concentrations, homogeneity, and distribution of the dopants are greatly improved; the PCF consists of a 105 μ m diameter core, a 375 μ m diameter inner-cladding, and a ~ 670 μ m diameter outer cladding. The core/inner cladding NA of the PCF is $\sim 0.05/0.46$ and the measured pump coefficient is ~ 24 dB at 976 nm. The system operates at a repetition rate of 10 MHz, corresponding to an estimated peak power of 1.18 MW and a pulse energy of 25 μ J. The slope efficiency is as high as 77%. At the maximum operating output power, an OSNR of 35 dB is recorded, indicating that ASE and nonlinear effects are well suppressed throughout the amplification system. With a lower peak power intensity and a shorter length of fiber, the effect of SPM is far weaker than conventional double-cladding fibers. Through co-doping the core with fluorine to compensate for the refractive index increase, the guiding properties of the PCF would be improved.

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