All-normal-dispersion ps-pulse generation from high-gain ytterbium-doped photonic crystal fiber laser

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A fiber laser system emitting high-quality ultrashort powerful light pulses is reported. The photonic crystal fiber featuring high-gain large -mode-core and short absorption length is used, and the fiber laser is passively mode-locked by a semiconductor saturable absorber mirror. Its output greatly exceeds the power limitation of single-mode fiber oscillators with 1.4-W average power at 1 039-nm center wavelength, 6.9-ps pulse width, and 45.4-MHz repetition rate.

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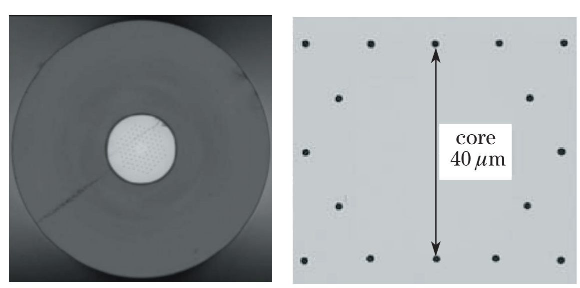
High power ps-pulsed fiber lasers have versatile scientific and industrial applications, including ultrafast science, pump sources for high power super-continuum generation[1,2], materials processing[3], and plasma physics[4] Passively mode-locked by saturable absorbers in fiber lasers has been proven to be a powerful and convenient way for fs-, ps-, and ns-pulse generation. Compareing to 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 to active volume ratio. High efficiencies and high output power are readily achieved without any thermo-optical problems even without additional external cooling. With the recent development of large-mode-area fibers, these devices can now be designed to support very high powers[5,6] More recently, significant energy scaling in mode-locked fiber lasers have been demonstrated using LMA photonic crystal fibers (PCF)[7−9] Indeed, passively mode-locked fiber lasers operating in the anomalous dispersion regime[7] as well as in the purely normal dispersion regime[8,9] have been reported with exceptional performances in terms of pulse energy and peak power. Additionally, these sources use only a semiconductor saturable absorber mirror (SESAM) as the mode-locking mechanism leading to very compact designs.

In this letter, a ps-high-gain double-clad PCF[10,11] laser with positively chirped 6.9-ps pulses and 1.4-W average output power has been achieved. In the experiment, a 976-nm LD with the maximum output power of 30 W is chosen as the pump source. PCF with an inner cladding diameter of 170 μm, the active core diameter of 40 μm is chosen as medium with the absorption coefficient of 13 dB/m at 976 nm. A SESAM is used for the mode-locking element. This picosecond PCF Laser system has a center wavelength of 1 039 nm, and the spectral bandwidth is about 0.5 nm. The pulse repetition rate is 45.4 MHz, which results in an energy of 30 nJ/pulse.

PCF were fabricated of fused silica by the standard technology[10,11].The incorporation of rare-earth dopants into the core of an air-silica microstructure fiber is challenging because the dopants and associated codopants itself modify the refractive index of the core. The fiber design has to be chosen carefully that the guiding properties are determined by the hole arrangement and not by the index-step of the dopants[12]. The inner cladding of our large-mode-area PCF is shown in Fig. 1.

The inner cladding has a hexagonal shape with a corner-to-corner diameter of $\sim$170 μm. The numerical aperture (NA) is as high as 0.62. The ytterbium-doped core has a diameter of $\sim$40 μm. With this structure, the pump light absorption is $\sim$13 dB/m at 976 nm. Because of the high NA of the inner cladding, which is realized by microstructuring, the pump core is very compatible with 200-μm, 0.22-NA standard pump delivery fibers. Consequently, the fiber is designed for several hundred watts of output power by use of state-of-the-art diode laser technology. It is important to note that, the high single-pass gain of the fiber is maintained even with an extremely short fiber length, because of the unchanged product of pump intensity and fiber length comparing with other double-clad fiber designs. Therefore, comparing with the conventional fiber, this high-gain type fiber also features a low lasing threshold and high efficiency.

The experimental setup of the passively mode-locked large-mode-area (LMA) fiber laser is shown in Fig. 2. A z cavity, which is usual in the end-pumped configuration, is employed with 1:1 lens of the coupling system. The two beams side the out-put coupler PBS2 have the different power, and the high power beam is chosen. The pump source is a commercial fiber-coupled LD,



(a) (b)

Fig. 1. (a) Microscope image of the air-clad ytterbium-doped large-mode-area fiber; (b) close-up of core region.

with rated maximum power of 30 W at 976 nm, a core diameter of 200 μm, and an NA of 0.22.

The semiconductor saturable absorber mirror (SESAM) (BATOP GmbH, Germany) is used for mode locking, which has a low-intensity absorption of 65%, the modulation depth of 35%, saturation fluence of 20 μJ/cm^2, and the relaxation time of about 500 fs. It is soldered on a small copper heat sink so that the loaded heat can be easily removed. In front of the SESAM, an aspheric focusing lens with focus of 8 mm is used to afford enough power density for continue wave (CW) mode locking.

A power meter and a fast detector connected to an oscilloscope are put into the two output beams for measurement and signal monitoring. The dependence of the output power on the incident pump power is shown in Fig. 3. The CW mode locked threshold incident pump power is about 5.7 W. When the total output power is exceeding 358 mW at the pump power of about 5.7 W, the laser changes from the Q-switched mode-locking (QML) regime to the CW mode-locking regime. With the increasing of the incident pump power, the output power increases, while the laser keeps stable at the CW mode-locking regime.

When the incident pump power reachs 8.3 W, the output power rise to 1.4 W, corresponding to optical to optical efficiency of 16.9%, and the pulse energy outside the cavity of about 30 nJ. The beam quality of the laser is very important for the stability of passively mode locking. Under incident pump power of 8.3 W, the laser pattern performed a Gaussian transversal mode. The stable CW mode-locking regime held well for more than one hundred hours.

Figure 4 shows the pulse train recorded with an oscilloscope. The repetition rate of the pulses is 45.4 MHz. The pulse duration is measured with an intensity autocorrelator (APE Inc. USA) at the maximum output power, as shown in Fig. 5(a). The measurement at the maximum pump power revealed that the pulse duration is about 6.9 ps (assuming a Sech shape). As shown in Fig. 5(b), the corresponding spectrum is centered at 1 039 nm measured with an optical spectrum analyzer, and has an FWHM of about 0.5 nm. With the laser output power, mode-locked spectrum is quite narrow, laser pulse shaping within the nonlinear absorption mainly determined by the SESAM. In this Experiment, laser runs an all-normal dispersion (ANDi) regime. Therefore, the ANDi regime can support higher output pulse energy than the anomalous dispersion regime.

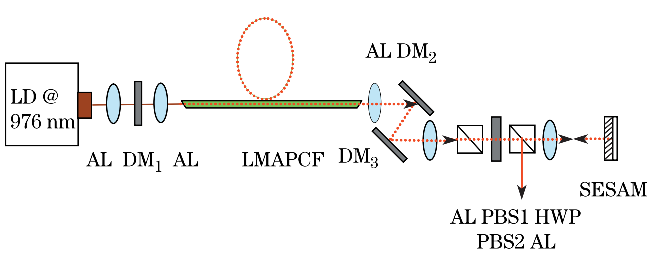


Fig. 2. Experimental setup of the Yb-doped large-mode-area PCF laser. (DM: dichroic mirror, HWP: half wave plate, PBS: polarization beam splitter, SESAM: semiconductor saturable absorber mirror).

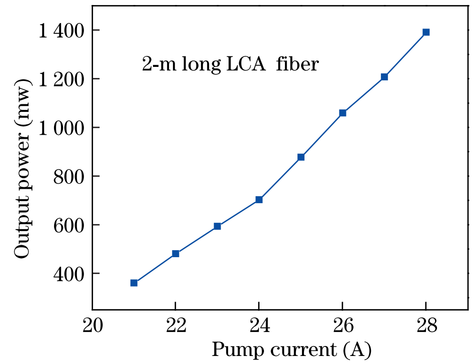


Fig. 3. Output power of the CW mode-locked PCF laser with the incident pump current.

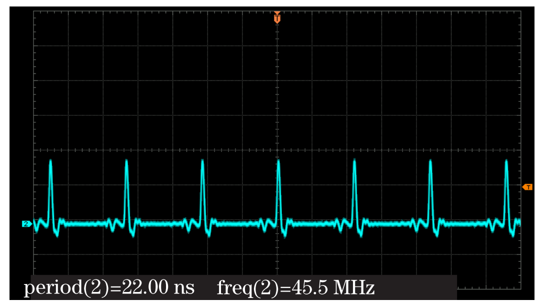


Fig. 4. Pulse trains observed with 22-ns/div time scales.

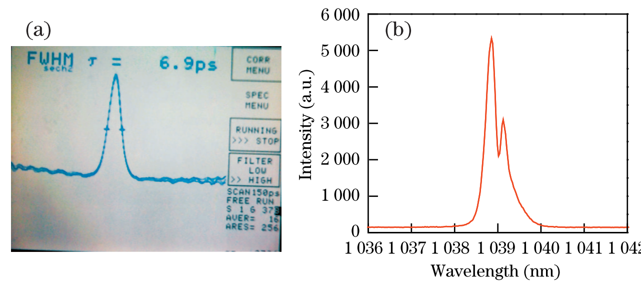


Fig. 5. (a) Autocorrelation trace of the output chirped pulses and (b) the corresponding mode-locked pulse spectrum with width of 0.8 nm.

In conclusion, we demonstrate a stable LD-pumped mode-locked PCF laser at 1 039 nm. The mode-locked pulses are emitted at a repetition rate of 45.4 MHz with pulse duration of 6.9 ps in the ANDi regime. The maximum average output power of 1.4 W is obtained at the incident pump power of 8.3 W.

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