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High-energy soliton pulse generation with a passively mode-locked Er/Yb-doped multifilament-core fiber laser

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Abstract We report the generation of high-energy short pulses from a mode-locked erbium/ytterbium-doped large-mode-area multifilament-core fiber laser operating in the purely anomalous dispersion regime. The self-starting fiber laser emits 400 mW of average output power at a pulse repetition rate of 44 MHz, corresponding to a pulse energy of 9.1 nJ. The laser produces near transform-limited output pulses with pulse duration of 1.6 ps, corresponding to 5 kW peak power. This new type of low-nonlinearity fibers demonstrates the power and energy scaling potential of fiber-based short pulse lasers in the eye-safe region.

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The generation of ultrashort pulses from rare-earth-doped fiber lasers has been under intense investigation for the past few years. One of the important trends is to develop powerful compact laser sources and extract maximum pulse energy in mode-locked fiber laser systems. Recent progress in the development of ytterbium-doped ultrashort-pulsed sources clearly demonstrate that newly designed fiber-based oscillators are promising power and energy scalable concepts. Unprecedented laser performances have been made possible due to a conjunction use of recent high technological key components, such as a high-brightness laser diode, a new generation of low-nonlinearity fiber, and a semiconductor-based saturable absorber mirror [1].

The conventional single-mode fibers at the 1.5-μm wavelength region present anomalous group-velocity dispersion (GVD), and the current pulse energy limitation in fundamental soliton mode-locked fiber laser systems generating $sech^2$-shaped transform-limited pulses [2] arises from the soliton area theorem. Due to the soliton energy quantization, the soliton fiber lasers operate in multiple-pulse mode when increasing the pump power [3]. The adaptation of a dispersion-shifted fiber segment providing normal GVD in the dispersion-managed configuration has led to the operation in the average soliton [4] or the stretched-pulse [5] regimes. Different pulse breathing ratios inside the resonator are obtained, and the reduction of the peak power allows a better control of excessive nonlinearity. The dispersion-managed fiber lasers can support higher pulse energies than soliton fiber lasers [6]. More recently, the generation of picosecond [7] and femtosecond [8] pulses in the large normal GVD regime has been demonstrated. Highly positively chirped pulses could be generated in this regime and femtosecond lasers with record pulse energies above 10 nJ have been recently reported [9]. The other approach to reduce the peak power inside the cavity is to operate in a regime of large anomalous GVD. An increase of pulse duration has been observed with increasing the magnitude of anomalous net-cavity GVD [10]. In this case, the laser generates near transform-limited picosecond pulses with energy up to the 10-nJ level [11].

The most promising approach to generate high pulse energy in fiber lasers is to scale up the effective mode-field

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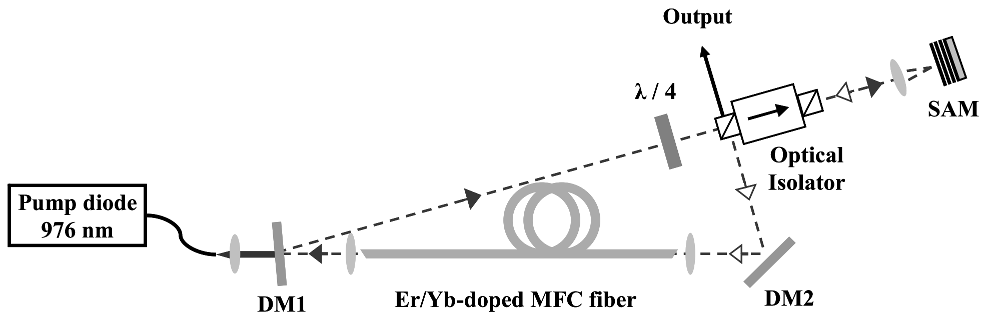

Fig. 1 Schematic representation of the passively mode-locked Er/Yb-doped multifilament-core large-mode-area fiber laser. SAM: Saturable absorber mirror, DM1, DM2: Dichroic mirrors

area to decrease the light intensity inside the fiber core. Recent advances in single-transverse mode, very large core Yb-doped photonic crystal fibers (PCF) have been successfully applied to develop powerful ultrashort pulse laser systems [1, 12–14]. This fiber concept has been pursued in both average soliton [12] and normal [1, 13, 14] dispersion operation regimes, and femtosecond pulses with pulse energies approaching the microjoule level with multiwatt average power have been reported [1].

There have been very few demonstrations of mode-locked large-mode-area (LMA) fiber lasers operating in the 1.5-μm wavelength region. Fermann et al. [15] have proposed to use a multimode (MM) Er/Yb-doped fiber as a gain medium with single-mode fibers spliced onto both ends of the MM fiber to excite only the fundamental mode. However, the high-order transverse mode content results in a poor pulse quality and stability. The other LMA fiber concept in mode-locked operation is to use a low-NA Er-doped core surrounded by a ring with raised refractive index, and single-mode operation was achieved by coiling the fiber [16]. The energy scaling up to 20 nJ has been demonstrated with relatively long duration of the pulses (20 ps). New LMA fiber designs have been recently investigated for the single-mode amplification [17–19]. The PCF technology has been applied to realize Er/Yb-doped LMA fibers. Fundamental mode operation of the unoptimized microstructured fiber was also achieved by coiling the fiber [17]. Record mode-field area of 1760 μm^2 with fundamental mode propagation has been demonstrated in a core-pumped conventional Er-doped fiber [18]. The excitation of the fundamental mode in this active fiber is obtained by the use of a single-mode fiber-based mode filter.

To develop a lower NA Er/Yb-doped fiber is more challenging because of the high concentrations of phosphorous and rare-earth ions needed to enable the efficient pump energy transfer. A new LMA structure has been proposed arranging small doped filaments within the core [19]. By surrounding the filaments with fluorine-doped silica, which has a lower refractive index value than pure silica, a further reduction of the effective core NA is obtained. Truly single-mode operation has been demonstrated based on such a multifilament-core fiber with large mode-field area [19].

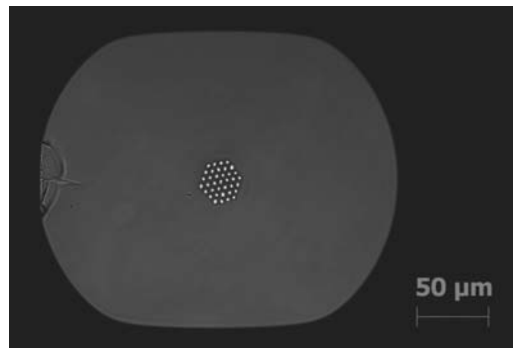

Fig. 2 Multifilament-core double-cladding fiber

In this article, we report what we believe to be the first experimental demonstration of a passively mode-locked Er/Yb-doped multifilament-core intrinsically single-mode large-mode-area fiber laser that is operated in the purely anomalous dispersion regime. The laser directly generates 1.6 ps pulse duration at a repetition rate of 44 MHz. In the soliton single-pulse regime, the laser delivers 400 mW of average power corresponding to pulse energy of more than 9 nJ.

The complete experimental setup of the passively mode-locked Er/Yb-doped LMA fiber laser in sigma cavity configuration is presented in Fig. 1. One key cavity element in this laser configuration is the erbium/ytterbium-doped multifilament-core LMA fiber. A cross section of this fiber is shown in Fig. 2. The process of preparation and the main optical properties of this fiber structure have been described in detail in reference [19]. The similar fiber presented here is prepared by the same stack and draw technique without polarization maintaining structure. The active core consists of a hexagonal lattice of 37 doped filaments with a diameter of 1.8 μm and filament-to-filament spacing of 5.1 μm, assembling a composed core with 28 by 31 μm in diameter. Numerical modeling based on the method of finite elements has been performed. The single-transverse-mode core has a mode-field diameter as large as 37 μm at the laser emission wavelength, which corresponds to an effective mode-field area of more than 1000 μm^2, and an effective numerical aperture of 0.022. In this structure, the V parameter is less than 2.4 providing robust and effectively single-mode

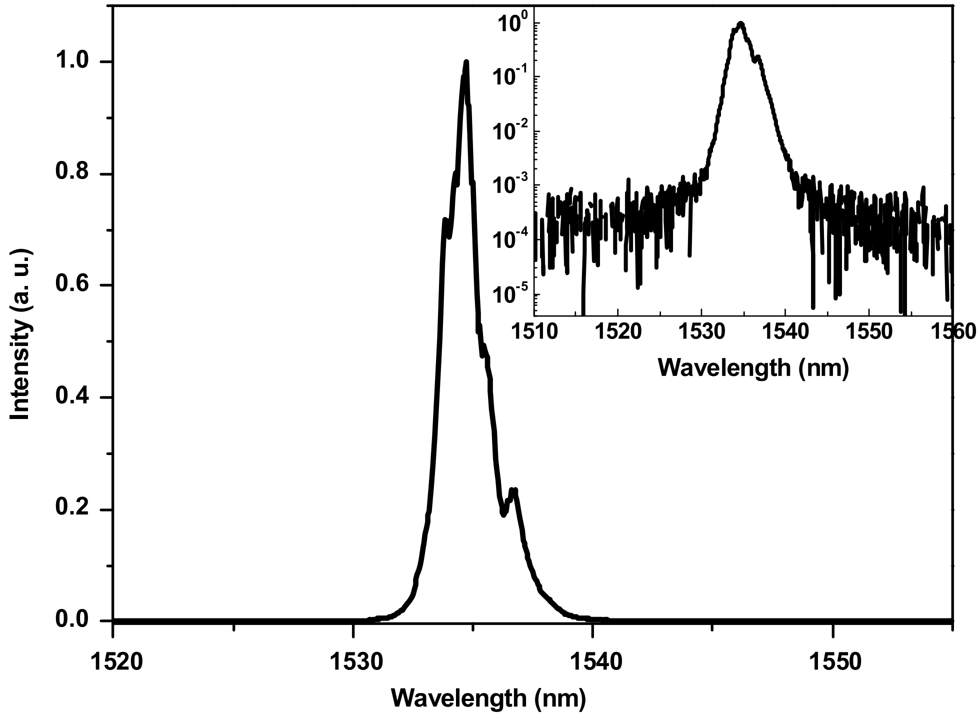

Fig. 3 Typical output spectrum of the output signal on a linear scale. *Inset* shows the optical spectrum on a logarithmic scale

large core guidance. The pump core has a double-D shape with dimensions 208 × 250 μm coated with a low index silicone (NA 0.37). The pump light absorption of this structure is 0.9 dB/m at 915 nm and larger than 3.4 dB/m at 976 nm. The length of the fiber inside the cavity is about 2 m to obtain efficient pump absorption. The gain fiber is pumped from one side by a fiber-coupled high-brightness laser diode emitting at 976 nm. The fiber end facets are angle polished to avoid undesired parasitic reflections. A dichroic mirror DM1 is used to separate the pump beam from the laser emission, which is centered at about 1535 nm. A second dichroic mirror DM2 removes unabsorbed pump radiation from the cavity. A polarizing isolator provides unidirectional operation and output coupling. A quarter-wave plate introduced between the polarizing isolator and the gain fiber allowed us to control the output coupling coefficient. In this configuration, the high output coupling ratio (more than 80%) is adjusted. Passive mode locking is achieved employing a saturable absorber mirror (SAM) placed at the end of the linear section of the sigma cavity. The commercial SAM (Batop 1550-35) presents a low intensity reflectivity of 65%, modulation depth of 21%, and saturation fluence of 20 μJ/cm^2 with a relaxation time of 2 ps. It should be noted here that even if we have carefully checked mode locking is not experimentally obtained without the real saturable absorber. It is also important to note that there is no additional dispersion compensation element. Hence, the laser operates in the purely anomalous dispersion regime.

The self-starting and stable mode-locked operation is obtained by optimizing the saturation threshold on the SAM for an adequate launched pump power. When the mode-locking threshold is reached, the laser delivers a single-pulse train with a repetition rate of 44 MHz. The stable mode-locked operation is observed by using an analog oscilloscope. The typical optical spectrum is shown in Fig. 3. The center wavelength is 1534.74 nm, and the optical spectrum bandwidth (FWHM) is approximately 1.75 nm. Figure 4 shows a measured autocorrelation trace obtained directly at the laser output. The clean output pulses present an autocorrelation width of 2.48 ps (FWHM). The best fit is obtained assuming a sech^2-pulse profile and the pulse duration is thus 1.61 ps. The corresponding time–bandwidth product is about 0.35 (close to the theoretical time-bandwidth product for a hyperbolic-secant-shaped pulse of 0.3148). This indicates that the fiber laser generates near transform-limited output pulses. To investigate single-pulse operation, a background-free autocorrelator with a scan range of 150 ps and a 200 ps rise time photodiode is used. No satellite pulses were observed with the use of the electronic detection systems. The average output power in single-pulse operation regime is as high as 400 mW for a pump power of 8 W, which corresponds to pulse energy of 9.1 nJ and soliton peak power of 5 kW. To the best of our knowledge, this is the first successful demonstration of high pulse energy soliton generation approaching the 10 nJ barrier by a high-power mode-locked new type of low-nonlinearity Er/Yb-doped multifilament-core fiber laser. The pulse energy achieved in this laser is approximately two times lower than that reported by Broderick et al. [16] but the pulse duration is a factor of 12 less, and the peak power is approx-

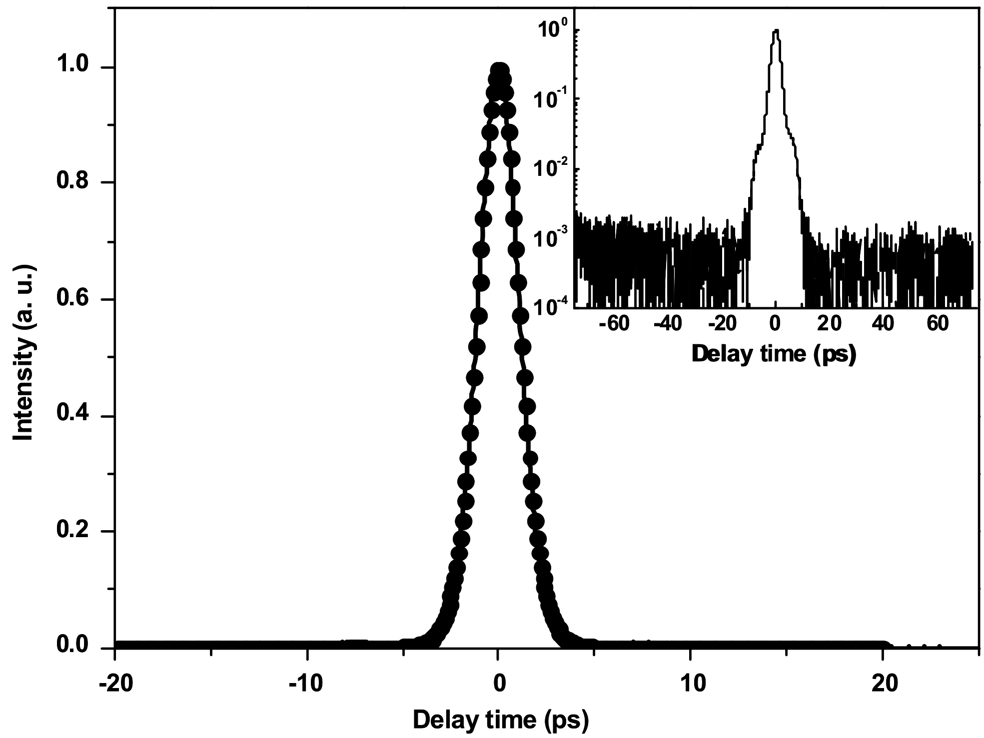

Fig. 4 Autocorrelation trace of the output pulses. The *circles* are a theoretical fit for a $sech^2$ pulse shape. *Inset* shows the autocorrelation trace on a logarithmic scale

imately five times higher that achieved by the LMA laser of [16].

In conclusion, for the first time to our knowledge, we have demonstrated the generation of high-energy short pulses in an Er/Yb-doped multifilament-core large-mode-area fiber laser operating in the purely anomalous dispersion regime. The fiber laser directly generates stable and clean 1.61 ps pulses at a repetition rate of 44 MHz. In the single-pulse regime, the laser delivers 400 mW of average power corresponding to pulse energy of more than 9 nJ with excellent beam quality determined by the intrinsically single-transverse-mode low-NA LMA fiber. The pulse energy is two orders of magnitude higher than so far reported for conventional single-mode fiber oscillators operating in the purely anomalous dispersion regime that typically generate few 100 pJ before pulse breakup occurs [2]. Scaling to 100-nJ pulse energy in femtosecond fiber lasers appears feasible by employing the single-mode LMA fiber concept operating in the other operation regimes, such as dispersion-managed soliton or stretched pulse.

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