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High-Pulse-Energy All-Normal-Dispersion Yb-Doped Fiber Laser Based on Nonlinear Polarization Evolution *

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We report an all-normal-dispersion ytterbium fiber laser mode locked by nonlinear polarization evolution. With a 347-m-long all-fiber ring cavity, a pulse energy of 263 nJ at a repetition rate of 613 kHz is achieved, which is the highest per-pulse energy directly obtained from an all-fiber mode-locked laser doped by ytterbium ions. The compact and operation-robust laser yields a well-shaped spectrum centered at 1032 nm with a bandwidth (FWHM) of 4 nm, and the slope efficiency is as high as 27.5%. The proposed low-repetition-rate high-pulse-energy mode-locked fiber laser will be a promising seed for all-fiber chirped pulsed amplification systems.

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Recent decades have witnessed a great development of pulsed fiber lasers operating in the regimes of picoseconds and nanoseconds, with wide applications in micromachining, medicine, national defense or optical communication.[1] To generate picosecond and nanosecond pulses, the passive mode-locked fiber laser is an efficient and ideal candidate due to its compact structure and stable operation in comparison with the Q-switched fiber laser.[2,3] Based on the net dispersion in the mode-locked resonator, they operate in four regimes: conventional solitons, stretched pulses, self-similar pulses and dissipative solitons.[4,5] Among them, the dissipative solitons with high chirp are particularly preferable to yield high-energy pulses due to their wide average duration stretched by excessive group velocity dispersion. The highly-chirped pulses can be dechirped to the Fourier transform limit outside the cavity.[6] Elongation of the laser cavity is another available way to scale up the pulse energy obtained in mode-locked fiber lasers. The low cost, high-energy low-repetition-rate nanosecond-pulse fiber laser can serve as an appropriate seed source for fiber chirped pulsed amplification (CPA) systems with no need for a pulse stretcher, a pulse picker and a preamplifier.

All-normal dispersion fiber lasers mode-locked by nonlinear polarization evolution (NPE) have attracted great attention due to their high efficiency and flexible setup. Typically, due to their broad emission bandwidth and high optical-to-optical conversion efficiency, Yb-doped fiber lasers (YDFLs) based on NPE have been considered as an innovative source for a variety of applications, such as high energy physics and material processing. Their excellent performance can be found in femtosecond fiber lasers,[6,7] high-repetition-rate fiber lasers,[8,9] tunable and switchable fiber lasers,[10,11] ultrabroad spectrum fiber lasers,[12,13] high-power fiber laser,[14,15] and high-order harmonic mode-locked fiber lasers.[8,16,17] Many studies have been conducted on low-repetition-rate, high-energy, passively mode-locked YDFLs by NPE. Using a 3.8-km-long resonant cavity mode-locked by free-space NPE, Sergey *et al.* have obtained a pulse energy of 3.9 μJ.[18] With the combination of a cascade long-period fiber grating and NPE mode locking technology, a maximum pulse energy of 26.8 nJ at 2.5445 MHz repetition rate has been demonstrated.[19]

A promising source for fiber CPA systems should include an all fiber configuration to guarantee robust running. Based on this requirement, an all-fiber environmentally stable mode-locked fiber laser based on NPE was first proposed in 2007.[20] The 217.4 kHz repetition-rate nanosecond pulses with a maximum pulse energy of 5 nJ after amplification have subsequently been achieved, constituting the foundation for a low-repetition-rate high-pulse-energy all-fiber YDFL mode locked by NPE.[21] By optimizing the coupling ratio (90%) and the position of the output coupler, stable mode-locked pulses are generated with a single pulse energy of 60 nJ at a repetition rate of 3.3 MHz, and the slope efficiency is as high as 68%, which is the best performance published previously.[22] Lin *et al.* have made a great contribution to the development of all-fiber high-energy low-repetition-rate YDFLs. They used NPE to achieve the low-repetition-rate of 365 kHz and high-energy pulses of 100 nJ.[23] With an elongated cavity length of 720 m, they also demonstrated 317 kHz low-repetition-rate rectangular

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pulses with the highest pulse energy of 182 nJ.[24] At the same time, Yu *et al.* reported high-energy square pulses in a mode-locked YDFL operating in dissipative soliton resonance; the maximum average output power and the corresponding pulse energy were 62.1 mW and 34 nJ, respectively.[25]

In this Letter, we propose an all-fiber YDFL with large normal dispersion mode-locked via NPE; highly chirped pulses are produced by a 347-m-long cavity. Without any dispersion-compensation, this layout is simple and highly efficient compared with other all-fiber mode-locked setups. A typical steep-edge spectral profile is obtained with a bandwidth (FWHM) of 4 nm, corresponding to a pulse duration of about 10 ns. The highest pulse energy of 263 nJ is produced under the maximal pump power of 600 mW. The accumulation of excessive nonlinear phase shift often causes the pulse to break up, and hence 1–9th order harmonic mode locking has been observed by changing the polarization or the pump power. To the best of our knowledge, this is the highest energy directly extracted from an all-fiber YDFL mode-locked via NPE with large normal dispersion. This result will be helpful for the research on dissipative soliton systems with high-energy pulse output.

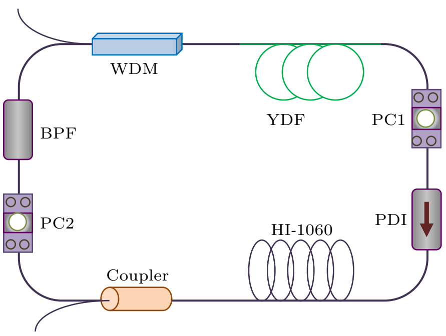

Fig. 1. Schematic diagram of the experimental layout. WDM, wavelength division multiplexer; YDF, ytterbium-doped fiber; PC1, PC2, polarization controller; PDI, polarization dependent isolator; BPF, bandpass filter.

The schematic diagram of the setup is depicted in Fig. 1. The all-fiber ring cavity configuration consists of net normal-dispersion fibers which offer a high value of normal group-velocity dispersion. The laser is pumped by a 976 nm single-mode pigtailed laser diode with a maximum power of 667 mW. A 980/1030 nm fused WDM is used for coupling the pump light into the oscillator. The gain material is made up of a 0.2-m-long Yb-doped fiber (YDF) (4.7/125 µm) with a core absorption of 1200 dB/m at 976 nm. For adjustment of the polarization in the laser, two in-line squeezing polarization controllers PC1 and PC2 are mounted onto the passive fiber HI-1060. The mode-locking technique of NPE is implemented with the combination of two PCs and a polarization-dependent isolator (PDI), which convert phase modulation to amplitude modulation forming a fast saturable absorber.[10,19,26] The PDI located in the middle of two PCs acts not only as an isolator ensuring unidirectional operation, but also as a polarizer. Dissipative processes play a crucial role in the formation of dissipative solitons, therefore an in-line bandpass filter (BPF) with a 3 dB bandwidth of 2 nm centered at 1030 nm is employed after PC1, to obtain stable mode locking. The laser energy is extracted from the cavity via a 50% output coupler. The full resonator length is designed as long as 347 m for increasing the nonlinear phase delay in a single cavity round trip and for boosting the output pulse energy. The entire scheme is misalignment free and largely immune to environmental perturbation owing to the fiber-integrated setup. All components are directly spliced to be compact in size.

The proposed laser cavity operates in the nonlinear regime for high energetic pulses. The standard HI-1060 has a dispersion of approximately 23 fs^2/mm at 1030 nm, and the total dispersion is estimated to be 8 ps^2, which leads to the formation of highly chirped pulses. The polarizer in the isolator acts as an attenuator on the dissipative soliton pulses propagating in the cavity. The attenuation is governed by the offset between the polarization state of the soliton pulse and the orientation of the polarizer.[27] The fast response time NPE provides efficient pulse formation mechanics and stabilizes mode locking at higher powers.[28] While tuning the pump power or changing the PCs, the output pulse characteristics are monitored in real time by a high speed photodetector combined with a 500 MHz oscilloscope (TEK DPO3052) and a commercial optical spectrum analyzer.

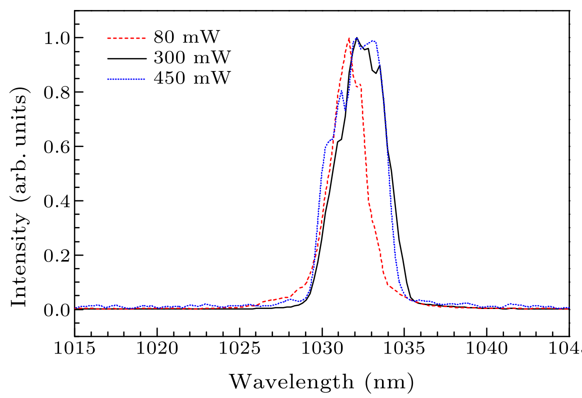

Fig. 2. Spectral characteristics of the fundamental mode-locking at different pump powers.

With appropriate rotation of the initial polarization ellipse and phase bias, the transmission rate of the NPE increases with pulse intensity, which can initiate mode-locking, and pulse shortening occurs.[29] The laser was operating in the cw regime when the pump power ranged from 20 mW to around 100 mW. Above this power, stable fundamental mode locking is initiated by adjusting two PCs to a certain respective position. The fundamental repetition rate is 613 kHz, which agrees well with the 347 m cavity length. A maximum output power of 161 mW is obtained at the maximum pump power of 600 mW. In the mode-locked regime, the cavity was optimized by minimizing the loss of splicing fiber and by increasing the output power through the large-ratio output coupler (50%). The stable mode-locked state was maintained until the pump power was decreased to 50 mW.

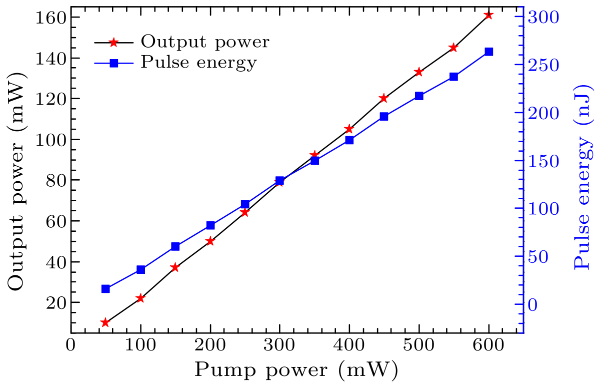

Fig. 3. Measured variation of output power and pulse energy as a function of the pump power.

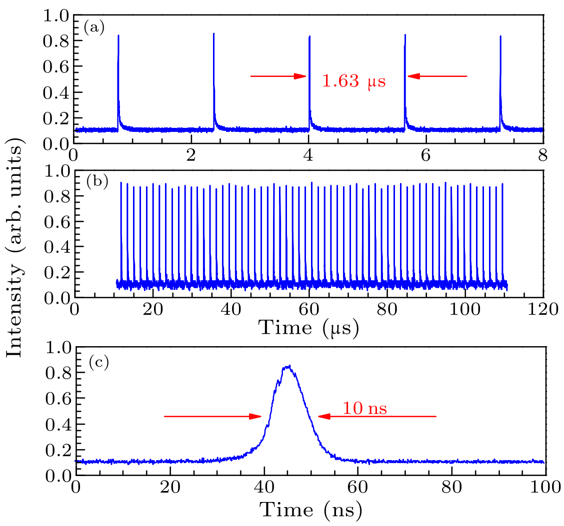

Fig. 4. Typical output oscilloscope traces under the pump power of 450 mW. (a) Pulse train of the mode-locked fiber laser on a short time scale. (b) Stable pulse train on a longtime scale. (c) The pulse duration of 10 ns.

The laser output spectral profiles at pump powers of 80 mW, 300 mW and 450 mW are shown in Fig. 2, clearly demonstrating the characteristic steep spectral edges of dissipative solitons generated in the chirped-pulse oscillator. At the pump power of 80 mW, the central wavelength was 1031.5 nm with a spectral bandwidth (FWHM) of approximately 2 nm. The central wavelength of the laser shifted towards longer wavelengths with increasing the pump power, while the spectrum broadened from 2 nm to 4 nm due to the stronger nonlinear effects with the enhanced pump power. In comparison with the giant spectral bandwidth generated from a 50%-coupler-ratio YDFL mode locked by the NPE mechanism,[13] the better performance in monochromaticity of the laser and spectral shape can be attributed to the bandpass filter with a 3 dB bandwidth of 2 nm centered at 1030 nm.

The measured output performance of the proposed oscillator is shown in Fig. 3. Generally, the output power (red stars) is proportional to the pump power, corresponding to a slope efficiency of 27.5%. The highest output power of 161 mW is reached at the pump power of 600 mW. The further increase in output power was limited by the available maximum pump power. The single pulse energy (blue squares) increased with the pump power at a slope of 44.9 nJ/mW and the maximal per-pulse energy of 263 nJ is achieved under the pump power of 600 mW. It is noteworthy that the pump power discussed here is the launched pump power. If the absorbed pump power was taken into consideration, a much higher slope efficiency would be obtained.

Figure 4 shows the output pulse characteristics of the mode-locked fiber laser under the pump power of 450 mW. Figure 4(a) shows the mode-locked pulse train with a repetition rate of 613 kHz, corresponding to a pulse period of 1.63 µs, and its stability is illustrated in Fig. 4(b). The pulse duration of 10 ns is detected by a high-speed InGaAs detector in combination with a 500 MHz oscilloscope, which is displayed in Fig. 4(c). The achieved energy of 263 nJ is, to the best of our knowledge, the highest single pulse energy directly obtained from an all fiber mode-locked laser with such a high slope efficiency.

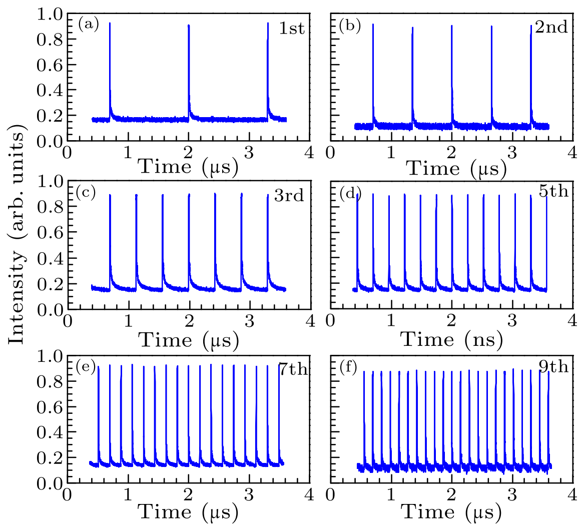

Fig. 5. Output pulse trains of the harmonic mode-locking laser measured by a high speed detector and a 500 MHz oscilloscope. (a) Pulse train of the fundamental mode locking with a repetition rate of 613 kHz. (b) The 2nd-order harmonic mode locking with a repetition rate of 1.227 MHz. (c) The 3rd-order harmonic mode locking with a repetition rate of 1.838 MHz. (d) The 5th-order harmonic mode locking with a repetition rate of 3.060 MHz. (e) The 7th-order harmonic mode locking with a repetition rate of 4.250 MHz. (f) The 9th-order harmonic mode locking with a repetition rate of 5.457 MHz.

The laser was not wavelength tunable owing to the appearance of harmonic mode locking caused by either the adjustment of the PCs with the fixed pump power or the increased pump power through polarization variation. Figure 5 shows the typical harmonic states from the 1–9th-order harmonic mode locking (HML). The repetition rate can be flexibly switched from 613 kHz to 5.457 MHz. In our setup, with the fixed pump power, the output power of various-order HML increased with raising order; for example, under the pump power of 250 mW, the 2nd-, 5th-, and 7th-order HML can be obtained with output powers of 54 mW, 58 mW, and 59 mW, respectively. Furthermore, the output power of HML was lower than that obtained from fundamental mode locking at the same pump power, for example, the 4th-order HML is achieved with an output power of 61 mW at the pump power of 300 mW, while the output power of fundamental mode locking is 79 mW. Therefore, the single pulse energy decreased dramatically in the HML regime either owing to the enhanced repetition rate or the reduced output power, which can account for the mechanism of pulse splitting. The switchable repetition rate fiber laser would satisfy some needs of high speed applications due to its interval-times of the fundamental repetition rate.

In summary, we have experimentally demonstrated dissipative solitons (DSs) with a giant chirp in an all-fiber laser. The NPE mode-locked system is self-starting, and generates a long pulse duration of 10 ns without any dispersion compensation elements. The spectrum centered at 1032 nm shows the characteristic steep edge of DSs with an FWHM of 4 nm. The calculated slope efficiency reaches 27.5%. A maximum 263 nJ of per-pulse output energy with a repetition rate of 613 kHz has been realized in the all-fiber mode-locked laser. Further optimization of the per-pulse energy can be achieved by employing a higher coupler ratio and extending the available maximum pump power. Additionally, we observe stable harmonic mode-locking from the 2–9th-order, broadening the theory of harmonic mode-locking and DS formation. The laser proposed in this work is highly stable since it is completely self-starting even after being powered off for multiple days. The generated low-repetition-rate and high per-pulse energy NPE mode-locked all-fiber laser would be an ideal seed for an all-fiber CPA system without stretcher, amplifier and pulse picker.

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