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Generation of 8.5-nJ pulse from all-fiber dispersion compensation-free Yb-doped laser

Panzheng Zhang (张攀政), Wei Fan (范薇), Xiaochao Wang (汪小超), and Zunqi Lin (林卓琪)

National Laboratory on High Power Laser and Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

∗E-mail: nwuzhangpanzheng@163.com

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We report the generation of an 8.5-nJ chirped pulse from a mode-locked all-fiber Yb-doped laser. Mode-locking is achieved through nonlinear polarization evolution (NPE) along with spectral filtering. The laser delivers 135 mW of average output power with positively chirped 10.9-ps pulses. The pulse repetition rate is 15.9 MHz, which results in an energy of 8.5 nJ per pulse. The externally dechirped pulse duration is 223 fs, and the pulse energy is 6 nJ, which corresponds to the peak power of ~27 kW.

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In recent years, femtosecond (fs) fiber lasers operating at 1-μm range have been developed. These lasers have increased pulse duration and energy performance due to the development of new mode-locking mechanisms. Stretched-pulse and self-similar mode-locked fiber lasers with dispersion compensation can generate pulses with energies from a few nanojoules (nJ) to over 10 nJ[1-5]. More recently, stable mode locking has been obtained in a passively mode-locked dispersion compensation-free fiber laser, wherein the pulse stabilization can be attributed to self-amplitude-modulation via spectral filtering[6]. This leads to the generation of pulses with more than 20-nJ energy from an all-normal-dispersion fs fiber laser[7].

Without discrete optical components influencing the effects of fiber format in the cavity, all-fiber fs lasers have tremendous potential for practical applications due to their advantages of better stability, being alignment free, and greater compaction compared with the lasers cited previously[1-7]. Several groups have investigated all-fiber lasers at 1-μm wavelength[8-11]. In 2007, Prochnow et al demonstrated an environmentally stable all-fiber laser, which was mode-locked with a semiconductor saturable absorber (SA) mirror and generated 627-fs pulses with an energy of 0.8 nJ[8]. In 2008, Schultz et al. demonstrated an all-fiber version of the all-normal-dispersion fiber laser demonstrated in Ref. [6], generating 179-fs pulses with the pulse energy of 1.8 nJ[9]. Kieu et al. reported the generation of 235-fs, 3-nJ pulses from an all-fiber laser mode-locked with a fiber-format SA combined with spectral filtering[10]. However, the SA degenerated after a few days, which made the mode locking of the laser more difficult.

In this letter, we show a significant improvement of the pulse energy from all-fiber Yb-doped mode-locked fiber lasers. The combined effects of a high output coupling ratio, all-normal cavity group velocity dispersion (GVD), and additional amplitude modulation produced by spectral filtering result in a desirable pulse output and ease of self-starting simultaneously. The laser is modelocked and stabilized with nonlinear polarization evolution (NPE) combined with spectral filtering. The 10.9-ps self-starting chirped-pulses with energy of 8.5 nJ have been achieved. To the best of our knowledge, it is the highest pulse energy in the wavelength range around 1 μm obtained for all-single-mode-fiber mode-locked Yb-doped lasers. The externally dechirped pulse duration is 223 fs, and the energy is 6 nJ, corresponding to the peak power of ~27 kW.

The experimental setup of the laser is shown in Fig. 1. A 30-cm Yb-doped gain fiber (975 dBm-1 absorption at 979 nm) was core pumped using a 980-nm diode laser with the maximum output power of 460 mW via a 980/1053-nm wavelength division multiplexer (WDM). Following the gain fiber, a fused coupler was spliced to output the power at an output coupling ratio of 70%. After the polarization controller (PC I) used to adjust the polarization state, an in-line polarizer (ILP) was utilized to realize NPE, and the extinction ratio of 35 dB between orthogonal polarizations was achieved. The intensity-dependent polarization modulation was converted into an amplitude modulation forming the virtual SA[12]. In the all-normal dispersion cavity, the nonlinear phase shift enlarges the positive chirp and bandwidth of the pulse significantly. Therefore, following PC II, a custom fiber-tailed band pass spectral filter (SF) was spliced to provide an additional amplitude modulation via spectral filtering of highly chirped pulses[6,9], thereby stabilizing the mode locking. The transmission curve of the SF is centered at 1053 nm with a pass-band about 18 nm wide (full-width at half-maximum, FWHM), as shown in Fig. 2. To enable unidirectional operation, a fiber-format polarization-independent isolator (ISO) was inserted after the ILP. The insertion losses of the PC, ISO, ILP, SF, and WDM are ~1, 2.3, 0.6, 0.7, and 0.2 dB, respectively. The fiber-format components were spliced directly to form the alignment-free cavity. All fibers used were single-mode fibers with a 6-μm core diameter. The total length of the ring cavity was 12.2 m, which corresponded to a 15.9-MHz repetition rate. No dispersion compensation segment was present in the cavity, so the total cavity dispersion was 0.305 ps².

In fiber lasers, pulse energies are limited primarily by...
fig. 2. transmission curve of the spectral filter.

The nonlinearity accumulated on propagation through the fiber. Nonlinearity can limit pulse energy through either of the following two mechanisms. Excessive energy can result in wave breaking through the combined effects of dispersion and nonlinearity\cite{13}. The effective SA can be overdriven at high peak powers, which can lead to multiple pulses\cite{14}. Theoretically, the pulse energy increases with normal net GVD increasing, which tends to “balance” the accumulated nonlinearity and make the pulse energy threshold of wave breaking significantly higher\cite{4,13}. Thus, in all fiber Yb-doped lasers, overdriving the SA is the more fundamental of the two limitations. In the presented laser, NPE is used as the effective SA. We can push the overdriving point to a higher pulse energy by decreasing the strength of NPE\cite{14}. The output coupler spliced close to the gain fiber exports the energy at a coupling ratio as high as 70%. Thus, the pulse energy in the cavity and the accumulated nonlinear phase shift should both decrease notably, assuming the same output power. Otherwise, the output pulse duration and chirp substantially increase when the cavity GVD is all-normal. Long and highly-chirped pulses experience less amplitude modulation from NPE than short pulses. However, there is a trade-off between the avoidance of overdriving the NPE and ease of self-starting\cite{2}. To self-start and stabilize mode locking, a SF was employed to offset the reduction in NPE action by additional amplitude modulation. The combined effects of high output coupling ratio, all-normal cavity GVD, and SF result in a desirable pulse output and ease of self-starting simultaneously.

Self-starting mode locking is obtained by adjusting the pump power and PC. The mode-locking threshold is achieved at the pump power of 350 mW. Figure 3 shows that the average slope efficiency is 33%, and the output power of 135.37 mW is achieved at the maximum pump power of 460 mW. The corresponding maximum pulse energy is 8.5 nJ with the pulse spacing of 63 ns. When the laser operates at the maximum pump power, no multiple pulsing is observed, indicating that the pulse energy is limited by the pump power but not by NPE overdriving.

The typical output spectrum of the laser is shown in Fig. 4. The spectrum exhibits the characteristics of pulse-shaping by spectral filtering at normal dispersion: Steep sides and peaks at the edges\cite{15}, which are consistent with the significant self-phase modulation within the cavity. However, the peak at the left edge (∼1040 nm) of the spectrum almost disappears due to the strong influence of the SF whose transmission decreases rapidly at 1040 nm (Fig. 2).

To confirm single-pulse operation, the emitted pulse train is observed with a fast photodiode (8-GHz bandwidth). No multiple pulsing is seen, as shown in Fig. 5. The pulse spacing is 63 ns, which corresponds to the 15.9-MHz pulse repetition rate. The autocorrelation function of the pulse measured with a long-range autocorrelator shows that the pulse duration is 10.9 ps assuming a Gaussian pulse shape (Fig. 6(a)). The chirped pulses are dechirped to 223 fs using a grating pair outside the cavity (Fig. 6(b)). The dechirped pulse energy is 6 nJ, which is due to the loss at the grating compressor. The corresponding peak power is ∼27 kW.

The laser operates quite stably, and the fluctuation of output power is within the confines of 0.5% during several hours of mode-locked operation without readjustment of the PC or pump power. If the pump laser is switched off then switched on again, the laser returns directly to the same mode-locked state, indicating easy

![Fig. 1. Schematic of the fiber ring cavity.](image)

![Fig. 2. Transmission curve of the spectral filter.](image)

![Fig. 3. Output power of the mode-locked operation with respect to pump power.](image)

![Fig. 4. Output spectrum of the mode-locked laser.](image)
In conclusion, we demonstrate the generation of 10.9-ps pulses with up to 8.5-nJ pulse energy from an all-fiber dispersion compensation-free passively mode-locked Yb-doped laser. The pulses are externally compressed to 223 fs, with a pulse energy of 6 nJ. To our knowledge, these energies are the highest ever reported directly from an all-single-mode-fiber mode-locked Yb-doped laser. The behavior of the laser depends crucially on the SF, output coupling ratio, position of the output coupler, and Yb-doped fiber. A detailed study on pulse formation, as well as the evolution in this laser and the optimization of its components, is in progress. A higher pulse energy and improved stability should be possible after further research on the topic.

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