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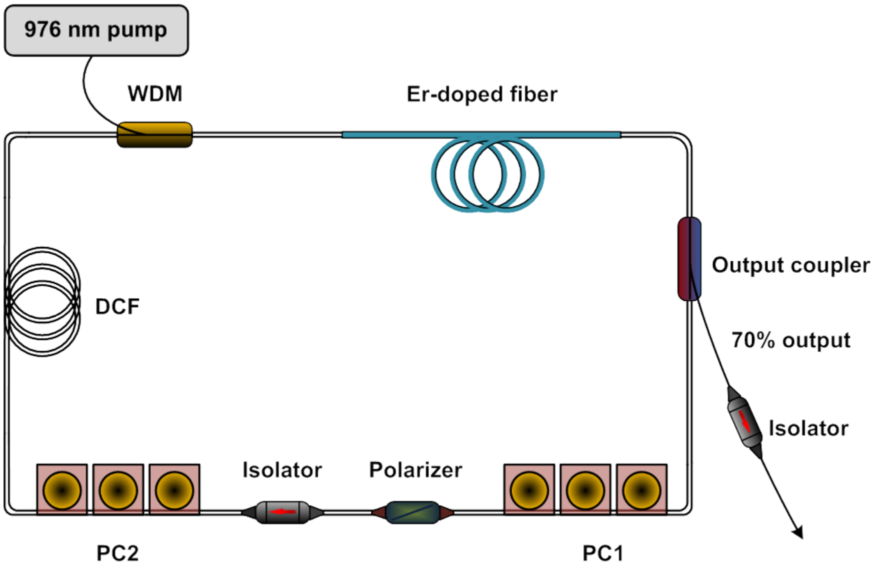

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# Dissipative Soliton (12 nJ) From an All-Fiber Passively Mode-Locked Laser With Large Normal Dispersion

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**Abstract:** We experimentally demonstrate an all-fiber erbium-doped fiber laser operating in the large normal dispersion regime. The laser is mode-locked by use of nonlinear polarization rotation and generates dissipative solitons (DSs) with large positive chirp and steep spectral edges. Within the cavity, there is no additional spectral filter used for self-starting and stabilizing the mode-locking of the laser. The output DSs have a duration of 30.5 ps with pulse energies up to 12 nJ, which can be compressed externally to 240 fs.

**Index Terms:** Fiber lasers, mode-locked lasers, pulse shaping, pulse compression.

## 1. Introduction

In recent years, it has been proved that passively mode-locked fiber lasers operating in the large normal dispersion regime can directly generate high-energy pulses with high chirp, which can be promising for candidates competing with their solid-state counterparts [1]–[6]. These types of fiber lasers produce typical pulses with large normal chirp and steep spectral edges, which are also called dissipative solitons (DSs). It has been shown that spectral filtering plays a crucial role in DS formation in fiber lasers with large normal dispersion [1], [5]. This is because DSs rely on a balance of group velocity dispersion (GVD), self-phase modulation, saturable absorption, and spectral filtering. They allow for an increase in output pulse energies by 1 order of magnitude in comparison with dispersion-managed solitons.

As ytterbium-doped fibers (YDFs) offer great potential, they are the preferred gain media for implementing high-energy DSs in the 1-$\mu$m region. Recently, in order to realize YDF high-energy DS lasers with an all-fiber cavity configuration, various approaches have been employed [7]–[9]. Actually, large normal dispersion fiber lasers also have been realized at wavelengths around 1.5 $\mu$m with erbium-doped fiber (EDF) as a gain medium. Employing nonlinear polarization rotation (NPR), Chichkov *et al.* attained 20 nJ of pulse energies from an all-normal-dispersion (ANDi) EDF laser stabilized with a bulk birefringent filter [10]. The same authors further realized 50-fs pulses by optimizing their laser cavity in another experiment [11]. The laser operated at a repetition rate of 109 MHz with output pulse energies of 1.6 nJ and broadband spectra covering the range from 1475 to 1620 nm. In fact, different from mode-locked YDF lasers, EDF lasers with large normal dispersion

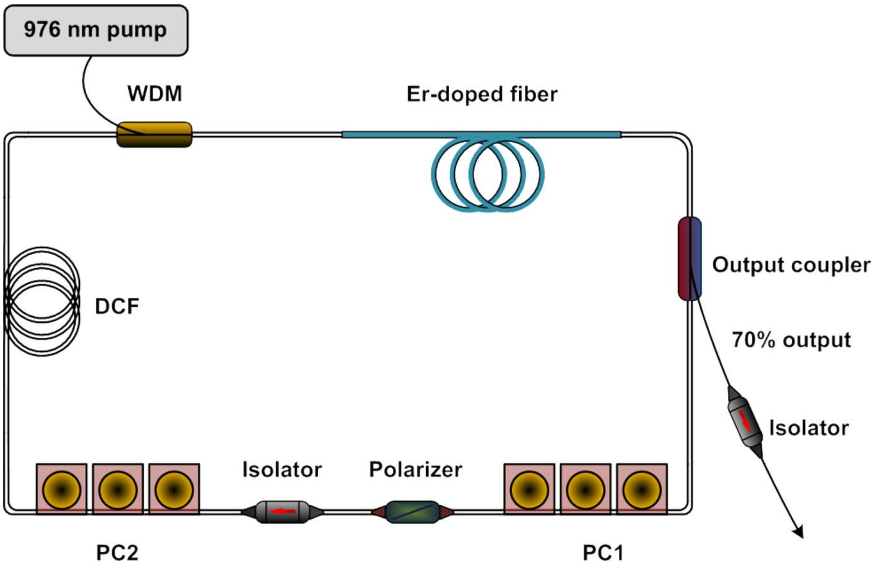

Fig. 1. Schematic diagram of the large normal dispersion EDF laser mode-locked using NPR. (WDM: wavelength division multiplexer, DCF: dispersion compensation fiber, PC: polarization controller).

even can generate high-energy DSs without using an additional spectral filter inside the cavity. The reason is, for the EDF lasers, the gain fibers have narrow gain bandwidth which functions as an effective spectral filter in the lasers. Ruehl *et al.* have demonstrated 10-nJ chirped pulses from a large normal dispersion EDF laser with no additional spectral filter for stabilizing the mode-locking [12]. Within their cavity, the pulse shaping of the DSs was dominated by the gain bandwidth limitation of the EDF gain medium. However, in those EDF pulsed lasers some bulk components were used to enable self-starting of the mode-locking in the lasers. For minimizing environmental effects on the laser systems, lasers with all-fiber configurations are preferred. More recently, Liu *et al.* presented 8 nJ pulse output from a compact, all-fiber EDF laser mode-locked by NPR [13]. The output chirped pulse was compressed to 290 fs external to the cavity.

It is well known that pulses can be effectively enhanced in energy by lengthening cavity length together with increasing cavity dispersion. In this paper, we propose an all-fiber EDF passively mode-locked laser with a configuration similar to reference [13]. Within the cavity, there is no additional spectral filter used for stabilizing the mode-locking. In order to enhance the energy per pulse, a long segment of dispersion compensation fiber (DCF) is employed within the cavity to decrease the repetition rate as well as increase the cavity dispersion, which leads to the stretching of the pulse duration. The output DSs have 12 nJ pulse energies and can be externally compressed to 240 fs with standard single-mode-fibers (SMFs). Compared with the result obtained in [13], the pulse energy is scaled by 50%. The overdriving of the effective saturable absorber, however, can arise as a restriction on further energy scaling. To the best of our knowledge, it is the highest pulse energy that is directly extracted from all-fiber passively mode-locked EDF lasers with large net normal dispersion. Using their chirped pulse laser with nanotube-based saturable absorber, Sun *et al.* implemented all-fiber chirped-pulse amplification and obtained 1.6 W average power and 11 kW peak power [6]. We believe the generated highly chirped pulses from the proposed all-fiber oscillator can also directly seed a fiber amplifier; thus, an all-fiber maser oscillator amplifier system can be realized. This compact laser source may find its position in high-power applications, such as micromachining and laser surgery.

## 2. Experimental Setup

The experimental setup is schematically shown in Fig. 1. A 15.5-m-long EDF with GVD of 28 $\text{ps}^2/\text{km}$ is forward core-pumped with a 976-nm laser diode delivering maximum output of 500 mW, with

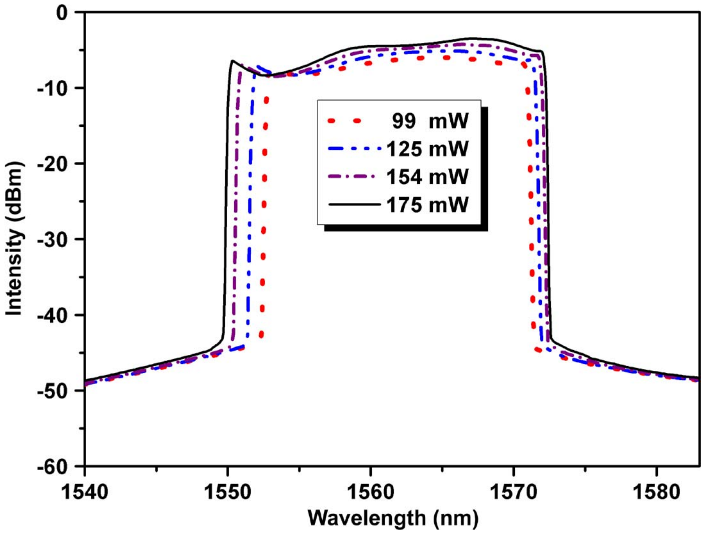

Fig. 2. Output optical spectra at different pump power.

the help of a WDM combining pump and signal light at 976 nm and 1550 nm. The intracavity pigtailed fiber of the WDM is a 1.5-m-long HI1060 Flex fiber with GVD of 20 $\mathrm{ps}^2/\mathrm{km}$. Following the EDF, a fused fiber coupler with 70% output coupling ratio is used to output the signals. The rest of the ring cavity contains two sets of polarization controllers (PCs) and a fiber-based polarizer suppressing one polarization to achieve mode-locking by NPR, a polarization-independent isolator to ensure unidirectional laser operation, and a 40-m-long DCF with GVD of 5.2 $\mathrm{ps}^2/\mathrm{km}$ to increase the cavity length and the net cavity dispersion. The polarizer and the isolator are made with the standard SMF with GVD of $-22$ $\mathrm{ps}^2/\mathrm{km}$, and the total pigtailed fiber is 1.5 m long. The PCs and the output coupler are specially made with the DCF of 4.5 m. Therefore, the total length of the cavity is 63 m, resulting in $\sim$3.3 MHz fundamental repetition rate, and the net cavity dispersion is about 0.68 $\mathrm{ps}^2$.

## 3. Experimental Results and Discussions

Experimentally, no additional spectral filter was inserted into the ring cavity, and the pulse shaping in the large normal dispersion cavity was dominated by the limited gain bandwidth of the EDF. Once the PCs were under proper settings, the laser was self-started, and single-pulse operation was obtained when the pump power was above 83 mW. Switching the pump diode off and on again led to the same state of operation. During more than two weeks, if keeping the laser setup unmoved, the laser can always self-start and get the same output characteristics when just increasing the pump power to above 83 mW. After mode-locking, the laser generated stable single-pulse operation with repetition rate of $\sim$3.3 MHz. When the pump power was increased above 175 mW, CW peaks appeared on the optical spectrum of the output pulse. Under *a* higher pump power, multiple-pulse operation was observed. Fig. 2 shows the output spectra at different pump power. Obviously, the optical spectrum of the pulses has the characteristic steep spectral edges of DSs, indicating that the generated pulses are DSs. With the increase of the pump power, the edge-to-edge bandwidth of the output spectrum is broadened due to self-phase modulation effect and the center wavelength slightly shifts toward the short-wavelength direction. When the pump power is 175 mW, the edge-to-edge spectral width is 22 nm centered at 1561 nm. In this case, the corresponding temporal output was characterized with a 20-GHz real time oscilloscope and an autocorrelator. The measured oscilloscope trace and the autocorrelation trace are shown in Fig. 3(a) and (b). The period of the pulse trains is about 301 ns, that is, the repetition rate is around 3.3 MHz, which agrees well with that expected from the 63-m-long cavity. No multiple pulses were observed when the pump power was below 180 mW. Fig. 3(b) shows that the autocorrelation trace has a full-width at half-maximum (FWHM) of about 43.1 ps. As the trace has a Gaussian profile [see Fig. 3(b)], the

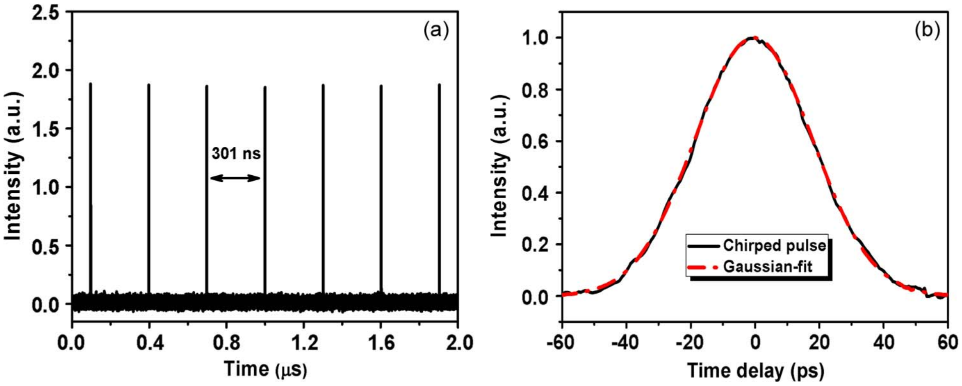

Fig. 3. (a) Oscilloscope trace of the output chirped pulse. (b) Autocorrelation trace of the chirped pulses.

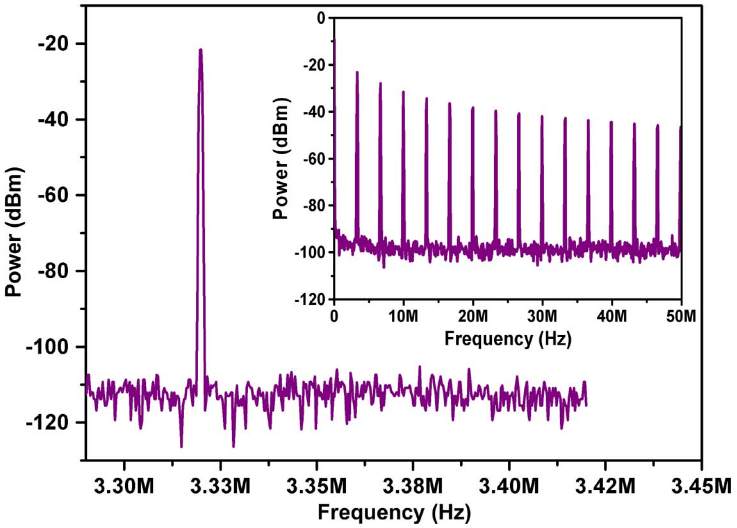

Fig. 4. RF spectra of the output pulse trains.

pulse duration is ~30.5 ps. The calculated time-bandwidth product is ~59.8, indicating that the output pulse has strong chirp. In order to filter out the residual 976-nm pump light from the output light, another fiber-based 1550-nm isolator was employed external to the cavity. By use of this isolator, the unabsorbed pump light was completely eliminated, verified by monitoring the optical spectrum of the output light with an optical spectrum analyzer. The measured average power is about 39.8 mW; thus, the calculated pulse energy is up to 12 nJ. This is the highest pulse energy obtained from all-fiber-integrated passively mode-locked DS lasers in the 1.5-$\mu$m region. Further lengthening the cavity by employing DCFs within the cavity cannot enhance the pulse energies because the overdriving of the effective saturable absorber and pulse-breaking will arise.

The radio frequency (rf) spectrum of the output pulse trains was measured by a 2-GHz photodetector and a signal-source analyzer (SSA, Rohde and Schwarz FSUP26), as shown in Fig. 4. The inset shows the flat background at $-100$ dBm, confirming that no Q-switching, period-doubling, or higher harmonic mode locking are present. Fig. 4 clearly demonstrates a stable operation of our laser, with a signal-to-noise ratio up to 80 dB at a 300-Hz resolution bandwidth.

Fig. 5 shows the output average power as a function of the pump power. It can be seen that the self-started mode-locking is achieved above a threshold of 83 mW, and the maximum single-pulse-operation output power of ~40 mW is obtained when the pump power is increased to 175 mW. The corresponding pulse energy calculated is also shown in Fig. 5 (right *Y* axis). Obviously, once

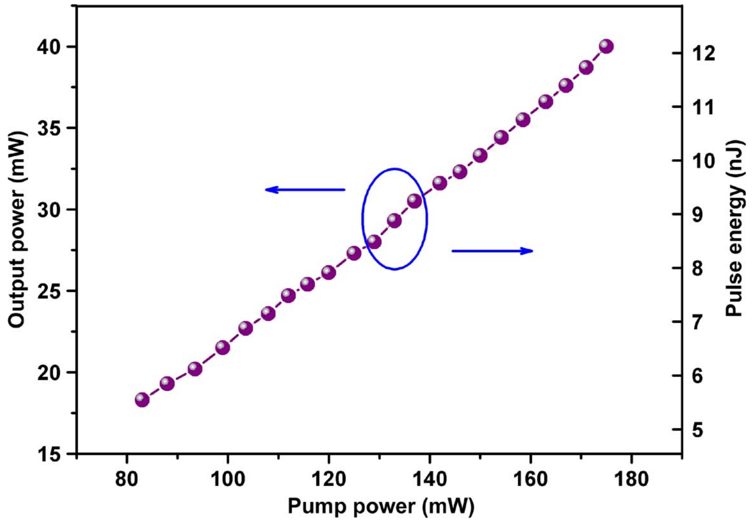

Fig. 5. Pump power versus the output power and the corresponding output pulse energy.

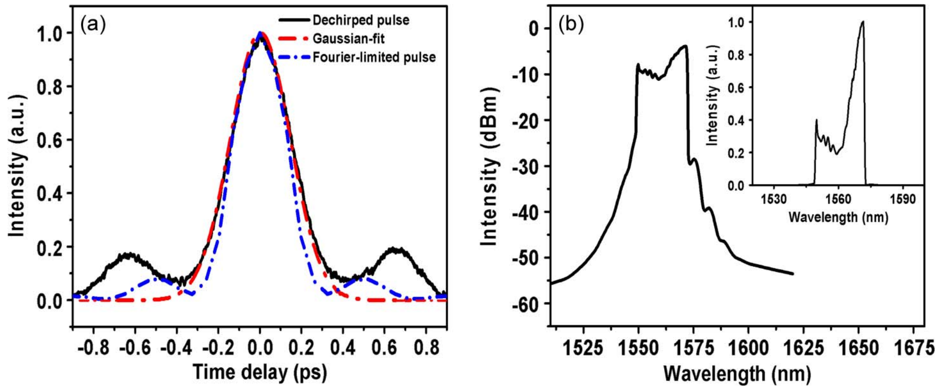

Fig. 6. (a) Autocorrelation of the dechirped pulse and the calculated Fourier-limited pulse. (b) Spectra after compression on logarithmic and linear (inset) scales.

mode-locking is self-started, more than 5 nJ pulse energies can be attained. With the increase of the pump power, the pulse energy is scaled up to 12 nJ. Moreover, it reveals a linear dependence of the average power as well as the pulse energy on the pump power, and the slope efficiency is ~23.6%.

As the standard SMF has anomalous dispersion at 1.5 $\mu$m region, we used 200 m SMF to compress the output chirped pulse initially. By use of cutting-back method, a shortest pulse was attained with 85.5-m-long SMF compensating the chirp accumulated inside the cavity. The compressed pulses were characterized with an autocorrelator and an optical spectrum analyzer. The measured autocorrelation trace of the compressed pulse is shown in Fig. 6(a) along with the calculated Fourier-limited pulse. The compressed pulses have an autocorrelation width of 340 fs, which corresponds to the pulse duration of 240 fs, i.e., 9% above the Fourier-transform-limited pulse width of 220 fs, assuming a Gaussian profile [see the Gaussian-fit curve in Fig. 6(a)]. Clearly, the compressed pulses exhibit two satellite pulses that contain ~20% of the pulse energy. The satellite pulses result partially from the uncompressed nonlinear chirp in the output pulses and are even present in the Fourier-limited pulse [see Fig. 6(a)]. Removing the energy contained in the satellite pulses, the main pulses have a peak power of about 33 kW. After compression, the output pulse spectra on logarithmic and linear scales are measured and given in Fig. 6(b). Compared with the spectrum obtained directly from the oscillator (see Fig. 2), the edge-to-edge spectral width changes slightly, but more frequency components appear in the pedestal of the spectrum. These

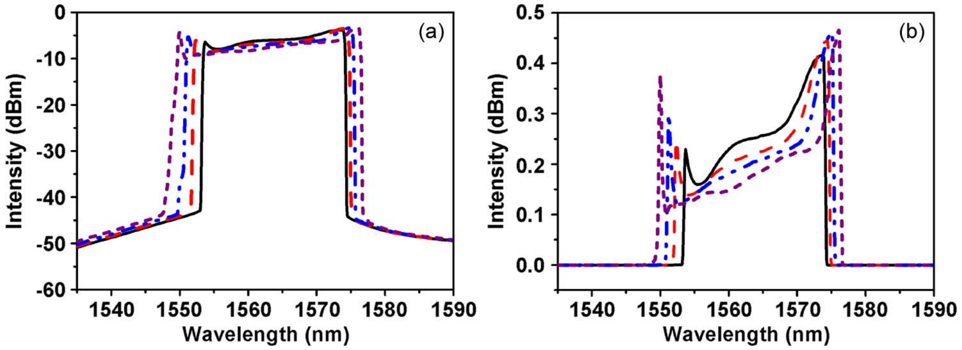

Fig. 7. (a), (b) Variation of the optical spectrum with cavity birefringence under fixed pump power on linear and logarithmic scales.

components are accumulated during compression process in the SMF, mainly due to the self-phase modulation effect.

In the experiment, the influence of the cavity birefringence on laser operation is also investigated. Under a fixed pump power, the adjustment of the PCs can lead to other stable operation states of the DSs laser. Fig. 7 shows the output spectra obtained when the pump power is 170 mW. In Fig. 7, the solid curve has an edge-to-edge spectral width of 20.9 nm, centered at 1564.0 nm. Keeping the pump power constant, when one of the paddles of the PC1 was continuously rotated from the state shown by the solid curve, the edge-to-edge spectral width changed to 26.8 nm (dotted curve), and its central wavelength shifted to 1563.0 nm. The corresponding pulse width also changed from 35.5 ps to 37.1 ps, while the pulse energy of $\sim$10 nJ was just slightly changed. The above process is reversible. When the paddle of the PC1 was rotated reversely, the DS operation can gradually change from the dotted curve state back to the solid curve state; see Fig. 7. The following reason can explain the variation of the spectrum with the cavity birefringence. It is well known that NPR mode-locked fiber lasers have a cavity transmission as a sinusoidal function of the linear and nonlinear phase shift of light in the cavity. Depending on the linear cavity birefringence, the cavity transmission has different transmission bandwidth, which can serve as an artificial cavity birefringence filter. It indicates that, although there is no discrete spectral filter used in our laser cavity, the artificial cavity birefringence filter, together with the gain bandwidth limitation, plays an important role in the DS pulse shaping within the cavity. With the adjustment of the paddles of the PCs, the bandwidth of the artificial cavity birefringence filter is changed, and consequently, the effective gain bandwidth can be changed correspondingly. That is why the output pulse characteristics vary with the cavity birefringence.

## 4. Conclusion

In summary, we experimentally reported on a large normal dispersion all-fiber-integrated DS EDF laser delivering up to 12 nJ pulse energies. The output highly chirped pulses have a duration of 30.5 ps, which have been compressed to 240 fs with a 85.5 m standard SMF external to the cavity. The peak power of the compressed pulses is about 33 kW. The dependence of the laser characteristics on the cavity birefringence also has been studied in this paper. By combination of the gain bandwidth and the cavity birefringence filter limitation, various output characteristics can be attained in the proposed compact DS laser.

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