Generation of single and multiple dissipative soliton in an erbium-doped fiber laser*

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We experimentally report on the generation of single and multiple dissipative soliton via nonlinear polarization rotation technique. The spectrum of the mode-locked dissipative soliton exhibits typical steep edges with a flat top; the pulse duration is 10.07 ps. It is found that with the pump power increasing from 110 mW to 161 mW, the top of the mode-locked spectrum becomes flater and the 3-dB spectral bandwidth is broadened, which indicates that the gain-dispersion effect is lowered under stronger pump. However, the full bandwidth of the spectrum is narrowed, which proves that the spectral filter effect increases and overcomes the effect of self-phase modulation induced spectral broadening. Such a phenomenon was not noticed nor reported before. Our experiment also demonstrates that the pulse interval is highly dependent on the input pump power: with pump power increasing, the pulse interval tends towards more uniform. So our observation qualitatively analyzes the relationship between mode-locked pulse characteristics and input pump power.

Keywords: fiber lasers, optical solitons, mode locking

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1. Introduction

Passively mode-locked fiber lasers have been extensively studied in the past decades for their many advantages over conventional solid-state lasers, such as lower cost, easier adjustment, and higher stability.[1–6] Nonlinear polarization rotation (NPR)[1] and saturable absorbers (including semiconductor saturable mirrors,[7] graphene,[8] black phosphorus,[9] tungsten disulfide,[10] etc.) are two kinds of common techniques to obtain mode-locked ultra-short pulses. Depending on the cavity dispersion design, different kinds of pulses could be generated in fiber lasers.[11–14] In an anomalous-dispersion fiber laser, conventional soliton was usually formed by the balance between negative group-velocity dispersion (GVD) and self-phase modulation (SPM).[15] The conventional soliton was characterized by spectral sidebands and chirp-free time bandwidth product (TBP). However, due to the effect of soliton area theory, its pulse energy was limited to a very low level of 0.1 nJ,[16] which greatly restricted its applicability. In a dispersion-management cavity, the net cavity dispersion was nearly zero, and stretched pulse was obtained.[17,18] The peak power of the mode-locked pulse was effectively lowered, and the allowed pulse energy was significantly increased to ∼ 1 nJ.[19] With a little normal dispersion, the self-similar pulse was expected to be generated, which could tolerate strong nonlinear phase shift without wave breaking.[20,21] While due to the restriction of the finite gain bandwidth in a fiber laser, the ultimate pulse energy was limited to a 10-nJ level.[22] In mode-locked fiber laser, the excessive nonlinear phase accumulation always induced the pulse to break up.[23–25] Therefore, the management of the nonlinearity was necessary to reach high-energy pulse emission. Furthermore, a dissipative system was proposed and investigated in the fiber laser with large normal dispersion.[26] Moreover, the dissipative soliton (DS) was realized both theoretically and experimentally.[27–30] In the dissipative system, the dispersion, nonlinearity, laser gain/loss, and spectral filter (SF) worked together to form the mode-locked pulses.[31] The SF effect could efficiently modulate the pulse amplitude,[32] which is beneficial to stabilizing the high-chirped DS mode locking state. Hence, the allowed pulse energy of DS was improved to ∼100 nJ, which was higher than that of conventional soliton by four orders of magnitude.[33,34] The strong SF effect also resulted in the fact that the spectra of DS exhibited a nearly rectangular profile with steep edges, which was commonly regarded as an important symbol of DS. However, the pulse energy of such a kind of DS was still limited by the tendency of multi-pulse arising when the input pomp power was excessive. Although reports of DS were very extensive, the research of the multi-pulse generation was relatively deficient, and the discussion about the relationship between the pulse characteristics and input pump power was also rare.

In this work, we experimentally obtain DS emission in an erbium-doped fiber (EDF) laser via NPR technique. Moreover, we report on the generation of single pulse, multiple pulses, and 2nd harmonic mode-locked pulses respectively. The spectrum of the mode-locked DS exhibits a typical rectangular shape with steep edges; the 3-dB bandwidth is measured to be 19.13 nm. In time domain, the pulse presents a Gaus-

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sian profile, and the pulse duration is 10.07 ps. The pulse train on oscilloscope is very uniform, and the fundamental repetition rate is 14.15 MHz. Our experiment also demonstrates that the pulse number and interval are both highly dependent on the input pump power. In our experiment, when increasing the pump power, the pulse number increases from one to five and the pulse interval tends to become more uniform. At the same time, a novel phenomenon is discovered. When the input pump power is increased form 110 mW to 161 mW, the top of the mode-locked spectrum turns flater, as a result, the 3-dB spectral bandwidth is broadened obviously. It shows that the gain-dispersion effect induced by the gain fiber is lowered under stronger pump. However, the full bandwidth of the spectrum is narrowed a little, which proves that the SF effect in the fiber laser increases and overcomes the effect of SPM induced spectral broadening. Such a phenomenon was not noticed nor reported before. So our observation qualitatively analyzes the relationship between mode-locked pulse characteristic and input pump power experimentally.

2. Experimental setup

The configuration of the fiber laser system is schematically shown in Fig. 1. One 976-nm laser diode with a maximum output power of 650 mW was coupled into the laser cavity by a 980 nm/1550 nm wavelength-division-multiplexer (WDM). A section of 10-m EDF (Nufern: EDFC-980-HP) with a dispersion parameter D of about -42 (ps/nm)/km at 1550 nm worked as the gain medium and contributed to the large-normal dispersion. The other fibers in the cavity were the single-mode-fiber (SMF) with a total length of ~ 4.5 m, the dispersion parameter D of SMF was ~ 17 (ps/nm)/km. The fundamental frequency and net dispersion of the cavity were estimated at ~ 14.1 MHz and ~ 0.44 ps^2, respectively. A polarization-sensitive isolator (PS-ISO) accompanied with two polarization controllers (PCs: PC-1 and PC-2) worked as an equivalent saturable absorber, and the NPR technique was utilized to realize mode locking state in this fiber laser. A fiber-pigtailed optical coupler (OC, 10% output) acted as the output port. A power meter (JDSU OLP-85), an optical spectrum analyzer (Yokogawa AQ6370D), an autocorrelator (Alnair Laboratories Corporation HAC-200), a 40-GHz radio-frequency analyzer (Agilent E4447A), and a 1-GHz digital oscilloscope (Rohde&Schwarz RTO1014) with a home-made 5-GHz photodiode detector were employed to simultaneously monitor the output pulses.

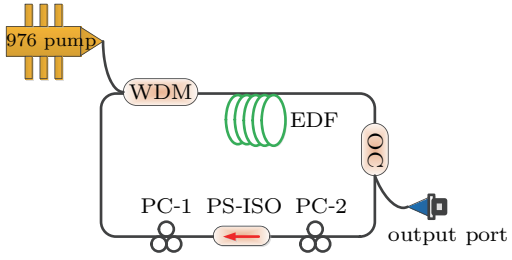


Fig. 1. (color online) Schematic diagram of the experimental setup.

3. Experimental results

By appropriately adjusting the polarization states of the two PCs, self-started mode locking state is realized when the input pump power reaches 110 mW. The mode-locked fiber laser emits typical DS, which is characterized by rectangular-profile spectrum with steep edges as shown in Fig. 2(a). Due to the strong SF effects caused by the gain fiber and other components in the laser system, the spectrum is restricted from 1545.22 nm to 1572.48 nm corresponding to a full bandwidth of 27.26 nm (herein, we take 20-dB bandwidth as the full bandwidth). The 3-dB spectral bandwidth is 19.13 nm. The corresponding autocorrelation trace performs a Gaussian shape as shown in Fig. 2(b), which means that the DS possesses a Gaussian profile in time domain. The pulse duration is estimated at 10.07 ps. The corresponding TBP is calculated to be 23.70, which is much larger than the transmission limit of 0.44. So the mode-locked DS is highly chirped. The pulse train on oscilloscope presents a uniform intensity on a scale of 2 μs as shown in Fig. 2(c). The pulse interval is ~ 70.6 ns as shown in the inset of Fig. 5(c), which is in agreement with the cavity round-trip time. The corresponding radio-frequency spectrum as shown in Fig. 2(d), reveals that the fundamental repetition frequency located at ~ 14.15 MHz is in agreement with the pulse interval, thereby confirming that the mode-locked pulse state runs at the fundamental repletion rate. The radio-frequency spectrum exhibits a high signal-to-noise ratio of ~ 60 dB, which indicates that the mode locking operation is stable. The average output power is measured to be 4.88 mW, so the single pulse energy and peak power are calculated to be ~ 0.345 nJ and 34.25 W, which are much higher than those of the conventional soliton. Such a mode locking state is very stable, which could operate for more than 24 hours at room temperature without significant degradation.

When the operation states of PCs are kept unchanged and the input pump power are increased to 161 mW, a little bulge appears on the flat top of the rectangular spectrum at the wavelength of 1557.82 nm as shown in Fig. 3(a), which is a sign of excessive pump power. The full bandwidth of the spectrum is narrowed on both sides (from 1546.83 nm to 1570.86 nm) to 24.03 nm, which indicates that the SF effect in laser cavity becomes stronger. Such a phenomenon was not noticed nor reported before. The 3-dB spectral bandwidth is broadened to 22.67 nm, which means that the top of the spectrum turns flater. This phenomenon was common in other reports.[35] At the beginning, the fiber laser still operates at single DS mode locking state (herein, the pulse intensity on oscilloscope has

a significant enhancement) as shown in Fig. 3(b). The output power is measured to be 7.13 mW, and the pulse energy is calculated to be 0.504 nJ, which is the maximum pulse energy we can obtain based on the current cavity. However, keeping all the cavity parameters fixed, about two minutes later, obvious spikes arise on the two edges of the rectangular spectrum and the little bulge disappears as shown in Fig. 3(c). The uniformity of the pulse intensity on oscilloscope degenerates and double pulses appear as shown in Fig. 3(d). Obviously, the spikes occurring on spectrum reduce the stability of mode locking state. The pulse interval between the accompanied double pulses is ~ 28 ns. The mode locking state jumps from single pulse to double pulses.

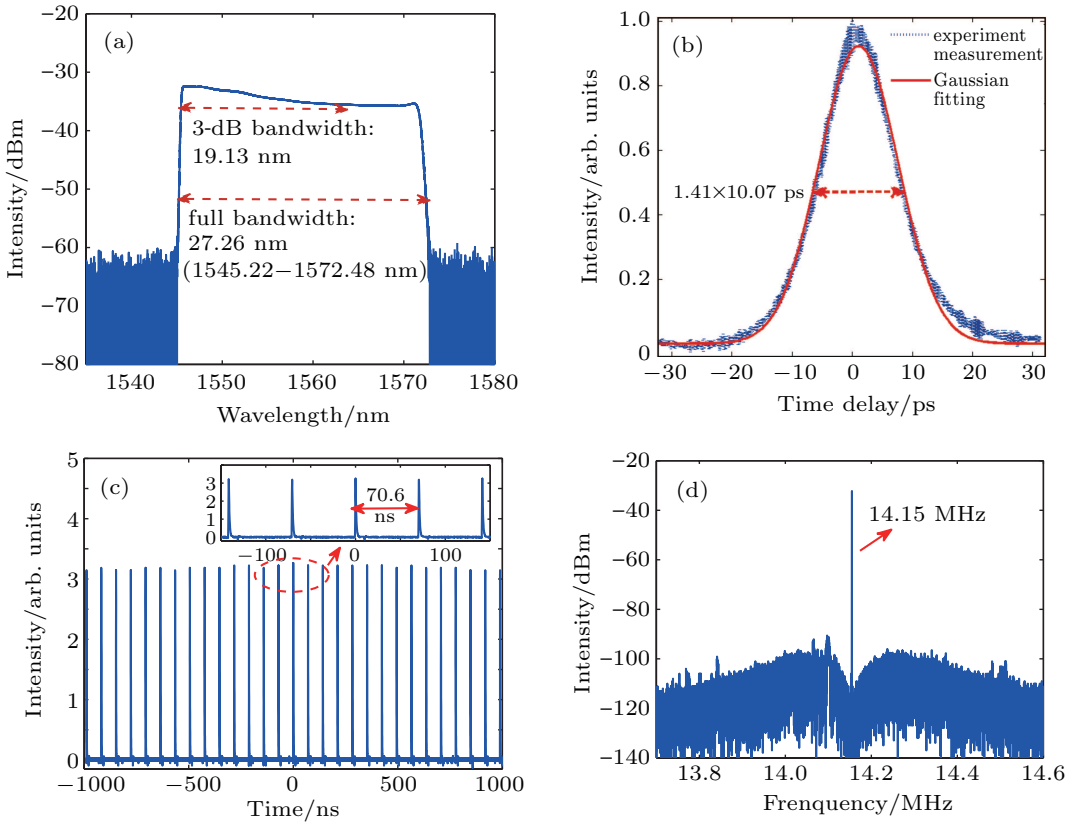


Fig. 2. (color online) Single DS at fundamental repletion rate: (a) spectrum, (b) autocorrelation traces, (c) oscilloscope trace, and (d) radio-frequency spectrum.

Those phenomena above could be explained as follows. With the enhancement of pump power, the gain-dispersion effect of the EDF decreases, so the top of the spectrum turns flater and the 3-dB bandwidth of the spectrum is broadened. With the increase of pulse intensity, the SPM and other Kerr nonlinear effects in laser cavity become stronger. It caused two kinds of results: first, new spectral components are stimulated, which means that the spectrum tends to broaden on both sides; on the other hand, the polarization difference among different wavelengths is expanded, therefore, the SF effects of the EDF, PS-ISO, and other devices become stronger. When the latter influence overcomes the former one, the full bandwidth of the output spectrum is narrowed. However, the mode locking state under excessive pump is unstable; the strong nonlinear effect leads to pulse splitting (single pulse divided into double pulse). Thereby, the pulse intensity largely decreases, and the SPM and other Kerr nonlinear effects are also degenerated greatly. So the full bandwidth of spectrum is still narrower than that of the original stable mode locking state. Because the input pump power is not enough to support the double pulses mode locking state, the pulse intensity in laser cavity is varying always and spikes appear on the spectrum.

When further increasing the pump to 165 mW, the spikes on spectrum disappear and the spectrum is broadened a little on both sides as shown in Fig. 4(a). Both the pulse intensity and interval on oscilloscope are very uniform as shown in Fig. 4(b), which shows that the mode locking state is stabilized. Herein, we could find that with the further enhancement of the pump power, the SPM induced spectral broadening effect shows a little stronger influence. The pulse interval is calculated to be 35.3 ns corresponding to a repetition frequency of ~ 28.33 MHz, which illustrates that the 2nd harmonic mode-locked state of DS is obtained. Herein, it is necessary to illustrate that because of the errors caused by the measuring equipment, the calculated repetition frequency of the 2nd harmonic mode-locked state of DS is different from the theoretical value by 0.03 MHz. Such an error was unavoidable and acceptable.

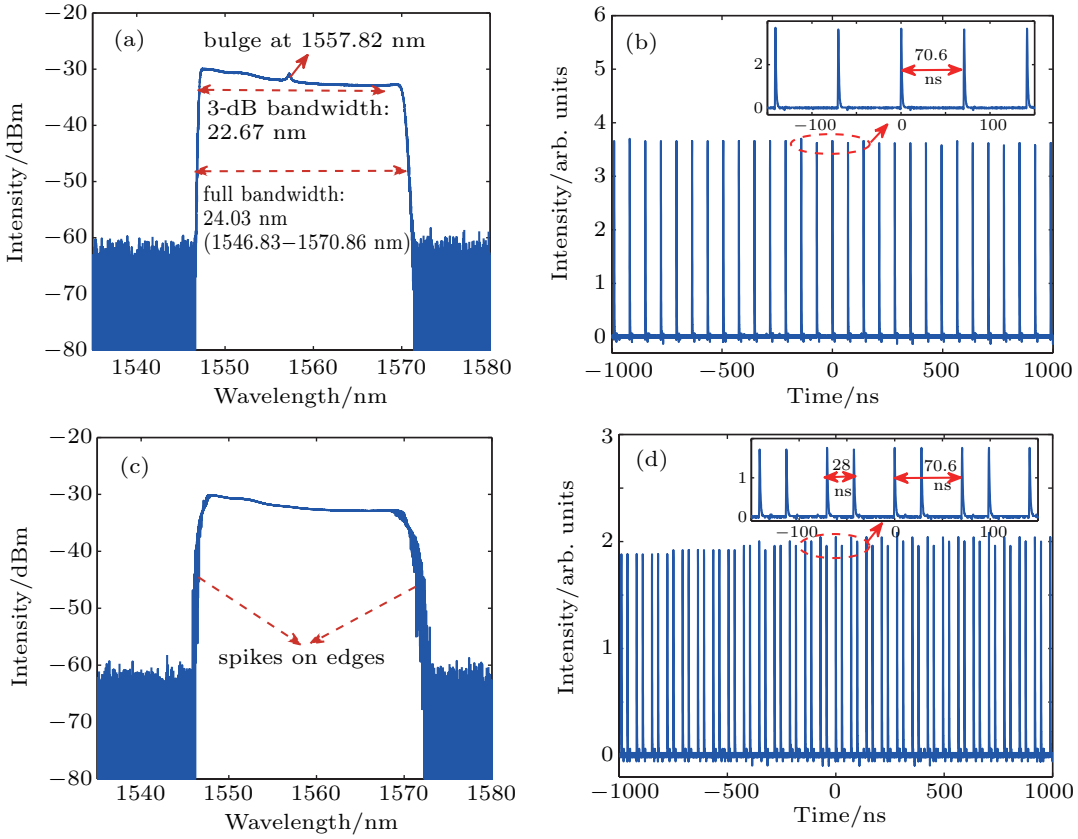


Fig. 3. (color online) Jump process of the mode locking state from single pulse to double pulses: (a) spectrum and (b) pulse train of single pulse mode locking state, (c) spectrum, and (d) pulse train of double pulses mode locking state.

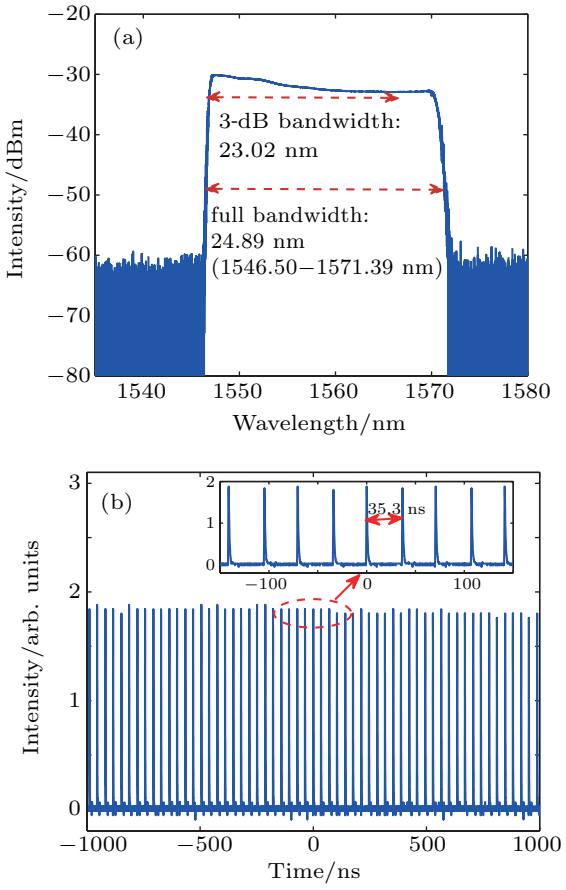


Fig. 4. (color online) The 2nd harmonic mode-locked state of DS: (a) spectrum and (b) pulse train on oscilloscope.

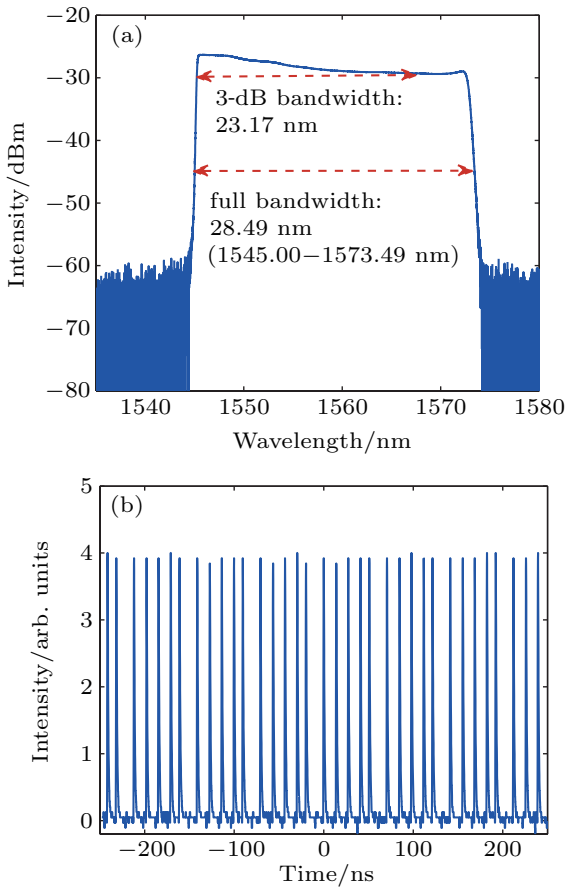


Fig. 5. (color online) Multiple pulse mode locking state: (a) spectrum and (b) pulse train on oscilloscope.

While the input pump power is continuously increased to 464 mW, the multiple pulse mode locking state is obtained as shown in Fig. 5. Both the 3-dB and full bandwidths of the spectrum are broadened (23.17 nm and 28.49 nm, respectively) as shown in Fig. 5(a). The pulse number rises to five as shown in Fig. 5(b) and the output average power is 20.14 mW. But such a multiple pulse DS mode locking state is unstable, the pulse intensity on oscilloscope has a slight variation, and the mode locking state would be destroyed several minutes later.

4. Conclusions

The generation of single and multiple DS by NPR technique in an EDF laser are reported in this work. The spectrum of the mode-locked DS exhibits typical rectangular profile with steep edges; the 3-dB spectral bandwidth is 19.13 nm. The pulse duration is 10.07 ps; the fundamental repetition rate of the mode locking state is 14.15 MHz. With the increasing of pump power, the gain-dispersion effect is lowered, which results in the enhancement of 3-dB spectral bandwidth. The SF effect and SPM induced spectral broadening effect both become larger. Under suitable conditions, the SF effect can overcome the spectral broadening effect, and the full bandwidth of the spectrum will decrease. Such a phenomenon is first noticed and reported in this paper. We also find that, with the increasing of the pump power, the pulse interval tends to be more uniform. Our observation on experiment give a clear understanding of the relationship between the nonlinear effects and pump power in a dissipative system.

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