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Generation of Q-Switched Mode-Locked Erbium-Doped Fiber Laser Operating in Dark Regime *

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We demonstrate a stable Q-switched mode-locked erbium-doped fiber laser (EDFL) operating in dark regime based on the nonlinear polarization rotation technique. The EDFL produces a pulse train where the Q-switching envelope is formed by multiple dark pulses. The repetition rate of the Q-switched envelope can be increased from 0.96 kHz to 3.26 kHz, whereas the pulse width reduces from 211 μs to 86 μs. The highest pulse of 479 nJ is obtained at the pump power of 55 mW. It is also observed that the dark pulses inside the Q-switching envelope consist of two parts: square and trailing dark pulses. The shortest pulse width of the dark square pulse is obtained at 40.5 μs when the pump power is fixed at 145 mW. The repetition rate of trailing dark pulses can be increased from 27.62 kHz to 50 kHz as the pump power increases from 55 mW to 145 mW.

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Mode-locked erbium-doped fiber lasers (EDFLs) are capable of operating in the telecommunication wavelength of about 1.55 μm and generate ultra-short pulses, which show promising potential for next-generation telecommunication applications. The generation of ultra-short pulses has also attracted wide attention in various areas of physics such as the ultrafast physics and nonlinear optics. Basically, mode-locking operation can be classified into two categories, which are continuous wave mode-locked (CWML)[1–3] and Q-switched mode-locked (QML).[4,5] For CWML lasers, the ultra-short pulses can be generated for each round trip time in the laser cavity, which typically produces megahertz pulse repetition rate. Different from CWML, QML possesses both Q-switching modulation frequency in kilohertz and frequency relates to the round trip time. Compared with CWML, QML lasers possess high peak power and high pulse energy over the CWML. These properties are attractive in achieving wavelength conversion and super continuum generation.

To date, most of the pulsed fiber lasers are operating under the bright pulse regime.[1–7] In addition to bright pulses, another type of pulses called dark solitons[8,9] are also governed by the nonlinear Schrödinger equation (NLSE).[10] Dark solitons are also further identified as solutions of the complex Ginzburg–Landau equation (CGLE).[11,12] Dark solitons are revealed to move more slowly in the presence of fiber loss and to be more stable in the presence of noise.[13] With the superior properties of QMLs and dark pulses, it would be interesting to produce a laser with both characteristics.

In this Letter, we have experimentally demonstrated the emission of Q-switched dark pulse in EDFL based on the nonlinear polarization rotation (NPR) technique. To the best of our knowledge, this is the first demonstration of Q-switched mode-locked laser operating in dark regime.

The experimental setup of the proposed EDFL is illustrated in Fig. 1, where the ring resonator consists of a 3.5-m-long EDF as the gain medium, a wavelength division multiplexer (WDM), a polarization-dependent isolator (PDI), a polarization controller (PC) and a 95:5 output coupler. The EDF used has an erbium ion concentration of 2000 ppm, core diameter of 4 μm, mode field diameter of 6 μm and NA of 0.24. This fiber was pumped by a 1480 nm laser diode via the WDM. Other fibers in the cavity are standard single-mode fibres (SMFs) (18 ps·nm^{-1}km^{-1}), which constitute the rest of the ring. The total cavity length is around 25 m. Unidirectional operation of the ring is achieved with the use of a PDI while an in-line PC is used to finely tune the linear birefringence of the cavity. The output of the laser is collected from the cavity via a 95:5 coupler which retains 95% of the light in the ring cavity to oscillate. The optical spectrum analyzer (OSA) with a spectral resolution of 0.02 nm is used to analyze the spectrum of the proposed EDFL whereas the oscilloscope (OSC) is employed in conjunction with a 1.2 GHz bandwidth photodetector to capture the output pulse train of the Q-switched dark pulse emission.

A dark pulse train is formed under the nonlinear polarization rotation (NPR) effect in the laser cavity at the threshold pump power of 45 mW. The dark pulse train operation is sustained up to the maximum pump power of 145 mW. Figure 2 shows the dark pulse train and output spectrum at pump power of 145 mW. As PDI-PC co-operated to generate the NPR effect, the propagating light resolved into two orthogonal components. The adjustment of PC changes the

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phase difference between the two orthogonal components. When two orthogonal components overlapped, the formation of dark pulse is achieved. Formation of dark pulse is represented as a narrow intensity dip in the strong cw laser emission background as shown in Fig. 2(a). The flat positive peaks consist of certain noise level, which indicate the cw noise floor. Moreover, the non-flat negative peaks are referring to the amplitude of intensity dip. The dark pulse is further investigated by using an auto-correlator (AC) as shown in Fig. 3. The curve fitting of the AC is using sech^2 pulse with 100 fs resolution. Conventionally, the AC can only be used to measure the positive pulse width. Therefore, by taking the ratio of negative width over positive width to multiply with the AC measured pulse width of 0.85 ps, the dark pulse width is estimated to be 0.55 ps. The output spectrum operating at central wavelength about 1590 nm, and spectral broadening due to the self-phase modulation effect in the cavity are shown in Fig. 2(b). Throughout the tuning range, the output pump power and pulse energy are directly proportional to the pump power. The output power linearly increases from 0.62 mW to 2.78 mW as pump power rises from 45 mW to 145 mW. With a constant pulse repetition rate of 7.92 MHz throughout the tuning range, the pulse energy is calculated to be 78–352 pJ as the pump power increases from 45 mW to 145 mW. The stability of the dark pulse is further studied by an rf spectrum analyzer. As shown in Fig. 4, the SNR is measured to be around 40 dB at the fundamental frequency of 7.92 MHz.

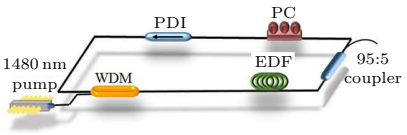

Fig. 1. Schematic configuration of the proposed EDFL.

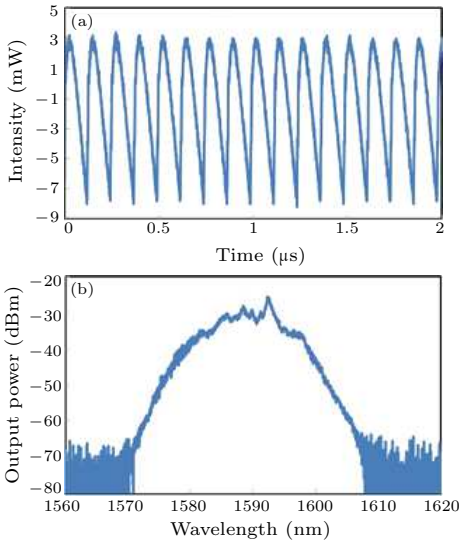

Fig. 2. (a) Emission of dark pulse train at the pump power of 145 mW. (b) Output spectrum at the pump power of 145 mW.

By shifting the PC orientation, the mode-locked dark pulse train can be changed to the Q-switched dark pulse. At the optimum polarization orientation, the Q-switched dark pulse is achieved as the pump power hits the pumping power threshold of 55 mW. The Q-switching pulse train can be sustained up to the pump power of 145 mW. Figure 5 shows a typical pulse train of the Q-switched dark pulse against the pump power. In the previous work, Zhao *et al.* have reported the co-existence of Q-switched and dark pulses.[14] However, the dark pulses were formed on the top of a Q-switched pulse and the whole Q-switched dark pulse operation was in the bright regime. In our experiment, we observe that the multiple dark pulses are combined to form the Q-switched envelope, which operates in the dark regime as shown in Fig. 6(a). Figure 6(b) shows the output spectrum of the Q-switched laser at pump power of 145 mW. As shown in Fig. 6(b), the laser operates at wavelength around 1570 nm. Spectral broadening is also observed due to the self-phase modulation effect in the cavity.

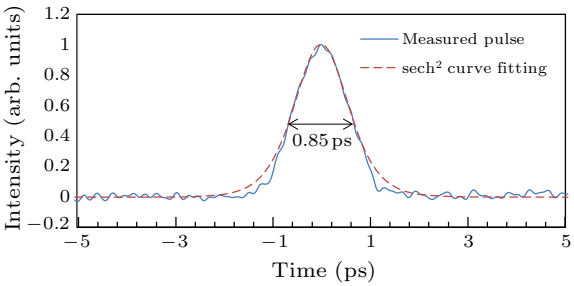

Fig. 3. AC sech^2 pulse curve fitting with 100 fs resolution.

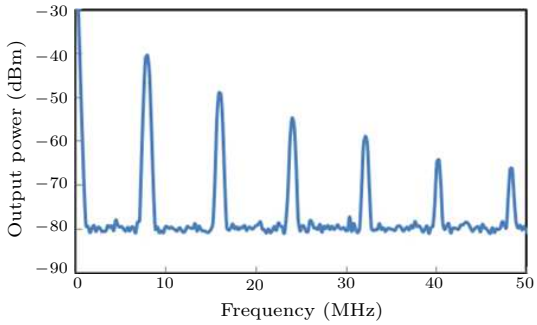

Fig. 4. The dark pulse rf spectrum of the proposed EDFL at the pump power of 145 mW.

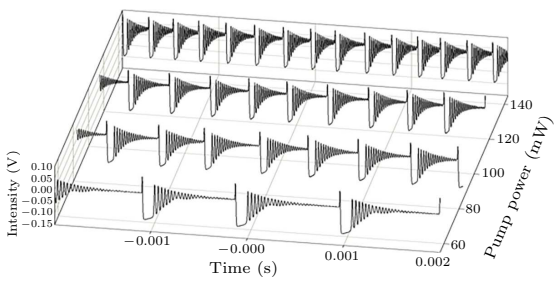

Fig. 5. Emission of Q-switched dark pulse train against the pump power.

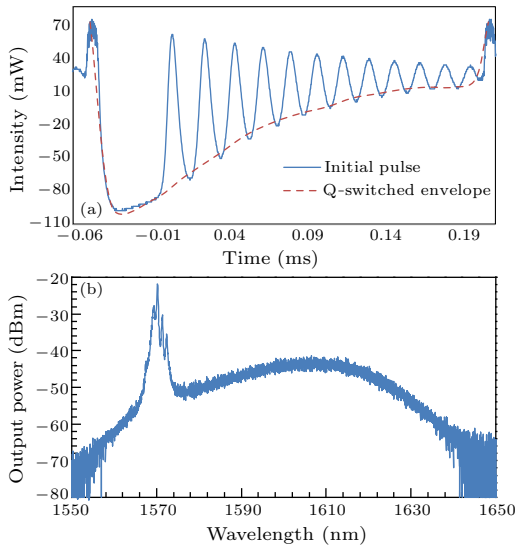

Fig. 6. (a) Emission of single Q-switched dark pulse at the pump power of 145 mW. (b) Output spectrum at the pump power of 145 mW.

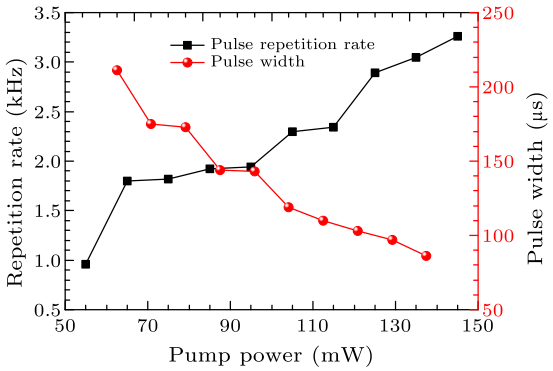

Fig. 7. Pulse repetition rate and pulse width of the proposed Q-switched dark pulse EDFL.

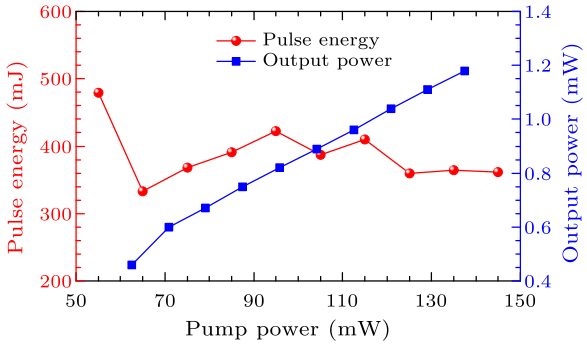

Fig. 8. Output power and pulse energy of the proposed Q-switched dark pulse EDFL.

Even though the Q-switched envelope operates in dark regime, the pulse characteristic is still compliant with the conventional Q-switched operation. Figure 7 shows the repetition rate and pulse width of the Q-switched envelope of the proposed EDFL against the pump power. Pulse repetition rate shows directly proportional relationship against the pump power. Pulse repetition rate increases from 0.96 kHz to 3.26 kHz by varying the pump power from 55 mW to 145 mW. The dependence of the pulse width can be seen to decrease almost linearly with the pump power. Pulse width decreases from 211 μs to 86 μs as the pump power increases from 55 mW to 145 mW. Figure 8 shows how the average output power and pulse energy of the Q-switched dark pulse EDFL are related with the pump power. As shown in Fig. 8, the average output power almost linearly increases from 0.46 mW to 1.18 mW as the pump power increases from 55 mW to 145 mW. Furthermore, the pulse energy fluctuates within 333–479 nJ in the same pump power range.

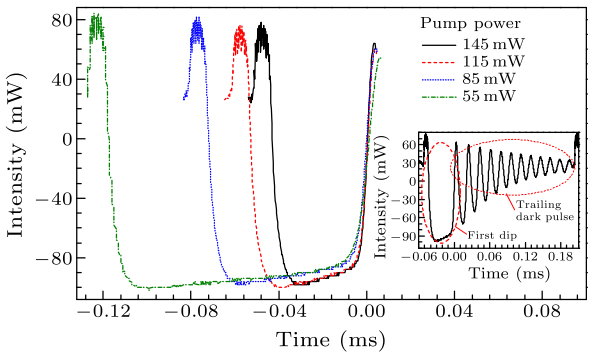

Fig. 9. Dark square pulse at different pump powers. Inset: the single Q-switched dark pulse consisting of the first dip and the trailing dark pulses.

By zooming to the dark pulses inside the Q-switched envelope, we observe that the pulse train consists of two different parts; the first dip and trailing dark pulses as shown in the inset of Fig. 9. The first dip represents the dark square pulse, whose pulse width experiences a decreasing trend from 114 μs to 40.5 μs as the pump power increases from 55 mW to 145 mW. However, the negative peak intensity is approximately constant at −96 mV throughout the tuning range of Q-switched dark pulse operation as shown in Fig. 9. For the trailing dark pulses, the repetition rate increases from 27.62 kHz to 50 kHz as the pump power increases from 55 mW to 145 mW. The dark pulse generation inside the Q-switched pulse envelope is most probably due to the Q-switching instability effect in the laser cavity.[15,16] The Q-switched instability intrinsically exists and could be suppressed by tuning the pump power.[17] The dark pulse train in the cavity is modulated by the Q-switching operation, which is created under a certain polarization state based on the NPR effect. The dark pulses are then bounded in a Q-switched envelope to form a bunch of dark pulse as shown in Fig. 6(a). The Q-switched modulation process exhibits similar characteristics as the conventional Q-switching pulse operation, which increases in pulse repetition rate and decreases in pulse width as the pump power increases. Therefore, the dark pulses under the Q-switched envelope are modulated and complied to conventional Q-switching pulse operation. Commonly, the Q-switched instability or QML cannot sustain under a wide pump power

tuning range. It is worth noticing that in this experiment, the pump power tuning range of Q-switched dark pulse operation is more than 90 mW. Compared between the negative peak voltage of −7.8 mV for dark pulse in Fig. 2(a) and negative peak voltage of −96 mV for Q-switched dark pulse in Fig. 6(a), the Q-switched modulation process has intensively increased the negative peak amplitude and pulse energy for the dark pulse. These properties are attractive to achieve wavelength conversion and super continuum generation.

In conclusion, we have demonstrated Q-switched dark pulse operation in an EDFL based on the NPR technique. The Q-switched envelope is formed by multiple dark pulses. The repetition rate of the Q-switched envelope can be increased from 0.96 kHz to 3.26 kHz, while the pulse width is reduced from 211 μs to 86 μs. The highest pulse of 479 nJ is obtained at the pump power of 55 mW. The dark pulses inside the Q-switched envelope are divided into two parts: dark square pulse and trailing pulses. The dark square pulse width decreases from 114 μs to 40.5 μs as the pump power increases from 55 mW to 145 mW. The repetition rate of the trailing dark pulses can be increased from 27.62 kHz to 50 kHz as the pump power is increased from 55 mW to 145 mW.

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