# Dark pulse emission in nonlinear polarization rotation-based multiwavelength mode-locked erbium-doped fiber laser

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We experimentally show dark pulse generation in all-normal dispersion multiwavelength erbium-doped fiber laser (EDFL) with a long cavity of figure-of-eight configuration. The EDFL generates a stable multiwavelength laser with 0.47 nm spacing at 24 mW threshold pump power, while the number of lines obtained increases with the pump power. A dark pulse emission is observed as the pump power is increased above 137 mW, with fundamental repetition rate of 29 kHz and pulse width of 2.7 μs. It is observed that the dark pulse train can be shifted to second-, third-, and fourth-order harmonic dark pulses by carefully adjusting the polarization controller. For the fundamental dark pulse, the maximum pulse energy of 32.4 nJ is obtained at pump power of 146.0 mW.

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Both multiwavelength and pulse erbium-doped fiber lasers (EDFLs)[1,2] have wide applications in optical communications, sensors, and instrumentations. Many approaches have been shown so far to achieve multi-wavelength lasing at room temperature such as cascaded stimulated Brillouin scattering[3,4], incorporating a semiconductor optical amplifier and four-wave mixing (FWM)[5]. Recently, nonlinear polarization rotation (NPR) technique is also widely used for both multiwavelength and pulse laser generations due to its simplicity[6,7]. To date, most of the reported works on pulsed lasers are operating under the bright pulse regime. Besides bright pulses, there are also other types of pulses called dark solitons that are also solutions of the nonlinear Schrödinger equation[8]. These solitons are also further identified as solutions of the complex Ginzburg–Landau equation[9,10]. Dark solitons were first shown by Emplit *et al.*[11] in 1987. A number of experiments have been proposed to generate dark solitons. For instance, Sylvestre *et al.*[12] experimentally generated dark pulse trains based on self-induced modulational instability laser. In this laser, the passive mode locking relies on dissipative FWM process. Harmonic operation of dark soliton is also demonstrated in recent year. Recently, Li *et al.*[13] experimentally showed the harmonic mode locking with dark pulse and dark–bright pulse pairs.

In this letter, dark pulse emission in multiwavelength EDFLs based on the NPR technique is reported. We found that under appropriate operating conditions, the proposed fiber laser with an all-normal dispersion cavity can emit a train of single or multiple dark pulses. To the best of our knowledge, this is the first demonstration of multiwavelength dark pulse emission laser.

The experimental setup of the proposed EDFL is shown in Fig. 1, wherein the ring resonator consists of a 3.5 m long EDF gain medium, wavelength division multiplexer (WDM), polarization-dependent isolator (PDI), polarization controller (PC), 50 m long photonic crystal fiber (PCF), 6.9 km long dispersion compensation fiber (DCF), and 3 dB couplers. The PCF has a group velocity dispersion (GVD) of 90 ps/nm/km at 1550 nm and mode field diameter of 9 μm. The EDF has a doping concentration of 2000 ppm and GVD parameter of about −21.64 ps/nm/km. This fiber was pumped by a 1480 nm laser diode via the WDM. Other fibers in the cavity are a 6.9 km long DCF with GVD of about −4 ps/nm/km and a standard single

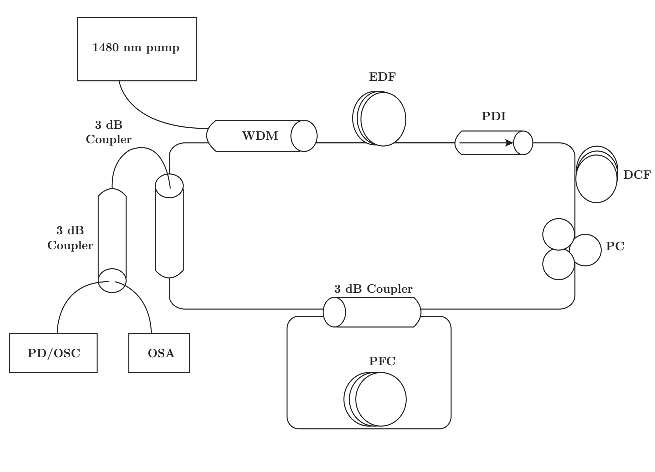


Fig. 1. Schematic diagram of the proposed multiwavelength mode-locked EDFL with a dark pulse emission.

 

mode fiber (SMF) (18 ps/nm/km), which constituted the rest of the ring. The cavity operates in large positive GVD where the net dispersion and fundamental repetition rate are estimated at 35.19 $ps^2$ and 29.0 kHz, respectively. Unidirectional operation of the ring was achieved using the PDI whereas an in-line PC was used to fine-tune the linear birefringence of the cavity. A 2×2 3 dB fiber coupler was used to form a figure-of-eight structure with a piece of PCF forming the lower loop. The output of the laser is obtained from the cavity via a 3 dB coupler, which retains 50% 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 used in conjunction with a 460 kHz bandwidth photodetector to capture the output pulse train of the mode-locked operation.

We used the NPR technique for both mode locking and multiwavelength generation in the proposed ring EDFL. Under the optimum polarization setting, a multiwavelength laser output started as the pump power increased above the threshold of 24 mW. Figure 2 shows the evolution of the output spectrum of the multiwavelength with 1480 nm pump power varied from 24 to 145 mW. It is observed that the number of lines and the peak power increase with pump power. At the maximum pump power of 145 mW, the laser produces at least nine lines with free spectral range of 0.47 nm, which is dictated by the length and the effective group indices of the PCF. It is worth noting that the multiwavelength laser disappears when the PCF is removed from the cavity. The multiwavelength generation is due to the intensity-dependent loss induced by the NPR. The PCF provides nonlinearity in the cavity so that it can function as an inline periodic filter with the assistance from PDI.

As the pumping power exceeded 133 mW, self-started mode-locked pulse train was obtained. Figure 3 shows

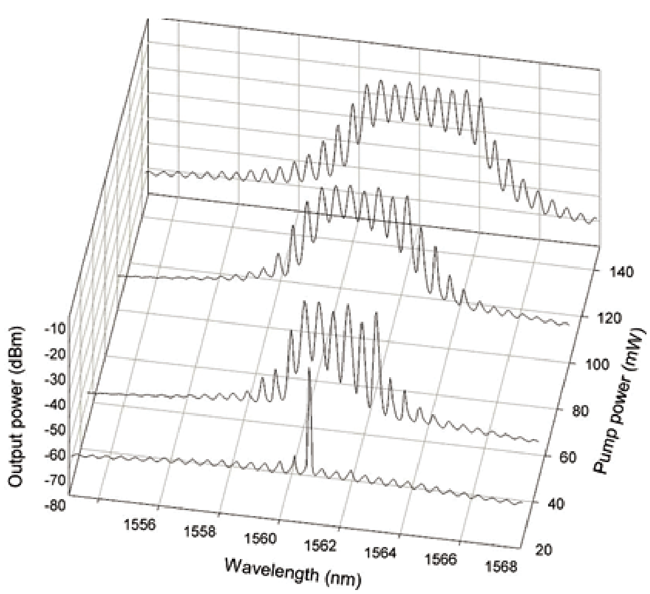


Fig. 2. Multiwavelength output spectrum evolution against 1480 nm pump power.

the optical spectrum and the OSC trace of the multiwavelength laser at four different orientations of the PC. By carefully adjusting the PC, dark pulse emission operating in a fundamental repetition rate of 29 kHz could be observed as shown in Fig. 3(a). As shown in the figure, in the time domain, the dark pulse is represented by a narrow intensity dip in the strong CW laser emission background, as shown in inset of Fig. 3(a). The full width at the half minimum of the dark pulse is about 2.7 µs. On the OSA trace of Fig. 3(a), the optical spectrum of the dark pulses shows a multiwavelength operation within a broad spectral region. The spectral broadening is due to the self-phase modulation (SPM) effect in the ring cavity. When the laser oscillates simultaneously at multiple wavelengths in the cavity, the laser emission could switch between these wavelengths due to their incoherent nonlinear coupling. This phenomenon forms vector dark domain wall pulses, which have an intensity dip on a strong CW background.

Compared to single bright pulse emission of the laser, the single dark pulse emission state was difficult to maintain. This is most probably due to the laser noise and/or weak environmental perturbations, which allow new dark pulses to appear automatically in the cavity. This causes the laser to operate in a state of multiple dark pulses. By carefully adjusting the PC, dark pulse train

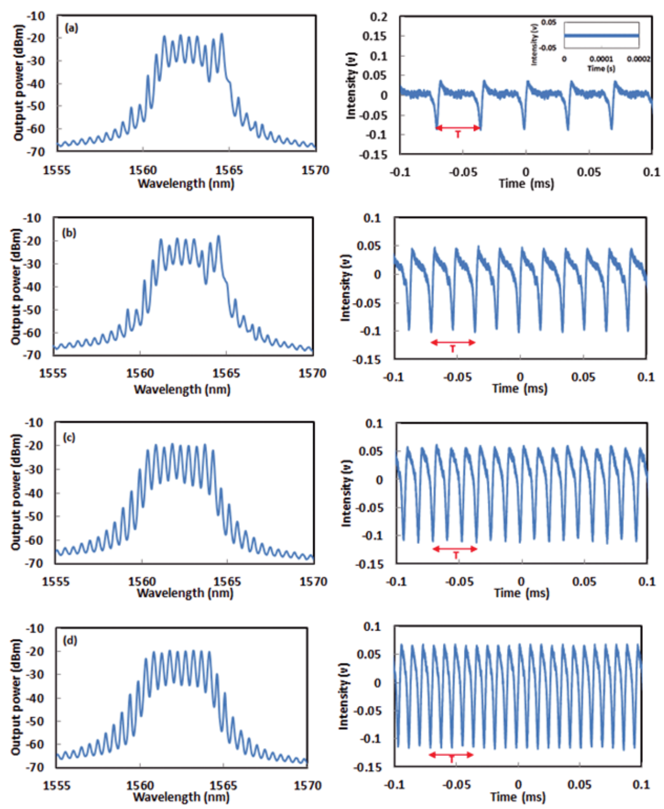


Fig. 3. Optical spectrum and typical mode-locked pulse train of the proposed multiwavelength mode-locked EDFL at four different orientations of PC when the pump is fixed at 146 mW: (a) fundamental, (b) second-order, (c) third-order, and (d) fourth-order harmonic mode locking. Inset of Fig. 3(a) shows the amplitude level of CW laser.

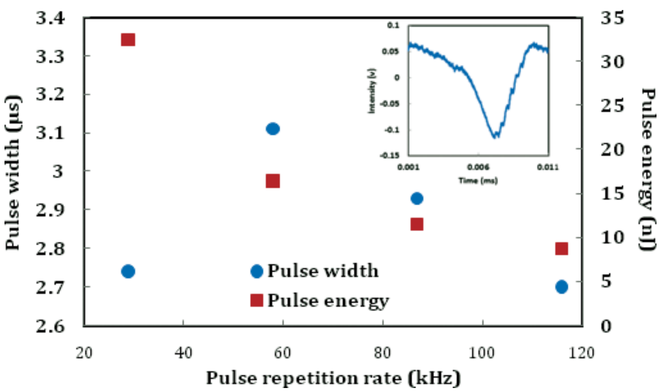


Fig. 4. Pulse width and pulse energy at different orders of harmonic. Inset shows a single dark pulse at fourth-order harmonic.

can be shifted to second, third, and fourth order of dark pulses as shown in Figs. 3(b), (c), and (d), respectively. Assuming the different rotational angle ($\Delta\alpha$) to achieve fundamental repetition rate is 0°, dark pulse train can be shifted to second order with $\Delta\alpha$ less than 15° in anti-clockwise direction. Besides, from second- to third- to fourth-order harmonic, $\Delta\alpha$ for each order change is also less than 15° in anti–clockwise direction. It is observed that the fifth-order harmonic cannot be achieved in the experiment. This is most probably due to the maximum pump power limitation, which constraints the pulse from further breaking after the fourth-order harmonic. Figure 4 compares the pulse width and pulse energy of different repetition rates of the harmonic operations when the 1480 nm pump is fixed at 146 mW. It is found that the pulse width varies from 2.70 to 3.11 μs as the repetition rate changes from the fundamental to the fourth-order harmonic of 116 kHz. Inset of Fig. 4 shows a single dark pulse of the fourth-order harmonic with pulse width of 2.70 μs. The pump to signal efficiency of the cavity is measured at 0.68%. Besides, the average output powers obtained at pump power of 146 mW are 940, 950, 1000, and 1010 μW for the fundamental, second-, third-, and fourth-order harmonic, respectively. Because the pump power is fixed and the order of dark pulse increases, pulse energy undergoes a decreasing trend as expected. The pulse energy is calculated by dividing the output power by the pulse repetition rate. It decreases from 32.4 at to 8.7 nJ with the pulse breaks from the fundamental to the fourth-order mode locking as shown in Fig. 4. The results suggest that the dark pulse formation could be an intrinsic feature of the all-normal dispersion cavity. It is found that the figure-of-eight setup induces competition between two cavity modes and cavity feedback, leading to the formation of vector dark domain wall solitons. This could have played an important role in the stability of the dark pulses in the laser.

In conclusion, a multiwavelength dark pulse emission is shown based on the NPR technique in all-normal dispersion EDFL with a long cavity of figure-of-eight configuration. The laser generates a stable multiwavelength output with a spacing of 0.47 nm after the pump power is increased above the threshold value of 24 mW. The dark pulse emission is obtained after the pump power exceeds 137 mW with a fundamental repetition rate of 29 kHz and pulse width of 2.7 μs. By carefully adjusting the PC, the dark pulse can be made to operate in the second-, third-, and fourth-order harmonic. The maximum pulse energy of 32.4 nJ is obtained at pump power of 146.0 mW.

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