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Bright–Dark Pulses in Nonlinear Polarisation Rotation Based Erbium-Doped Fiber Laser

R. Z. R. R. Rosdin, N. M. Ali, S. W. Harun, H. Arof

***Abstract*—**We have experimentally demonstrated bright-dark pulses in a nonlinear polarization rotation (NPR) based mode-locked Erbium-doped fiber laser (EDFL) with a long cavity configuration. Bright–dark pulses could be achieved when the laser works in the passively mode-locking regime and the net group velocity dispersion is quite anomalous. The EDFL starts to generate a bright pulse train with degenerated dark pulse at the mode-locking threshold pump power of 35.09 mW by manipulating the polarization states of the laser oscillation modes using a polarization controller (PC). A split bright–dark pulse is generated when further increasing the pump power up to 37.95 mW. Stable bright pulses with no obvious evidence of a dark pulse can also be generated when further adjusting PC and increasing the pump power up to 52.19 mW. At higher pump power of 54.96 mW, a new form of bright-dark pulse emission was successfully identified with the repetition rate of 29 kHz. The bright and dark pulses have a duration of 795.5 ns and 640 ns, respectively.

***Keywords*—**Erbium-doped fiber laser, Nonlinear polarization rotation, bright-dark pulse.

I. Introduction

PULSE fiber lasers have gained tremendous interest in recent years due to their practical applications in laser communications, LIDAR, material processing, sensing, medical care, laser acceleration and nonlinear frequency conversion [1], [2]. Generally, there are two types of pulse in fiber lasers: the bright pulse, which is a sharp increment of laser intensity beyond a continuous laser background with lower or near zero intensity, and the dark pulse, which is, in contrast, a deep intensity dip below a continuous laser background with nonzero intensity [3]. There are various types of dark or bright pulse/soliton, such as group-velocity-locked vector solitons (GVLVSs) [4], phase (or polarization)-locked vector solitons [5], dissipative solitons [6], and vector dark polarization domain wall solitons [7]. The dynamics of pulses/solitons in a fiber laser cavity can be described by the nonlinear Schrödinger equation (NLSE) [8]. Moreover, the complex Ginzburg–Landau equation (CGLE) and the coupled higher-order NLSE have also been used to interpret the dynamics of pulses/solitons in fiber lasers [7]-[9] Compared with dark pulses, bright pulses are relatively more convenient to generate and have been widely investigated and applied in various practical applications. However, dark pulses have also attracted intense attention owing to their unconventionality in the generating process, which provides a powerful tool for investigating the mechanism of laser pulse evolution and oscillation [10], [11]. Moreover, dark pulses have some unique advantages such as being less sensitive to fiber loss than bright pulses, less affected by intra pulse-stimulated Raman scattering, and having better stability in long-distance communications with respect to the Gordon–Haus jitter [12].

In this paper, we report on a bright-dark pulse emission in EDFL based on nonlinear polarization rotation (NPR) technique. The bright and dark are two orthogonal linear polarization components that are coupled incoherently in the laser cavity. Bright–dark pulses could be achieved when the laser works in the passively mode-locking regime and the net group velocity dispersion is quite anomalous. We show experimentally that under appropriate operation conditions, an all-normal dispersion cavity fiber laser can emit a train of bright-dark pulses.

II. Experimental Arrangement

A schematic of the NPR-based mode-locked fiber laser cavity is shown in Fig. 1. The pump source was a laser diode (LD) with emission centered at 1480 nm. A 3m long erbium-doped fiber (EDF) was used as the laser gain medium, pumped by the LD via a 1480/1550 fused wavelength division multiplexer (WDM) coupler. To realize the bright-dark pulse at ~1550 nm, the total intra cavity group velocity dispersion (GVD) is set to be quite anomalous. The EDF used has an absorption coefficient of approximately 11 dBm-1 and dispersion of -21.64 ps/nm.km at 1550 nm. Other fibers in the cavity are a 7.0 km long of dispersion-shifted fiber (DSF) with dispersion of about 2.7 ps/nm.km and a 5.5 m long standard SMF (18 ps/nm.km), which constituted the rest of the ring. The cavity operates in anomalous where the net GVD and fundamental repetition rate are estimated as -24.47 ps2 and 29.0 kHz, respectively. A polarization dependent isolator (PDI) was used in the cavity to force the unidirectional operation of the ring, and eliminate undesired feedback from the output end facet. A 20/80 fused fiber optical coupler was used to extract 20% energy from the cavity. To match the polarization states from one round trip to the next, a polarization controller (PC), consisting of three spools of SMF-28 fiber, was placed in the ring cavity after the PDI. The pump power and average output power were measured by an optical power meter (OPM). The monitoring of the output spectra and pulse trains was performed using an optical spectrum analyzer (OSA, AQ6370B) with a minimum resolution of 0.02 nm and a 500 MHz digital phosphor oscilloscope (Tektronix TDS 3052C). The pulse width was measured by an autocorrelator (Alnair). The total length of the laser cavity is estimated to be around 7.01 km.

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III. Experimental Setup

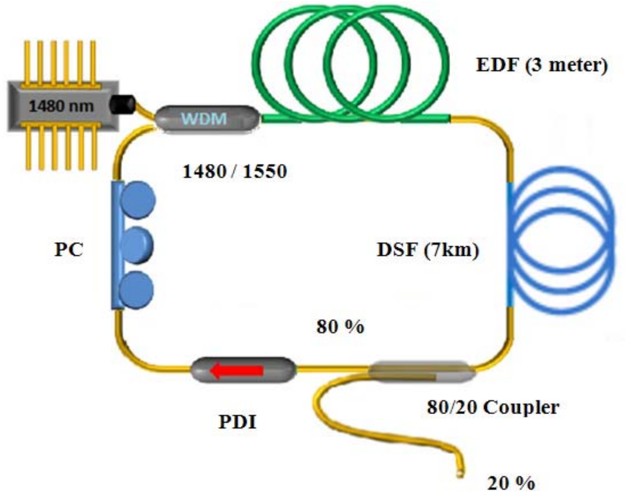


Fig. 1 Schematic diagram of the proposed mode-locked EDFL with a bright-dark pulse emission

IV. Results and Discussion

The laser cavity has a typical configuration as that of a fiber laser that uses the nonlinear polarization rotation (NPR) technique for mode locking. Indeed under appropriate PC orientation, self-started mode-locking could be achieved in the laser as the pump power is above the pumping power threshold of 35.09 mW. The pulse train had the fundamental cavity repetition rate of 29.0 kHz. Fig. 2 shows the output spectrum of the mode-locked laser at various pump powers. The mode-locked laser operates at 1561.4 nm at the threshold pump power of 35.09 mW before it is red-shifted to 1562.0 nm as the pump power is increased to 37.95 mW. However, the operating wavelength shifted a little to the opposite direction as the pump power is further increased due to the saturation effect. At the pump power of 54.96 mW, the laser operates at 1561.8 nm. The spectrum is also broadened as the pump power increases due to the self-phase modulation effect in the laser cavity. The side band is only observed in the spectra of the threshold pump power of 35.09 mW due to the degeneration of dark pulses in bright pulse train, which have different spectral distribution. Note that the operating wavelengths of the mode-locked pulses may be altered by adjusting the setting of the PC. Fig. 3 shows the typical pulse trains of the mode-locked fiber laser at three different operating regimes, which are obtained by increasing the pump power while adjusting the PC.

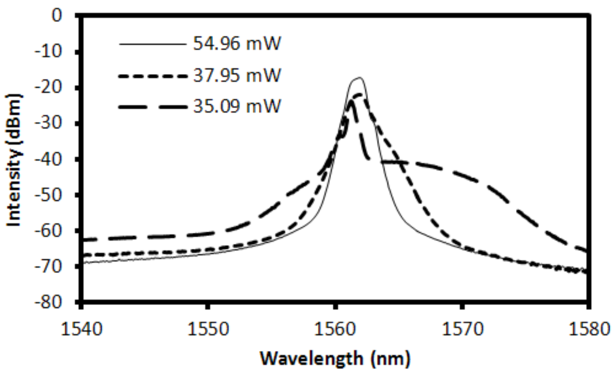
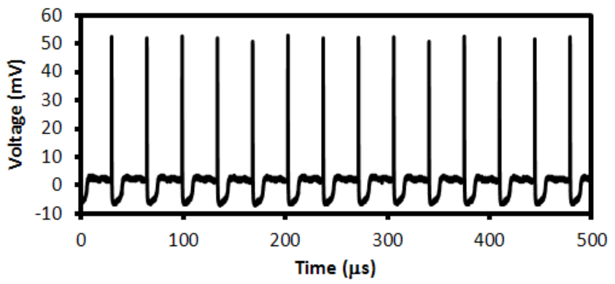
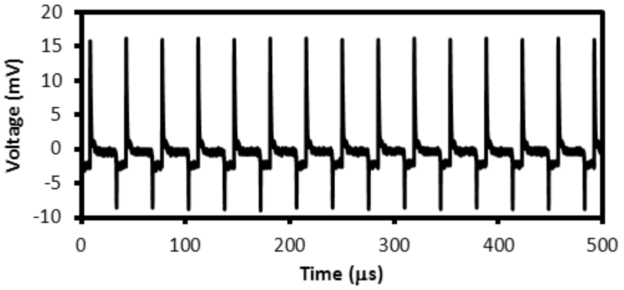


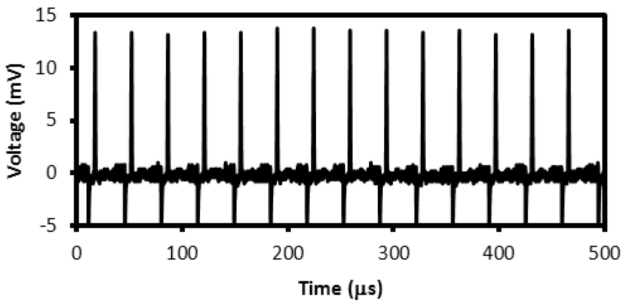
Fig. 2 Output spectrum of the mode-locked fiber laser at different pump powers



(a) Pump power of 35.09 mW

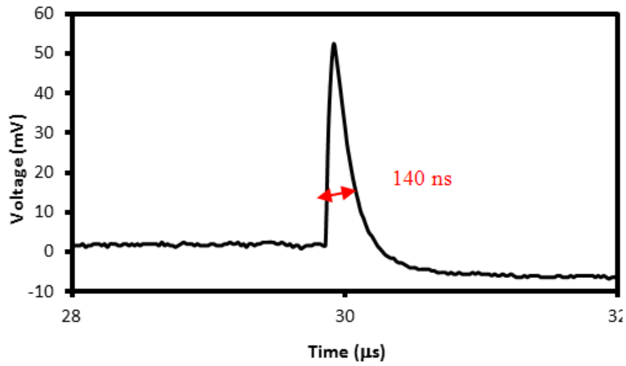


(b) Pump power of 37.95 mW

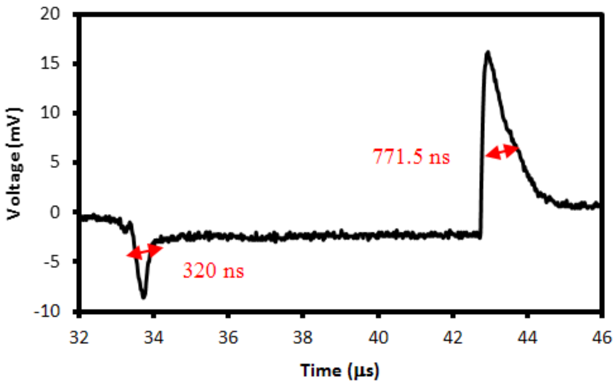


(c) Pump power of 54.96 mW

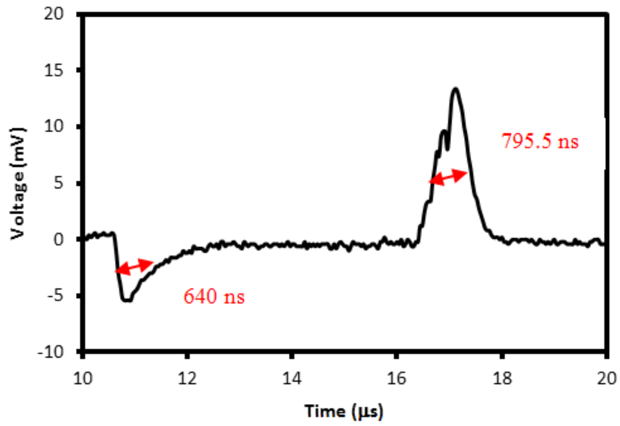
Fig. 3 Oscilloscope traces of the mode-locked pulses train: (a) Bright pulse train with degenerated dark pulse (b) split bright–dark pulse (c) bright-dark pulse



(a) Pulse duration of 140 ns (bright)



(b) Pulse duration of 771.5 ns (bright) and 320 ns (dark)



(c) Pulse duration of 795.5 ns (bright) and 640 ns (dark)

Fig. 4 Oscilloscope traces of the zoom-in into the single pulse: (a) Bright pulse with degenerated dark pulse (b) split bright–dark pulse (c) bright-dark pulse

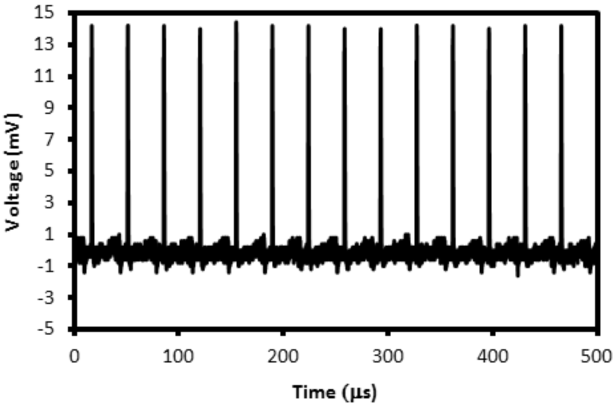
The mode-locking effect involves laser signal modulations at a period corresponding to the fundamental cavity repetition period. This effect originates from the beats between the oscillating longitudinal modes of the cavity and is further supported by mode coupling resulting from gain saturation in a Continuous Wave (CW) fiber laser [13]. At the threshold pump power of 35.09 mW, a bright pulse train with degenerated dark pulse is obtained as shown in Fig. 3 (a). The dark pulse seems largely degenerated since the intensity of the bright pulse apparently much larger than the dark pulse. Fig. 4 (a) shows an expanded version of a single pulse, which has a steep rising edge. This is a clear qualitative evidence of the existence of dissipative soliton resonance, which the operation can be explained as a result of the nonlinear polarization switching. This switching becomes significant in the proposed laser, which has a long cavity fiber length and thus produces a large cavity birefringence. The bright pulses duration is about 140 ns.

A split bright–dark pulse is generated as the bright pulses and dark pulses are further apart when further increasing the pump power up to 37.95 mW as shown in Fig. 3 (b). Actually, the similar shape of the split bright–dark pulse can also be obtained by tuning the settings of PC when the pump power is sufficiently high. As shown in Fig. 4 (b), the split bright–dark pulse duration for bright pulse is obtained at 771.5 ns and for dark pulse is obtained at 320 ns, which is much broadened compared to the bright pulse with degenerated dark pulse.

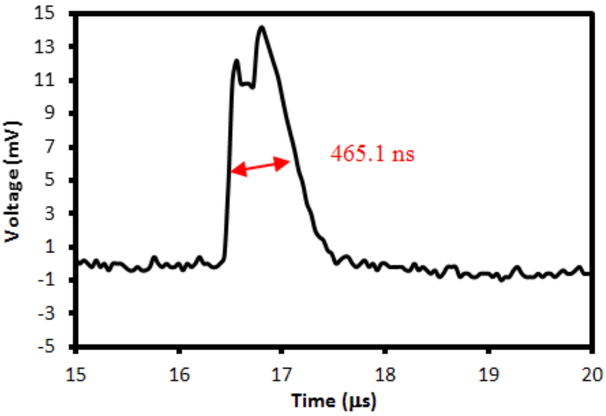
Apart from these operations, another regime of the soliton laser operation, where an obvious bright-dark pulse emission is shown in Fig. 3 (c) which the bright and the dark pulses are not too much further apart. The bright-dark soliton is obtained when the pump power is increased to 54.96 mW which the repetition rate is identical to that of the bright pulses. The bright pulse duration is obtained at 795.5 ns while the dark soliton has a pulse duration of 640 ns as shown in Fig. 4 (c).

We have experimentally further identified the pulse width and period that measured from the oscilloscope traces. The actual pulse width may be even shorter using some more precise methods such as autocorrelation [14]. The period of the bright pulse with degenerated dark pulse of the pump power of 35.09 mW is at 34.55 μs while the period for the split bright–dark pulse of the pump power of 37.95 mW is at 34.53 μs and lastly the period of the bright-dark pulse of the pump power of 54.96 mW is at 34.52 μs which indicate that repetition rate for all the pulses is similar which is about of 29 kHz.

With an appropriate adjustment to the PC and increasing the pump power to 52.19 mW, a stable bright pulses with no obvious evidence of a dark pulse can be generated as shown in Fig. 5 (a). Thus, a higher pump power increases the cavity gain and consequently breaks the counterpoise between the dark and bright pulses. The bright pulse duration is obtained at 465.1 ns as shown in Fig. 5 (b), which is broadened compared to the bright pulse with degenerated dark pulse but narrower than the bright-dark pulses. The period of bright pulse is measured also to be 34.52 μs. One can see from Figs. 5 that stable bright pulses clearly exist in the cavity when the trigger value of the oscilloscope is well above the constant laser.



(a) Pump power of 52.19 mW



(b) Pulse duration of 465.1 µs

Fig. 5 Oscilloscope traces of the mode-locked (a) bright pulse train (b) of the zoom-in into the single bright pulse

The RF spectrum of the proposed mode-locked laser with bright-dark pulses is also investigated. The result is shown in Fig. 6, which showing the repetition rate of 29 kHz at pump power of 54.96 mW. Also had mentioned earlier, the repetition rate for all the pulses are similar which is about of 29 kHz. The signal to noise ratio of more than 50 dB is obtained, which indicates the stability of the laser. The bright and dark pulses are two linear polarization modes of the laser cavity of the laser cavity and have different wavelengths and spectral distributions. The bright pulse are relatively convenient to generate and have been widely investigated and applied in practical application. The dark pulse have advantages for being less sensitive to fiber loss than bright pulse. This laser can be used in various applications using either a bright-dark pulse train or only a linear polarized dark or bright pulse train by separating the bright-dark pulses via a polarization beam splitter (PBS). Further efforts would be made to precisely control the wavelengths of the bright and dark pulse trains to enhance the availability of spectral selecting in practical applications, such as fiber communications and sensing.

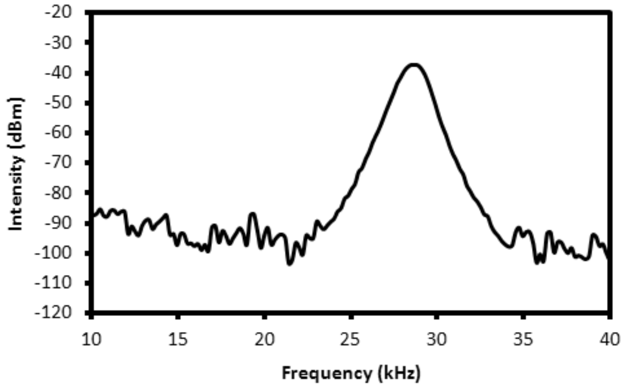


Fig. 6 RF spectrum of the mode-locked fiber laser

V. Conclusion

We have demonstrated the bright–dark pulse generation in an NPR-based mode-locked EDFL with net anomalous dispersion. A stable bright–dark pulse train is observed when the pump power is well above the threshold. Three operational states were obtained by adjusting a PC and the pump power; bright pulse with degenerated dark pulse, split bright–dark pulse and bright-dark pulse operating at 1561 nm region with repetition rate of 29 kHz. The bright pulse train with degenerated dark pulse is obtained at the mode-locking threshold pump power of 35.09 mW with bright pulse duration of 140 ns. A split bright–dark pulse is obtained when further increasing the pump power up to 37.95 mW with bright pulse duration of 771.5 ns and dark pulse duration of 320 ns. A stable bright pulses with pulse duration of 465.1 ns is also observed when further adjusting PC and increasing the pump power up to 52.19 mW. At higher pump power of 54.96 mW, an obvious form of bright-dark pulse emission was successfully identified with the bright and dark pulses durations of 795.5 ns and 640 ns, respectively.

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