Dual-wavelength dissipative soliton operation of an erbium-doped fibre laser using a nonlinear polarization rotation technique*

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We report on the generation of dual-wavelength dissipative solitons in a passively mode-locked fibre laser with a net normal dispersion using the nonlinear polarization rotation (NPR) technique. Taking the intrinsic advantage of the intracavity birefringence-induced spectral filtering effect in the NPR-based ring laser cavity, the dual-wavelength dissipative solitons are obtained. In addition, the wavelength separation and the lasing location of the dual-wavelength solitons can be flexibly tuned by changing the orientation of the polarization controller.

Keywords: normal dispersion, dual-wavelength dissipative soliton, passive mode-locking fibre laser

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1. Introduction

Recently, the solitary wave observed in the fibre laser within the positive group-velocity dispersion (GVD) regime has been intensively investigated.[1−5] This type of solitary wave is characterized by a steep edge of the spectrum and a large frequency chirp[6] and is known as the dissipative soliton. The dissipative soliton formation is a result of the balance of the cavity group-velocity dispersion, the fibre nonlinear Kerr effect, the gain saturation and the gain spectral filtering effect, which can be described by the complex cubic Ginzburg–Landau equation (CGLE, which is sometimes referred to as the master equation).[7] So far, different mode-locking techniques have been employed to achieve the dissipative soliton output from a fibre laser with a net normal dispersion, which include the semiconductor saturable absorption mirror (SESAM),[8] the carbon nanotube mode locker,[9] the graphene mode locker[10,11] and the nonlinear polarization rotation technique (NPR).[12]

In addition, the multi-wavelength mode-locked fibre laser has also attracted much attention due to its wide applications in optical fibre sensing, optical signal processing, biomedical research and wavelength-division multiplexed (WDM) fibre communication systems.[13−15] Compared with the multi-wavelength actively mode-locked fibre laser, the passively mode-locked fibre laser has the advantages of good stability, low time jittering and short pulse width. The multi-wavelength passively mode-locked fibre laser operating in the negative dispersion regime has been demonstrated with the NPR[16−18] or a saturable absorber.[19,20] For the fibre laser working in the normal dispersion regime, Zhang *et al.*[21] reported a triple-wavelength dissipative soliton fibre laser passively mode-locked with a SESAM. However, no polarizer was inserted into the laser cavity to form the spectral filter. The multi-wavelength lasing operation is attributed to the interaction between the residual polarization asymmetry of the optical components and the fibre birefringence. The residual polarization asymmetry is random, which makes the multi-wavelength pulsed operation inefficient.

In fact, the NPR technique provides not only an artificial saturable absorbing effect, but also an intrin-

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sic feature of the spectral filtering effect. Therefore, it is possible to obtain multi-wavelength dissipative solitons by using the NPR technique. In this paper, we report on the generation of dual-wavelength dissipative solitons in a passively mode-locked fibre laser with a net normal dispersion using the NPR technique. The dual-wavelength dissipative solitons are obtained by using an intracavity birefringence-induced spectral filter. By properly rotating the orientation of the polarization controller (PC), the wavelength separation and the lasing location of the dual-wavelength solitons can be flexibly tuned. Moreover, the polarization states of the dual-wavelength dissipative solitons are also studied, which shows that the solitons at different wavelengths have the same polarization state.

2. Experiments setup and operation principle

The schematic diagram of the dual-wavelength dissipative soliton fibre laser is shown in Fig. 1, which is a typical setup based on the NPR technique. The laser cavity consists of three types of fibres: 1.8-m-long erbium doped fibre (EDF) with a GVD of -15 ps/nm/km, 2-m-long dispersion compensation fibre (DCF) with a GVD of -134 ps/nm/km, and 10-m-long standard single mode fibre (SMF) with a GVD of 17 ps/nm/km. The total length of the cavity is 13.8 m and the net cavity dispersion is 0.159 ps^2 at 1550 nm. The polarization dependent isolator (PD-ISO), apart from assuring the unidirectional operation, also provides the spectral filtering effect by combining with the intracavity birefringence. The fibre laser is pumped by a 974.8 nm laser diode (LD) with up to 120 mW output power through a 980/1550 wavelength-division multiplexer. Since all the fibres are fastened to an optical table to prevent any movement, the fibre laser operates in the stable passive mode-locking regime. The laser output is taken out by a 10% fibre coupler. An optical spectrum analyzer (OSA) and an oscillograph are used to study the laser spectrum and the output pulse train, respectively.

Since the fibre laser is mode-locked based on the NPR technique, a polarizer should be inserted into the laser cavity to generate the artificial saturable absorbing effect. Therefore, it is equivalent to a length of birefringent fibre with two polarizers at both ends. The setup can be treated as a Lyot comb filter and the transmission function can be described as[22,23]

$$T = \cos^2\theta_1\cos^2\theta_2 + \sin^2\theta_1\sin^2\theta_2 + \frac{1}{2}\sin(2\theta_1)\sin(2\theta_2)\cos(\Delta\varphi_{\rm L} + \Delta\varphi_{\rm NL}),$$

where θ_1 and θ_2 are the angles between the polarization directions of the polarizers and the fast axe of the fibre, $\Delta\varphi_{\rm L} = 2\pi L(n_y - n_x)/\lambda$ and $\Delta\varphi_{\rm NL} = 2\pi n_2 PL\cos(2\theta_1)/(A_{\rm eff})$ are the linear and the nonlinear cavity phase delays, respectively, n_y and n_x are the refractive indices of the fast and the slow axes of the optical fibre, respectively, L is the laser cavity length, λ is the operating wavelength, n_2 is the nonlinear coefficient, P is the instantaneous power of the input signal and $A_{\rm eff}$ is the effective fibre core area. Here, the channel spacing depends on the cavity birefringence, which is given by $\Delta\lambda = \lambda^2/L\Delta n$. Note that the rotation of the PC changes not only θ_1 and θ_2 but also the cavity birefringence in our experiment. Moreover, the transmission peak locations are related to the settings of θ_1 and θ_2. Therefore, by properly adjusting the PC, we can obtain the dual-wavelength dissipative solitons as well as the wavelength tunable operation.

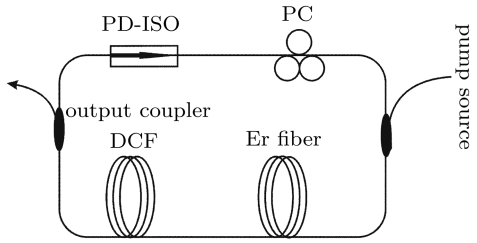


Fig. 1. Schematic diagram of the dissipative soliton fibre laser.

3. Results and discussion

In the experiment, when the PC is properly adjusted, the mode-locking of the fibre laser can be achieved with a pump power of 68 mW. The mode-locked spectrum exhibits the characteristics of steep spectral edges, showing that the fibre laser operates in the normal dispersion regime. Then we increase the pump power to about 110 mW and fix it there in the following experiment. When the orientation of the PC is tuned, namely, the transmission peaks of the cavity birefringence-induced spectral filter are changed, the central wavelength of the dissipative soliton can be continuously tuned, as shown in Fig. 2(a). Figure 2(b) shows the typical output mode-locked pulse train. As can be seen in Fig. 2(b), the fundamental repetition rate is about 15.28 MHz, which is determined by

the cavity length. Correspondingly, we show the autocorrelation trace in the insert of Fig. 2(b). We assume the pulse has a hyperbolic secant shape, then the pulse duration is found to be ∼23 ps.

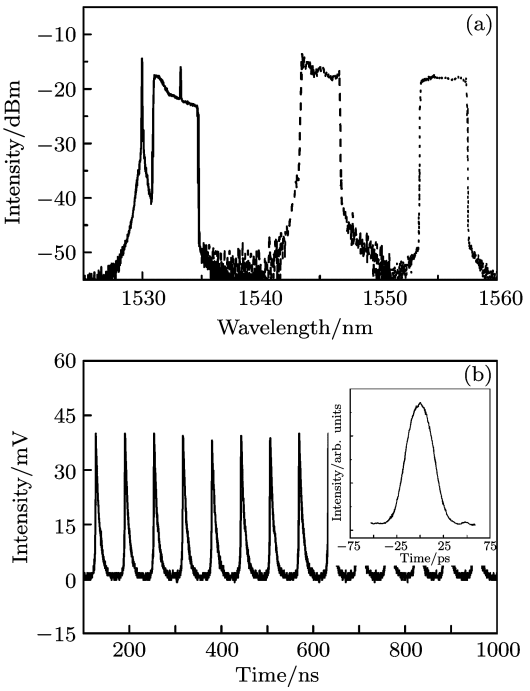


Fig. 2. (a) Wavelength tunable dissipative soliton operation and (b) typical output pulse train. The insert shows the autocorrelation trace.

Then we concentrate on the tunable dual-wavelength dissipative soliton operation in our fibre laser. As discussed above, the channel spacing of the spectral filter is related to the cavity birefringence. Note that the cavity birefringence can be tuned by rotating the PC. Thus, when the PC is further carefully adjusted, the dual-wavelength dissipative solitons are obtained, as shown in Fig. 3(a). It should be pointed out that the channel isolation of the cavity birefringence-induced spectral filter is also related to the adjustment of the PC. Therefore, when the channel isolation is changed and becomes sufficiently small, the dual-wavelength soliton disappears and becomes the single wavelength soliton shown in Fig. 3(b). In the experiment, there is little difference in the pulse train between the single- and the dual-wavelength mode-locked operations. It is because of the limited bandwidth of the photodetector used in our experiment. Moreover, the dual-wavelength mode-locked dissipative solitons with different wavelength separations and lasing locations can also be observed by adjusting the PC. Figure 4 presents the dual-wavelength operations with 9 nm and 4 nm wavelength separations. As can be seen in Fig. 4, the lasing locations of the dual-wavelength solitons can be flexibly tuned from 1530 nm to 1550 nm.

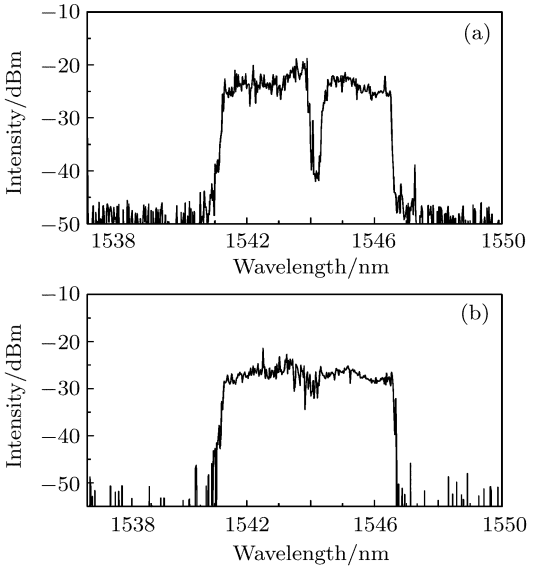


Fig. 3. (a) Dual-wavelength dissipative soliton operation and (b) single wavelength regime evolved into.

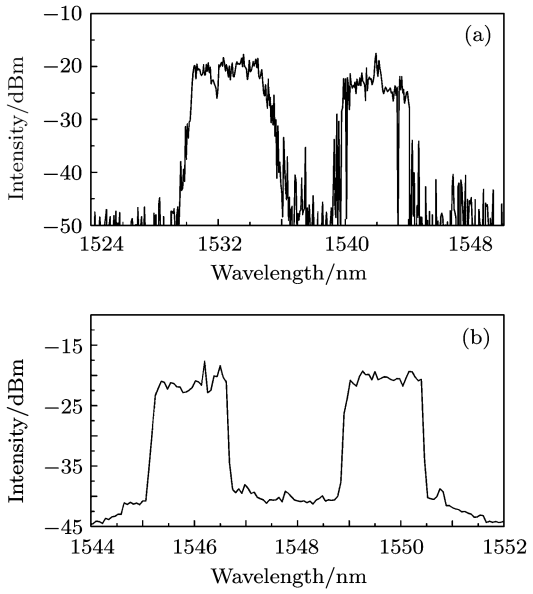


Fig. 4. Dual-wavelength dissipative solitons with wavelength separations of (a) 9 nm and (b) 4 nm.

The polarization features of the dual-wavelength dissipative solitons centred at 1542.5 nm and 1545.5 nm are also studied by using an external cavity polarizer. Through rotating the external cavity polarizer, it is identified that the dual-wavelength square-shape spectrum can be almost suppressed in the optical spectrum, as shown by the dotted curve in Fig. 5. Thus, it can be deduced that the dual-wavelength solitons have the same polarization states, which are almost linearly polarized. The polarization features are different from that in Ref. [21], which is because the

NPR is used as the mode-locking technique. When the polarizer is incorporated into the laser cavity, the polarization states of the solitons circulating in the cavity are forced into aligning with the polarizer in the successive roundtrips. And finally the dual-wavelength solitons possess the same polarization features.

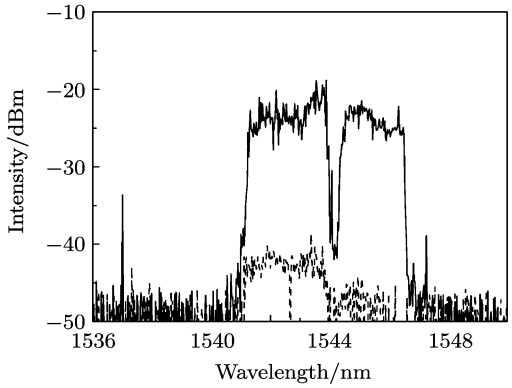


Fig. 5. Dissipative soliton spectrum evolution by rotating the polarizer.

4. Conclusion

We experimentally observe dual-wavelength dissipative soliton operation by using the intracavity birefringence-induced spectral filtering effect in an NPR-based mode-locked fibre ring laser. The wavelength separation of the dual-wavelength mode-locked solitons as well as the lasing locations can be flexibly tuned via simply rotating the PC. Furthermore, the polarization features of the dual-wavelength dissipative solitons are also studied.

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