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Multi-pulse operation of a dissipative soliton fibre laser based on nonlinear polarisation rotation

H.L. Yu, X.L. Wang, P. Zhou, J.B. Chen

Abstract. **We report an experimental observation of multiple dissipative soliton (DS) operation states in an all-normal-dispersion passively mode-locked Yb-doped fibre laser, including DS bound and oscillating states. In the bound state, multiple DSs up to 11 can coexist in the cavity. In the oscillating state, the DSs' movements are not purely random and three typical states are generalised and illustrated. A single-pulse mode-locked state is established at a high pump power by carefully adjusting the polarisation controllers. The broad spectrum indicates that it may be noise-like pulses, which can serve as a pump to generate a supercontinuum.**

Keywords: *fibre lasers, mode-locking, dissipative soliton.*

1. Introduction

Passively mode-locked fibre lasers (PMLFLs) have been widely investigated due to their unique properties for scientific research [1, 2] and practical applications in high-energy ultrashort pulse [3 – 5] generation. In particular, dissipative soliton (DS) fibre lasers in the 1 μm range with an all-normal-dispersion (ANDi) cavity have attracted much attention in the last few years because of a much higher energy of output pulses and better tolerance of wavelengths compared to transform-limited soliton pulses generated in an anomalous-dispersion cavity. A pulse energy over 20 nJ has been reported in all-fibre mode-locked lasers with an ANDi cavity [3, 6].

However, multi-pulse operation always occurs in practice and has been experimentally observed in anomalous-dispersion [7, 8] and normal-dispersion cavities [9 – 12], which hinders an energy enhancement of a single pulse. Zhao et al. [11] were first to report the generation of multiple pulses in an ANDi fibre laser. Liu et al. [12] studied the evolution of bound dissipative pulses in an ANDi cavity. Some theoretical models [13 – 16] were also established to explain the formation and evolution of multiple pulses in a PMLFL. The authors of Refs [11, 13] proposed that the formation of multiple pulses can be attributed to the cavity pulse peak clamping effect. Tang et al. [8] showed that various soliton operation states are the direct consequence of soliton interaction. The use of a long cavity scheme made it possible to increase the pulse energy of a DS fibre laser by reducing the repetition rate [17]. Studying the formation of multiple DSs in a long cavity is of great significance to suppress wave breaking and to obtain a much higher pulse energy in ANDi PMLFLs. Nonetheless, the investigations of this phenomenon in a long cavity are not enough.

In this paper, we experimentally study the multiple DS operation states of a passively mode-locked Yb-doped fibre laser with a long ANDi cavity. The nonlinear polarisation rotation (NPR) technique is used to implement self-starting mode locking of the laser. By increasing the pump power or finely adjusting the polarisation controllers, we observed a bound state of multiple DSs (with up to 11 sub-DSs) and an oscillating state of five DSs at a pump power of 141 mW. Unlike previous observations [7, 8], this oscillating state in our laser is not purely random and three typical states are generalised and illustrated. In addition, a single-pulse mode-locked state can be achieved at a high pump power level by finely adjusting the PCs and the broad spectrum of this state indicates that it may be noise-like pulses.

2. Experimental setup

The experimental setup of the PMLFL is shown in Fig. 1. The gain medium is a 25-cm-long Yb-doped fibre (YDF) with core and clad diameters of 6 and 125 μm, respectively, and a 300 dB m^{-1} absorption coefficient at 975 nm. The fibre is core-pumped by a 974-nm laser diode (LD) with a maximum out-

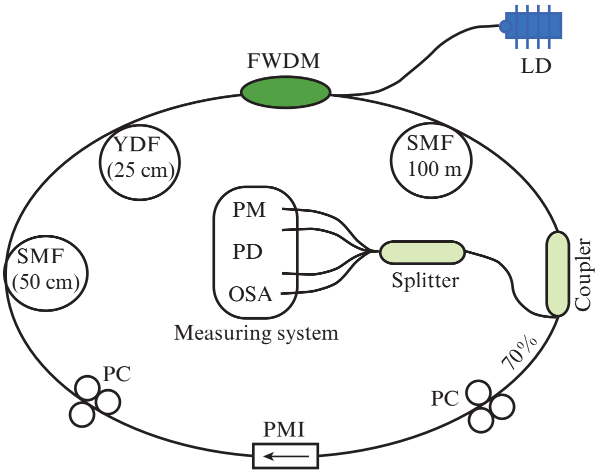

Figure 1. Schematic of the experimental setup: (LD) laser diode; (FWDM) filter wavelength division multiplexer; (YDF) Yb-doped fibre; (SMF) single-mode fibre; (PC) polarisation controller; (PMI) polarisation maintaining isolator; (PM) power meter; (PD) photodetector; (OSA) optical spectrum analyser.

H.L. Yu, X.L. Wang, P. Zhou, J.B. Chen College of Optoelectronic Science and Engineering, National University of Defense Technology, Changsha 410073, China; e-mail: topgun1988@gmail.com

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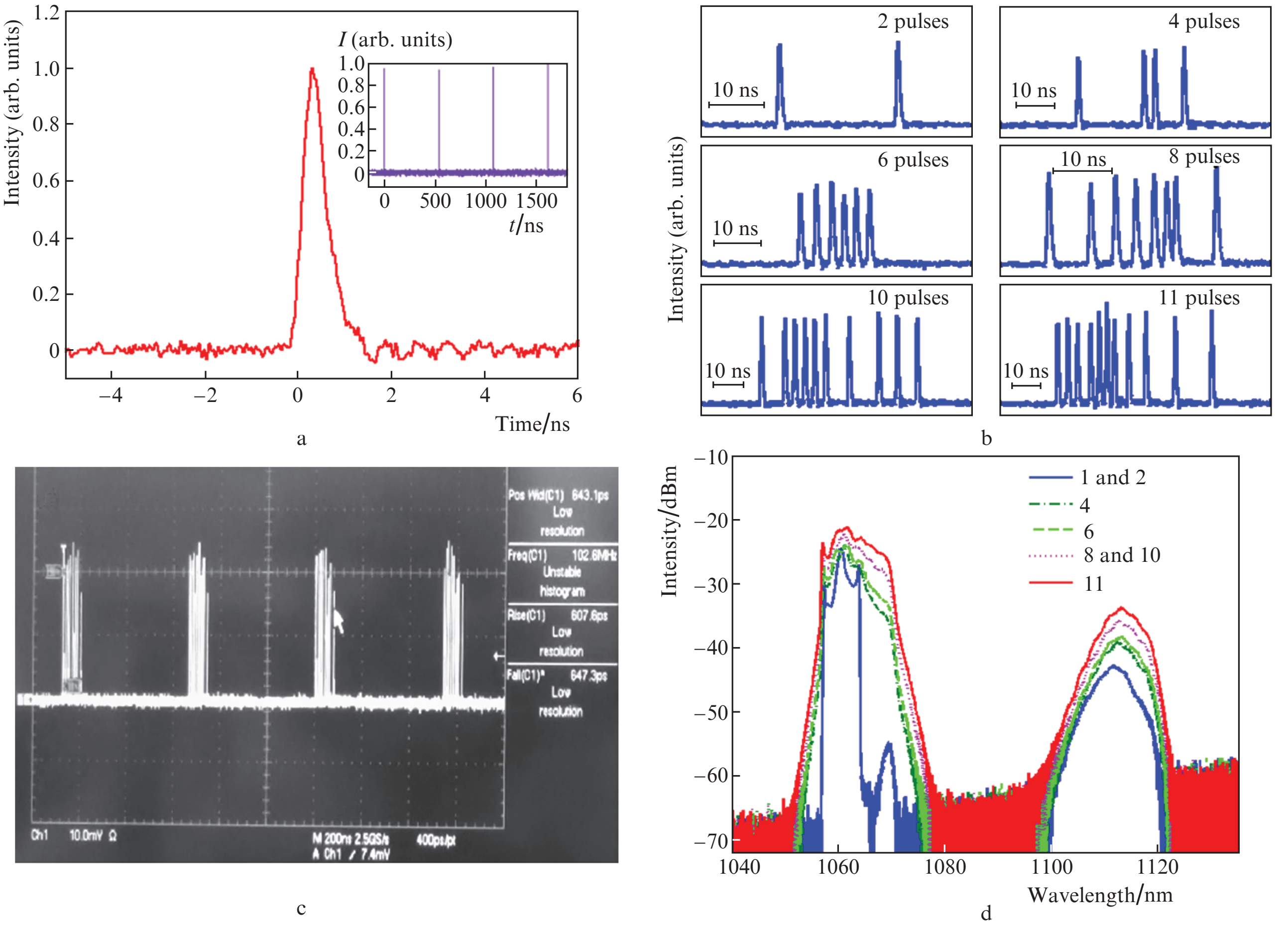
put power of 334 mW via a filter wavelength division multiplexer (FWDM). The bandwidth of the FWDM centred at 1060 nm is ±3.5 nm. Two polarisation controllers (PCs) and a polarisation maintaining isolator (PMI) are used to achieve mode locking through NPR. Besides, the PMI also ensures unidirectional propagation of the laser output. A standard single-mode fibre (SMF) of about ~100 m is inserted to enhance the nonlinear effect. Moreover, another 50-cm-long passive SMF is used to prevent a direct contact of the PC with the YDF. The total cavity length is about 110 m. The laser operates in the normal dispersion regime without any means of dispersion compensation. The normal cavity dispersion in one roundtrip is estimated to be 2.49 ps^2. The laser is coupled out through the 30% end of the 1×2 coupler which simultaneously provided a 70% laser feedback. The laser characteristics are measured simultaneously by a 1×4 splitter. The output spectra are measured by a YOKOGAWA AQ6370C optical spectrum analyser (OSA). The temporal characteristics of the pulse train are measured by a high-speed photodetector (PD) with a bandwidth of 5 GHz and observed by an oscilloscope with a bandwidth of 1.5 GHz.

3. Results and discussion

In our experiment, at a pump power below a certain threshold (56.2 mW), mode locking cannot be established no matter how to adjust the two PCs; however, the laser can operate in the continuous wave (cw) regime when the pump power is above the laser threshold of 37.3 mW. Self-starting mode locking can be achieved when the pump power is beyond the mode-locked threshold and the two PCs are properly rotated. The shape of typical mode-locked pulses and the pulse train are shown in Fig. 2a. The pulse width is 537 ps. The time of the laser cavity roundtrip is about 538 ns, which means the pulse train is mode-locked with a fundamental repetition rate of 1.86 MHz, specified by the total cavity length. The peak power and energy of pulses is about 3.4 W and 2.18 nJ.

However, with the two PCs fixed and increasing the pump power, a bound state of multiple DSs is formed in the cavity and their number in each soliton bundle increases from 1 to 11, as shown in Fig. 2b. The relative position of the DSs in the same soliton bundle is fixed but the separations among them vary randomly. The DS bundles repeat with a fundamental repetition rate of 1.86 MHz, one typical case of the oscilloscope traces being shown in Fig. 2c with 10 DSs in each pulse bundle. The pulse width of each sub-DSs is uniform and measured to be about 557 ps. The corresponding spectra of the pulse bunch with a different number of DSs are shown in Fig. 2d. The optical spectra of the pulses have steep spectral edges that are typical of DSs [18–20]. Self-phase modulation results in uneven spectra. Moreover, the first-order Stokes light is observed in the spectra (see Fig. 2d) and



a

b

c

d

Figure 2. Characteristics of the bound state of multiple DSs: (a) mode-locked pulse shape (the inset shows a pulse train with a fundamental repetition rate of 1.86 MHz); (b) typical states of DS bundles; (c) typical oscilloscope trace of bundles with 10 DSs; (d) corresponding spectra of pulse bundles with a various number of DSs in the pulse bundle.

the Raman level increases significantly with increasing pump power. The DS output in the presence of stimulated Raman scattering (SRS) has been experimentally observed and theoretically discussed in Refs [1, 2]. Although Raman scattering can result in destabilisation of mode-locked long-cavity fibre lasers [1], the wave breaking in our laser cannot be attributed to the presence of SRS because of the fact that SRS exist even if the laser operates in the stable single-pulse mode-locked regime. Bednyakova et al. [2] also show that Raman pulses can support the formation of DSs in a laser cavity without a narrow-bandpass filter (as in our case). We assume that the wave breaking is mainly due to the cavity pulse peak clamping effect [11] and overdriven nonlinear effect [21]. Due to the peak clamping effect, a DS has a fixed energy. Therefore, increasing pump power cannot change the DS parameters (such as peak power and pulse width) but enhance the nonlinear effect in the cavity and then multiple DSs are generated with almost the same pulse parameters.

Hysteresis phenomenon [14, 15] of the bound state of multiple DSs is also observed when the PCs' positions are fixed (Fig. 3). As the pump power is increased, the laser first operates in the cw regime and then in the regime of multiple DSs with the number of DSs in each pulse bundle increasing from 1 to 11. As the pump power is decreased, the number of DSs in each pulse bundle disappears one by one at different pump powers and finally the laser operates in the cw regime again at a pump power of 43.7 mW. However, it is not a reverse process of increasing the pump power. When the laser operates in the tree-pulse regime, the value of the pump power for forming the third pulse by increasing the pump power is higher than its corresponding value for the third pulse vanishing by decreasing the pump power. The laser can operate in a bistability state [14] between the cw and mode locking regimes when the pump power is between 43.7 and 56.2 mW.

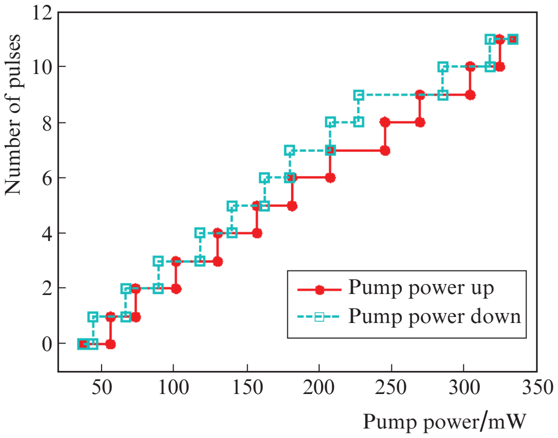


Figure 3. Number of DSs over a roundtrip time vs. pump power.

In our experiment, when the two PCs are finely adjusted, an oscillating state of five DSs can be observed at a pump power of 141 mW, as shown in Fig. 4. The position of the main DS is invariable, but other four sub-DSs in the bundle oscillate ceaselessly. Their relative positions and typical states are shown in Fig. 4a. The DS movements are not purely random, which is different from previous observations [7, 8]. Three typical states can be generalised. In the first state, four sub-DSs are in a quasi-bound state in which the separations among them are almost fixed and uniform. They slowly move apart from the main DS as a whole but come close to the main DS with a strong interaction and higher speed. The separations among the four sub-DSs are less than 5 times of the pulse width and the quasi-bound state of sub-DSs is the results of the direct interaction of solitons [8]. The laser mostly operates in this state. However, this state is unstable and easy to be destroyed by the unavoidable environmental perturbations. Then, they spontaneously evolve into the second and third states without artificially changing the cavity parameters. In the second state, most phenomena keep the same as the first state except that the separations among the sub-DSs are not uniform any longer, in which the separations of three of the sub-DSs are still fixed and uniform but the other one is far away from the three sub-DSs. In the third state, four sub-DSs with endlessly variable separations oscillate alongside the main DS in a more complex way, which is probably mainly due to the existence of the long-range soliton interaction mediated through dispersive waves [8]. Furthermore, the digital oscilloscope trace of the pulse bundles with five DSs is shown in Fig. 4b, which demonstrates that the pulse bundles circulate in the cavity with a fundamental repetition rate of 1.86 MHz. The spectrum with steep spectral edges and first-order Stokes wave is shown in Fig. 4c. In this state, the SRS may be also responsible for the DS oscillating state through the energy transfer between Raman pulses and DSs.

Note that by rotating the two PCs, a single-pulse mode-locking state can also be obtained at a high pump power of 334 mW, as shown in Fig. 5. The pulse width is 292 ps and the repetition rate is about 1.86 MHz. The real pulse width can be shorter than 292 ps due to a limited transmission bandwidth of the oscillator. The pulse amplitude (Fig. 5b) is unstable and spectrum shown in Fig. 5c is smooth and broad, which indicates that the laser may operate in the noise-like pulse regime [22, 23]. In this state, the cavity loss increases markedly and the average output power is only 8.4 mW (62.1 mW in the multiple-DS bound state at the same pump power level). The energy and peak power of the output pulse is calculated to be 4.5 nJ and 13 W, respectively. Because the peak output power decreases, nonlinear effects in the cavity are not strong enough to result in wave breaking. The laser operating in this regime can be amplified to serve as a pump to generate a supercontinuum [24, 25].

4. Conclusions

Thus, we have demonstrated a passively mode-locked Yb-doped fibre laser with different operation states based on nonlinear polarisation rotation. A bound state of multiple DSs is observed by increasing the pump power without changing other cavity parameters, the maximum number of DSs in one pulse bundle being up to 11. An oscillating state of five DSs is also investigated at a pump power of 141 mW by adjusting two PCs. Their oscillations are not purely random and three typical states are generalised and illustrated. We have also shown that a single-pulse mode-locking state can be established at a high pump power level by finely adjusting the PCs to increase the cavity loss. The broad spectrum indicates that it may be noise-like pulses, which can be used as a seed and then amplified to generate a supercontinuum.

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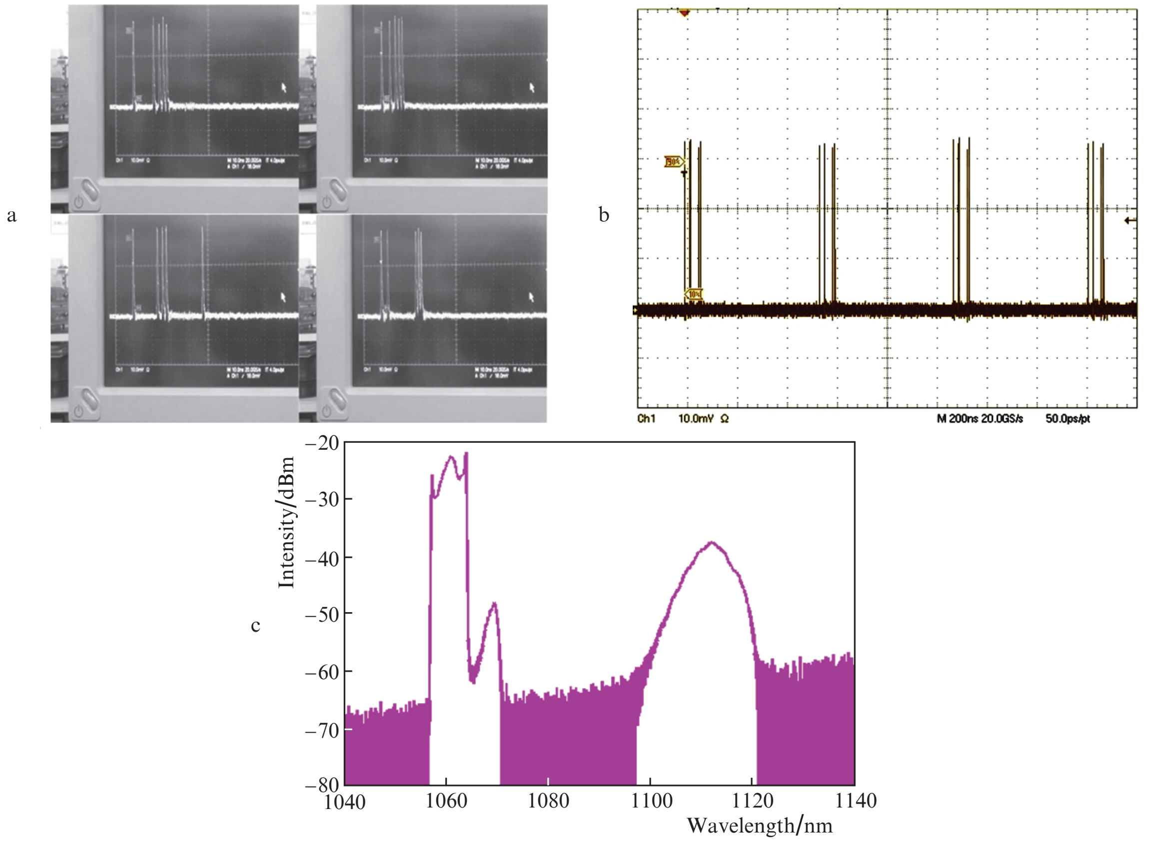

Figure 4. Characteristics of the oscillating state of five DSs in a pulse train: (a) typical state of five DSs; (b) pulse train; (c) emission spectrum.

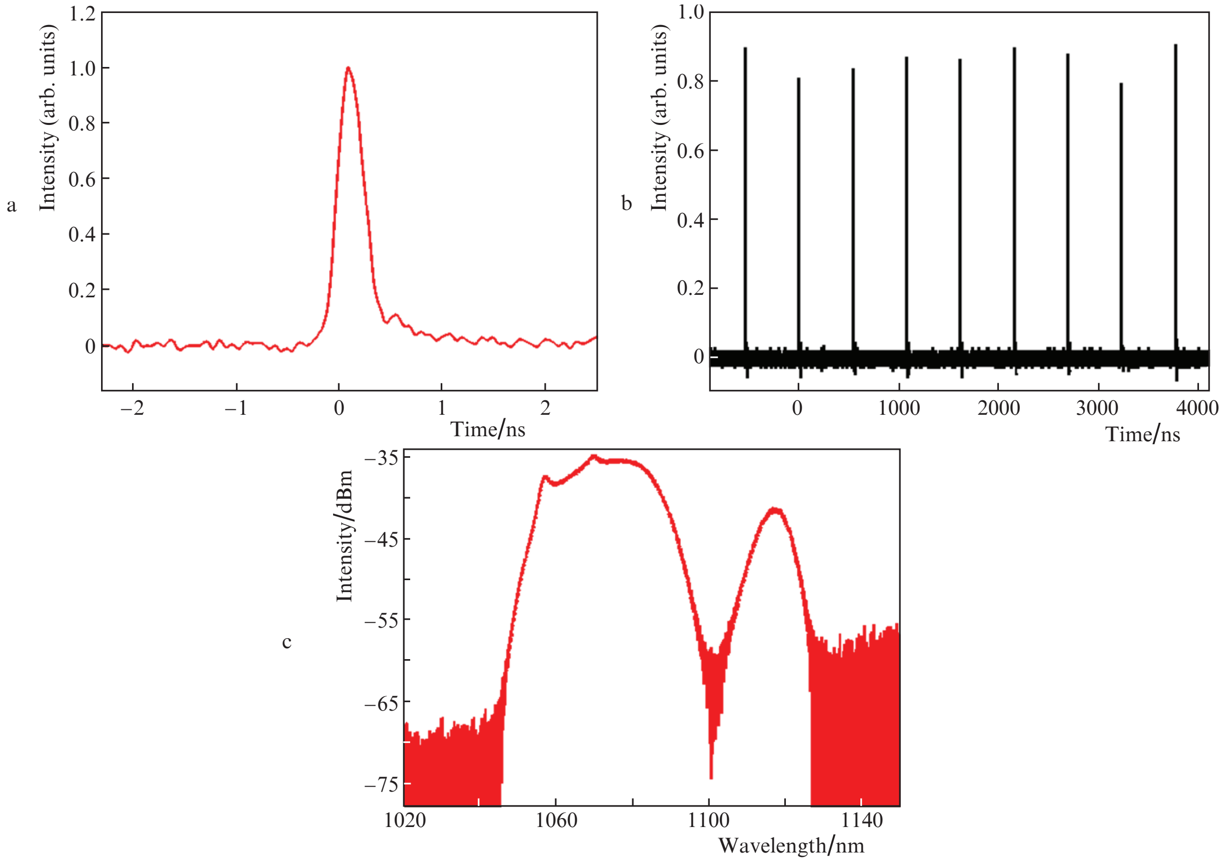

Figure 5. Characteristics of a single-pulse mode-locking state at a high pump power of 334 mW: (a) pulse shape, (b) pulse train, and (c) spectrum.

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