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Different operation states of soliton pulses in an erbium-doped fibre ring laser*

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We report on the experimental observation of soliton pulses in an erbium doped fibre ring laser. The passive mode-locking is achieved using the nonlinear polarization rotation technique. By adjusting the pump power and the intracavity polarization controllers, a normal soliton, a stable 8th harmonic mode-locked pulse and a noise-like pulse have been observed in our laser. The experimental results revealed that the noise-like pulse is not suitable for the optical telecommunication, and in order to obtain the stable harmonic mode-locked soliton, a strong unstable CW laser field is necessary to mediate global soliton interaction. The formation mechanism of the harmonic mode-locked pulse has also been analysed.

Keywords: fibre laser, soliton, mode-locking
PACC: 4255

1. Introduction

The ultra-short optical solitons have attracted much attention because of their potential applications in optical communications and signal processing.[1−5] The self-started, passively mode-locked fibre laser is a simple and economic ultra-short pulse source. Several techniques, including nonlinear polarization rotation (NPR),[6] stretched pulse and additive pulse mode locking, have been used to mode-lock the lasers.[7−9] In addition to the single-soliton, multi-solitons (including the pulses randomly spaced and harmonic mode-locking) and noise-like pulses have also been observed and reported by some researchers.[10−12] However, the results are reported and analysed separately, and the relationship between the configurations and the working principle of a fibre soliton laser has so far not been clearly analysed.

In this paper, we report on the existence of soliton pulses in different operation states of our NPR fibre ring laser. We have obtained a stable single soliton pulse with the repetition frequency of 12.5 MHz and the pulse width of 352 fs, a stable 8th harmonic mode-locked pulse and a noise-like pulse. Furthermore, we have established a relationship between the configurations and the working principle of the soliton fibre laser, and analysed the formation mechanism of the harmonic mode-locked pulse. We believe our results would provide a guidance for the design of the passively mode-locked fibre lasers.

2. Experimental setup

The passively mode-locked fibre ring laser used in the experiment was schematically shown in Fig.1. A piece of 8 m length erbium-doped fibre (EDF) with Er^{3+} concentration about 980 ppm and group velocity dispersion ~ -6 ps/nm/km acts as the gain medium of the laser. A 1480/1550 nm Wavelength Division Multiplexer (WDM) was used to couple the pump light into the ring cavity. A pigtailed InGaAsP laser diode (LD) operating at 1480 nm with maximum pump output power of 205.0 mW was used as the pump source for the system. A polarization-dependent isolator (P-I) was used to enforce the unidirectional operation of the laser and to determine the polarization of the light at the position. Two polarization controllers PC1 and PC2, PC1 consisting of two quarter-wave plates and PC2 of two quarter-wave plates and one half-wave plate, were used to control the polarization of the light in the cavity. The wave

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plates and the P-I were mounted inside a 7 cm-long fibre bench to achieve accurate polarization adjustment. The output of the laser was taken via a 10% fibre coupler and the total length of the laser was 16 m. An optical spectrum analyser (Ando AQ-6315B) was used to monitor the optical spectrum of the laser. An autocorrelator (APE PulseScope 50 Autocorrelator), a 5 GHz sampling oscilloscope and a 5 GHz photodetector were used to study the evolution of the solitons.

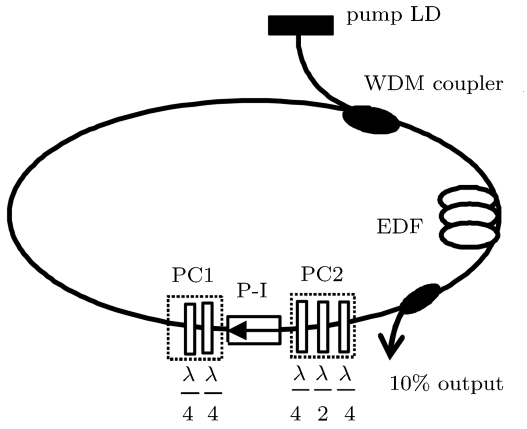


Fig.1. Schematic diagram of the passively mode-locked ring fibre laser: LD, A pigtailed InGaAsP laser diode; WDM, wavelength-division-multiplexing; PC's, polarization controller; P-I, polarization dependent isolator; EDF, erbium-doped fibre.

3. Experimental results

3.1. The stable single-soliton

The threshold of continuous-wave light oscillation of the laser was 12.00 mW. When the pump power was increased to 25.07 mW, by carefully adjusting the orientations of the wave-plates in suitable positions, self-started mode-locking of the laser was obtained, and the single-soliton was observed. Figure 2(a) presents the oscilloscope trace of a typical experimentally measured single-soliton operation state of the laser. The pulse repetition frequency was 12.5 MHz, which corresponded to the round trip time of the laser cavity ($f = c/n_{\text{eff}}L$, where n_{eff}, which equals 1.5, is the effective refractive index in the fibre, L is the cavity length of the ring laser, and c is the speed of light in vacuum). Figures 2(b) and 2(c) show the corresponding optical spectrum and the autocorrelation trace, respectively. The 3 dB spectrum width was about 7.8 nm, and the FWHM autocorrelation trace was 546 fs, which corresponded to an FWHM pulse width of 352 fs when the sech^2 pulse profile was assumed. The time–bandwidth product (TBP) of the single soliton was about 0.34. Therefore, our laser was nearly transform-limited.

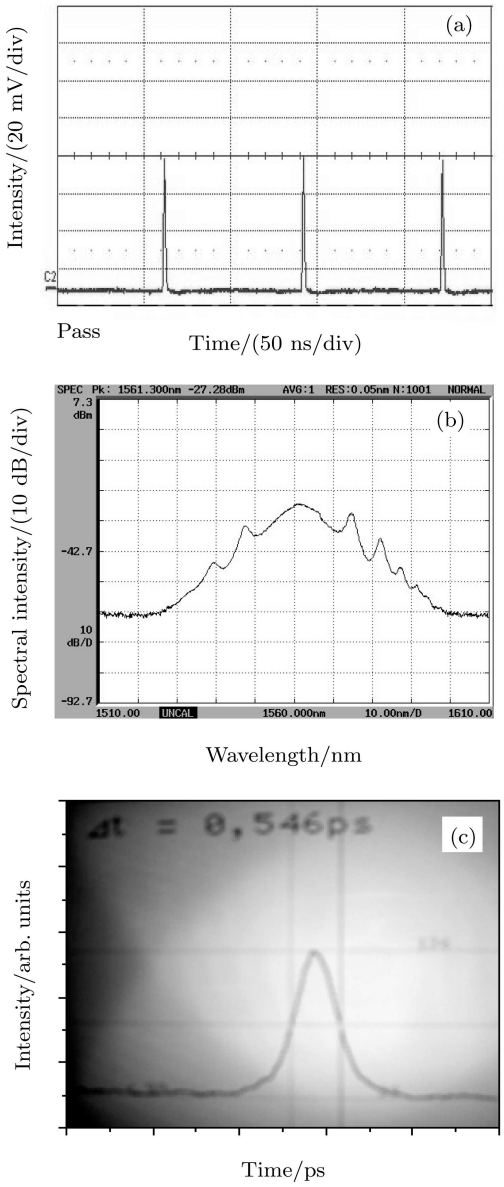


Fig.2. The measured (a) oscilloscope trace, (b) the optical spectrum and (c) the autocorrelation trace of the single soliton operation.

3.2. The formation of the harmonic mode locked pulses

The soliton pulse peak power can be increased and the pulse width would narrow with the pump power. However, when the pump power increased to 97 mW, the mode-locked pulse became unstable. On further increasing the pump power, as a result of the soliton energy quantization, the multiple fundamental soli-

ton pulses are formed easily by adjusting the PCs in the cavity. At the beginning, the soliton positions on the oscilloscope trace seemed random and one could not discern a stable soliton trace. The phases of the solitons varied randomly because of the unavoidable environmental perturbations and the interaction between solitons and the dispersion waves. We named this mode of the multiple solitons as the complicated soliton motion mode.

In order to suppress the random soliton phase variations, we used an intercavity phase-locked technique to synchronize the random phase of the solitons. In our experiment, by adjusting the PCs in the cavity, a strong CW laser field in the ring cavity, which coexisted with the solitons, was built up first. By carefully setting the CW mode-frequency position in the soliton spectrum, a phase locking between one of the dynamical modes of the solitons and the CW mode would take place automatically. In this way, the phases variations of all the solitons in the laser cavity could be synchronized to those of the CW mode except for an arbitrary phase constant. Then we obtained the stable irregular soliton distribution mode.

Figure 3 shows the oscilloscope trace and the laser spectrum of the stable irregular soliton distributions. From the oscilloscope trace we could see that three solitons were scattered in the cavity. A CW lasing coexisting with the single-pulse solitons in the cavity could be seen in the laser spectrum. Further study showed that the number of soliton could be increased or reduced by adjusting the pump power.

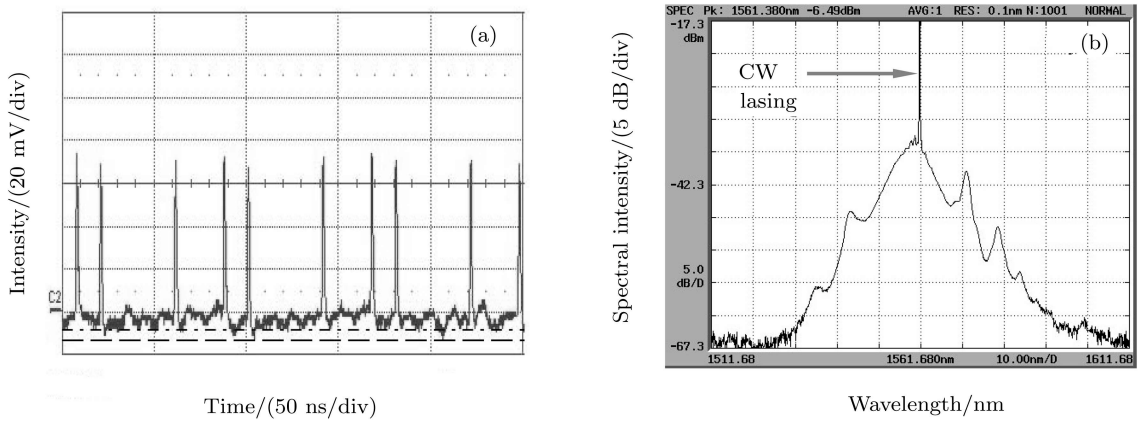


Fig.3. The measured (a) oscilloscope trace and (b) typical optical spectrum of the stable irregular solitons.

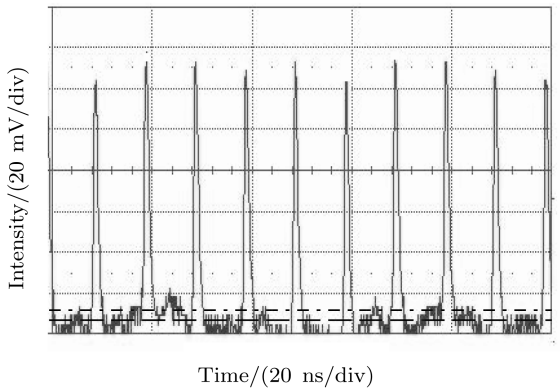


Fig.4. Oscilloscope trace of the stable harmonic pulse.

If we further adjusted the pump power and the PCs until the strong CW lasing became unstable as characterized by the appearance of the CW spectral component in the laser spectrum, the stable harmonic mode locking could be easily formed. Figure 4 shows the oscilloscope trace of a typical 8th harmonic mode-locked soliton under the pump power of 205 mW. The laser spectrum was the same as Fig.3(b), except for the CW lasing becoming unstable. Based the experimental results, it is believed that, apart from the gain recovery and the acoustic effect,[13,14] the unstable CW lasing in the cavity can be another mechanism for the formation of the passive harmonic mode locking in the fibre lasers. We understand the above explanation as follows. In general, the existence of the weak CW wave would not affect the property of the solitons in the cavity. However, when the strength of the CW component becomes strong, as all linear waves are intrinsically unstable in the laser because of the modulation instability, it eventually becomes unstable. From

the oscilloscope traces we can see that, whenever the CW components become unstable, all solitons in the cavity start to move. That is to say, the unstable CW component can introduce a kind of global soliton interaction mechanism to all the solitons. Only when all the solitons in the cavity are equally distributed over the whole cavity, does the moving of the solitons cease, a steady soliton distribution state is obtained, and then the harmonic mode-locking is formed.

The autocorrelation trace of the harmonic mode-locked soliton was the same as that of the single soliton, except for the slight difference in the pulse width.

3.3. Noise-like pulse

In our experiment, we also observed the noise-like pulse output by adjusting the PCs in the ring cavity. In this case, the pulse had the fixed repetition rate, which corresponded to the round trip time of the laser cavity; the transition from the CW to the pulsed operation was sudden, and the spectrum became wide and continuous, all the above phenomena indicated that the mode of our laser was locked. Figure 5 presents the spectrum and the autocorrelation trace of this pulse. The 3 dB spectral width of the noise-like pulse was very broad (about 20 nm) and a little asymmetrical. Furthermore, the spectrum of the noise-like pulse was very smooth and did not have any side-lobes as the soliton pulses. The autocorrelation trace output gave a very narrow pulse with a very broad pedestal. If sech^2 profile was assumed, the pulse width was 196 fs. From the voltage level, the ratio between the peak and the shoulder of the autocorrelation trace was about 2 : 1, which indicated that the power of the noise-like part of the pulse intensity was similar to the average pulse power, that is to say, most of the pulse amplitude consisted of noise and did not have a significantly ordered structure, much the same as reported by Refs.[12,15]. So we believe it was noise-like pulse with the fine structure of a very narrow pulse. Further study showed that the noise-like pulse is less stable and has a higher threshold than that of the soliton pulses, and the pulse width would broaden with the pump power, so it is not suitable for optical telecommunications.

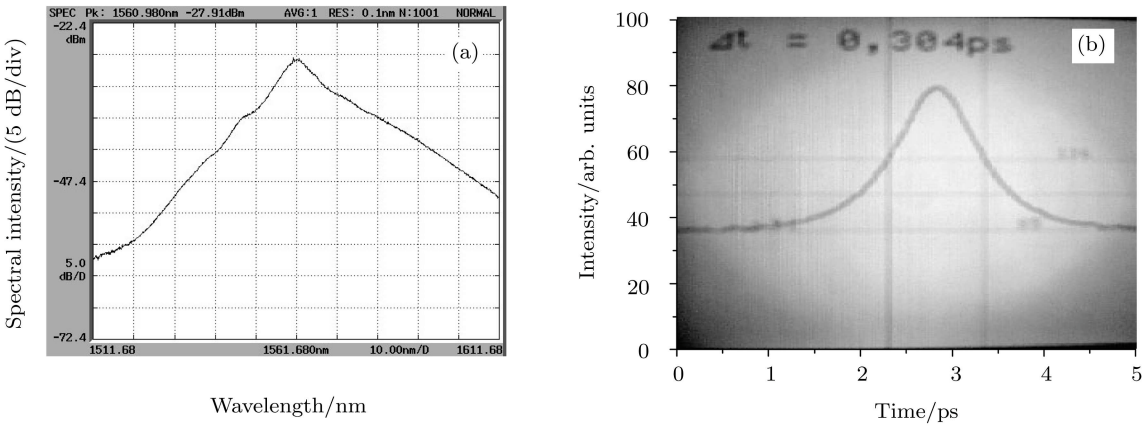


Fig.5. The measured (a) optical spectrum and (b) autocorrelation trace of the noise-like pulse.

4. Conclusion

We have reported on the experimental observation of different operation states of the soliton pulses in a passively mode-locked fibre ring laser. By adjusting the PCs and the pump power in the ring cavity, we have observed the stable single soliton pulse, the stable 8th harmonic mode-locked pulse and the noise-like pulse. The single soliton pulse has the repetition frequency of 12.5 MHz and the pulse width of 352 fs. The experimental results revealed that, apart from the gain recovery and the acoustic effect, a strong unstable CW laser field is also necessary to mediate global soliton interaction in the formation of the harmonic mode-locked pulse. The pulse width of the noise-like pulse would broaden with the pump power, so it is not suitable for the telecommunications. We believe our results will provide guidance for the generation of the best pulses.

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