

Period doubling of multiple dissipative-soliton-resonance pulses in a fibre laser

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Abstract: We report on the experimental observation of period doubling of multiple dissipative-soliton-resonance (DSR) pulses in an all-normal-dispersion fibre laser, based on a nonlinear amplifying loop mirror. By increasing the pump power, the transition from a single DSR pulse to multiple DSR pulses was observed, in addition to the typical linear pulse broadening, under a fixed pulse peak power. During this process, period doubling appeared because the DSR pulses can exhibit the characteristics of period doubling in a multi-pulse state. The typical DSR performance of a linear pulse duration change, versus the variation of pump power, can be maintained when the period doubling of multiple DSR pulses appears.

1. Introduction

Ultrafast fibre lasers have attracted extensive attention as an ultrashort pulse source due to their significant applications in areas of micro-machining [1], biomedicine [2, 3], optical communications [4], and metrology systems [5]. Ultrafast fibre lasers are also an excellent platform for the investigation of nonlinear optical systems. Ultrafast fibre lasers can be used to observe a variety of nonlinear phenomena, such as period doubling bifurcation. Period doubling bifurcation is a typical route to chaos but it is a stable state in nonlinear systems. The period doubling in fibre lasers was first reported by Tamura et al. [6]. By introducing a bandpass filter in a negative dispersion fibre laser, Tamura et al. realised the period doubling of solitons. The period doubling bifurcation can be generated in fibre lasers operated in different dispersion regions, and is independent of the mode-locking mechanism and wavelength. Using the nonlinear polarisation rotation (NPR) technique, Zhao et al. observed period doubling bifurcation in a dispersion-managed soliton fibre laser for the first time [7]. In 2018, Mélo et al. experimentally studied the nonlinear dynamics of a femtosecond ytterbium doped mode-locked fibre laser. With the laser operating in the pulsed regime a route to chaos was presented, starting from stable mode-locking, period two, period four, chaos and period three regimes [8]. Then Wang et al. reported period doubling of DSR pulses in a ytterbium-doped fibre laser, using nonlinear optical loop mirror mode-locking [9].

The excessive nonlinear effects in ultrafast fibre lasers restricts the increasing of pulse energy, which leads to pulse splitting [10]. In 2008, Chang et al. theoretically discovered a dissipative-soliton-resonance (DSR) area, where pulse energy can be increased indefinitely,

without pulse splitting [11]. In the DSR regime, the peak of the pulse remains constant, while the pulse width broadens linearly with the increase in pump power [12-14]. Therefore, DSR is useful to generate high energy pulses in passively mode-locked fibre lasers without additional amplifiers [15-17]. Under certain conditions, DSR will undergo pulse splitting into a multi-pulse state [18, 19]. Komarov et al. theoretically investigated the multi-pulse state of DSR harmonic mode-locking and they concluded that the number of DSR pulses in the steady state is related to the initial condition, regardless of the increasing pump power [18]. Wang et al. experimentally demonstrated the multiple-pulse DSR, evolving from the original DSR pulse in an all-normal-dispersion fibre laser [19]. A recent theoretical work done by Sakaguchi et al considered period doubling effect in near zero dispersion regime where the third order dispersion plays a significant role for soliton molecule dynamics [20].

In ultrafast fibre lasers, the nonlinear effects are very strong due to high peak power of ultrafast pulses, which makes it easy to observe period doubling bifurcation. The generation of DSR in a fibre laser is the result of a strong peak power clamping effect [21], its peak power is relatively low, and the accumulated nonlinear effects are not significant. Therefore, it is relatively difficult to observe the period doubling bifurcation of DSR pulses in fibre lasers. However, we can enhance the nonlinear effects by inserting enough long fibre. Period doubling of DSR pulses was recently reported by Wang et al [9]. Therefore, it is interesting to investigate whether period doubling could be maintained while multiple DSR pulses appeared. In this paper, we further report on the experimental observation of period doubling of multiple DSR pulses, in an all-normal-dispersion fibre laser. The fibre laser was mode-locked by a nonlinear amplifying loop mirror (NALM). A 380 m optical fibre was inserted in the cavity to increase the accumulated nonlinear phase shift. When the nonlinear phase shift was large enough, which led to considerable nonlinear effects, multi-pulse DSR and period doubling of multi-pulse DSR were observed. To the best of our knowledge, period doubling of multi-pulse DSR has not been reported thus far.

2. Experimental setup

Figure 1 shows the schematic of the all-normal-dispersion fibre laser used in our experiment.

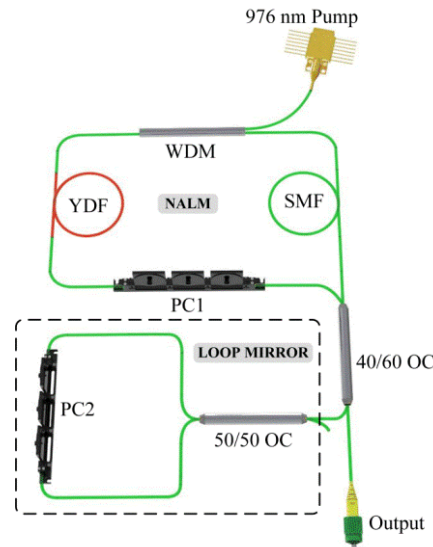


Fig. 1. Schematic of the all-normal-dispersion fibre laser. WDM: wavelength division multiplexer; YDF: ytterbium-doped fibre; PC: polarization controller; OC: fibre coupler; SMF: 380 m single-mode fibre.

An NALM (shown at the top of Fig. 1) acts as a fast saturable absorber. The pulses exiting the NALM were coupled into a loop mirror (framed by the dashed line) through a 40/60 fibre coupler (OC). In the NALM, the gain is provided by a 45 cm single-cladding, ytterbium-doped fibre (YDF, CorActive Yb501) with a core absorption of 139 dB/m at a wavelength of 915 nm. The YDF was pumped through a wavelength division multiplexer (WDM), using a 976 nm pigtailed laser diode, which provided a maximum pump power of 600 mW. A 380 m single-mode fibre (SMF, Nufern, 1060-XP), inserted in the NALM, was used to enhance the nonlinear effects. A fibre coupler, with the 40% port acting as an output, was installed after polarisation controller PC1. The loop mirror, which served as a reflective mirror, comprised of a polarisation controller (PC2) and a 50/50 OC. The fibre pigtail used for all the optical components in this laser was the HI1060. The total cavity length was 405 m, corresponding to the fundamental repetition rate of 494 kHz. The net cavity dispersion was calculated to be 8.86 ps². A 1 GHz oscilloscope (Agilent, DSO9104H), 1.2 GHz photodetector (Thorlabs, DET01CFC/M), optical spectrum analyser (OSA, Yokogawa AQ6317C), optical power meter (Thorlabs, PM100D), and radio frequency (RF) signal analyser (Agilent, N9320B) were used to monitor the mode-locked pulse train output.

3. Experimental results and discussion

In our experiment, a single DSR pulse was easily obtained because of the large normal dispersion. Provided that the orientations of the polarisation controllers were appropriately set, period doubling of single DSR pulses was obtained by increasing the pump power beyond the mode-locking threshold [9].

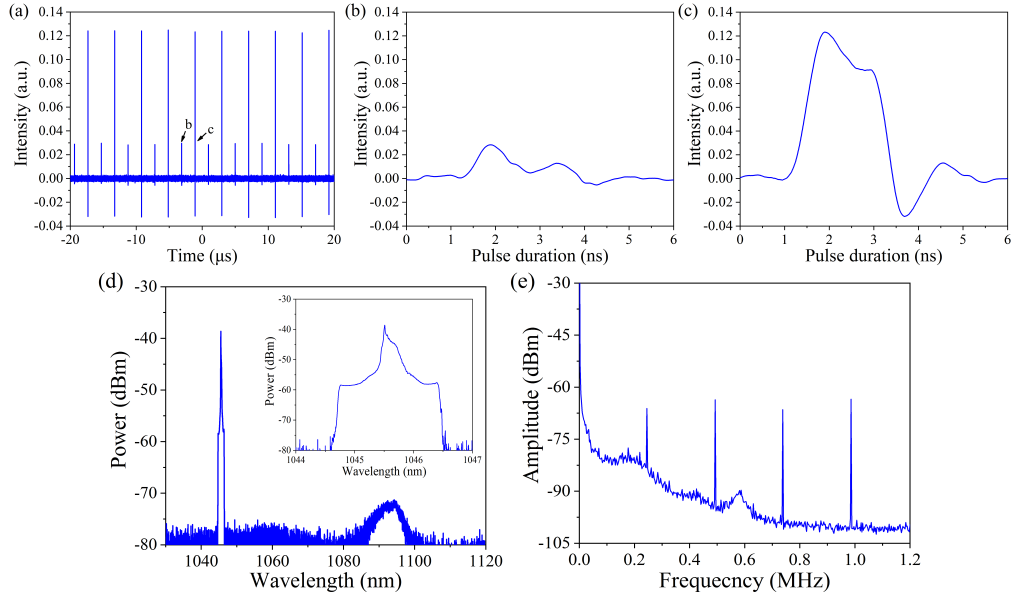


Fig. 2. Period doubling of a single DSR pulse. (a) Pulse train; (b) (c) The details of a single DSR pulse under two different states; (d) Corresponding optical spectrum. Inset: A zoom of the corresponding optical spectrum; (e) RF spectrum with a span of 1.2 MHz and a resolution bandwidth of 10 Hz.

Figure 2 shows an example of an experimentally observed period doubling of single DSR pulses. Figure 2(a) shows the oscilloscope trace of the period doubling of single a DSR pulse at a pump power of 30 mW. The details of the single DSR pulse are shown in Fig. 2(b) and

Fig. 2(c), which corresponds to the two distinct states in Fig. 2(a) (indicated by arrows). The pulse temporal profile exhibits an asymmetrical structure, because the pulse front had a higher intensity than the trailing edge. Figure 2(d) shows the corresponding optical spectrum of the period doubling of a single DSR pulse. The inset in Fig. 2(d) shows the typical bell-shaped optical spectrum of the DSR pulse [22-26]. The central wavelength was 1045.5 nm and the 3 dB bandwidth of the spectrum was approximately 0.039 nm. The signal near 1095 nm was due to the stimulated Raman scattering (SRS) effect. The long-cavity configuration can induce the low threshold required for the SRS. Figure 2(e) shows the RF spectrum of the laser output. In addition to the fundamental repetition rate, a new frequency component appeared at half of the fundamental repetition frequency and its harmonic, indicating that the single DSR pulse was in the state of period doubling.

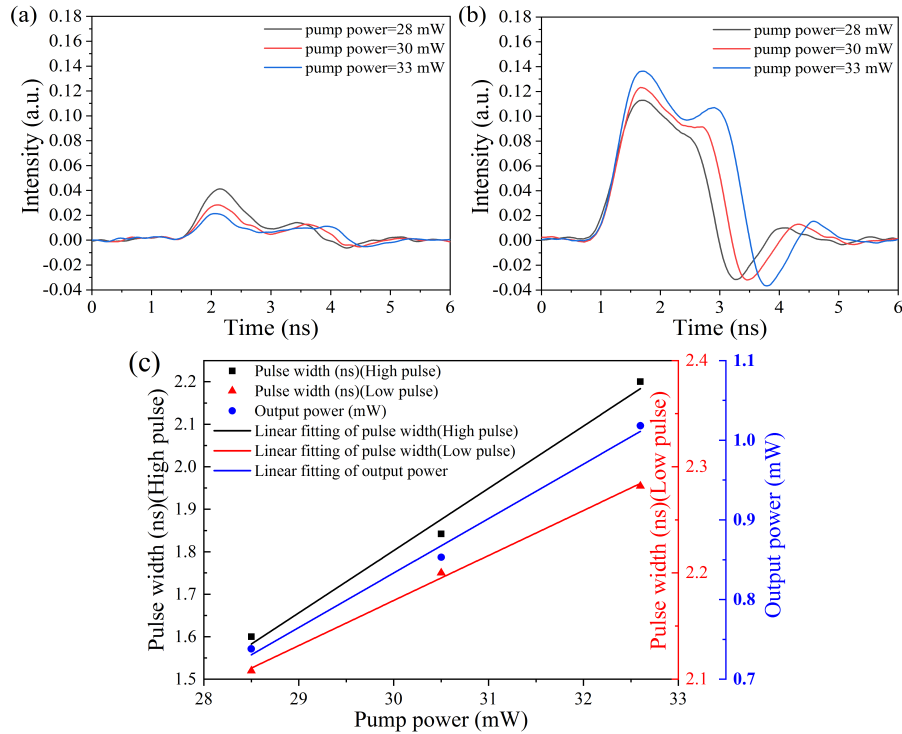


Fig. 3. Tuning the pump power from 28 mW to 33 mW. (a) (b) Oscilloscope trace of pulse evolution under two different states; (c) Pulse width and average output power versus pump power.

With fixed PC paddles, the single DSR pulse broadened gradually with an increase in the pump power, from 28 to 33 mW. During this process, the period doubling always existed, as shown in Fig. 3. A low-intensity pulse broadened from 2.1 to 2.3 ns (Fig. 3(a)), and a high-intensity pulse broadened from 1.6 to 2.2 ns (Fig. 3(b)). In Fig. 3(c), the pulse width and average output power are plotted as a function of the pump power delivered to the active fibre. Both the pulse width and average output power were proportional to the pump power, and were approximated with a linear fit.

As the pump power continued to increase, the single DSR pulse transitioned into a dual-pulse DSR, and eventually exhibited period doubling of dual-pulse DSR. The period doubling of dual-pulse DSR is depicted in Fig. 4. Figure 4(a) shows the oscilloscope trace of the period doubling of dual-pulse DSR at a pump power of 44 mW. Two DSR pulses existed in the

cavity, with a pulse separation of approximately 20 ns. The details of dual-pulse DSR are shown in Fig. 4(b) and Fig. 4(c), which corresponds to the two distinct states in Fig. 4(a) (indicated by arrows). The corresponding optical spectrum and RF spectrum of the period doubling of dual-pulse DSR are shown in Fig. 4(d) and Fig. 4(e), respectively. The central wavelength was slightly red-shifted to 1045.8 nm and the 3 dB bandwidth of the spectra was broadened to approximately 0.061 nm. The RF spectrum confirmed that the dual-pulse DSR was in a period doubling state.

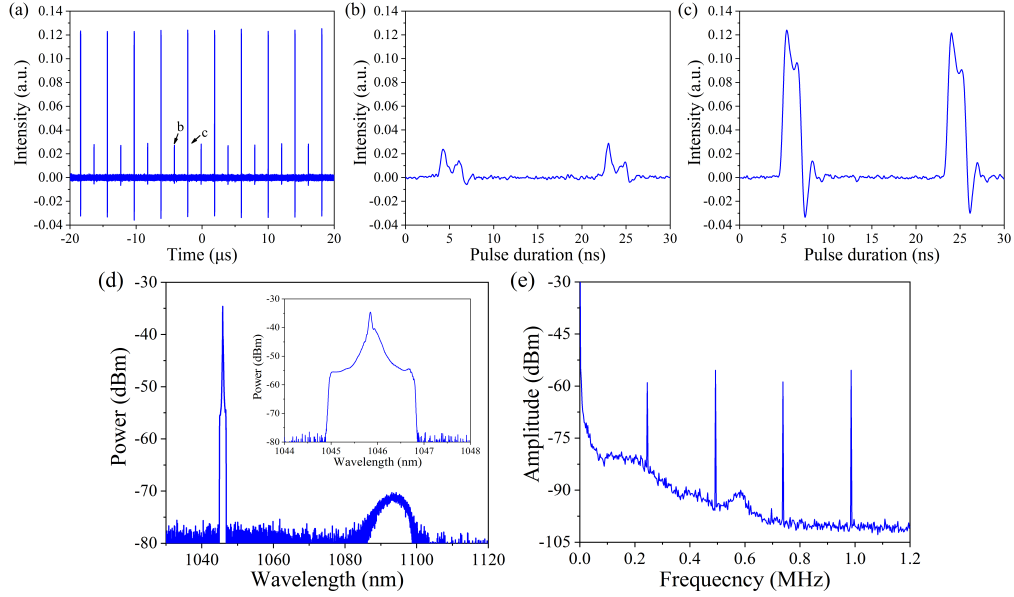


Fig. 4. Period doubling of dual-pulse DSR. (a) Pulse train; (b) (c) Corresponding to the details of dual-pulse DSR under two different states; (d) Corresponding optical spectrum. Inset: A zoom of the corresponding optical spectrum; (e) RF spectrum with a span of 1.2 MHz and a resolution bandwidth of 10 Hz.

Similar to the case of period doubling of a single DSR pulse, the dual-pulse DSR also broadened linearly with an increase in the pump power, while the period doubling state was maintained. As shown in Fig. 5(a) and Fig. 5(b), when the pump power increased from 42 to 49 mW, the first of the low-intensity pulses, in the state of dual-pulse, broadened from 2.4 to 2.8 ns, and the first of the high-intensity pulses broadened from 2 to 2.6 ns. The pulse width and average output power increased linearly with respect to the pump power, and was approximated with a linear fit (Fig. 5(c)). We noted that the pulse separation between the two DSR pulses decreased as the pump power increased, but the pulse intensity difference between the low-intensity and high-intensity pulses increased.

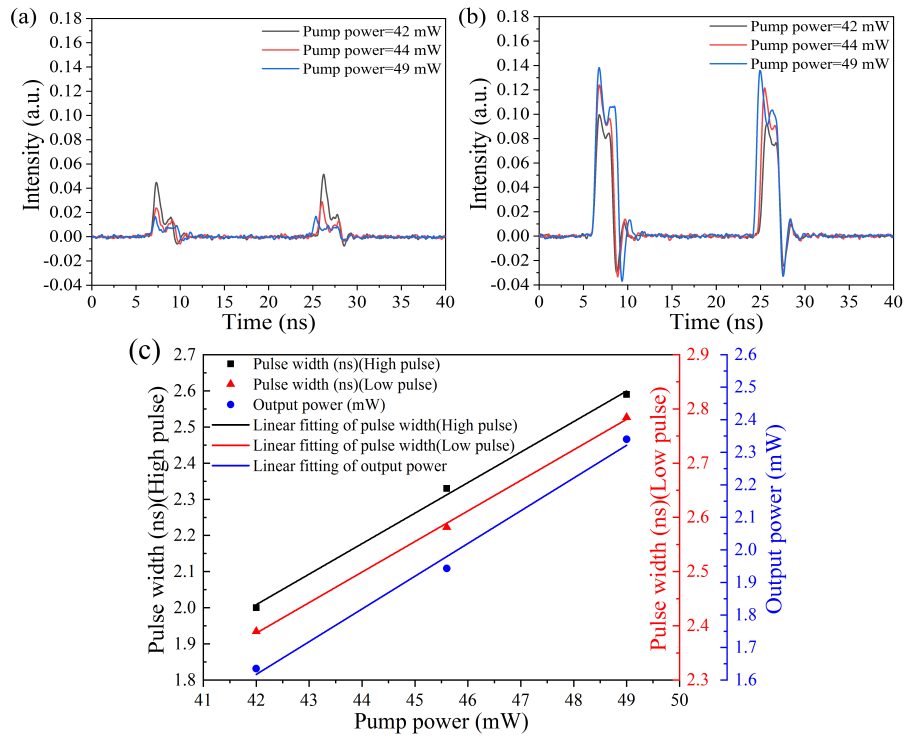


Fig. 5. Tuning the pump power from 42 mW to 49 mW. (a) (b) Oscilloscope trace of the pulse evolution under two different states; (c) The pulse width of the first of the low-intensity pulses, in the state of dual-pulse, the pulse width of the first of the high-intensity pulses in the state of dual-pulse, and average output power as a function of pump power.

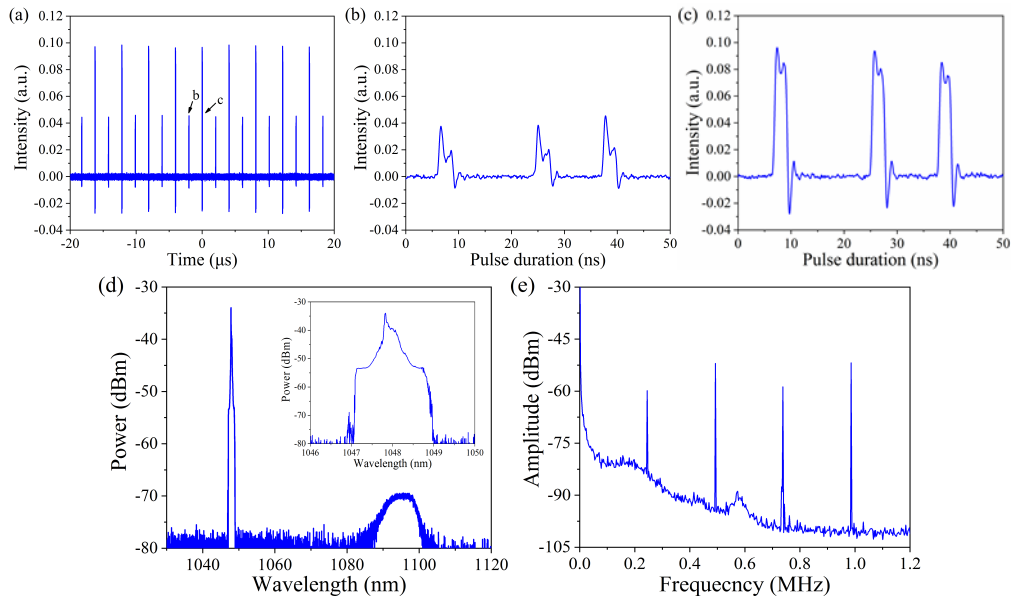


Fig. 6. Period doubling bifurcation of a three-pulse DSR. (a) Pulse train; (b) (c) Corresponding to the details of the three-pulse DSR under two different states; (d) Corresponding optical spectrum. Inset: A zoom of the corresponding optical spectrum; (e) RF spectrum with a span of 1.2 MHz and a resolution bandwidth of 10 Hz.

When the pump power was further increased, three DSR pulses were obtained. The period doubling of three DSR pulses was also achieved. Figure 6 depicts the case of period doubling for three DSR pulses at a pump power of 57 mW. Figure 6(a) shows the oscilloscope trace of three DSR pulses, coexisting in the cavity. Details of the three DSR pulses are shown in Fig. 6(b) and Fig. 6(c). The optical spectrum is shown in Fig. 6(d). The central wavelength was further red-shifted to 1047.8 nm, but the 3-dB bandwidth of the spectra reduced to approximately 0.050 nm. The RF spectrum again confirmed the appearance of period doubling (Fig. 6(e)).

When the pump power was tuned from 57 to 61 mW, the three pulses maintained period doubling, with the gradual broadening of the pulse width. We measured the first pulse in the state of the three pulses; the low-intensity and high-intensity pulses broadened from 2.7 to 3 ns and 2.3 to 2.6 ns, respectively (Fig. 7(a)-(b)). The pulse width and average output power increased linearly with respect to the pump power, as shown in Fig. 7(c), which was approximated with a linear fit. We noted that the pulse separation was reduced with an increase in the pump power.

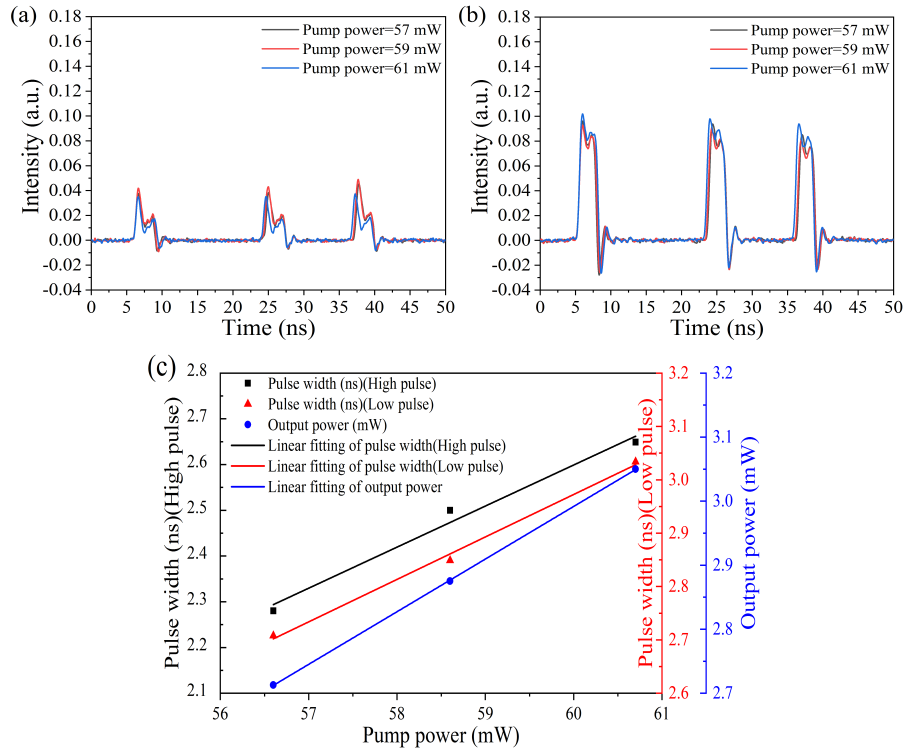


Fig. 7. Tuning the pump power from 57 to 61 mW. (a) (b) Oscilloscope trace of pulse evolution under two different states; (c) The pulse width of the first pulse of the low-intensity and high-intensity pulses, in the state of three pulses and the average output power as a function of pump power.

When the pump power continued to increase, the fibre laser was not able to work stably in the period doubling of multiple DSR pulses. The SRS effect was getting stronger and stronger, as shown in Fig. 2(d), Fig. 4(d), and Fig. 6(d), which made the pulses fluctuate violently and affected the stability of the pulses [27]. We note that the development from period doubling of a single DSR pulse to double DSR pulses, and then to three DSR pulses, can be repeated, even after the mode locking state was destroyed, due to over-pumping. However, the

achievement of period doubling of a single DSR pulse is the precondition for obtaining such a route. If the original single DSR pulse does not exhibit period doubling, period doubling of multiple DSR pulses cannot be obtained with the increase in pump power. In the case of two DSR pulses or three DSR pulses, the pulse separation is not fixed. So far, we are not sure what are the factors determining the pulse separations. The different settings of the polarization controllers could affect the pulse separations.

4. Conclusion

We experimentally observed period doubling of multi-pulse DSR in an all-normal-dispersion fibre laser, based on a NALM. With the increase of pump power, a single DSR pulse can evolve into a multi-pulse state, in addition to the typical pulse broadening at the fixed pulse peak power. In this process, the DSR pulses can exhibit period doubling in a multi-pulse state. Thus far, period doubling of double pulses and three pulses were observed. Further increase of the pump power will destroy the mode locking state. When the period doubling of multiple pulses was achieved, slightly increasing the pump power made the pulse exhibiting a linear pulse duration change with a dependence on the pump power, i.e., the DSR performance was maintained when multiple pulses exhibited period doubling behaviour. The experimental observations enrich the dynamics of DSR pulses in fibre lasers.

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Disclosures

The authors declare that there are no conflicts of interest related to this article.

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