

Harmonic dissipative soliton resonance pulses in a fiber ring laser at different values of anomalous dispersion

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Received 24 July 2017; revised 12 September 2017; accepted 27 September 2017; posted 28 September 2017 (Doc. ID 303146); published 27 October 2017

The pulse dynamics of harmonic mode-locking in a dissipative soliton resonance (DSR) region in an erbium-doped fiber ring laser is investigated at different values of anomalous dispersion. The fiber laser is mode-locked by a nonlinear polarization rotation technique. By inserting 0–200 m anomalous dispersion single-mode fiber in the laser cavity, the cavity length is changed from 17.3 to 217.3 m, and the corresponding dispersion of the cavity ranges from -0.27 to -4.67 ps². The observed results show that the tuning range of repetition rate under a harmonic DSR condition is highly influenced by the cavity dispersion. Furthermore, it is found that, by automatically adjusting their harmonic orders, the lasers can work at certain values of repetition rate, which are independent of the cavity length and dispersion. The pulses at the same repetition rate in different laser configurations have similar properties, demonstrating that each achievable repetition rate represents an operation regime of harmonic DSR lasers. © 2017 Chinese Laser Press

OCIS codes: (060.4370) Nonlinear optics, fibers; (060.5530) Pulse propagation and temporal solitons; (140.3510) Lasers, fiber; (140.4050) Mode-locked lasers.

<https://doi.org/10.1364/PRJ.5.000612>

1. INTRODUCTION

Passively mode-locked fiber lasers are known as powerful tools for the investigation of pulse dynamics in nonlinear systems. In 2008, a new concept of soliton formation known as dissipative soliton resonance (DSR) was predicted by Chang *et al.* in the frame of a complex cubic-quantum Ginzburg–Landau equation with certain parameter selections [1]. It indicated that, in the DSR regime, the pulse energy could increase without wave breaking, while simultaneously keeping the amplitude at a constant level. Therefore, DSR is an effective way to scale single-pulse energy in fiber lasers. Followed by numerous successive publications, researchers investigated DSR mode-locking in a variety of laser configurations under both anomalous and normal dispersion regimes [2–6]. Both theoretical and experimental investigations suggested that the dispersion plays an important role in DSR pulse generation. In 2016, Armas-Rivera *et al.* performed an experimental study on the correlation between pulse parameters and net normal dispersion of the cavity in a full polarization-maintaining ytterbium-doped DSR mode-locked fiber ring laser [7]. Meanwhile, Krzempek and Abramski studied the influence of anomalous dispersion on DSR pulses in a co-doped erbium–ytterbium (Er:Yb)

double-clad mode-locked laser [8]. The experimental results demonstrated that the DSR pulses in different dispersion regimes could have different shapes, durations, and peak powers.

Recently, the coexistence of DSR pulses in a passively mode-locked fiber laser was theoretically investigated by Komarov *et al.*, which predicted that harmonic mode-locking (HML) can occur in the DSR regime, and the number of generated harmonic DSR pulses remains constant with increasing pumping strength [9], which is different from the HML of conventional soliton. Experimental observation of harmonic DSR pulses up to the 13th harmonic was also presented in a co-doped Er:Yb double-clad fiber ring laser operating in an all anomalous dispersion regime [10]. Recently, we developed an erbium-doped fiber (EDF) ring laser mode-locked by nonlinear polarization rotation (NPR), which can generate DSR pulses up to the 86th harmonic [11], and the results matched well with the theoretical simulations.

In this paper, we investigated the influence of different values of anomalous dispersion on the properties of harmonic DSR pulses. The harmonic DSR pulses under investigation were generated by a passively mode-locked EDF ring laser, which was based on the laser we previously developed in

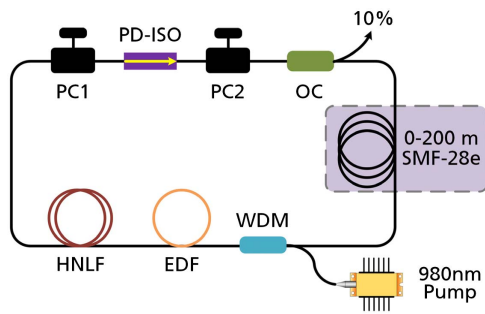


Fig. 1. Experimental setup to achieve the harmonic DSR pulses.

Ref. [11]. Its cavity length was varied by changing the length of a section of anomalous single mode fiber (SMF) in the cavity. We have observed that the harmonic DSR pulses were obtained in the laser cavity at various values of lengths, anomalous dispersions, and harmonic orders. Although different cavity lengths correspond to different fundamental repetition rates, these harmonic DSR pulses could operate at virtually the same repetition rates by automatically adjusting their own harmonic orders.

2. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1, which is based on a simple all fiber ring laser mode-locked by NPR. The gain is provided by a 0.8 m EDF (Liekki, Er80-8/125) with a dispersion parameter of 15.5 ps/nm/km. A 5 m highly nonlinear fiber (HNLF) is used to enhance the nonlinearity of the cavity, which has a nonlinear coefficient $\gamma = 10 \text{ W}^{-1} \cdot \text{km}^{-1}$ with dispersion of $0 \pm 1 \text{ ps/nm/km}$. The high nonlinearity plays an important role in broadening the tuning range of the pulse width [3,12] and multipulse operation [4,13]. The pigtailed of other optical components are 11.5 m standard SMFs with a dispersion of 17 ps/nm/km. The 0–200 m additional stretches of Corning SMF-28e fiber are spliced into the laser cavity to control the cavity length and dispersion. Thus, the cavity length is changed from 17.3 to 217.3 m, and the corresponding dispersion of the cavity ranges from -0.27 to -4.67 ps^2 . A polarization-dependent isolator (PD-ISO) together with two polarization controllers (PCs) act as an artificial saturable absorber, which also force the unidirectional operation within the ring cavity. The laser is pumped by a 980 nm laser diode via a 980/1550 nm wavelength division multiplexer (WDM). The 10% laser output is taken by a 90:10 optical coupler (OC).

An optical spectrum analyzer (YOKOGAWA AQ6370C), a photodetector (Agilent 11982A, 20 GHz), an oscilloscope (Agilent 86100A, 50 GHz), a radio-frequency (RF) spectrum analyzer (R&S FSU50, 50 GHz), and a commercial autocorrelator (Alnair Labs, HAC 200, maximum scan range 100 ps) are employed to monitor the laser output.

3. EXPERIMENT AND DISCUSSION

In the laser cavity without additional SMF-28e, we have already investigated the single pulse and HML operation in the DSR region in Ref. [11]. The fundamental repetition rate is

11.86 MHz because the laser has a 17.3 m long cavity. The harmonic DSR pulses with repetition rates of 782.6, 831.1, 923.7, 972.2, and 1019.7 MHz were observed in the laser, corresponding to the 66th, 70th, 78th, 82nd and 86th harmonic orders, respectively. Further details can be found in Ref. [11].

First, we added a 25 m long SMF-28e to the initial laser cavity, which increases the cavity length to 42.3 m. Thus, the net dispersion of the cavity grows to -0.82 ps^2 , and the fundamental repetition rate reduces to 4.839 MHz. In this case, stable single-pulse operations in the DSR region can still be achieved by adjusting the PCs when the pump power is beyond 120 mW. Figure 2(a) shows the evolution of a single DSR pulse. The pulse duration broadens linearly from 0.7 to 7.6 ns with the pump power increasing from 200 to 800 mW (with a step of 100 mW), while the peak power keeps constant. As shown in Fig. 2(b), the RF spectrum under the maximum pump power of 800 mW measured at 2 kHz resolution bandwidth (RBW) shows a signal-to-noise ratio exceeding 70 dB. The inset shows the characteristic amplitude envelope modulation with a period of around 130 MHz corresponding to the pulse duration. The optical spectra are similar to those obtained in the 17.3 m cavity in Ref. [11].

Next, by carefully adjusting the PCs in the cavity, we observed the harmonic DSR pulses with repetition rates of 551.4, 692.3, 783.2, 831.6, 924.7, and 972.8 MHz, corresponding to the 114th, 143rd, 162nd, 172nd, 191st, and 201st harmonic orders, respectively. In this case, when the PCs are fixed, the repetition rate remains unchanged with the increasing pump power. The evolutions of pulses with a repetition rate of

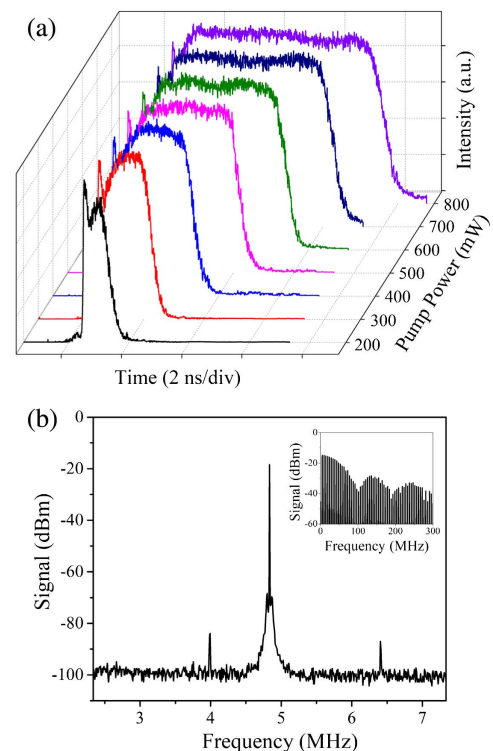


Fig. 2. Single-pulse operation in DSR regime in the 42.3 m long cavity. (a) Pulse profile versus pump power. (b) RF spectrum under 800 mW pump power.

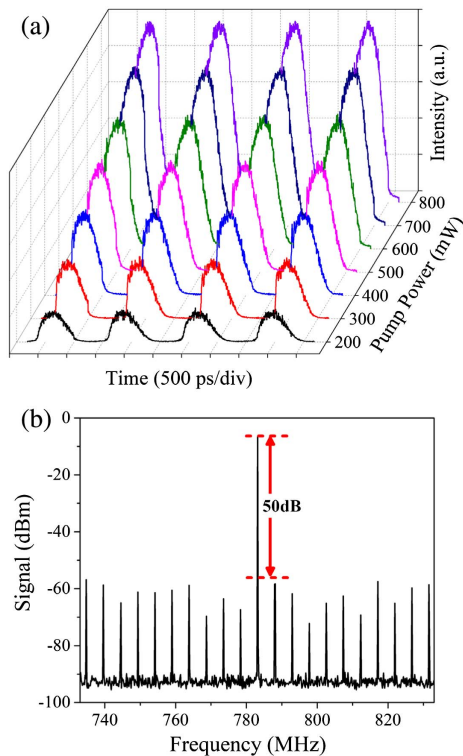


Fig. 3. Harmonic DSR pulses with the repetition rate of 783.2 MHz in the 42.3 m long cavity. (a) Pulse profile versus pump power. (b) RF spectrum under 800 mW pump power.

783.2 MHz are presented in Fig. 3(a), which shows a similar pulse dynamic to that obtained in Ref. [11]. Because the maximum pump power of our pump laser diode is relatively low, and a large number of DSR pulses coexist in the cavity, the pulse peak power does not reach the limitation caused by the peak power clamping effects. Figure 3(b) shows the RF spectrum under the maximum pump power of 800 mW with a 2 kHz RBW. The generation of supermode noise spurs is an intrinsic feature of HML [14], and the supermode suppression ratio is beyond 50 dB, indicating a stable HML. The supermode suppression ratio is beyond 50 dB, indicating stable HML. The measured autocorrelation traces presented in Fig. 4 show flat signals, which confirm that the pulses were not noise-like pulses [10,15].

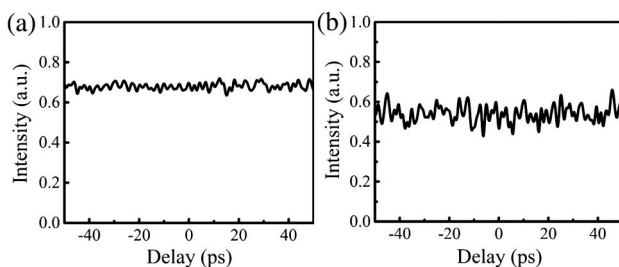


Fig. 4. Autocorrelation traces under 800 mW pump power in the 42.3 m long cavity. (a) Single-pulse operation. (b) Harmonic DSR pulses with the repetition rate of 783.2 MHz.

It is not difficult to find that the harmonic DSR pulses with repetition rates of around 783, 831, 924, and 972 MHz were observed in both the 17.3 and 42.3 m laser cavity, though the harmonic orders are different. By inserting different lengths of SMF-28e in the cavity, being 25, 50, 75, 100, 150, and 200 m, we further investigated the properties of harmonic DSR pulses. The achievable repetition rate in function of the length of inserted SMF-28e is plotted in Fig. 5. It can be seen that, with the growth of cavity length, the tuning range of repetition rate increases and then reaches the maximum value (from 410.3 to 924.9 MHz) when 50 m SMF-28e is inserted in the cavity with the dispersion increased to -1.37 ps^2 . Further increasing the cavity length leads to the decrease of repetition rate tuning range. Finally, when the cavity length reaches 217.3 m (200 m additional SMF-28e), the harmonic DSR mode-locked laser can only operate at the repetition rate of 317.3 MHz. When we inserted 250 m SMF-28e in the cavity, no harmonic DSR pulses were observed. Thus, 317.3 MHz is the lowest repetition rate for the HML of DSR in our laser configurations. This result indicates that the distance between pulses should not be too long, since the HML is formed by pulse-pulse interaction. In Ref. [8], it was experimentally verified that there are boundaries of anomalous dispersion for the single-pulse DSR operation in fiber lasers. Obviously, the boundaries of dispersion also exist in harmonic DSR mode-locking regime, and the dispersion plays an important role in the tuning range of repetition rate. Besides, the nonlinearity induced by additional SMF could also have an influence on the tuning range. Moreover, the repetition rate has a general downward trend with the growth of the cavity length. In addition, we found that, when adding 0–100 m SMF-28e in the cavity, the laser can keep the harmonic DSR mode-locking state achieved by adjusting the PCS, and it was not sensitive to the environmental fluctuations. However, when the length of inserted SMF continued to increase, the stability decreased. For example, when 200 m SMF was added in the cavity, it was very difficult to achieve the HML state, and the operation was also sensitive to the environmental fluctuations. Thus, we consider that in longer cavities, more stringent conditions are required to operate at harmonic DSR mode-locking state.

The interesting fact is that, the repetition rates of these harmonic DSR mode-locked lasers with different cavity lengths

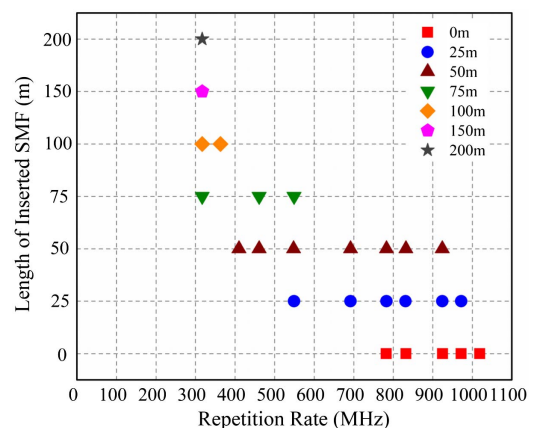


Fig. 5. Repetition rate in function of the length of Inserted SMF-28.

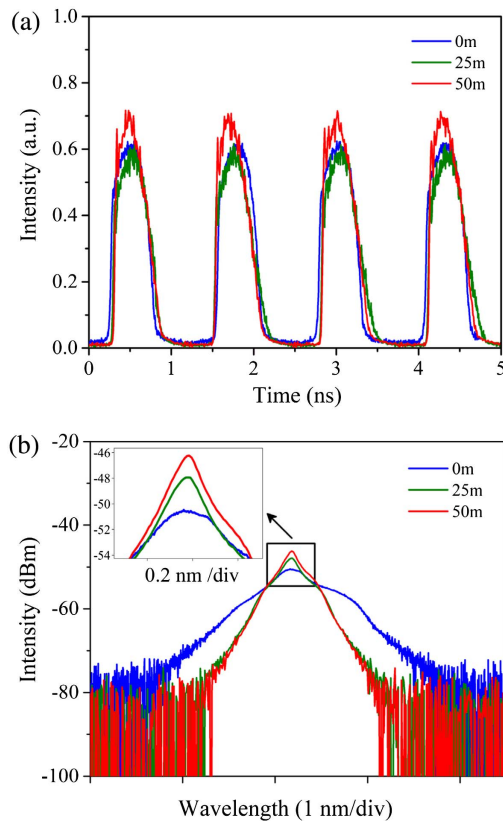


Fig. 6. Comparison of the pulses in laser cavities with different lengths of additional SMF-28e. (a) Temporal profiles. (b) Corresponding optical spectra.

can be closed to several certain values. For example, as shown in Fig. 5, when we inserted 0, 25, and 50 m SMF-28e in the laser cavity, the lasers can operate at the repetition rates of 782.6 MHz (66th harmonic), 783.2 MHz (162nd), and 782.2 MHz (259th), respectively. The comparison of the temporal profiles of these pulses under the pump power of 500 mW is presented in Fig. 6(a). It shows that these pulses have almost the same parameters despite the slight differences in the pulse amplitude and repetition rate, though the states of PCs and the cavity dispersions are different. In the previous works [7,8], the shapes of DSR pulses were changed with different values of dispersion. It was found that the DSR pulse with different repetition rates and dispersion could have different peak powers and durations. The results indicated that the dispersion could influence the peak power clamping effects in the cavity. However, because the pulses in our experiments are still in initial states and do not have enough energy to reach the limitation of peak power, our results do not contradict the previous works. This result also indicates that, in these lasers, the operation with the closed repetition rate works in the same regime. Note that these repetition rates favored by the HML of DSR are independent of the cavity length and dispersion. In the previous works [5,11], it has been demonstrated that multipulse operation under DSR is derived from the generation of multiple dissipative solitons (DSs). With selected parameters of laser cavity with a sinusoidal saturable absorber, the laser can realize multipulse operation of DSs or single DSR pulse

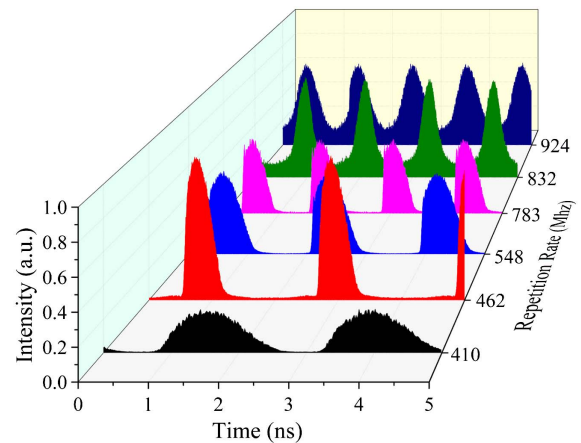


Fig. 7. Temporal profiles of harmonic DSR pulses in the 67.3 m long cavity.

operation [5]. Both stable multiple DSs and single DSR pulse cannot evolve into harmonic DSR pulses. To realize harmonic DSR operation, the laser needs to work at the unstable multipulse operation of DSs, which is an intermediate state between stable multiple DSs and single DSR pulse. We surmise that, to work at this intermediate state, the laser should operate under strict conditions. Consequently, these strict conditions lead to several specific repetition rates. Besides, the interaction force between these harmonic DSR pulses could also be responsible for this pulse arrangement. The comprehensive understanding the physical origin of this phenomenon is still under investigation. With the increase of cavity length, the suitable situations of the cavity for reaching a stable harmonic DSR mode-locking state become less and less; consequently, it also leads to the decrease of repetition rate tuning range. Figure 6(b) shows the corresponding optical spectra. Their central wavelengths (bandwidth) are 1591.2 nm (0.42 nm), 1563.5 nm (0.22 nm), and 1563.1 nm (0.19 nm), respectively, and they are presented together in Fig. 6(b) for better comparison.

Figure 7 shows the HML operations at different repetition rates in the 67.3 m long cavity (50 m additional SMF-28e) under the same pump power of 500 mW because it has the largest tuning range of repetition rate. The pulses have different amplitudes, durations and shapes, and we cannot find a trend in their variations. This result confirms that these repetition rates of different certain values represent different operation regimes, and in the same regime the pulses have similar properties.

4. CONCLUSION

In conclusion, we have experimentally investigated the pulse dynamics of HML in the DSR region in a fiber ring laser with different anomalous dispersions. In order to control the dispersion and cavity length, we inserted 0–200 m SMF-28e in the cavity, which allows the variation of the net cavity dispersion in the range from -0.027 to -4.67 ps². We found that the tuning range of repetition rate for the HML of DSR can be influenced by the cavity length, dispersion, and nonlinearity, which are induced by SMF-28e. With appropriate cavity parameters, the tuning range can reach the maximum. When

the net anomalous dispersion of the cavity goes beyond a certain value, harmonic DSR pulses cannot be obtained in our lasers. It was also found that the harmonic DSR lasers with different cavity lengths and dispersions can operate at certain repetition rates, and the harmonic DSR pulses at the same repetition rate have similar properties. This phenomenon can be attributed to the long-range pulse interaction and the strict conditions to realize HML of DSR.

Funding. National Natural Science Foundation of China (NSFC) (61435003, 61421002, 61327004, 61377042, 61505024, 61378028); Science and Technology Project of Sichuan Province (2016JY0102).

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