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Abstract: Noise-like square pulses (NLSPs) have been experimentally investigated in both normal and anomalous dispersion regimes. A chirped fiber Bragg grating (CFBG) has been employed as a dispersion management element in the compact linear-cavity mode-locked Yb-doped fiber laser. The net cavity dispersion could be switched from large anomalous dispersion (−2.71 ps²) to large normal dispersion (+5.33 ps²), depending on the direction of CFBG inserting in laser cavity. Two kinds of NLSPs with different temporal profiles are achieved in the proposed laser. In anomalous dispersion regime, the square pulse duration can be tuned from 0.91 ns to 5.39 ns, and the maximum square pulse energy is 39.57 nJ. In normal dispersion regime, the top of the pulse is flatter, the square pulse duration can be tuned from 0.89 ns to 5.97 ns, and the maximum square pulse energy is slightly higher, up to 40.17 nJ. The output laser is linearly polarized.

Index Terms: Fiber lasers, mode-locked lasers, fiber gratings.

1. Introduction

Recently, high-energy mode-locked pulses have attracted particular attention due to their wide applications, including scientific research, industry, and biomedicine, etc. Passively mode-locked fiber laser is an ideal way to generate high-energy pulses due to their compact structure, environmental stability, high efficiency, and low cost. To scale up the pulse energy, various pulse-shaping techniques have been applied in passively mode-locked fiber lasers by the management of dispersion and nonlinearity, including stretched pulse [1], conventional soliton [2], [3], similariton [4], and dissipative soliton [5]–[7]. Due to the soliton area theorem [2] and spectral gain filtering effect [8], [9], the pulse energy is limited to tens of nanojoules. Attempts to further increase the pulse energy always lead to pulse breaking due to the excessive nonlinearity induced by higher pump power [10], [11].

To achieve higher-energy pulses, more and more attention has been paid to a particular pulse forming mechanism, dissipative soliton resonance (DSR). The pulse energy and width under DSR conditions can increase infinitely with increasing pump power while the amplitude remains constant.
Since the DSR was proposed, there are many studies about DSR [13]–[16]. During the studies, people have found another pulse mechanism, NLSPs, whose characteristics are similar to the DSR pulses. Even, NLSPs and DSR can be switched in the same laser [17]–[19]. NLSP is a square wave packet consisting of many ultrashort subpulses, which is different from DSR. DSR pulse is a single pulse. NLSPs can be proved by measuring the pulse autocorrelation trace, which has an obvious narrow spike on top of a broad pedestal. NLSP is an ideal way to achieve high-energy noise-like pulse, and it can have some potential applications in many important areas, such as low spectral coherence interferometry, laser micromachining, optical sensing, medical imaging, and supercontinuum (SC) generation [13], [15], [20].

It is worth noting that NLSPs can be obtained in both normal and anomalous dispersion regimes, but the forming mechanism is different. In normal dispersion regime, the formation of the noise-like pulses attributes to the peak power clamping effect, in which the reverse saturable absorption (RSA) effect plays a key role [20]–[22]. In anomalous dispersion regime, it is caused by the combined effect of soliton collapse and positive cavity feedback [23].

It is important for the generation of NLSPs to manage the intracavity dispersion in passively mode-locked lasers. In the past decades, various dispersion-management elements have been applied in the fiber lasers, including grating pairs [24], photonic crystal fibers [25], dispersion compensation fiber [26], normal dispersion fiber [27], [28], fiber taper [29], and chirped fiber Bragg grating (CFBG). Among them, CFBG has been paid more attention because of its unique advantages, such as all-fiber configuration, introducing positive and negative dispersion, and low insertion loss. Fermann et al. have first used a CFBG to manage dispersion in a mode-locked fiber laser [30]. CFBGs have been utilized as anomalous [31] or normal dispersion components [32] in different rare-earth-doped fiber lasers, respectively. By designing appropriate cavity structures, a CFBG can even introduce positive and negative dispersion simultaneously in a laser cavity [33], [34]. Among them, many different kinds of solitons have been achieved, including conventional soliton (CS), dissipative soliton (DS), and stretched pulses. However, the generation of NLSPs using a CFBG for dispersion management has not been reported.

In this paper, A CFBG is used as a dispersion management element in a compact linear-cavity NPR mode-locked Yb-doped fiber laser, and the net cavity dispersion could be switched from anomalous dispersion to normal dispersion by inserting a CFBG into the laser cavity in different orientations. By appropriately adjusting polarization controller (PC), we generate two kinds of NLSPs with different temporal profiles in normal and anomalous dispersion regimes. Further, we respectively investigate the output characteristics of the proposed laser in different dispersion regimes. The square pulse duration can both be broadened from $\sim 1$ ns to $\sim 5.5$ ns. The top of
the square pulse in normal dispersion regime is flatter, and the maximum square pulse energy is slightly higher, up to 40.17 nJ. However, the slope efficiency of the proposed laser in anomalous dispersion regime is higher, which is about 20.5%. In addition, the output laser is linearly polarized.

2. Experimental Setup
The schematic diagram of the linear-cavity noise-like mode-locked fiber laser is illustrated in Fig. 1. The CFBG is not only used as a cavity mirror but also as a dispersion management element. The reflectivity of CFBG is above 95%. It is fabricated with a chirped phase mask of a 10 nm/cm chirp rate. It has a central wavelength of 1064 nm with a spectral bandwidth of 12 nm, as shown in the lower left of Fig. 1. Its dispersion is approximately ±4 ps² by calculation, which depends on the direction inserted into the laser cavity. The gain medium is a 55 cm Yb-doped fiber with a group velocity dispersion (GVD) parameter of 26.2 ps²/km. The gain fiber is pumped by a 974 nm laser diode (LD) with a maximum output power of 785 mW through a wavelength-division multiplexer (WDM). A fiber-pigtailed PBS is used as a polarizer, combined with a PC, to achieve NPR mode-locking. The pigtails of port 2 and 3 of PBS are polarization-maintaining (PM) fibers, and port 1 is single mode fiber (SMF). The PBS also serves as an output coupler which ensures linearly polarized output. The pigtail of mirror is PM fiber, and it can reflect the linearly polarized laser without changing the polarization state. In addition, the 20-m-long SMF with GVD parameter of 24 ps²/km is utilized in the laser cavity to balance the nonlinearity and dispersion.
3. Experimental Results and Discussions

3.1 Mode Locked Fiber Laser Operating in Anomalous Dispersion Regime

In this experiment, the CFBG inserted into the cavity introduces a large anomalous dispersion, and the net cavity dispersion is $-2.71 \text{ ps}^2$. The total laser cavity length is around 26.74 m. When the pump power exceeds 199 mW, the NPR mode-locking can be established with an appropriate PC state. The stable nanosecond square pulse with steep edges is observed in the oscilloscope. The typical output characteristics of the proposed laser operating in anomalous dispersion regime at the pump power of 523 mW are presented in Fig. 2. The temporal profile of single square pulse is presented in Fig. 2(a), and the square pulse duration is 3.18 ns. To prove whether it is DSR or NLSP, we measure the pulse autocorrelation trace although the square pulse duration is too wide to be integrally traced within the maximum scanning range of autocorrelator (600 ps). It is found that there is always a spike on the top of a broad pedestal, which is a typical characteristic of noise-like pulse. The pulse autocorrelation trace within the scanning range of 51 ps is shown in the inset of Fig. 2(a), and the full width at half maximum (FWHM) of the spike is 0.6 ps. The double-scaled autocorrelation trace proves the nanosecond square pulses we have achieved in our laser are NLSPs. The spectrum of our proposed laser is shown in Fig. 2(b), and its central wavelength is 1063.4 nm. Fig. 2(c) illustrates the stable mode-locked pulse train. The frequency spectrum is shown in Fig. 2(d). The signal-to-noise ratio (SNR) is about 65 dB at the fundamental frequency of 3.74 MHz, which indicates the good stability of the mode-locking state. The frequency spectrum measured at a span of 1 GHz is shown in the inset of Fig. 2(d). The envelope modulation with a period of 314 MHz is observed in the frequency spectrum at the wider span range. The period of modulation is inversely proportional to the square pulse duration, corresponding to the square pulse duration of about 3.18 ns, which varies with the pump power.

To further investigate the dynamic evolution of NLSPs, we increase the pump power from 199 mW to 785 mW and keep the PC fixed. The square pulse duration can be broadened from 0.91 ns to 5.39 ns, while the amplitude almost remains constant, as shown in Fig. 3(a), which is similar to
DSR. It concretely shows the relationship between the square pulse duration and the pump power in Fig. 3(c), in which the square pulse duration linearly increases along with the pump power. The relationship between the square pulse amplitude and the pump power are also shown in Fig. 3(c). We haven’t observed the pulse splitting or harmonic mode-locking phenomenon under our experimental conditions, which is probably due to the limitation of pump power.

The corresponding spectra of our proposed laser at different pump power are illustrated in Fig. 3(b). The 3-dB bandwidth increases from 8.37 nm to 8.44 nm, and the peak intensity increases from -31.77 dBm to -26.57 dBm, while their central wavelengths remain around 1063.4 nm. The slight broadening and heightening of spectra result from the self-phase-modulation (SPM) effect [19]. We also measure the average output power of our laser at different pump power, as shown in Fig. 3(d). The average output power linearly increases from 32.2 mW to 148 mW along with the pump power, and the slope efficiency is about 20.5%. The maximum average output power is 148 mW under our experimental conditions. By calculation, the maximum peak output power is 7.34 W, and the single square pulse energy is 39.57 nJ.

### 3.2 Mode Locked Fiber Laser Operating in Normal Dispersion Regime

By inserting the CFBG into the laser cavity in the opposite direction, the net cavity dispersion can be changed to $+5.33 \text{ ps}^2$. Due to the different lengths of the fiber pigtail of CFBG, the laser cavity length has been changed to 27.62 m. When the pump power is above 199 mW, we generate another kind of NLSP that has a different temporal profile than the square pulse achieved in anomalous dispersion regime, by properly adjusting the PC. The output characteristics of the
proposed laser operating in normal dispersion regime at the pump power of 451 mW are shown in Fig. 4. This kind of square pulse has a flatter top, and the square pulse duration is about 3.07 ns, as shown in Fig. 4(a). We also measure the pulse autocorrelation trace within the scanning range of 51 ps. A spike with the FWHM of 0.6 ps also exists on the top of a broad pedestal, as shown in the inset of Fig. 4(a), which proves the square pulses we have achieved in normal dispersion regime are also NLSPs. The corresponding spectrum is presented in Fig. 4(b), and the central wavelength is located at around 1068.5 nm. It differs from the shape of spectrum of anomalous dispersion regime, which may attribute to the difference of gain saturation energy [21]. Fig. 4(c) shows the stable square pulse train. The fundamental frequency is 3.62 MHz, as shown in Fig. 4(d), which is fixed by the cavity length. The signal-to-noise ratio (SNR) is 58 dB, which indicates that the proposed mode-locked laser also has good stability in normal dispersion regime. The inset of Fig. 4(d) illustrates the frequency spectrum at a wider span of 1 GHz. We also observe the envelope modulation, and the period of modulation is 326 MHz which agrees well with the square pulse duration of 3.07 ns.

Fig. 5(a) illustrates the dynamic evolution of the NLSPs in normal dispersion regime. When the pump power increases from 199 mW to 785 mW, the square pulse duration linearly broadens from 0.89 ns to 5.97 ns with constant amplitude, as shown in Fig. 5(a) and (c). The relationship between the square pulse amplitude and the pump power are also shown in Fig. 5(c). We also don’t observe the pulse splitting or harmonic mode-locking phenomenon under our experimental conditions. The spectra of the proposed laser in normal dispersion regime at different pump power are presented in Fig. 3(b). The 3-dB bandwidth decreases from 2.4 nm to 1.8 nm, and the peak intensity increases from -20.5 dBm to -12.7 dBm, while the central wavelength remains around 1068.5 nm. When we measure the average output power of the proposed laser in normal dispersion regime, we note that the output power has little difference from that in anomalous dispersion regime. The average output power linearly increases from 29.9 mW to 145.4 mW along with the pump power, as shown
in Fig. 5(d). The maximum peak power is 6.73 W, and the slope efficiency is about 19.6%, which is lower than that in anomalous dispersion regime. The maximum single square pulse energy is 40.17 nJ, which is slightly higher than that in anomalous dispersion regime.

In addition, when we fix the pump power and adjust the PC, we also observe the mode-locked square pulses with different amplitudes and shapes in the proposed laser in both normal and anomalous dispersion regimes, which is shown in Fig. 6.

4. Conclusion

In conclusion, we have experimentally demonstrated the generation of NLSPs in a linear-cavity mode-locked fiber laser with normal and anomalous cavity dispersions. The PBS is not only used as a polarizer to achieve NPR mode-locking but also a linearly polarized output coupler in our proposed laser. We insert a chirped fiber Bragg grating (CFBG) into the laser cavity for dispersion management in two different orientations, and the net cavity dispersion can be switched from large anomalous dispersion ($-2.67 \text{ ps}^2$) to large normal dispersion ($+5.33 \text{ ps}^2$). Two kinds of NLSPs with different temporal profiles are achieved in anomalous and normal dispersion regimes by properly adjusting PC, respectively. In anomalous dispersion regime, the square pulse duration can be tuned from 0.91 ns to 5.39 ns by increasing the pump power up to 785 mW. The maximum average output power is 148 mW, the corresponding single square pulse energy is 39.57 nJ, and the slope efficiency is higher, up to 20.5%. In normal dispersion regime, the top of the square pulse is flatter, and the square pulse duration can be tuned from 0.89 ns to 5.97 ns. The maximum average output power is 145.4 mW, the slope efficiency is about 19.6%, and the maximum single square pulse energy is up to 40.17 nJ, which is slightly higher than that in anomalous dispersion regime. Due to the compact linear-cavity configuration, linearly polarized output, and higher slope efficiency, we believe that our work provides a promising way to achieve high-energy noise-like pulse in a passively mode-locked fiber laser.

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