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Two-dimensionally controllable DSR generation from dumbbell-shaped mode-locked all-fiber laser*

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An all-fiber dumbbell-shaped dual-amplifier mode-locked Er-doped laser that can function in dissipative soliton resonance (DSR) regime is demonstrated. A nonlinear optical loop mirror (NOLM) and a nonlinear amplifying loop mirror (NALM) are employed to initiate the mode-locking pulses. Unlike conventional single-amplifier structure, the output peak power of which remains unchanged when pump power is varied, the proposed structure allows its output peak power to be tuned by changing the pump power of the two amplifiers while the pulse duration is directly determined by the amplifier of nonlinear amplifying loop mirror. The entire distribution maps of peak power and pulse duration clearly demonstrate that the two amplifiers are related to each other, and they supply directly a guideline for designing tunable peak power DSR fiber laser. Pulse width can change from 800 ps to 2.6 ns and peak power varies from 13 W to 27 W. To the best of our knowledge, the peak power tunable DSR pulse is observed for the first time in dumbbell-shaped Er-doped all-fiber mode-locked lasers.

Keywords: mode-locked lasers, fiber lasers, dissipative soliton resonance

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1. Introduction

Passively mode-locked fiber lasers have attracted much attention of scientists due to their advantages of high beam quality, compact structure, exceptional stability, and alignment-free operation, which bring about explosive growth of related researches.[1–3] Based on passively mode-locked fiber laser, a plenty of new nonlinear pulses have been discovered, such as dissipative soliton resonance (DSR), noise-like pulse, soliton rain, and soliton molecules.[4–9] In the anomalous dispersion regime, researchers can easily obtain a conventional soliton, static solution of nonlinear Schrödinger equation, which is a result of the interplay between the anomalous fiber dispersion and the fiber nonlinear Kerr effect.[10] But due to the limitation of soliton area theorem, the soliton pulse is easy to split and the pulse energy is limited. The DSR pulse allows the pulse duration to widen linearly with pump power increasing and can avoid overmuch accumulating the nonlinear phase shift in anomalous dispersion.[11,12] So, the DSR is a potential candidate for obtaining higher pulse energy.

Classical artificial saturable absorbers (SAs), nonlinear loop mirror dependent on nonlinear interferometry and nonlinear polarization rotation based on Kerr nonlinearity, can be employed to obtain high energy pulse.[13,14] In the last few years, traditional figure-eight structure has swarmed into researchers' horizon rapidly.[14,15] Conventional single-amplifier figure-eight structure working in the DSR regime owns tunable pulse duration and constant peak power. Whether the peak power could be tuned is worth studying. In Ref. [16], a dual-amplifier figure-eight passively mode-locked Yb-doped fiber laser that generated width- and peak-power-tunable DSR pulses was first demonstrated. In 2016, Semaan *et al.* realized a DSR square pulse in a dual-amplifier figure-eight structure and also observed a width-and-peak-power-tunable DSR pulse.[17] In the figure-eight structure, an optical isolator (ISO) needs to be integrated to keep unidirectional operation of laser. Strictly speaking, a laser containing ISO is not an all-fiber scheme. By utilizing a fiber bragg grating (FBG) and reflectivity character of nonlinear loop mirror to build dumbbell-shaped or σ-structure, strict all-fiber laser can be established.[18] The dumbbell-shaped dual-amplifier mode-locked laser which can generate DSR pulse has not been studied, and the width and peak power tunable DSR pulses have not been observed in similar structure either. At the same time, previous reports only mentioned the change rule for a specific power level and no reports have presented the analysis of the entire distribution characteristic of peak power and pulse duration. Under the condition of dual-amplifier, the important and meaningful issue of how to realize large peak power tunable range and highest peak power have not been studied.

In this paper, a dumbbell-shaped dual-amplifier all-fiber laser is designed to generate stable DSR pulse. The pulse peak power can be tuned by two amplifiers while the pulse duration is determined by the amplifier of nonlinear amplifying loop

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mirror (NALM). To our best knowledge, two-dimensionally controllable DSR square pulse in a dumbbell-shaped fiber laser is first reported. The entire distribution maps of peak power and pulse duration which can clearly describe the output characteristic of cavity are first used to analyze and demonstrate the correlation between the dual-amplifiers. According to entire distribution maps, we demonstrate that the increase of dual pump power has an opposite effect on the output peak power and the change of amplifier of linear part almost directly determines the tunable range of peak power. The result is helpful in understanding the interaction between dual-amplifiers and guiding the design of peak-power tunable DSR laser.

2. Experimental setup

The schematic diagram of the dumbbell-shaped dual-amplifier all-fiber Er-doped laser is depicted in Fig. 1, which is established with strict all-fiber structure without using the ISO. The oscillator is composed of one nonlinear optical loop mirror (NOLM), one NALM and the linear cavity section between them. One 40:60 fused coupler, one 976/1550 wavelength division multiplexer (WDM1), a 9-m-long Er-doped fiber (EDF1, YOFC EDF3/6/125-23), and a section of 70-m-long SMF-28e passive fiber constitute the NALM. The cavity length of NALM is about 82 m. The right NOLM has a 3-dB fused coupler and a 4-m fiber loop. The linear part between NOLM and NALM is 13-m long, which is composed of one 976/1550 wavelength division multiplexer (WDM2) and a 9-m-long Er-doped fiber (EDF2). The Er-doped fiber has core/cladding diameters of 5 μm/125 μm with 3.4-dB/m core-absorption at 976 nm. Two single-mode fiber-coupled 976-nm laser diodes (LD) with the protection of bandpass filter have maximum output power of 400 mW (pump 1) and 440 mW (pump 2). Three polarization controllers(PCs) are integrated to stabilize polarization state of intra-cavity. The laser works in net anomalous dispersion region without intra-cavity dispersion compensation components.

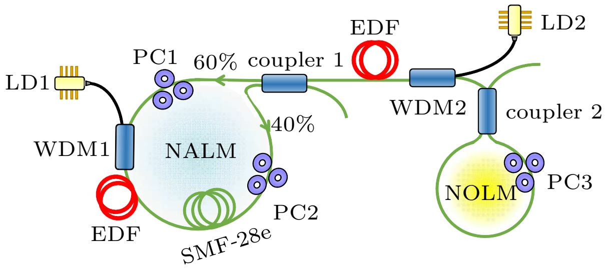

Fig. 1. Experimental setup consisting of laser diode (LD), wavelength division multiplexer (WDM), erbium-doped fiber (EDF), and polarization controller (PC).

The NALM primarily serves as an artificial fast SA to start the mode-locked fiber laser. At the same time, another significant function of NALM is used as a reflective mirror and an output coupler. Employing a relatively long passive fiber in NALM is helpful in increasing the difference in asymmetric nonlinear phase shift between counter propagating light and reducing the mode-locking threshold. Meanwhile, the peak power of pulse is easier to be clamped in a long cavity, so that the DSR is effortless to generate. By carefully squeezing and stretching fiber, the three PCs (PC1, PC2, and PC3) can adjust the nonlinear transmission function of NALM, which is important for optimizing dynamical process of DSR and stabilizing polarization state of intra-cavity.[19] The NOLM is formed by a standard 3-dB coupler and only acts as a high reflection mirror. The time-domain characteristic of output pulses is detected by a real-time oscilloscope (Tektronix MSO5000B 2-GHz bandwidth) and a 5-GHz InGaAs photodiode detector (PD). An optical spectrum analyzer spectrometer (Yokogawa AQ6370D 600 nm–1700 nm) is used to measure the output spectrum.

3. Results and discussion

With the increase of pump power and fine adjusting PC, mode-locking sate is very easy to be observed. We find that PC1 and PC2 can obviously influence the stability of mode-locking state while the effect of PC3 is smaller compared with those of the others. The mode-locking state is measured under the condition of maximum pump power. Figure 2(a) shows the typical pulse sequence with a pulse interval of 540 ns, which corresponds to the repetitive frequency of 1.85 MHz. Weak amplitude fluctuation means that our results have fine stability. The measured fundamental repetitive frequency is 1.85 MHz by a radio frequency (RF) spectrum analyzer which matches very well with cavity length of laser and signal-to-noise ratio (SNR) is around 80 dB as illustrated in Fig. 2(b) with a scan span of 500 kHz and a resolution bandwidth of 10 Hz. The 80-dB SNR indicates the high stability of the mode-locking operation.

In Fig. 3(a) (the black envelop), one can see that single pulse envelope has a 3-dB pulse duration of 2.63 ns with a typical rectangular shape. At the same time, the intensity autocorrelation trace of the square pulse is measured but not shown here. Due to the relatively wide pulse duration, the autocorrelation intensity is almost kept at the same level over the entire time window and coherent peak with a large pedestal is not observed. So we can confirm that laser does not work in the noise-like DSR state.[20] As is well known, the NALM and NOLM have periodical sinusoid reflectivity and can induce peak power clamping effect easily. In our experiment, the generation of DSR pulse results from peak power clamping effect of NALM. The spectrum is shown in Fig. 3(b) (the black envelop). The central wavelength and the 3-dB width of spectrum are 1567.5 nm and 12.6 nm respectively. Kelly sideband does not appear and the entire spectral profile is more similar to Gauss function. Any unstable nonlinear phenomena are not found. Then we would discuss the self-start character and the relationship between the output parameters of laser and the pump power of both amplifiers. The positions of three PCs' knobs are locked to keep constant polarization state of intra-cavity.

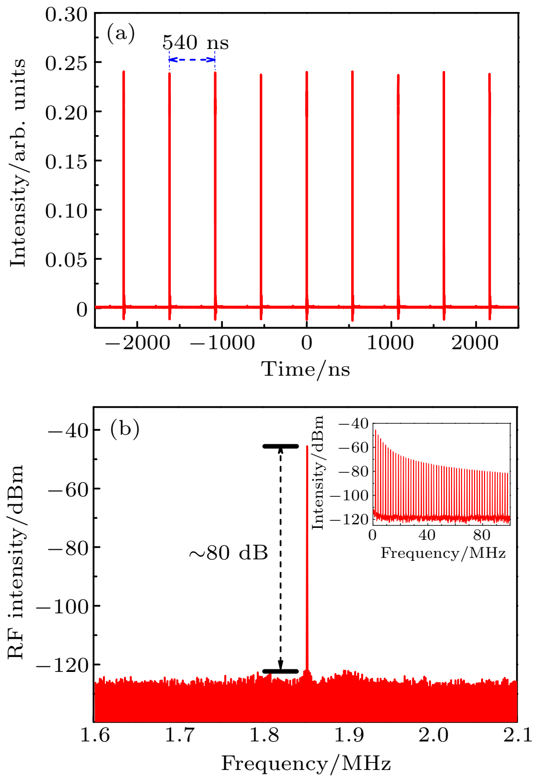

Fig. 2. (a) Typical oscilloscope pulse trace, and (b) RF spectrum at fundamental frequency, with inset showing broadband RF spectrum at 100-MHz span.

Character of self-start is investigated. Because of the dual-amplifier structure, only two cases for self-start are considered. In the case 1, LD2 is turned on while LD1 is turned off. With the increase of pump power, continuous wave emerges and mode-locking state cannot be obtained even under maximum pump power. This is a joint result of the usage of small-splitting-ratio fused coupler which can result in insufficient nonlinear phase shift accumulation of bidirectional propagation light and unpumped active fiber that gives rise to a larger cavity loss. The case 2 is opposite. Laser can self-start at pump power of 350 mW and stable mode-locking pulse is observed. NALM which could amplify counterclockwise propagation light first induces larger difference in nonlinear phase shift accumulation between bidirectional light beams. So NALM plays a key role from the point of self-start.

Because of the dual-amplifier structure, there are a lot of power combinations. Now we temporarily consider two circumstances to introduce the characters of laser. One circumstance is to set LD1 to have maximum output power, and to adjust LD2. Figure 3(a) shows the variation of pulse waveform with pump power of LD2. Unlike the reported experiment of Refs. [14,21] where the peak power and spectral width are kept constant and pulse duration varies regularly when changing pump power, our experiment has a pulse duration that keeps around 2.63 ns and has no obvious change when tuning power of LD2. The square-wave pulses keep stable without spittingc or shaking phenomenon in the whole tuning process. The output power rising from 62 mW to 78 mW and the single pulse energy increasing from 33 nJ to 42 nJ almost linearly vary with the increase of pump power applied to LD2. Peak power rises from 13 W to 16 W with the increase of pump power. Optical spectrum evolution process with the increase of pump power is illustrated in Fig. 3(b). The central wavelength is around 1567.5 nm and keeps stable. The 3-dB bandwidth of optical spectrum changes from 9.4 nm to 12.6 nm. Due to the enhancement of peak power, stronger self-phase modulation (SPM) effect can further broaden the optical spectrum.

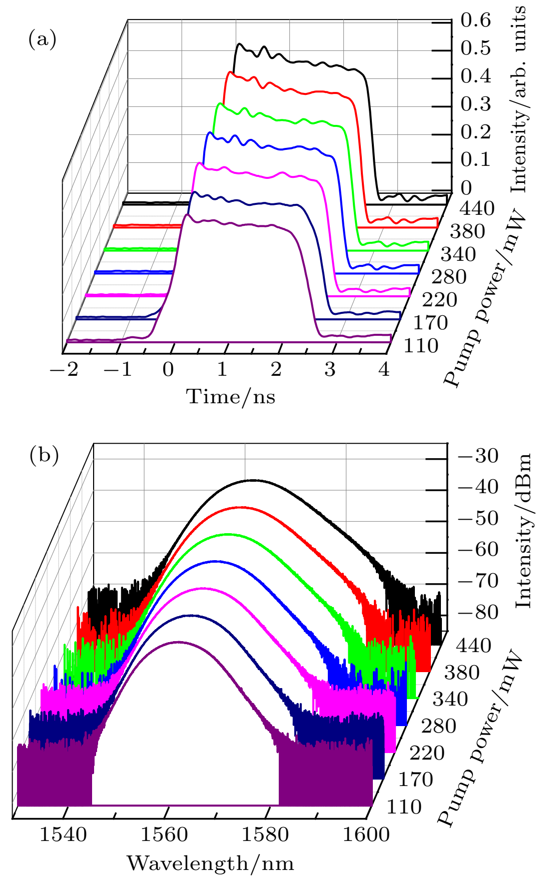

Fig. 3. Output character with power of LD2 increasing from 110 mW to 440 mW when power of LD1 is set to be maximum, (a) pulse shape *versus* power of LD2, and (b) spectral envelop *versus* power of LD2.

The other circumstance is set the output power of LD2 to be maximum, and adjust the power of LD1 from 140 mW to its maximum of 400 mW. Figure 4(a), pump-power-dependent pulse evolution map, exhibits that our regime is a typical DSR mode-locking. The duration of rectangular-shaped envelope changes from 800 ps to 2.63 ns proportionally with the increase of LD1 pump power. The output power increases linearly from 47 mW to 78 mW, and the single pulse energy rises also linearly from 25 nJ to 42 nJ. As shown in Fig. 4(b), the center wavelengths of the spectra are around 1567.5 nm throughout the whole pump power changing range. No deterioration or other nonlinear modulation occurs in the entire process. The 3-dB spectral width varies from 16.5 nm to 12.6 nm and peak power decreases from 26 W to 16 W continually with the increase of pump power. The narrowing of spectrum width results from the decreasing of peak power.

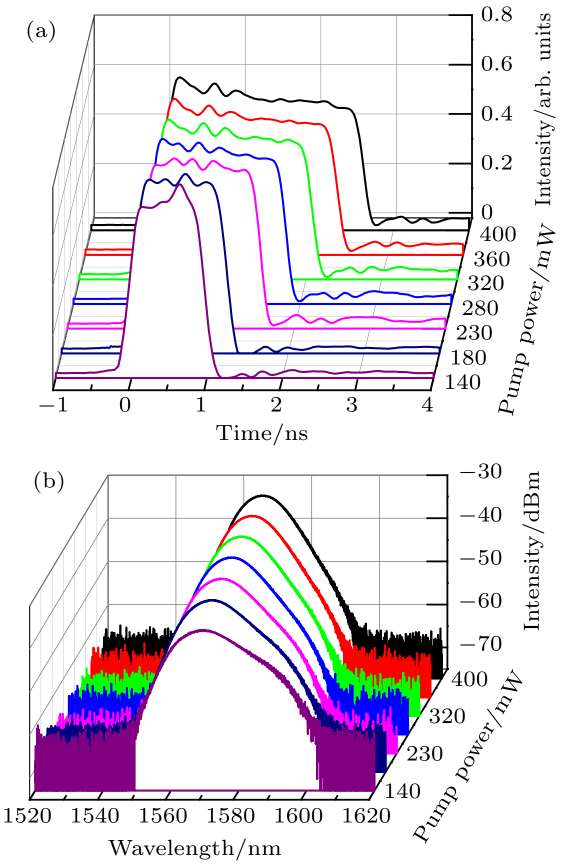

Fig. 4. (a) Pulse shape and (b) spectrum envelop with power of LD1 increasing from 140 mW to 400 mW when power of LD2 is set to be maximum.

In order to study the output characteristics in detail, the entire distribution map of output pulse width and peak power are depicted in Fig. 5. When the pump power of LD2 increases from 0 mW to 440 mW and LD1 is kept at a fixed power value, the output pulse duration keeps almost unchanged and peak power always goes up. This result is unusual viewing from the conventional peak power clamping phenomenon that leads the pulse duration to expand.[14] In Ref. [16], the peak power of the pulse was determined by the balance between the loss and the saturation of the two pumps in the cavity and hence the special appearance is probable. We think, this is the intrinsic character of dumbbell dual-amplifier structure in some specific cavity parameter. Although the dumbbell-shaped dual-amplifier structure possesses a reflective character of nonlinear loop mirror and is slightly different from the dual-amplifier figure-eight structure, the principle of mode-locking is also based on nonlinear interference effect.

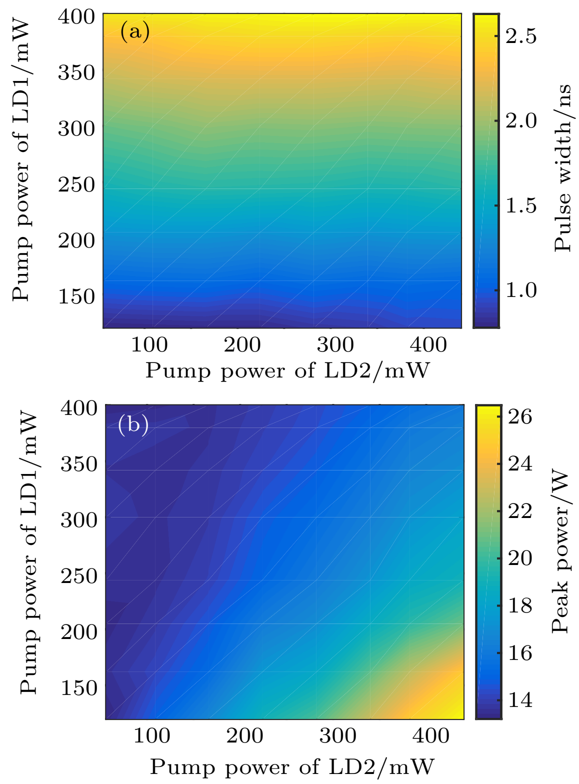

Fig. 5. Entire distribution map of (a) pulse width *versus* power of LD1 and LD2, and (b) peak power *versus* power of LD1 and LD2.

On the contrary, when fixing the pump power of LD2, the pulse duration can increase from 800 ps to 2.63 ns with tuning the LD1 from 130 mW to 400 mW. Unlike previous common result that pulse peak power is independent of pumping power and keeps constant, it is obvious that the pulse peak power always decreases with the power of LD1 rising. The highest peak power appears in the lower right corner of Fig. 5(b). Due to the increase of dual pump power having the opposite effects on the peak power, we firstly demonstrate that launching high pump power does not mean that high peak can be obtained. In order to obtain high peak power and high average output power, pump power of dual-amplifier structure needs to be designed and optimized. The change of power of LD2 almost directly determines the peak power tunable range. The pulse duration is directly determined by the pump power of LD1 and unrelated to the pump power of LD2. According to this phenomenon, both amplifiers are independent seemingly. However, both amplifiers could tune peak power. This is totally different from conventional single-amplifier structure that the peak power almost keeps constant. The peak power of the DSR pulse is limited by the saturation power of NALM, so the change of saturation power could induce tunable peak power.

The theoretical NALM transmissivity can be described by[4]

$$T = G_1 \cdot [1 - 2\alpha(1-\alpha)(1+\cos\delta\varphi)], \quad (1)$$

where

$$\delta\varphi = \gamma P_{\text{in}} L(\alpha G_1 + \alpha - 1), \quad (2)$$

$$P_{\text{in}} = G_2 P_{\text{out}}, \quad (3)$$

with G_1 being the amplification coefficient of EDF1, α the coupling ratio, and $\delta\varphi$ the difference in phase shift between the counter-propagating light beams, L, γ, and P_{in} the loop length of NALM, fiber nonlinear coefficient, and the peak power of the input beam, respectively, P_{in} being closely related to the peak power of reflected light beam of NALM (P_{out}), and G_2 being the amplification coefficient of EDF2 . From Eq. (1), we can clearly see that the NALM transmissivity is directly related to G_1 and G_2, and then the two amplifiers present strong intercoupling. The saturation power will change at different values of G_1 and G_2.[4,22,23] Due to the gain saturation of the amplifier, an incident pulse with lower peak power can be amplified more than that with a higher one. The change of power of LD2 will directly affect the peak power of incident pulse (P_{in}), which results in the change of G_1. On the other hand, the change of power of LD1 will induce the value of P_{out} to change, and then to influence the value of G_2. Hence, the saturation power can change with the two amplifiers, inducing adjustment of the pulse peak power. Due to the existence of close connection between two amplifiers, these peculiar phenomena can be observed. These conclusions can present the direct guideline for designing the tunable peak power DSR fiber laser. All the discussion above is qualitative analysis and only help understand the output character of laser to some extent. The detailed pulse dynamic evolution process needs to be strictly simulated by a combined numerical model of laser rate equation and Ginzburg–Landau equation.[24] In future, we will further study character of dual-amplifier structure in more detail.

4. Conclusions

In this work, we demonstrate a passively dumbbell-shaped dual-amplifier mode-locked Er-doped laser that works in a DSR state. The width and peak power of output pulse can be tuned by adjusting the pump power of two amplifiers. By analyzing entire distribution map, we can directly obtain some meaningful conclusions. Pulse duration is directly determined by power of LD1 but unrelated to the power of LD2. Dual-amplifiers have the opposite effects on the peak power while the change of power of LD2 almost directly determines the peak power tunable range, which means that launching high pump power does not mean that high peak can be obtained. This phenomenon is first observed. Because of close interaction between two amplifiers, these special phenomena can be observed. Output pulse width can change from 800 ps to 2.6 ns, and output peak power varies from 13 W to 27 W. The SNR can approach to 80 dB without seeing any unstable phenomenon.

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