Wavelength-Tunable Rectangular Pulses Generated from All-Fiber Mode-Locked Laser Based on Semiconductor Saturable Absorber Mirror *

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The wavelength-tunable rectangular mode-locking operation is demonstrated in an all-fiber laser based on semiconductor saturable absorber mirror. As the dissipative soliton resonance signature, the pulse duration varies from 580 ps to 2.1 ns as a function of the increasing pump power. Correspondingly, the maximum pulse energy is 9.11 nJ. Moreover, it is found that the wavelength tunable operation with a range of approximately 10 nm could be obtained by properly adjusting the polarization controllers. The characteristics of the rectangular pulses at different wavelengths are similar to each other. The demonstration of the wavelength tunable rectangular pulses would be beneficial to some applications for many fields such as spectroscopy and sensing research.

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During the past two decades, passively mode-locked Yb-doped fiber lasers (YDFLs) operating in an all-normal dispersion regime have attracted increasing attention in widespread applications in material processing and fiber sensing due to their compactness and low cost.[1–3] In this normal regime, dissipative solitons (DS)[4,5] have enlarged the pulse energy to several tens of nJ. However, as the pump power increases, the pulse energy is usually limited due to the wave breaking. To improve the pulse energy scaling ability, new pulse formation mechanisms and dynamics should be researched. Recently, a new soliton formation mechanism called dissipative soliton resonance (DSR) was theoretically proposed to achieve a pulse through selecting proper parameters in the frame of the complex Ginzburg–Landau equation.[6,7] It could be clearly seen that the pulse energy could increase and the pulse width could increase indefinitely with increasing the pump power under the DSR condition. The rectangular-pulse effect was observed experimentally in an Er-doped all-normal dispersion laser cavity for the first time.[8] Indeed, the rectangular pulse could be experimentally obtained despite dispersion regime and gain medium, even in all-normal dispersion YDFLs.[9–14] The DSR phenomenon was observed in an all-fiber passively mode-locked Yb-doped laser for the first time based on the nonlinear polarization rotation (NPR) technique.[9] By using the nonlinear optical loop mirror (NOLM) technique, Huang *et al.* reported the generation of square-pulse DSR with 2.06 W average power and pulse energy of 232 nJ.[14]

So far, the DSR phenomenon has been observed in operation of fiber ring lasers usually by using NPR[9] or the NOLM[13] mode-locking technique. It can be modeled by using the complex cubic–quintic Ginzburg–Landau equation (CGLE), which adds cubic and quintic saturable absorption terms. In the DSR region, the square-wave pulses could increase their width indefinitely while keeping their amplitude constant. It is worth noting that these square-wave pulses were reported to have no internal fine structures within the square profile packet, and therefore they maintain the pulse-to-pulse coherence. However, according to theoretical prediction of DSR phenomenon, the observation of DSR in mode-locked fiber lasers is independent of the mode locking technique. The real saturable absorbers (SESAM, graphene,[15] carbon nanotubes[16] and so on) generally permit a more reliable mode-locking operation compared with NPR and NOLM. Among them, the SESAM technology has many advantages compared with the other methods since it offers a self-starting pulse operation and good environmental stability. Nowadays, although the SESAM technology has been widely used to initiate and to support the DS operation in different fiber lasers, all-in-fiber DSR operation based on SESAM in all-normal dispersion regime are never found in literature. Furthermore, the all fiber wavelength tun-

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able operation of rectangular pulses has been rarely reported. In some applications, fiber lasers that generate tunable-wavelength pulses would be more favorable.

In this Letter, we experimentally demonstrate the wavelength tunable rectangular pulse generation in an all-fiber laser based on SESAM to for the first time. By properly rotating the polarization-controller (PC), we achieve the rectangular pulse varying from 580 ps to 2.1 ns with increasing the pump power. At a maximum pump power of 330 mW, the output pulse energy could be up to 9.11 nJ. In addition, wavelength tunable operation with a range of approximately 10 nm is observed. The intracavity birefringence caused by the loop mirror is responsible for the tunable operation. The demonstrated wavelength-tunable rectangular pulse YDFL possesses flexible pulse output, which might provide more possible applications for the related fields.

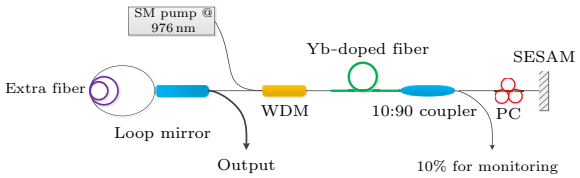

Fig. 1. Schematic setup of the SESAM mode-locked Yb-doped fiber laser. WDM: wavelength-division-multiplexer coupler; PC: polarization controller.

The laser setup of the SESAM-based passively mode-locked Yb-doped fiber laser is illustrated in Fig. 1. It has a linear cavity configuration made of pure normal-dispersion fibers. The 600 mW single-mode pigtailed laser diode emitting at 976 nm is coupled into the cavity through a 976/1030 nm fiber pigtailed multiplexer. A 1-m-long highly Yb-doped single-mode fiber with nominal core absorption of more than 250 dB/m at 976 nm is used as a gain medium. An approximately 100-m-long fiber is inserted into the fiber loop mirror which is formed by a 50:50 fiber coupler and serves as an output coupler. The output ratio is about 8%, since the output coupler is not strictly 50:50. An SESAM with 500 fs relaxation time and 38% modulation depth is used at the end of the laser cavity to permit stable mode-locked operation. To control the polarization state obtained inside the cavity, a PC is added on the active fiber. The fiber end at the output was angle-cleaved to avoid the back reflection into the laser cavity, which would prevent or extinguish stable mode-locked operation. Approximately 10% of the beam is extracted from the cavity through a fiber coupler for monitoring. The overall fiber length of the laser cavity is about 110 m.

The output laser is detected by an optical spectrum analyzer (Yokogawa AQ6370B) and a 600-MHz digital storage oscilloscope (DSO) together with a 1.25-GHz photo detector (PD). Moreover, the rf spectrum is measured by an rf-spectrum analyzer (Agilent). Fine structures of the pulse profile are measured with a commercial autocorrelator (APE).

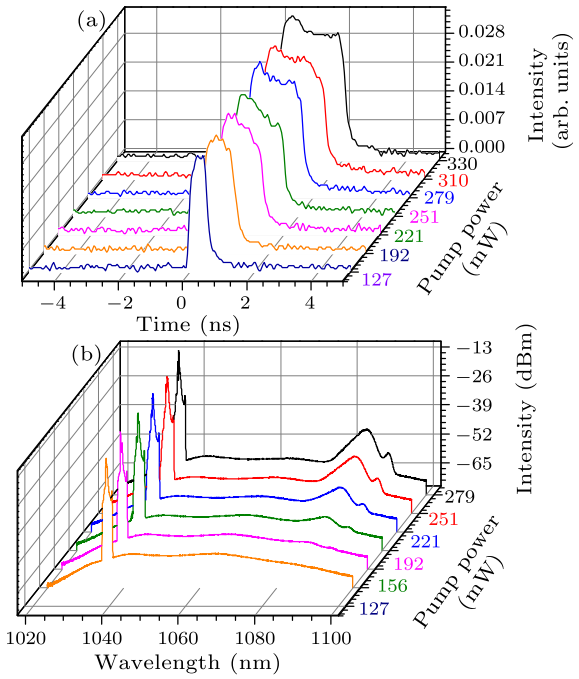

Fig. 2. (a) Evolution of pulse broadening as a function of the pump power, and (b) the corresponding spectra.

The stable rectangular pulses, in nanosecond timescale, were realized based on SESAM with proper adjustment of the PC. Although the self-starting mode-locking threshold is about 170 mW, the mode-locking state could also be observed when the pump power was decreased to 125 mW due to the pump hysteresis phenomenon. Figure 2(a) shows the dynamic of the pulse broadening as a function of the pump power. The pulse width varied obviously from 580 ps to 2.1 ns as the pump power was increased from 125 mW to 330 mW, and we believe that the pulse width could be broadened with higher pump. In addition, the pulse amplitude almost stayed at a constant level during the pulse broadening. Some ripples on the top of the pulses which can be observed are attributed to the Q-switched effect in the laser. These rectangular pulse characteristics mentioned above are fully in line with those in the DSR region. Figure 2(b) shows the evolution of the optical spectra at different pump powers. The central-wavelength shift is not so evident despite the increasing intensity, which is limited in ∼0.5 nm. We think that the difference of the spectra at different pump powers is mainly due to the change of comb filtering effect caused by the increasing pump power. The increasing pump power could lead to the variation of the gain-and-loss distribution, and finally can shift the central wavelength of the DSR operation to other wavelength.[6] Moreover, there is a spectral peak on the top of the mode-locking spectrum, indicating

that there could be the cw component.

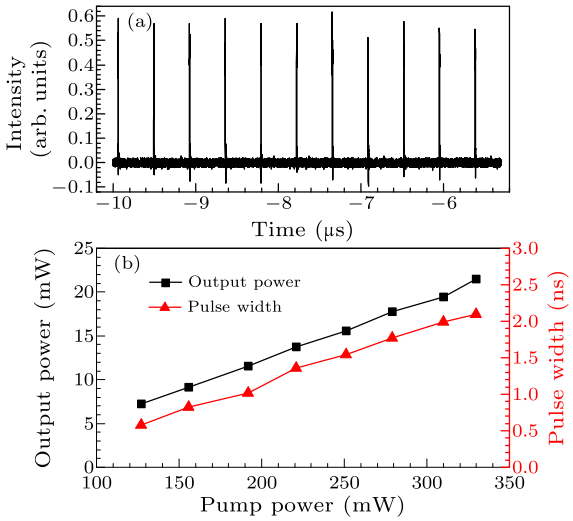

Fig. 3. (a) Pulse trains under the pump power of 160 mW, and (b) pulse width and output power versus pump power.

To investigate the pulse evolution in more detail, Fig. 3(a) presents the mode-locking pulse trains at the pump power of 160 mW. The generated train of pulses has a repetition rate of 2.36 MHz, corresponding to the length of the cavity. Due to the insufficient oscilloscope bandwidth, the acquired pulse sequence is unstable. We have further shown the measured pulse width and the average output power versus the pump power in Fig. 3(b). The output power of 21.5 mW is reached when the maximum pump power is up to 330 mW. The pulse width increases linearly to 2.1 ns at the pump power. Correspondingly, the maximum output pulse energy is 9.11 nJ and the peak power of the rectangular pulses is about 4.33 W.

It should be noted that no pulse signal could be detected with the autocorrelator, due to the fact that the nanosecond duration of the rectangular pulse is beyond the maximum measurement range of the autocorrelator, which indicates that the rectangular pulse is not the multi-soliton. It should be noted that no pulse bunching was observed with increasing the pump power, showing that the broadening pulse is single-pulse operation. Moreover, unlike the noise-like DSR operation, the pulse energy is accumulated to a large value without pulse breaking as increasing the pump power. Thus this pulse operation is attributed to be DSR region.

The rf spectrum shown in Fig. 4 has also been measured. The signal-to-noise ratio is nearly 60 dB, indicating good mode-locking stability. Furthermore, to demonstrate the environmental robustness of the fiber laser, the relevant average output power was measured as shown in Fig. 5. The fiber laser can keep working for more than 4 h without losing mode-locking state. As is shown, the output power is vulnerable to environmental effects, while the power fluctuation of the laser is less than 3%, thus the laser is robust and reliable. The periodic jitter of the output power is attributed to the temperature drift of the controlling circuit board.

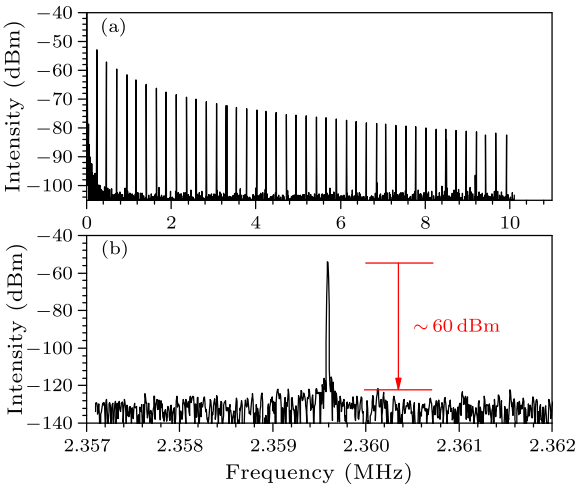

Fig. 4. The rf spectrum of the mode-locked square-wave pulses.

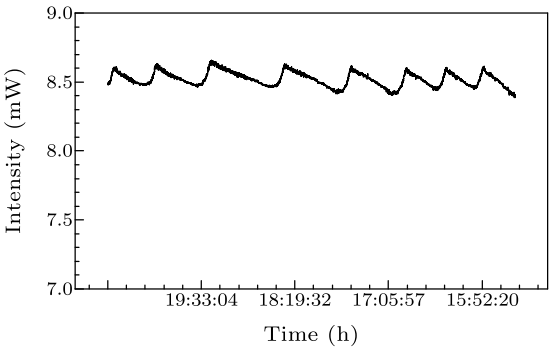

Fig. 5. Long-term output power stability from the fiber laser.

As we know, different polarization-dependent losses could be generated by adjusting the PC. The combination of the intracavity birefringence caused by the loop mirror and the polarization-dependent loss which could induce the comb filtering effect would be used to achieve wavelength-tunable operation.

Keeping the pump power fixed when the pump power exceeds the mode-locking threshold, the lasing wavelength of the DSR operation could be continuously tuned just by adjusting the PC. Figure 6(a) presents the tunability of the central wavelength of the DSR operation at the pump power of 279 mW. The central wavelength of the pulses could be tuned from 1027.8 nm to 1037.8 nm, giving the system a range of approximately 10 nm. It could be seen that the overall shape of the spectra at the DSR operation remains almost unchanged although the central wavelength is tuned and the Raman laser output is emitted at 1075 nm. When the PC is adjusted, the loss of different wavelengths would be changed due to the wavelength dependent loss mechanism. Thus the

wavelengths of the transmission peaks will be flexibly tuned. In contrast, when the wavelength of the optical spectrum is tuned beyond the range of 1027.8–1037.8 nm, we would no longer be able to observe the mode-locking pulses. It should be noted that the cw component centered at about 1040 nm would appear when the wavelength of the DSR operation is tuned towards to 1027.8 nm. We think that the reason for this case is the maximum reflectivity of SESAM used that is located at 1040 nm.

The laser pulse duration corresponding to different DSR operating wavelengths is shown in Fig. 6(b). The pulse duration varies from 1.70 ns to 1.93 ns, and this situation is due to the different loss in the laser cavity caused by the adjustment of PC. No significant changes of the output power and pulse width at different output wavelengths have been observed. In each mode-locking channel, the pulse width could broaden linearly as the pump power is increasing. To observe the stability of the laser at different wavelengths, the output power is monitored for some time, respectively. The output power curves are the same as shown in Fig. 5.

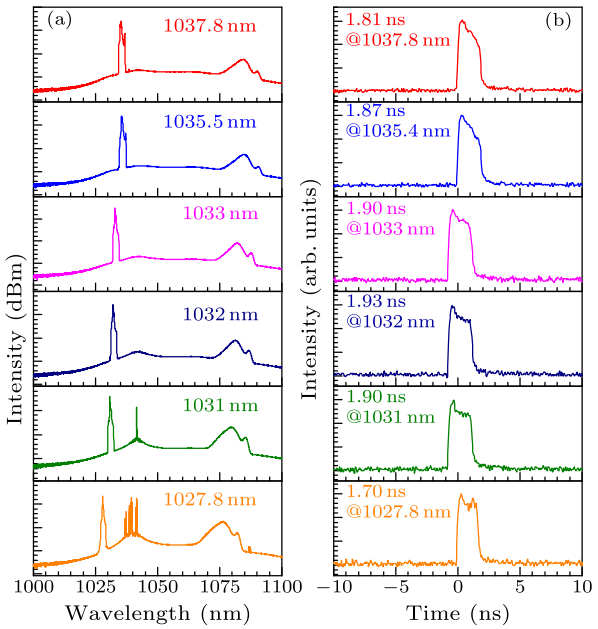

Fig. 6. (a) The tunability of the DSR operation at the pump power of 279 mW. (b) The corresponding rectangular ns pulse.

In this experiment, with the adjustment of PC, many factors such as the cavity loss and spectral filtering effect could be changed. Thus the wavelength-tunable DSR operation could be obtained. Higher energies may be increased by optimizing the laser in a number of ways such as employing a higher power of pump source. The DSR operation based on SESAM provides new potential in the field of high-energy pulse fiber lasers.

In conclusion, the wavelength-tunable DSR phenomenon in a YDFL based on SESAM has been investigated for the first time. The rectangular pulse duration broadens from 580 ps to 2.1 ns as a function of the pump power. The maximum pulse energy of 9.11 nJ is achieved at the pump power of 330 mW. The rectangular pulse repetition is about 2.36 MHz. By properly adjusting PC, a 10 nm wavelength tuning range covering 1027.8 nm to 1037.8 nm has been observed. Such a wavelength tunable fiber laser with flexible rectangular pulse outputs at 1.0 μm would be beneficial to some applications in many related areas.

References

[1] Wise F W, Chong A and Renninger W H 2008 *Laser Photon. Rev.* **2** 58
[2] Ortaç B, Schmidt O, Schreiber T, Limpert J, Tünnermann A and Hideur A 2007 *Opt. Express* **15** 10725
[3] Nishizawa N, Chen Y, Hsiung P, Ippen E P and Fujimoto J G 2004 *Opt. Lett.* **29** 2846
[4] Chong A, Renninger W H and Wise W 2007 *Opt. Lett.* **32** 2408
[5] Renninger W H, Chong A and Wise F W 2008 *Phys. Rev.* A **77** 023814
[6] Chang W, Soto-Crespo J M, Ankiewicz A and Akhmediev N 2009 *Phys. Rev.* A **79** 033840
[7] Chang W, Ankiewicz A, Soto-Crespo J M and Akhmediev N 2008 *Phys. Rev.* A **78** 023830
[8] Wu X, Tang D Y, Zhang H and Zhao L M 2009 *Opt. Express* **17** 5580
[9] Liu L, Liao J H, Ning Q Y, Yu W, Luo A P, Xu S H, Luo Z C, Yang Z M and Xu W C 2013 *Opt. Express* **21** 27087
[10] Zhao N, Liu M, Liu H, Zheng X W, Ning Q Y, Luo A P, Luo Z C and Xu W C 2014 *Opt. Express* **22** 10906
[11] Ding E, Grelu P and Kutz J N 2011 *Opt. Lett.* **36** 1146
[12] Li X, Zhang S, Zhang H, Han M, Wen F and Yang Z 2014 *IEEE Photon. Technol. Lett.* **26** 1041
[13] Mei L, Chen G, Xu L, Zhang X, Gu C, Sun B and Wang A 2014 *Opt. Lett.* **39** 3235
[14] Huang Y Z, Luo Z Q, Xiong F F, Li Y Y, Zhong M, Cai Z P, Xu H Y and Fu H Y 2015 *Opt. Lett.* **40** 1097
[15] Ortaç B, Plötner M, Limpert J and Tünnermann A 2007 *Opt. Express* **15** 16794
[16] Tian X L, Tang M, Shum P P, Gong Y D, Lin C L, Fu S N and Zhang T S 2009 *Opt. Lett.* **34** 1432