# Generation of high-energy dual-wavelength domain wall pulse with low repetition rate in an HNLF-based fiber ring laser*

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The generation of high-energy dual-wavelength domain wall pulse with a low repetition rate is demonstrated in a highly nonlinear fiber (HNLF)-based fiber ring laser. By introducing the intracavity birefringence-induced spectral filtering effect, the dual-wavelength lasing operation can be achieved. In order to enhance the cross coupling effect between the two lasing beams for domain wall pulse formation, a 215-m HNLF is incorporated into the laser cavity. Experimentally, it is found that the dual-wavelength domain wall pulse with a repetition rate of 77.67 kHz could be efficiently obtained through simply rotating the polarization controller (PC). At a maximum pump power of 322 mW, the 655-nJ single pulse energy in cavity is obtained. The proposed configuration provides a simpler and more efficient way to generate high energy pulse with a low repetition rate.

**Keywords:** fiber lasers, high-energy pulse, domain wall, low repetition rate

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## 1. Introduction

In recent decades, high-energy pulses are increasingly required for various applications such as micromachining, ophthalmic surgery, remote sensing, and light detection.[1–5] Many efforts have been made to generate high-energy pulses. The Q-switching is one of the successful methods.[6,7] Another way to increase per-pulse energy is to lower the repetition rate of mode-locked lasers by using a modulator as a pulse picker.[8] However, reduction of the repetition rate in this way introduces significant energy loss and a complex configuration. By shifting the laser mode-locked operation from anomalous to the normal dispersion regime or generating similaritons in lasers, the pulse energy can also be greatly enhanced.[9–13] Nevertheless, the oscillation of multiple pulses may occur with the increasing of intracavity pulse energy. Recently, increasing the cavity length has become a popular way to achieve higher per-pulse energy in fiber lasers with semiconductor saturable absorber mirrors (SESAM) or nonlinear polarization rotation (NPR) techniques.[14–16] With this method, the pulse repetition rate is efficiently reduced so that the energy is correspondingly enhanced. However, the investigation mainly focused on the Yb-doped fiber lasers with normal dispersion, because in the anomalous dispersion regime the multiple pulses are easily generated due to the over accumulated nonlinear effect. Therefore, it is more difficult to obtain low repetition rate pulses in Er-doped fiber lasers operating in an anomalous dispersion regime. Very recently, Li *et al.*[17] reported on a long-cavity passively mode-locked fiber laser with the NPR technique in the anomalous dispersion regime and obtained stable mode-locked pulses at a repetition rate of 278 kHz with single pulse energy 715 nJ in the cavity. Dong *et al.*[18] also obtained 198-nJ single pulse energy with a 85.8-kHz repetition rate at 250-mW pump power by the NPR technique. However, in order to achieve the mode-locked operation in an anomalous dispersion fiber laser with the NPR technique, the cavity parameters such as pump power and polarization controller (PC) should be carefully adjusted, which could lead to the less effective generation of the low repetition rate pulses.

On the other hand, the domain-wall theory was recently introduced into the fiber laser to obtain dark or bright pulse. The so-called polarization domain wall solitons, which were first put forward by Haelterman and Sheppard[19] in optical fibers, have been successfully observed in fiber lasers.[20] It was also found that a stable localized structure separating domains could be generated as a result of the cross coupling between two optical waves at different wavelengths with the same polarization.[21] Zhang *et al.*[22] reported on a dark soli-

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ton fiber laser based on the dual-wavelength domain wall theory. It was shown that when the fiber laser operates in the dual-wavelength regime, if the cross-coupling between the two lasing beams occurs, the domain-wall dark (or bright) pulse can be efficiently generated in fiber lasers operating in either normal- or anomalous-dispersion regimes. In our previous experiments, we have found that the highly nonlinear fiber (HNLF) was favorable for generating stable domain walls.[23] Considering the important applications of high energy pulses with a low repetition rate, it would be important to know whether the dual-wavelength high-energy domain wall pulses with a low repetition rate could be obtained in a fiber laser.

In this work, we report on a low repetition rate fiber laser with high-energy dual-wavelength domain wall pulse output. The laser delivers a single pulse energy of 655 nJ in the cavity at a repetition rate of 77.67 kHz under a pump power of 322 mW. Compared with the high energy pulse generation through the passive mode-locking technique, this method relaxes the requirements for cavity parameters and could more easily achieve a high energy pulse with a low repetition rate.

## 2. Experimental setup and operation principle

The experimental setup of the proposed high-energy dual-wavelength domain wall pulse fiber laser is schematically shown in Fig. 1. Here, a 4-m long erbium-doped fiber with a dispersion parameter of $-15$-ps/(nm·km) is used as a gain medium. A polarization-dependent isolator (PD-ISO) is employed to force unidirectional operation of the cavity. To enhance the output power, the laser is pumped by two 980-nm laser diodes through two 980 nm/1550 nm wavelength-division multiplexers (WDM). A polarization controller (PC) is employed to adjust the polarization states of the circulating light. For extending the cavity length, we insert a 2.37-km long single mode fiber (SMF) with a dispersion parameter of 17-ps/(nm·km). In order to enhance the nonlinear effect in the laser cavity, a 215-m long HNLF (NL1016-B, YOFC) with a dispersion parameter of $0.0 \pm 1$ ps/(nm·km) is introduced in this experiment. The nonlinear coefficient of HNLF is about 10 $(\mathrm{W \cdot km})^{-1}$. Thus, the cavity dispersion is anomalous in our laser. The laser output is taken by a 10% fiber coupler. An optical spectrum analyzer (OSA) and an oscilloscope with a photodetector are used to investigate the laser spectrum and the output pulse train, respectively.

It can be seen from Fig. 1 that our fiber laser is a typical setup based on the NPR technique. It is known that a spectral filtering effect could exist in the NPR-based ring cavity.[24] So we can use the spectral filtering effect to achieve multi-wavelength lasing output. In our experiment, by appropriately adjusting the PC state, we can achieve dual-wavelength operation. With a 215-m HNLF, the nonlinear effect is largely enhanced to make it favorable for the cross coupling between the two lasing beams, which is beneficial to the formation of stable domain walls. In addition, a 2.37-km long SMF is inserted into the laser cavity to lower the laser repetition rate. Therefore, by carefully tuning the interval between the rectangular-shape pulses of two domain walls, one could achieve the low repetition rate, high-energy dual-wavelength domain wall pulses in the proposed fiber laser.

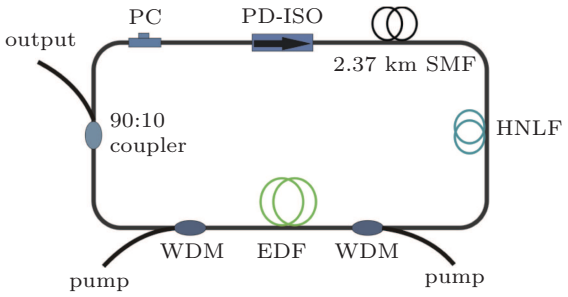



**Fig. 1.** (color online) Schematic plot of the proposed fiber ring laser.

## 3. Results and discussion

In the experiment, the CW lasing operation is achieved when the pump power is increased to about 30 mW. By appropriately adjusting PC and pump power, we found that it is easy to achieve domain-wall-liked pulses with dual-wavelength output, which indicates that the generated pulses are dual-wavelength domain wall pulses.[22] We deem that it is due to the HNLF that could greatly enhance the nonlinear effect, which is favorable for the cross coupling between the two lasing beams. The long SMF is incorporated to reduce the repetition rate, making it possible to achieve high-energy domain wall pulses. Therefore, the PC is firstly adjusted to achieve the dual-wavelength pulse operation with a threshold of about 60 mW. In order to obtain a better laser performance, the pump power is then further increased to about 180 mW.

Figure 2(a) displays the spectrum of dual-wavelength operation by adjusting the PC. It exhibits two spectral humps centered at 1529.9 nm and 1536.2 nm. The wavelength separation of the dual-wavelength is about 6.3 nm, which is due to the intracavity birefringence.[24] Note that the spectral bandwidths of the two wavelengths are different from each other in Fig. 2(a). However, the spectrum of dual-wavelength operation could be improved by properly adjusting the PCs. Figure 2(b) shows the corresponding pulse profiles with a fundamental repetition rate of 77.67 kHz. In the experiment, the dual-wavelength domain wall pulses centered at different wavelengths could also be achieved. However, the output pulse is not so stable as that in the case of Fig. 2. To better observe the pulse characteristics, figure 3 further shows the experimentally measured average output power versus the pump power. With the increasing of pump power, the average output power also rises. At a maximum pump power of

322 mW, the output power is up to 6.375 mW. Considering that the pulse train is not background free, the pulse energy that we calculated is 73 nJ. Thus, taking into account the output coupling ratio, the single pulse energy circulating in the laser cavity is up to 655 nJ. In the experimental observation, no pulse splitting is observed under the available pump power level, indicating that the pulse without wave breaking can be further increased if higher pump power is employed.[25,26]

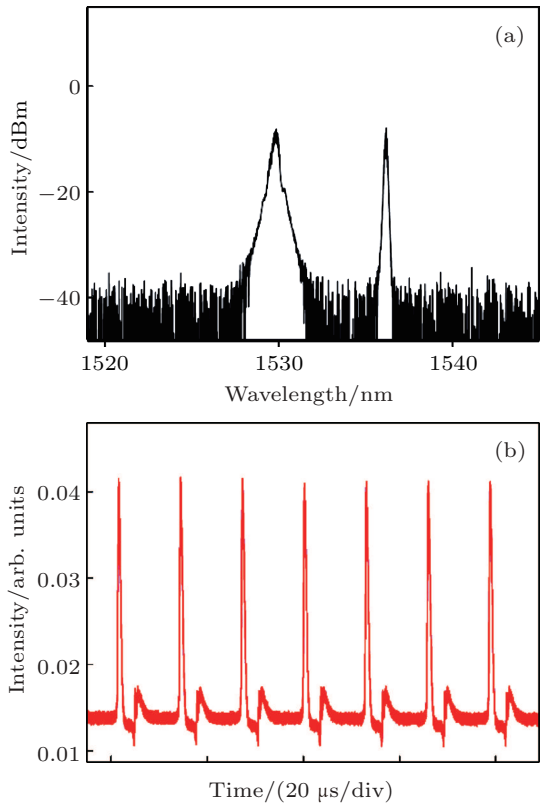



**Fig. 2.** (color online) (a) Typical spectrum of dual-wavelength operation; (b) corresponding output pulses train.

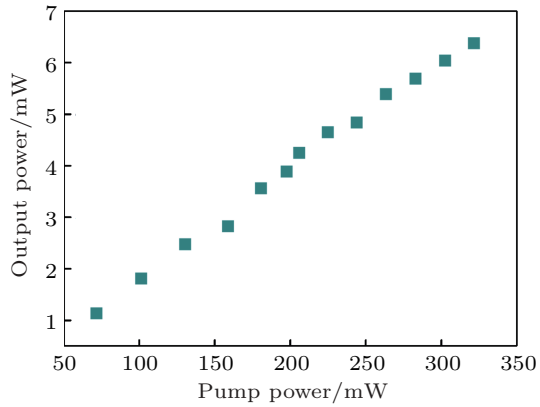



**Fig. 3.** (color online) Experimentally measured average output power versus pump power.

In order to confirm that the pulses observed in our experiment are the dual-wavelength domain wall pulses, we measure the two lasing wavelengths separately by a 0.9-nm bandwidth filter with a tuning range between 1515 nm and 1585 nm. Figure 4 displays the results of the wavelength resolved measurements under a pump power of 180 mW. Figures 5(a) and 5(b) show the corresponding pulse trains at each lasing wavelength. It should be noted that there is a peak appearing on the pulse-train at a wavelength of 1529.9 nm, which could be caused by the imperfect filter used in our experiment. Here, the average output powers are 1.1 mW at wavelength 1529.9 nm and 0.5 mW at wavelength 1536.2 nm. Being different from the multiwavelength passively mode-locked fiber lasers,[27–30] what we can see from Fig. 5 is that the pulses at two wavelengths are both rectangular shapes, which matches well with the results reported in Ref. [22]. Therefore, we believe that the observed pulses are dual-wavelength domain wall pulses. The total output is the combination of the optical waves of two domain walls. In addition, the interval of two domain walls can be adjusted by simply tuning the linear cavity phase delay. Thus, by appropriately adjusting the PC, it may result in the achievement of a bright pulse with a low repetition rate rather than the dark one in our experiment. In the experiment, in order to verify the influence of HNLF on the domain wall pulse formation, the HNLF is removed from the ring cavity. In this case, even if the PCs are rotated and the pump power is adjusted, the stable domain wall pulse could not be observed. The comparative results demonstrate that the generation of a stable domain wall pulse in the proposed fiber laser is indeed induced by the HNLF.

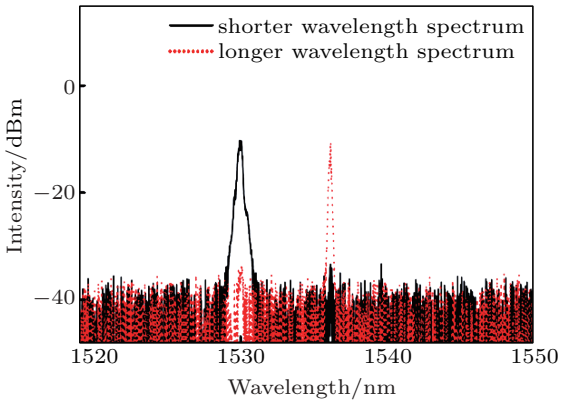



**Fig. 4.** (color online) Wavelength resolved measurement.

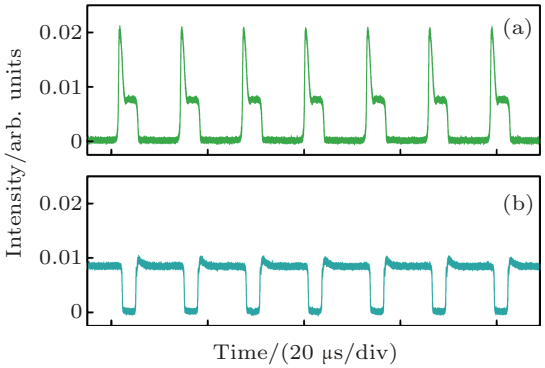



**Fig. 5.** (color online) (a) Pulse-train at a wavelength of 1529.9 nm, (b) pulse-train at 1536.2 nm.

## 4. Conclusion

In this paper, we experimentally observed the dual-wavelength high-energy domain wall pulses with a low repetition rate in an HNLF-based fiber ring laser. We used the intra-cavity birefringence-induced spectral filtering effect to achieve the dual-wavelength operation. In order to enhance the nonlinear effect of the cross coupling between the two lasing beams, a 215-m HNLF is incorporated into the laser cavity. A 2.37-km long SMF is used to reduce the repetition rate. With the proper adjustment of the PC, the dual-wavelength high-energy domain wall pulses could be efficiently obtained with 655-nJ energy inside the laser cavity and 73-nJ output energy under a pump power of 322 mW. The proposed fiber laser possesses advantages such as simple and efficient implementation to generate high-energy pulses with a low repetition rate.

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