Observation of stable bound soliton with dual-wavelength in a passively mode-locked Er-doped fiber laser*

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A phase-locked bound state soliton with dual-wavelength is observed experimentally in a passively mode-locked Er-doped fiber (EDF) laser with a fiber loop mirror (FLM). The pulse duration of the soliton is 15 ps and the peak-to-peak separation is 125 ps. The repetition rate of the pulse sequence is 3.47 MHz. The output power is 11.8 mW at the pump power of 128 mW, corresponding to the pulse energy of 1.52 nJ. The FLM with a polarization controller can produce a comb spectrum, which acts as a filter. By adjusting the polarization controller or varying the pump power, the central wavelength of the comb spectrum can be tuned. When it combines with the reflective spectrum of the fiber Bragg grating, the total spectrum of the cavity can be cleaved into two parts, then the bound state soliton with dual-wavelength at 1549.7 nm and 1550.4 nm is obtained.

Keywords: mode-locking, Sagnac interference, dual-wavelength soliton, bound state

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1. Introduction

Different passively mode locking methods have been explored to generate ultra-short pulses, such as nonlinear polarization rotation technique,[1] semiconductor saturable absorber mirrors,[2,3] single-wall carbon nanotubes,[4] grapheme,[5] and nonlinear optical loop mirrors (NOLMs),[6–8] which act as the saturable absorber. He *et al.* presented a laser-diode-pumped passively mode-locked femtosecond disordered crystal laser by using Nd: $CaGdAlO_4$ (Nd:CGA) as the gain medium.[9] A passively mode-locked erbium-doped fiber laser based on a D-shape-fiber using a MoS_2 saturable absorber with a very low non-saturable loss was reported.[10]

In recent years, dual-wavelength and multi-wavelength fiber lasers have attracted much interest due to their potential applications in wavelength division multiplexing systems, optical sensing, spectroscopy, microwave generation, optical component testing, and terahertz generation.[11–13] The observation of dual-wavelength soliton and bound state soliton in a passive mode-locked fiber laser was reported.[14] Pottiez *et al.* studied numerically an EDF figure-of-eight fiber laser including a double-band-pass optical filter for dual-wavelength pulse lasing.[15] A tunable narrow-line-width multi-wavelength Er-doped fiber (EDF) laser based on a high birefringence fiber loop mirror and an auto-tracking filter was obtained,[16] in which a fiber loop mirror and a polarization controller acted as a filter for the dual-wavelength output. The dual-wavelength square pulse was generated in a figure-of-eight EDF laser with ultra-large net-anomalous dispersion,[17] in which a 2.7-km single mode fiber (SMF) with small birefringence supported the Sagnac interference filter to manage the dual-wavelength lasing. The tunable dual-wavelength passively mode-locked thulium-doped fiber laser using carbon nanotubes was reported.[18] Wang *et al.* obtained mode-locked dual-wavelength output directly from an Er-fiber laser oscillator using the dual-branch NPR technique.[19] Jiang *et al.* demonstrated the switchable dual-wavelength mode locking of thulium-doped fiber laser based on SWNTs.[20] Liu *et al.* reported a passively *Q*-switched Yb:LSO laser based on a tungsten disulphide (WS_2) saturable absorber operating at 1034 nm and 1056 nm simultaneously.[21]

Bound state solitons in nonlinear optical fiber systems have been reported theoretically and experimentally.[22–25] One possible reason for the formation of the bound-state pulses is the direct interaction between the pulses.[26,27] Usually such a bound state soliton consists of two pulses and is characterized by the peak-to-peak separation and the phase difference between the two pulses.[25,28] Grelu *et al.* have experimentally obtained the bound state of the soliton in a fiber laser.[29] The bound state of single-pulse soliton in a figure-of-eight fiber laser has been observed.[30] The generation of a high-power bound state of three pulses and the self-similar bound state pulses propagation in ytterbium-doped double-clad fiber lasers was presented by Ortac *et al.*[31] Bound-soliton pairs and trains could be emitted from Er-doped fiber ring lasers.[32] Haboucha *et al.* have experimentally observed the bound state of 350 pulses in an Er/Yb-doped double-clad

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fiber laser[33] and investigated the quantization of the bound soliton.[34] The bound state of the soliton in an L-band passively mode-locking ring fiber laser has been achieved.[35] There are many works on the dual-wavelength or bound-state soliton, but there are not many cases in which both phenomena coexist.[14]

In this paper, a stable bound state soliton of dual-wavelength is obtained in a passively mode-locked Er-doped fiber laser. The fiber loop mirror (FLM) in the cavity consists of a 50-m-long SMF and a comb filter based on a Sagnac interference. By adjusting the polarization controller or varying the pump power, the central wavelength of the comb spectrum can be tuned. The total spectrum of the cavity can be cleaved into two parts, and the bound state soliton with dual-wavelength at 1549.7 nm and 1550.4 nm is obtained.

2. The principle of dual-wavelength generation

The experimental setup of the mode-locked EDF laser is shown in Fig. 1. The total cavity length is about 57 m. A 50 cm long erbium-doped fiber with absorption loss of 61 dB/m at 1550 nm is used as the gain medium. The EDF is pumped by a 976 nm laser diode (LD) through a 976/1550 nm wavelength-division multiplexer (WDM). The linear cavity is simply constructed by a fiber Bragg grating (FBG) with high reflectivity of >99% at 1550 nm, a fiber loop mirror (FLM) and a 50-m-long SMF. The FLM consists of a 2×2 optical coupler (OC), whose coupling ratio is 9.05/90.95. The SMF is used to enhance the nonlinear effects. The polarization controller (PC) is used to optimize the mode-locking operation. As we all know, the reflectivity R of the NOLM can be calculated by

$$R = 4\alpha(1-\alpha),$$

where α is the power-coupling ratio of the OC. When there is no nonlinear effect, the NOLM acts as a normal FLM. Therefore, the 9.05/90.95 FLM has a reflectivity of 33%. The FLM is used as an output mirror for extracting 67% laser signal. When there is nonlinear effect, it is employed as a nonlinear optical loop mirror device to achieve passively mode-locking in the fiber laser.

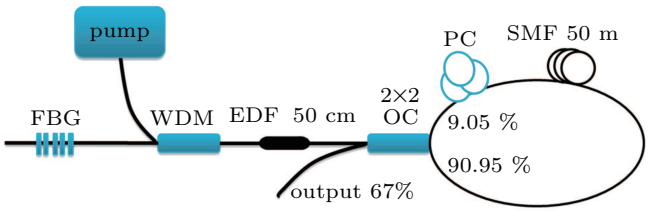


Fig. 1. (color online) Schematic of the mode-locked Er-doped fiber laser.

The Er-doped fiber is a kind of uniform gain medium that will lead to strong mode competition and unstable lasing. It is the biggest challenge to achieve multi-wavelength output in an EDF laser at room temperature. The mode competition can be solved using a comb filter in the cavity. The Sagnac fiber loop mirror, which is composed of a fiber coupler, a birefringence fiber (BF), and a polarization controller, may just act as the comb filter in the system. To interpret the principle of the comb filter more clearly, we present the structure of the Sagnac fiber loop mirror in Fig. 2.

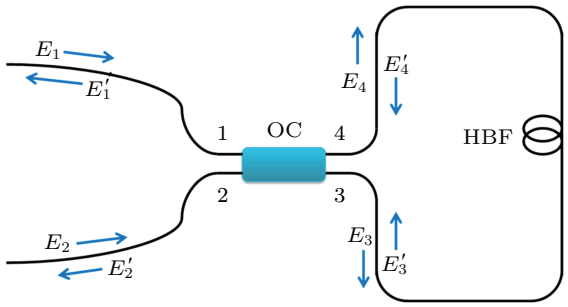


Fig. 2. (color online) Structure diagram of the Sagnac fiber loop mirror.

In Fig. 2, the input light that enters from port 1 through the OC is divided into two beams. The two beams output from port 3 and port 4 transmit in the opposite directions and interfere in the central coupler when they come back from port 4 and port 3 after transmitting along the fiber ring. They go back from port 1 and port 2. The spectrum transmittance of the Sagnac fiber loop mirror is written as

$$T = \sin^2\varphi\left[1-\frac{1}{2}(1+\cos\Delta\varphi)\right]. \tag{1}$$

Due to the birefringence effect of the birefringence fiber, a phase difference $\Delta\varphi$ is generated between the fast axis and the slow axis of the birefringence fiber

$$\Delta\varphi = \frac{2\pi(n_0-n_e)L}{\lambda} = \frac{2\pi\Delta nL}{\lambda}. \tag{2}$$

Here φ is the deflection angle of the optical field obtained by adjusting the PC. According to formulas (1) and (2), we know that the transmittance of the fiber ring loop mirror is a periodic function of the wavelength and therefore the Sagnac fiber loop mirror can be used as a comb filter. By adjusting the PC, the contrast of the comb filter can be changed; when $\varphi=\pi/2$, the comb filter has the highest contrast. The wavelength interval $\Delta\lambda = \lambda^2/(\Delta nL)$ of the comb spectrum is independent of the adjustment of the PC.

Figure 3 shows the comb spectrum of the Sagnac ring loop mirror with the maximum contrast when we take $\Delta n = 6\times10^{-5}$ and $L=50$ m. As shown in Fig. 3, the Sagnac fiber loop mirror can be used as a comb filter, whose spectrum is uniform, high contrast and the peak transmittance is consistent.

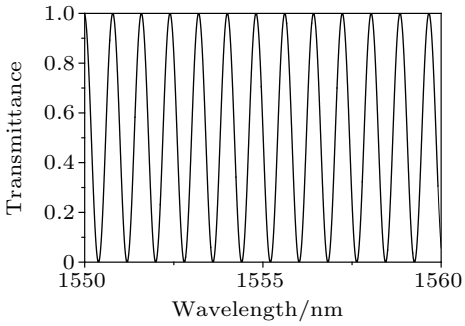


Fig. 3. Transmittance of the Sagnac fiber loop mirror.

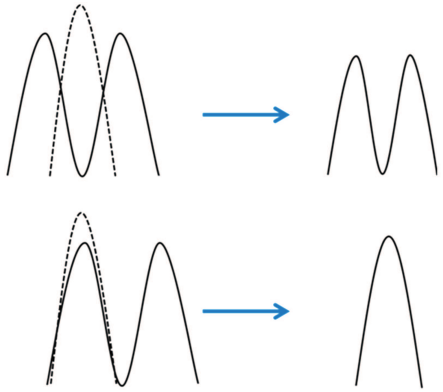


Fig. 4. (color online) Illustration of the convolution filter.

The slight residual polarization asymmetry of the SMF could cause the formation of a linear artificial birefringence filter in the cavity. The birefringence determines the wavelength interval between the transmission max of the birefringence filter, $\Delta\lambda = \lambda^2/(\Delta nL)$, where λ is the central wavelength, Δn is the strength of birefringence and L is the cavity length. The weaker the cavity birefringence is, the larger the interval is.

A convolution filter is formed when both the FBG and the comb filter are inserted into the EDF laser. The comb filter consists of FLM and PC. An illustration of the convolution filter is presented in Fig. 4. The solid line on the left-hand side of Fig. 4 shows the comb spectrum of the comb filter, while the dotted line shows the reflection spectrum of the FBG. The right-hand side of Fig. 4 shows the result of convolution filtering of the total spectrum in the cavity. By adjusting the PC or changing the pump power, a stable dual-wavelength or switchable single wavelength can be obtained.

3. Experimental results

The mode-locking threshold of the erbium-doped passively mode-locked laser is about 100 mW. We obtain a mode-locked bound soliton at the pump power of 128 mW. The output power is 11.8 mW with the pump power of 128 mW. Figure 5 shows the characteristics of the bound state soliton in the mode-locked fiber laser. We believe that the formation of the bound state soliton can be achieved by the balance between the soliton direct interaction and the attraction introduced by the phase modulation and the negative GVD of the cavity. The optical spectrum of the bound soliton is shown in Fig. 5(a). The spectrometer resolution is 0.02 nm, and the modulation period of the spectrum is about 0.07 nm, which corresponds

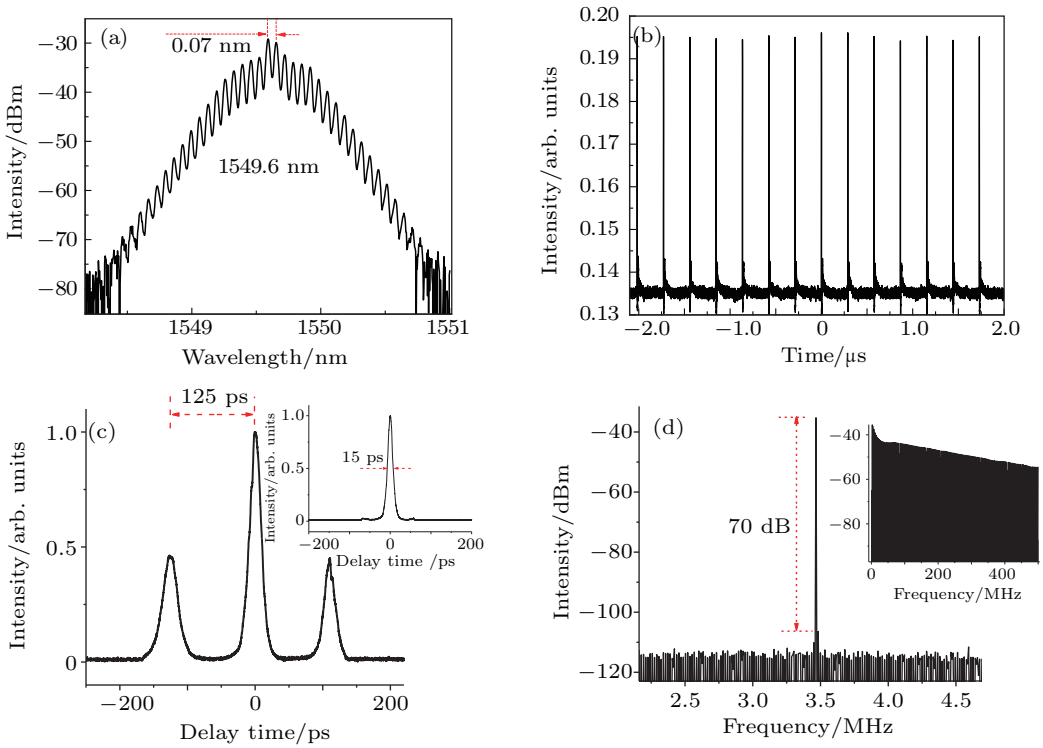


Fig. 5. (color online) The characteristics of the bound state soliton in mode-locked fiber laser: (a) spectrum, (b) pulse train, (c) autocorrelation trace, (d) RF spectrum.

to a soliton separation of 125 ps ($\Delta\nu = -c\Delta\lambda/\lambda^2$, where c is the light speed, λ is the operation wavelength, $\Delta\nu$ and $\Delta\lambda$ are the frequency interval and the spectral interval). Figure 5(b) shows the corresponding oscilloscope pulse train of the bound state soliton. The interval between the pulses is about 300 ns, corresponding to the basic repetition frequency of 3.47 MHz. Figure 5(c) shows the autocorrelation trace of the bound state, which clearly shows the existence of two pulses. The two pulses are almost identical. The FWHM of the pulse width is 15 ps, and the temporal separation between the two pulses is 125 ps. Figure 5(d) shows that the signal/noise ratio of the pulse is more than 70 dB, which indicates the high stability of the laser.

The birefringence of the FLM can be changed by adjusting the PC in the cavity. Figure 6 shows the characteristics of the dual-wavelength mode-locked fiber laser when adjusting the PC at the pump power of 160 mW. Figure 6(a) shows the oscilloscope trace under different conditions of the PC and figure 6(b) shows the corresponding single-wavelength and dual-wavelength spectra. The interval of the adjacent multiple-pulse train is about 300 ns, which is equal to the round-trip time of the cavity.

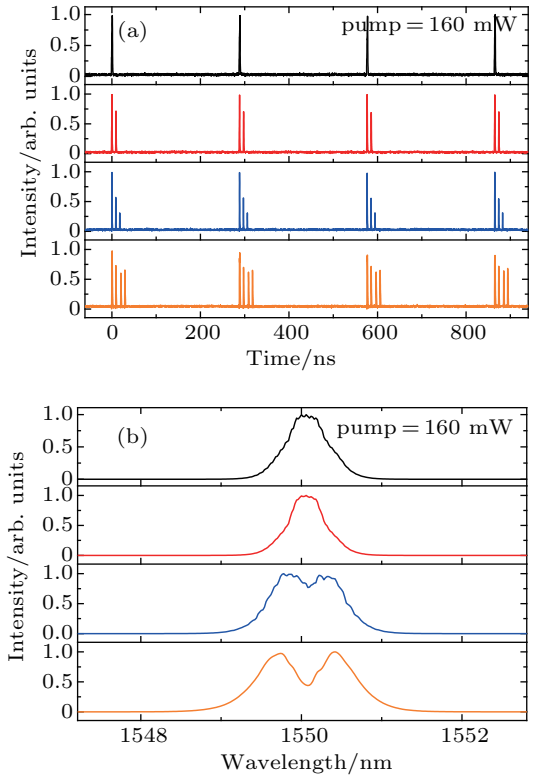


Fig. 6. (color online) The characteristics of the dual-wavelength mode-locked fiber laser: (a) pulse sequences under different conditions of the PC, (b) corresponding spectra.

When we change the pump power, the laser gives multi-pulse and dual-wavelength output. When the pump power is increased slowly from 128 mW to 188 mW, the number of pulses is also increased (Fig. 7(a)). The corresponding single-wavelength and dual-wavelength spectra are shown in Fig. 7(b). The intensity of the spectrum is normalized.

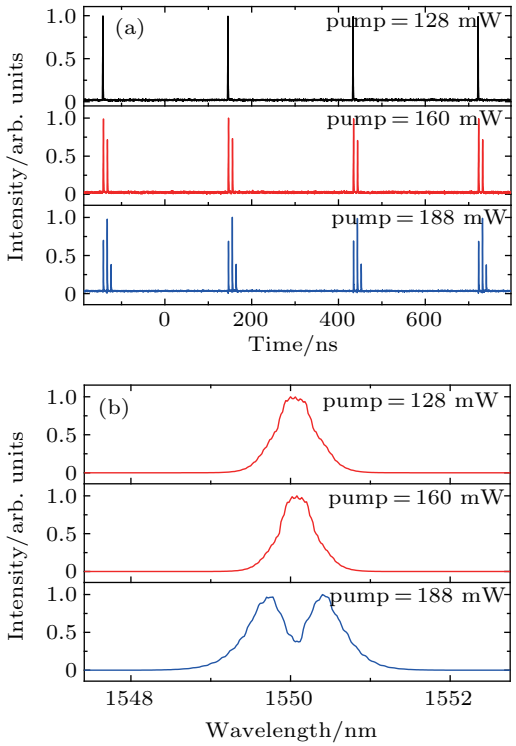


Fig. 7. (color online) The characteristics of the dual-wavelength mode-locked fiber laser: (a) pulse sequences under different pump power, (b) corresponding spectra.

Figure 8 shows the dual-wavelength output of the fiber laser at the pump power of 188 mW. The central-wavelengths of the dual-wavelength are 1549.7 nm and 1550.4 nm with a separation of 0.7 nm.

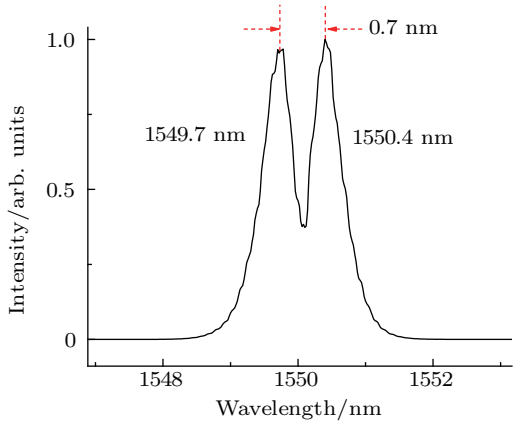


Fig. 8. (color online) Spectrum of the dual-wavelength output at the pump power of 188 mW.

4. Conclusion

We have observed dual-wavelength and bound-state soliton output in a passively mode-locked Er-doped fiber laser experimentally. The pulse width and the pulse interval of the bound soliton are 15 ps and 125 ps, respectively. The output

power is 11.8 mW with the pump power of 128 mW, corresponding to the pulse energy of 1.52 nJ. The repetition rate of the pulse sequence is 3.47 MHz. A comb filter composed of FLM and PC can output a comb spectrum. By adjusting the polarization controller or varying the pump power, the central wavelength of the comb spectrum can be tuned. When the comb spectrum is combined with the reflective spectrum of the fiber Bragg grating, the total spectrum of the cavity can be split into two parts, and the bound state soliton with dual-wavelength at 1549.7 nm and 1550.4 nm is obtained.

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