Flexible pulses from carbon nanotubes mode-locked fiber laser*

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We demonstrate a flexible erbium-doped pulsed fiber laser which achieves the wavelength and pulse width tuning by adjusting an intracavity filter. The intracavity filter is flexible to achieve any of the different wavelengths and bandwidths in the tuning range. The wavelength and width of pulse can be tuned in a range of ∼ 20 nm and from ∼ 0.8 ps to 87 ps, respectively. The flexible pulsed fiber laser can be accurately controlled, which is insensitive to environmental disturbance.

Keywords: fiber laser, mode-locked laser, wavelength and pulse width tunable, carbon nanotubes

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1. Introduction

The various advantages of a fiber laser such as simplicity, compactness and high stability have attracted extensive attention in recent decades.[1–4] Mode-locked techniques have made a major contribution to fiber communication, spectroscopy, and biomedical research.[5,6] At present, a lot of saturable absorbers (SA) including the nonlinear polarization rotation (NPR),[7,8] nonlinear optical loop mirror,[9,10] semiconductor saturable absorber mirrors (SESAMs),[11] graphene,[12,13] and single-walled carbon nanotubes (SWNTs)[14,15] have been reported to be used in the mode-locked fiber lasers. SESAM is the dominant mode-locking technology. However, SESAM has a narrow tuning range and slow recovery time, and require complex fabrication. An alternative saturable absorber is to use SWNT, due to its broad operation range, quick recovery time, high environmental stability and easy fabrication.[16] Many people pay attention to how to achieve shorter pulses,[17] high energy,[18] multi-wavelength,[19,20] high or low repetition frequency,[17,21] wavelength tunable lasers,[3,22–24] and so on. Inserting an intracavity bandpass filter can achieve wavelength tuning easily, whereas the pulse width is difficult to change. People can only change them slightly by adjusting the pump power or the component of the cavity.[19] However, the wavelength and pulse-width tunable mode-locked fiber laser are rarely reported. In 2015, Liu and Cui reported a flexible structure based on fiber Bragg grating (FBG) which can achieve the wavelength and width of pulse tuning by vertically and horizontally translating a cantilever beam.[25]

According to the dispersion management of the laser cavity, various pulses have been observed experimentally such as conventional solitons (CSs),[26] stretched pulses,[16] self-similar pulses,[27] and dissipative solitons (DSs).[28] In accordance with the soliton theory, CSs can be formed by balancing the nonlinearity of the material and the negative dispersion effect.[29] To increase the pulse energy, the DSs have been investigated extensively. The hysteresis phenomenon of DSs was discovered firstly by Liu.[30] The wave-breaking-free DSs with the high energy were achieved from the passively mode-locked fiber laser with large net-normal dispersion.[31,32] The giant-chirp DSs were observed in the ultra-large net-normal-dispersion fiber laser.[33]

Because the CSs have the good stability in comparison with the DSs,[29,34] the CS fiber lasers with the multiple wavelengths or the tuning have been reported widely.[19,24] In this paper, we report a flexible erbium-doped pulse fiber laser in which the wavelength and width can be managed precisely by adjusting an intracavity filter. The wavelength and width of pulse can be tuned in a range of ∼ 20 nm and from ∼ 0.8 ps to ∼ 87 ps, respectively.

2. Experimental setup

Figure 1 shows the schematic diagram of the pulsed fiber laser. The laser consists of a 980-nm pump laser diode (LD), a 980-nm/1550-nm wavelength-division multiplexer (WDM), an erbium-doped fiber (EDF) with 8 m in length and 6 dB/m in absorption at 980 nm, a piece of single-mode fiber (SMF), an optical coupler (OC) with a coupling ratio of 90:10, a polarization controller (PC), a tunable filter, a SWNT-SA, and an optical isolator (ISO). The dispersion parameters of EDF and SMF are about 11.6 and -22 ps^2/km at 1550 nm, respectively. The net cavity dispersion is estimated at -0.60 ps^2.

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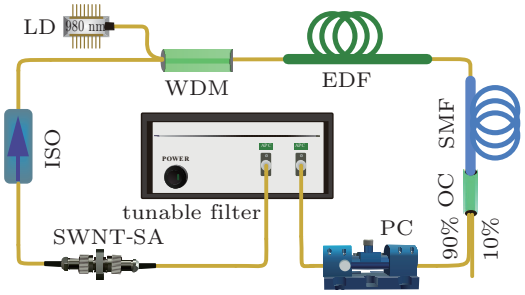


Fig. 1. (color online) Schematic diagram of the laser setup.

3. Experimental results

The intracavity filter is based on the principle of grating. It can achieve any of the different wavelengths and bandwidths in a tuning range of 1528.579 nm–1566.928 nm and an accuracy of 0.05 nm. The typical output spectra are shown in Figs. 2(a) and 2(b), respectively. It is seen that the output spectra are regular, and the spectral envelope is determined by the spontaneous emission. It can also filter the output spectrum of an arbitrary shape with an appropriate bandwidth and attenuation setup.

The laser delivers a continuous wave with a pump power of 18 mW. Figure 3(a) shows the output spectrum at $P \approx 45$ mW when the filter is used. It is observed that both ends of the spectrum distribute the sidebands symmetrically. The sidebands show that the pulse is caused by CS, and the sidebands are restrained by the filtering effect.[26] Figure 3(b) shows the autocorrelation trace of the experimental data (circle symbols) and the sech^2-shaped fit (solid curve). The full width at half maximum (FWHM) spectral bandwidth at the representative output is about 2.847 nm. The pulse width is about 0.909 ps. The time-bandwidth product (TBP) is 0.33, which is

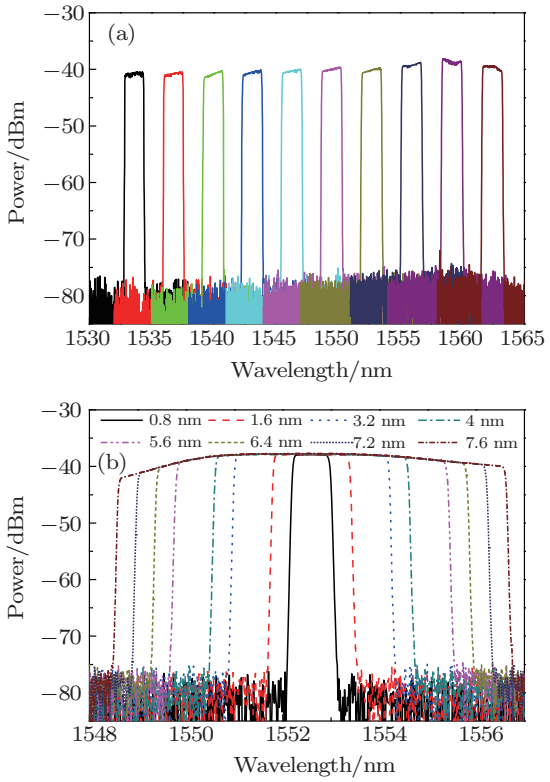


Fig. 2. (color online) Typical output spectra of tunable filter. (a) Different central wavelengths. (b) Different bandwidths about 0.8, 1.6, 3.2, 4, 5.6, 6.4, 7.2, 7.6 nm from inner to outer.

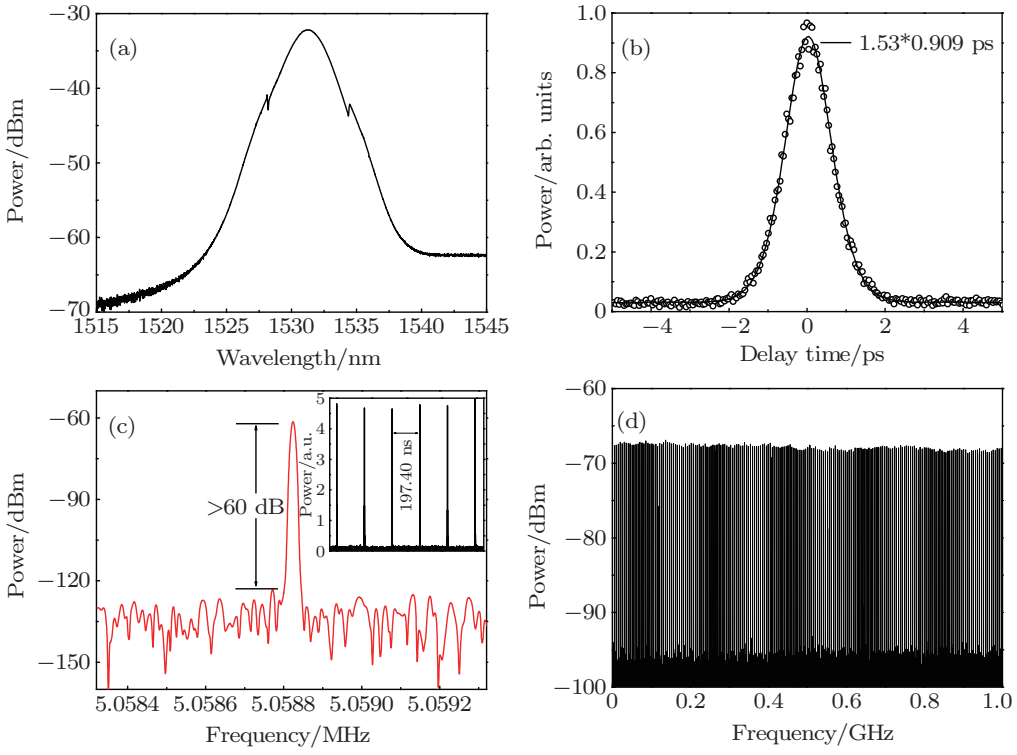


Fig. 3. (color online) Mode-locking characteristics. (a) The output spectrum. (b) Autocorrelation traces of the experimental data (circles) and sech^2-shaped fit (solid curve). (c) Fundamental RF spectrum (10-Hz resolution and 1-kHz span). Inset in the top right corner shows the oscilloscope trace of the laser. (d) Wide-band RF spectrum up to 1 GHz.

close to the value of the transform-limited sech^2-shaped pulse (0.315). Figures 3(c) and 3(d) are the characteristics of radio frequency (RF) spectra with 10 Hz in resolution and 1 kHz in span and the wideband RF spectra up to 1 GHz, respectively. The $>$ 60 dB signal-to-noise ratio in Fig. 3(c) is observed. The repetition rate is 5.059 MHz (Fig. 3(c)), corresponding to 197.4 ns of round-trip time (inset in Fig. 3(c)). No spectrum modulation is observed over 1 GHz (Fig. 3(d)). The results show a good mode-locking stability and low timing jitter.

The different wavelengths and pulse widths are demonstrated by setting the filter bandwidth and polarization controller appropriately. The output central wavelength is tunable from 1542 nm to 1560 nm and shown in Fig. 4(a). The autocorrelation traces and sech^2-shaped fitting are shown in Fig. 4(b). The FWHM spectral bandwidths are about 1.738, 2.111, 1.747, 1.516, and 1.202 nm, respectively. The pulse widths are about 1.671, 1.356, 1.513, 1.76, and 2.235 ps, respectively. The TBPs are about 0.36, 0.35, 0.33, 0.33, and 0.33, respectively, which are close to 0.315. The variation of TBPs stems from the fluctuation of the filter bandwidth, the output optical spectrum, and the total cavity dispersion. The wavelength tuning range is limited by the filter, not by the SWNT-SA, and a 40-nm tunable range was achieved in 2008.[24]

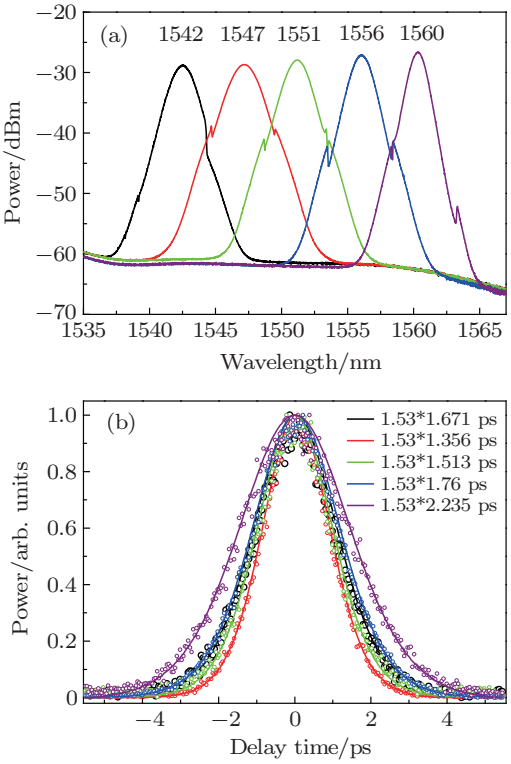


Fig. 4. (color online) Wavelength tuning. (a) Five different central wavelengths of 1542, 1547, 1551, 1556, and 1560 nm by adjusting the filter. (b) Autocorrelation traces of the experimental data (circles) and sech^2-shaped fit (solid curves).

The proposed laser can not only deliver different central wavelengths, but also deliver pulses with different widths. The output spectra with the central wavelength about 1530 nm are shown in Fig. 5(a). The corresponding autocorrelation traces and sech^2-shaped fit are shown in Fig. 5(b). The FWHM spectral bandwidths are about 0.087, 0.274, 0.58, 1.222, 2.12, 2.847, and 3.203 nm, respectively. The corresponding bandwidths of filter set are 0.5, 1.0, 2.0, 5.0, 10.0, 15.0, and 17.0 nm, respectively. The pulse widths are about 87.406, 17.718, 8.519, 4.016, 1.538, 0.909, and 0.857 ps, respectively. The TBPs are about 0.97, 0.62, 0.63, 0.62, 0.37, 0.33, and 0.35, respectively, indicating slightly chirping.

The proposed SA here is placed between a pair of fiber connector ends, where only the pinhole area is used for SA. However, this physically touching scheme can lead to the distortion and damage to the carbon nanotubes for the high power fiber laser. As an improved scheme, a graphene-clad microfibre SA has been proposed for generating ultrafast pulses.[35] On the other hand, the all-fiber figure-eight laser can improve the pump power.[36]

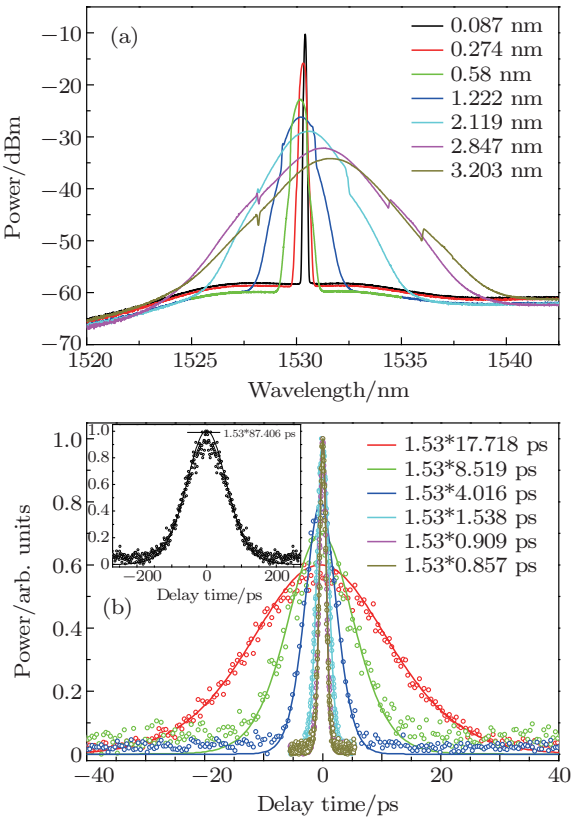


Fig. 5. (color online) Pulse width tuning. (a) Optical spectra with different bandwidths. (b) Autocorrelation traces of the experimental data (circles) and sech^2-shaped fit (solid curves). Inset in the top left corner shows the autocorrelation traces of 87.406 ps.

4. Conclusions

In the experiments, the pulse wavelength and width can be controlled precisely by adjusting an intra-cavity filter separately. The wavelength of pulse is precisely tunable in a range of $\sim$ 20 nm. The range of pulse width is accurately tunable from $\sim$ 0.8 ps to $\sim$ 87 ps. If the filter has a wider tuning range, more wavelengths can be delivered. Although the

pulse width tuning is realized at 1530 nm in this experiment, it can be achieved continuously in the tuning range because of the flexible filter. The demonstrated flexible pulsed fiber laser can possess more widespread applications such as fiber sensor, metrology and biomedical research.

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