Passively mode-locked fiber laser by using monolayer chemical vapor deposition of graphene on D-shaped fiber

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We demonstrate a monolayer graphene saturable absorber (SA) based on D-shaped fiber for operation of the mode-locked fiber laser. The monolayer graphene is grown by chemical vapor deposition (CVD) on Cu substrate and transferred onto the polymer, and then covered with D-shaped fiber, which allows light–graphene interaction via the evanescent field of the fiber. Due to the side-coupled interaction, the length of graphene is long enough to avoid optical power-induced thermal damage. Using such a graphene-based SA, stable mode-locked solitons with 4.5 nm spectral bandwidth and 713 fs pulsewidth at the 1563 nm wavelength have been obtained under 280 mW pump power. The influence of total cavity dispersion on the optical spectrum and pulse is also investigated by adding different lengths of single-mode fiber in the laser cavity.

OCIS codes: (140.4050) Mode-locked lasers; (140.7090) Ultrafast lasers; (320.5550) Pulses.
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1. Introduction

Graphene exhibits outstanding optical properties, such as ultrafast recovery time, broad operation bandwidth, and nonlinear optical response [1]. Recently, graphene has attracted huge interest in the development of passively mode-locked fiber lasers owing to its excellently saturable absorption feature [2–15]. To fabricate the graphene-based saturable absorber (SA), several methods have been developed. The first one is transferring the atomic-layer graphene onto a fiber ferrule to form a SA, and the graphene materials can be obtained from chemical vapor deposition (CVD) synthetical graphene on SiO_2/Si substrates with Ni films [16–18], mechanical exfoliation of graphene from bulk graphite [19,20], self-assembled graphene membrane [21], graphene–PVA (polyvinyl alcohol) composite [22], etc. The second method is filling the hollow-core photonic crystal with few-layered graphene oxide solution [23], filling the hollow optical fiber with graphene/PVA composite [24], and syphoning the graphene nanoparticles into a multicore photonic crystal fiber (PCF) [25]. The third technique is employing the evanescent field interaction of the propagating light with the graphene covered on the surface of side-polished D-shaped fiber [26], microfiber [27], and tapered fiber [28]. In such a scheme, the interaction length of the light beam with graphene is adjustable, which can essentially overcome the difficulty of optical power-induced thermal damage. When compared with the microfiber and tapered fiber, the D-shaped

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fiber can be tightly attached by graphene film, and is robust and convenient for packaging. Very recently, mode-locked fiber lasers based on the graphene oxide-deposited D-shaped fiber were demonstrated for producing femtosecond pulses [29,30].

Up to now, multilayer graphene as well as graphene composites have been widely used as the SAs in passively mode-locked fiber lasers. Although monolayer graphene has relatively low excitation intensity of saturable absorption and, hence, can act as a more effective SA for mode-locking fiber lasers [31], the transfer and manufacture of monolayer graphene is rather difficult because of its thin thickness. To develop a simple method for preparation, the polymer-supported monolayer graphene film becomes an attractive approach. In our previous work, polymer-supported monolayer graphene, covered on the microfiber, has been fabricated and used as a SA for wavelength-tunable and passively mode-locked pulse generation [32].

In this paper, the D-shaped fiber covered by polymer-supported monolayer graphene film is used as the SA. Such a structure enables strong light–graphene interaction along the fiber length, and as a result, mode-locked femtosecond laser pulses of ~713 fs with repetition rate of 11.53 MHz can be obtained under 280 mW pump power.

2. Fabrication and Polarization Characterization of Saturable Absorber

The side-polished fiber device for preparing D-shaped fiber is shown in Fig. 1(a). Here, the single-mode fiber (SMF) is burnished by the grinding wheel, and then is burned using the electrode discharge to improve the smoothness. The resulting fiber is viewed by using a Nikon Eclipse 80i microscope with 20× objective lens. From the side view of the right picture, the fiber core is near the edge and the thickness is ~72 μm. The vertical view of the right picture

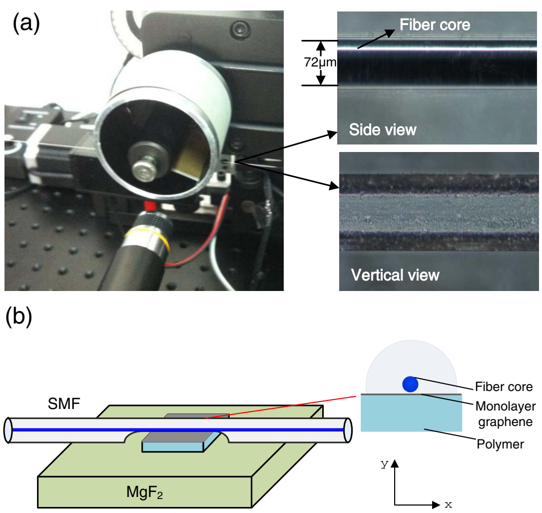

Fig. 1. (a) D-shaped fiber preparation through side-polished fiber device; the right pictures are the side and vertical views of the end product. (b) Schematic structure of the graphene-based SA; the right schematic diagram is the cross section.

is the photo of the polished surface. The total D-shaped fiber is 2 cm in length, and its minimum insertion loss and polarization-dependent loss (PDL) are measured to be 1.3 and 0.5 dB at the wavelength of 1560 nm, respectively. Figure 1(b) illustrates the schematic structure of the graphene-based SA. The monolayer graphene film is directly synthesized by the CVD method on polycrystalline Cu substrate. The polymer clad resin (EFiRON, PC-373, refractive index of 1.376) is uniformly adhered to the graphene film on a Cu substrate without an air bubble in it, and is then cured by ultraviolet (UV) light. After 24 h, the polymer/graphene/Cu layers are soaked with 0.05 mg/ml $FeCl_3$ solution to remove the Cu layer. Then the ferric icon is washed away from polymer/graphene layers using distilled water. The length of the graphene is ~10 mm. Finally, after cleaning the polished surface of the D-shaped fiber with 99.5% propyl alcohol, the polymer-supported monolayer graphene film is transferred onto the flat surface of the D-shaped fiber for interaction with the evanescent field. Such a structure is used as the graphene-based SA in our fiber laser system. In addition, it should be noted that the thickness of D-shaped fiber should be between 67 μm (on top of fiber core) and 77 μm, in order to obtain a low loss and strong evanescent field simultaneously. Considering the interaction length of ~10 mm of graphene, the 72 μm thickness of D-shaped fiber is appropriate for our structure.

3. Experimental Setup

The experimental setup of the proposed graphene-based passively mode-locked erbium-doped fiber (EDF) laser with a ring cavity configuration is presented in Fig. 2. A 1.3 m high-concentration EDF (OFS EDF-80) is used as the gain medium, pumped by a 1480 nm high-power laser diode (LD, Anritsu AF4B150FA75L) via a 1480/1550 nm wavelength division multiplexer (WDM) coupler. A polarization-independent isolator is used to force the unidirectional operation of the ring, and an intracavity PC is

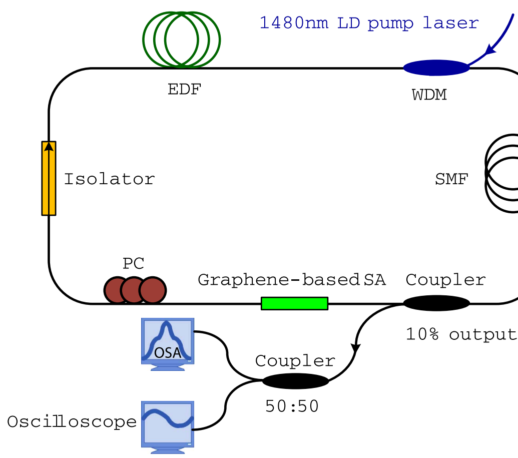

Fig. 2. Experimental setup of the graphene mode-locking fiber laser.

used to adjust the linear cavity birefringence. The graphene-based SA is inserted in the cavity between the PC and the optical coupler. The SMF is added in the cavity to change the total cavity dispersions. The PDLs of the 90:10 fiber coupler, WDM, and optical isolator are less than 0.1 dB. The generated mode-locked pulses are directed out by the optical coupler, and then pass through a 3 dB coupler. The pulses are simultaneously monitored by an optical spectrum analyzer (ANDO AQ 6319) with 0.01 nm resolution and a high-speed photodetector (Newfocus 1414, 25 GHz) connected to an oscilloscope (Tektronix, TPS 2024). The radio frequency (RF) spectrum of the passively mode-locked laser output is measured by use of the same photodetector connected to a real-time spectrum analyzer (Tektronix RSA 3303A, 3 GHz). The pulse profile is measured by a second harmonic generation (SHG) autocorrelator (FEMTOCHROME FR-103XL, resolution <5 fs) and recorded by the Tektronix oscilloscope.

4. Results and Discussion

Group velocity dispersion (GVD) plays an important role in maintaining the mode-locked fiber laser stability. The GVD of the EDF and the SMF used in the system is −46.25 ps/nm/km and 18 ps/nm/km at the wavelength of 1560 nm, respectively. We first add 5 m SMF in the laser cavity, and the total laser cavity length is ~14.3 m. By ignoring the dispersion of the short D-shaped fiber, the round-trip dispersion of the whole cavity is ~ – 0.222 ps^2. The continuous-wave (CW) operation pump threshold of the laser is ~40 mW. Owing to the asymmetry of D-shaped fiber—it is well known that graphene or graphene oxide-deposited D-shaped fibers exhibit non-negligible PDL [29,33]—the intracavity pulse loss is changed for different pulse polarization states in graphene-based SA [15]. Increasing the pump power to 80 mW and slightly tuning the PC, the fiber laser can operate in states such as CW, stable Q-switching, Q-switched mode-locking, and CW mode-locking [30]. Here, we mainly investigate the laser in the steadily mode-locked state. Once the laser is in mode-locking, the operation can be maintained for a long time. During the operation, the pump power may be increased to 300 mW, until multipulse generation is observed. Under 280 mW pump power, the pulse train of the output solitons is shown in Fig. 3(a). The laser pulse train has a period of 86.7 ns, which matches well with the cavity round-trip time and indicates that the laser is in the passive mode-locked regime. Figure 3(b) shows the optical spectrum of the output. The central wavelength is 1563 nm, and the full width at half-maximum (FWHM) bandwidth is 4.5 nm. The Kelly sidebands, resulting from the intracavity periodical perturbation, clearly appear with discrete and well-defined peaks in the optical spectrum. For chirp-free soliton pulses, the mth order of the Kelly sideband position relative to the center wavelength is given by [29]

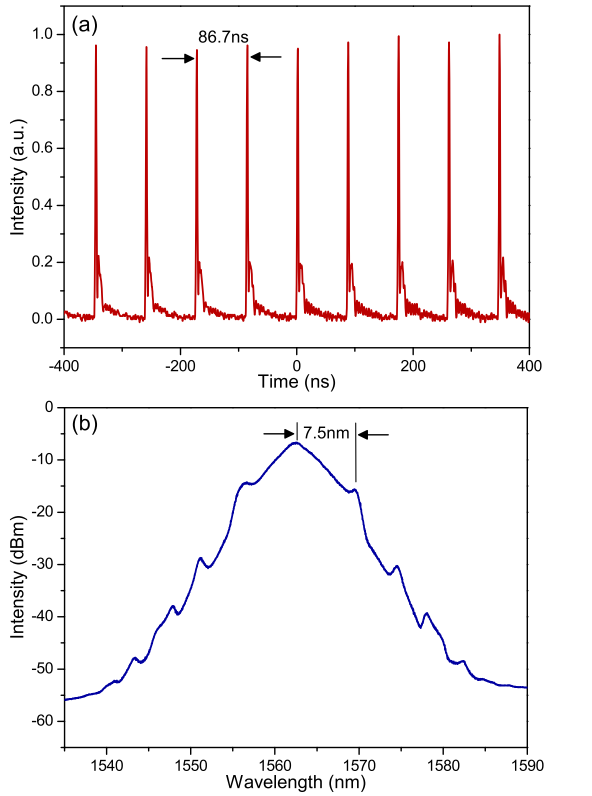

Fig. 3. Under 280 mW EDF pump power, (a) oscilloscope trace of pulse train and (b) optical spectrum of output pulse of mode-locked fiber laser.

$$\Delta\lambda = \frac{2\ln(1+\sqrt{2})\lambda^2}{2\pi c\tau}\sqrt{\frac{4m\pi}{|L\beta_2|}\left(\frac{\tau}{2\ln(1+\sqrt{2})}\right)^2 - 1}, \quad (1)$$

where λ is the center wavelength, τ is the temporal FWHM value of the pulses, L is the cavity length, β_2 is the cavity dispersion parameter, and the total cavity dispersion $|L\beta_2|$ is ~0.222 ps^2. The $\Delta\lambda$ for the first-order Kelly sideband is 7.5 nm in Fig. 3(b), and the transform-limited τ is calculated to be ~0.4 ps by using Eq. (1).

Figure 4(a) depicts the recorded AC trace of the laser pulses. The FWHM value of the pulses is ~1.1 ps. Assuming a Sech^2 pulse profile, its decorrelation factor is 0.648, and the actual pulsewidth is ~713 fs. This measured τ is different from the theoretical value (~0.4 ps), and the time-bandwidth product of the pulses is 0.395, indicating that the soliton pulses are small chirped. The measured RF results are shown in Fig. 4(b). The fundamental peak is located at the repetition rate of 11.53 MHz, with a signal-to-noise ratio (SNR) of 60 dB. It is found that there is a pedestal around the peak; it may result from the influence of vibration or thermal variations on the length of the fiber oscillator. Such a pedestal could be removed by using temperature and vibration control, or the phase-locking technique. The average output power is ~10.5 dBm, with pulse energy ~1 nJ. The inset of Fig. 4(b) reveals the higher

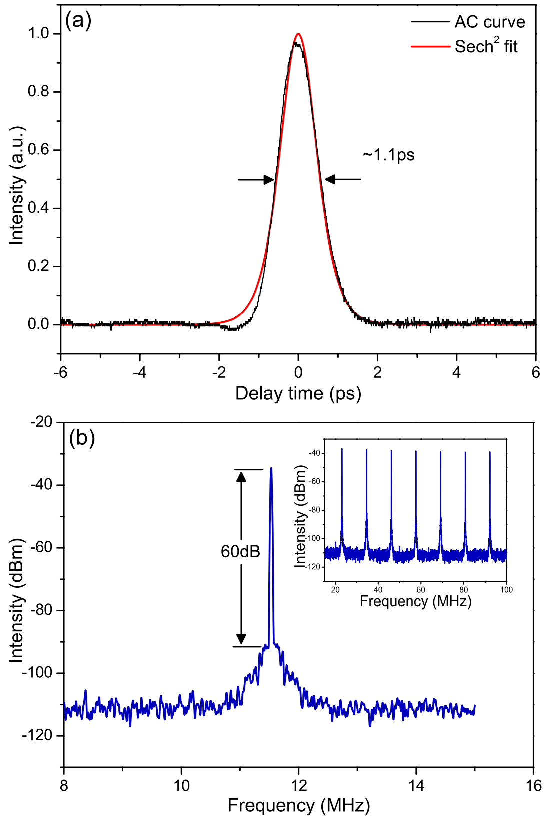

Fig. 4. (a) Autocorrelation traces of the solitons. (b) Fundamental RF spectrum of mode-locked laser; the inset is the RF spectrum of the high-order harmonic pulse.

order of the harmonic RF spectrum, in which a high SNR can also be observed. This indicates the good stability and high reliability of our system.

In order to investigate the dependence of pulses and net cavity dispersion, the length of SMF is varied while other equipment is unchanged. When the net cavity dispersion is small, the polarization controller needs to be fine tuned to start the mode locking. Figure 5 shows the optical spectra of our pulses with different SMF lengths, and the obvious sideband and narrow FWHM are obtained with larger dispersion. Table 1 summarizes the relationship between the total cavity dispersion and the laser characteristics including four groups of data. When the total dispersion is varied from 0.107 to 0.560 ps^2, the pulsewidth of the generated pulses is between 0.668 and 1.119 ps at a repetition rate of 16.47–6.66 MHz.

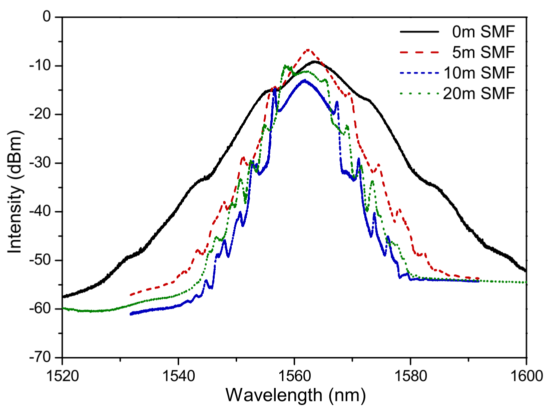

Fig. 5. Optical spectra of output pulse of mode-locked fiber laser with different lengths of added SMF under 280 mW EDF pump power.

Table 1. Optical Parameters of Mode-Locked Fiber Laser When Adding Different Lengths of SMF

Cavity Length (m)	Total Dispersion (ps^2)	Frequency (MHz)	FWHM (nm)	Pulsewidth (ps)
9.3	−0.107	16.47	7.8	0.668
14.3	−0.222	11.53	4.5	0.713
19.3	−0.336	8.74	4.2	0.809
29.3	−0.560	6.66	—	1.119

5. Conclusion

In conclusion, a femtosecond passively mode-locked fiber laser based on D-shaped fiber and monolayer graphene has been demonstrated. The method of transferring polymer-supported monolayer graphene film onto the flat surface of the D-shaped fiber is simple and effective. By varying the length of SMF, the total dispersion can be changed from 0.107 to 0.560 ps^2. The corresponding pulsewidths of 0.668–1.119 ps were obtained at a repetition rate of 16.47–6.66 MHz. The easy fabrication and good stability of our system will facilitate potential applications of monolayer graphene in ultrafast photonics.

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