Graphene mode locked, wavelength-tunable, dissipative soliton fiber laser

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Atomic layer graphene possesses wavelength-insensitive ultrafast saturable absorption, which can be exploited as a "full-band" mode locker. Taking advantage of the wide band saturable absorption of the graphene, we demonstrate experimentally that wide range (1570–1600 nm) continuous wavelength tunable dissipative solitons could be formed in an erbium doped fiber laser mode locked with few layer graphene. © *2010 American Institute of Physics*. [doi:10.1063/1.3367743]

Recently, passive mode locking of fiber lasers with single walled carbon nanotubes (SWCNTs) has attracted considerable attention.[1–7] It has been shown that SWCNT mode lockers have the advantages such as intrinsically ultrafast recovery time, large saturable absorption, easy to fabricate, and low cost. In particular, as SWCNTs are direct band gap materials with a gap that depends on the nanotubes' diameter and chirality, through mixing SWCNTs with different diameters, a broadband saturable absorption mode locker could be made. A wideband wavelength tunable erbium-doped fiber laser mode locked with SWCNTs was experimentally demonstrated.[2]

However, the broadband SWCNT mode locker suffers intrinsic drawbacks: SWCNTs with a certain diameter only contribute to the saturable absorption of a particular wavelength of light, and SWCNTs tend to form bundles that finish up as scattering sites. Therefore, coexistence of SWCNTs with different diameters introduces extra linear losses to the mode locker, making mode locking of a laser difficult to achieve. In this paper, we show that these drawbacks could be circumvented if graphene is used as a broadband saturable absorber. Implementing graphene mode locking in a specially designed erbium-doped fiber laser, we have first demonstrated a wide range (1570–1600 nm) continuous wavelength tunable dissipative soliton fiber laser.

Soliton operation of mode locked fiber lasers has been extensively investigated previously. Conventionally, the study on soliton operation of fiber lasers was focused on lasers with anomalous cavity dispersion, where a soliton is formed due to the natural balance between the anomalous cavity dispersion and fiber nonlinear optical Kerr effect, and the dynamics of the formed solitons is governed by the nonlinear Schrödinger equation. Recently, it was further shown both experimentally and theoretically that a soliton could even be formed in fiber lasers with large normal cavity dispersion.[8,9] Formation of solitons in the normal dispersion fiber lasers is a result of the mutual nonlinear interaction among the normal cavity dispersion, fiber Kerr nonlinearity, and the effective laser gain bandwidth filtering,[8] and the dynamics of the formed solitons is governed by the complex Ginzburg–Landau equation (GLE). A soliton whose dynamics is governed by the GLE is also known as a dissipative soliton. Comparing with the operation of the conventional soliton fiber lasers, where subpicosecond optical pulses could be routinely generated but the pulse energy is limited at the level of tens of picojoules, the operation of a dissipative soliton fiber laser can naturally generate large energy strongly chirped optical pulses.[8,10] Due to its strongly chirped feature, a dissipative soliton can be easily amplified.[11] After compression large energy ultrashort pulses can further be generated. However, because a dissipative soliton fiber laser is operating in the large positive cavity dispersion regime, self-started mode locking in the laser is much more difficult to achieve than in the conventional soliton fiber lasers.

Unlike the conventional semiconductor saturable absorbers, the energy band diagram of graphene has zero band gap and a linear dispersion relation.[12] These unique energy band properties combined with the Pauli blocking principle renders graphene a full band ultrafast saturable absorber.[13] Figure 1(a) shows a schematic illustration of the energy band structure and photon absorption of graphene. Li *et al.*[14] had experimentally shown that atomic layer graphene could absorb a considerable amount of infrared light without any bandwidth limitation. In previous papers we have also experimentally shown passive mode locking of an erbium-doped fiber laser[15] and a solid-state Nd:YAG ceramic laser[16] respectively using graphene as a mode locker. It is to point out that determined by its unique energy band structure the saturation intensity of graphene is wavelength sensitive. We had experimentally measured the saturation intensity of graphene at $\sim$1.06 μm and 1.56 μm, respectively. It varies from $\sim$0.87 MW cm^{-2} at 1.06 μm to $\sim$0.71 MW cm^{-2} at 1.56 μm.[13,15,16]

To exploit the wideband saturable absorption of graphene for wavelength tunable soliton generation, we further specially designed an erbium-doped dissipative soliton fiber laser. We note that dissipative soliton operation of fiber lasers mode locked with SWCNTs was reported by Kieu and Wise,[7] and Sun *et al.*[11] However, dissipative soliton operation of fiber lasers mode locked with atomic layer graphene has not been demonstrated. Moreover, no wavelength tunable dissipative soliton lasers were ever reported. Our fiber laser is schematically shown in Fig. 1(b). The laser cavity is made of a piece of 5.0 m erbium-doped fiber (EDF) with erbium-doping concentration of 2280 ppm and a group velocity dispersion (GVD) parameter of -32 (ps/nm)/km, a total length

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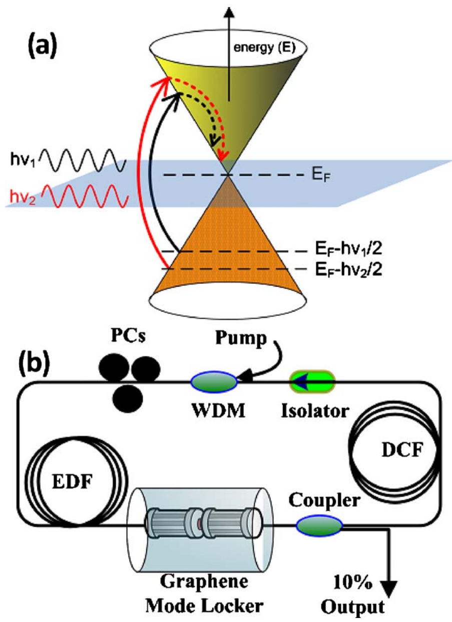

FIG. 1. (Color online) (a) Schematic of graphene's energy band structure and photon absorption. (b) Schematic of the dissipative soliton fiber laser. WDM denotes: Wavelength division multiplexer, EDF denotes erbium-doped fiber, PC denotes polarization controller, and DCF denotes dispersion compensation fiber.

of 9.0 m single mode fiber with GVD parameter of 18 (ps/nm)/km from optical components, and 118 m dispersion compensation fiber (DCF) with GVD parameter of about −2 (ps/nm)/km. A polarization independent isolator was used to force the unidirectional operation of the ring, and an intracavity polarization controller (PC) was used to adjust the cavity birefringence. The laser was pumped by a high power Fiber Raman Laser of wavelength 1480 nm. The graphene saturable absorber was inserted in the cavity through transferring a piece of free standing few layers graphene film onto the end facet of a fiber pigtail via the van der Walls force. Details on the graphene preparation and graphene saturable absorber characterization were reported in Ref. 13. The main difference of the current fiber laser from that reported in Ref. 15 is that normal dispersion EDF instead of anomalous dispersion EDF was employed as the gain medium. To assure large net positive cavity dispersion we also added a long piece of DCF to the cavity. In addition, we deliberately introduced large cavity birefringence in the laser, which strengthens the effect of the artificial birefringence filter formed in the cavity.[17]

Mode locking of the laser was always achieved. Figure 2 shows a typical mode locking state of the laser. Figure 2(c) is the oscilloscope trace of the measured laser emission. The pulse-to-pulse separation is ~660 ns, which matches the cavity roundtrip time, indicating that the pulses were formed as a result of the laser mode locking. Figure 2(a) is the optical spectrum of the mode locked pulses. It has sharp steep spectral edges and a 3 dB spectral bandwidth of ~7.2 nm. Using a 50 GHz high-speed oscilloscope (Tektronix CSA 8000) together with a 45 GHz photodetector (New Focus 1014), we measured the pulse profile of the mode locked pulses, as shown in Fig. 2(b). The pulse width is ~49 ps. Therefore, the time-bandwidth product of the pulses is ~44.3, indicating that the mode locked pulses are strongly chirped. In our experiment we had also measured the mode

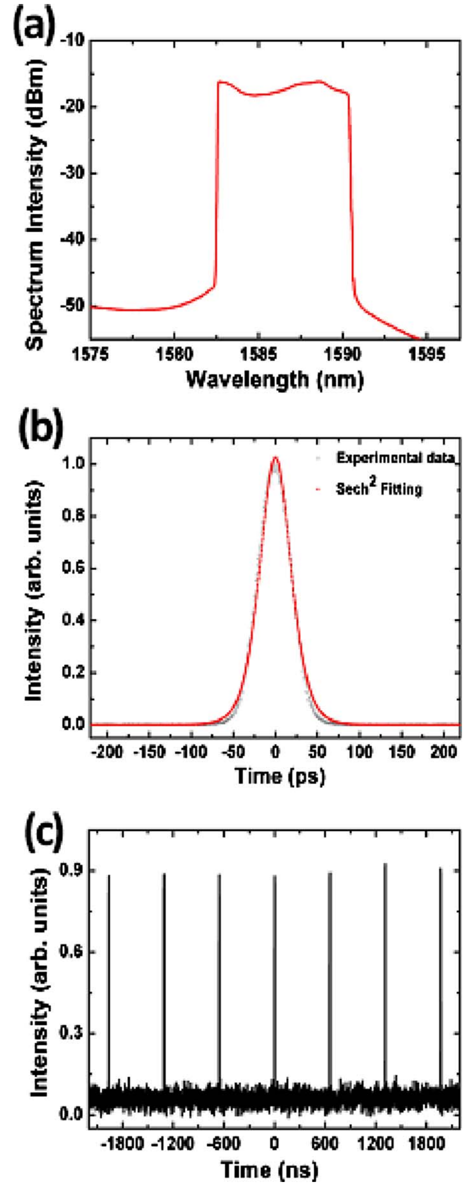

FIG. 2. (Color online) Dissipative soliton operation of the laser. (a) Optical spectrum measured. (b) Pulse profile. (c) Oscilloscope trace of pulse train.

locked pulses with a commercial autocorrelator and confirmed that no fine structures within the pulses. We note that the pulses possess the typical features of the dissipative solitons formed in positive dispersion cavity fiber lasers.[7–11] As the total cavity dispersion of our laser is ~0.3047 ps^2, the above experimental result suggests that the mode locked pulses in our laser have been shaped into dissipative solitons.

In weakly birefringent cavity fiber lasers, where the cavity birefringence induced artificial birefringence filter has a large bandwidth, the filtering effect of the birefringence filter could normally be ignored. In our laser, the effect of cavity artificial birefringence filter no longer can be ignored, instead it together with the erbium fiber determines the effective laser gain and gain profile. As transmission of the artificial birefringence filter varies with the cavity birefringence, therefore, in our laser simply adjusting the orientation of the intra cavity polarization controller both the peak wavelength and the pulse width of the formed dissipative solitons could be continuously tuned. Figure 3(a) shows the optical spectral evolution of the formed dissipative solitons with the orienta-

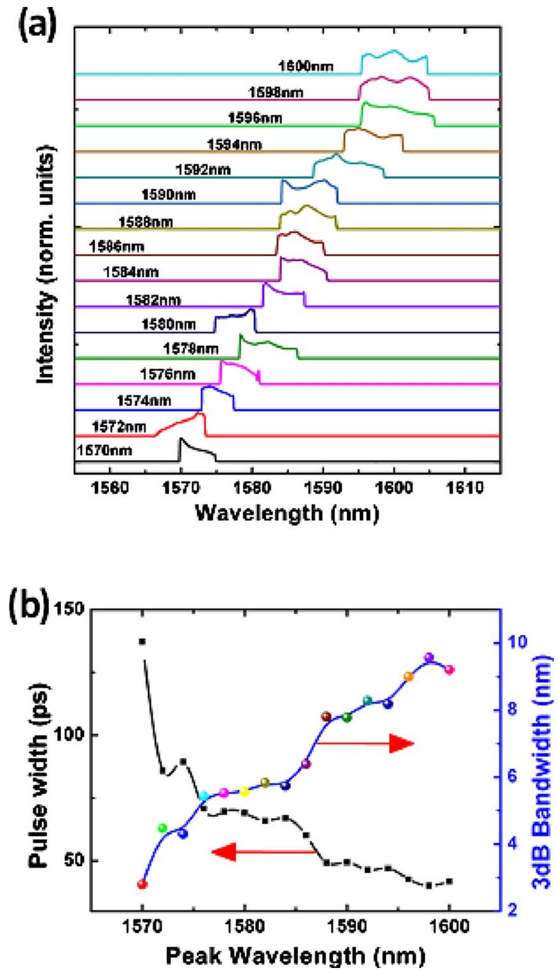

FIG. 3. (Color online) (a) Wideband output spectra from 1570 to 1600 nm and inserted numbers indicates the corresponding peak wavelengths; (b) Output pulse duration and spectral bandwidth at different peak wavelengths.

tion variation of the intra cavity polarization controller. It is to see that the wavelength of the formed dissipative solitons could continuously be shifted from 1570 to 1600 nm. We note that in order to keep stable dissipative soliton operation, as the PC orientation changed, the pumping strength was also adjusted. Figure 3(b) further shows the soliton pulse width and the 3 dB spectral bandwidth variations. The soliton pulse width changed from ~140 to 40 ps, and the corresponding 3 dB spectral bandwidth changed from ~3 to 9 nm. It is worth of mentioning that in our experiment we had also constructed a wavelength tunable conventional soliton fiber laser mode locked with graphene. Continuous wavelength tuning of the formed solitons in the same wavelength range (1570–1600 nm) was also observed.

We point out that the artificial cavity birefringence filter in our laser has played the same role as the intracavity tunable band-pass filter reported in Ref. 2. Although with an intracavity tunable bandpass filter even larger wavelength tuning range may be achievable, our laser has nevertheless a much simple configuration and less demand on the cavity components. In addition, in contrast to using tunable filter with only 3 nm bandwidth,[2] the current artificial birefringence filter possesses the advantage of always having a relatively broader transmission bandwidth variable through adjusting the cavity birefringence. The effective gain bandwidth limitation effect in our laser is less significant. Consequently, large energy dissipative soliton pulses could be formed in the laser. In our laser dissipative solitons with single pulse energy of 2.3 nJ have been directly generated. It is anticipated that larger pulse energy could be readily generated through further improving the cavity design, such as larger cavity output ratio. Wavelength tunable lasers have widespread applications in many fields, e.g., laser spectroscopy, biomedical research, and telecommunications. The developed wavelength tunable dissipative soliton fiber laser provides a cost effective solution for such a light source. Furthermore, the fiber laser could also be used as a compact, cost effective seed source for the generation of large energy wavelength tunable ultrashort pulses.

In conclusion, we have reported a wavelength tunable erbium-doped dissipative soliton fiber laser with atomic layer graphene as the mode locker. We have shown experimentally that by taking advantage of the artificial cavity birefringence filter effect and the broad band saturable absorption of atomic layer graphene, a wide range wavelength tunable dissipative soliton fiber laser could be constructed. Our studies clearly show that graphene could be a promising wide-band saturable absorber.

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