Dissipative soliton operation of an ytterbium-doped fiber laser mode locked with atomic multilayer graphene

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Mode locking of an ytterbium-doped fiber laser with atomic multilayer graphene is, to the best of our knowledge, experimentally demonstrated for the first time. Dissipative solitons with duration of 580 ps at 1069.8 nm were generated. Since graphene can also be used to mode lock erbium-doped fiber lasers, our result shows that graphene indeed has wavelength-independent saturable absorption, which could be exploited to mode lock fiber lasers with various operating wavelengths.

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Passively mode-locked fiber lasers, owing to their ultrashort pulse emission, excellent pulse stability, compactness, and low cost, have been extensively investigated. To achieve passive mode locking of a fiber laser, different techniques have been used. These include the figure-of-eight cavity (F8C) method [1], the nonlinear polarization rotation (NPR) method [2], the semiconductor saturable absorption mirror (SESAM) method [3], and the carbon nanotube (CNT) method [4]. However, each of these techniques has its advantages and drawbacks. The F8C and the NPR techniques are based on the nonlinear wave interference in the laser cavity. They are independent on the laser operation wavelength, easy to implement, and have ultrafast saturable absorption. However, the methods are intrinsically environmental unstable. The SESAM method has the advantages of being easy to employ and intrinsically environmental stable, but the SESAM itself is difficult to fabricate. Moreover, for lasers operating at different wavelengths, different SESAMs need to be designed and used. The CNT method has recently been intensively investigated. It shows the advantages of easily controllable saturable absorption strength, excellent environmental stability, and ultrafast saturable absorption but suffers from low damage threshold. The saturable absorption wavelength of a CNT is determined by its tube diameter. To mode lock lasers with different operation wavelengths, CNTs with different tube diameters are needed. Although it was recently demonstrated that a single CNT saturable absorber could be used to mode lock Yb-, Er-, and Tm-doped fiber lasers operating at wavelengths of 1.0, 1.56, and 1.99 μm, respectively, CNTs with a wide range of tube diameter distribution were used to construct the saturable absorber [5]. Such a CNT saturable absorber has large insertion loss for practical applications. Very recently, Travers *et al.* demonstrated that the second transition (E_{22}) of CNTs can be used to mode lock fiber lasers [6]. This shows the possibility of using purified CNTs to mode lock a specific dual-wavelength fiber laser.

In a previous paper, we first experimentally demonstrated self-started mode locking of an erbium-doped fiber laser with the multiple atomic layer graphene as a saturable absorber [7]. Other groups have also confirmed mode locking of erbium-doped fiber lasers with graphene [8]. It was found that using graphene as a saturable absorber has the following advantages: intrinsically super broadband saturable absorption, which potentially covers the wavelength range from visible to mid-IR, ultrafast recovery time, controllable modulation depth, low nonsaturable absorption loss, and ease of fabrication. The erbium-doped fiber lasers operated in the 1.55 μm wavelength range with a limited gain bandwidth of about 20 nm. Despite of the fact that previous experiments have well confirmed the saturable absorption feature of the atomic layer graphene and its passive mode-locking ability, its wavelength-independent saturable absorption characteristic could not be fully exploited. To further demonstrate the super broadband saturable absorption nature of the atomic layer graphene, we designed a passively mode-locked ytterbium-doped fiber (YDF) laser with the atomic layer graphene as a mode locker. The YDF laser operates in the 1 μm wavelength range, which is sufficiently away from that of erbium-doped fiber lasers. We found that, with graphene made with the same method as a saturable absorber, self-started mode locking of the YDF laser could still be achieved. Specifically, dissipative solitons (DSs) with large pulse width and low peak power have been experimentally obtained.

The atomic multilayer graphene was synthesized by the chemical vapor deposition approach on a Ni substrate [7]. The graphene film (5 mm × 5 mm) was isolated by etching off the Ni layer in an aqueous iron (III) chloride ($FeCl_3$) solution and then was transferred onto the cross section of a single-mode fiber (SMF). Figure 1 shows the Raman characterizations of the atomic multilayer graphene film in the core area of the SMF, carried out on a WITEC CRM200 Micro-Raman system (532 nm, ×100 objective lens). The location of the fiber core can be easily identified by the green light incident from another end of the fiber. Figures 1(a) and 1(b) show the Raman maps plotted by the G and D bands, respectively. The inhomogeneous contrast indicates that the fiber core area is covered with few-layer graphene with nonuniform

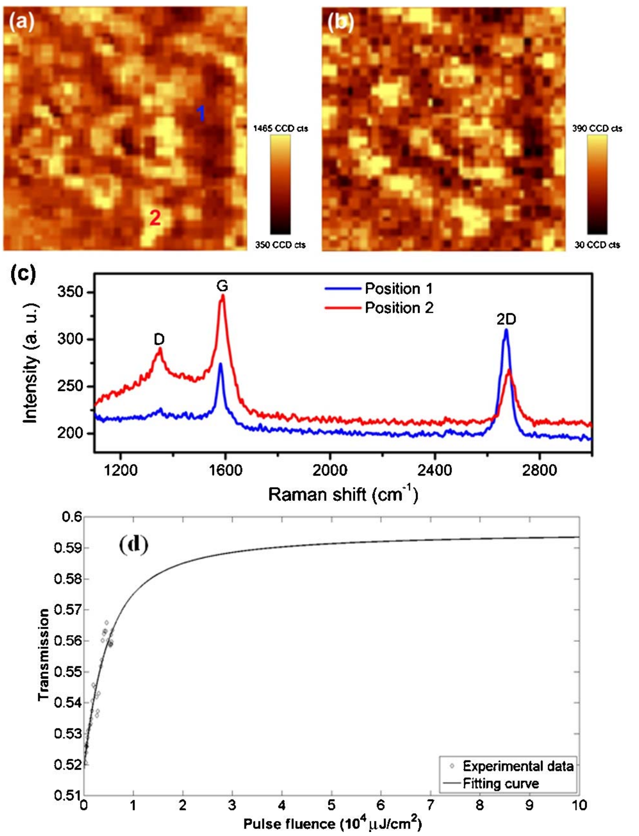

Fig. 1. (Color online) Micro-Raman characterizations of the atomic multilayer graphene film in the area of the fiber core. (a) Raman map integrated by the *G* band and (b) the *D* band of the graphene; (c) Raman spectra taken from the positions marked in (a). (d) Nonlinear transmission versus incident pulse fluence.

thickness. The similarity between these two maps reveals that thicker graphene has stronger disorder-related *D* band intensity, which might originate from the edges of a stacking graphene plane or wrinkled/folded graphene film caused during the transfer process. Single Raman spectra were taken for the thin [marked as 1 in Fig. 1(a)] and thick [marked as 2 in Fig. 1(a)] areas, as shown in Fig. 1(c). The strong and narrow two-dimensional (2D) peak at position 1 suggests that it could be as thin as monolayer graphene. In comparison, the relative weak and broad 2D peak at position 2 can be fitted by several Gaussian or Lorentzian peaks, representing the characteristics of a few layers. Thus, the saturable absorber used here is nonuniform atomic multilayer graphene, and its thickness varied from 0.4 to 2.8 nm based on atomic force microscopy measurement. The linear insertion loss of our graphene film is about 1.25 dB. Figure 1(d) shows the nonlinear transmission of the graphene film. The modulation depth was estimated to be about 8%.

We have constructed an YDF laser, as schematically shown in Fig. 2, for the passive mode locking experiment. A ring cavity configuration was adopted. The laser was bidirectionally pumped with two 975 nm pump lasers, each with a maximum output power of 150 mW. A segment of 72 cm YDF with absorption of 1020 dB/m at 977 nm (AD465-00 from FIBERCORE) was used as the gain medium. All the other fibers used were the standard

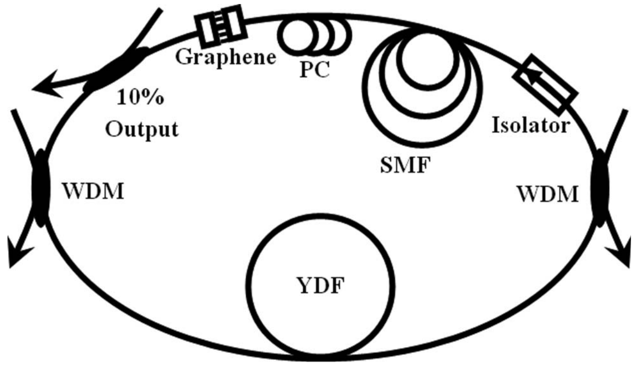

Fig. 2. Schematic of the fiber laser. WDM, wavelength-division multiplexer; YDF, ytterbium-doped fiber; SMF, single-mode fiber; PC, polarization controller.

SMF (Corning HI1060). A segment of around 210 m SMF was used to lengthen the cavity. The total cavity length was about 222 m. A fiber pigtailed polarization-independent isolator and an inline polarization controller (PC) were used to force the unidirectional operation of the laser cavity and to fine-tune the linear cavity birefringence, respectively.

With appropriate PC setting, self-started mode locking of the fiber laser occurred at a pump power of 115 mW (with forward pump power of 60 mW and backward pump power of 55 mW). Similar to the operation of the other passively mode-locked fiber lasers, multiple pulses were initially obtained immediately after the laser mode locking. However, carefully reducing the pump power to 100 mW (with forward pump power reducing to 45 mW while maintaining the backward pump power of 55 mW), single pulse operation could be obtained, as shown in Fig. 3. The optical spectrum and pulse profile, pulse train, and the rf spectrum of the mode-locked pulses are shown

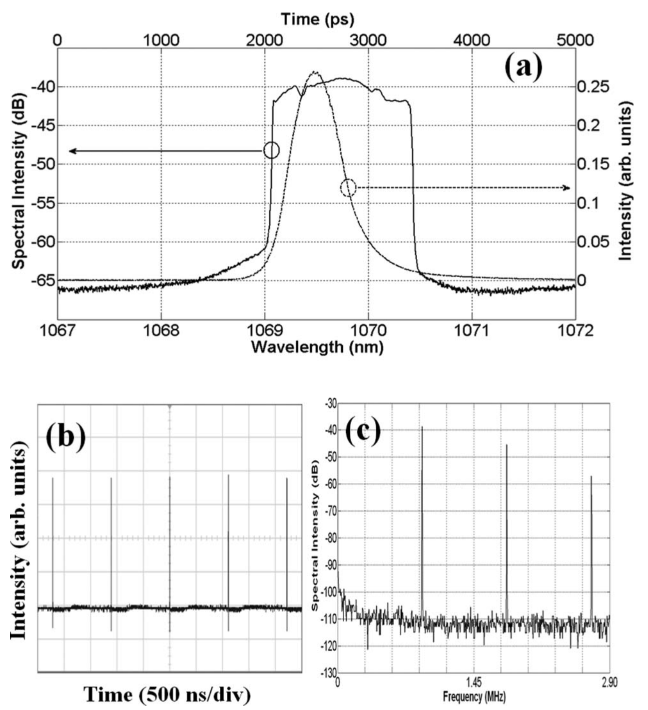

Fig. 3. (a) Optical spectrum and pulse profile, (b) pulse train, (c) rf spectrum of the mode-locked pulses.

in Figs. 3(a)–3(c), respectively. The optical spectrum shown in Fig. 3(a) exhibits the characteristic steep spectral edges, which clearly shows that the mode-locked pulses have been shaped to DSs. DS generation is a generic feature of nonlinear pulse propagation in normal dispersion fiber lasers. It is a result of the mutual interaction among the effects caused by normal cavity dispersion, the fiber nonlinear Kerr effect, laser gain and loss, and the effective cavity gain bandwidth filtering [9,10]. The central wavelength of the DS is located at 1069.8 nm and the spectrum has a 3 dB bandwidth of about 1.29 nm. Similar narrow bandwidth DSs were also obtained in the CNT mode-locked YDF lasers [11,12]. The DS pulse width was measured with a high-speed oscilloscope (Agilent 86100A) and a 45 GHz photodetector (New Focus 1014). It was 580 ps. The time–bandwidth product is therefore 196, which shows that the DSs are strongly chirped, a typical feature of the DSs. Because of the lack of required devices, we did not carry out the continuous pulse compression versus compensating dispersion. However, with the help of a chirped mirror with a bandwidth larger than 90 nm and group velocity dispersion of $-100\ \mathrm{fs}^2$, we found that the pulses could be compressed to 560 ps, showing that they are compressible. The pulse train has a pulse repetition rate of about 0.9 MHz, which agrees with the cavity length. The signal-to-noise ratio of the fundamental repetition rate is larger than 70 dB above the noise level, indicating that the laser mode-locking operation is very stable. The laser output power coupled through a 10% fiber coupler was about 0.37 mW. Therefore, the output pulse energy is about 0.41 nJ. The low peak power and broad pulse width of the generated DS made it a perfect seed pulse source for pulse amplification.

To verify that the mode locking resulted from the graphene, we purposely removed the graphene film from the cavity. As no polarization-dependent components were used in the cavity, no mode locking was observed, even under the maximum available pump power. We also studied the short cavity laser operation by removing the 210 m SMF; no DSs could be obtained even when both pump lasers were operated at the maximum pump power. The long cavity corresponds to a small fundamental repetition rate, which greatly increases the pulse energy of the random surge of the background noise. As the saturable absorption of the atomic layer graphene is wavelength independent, larger pulse energy facilitates mode locking. Therefore, mode locking could be achieved in a long cavity. The narrow bandwidth of the generated DSs was not expectated, as there is no narrow bandpass filter in the cavity. We suspect that the narrow bandpass filtering might result from the large cavity birefringence and the associated birefringence filter effect, which frequently appeared in fiber ring lasers with long cavity length [13].

In conclusion, we have experimentally demonstrated passive self-started mode locking of an YDF laser with multilayer graphene as the mode locker for the first time, to the best of our knowledge. Stable DSs with pulse width of 580 ps were generated. Together with our previous result on graphene mode locking of erbium-doped fiber lasers at 1.5 μm wavelength, our experiment clearly demonstrated the wavelength-independent saturable absorption feature of the atomic layer graphene and the feasibility of using graphene to passively mode lock fiber lasers of various operating wavelengths.

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References

1. I. N. Duling III, Opt. Lett. **16**, 539 (1991).
2. V. J. Matsas, T. P. Newson, D. J. Richardson, and D. J. Payne, Electron. Lett. **28**, 1391 (1992).
3. O. G. Okhotnikov, T. Jouhti, J. Konttinen, S. Karirinne, and M. Pessa, Opt. Lett. **28**, 364 (2003).
4. S. Y. Set, H. Yaguchi, Y. Tanaka, M. Jablonski, Y. Sakakibara, A. Rozhin, M. Tokumoto, H. Kataura, Y. Achiba, and K. Kikuchi, in *Optical Fiber Communication Conference*, Technical Digest (CD) (Optical Society of America, 2003), paper PD44.
5. S. Kivistö, T. Hakulinen, A. Kaskela, B. Aitchison, D. P. Brown, A. G. Nasibulin, E. I. Kauppinen, A. Härkönen, and O. G. Okhotnikov, Opt. Express **17**, 2358 (2009).
6. J. C. Travers, J. Morgenweg, E. D. Obraztsova, A. S. Lobach, A. I. Chernov, E. J. Kelleher, S. V. Popov, and J. R. Taylor, in *Conference on Lasers and Electro-Optics*, OSA Technical Digest (CD) (Optical Society of America, 2010), paper JWA90.
7. Q. Bao, H. Zhang, Y. Wang, Z. Ni, Y. Yan, Z. X. Shen, K. P. Loh, and D. Y. Tang, Adv. Funct. Mater. **19**, 3077 (2009).
8. Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D. M. Basko, and A. C. Ferrari, ACS Nano **4**, 803 (2010).
9. L. M. Zhao, D. Y. Tang, and J. Wu, Opt. Lett. **31**, 1788 (2006).
10. A. Chong, J. Buckley, W. Renninger, and F. Wise, Opt. Express **14**, 10095 (2006).
11. E. J. R. Kelleher, J. C. Travers, Z. Sun, A. G. Rozhin, A. C. Ferrari, S. V. Popov, and J. R. Taylor, Appl. Phys. Lett. **95**, 111108 (2009).
12. E. J. R. Kelleher, J. C. Travers, E. P. Ippen, Z. Sun, A. C. Ferrari, S. V. Popov, and J. R. Taylor, Opt. Lett. **34**, 3526 (2009).
13. H. Zhang, D. Y. Tang, X. Wu, and L. M. Zhao, Opt. Express **17**, 12692 (2009).