Dual-wavelength single-longitudinal-mode fiber laser with switchable wavelength spacing based on a graphene saturable absorber

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Received January 6, 2015; revised February 10, 2015; accepted February 13, 2015;
posted February 17, 2015 (Doc. ID 231522); published March 17, 2015

We propose and demonstrate a dual-wavelength single-longitudinal-mode (SLM) fiber laser with switchable wavelength spacing based on a graphene saturable absorber (GSA) and a WaveShaper. By virtue of the excellent saturable absorption ability of graphene, the linewidths of the lasing wavelengths can be effectively reduced and eventually SLM operation can be obtained. The linewidths of both wavelengths are measured to be narrower than 7.3 kHz. The obtained results suggest that the graphene would be a good candidate nonlinear optical material for applications in related photonic fields, such as SLM oscillation generation for microwave generation and optical sensing.

OCIS codes: (140.3510) Lasers, fiber; (140.3570) Lasers, single-mode; (160.4330) Nonlinear optical materials.
http://dx.doi.org/10.1364/PRJ.3.000A21

1. INTRODUCTION

Dual-wavelength single-longitudinal-mode (SLM) lasers have been extensively studied because of their special applications in microwave generation [1–6] and optical fiber sensing [7,8] due to their advantages of low phase noise, low power consumption, and narrow linewidth. To date, there are mainly three kinds of techniques reported to achieve dual-wavelength SLM fiber lasers: (1) the use of a short cavity, such as distributed feedback (DFB) and distributed Bragg reflector fiber lasers, combined with special fiber Bragg gratings [1,2,7,8] has relatively good stability, but suffers from very low output power, and the wavelength spacing is not easily tunable; (2) the employment of high-fineness subcavity or ultranarrow filters in the cavity [3,4], but it is somewhat complicated to optimize the subcavity length; and (3) the utilization of the combined filtering effect of a dual-wavelength filter and an unpumped erbium-doped fiber as a saturable absorber [5,6], in which the length of the unpumped fiber must be optimized to obtain SLM output.

In recent years, graphene, which is an atomic layer of conjugated sp^2 carbon atoms arranged in a two-dimensional hexagonal lattice [9], has attracted much interest in both photonics and optoelectronics applications. Its ultrafast carrier dynamics combined with large absorption and Pauli blocking make graphene possess excellent features, such as high mobility, good optical transparency, and ultrawideband absorption [10]. So far, graphene saturable absorbers (GSAs) have been used mostly for pulse generation in fiber lasers [11–16]. However, according to the principle of saturable absorbers, it is expected that the GSA could be used to narrow the lasing linewidth. This feature would find potential application in achieving SLM operation in fiber lasers [17]. Considering the wide applications of dual-wavelength SLM lasers, it would be interesting to realize dual-wavelength SLM operation in a fiber laser with a GSA.

In this paper, a dual-wavelength SLM fiber laser with switchable wavelength spacing based on a GSA and a WaveShaper is proposed and demonstrated. Saturable absorption of the graphene and the narrow bandwidth filtering effect of the WaveShaper guarantee SLM operation of the laser. By appropriate adjustments of the filtering characteristic of the WaveShaper, dual-wavelength SLM oscillation with switchable wavelength spacing has been achieved. Each wavelength has a linewidth of less than 7.3 kHz and a side-mode suppression ratio (SMSR) larger than 50 dB. The wavelength spacing can be switchable among 0.33, 0.50, 0.70, and 0.92 nm. Furthermore, a tunable multiwavelength SLM fiber laser can be possibly obtained by employing a tunable multiwavelength filter.

2. EXPERIMENTAL SETUP AND OPERATION PRINCIPLE

The experimental setup of the proposed dual-wavelength SLM fiber laser is shown in Fig. 1. It consists mainly of a semiconductor optical amplifier (SOA), a WaveShaper, a GSA, two polarization controllers (PCs), and an 80:20 output coupler. The SOA is used as a gain medium and has a maximum gain of about 23 dB and a bandwidth of about 60 nm. Two isolators (ISOs) are inserted before and behind the SOA to ensure unidirectional operation. PCs are used before the SOA and GSA for optimum performance since the gain of the SOA and the property of the GSA here are polarization dependent.

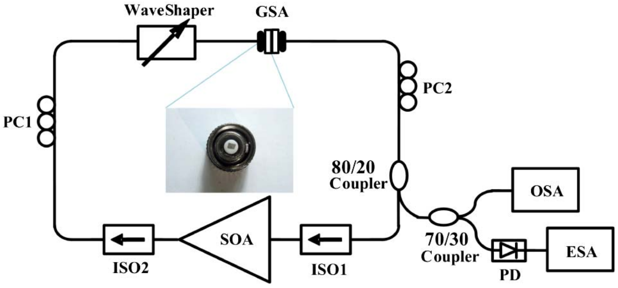

Fig. 1. Experimental setup of the proposed fiber laser.

The GSA is sandwiched between two fiber connectors with a fiber adaptor, using alcohol for our experiment, as shown in the inset of Fig. 1. The 20% output is divided into two parts by a 30:70 coupler: the 30% part is measured by an optical spectrum analyzer (OSA) with a resolution of 0.02 nm; the other part is measured using a 13 GHz electronic spectrum analyzer (ESA) after being detected at a photodetector (PD).

One of the key components in the proposed scheme is the GSA. The GSA is composited by polyvinyl alcohol (PVA) to make it as a filmy type [18]. The process of the PVA-GSA fabrication is as follows: the dispersion enriched graphene dimethylformamide (DMF) solution with a concentration of 0.075 mg/mL is prepared by ultrasonicating for 1 h. Then a 1 mL graphene DMF solution is mixed with a 5 mL aqueous solution of PVA and ultrasonicated for 30 min. The mixture is then evaporated at room temperature on a slide glass, resulting in the formation of a filmy PVA–graphene composite.

The principle of the spectral narrowing effect of the GSA can be explained as in Ref. [17], and the saturable absorber can be used to suppress the multi-longitudinal-modes and noises in a fiber laser. Thus, SLM oscillation can be possibly achieved by using the GSA in the laser cavity.

Another key component in the proposed scheme is the WaveShaper, which is a programmable optical filter with full control of filter amplitude, center wavelength, bandwidth, and shape characteristics. The WaveShaper 4000S supports arbitrary user-generated filter shapes. In this experiment, the WaveShaper is programmed to act as a dual-wavelength narrow bandpass filter. Both the passband spacing and the passband amplitude can be controlled with a minimum grid of 0.1 nm. When the center wavelength of the WaveShaper is fixed, the specified two channels can be programmed, respectively, to the preceding grid and the next grid. That is, the wavelength spacing can be variable with a step of about 0.2 nm during the switching process. Therefore, dual-wavelength SLM operation with switchable wavelength spacing can be achieved by combination of the narrowing effect of the GSA and the WaveShaper from the proposed fiber laser.

3. RESULTS AND DISCUSSION

In the experiment, lasing operation could be obtained with ~35 mA drive current of the SOA. For better performance, we set the drive current to be 85 mA. The center wavelength of the WaveShaper was fixed at 1545 nm, while the passband spacing between the defined two wavelengths varied from about 0.3 to 0.9 nm with a step of 0.2 nm, and each of the longer wavelengths was given an attenuation of 0.3 dB for less amplitude difference between wavelengths. In this case, the dual-wavelength SLM lasing with switchable wavelength spacing has been achieved through proper adjustment of the PCs. The output optical spectra of switchable dual-wavelength operation are summarized in Fig. 2. As can be seen here, the wavelength spacing can be switched among about 0.33 nm (black solid line), 0.50 nm (red dashed line), 0.70 nm (blue dashed–dotted line), and 0.92 nm (green short dashed line), which is well consistent with the passband spacing defined by the WaveShaper. All the output oscillations have a SMSR of at least 50 dB.

To verify the SLM operation of the proposed laser system, we measured the beating radio frequency (RF) spectrum of the laser output using an ESA with a resolution bandwidth (RBW) of 100 kHz. Figure 3(a) shows the RF spectrum of the laser output when the wavelength spacing of the oscillation is 0.70 nm. Since the estimated longitudinal-mode spacing of the laser is to be about 10 MHz, the RF spectrum confirms that only a single longitudinal mode exists and the laser is

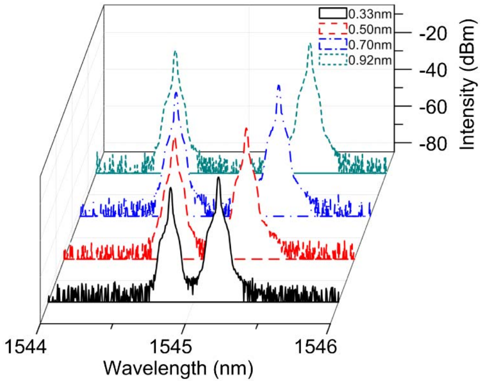

Fig. 2. Optical spectra of the laser with switchable wavelength spacing.

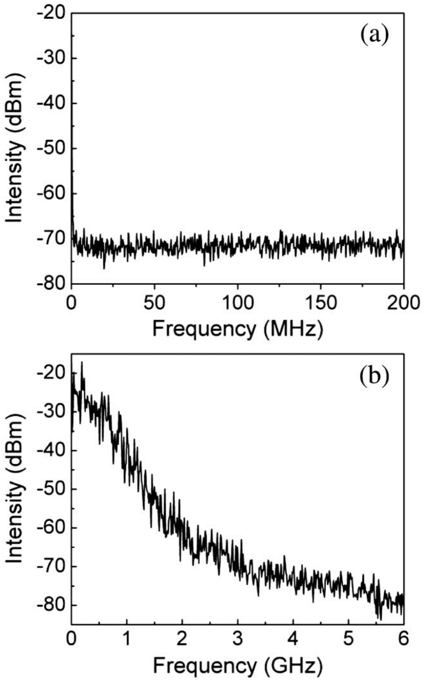

Fig. 3. RF spectra of the laser output under (a) SLM operation with the GSA, and (b) multi-longitudinal-mode operation without the GSA in the laser cavity.

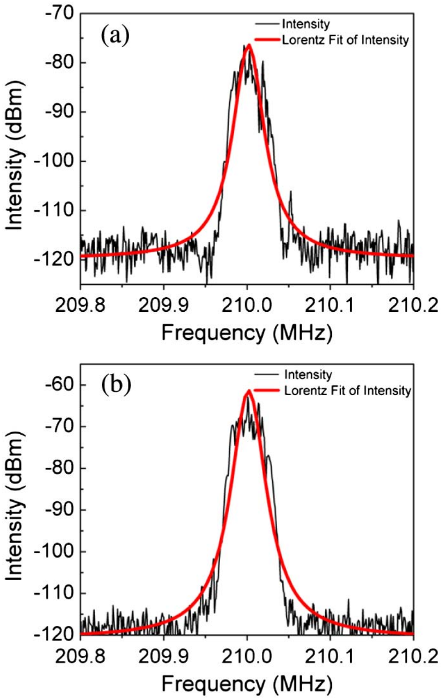

Fig. 4. Typical delayed self-heterodyne RF spectra of lasing wavelengths of (a) 1544.66 and (b) 1545.36 nm.

under SLM operation since there are no beat notes between longitudinal modes. The RF spectrum of the laser output without the GSA in the laser cavity is also shown in Fig. 3(b) for comparison. The RF spectra in Fig. 3(b) actually represent the envelopes of the beat frequency signals between the longitudinal modes in the detected signal, so we can estimate the linewidth of the signal from the width of the envelope to be less than 500 MHz. There were beat frequency signals between the longitudinal modes spaced at about 10 MHz (according to the longitudinal-mode spacing of the laser cavity) under the envelope. Clearly, the laser was under multi-longitudinal-mode operation without the GSA, which confirmed the important function of the GSA in obtaining SLM laser output.

The linewidth of each wavelength of the laser output was measured using the delayed self-heterodyne method. Figures 4(a) and 4(b), respectively, show the delayed self-heterodyne RF spectra of lasing wavelengths of 1544.66 and 1545.36 nm when the wavelength spacing of the output is 0.70 nm. The Lorentz curve fittings of intensity are also shown (the red line). Assuming the laser spectrum to be Lorentzian-shaped, the full width at half-maximum (FWHMs) of the two wavelengths are estimated to be about 7.27 and 6.83 kHz, calculated, respectively, from the −10 dB bandwidths of 43.6 and 41 kHz.

To characterize the stability of the proposed fiber laser, the output power fluctuation of each wavelength was also investigated. The measured power variation as a function of time is shown in Fig. 5. The power fluctuations of the two wavelengths are less than 0.6 and 0.4 dB in a period of 10 min. The average output powers of the two wavelengths are about −17.40 and −11.70 dBm. The measured results show that the fiber laser operated stably at room temperature. However, it is expected that the power stabilities can be further improved when the external environmental conditions are better.

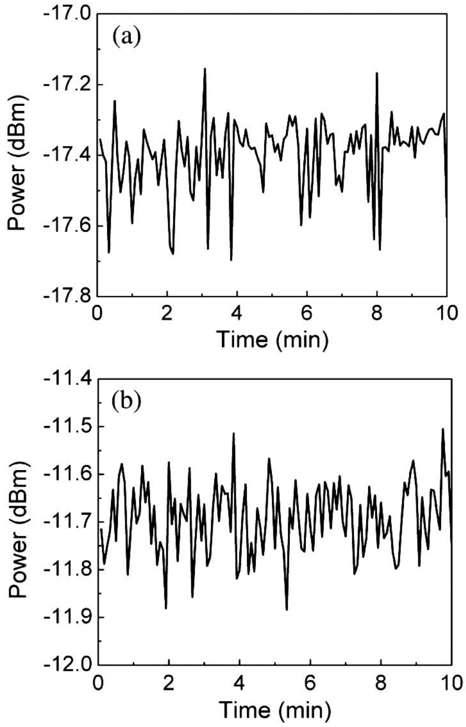

Fig. 5. Power fluctuation of lasing wavelengths of (a) 1544.66 and (b) 1545.36 nm.

One point to note is that other, less expensive dual-wavelength filters can replace the WaveShaper to perform the same function. A tunable multiwavelength SLM fiber laser can be possibly obtained by using another narrow bandwidth comb filter, such as a F-P filter or a high-birefringence-fiber loop mirror, though the filtering effect and the stabilities of these filters may not be as good as that of the WaveShaper.

4. CONCLUSION

In conclusion, we have successfully proposed and experimentally demonstrated a dual-wavelength SLM fiber laser based on a GSA and a WaveShaper. The WaveShaper is responsible for the dual-wavelength selection. Both the GSA and the WaveShaper introduce a narrow bandwidth filtering effect to guarantee SLM operation of the laser. The obtained results suggest that graphene could be a good candidate for the nonlinear optical material for generation of multiwavelength single-frequency oscillations for microwave generation and optical sensing.

ACKNOWLEDGMENTS

This work was supported by the National Natural Science Foundation of China (No. 61475065).

REFERENCES

1. J. Sun, Y. T. Dai, X. F. Chen, Y. J. Zhang, and S. Z. Xie, “Stable dual-wavelength DFB fiber laser with separate resonant cavities and its application in tunable microwave generation,” IEEE Photon. Technol. Lett. **18**, 2587–2589 (2006).
2. S. P. Mo, Z. M. Feng, S. H. Xu, W. N. Zhang, D. D. Chen, T. Yang, C. S. Yang, C. Li, and Z. M. Yang, “Photonic generation of tunable microwave signals from a dual-wavelength distributed-Bragg-reflector highly Er^{3+}/Yb^{3+} co-doped phosphate fiber laser,” Laser Phys. Lett. **10**, 125107–125110 (2013).

3. Y. Yao, X. F. Chen, Y. T. Dai, and S. Z. Xie, "Dual-wavelength erbium-doped fiber laser with a simple linear cavity and its application in microwave generation," IEEE Photon. Technol. Lett. **18**, 187–189 (2006).
4. S. L. Pan and J. P. Yao, "Frequency-switchable microwave generation based on a dual-wavelength single-longitudinal-mode fiber laser incorporating a high-fineness ring filter," Opt. Express **17**, 12167–12173 (2009).
5. S. L. Pan and J. P. Yao, "A wavelength-switchable single-longitudinal-mode dual-wavelength erbium-doped fiber laser for switchable microwave generation," Opt. Express **17**, 5414–5419 (2009).
6. S. C. Feng, C. H. Qi, Q. Li, W. J. Peng, S. Gao, and S. S. Jian, "Photonic generation of microwave signal by beating a dual-wavelength single longitudinal mode erbium-doped fiber ring laser based on the polarization maintaining fiber Bragg grating," Microw. Opt. Technol. Lett. **55**, 347–351 (2013).
7. L. Y. Shao, X. Y. Dong, A. P. Zhang, H. Y. Tam, and S. L. He, "High-resolution strain and temperature sensor based on distributed Bragg reflector fiber laser," IEEE Photon. Technol. Lett. **19**, 1598–1600 (2007).
8. B. O. Guan, L. Jin, Y. Zhang, and H. Y. Tam, "Polarimetric heterodyning fiber grating laser sensors," J. Lightwave Technol. **30**, 1097–1112 (2012).
9. Q. L. Bao, H. Zhang, Z. H. Ni, Y. Wang, L. Polavarapu, Z. X. Shen, Q. H. Xu, D. Y. Tang, and K. P. Loh, "Monolayer graphene as a saturable absorber in a mode-locked laser," Nano Res. **4**, 297–307 (2011).
10. F. Bonaccorso, Z. Sun, T. Hasan, and A. C. Ferrari, "Graphene photonics and optoelectronics," Nat. Photonics **4**, 611–622 (2010).
11. Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D. M. Basko, and A. C. Ferrari, "Graphene mode-locked ultrafast laser," ACS Nano **4**, 803–810 (2010).
12. H. Zhang, Q. L. Bao, D. Y. Tang, L. M. Zhao, and K. P. Loh, "Large energy soliton erbium-doped fiber laser with a graphene-polymer composite mode locker," Appl. Phys. Lett. **95**, 141103 (2009).
13. Z. Q. Luo, M. Zhou, J. Weng, G. M. Huang, H. Y. Xu, C. C. Ye, and Z. P. Cai, "Graphene-based passively Q-switched dual-wavelength erbium-doped fiber laser," Opt. Lett. **35**, 3709–3711 (2010).
14. A. P. Luo, P. F. Zhu, H. Liu, X. W. Zheng, N. Zhao, M. Liu, H. Cui, Z. C. Luo, and W. C. Xu, "Microfiber-based, highly nonlinear graphene saturable absorber for formation of versatile structural soliton molecules in a fiber laser," Opt. Express **22**, 27019–27025 (2014).
15. N. Zhao, M. Liu, H. Liu, X. W. Zheng, Q. Y. Ning, A. P. Luo, Z. C. Luo, and W. C. Xu, "Dual-wavelength rectangular pulse Yb-doped fiber laser using a microfiber based graphene saturable absorber," Opt. Express **22**, 10906–10903 (2014).
16. A. Martinez, K. Fuse, and S. Yamashita, "Mechanical exfoliation of graphene for the passive mode-locking of fiber lasers," Appl. Phys. Lett. **99**, 121107 (2011).
17. F. D. Muhammad, M. Z. Zulkifli, A. A. Latif, S. W. Harun, and H. Ahmad, "Graphene-based saturable absorber for single-longitudinal-mode operation of highly doped erbium-doped fiber laser," IEEE Photon. J. **4**, 467–475 (2012).
18. H. Liu, X. W. Zheng, M. Liu, N. Zhao, A. P. Luo, Z. C. Luo, W. C. Xu, H. Zhang, C. J. Zhao, and S. C. Wen, "Femtosecond pulse generation from a topological insulator mode-locked fiber laser," Opt. Express **22**, 6868–6873 (2014).