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Huiquan Li
Yonggang Wang
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Huiquan Li,^a Yonggang Wang,^b Peiguang Yan,^{a,*} Guangzhong Cao,^c Junqing Zhao,^a Gelin Zhang,^a Shisheng Huang,^a and Rongyong Lin^a

^aShenzhen University, College of Electronic Science and Technology, Shenzhen Key Laboratory of Laser Engineering, Key Laboratory of Advanced Optical Precision Manufacturing Technology of Guangdong Higher Education Institutes, Shenzhen, Guangdong 518060, China

^bXi'an Institute of Optics and Precision Mechanics, Chinese Academy of Sciences, The State Key Laboratory of Transient Optics and Photonics, Xi'an 710119, China

^cShenzhen University, Shenzhen Key Laboratory of Electromagnetic Control, Shenzhen, 518060 Guangdong, China

Abstract. We have demonstrated the dissipative solitons generated in an ytterbium-doped fiber laser cavity using graphene oxide as the saturable absorber. The lasing light, centered at 1077.2 nm, has a 3 dB spectral bandwidth of ~ 1.12 nm. Under different launched pump powers and appropriate polarization orientations, harmonic mode-locked of second- and third-order pulse trains have been achieved; the corresponding 3-dB bandwidth and pulse duration have been detected. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.OE.52.12.126102](https://doi.org/10.1117/1.OE.52.12.126102)]

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1 Introduction

Since the first demonstration on graphene mode-locked fiber lasers by Bao et al.,¹ carbon-based materials of graphene²⁻⁴ and nanoscale graphite^{5,6} have been widely investigated in a fiber ring cavity as a novel saturable absorber (SA) for femto-second/picosecond pulse generation. Compared with the semiconductor saturable absorber mirrors⁷⁻⁹ and carbon nanotubes,¹⁰⁻¹² graphene as the saturable absorber shows some terrific properties, which includes lower saturation intensity, less nonsaturable loss, higher damage threshold, larger absorption (2.3% per single graphene sheet), and wavelength independence from visible to infrared due to its zero bandgap property.¹ Up to now, many investigations¹³⁻¹⁷ have been reported on the GSA-based mode locking fiber laser emitting in different regions of wavelengths. Zhang et al.¹³ and Popa et al.¹⁵ have reported 1550-nm region wavelength emitting from erbium-doped mode locking fiber laser, with the pulse duration of 415 fs and sub-200 fs, respectively. In 2010, 1- μm region pulses were realized by Zhao et al. first by fabricating multilayer graphene in ytterbium-doped fiber (YDF) laser,¹⁴ later in 2011, Jiang et al. demonstrated 163-nJ pulse energy and the wavelength of 1074.5-nm fiber laser realized with the graphene membrane.¹⁶ For 2- μm region wavelength, Wang et al. reported using a few layers of graphene micro-sheets as the SA and constructed an all-fiber passively mode-locked thulium-doped fiber (TDF) ring oscillator with a central wavelength of 1953.3 nm.¹⁷ All the above show that the graphene indeed has a wavelength-independent SA, which could be exploited to mode lock fiber lasers with various operating wavelengths.¹

The graphene oxide (GO) is an atomically thin sheet of carbon covalently bonded with the functional groups containing oxygen. As a saturable absorber, recent research

proved that GO almost has all the characteristics of graphene, but much easier and cheaper to obtain.¹⁸ In Ref. 19, Xu et al. used a GOSA realized mode locking of an erbium-doped fiber laser with a 200 fs pulse duration. Later, they achieved dissipative soliton (DS) of 11 ps laser pulses in normal dispersion cavity.²⁰ The earliest mode-locked EDF laser with GO was demonstrated by Liu et al.²¹ by filling few-layered GO solutions into the hollow core of a PCF; they obtained 4.85 ns pulses at a 7.68 MHz repetition rate. GOSA can also be used for the mode locking of TDF lasers. In Ref. 22, Jung et al. realized ~ 1.3 ps, ~ 15.9 MHz pulse laser by depositing a GO layer on a D-shaped fiber to form an SA. Most recently, Li et al. first reported a GOSA-based passive mode-locked YDF laser with the pulse duration from 191 ps to 1.6 ns with the increase of the cavity length.²³ However, no previous works reported the harmonic mode locking in a GOSA-based YDF laser so far.

In this paper, we have reported a GOSA fabricated all-normal dispersion Yb-doped mode-locked fiber laser with a generation of 2.2 ns pulses duration and 1.58 MHz repetition rate. The YDF lasers oscillated at 1077.2 nm with the 3 dB spectral width of 1.12 nm. Carefully adjusting the polarization controller at different launched powers, second- and third-orders of the harmonic mode-locked pulses are also achieved.

2 Sample Preparation and Experimental Setup

The GO for the experiment was prepared through the vertical evaporation method from chemical oxidized graphite, as in the previous works in Refs. 24-26. The flake of the oxidized graphite is about 1 to 3 atomic layers and 0.1 to 5.0 μm of the diameter. At the first step, several milligrams of the powder were poured into 10 ml 0.1% sodium dodecyl sulfate (SDS) aqueous solution and ultrasonically agitated for 10 h, with SDS used as surfactant; following that, we centrifugated the hybrid solution to remove sedimentation of large GO

*Address all correspondence to: Peiguang Yan, E-mail: yanpg@szu.edu.cn

clusters. Next, we got the upper portion of the centrifuged solution for use, then diluted and poured into a polystyrene cell. A hydrophilic quartz substrate was also inserted vertically into the cell. The polystyrene cell was placed on a table in the atmosphere for gradual evaporation. Several days later, a GO thin film was obtained from coating on the substrate. The GO sample showed a difference of both thickness and concentration from the top to the bottom, providing a flexible choice for different needs. The concentration of the used GO sample was reported in Ref. 26, with a thickness of ~ 0.03 nm. We cut $\sim 1 \times 1$ mm² GOSA sample of needed thickness and concentration and sandwiched it between two fiber connectors (FC-PC), then finally mounted it on the fiber laser.

The SA property of the GO was shown in Fig. 1. The laser source used was a homebuilt mode-locked oscillator with a 5 MHz repetition rate and a 150 ps pulse duration operating at about 1064 nm. The data obtained from the experiment were then fitted according to

$$\alpha(I) = \alpha_0 \left(1 + \frac{I}{I_{\text{sat}}} \right)^{-1} + \alpha_{\text{ns}}, \quad (1)$$

where I is the input laser intensity, I_{sat} is the saturation intensity (the intensity with the absorption coefficient of half the initial value), $\alpha(I)$ is the intensity-dependent absorption coefficient, and α_0 and α_{ns} are the modulation depth and the nonsaturable loss, respectively. The results give a saturation intensity of ~ 8.5 MW/cm², modulation depth of $\sim 25.2\%$, and nonsaturable loss of $\sim 42.1\%$. The larger modulation depth may benefit the shorter mode-locked pulses oscillating.

The fiber laser was schematically shown in Fig. 2. The total length of the cavity was about 125 m and consisted of 5.5 m YDF and ~ 100 m Corning HI1060 Flex single-mode fiber (SMF). The inserted SMF could lengthen the laser cavity so as to increase the single pulse energy out from the background noise, benefiting the mode locking operation.¹⁴ The YDF had a core absorption of 1000 dB/m at 976 nm, and was pumped by the 974 nm laser diode through a 980/1060 wavelength division multiplexer. To ensure unidirectional operation and eliminate undesired feedback from the output end facet, an isolator was inserted into the cavity. The polarization controller (PC) mounted on the cavity was used to achieve different polarization orientation states. The

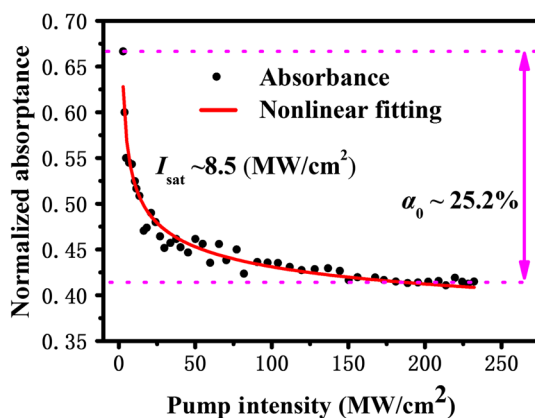


Fig. 1 Nonlinear absorbance of the utilized graphene oxide saturable absorber (GOSA) piece.

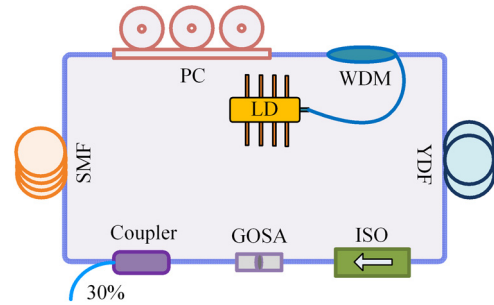


Fig. 2 The schematic configuration of the laser cavity integrated with the GOSA. PC, polarization controller; WDM, wavelength division multiplexer; YDF, ytterbium-doped fiber; ISO, isolator; GOSA, graphene oxide saturable absorber; SMF, single mode fiber.

sandwich fabricated GOSA and a 30:70 couple were also incorporated in laser cavity. The spectra were monitored by an optical spectrum analyzer (Yokogawa AQ-6370, Tokyo, Japan), and the mode-locked pulse trains were detected by a 1 GHz digital storage oscilloscope, together with a 1 GHz photodetector.

3 Experimental Result and Analyses

In this experiment, the continuous wave operation started at a pump power of ~ 100 mW. We continued to increase the pump power and carefully adjust the PC, until the mode locking pulse trains occurred at 106.5 mW. Slightly reducing the pump power to 104 mW, the stable pulse train remained stable. The output pulse was depicted in Fig. 3(a), showing that the pulse duration was ~ 2.0 ns. The repetition rate of the laser was measured as 1.583 MHz with the side-mode suppression ratio of 50 dB, as shown in Fig. 3(b). With the fundamental frequency pulse train depicted in Fig. 4(a), the pulse train had a period of 631.7 ns, rightly matching with the cavity round trip time, which were the characteristics of the mode locking operation. The inset in Fig. 4(a) at the top right presented a typical measured optical spectrum centered at 1077.68 nm, with the 3-dB bandwidth of 1.22 nm. The time-bandwidth product showing strongly chirped in the cavity. The steep spectral edges clearly indicated that the mode-locked pulses had been shaped to DSs. DSs generally generated in the normal dispersion fiber laser cavity; it is caused by the mutual interactive effect among the fiber nonlinear Kerr effect, laser gain and loss, and the effective cavity gain bandwidth filtering.¹⁴ Figures 4(d) showed the pulse duration and the 3 dB spectral width evolution during the pump power variation. The DSs pulses were not destroyed until the pump power was up to 108.5 mW.

In our experiment, further increasing the launched power and appropriately adjusting the PC, second- and third-order harmonic mode-locked pulses were also observed, as depicted in Figs. 3(a) and 3(b). In Figs. 4(d) to 4(f), the pulse duration and the 3-dB bandwidth versus the launched power were plotted. From the plots, it could be seen that both of them become larger when the pump power increased. By increasing the launched power, the pulse duration varied from 2.03 to 2.22 ns in the fundamental operation while in the third-order, it varied from 1.97 to 2.07 ns. Simultaneously, the 3-dB bandwidth of the fundamental operation varied within 0.99 to 1.12 nm, while the third harmonic varied from 0.93 to 0.99 nm. The simulation experiments had been reported in Ref. 27. Qualitatively, increasing the pump power would

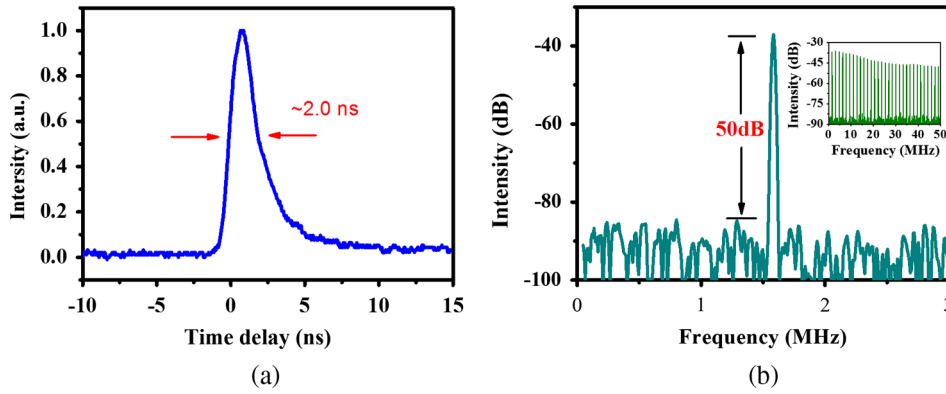


Fig. 3 (a) Typical mode-locked pulse profile and (b) fundamental frequency of a typical RF spectrum of the laser output.

enhance the nonlinear effects such as SPM and the dispersion induced chirp and lead the spectral to become broader. Due to the larger normal dispersion of the fiber laser and without a compressor, the broader spectrum induced longer duration of pulses. Also from the Figs. 4(d) to 4(f), we could see that higher-order harmonic exhibited a relatively narrower bandwidth and shorter pulse duration. Cheng et al. had explained

in detail the mechanism of the formation in an anomalous fiber laser.²⁸ What was interesting was that in our experiment, it showed the same consequence in enormous normal dispersion fiber cavity qualitatively. From the view of Haboucha,²⁹ the multiple pulse formation in the normal dispersion regime of passively mode-locked fiber ring lasers was caused by the influence of the spectral filtering effect in

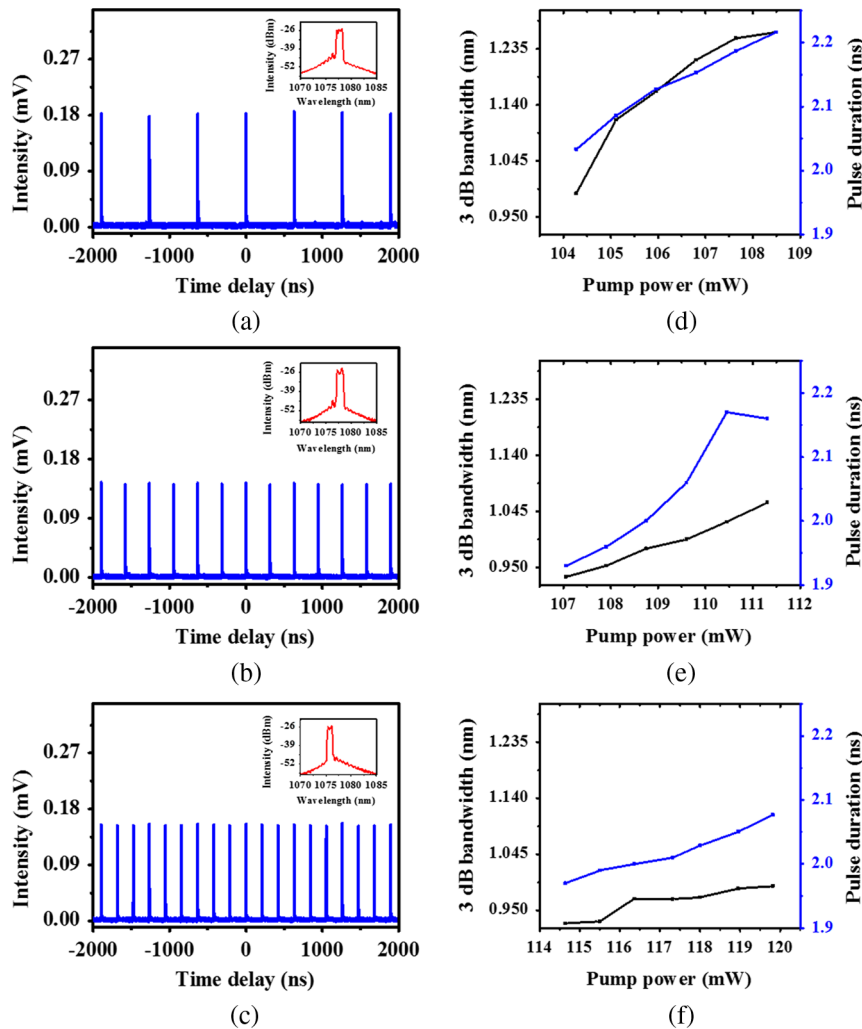


Fig. 4 (a–c) The oscilloscope traces of harmonic mode locking pulses of orders from 1 to 3 and the matching spectra; (d–f) the pulse duration and the 3-dB bandwidth variation versus the launched power.

the cavity. It was shown numerically that the number of pulses increases as the filter bandwidth decreases. Peng et al.³⁰ reported higher-order harmonic emitting narrower spectrum pulses, and all the normal dispersion laser cavity in our work emitted shorter duration pulses.

Similar to soliton operating in fiber laser with net negative cavity group-velocity dispersion, the mechanism of multiple DSs formation is also mainly caused by the cavity pulse peak clamping effect.³¹ When increasing the pump strength, the soliton peak intensity increased and was then clamped by the cavity. Further increasing, the background dispersive waves caught the energy, and then shaped it into a new DS, spatially separated from the dispersive waves. In this latter case, pulses could rearrange themselves to occupy the cavity uniformly, leading to harmonic mode locking.

4 Conclusion

We had experimentally achieved DSs with GOSA in all fiber laser cavities. The single pulse duration was ~ 2 ns at 1077.2 nm. Under the advisable pumping power and suitable rotation position of the PC, second and third-order harmonic mode-locked pulses were also achieved; the evolution of the 3-dB bandwidth and the pulse duration of the output pulse with different launched power of each condition had been detected, speculating that higher-order harmonics went with narrower bandwidth and shorter pulse duration.

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Li Huiquan is studying for a master's degree at the Shenzhen Key Laboratory of Laser Technology, College of Electronic Science and Technology, Shenzhen University. His current research interests concentrate on mode-locked fiber lasers based on graphene oxide as well as on other kinds of saturable absorbers.

Yan Peiguang received a PhD degree in the College of Physics Science from Nankai University (China) in 2005. Currently, he works at the Shenzhen Key Laboratory of Laser Technology, and the College of Electronic Science and Technology, Shenzhen University. Recently, he obtained a grant from the National Natural Science Foundation of China (NSFC) under Grant No. 61007054. His research interests include fabrication and characterization of photonic crystal fibers, photonic crystal fiber-based supercontinuum sources, components and development of rare earth-doped photonic crystal fiber laser systems.

Biographies of the other authors are not available.