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860 femtoseconds mode-locked fiber laser by Gallium co-doped erbium fiber (Ga-EDF)

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ABSTRACT

We proposed and demonstrated a high power mode-locked fiber laser using a new type of gain medium which is called as Erbium Gallium co-doped fiber (Ga-EDF). The mode-locking mechanism is enabled by a graphene-based saturable absorber, which is fabricated by slotting a single layer graphene (SLG) thin film in between two fiber ferrules connected through an adaptor. The Ga-EDF has an absorption rate of 25 dB/m at 980 nm. With a 2-m-long Ga-EDF utilized as the primary gain medium in the laser system, the proposed laser can generate mode-locked solitons, with the central wavelength of 1560 nm, a 3 dB bandwidth of 3.20 nm and an average output power of 18.23 mW. The generated pulse yields a repetition rate of 12.25 MHz with pulse duration and pulse energy of 860 fs and 1.49 nJ respectively. For comparison purpose, the experiment is repeated by replacing the Ga-EDF in the laser cavity with the same length of 2-m-long conventional erbium-doped fiber (EDF), and similar measurement of the mode-locked output performance is undertaken. The result obtained shows in comparison an improvement of the mode-locked Ga-EDF laser output performance to that of the mode-locked EDF laser in terms of the 3 dB bandwidth, pulse width and signal-to-noise ratio. The proposed work is the first time, to the knowledge of the authors, that the application of Ga-EDF as an active gain medium in the development of mode-locked fiber laser incorporating graphene which is a thin layer film as a saturable absorber is explored.

Introduction

The fast advancement of optical technology has drawn great consideration among the researchers across the globe, especially in the field of biomedical research [1], spectroscopy [2], microscopy [3] and tomography [4,5]. The rapid progress of the technology was made possible by the generation of laser pulses that are utilized as a tool in supporting the applications above. The mode-locked fiber laser is the pulsed laser which is commercially used apart from the Q-switched pulsed lasers. Significant differences between these two types of pulsed lasers can be highlighted in terms of the pulse duration, whereby the pulse duration of a Q-switched laser is higher than that of the mode-locked laser which leads to lower repetition rate in Q-switched lasers [6]. Another difference between mode-locked and Q-switched pulsed lasers can be described in terms of the pulse energy whereby the Q-switched laser emits higher pulse energy, in the range of millijoules, compared to a mode-locked pulse energy of within nanoJoules [7,8]. In general, a variety of wavelength emission regions such as 1060 nm, 1530 nm, 1565 nm and 2000 nm are presently accessible by using different types of gain media in the laser cavity [9–12].

To create a pulsed fiber laser, a saturable absorber can be incorporated in the laser cavity, which can be formed by various types of nanomaterials. These nanomaterials, namely graphene [13], carbon nanotubes [14], molybdenum disulfide [15], MXene [16] and bismuth selenide [17] are currently reflected as great candidates to be functionalized as the saturable absorbers due to their advantages of high ability to absorb and release light typically within nanoseconds time interim [18]. Above all, graphene material has its own advantage when working as saturable absorbers, by its fast response time, broadband operation suitable for tunable operation and cost-effective fabrication [19,20]. As in the case of generating the necessary laser output wavelength, the erbium-doped fibers (EDFs) [21] and semiconductor optical amplifiers (SOAs) [22] have long been dominantly used as the active gain media in the laser cavity for emitting the laser in the C- and L-band wavelength region respectively. In comparison, the EDFs are more pronounced than the SOAs as they emit a higher signal to noise ratio [23,24] which is useful in gaining high purity of laser output.

The EDFs that are commonly used are the conventional type of EDFs which are available in the market. The length of the EDFs used typically ranges from 4 to 20 m depending on the absorption coefficient of the fiber [25–28]. However, a drawback of using a longer length of EDF is that the output pulse generated tends to become unsteady, since the

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longer cavity length will result in a higher number of longitudinal modes oscillating inside the optical cavity [29]. As a consequence, the possibility of obtaining the harmonics mode-locking becomes higher which degrades laser stability [30]. In this regards, numerous co-dopant materials have been introduced to provide a higher nature of amplification [31,32]. This is important to reduce the clustering effect in the silica-based EDF. Materials, for example, bismuth, telluride, alumina and phosphate have been used as the co-dopant materials which can overcome the aforementioned limitation.

The application of Ga-EDF as an active gain medium is investigated in order to design a mode-locked fiber laser utilizing graphene as the saturable absorber. The Ga-EDF provides the benefit of improving the gain per length of the commercial EDF, thus improving the stability by having a sufficient amount of erbium ion concentration accordingly, with a minimal length of fiber used in the cavity. The Ga-EDF is fabricated with physical specification equal to conventional optical fiber available in the market, whereby investigation on the characteristics of the fiber is carried out by Dissanayake et al. [33] in 2014. The Ga-EDF has an absorption rate of 25 dB/m at 980 nm. With a 2-m-long Ga-EDF used as the primary gain medium in the laser system, the proposed laser can generate mode-locked solitons, with the central wavelength of 1560 nm, a 3 dB bandwidth of 3.20 nm and an average output power of 18.23 mW. The generated pulse yields a repetition rate of 12.25 MHz with pulse duration and pulse energy of 860 fs and 1.49 nJ respectively. This experiment has been reprised by replacing the Ga-EDF with a 2-m-long conventional EDF and a comparative analysis on the mode-locked output performance using the Ga-EDF and conventional EDF is analyzed. It is observed that the mode-locked Ga-EDF laser has a superior performance compared to the mode-locked EDF laser regarding the 3 dB bandwidth, pulse width and signal-to-noise ratio. This is the first time, to the knowledge of the authors, that the application of Ga-EDF as an active gain medium for generating a compact mode-locked fiber laser using graphene as the saturable absorber is explored.

Experimental setup

Fig. 1 shows the experimental setup of the proposed mode-locked Ga-EDF laser. The procedure of designing Ga-EDF is by utilizing a standard MCVD and solution doping technique reported by Dissanayake [30]. Around 1.45 M concentration of Ga (NO3)3 and 0.025 M concentration of ErCl3 is prepared with a water-based solution. A silica tube is soaked in this solution for an hour and a half in the vertical solution doping apparatus. After solution doping, the tube is then sintered before collapsing into a solid preform. The fiber is then pulled using a standard pulling tower. The core and cladding size of the Ga-EDF produced was 10.1 µm and 125 µm, respectively.

A 980 nm Laser Diode (LD) is used as a pump source to provide energy excitation to the Ga-EDF. The 980 nm pump source is introduced into the cavity through a 980 nm port of a fused 980/1550 nm Wavelength Division Multiplexer (WDM), whereby the 980/1550 nm port of the WDM is connected to the Ga-EDF gain medium. The length of the Ga-EDF used is 2 m and the signal absorption coefficient of the fiber is 45 dB/m at 1540 nm. The output of Ga-EDF is then connected to the input port of an optical isolator (ISO 1) as to ensure uni-directional oscillation in the clockwise direction within the ring cavity, which is then connected to the graphene-based saturable absorber (SA) which have been characterized with a modulation depth of 6% and saturation intensity of 2.2 MW/cm^2. Since the SA is formed by sandwiching a thin layer of graphene between two FC/PC connectors, this SA assembly is exposed to Fresnel reflection which would disrupt the laser stability. Hence, to minimize this defect, the signal passing through the SA assembly is channeled to another optical isolator (ISO 2) to further prevent the backward reflections in the cavity. The output from ISO 2 is then connected to an optical polarization controller (OPC) to reduce cavity birefringence effect by adjusting the signal polarization state and subsequently to a 70:30 fused coupler. The 70% port of the optical coupler is connected back to the 1550 nm port of the WDM, thereby completing the laser cavity. On the other hand, the 30% port of the optical coupler is used to extract a portion of the oscillating signal for further analysis and is connected to a Yokogawa AQ6370B optical spectrum analyzer (OSA) with a resolution of 0.02 nm for spectral measurements. To analyze the pulse train characteristics of the laser's output, a Tektronix TDS3012C oscilloscope together with a photodetector is used in place of the OSA. The total cavity length of this proposed setup is 17.5 m. For performance appraisal and comparison purpose, the Ga-EDF is withdrawn from the cavity and replaced with the conventional Ge/Al co-doped Erbium-doped fiber (Lucent HP 980) of the same length which is denoted as HP-EDF and the same measurement is repeated by using the HP-EDF as the active gain medium.

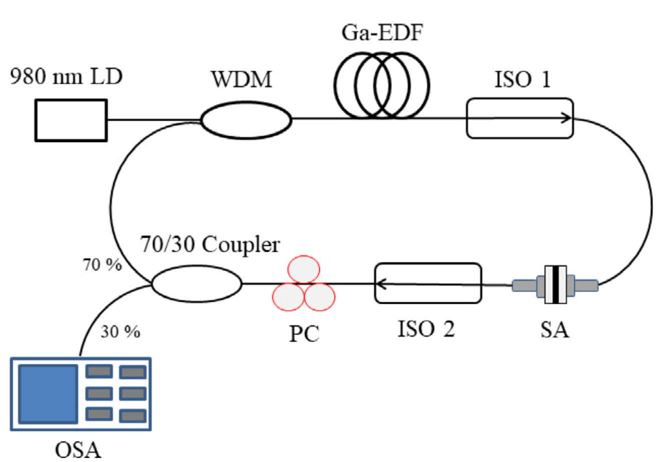

Fig. 1. Experimental setup of the mode-locked Ga-EDFL.

Results and discussion

Fig. 2 shows the amplified spontaneous emission (ASE) spectra of both Ga-EDF and HP-EDF, which are plotted together in a single graph. As can be seen from the figure, in overall, the output power level of the ASE emitted by the Ga-EDF is higher than that of the HP-EDF, which is attributed to the higher amount of erbium-dopant in Ga-EDF. For the Ga-EDF, the highest peak emission of the ASE is observed at 1533 nm with an output power of −32 dBm. On the other hand, the maximum peak emission for the HP-EDF is observed at 1530 nm with an output power of −65 dBm. The ASE spectrum of the Ga-EDF also possesses a slightly wider bandwidth compared to that of the HP-EDF, thus, concomitant to broad wavelength operation of the graphene layer, utilized in the experiment.

Fig. 3 shows the output spectra of the mode-locked lasers, whereby the blue trace indicates the output spectrum generated from the mode-

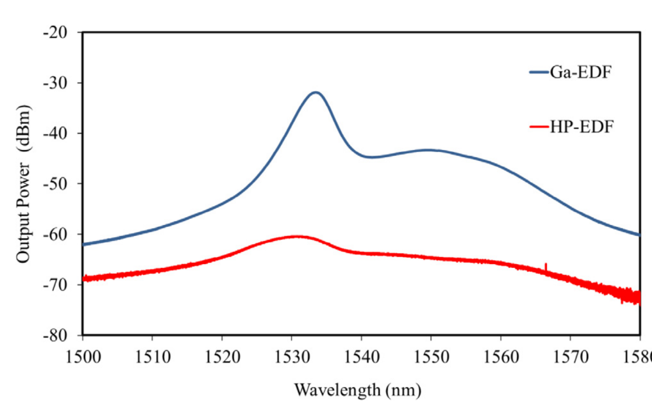

Fig. 2. ASE spectra from Ga-EDF and HP-EDF under the same pumping power.

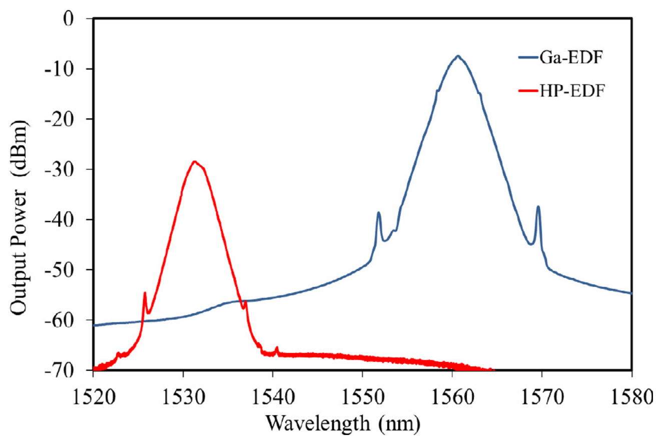

Fig. 3. Output spectra of the mode-locked Ga-EDFL and HP-EDFL at a pump power of 113.1 mW.

locked Ga-EDFL and the red trace indicates the output spectrum generated from the mode-locked HP-EDFL. Both of these output spectra are taken at the pump power of 113 mW. The threshold pump power for obtaining the mode-locked operation in the Ga-EDFL and conventional HP-EDFL are 60.43 mW and 53.44 mW, respectively. The threshold power for the mode-locked Ga-EDFL is higher than that of the conventional HP-EDF due to the greater ability of erbium ions confinement without clustering in Ga-EDF. It can be observed that both output spectra have different central wavelengths, which are 1560.7 nm for the Ga-EDFL and 1531.29 nm for the HP-EDFL. The 3 dB bandwidths estimated for the mode-locked Ga-EDFL and HP-EDFL are 3.20 nm and 2.28 nm respectively. This shows in comparison an improvement of 3 dB bandwidth of the mode-locked Ga-EDFL to that of the mode-locked HP-EDFL, with a difference of 0.92 nm. In addition, the peak power of the Ga-EDFL output spectrum is 20 dB higher compared to the peak power of the HP- EDFL output spectrum.

The output pulse train of both mode-locked Ga-EDFL and HP-EDFL as measured from the oscilloscope which is combined in a single graph is shown in Fig. 4. The pulses from both lasers are observed to have a similar repetition rate of about 12.25 MHz, corresponding to their similar total cavity length of about 17.5 m. Based on the total cavity length, the estimated theoretical value of the repetition rate is ~11.60 MHz which augurs well with the obtained experimental value. Since the repetition rate of the pulse train is reflected by the cavity length, it can be therefore expected that by shortening the cavity length, the repetition rate can be further increased. Measurement of the average output power and pulse energy of the pulse produces values of approximately 18.23 mW and 1.49 nJ, and 11.57 mW and 0.94 nJ for Ga-EDF and HP-EDF respectively.

The mode-locked pulse duration is measured by using an Alnair

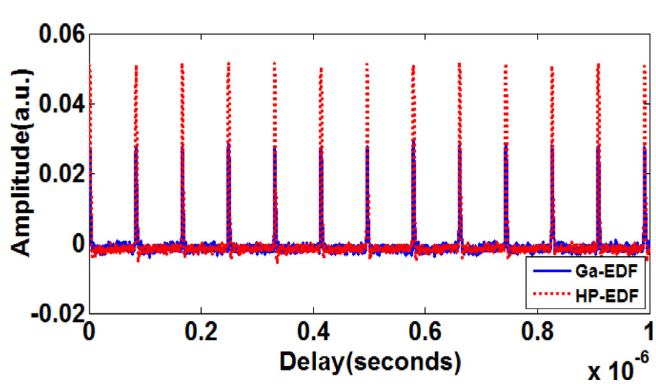

Fig. 4. Output pulse train of the mode-locked Ga-EDFL and HP-EDFL at a pump power of 113.1 mW.

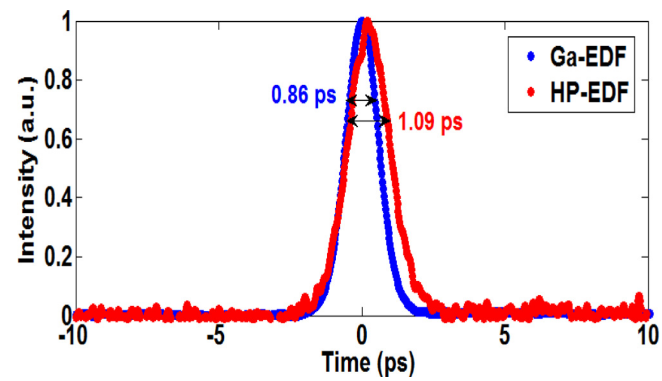

Fig. 5. The autocorrelation traces of the mode-locked Ga-EDFL and HP-EDFL in a single graph.

autocorrelator (model: HAC-200-10). Fig. 5 shows the comparison of the autocorrelation traces obtained from both mode-locked Ga-EDF and HP-EDF laser systems. The full-wave at half-maximum (FWHM) pulse duration is assumed as the fit of hyperbolic secant (sech2) pulse shape, which is measured to be 860 fs for the mode-locked Ga-EDFL and 1090 fs for the mode-locked HP-EDFL. The time-bandwidth product (TBP) values calculated for both laser systems are 0.339 and 0.319 respectively, which are slightly higher than the minimum validated transform-limited sech2 pulse of 0.315. The slight difference between the experimental value and the transform-limited value is endorsed by the occurrence of minor chirping in pulse [21], whereby the factor for the formation of this chirp originates from residual dispersion in the laser cavity [22]. From the graph in Fig. 5, it can be deduced that the mode-locked Ga-EDFL is able to emit a narrower pulse duration compared to the pulse duration emitted by the mode-locked HP-EDFL, with a difference of 230 fs. This is possible due to a higher concentration of erbium ion doped in the Ga-EDF contributes to a higher gain bandwidth of the erbium-doped fiber, therefore creating a sharper pulsewidth as compared to the lower concentration of the conventional erbium-doped fiber [34].

The measurement of signal-to-noise ratio (SNR) is obtained from the radio frequency (RF) spectrum analyzer which is set at a span of 3 MHz and 30 kHz resolution bandwidth (RBW). Fig. 6(a) and (b) show the RF spectrum of the mode-locked laser output in Ga-EDFL and HP-EDFL respectively. Both of the measured RF spectra in Fig. 6(a) and (b) indicate that the mode-locked laser output of both laser systems operates in their fundamental regime, which is about 12.25 MHz. The measured SNR value indicated by the fundamental frequency peak in the RF spectrum is about 55.21 dB for the mode-locked Ga-EDFL, as shown in Fig. 6(a). On the other hand, the mode-locked HP-EDFL exhibits a lower SNR value, which is about 45.46 dB, as shown in Fig. 6(b), thus giving a difference of about 9.75 dB to that of mode-locked Ga-EDFL. Comparison of the SNR value between both laser systems proves that the mode-locked Ga-EDFL performs better than the mode-locked HP-EDFL in terms of mode-locking stability as well as minimization of noise fluctuations and timing jitter.

The stability measurement of the mode-locked output spectrum is carried out for an hour at an interval of 60 min, which has been taken at a pump power of 113.1 mW. The results of the stability measurement are shown in Fig. 7(a) for mode-locked Ga-EDFL and Fig. 7(b) for mode-locked HP-EDFL. Insignificant deviation of the laser output spectrum is detected over a one hour period of observation time, indicating decent temporary stability of both laser outputs. Kelly's sidebands are seen which is an apparent sign that the laser works in the net anomalous dispersion of ordinary soliton operation regime [35]. A soliton mode-locked shows the balanced transaction between negative dispersion and the nonlinear effect in the laser cavity [35], which leads to higher stability that can be seen from the spectrum evolution towards time as illustrated in Fig. 7.

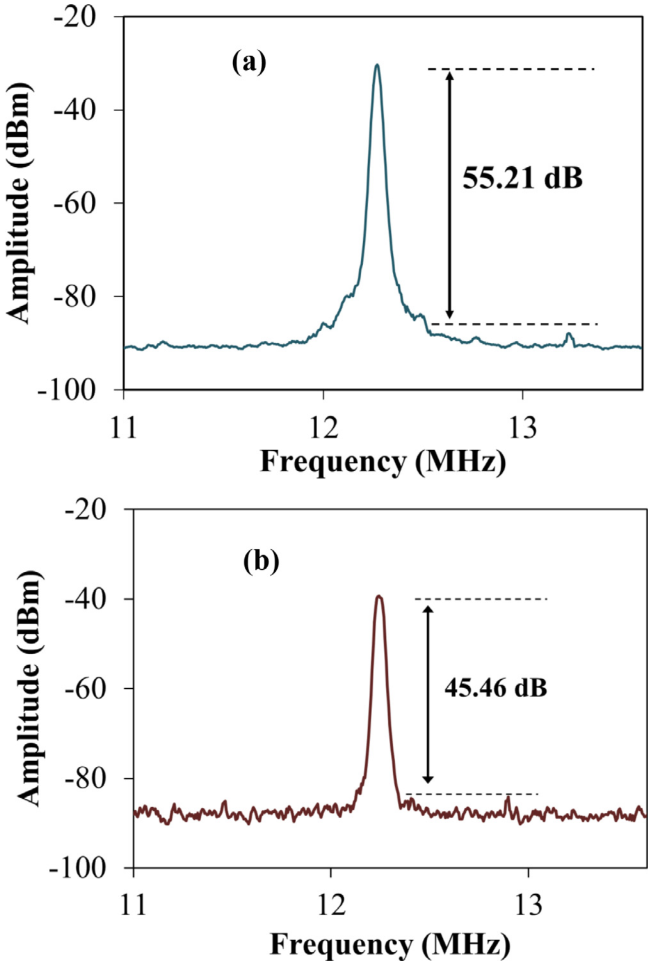

Fig. 6. RF spectrum of the mode-locked laser output in (a) Ga-EDFL and (b) HP-EDFL.

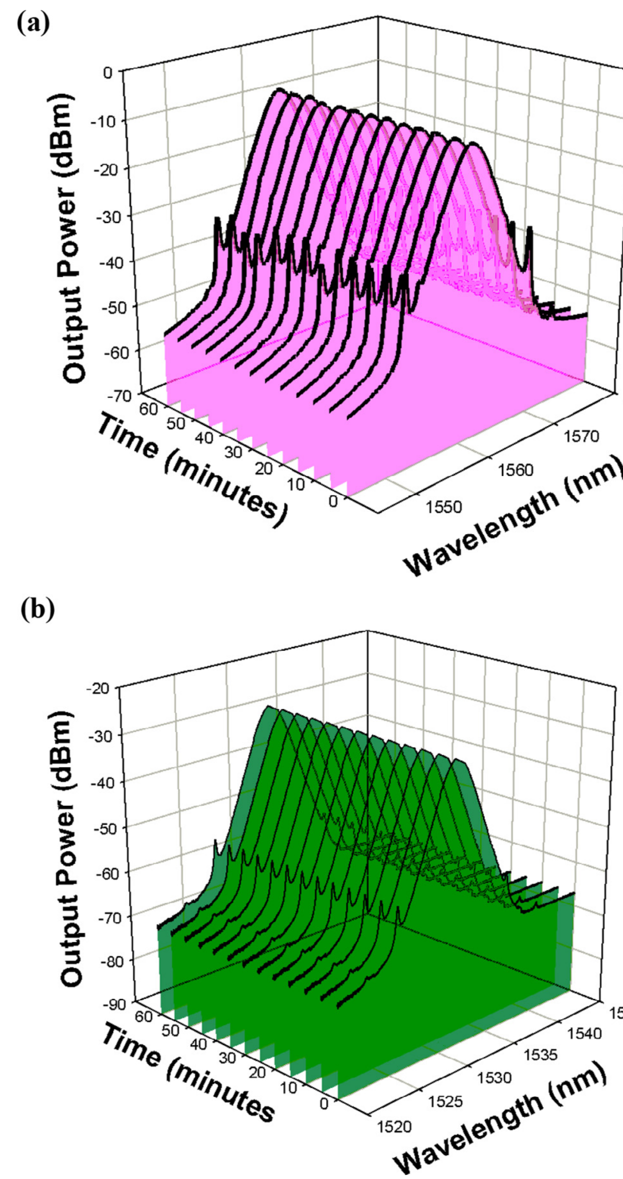

Fig. 7. Stability measurement of (a) mode-locked Ga-EDFL and (b) mode-locked HP-EDFL for 1-hour duration taken at a pump power of 113 mW.

Conclusion

In summary, we proposed and experimentally demonstrated a high power femtosecond mode-locked fiber laser using a new type of gain medium (Ga-EDF). The mode-locking mechanism is enabled by the graphene-based saturable absorber, in the form of a thin film which is sandwiched in between two fiber ferrules connected through an adaptor. Using a 2-m-long Ga-EDF as the primary gain medium in the laser system, the proposed laser is able to generate mode-locked solitons, with the central wavelength of 1560 nm, a 3 dB bandwidth of 3.20 nm and an average output power of 18.23 mW. The generated pulse yields a repetition rate of 12.25 MHz with pulse duration and pulse energy of 860 fs and 1.49 nJ respectively. The threshold power of the proposed system is 60.43 mW. Comparison of the output performance between the mode-locked Ga-EDFL and mode-locked HP-EDFL within the same laser cavity shows that the mode-locked Ga-EDFL is able to provide a higher output power, wider 3 dB bandwidth, shorter pulse width and higher SNR value to that of the mode-locked HP-EDFL with the respective value difference of 6.66 mW, 0.92 nm, 230 fs and 6.65 dB, thus inferring that the mode-locked Ga-EDFL has a superior performance compared to the conventional mode-locked HP-EDFL. This is the first time, to the knowledge of the authors, that the application of Ga-EDF as an active gain medium in the development of mode-locked fiber laser using graphene as the saturable absorber is explored.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rinp.2019.102644.

References

[1] Litchner Dausinger F, Lubatschowski H. Top Appl Phys 2004;96.
[2] Whitenett G, Stewert G, Yu H, Culshaw B. J Light Technol 2004;22:813–9.
[3] Curley PF, Ferguson AI, White JG, Amos WB. Opt Express 1992;16:851–9.
[4] Eigenwillig CM, Biedermann BR, Palte G, Huber R. Opt Express 2008;16:8916–37.
[5] Bouma B, Brezinski ME, Fujimoto JG, Tearney GJ, Boppart SA, Hee MR. Opt Lett

1995;20:1486–8.
[6] Chen Yung-Fu, Tsai SW, Wang SC. Opt Lett 2000;25:1442–4.
[7] Paschotta R, Häring R, Gini E, Melchior H, Keller U, Offerhaus HL, et al. Opt Lett 1999;24:388–90.
[8] Tamura K, Doerr C, Nelson L, Haus H, Ippen E. Opt Lett 1994;19:46–8.
[9] Sun Z, Rozhin AG, Wang F, Scardaci V, Milne WI, White IH, et al. Appl Phys Lett 2008;93:61114.
[10] Lu ZG, Liu JR, Raymond S, Poole PJ, Barrios PJ, Poitras D. Opt Express 2008;16:10835–40.
[11] Okhotnikov OG, Gomes L, Xiang N, Jouhti T, Grudinin AB. Opt Lett 2003;28:1522–4.
[12] Schmidt A, Choi SY, Yeom DI, Rotermund F, Mateos X, Segura M, et al. Appl Phys Lett 2012;5:092704.
[13] Sun Z, Hasan T, Torrisi F, Popa D, Privitera G, Wang F, et al. ACS Nano 2010;4:803–10.
[14] Yamashita S, Inoue Y, Maruyama S, Murakami Y, Yaguchi H, Joblonski M, et al. Opt Lett 2004;29:1581–3.
[15] Du J, Wang Q, Jiang G, Xu C, Zhao C, Xiang Y, et al. Scientific Report on Ytterbium-doped Fiber Laser Passively Mode-Locked by Few-Layer Molybdenum Disulfide (Mos2) Saturable Absorber Functioned with Evanescent Field Interaction. 2014.
[16] Jiang X, Liang W, Luo S, He Z, Ge Y, Wang H, et al. Laser Photon Rev 2018;12:2.
[17] Sun Liping, Lin Zhiqin, Peng Jian, Weng Jian, Huang Yizhong, Luo Zhengqian. Preparation of few-layer bismuth selenide by liquid-phase-exfoliation and its optical absorption properties. Sci Rep 2015;4(1). https://doi.org/10.1038/srep04794.
[18] Bao Q, Zhang H, Ni Z, Waang Y, Polavarapu L, Shen Z, et al. Nano Res 2011;4:297–307.
[19] Bao Q, Zhang H, Wang Y, Ni Z, Yan Y, Shen ZX, et al. Adv Funct Mater 2009;19:3077–83.
[20] A. Martinez Z. Sun Nature Photon 11 842-845.
[21] Sotor J, Sobon G, Grodecki K, Abramski KM. Appl Phys Lett 2014;104:251112.
[22] Kumavor PD, Donkor E. IEEE J Quantum Electron 2011;47:865–9.
[23] Mears RJ, Reekie L, Jauncey IM, Payne DN. Electron Lett 1987;19:1026–8.
[24] Yeh CH, Chi S. Laser Phys Lett 2007;4:433–6.
[25] Luo ZC, Wang FZ, Liu H, Liu M, Tang R, Luo AP, et al. Opt Eng 2016;55:081308.
[26] Bao Q, Zhang H, Ni Z, Wang Y, Polavarapu L, Shen Z, et al. Nano Res 2011;4:297–307.
[27] Guo B, Yao Y, Yang YF, Yuan YJ, Wang RL, Wang SG, et al. J Appl Phys 2015;117:063108.
[28] Mao Dong, Wang Yadong, Ma Chaojie, Han Lei, Jiang Biqiang, Gan Xuetao, Hua Shijia, Zhang Wending, Mei Ting, Zhao Jianlin. WS2 mode-locked ultrafast fiber laser. Sci Rep 2015;5(1). https://doi.org/10.1038/srep07965.
[29] Rawat VS, Mukhreje J, Gantayet LM. Prog Quantum Electron 2015;43:31–77.
[30] Wang Y, Mao D, Gan X, Han L, Ma C, Xi T, et al. Opt Express 2015;23:205–10.
[31] Lin Z, Yu C, He D, Feng S, Chen D, Hu L. IEEE Photon Technol Lett 2016;28:2673–6.
[32] Lourenco MA, Milošević MM, Gorin A, Gwilliam RM, Homewood KP. Scientific reports on super-enhancement of 1.54 Mm emission from erbium co-doped with oxygen in silicon-on-insulator. 2016.
[33] Dissanayake KPW, Abdul-Rashid HA, Safaei A, Oresegun A, Shahrizan N, Omar NY, Yusoff Z, Zulkiflu MI, Muhamma-Yassin SZ, Mat Sharif KA, Tamchek N. IEEE 5th Int. Conf. on Photonics. 2014. p. 113–5.
[34] Ruehl A, Kuhn V, Wandt D, Kracht D. Opt Express 2008;16:3130.
[35] Zhao L, Tang D, Wu X, Zhang H. Opt Lett 2010;35:2756.