Generation of Ultrafast Erbium-Doped Fiber Laser (EDFL) utilizing Graphene Thin Film

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Abstract. We have demonstrated an ultrafast mode-locked pulses generation by sandwiching graphene thin film between fiber ferrules in a simple erbium-doped fiber laser (EDFL) ring cavity setup. The incorporation of graphene thin film acted as a saturable absorber (SA) and had generated a stable mode locked pulse with repetition rate of 8.3 MHz, narrowest pulse duration of 1.38 picoseconds and 1558.8 nm wavelength.

1. Introduction

Ultrafast pulse fiber laser has attracted interest in pulse fiber laser application due to its uniqueness, compactness, a low cost deployment and flexibility packaging [1, 2]. Ultrafast laser can be generated by active method such as electro-optic modulator or acusto-optic modulator whereas passive method is achieved by incorporating saturable absorber (SA) has open up an ample opportunity in laser applications such as generation of supercontinuum [3, 4], laser cutting and laser marking [5] and non-linear frequency conversion [6, 7].

Generally, passive method which use saturable absorber (SA), is an effective method to generate Q-switching or mode-locking pulse inside a laser. Until a few years ago, semiconductor saturable absorber mirror (SESAM) was the dominant SA [8, 9]. Though, a number of disadvantages related to SESAM such as complex fabrication and packaging, which require costly clean room facilities too [10, 11]. Another
disadvantage is their narrowband operating bandwidth – which rarely exceed one telecom optical wavelength band [12]. Recently, carbon-based nanomaterials, e.g. carbon nanotubes [12-15] and graphene [16, 17] have been utilized as saturable absorbers due to their advantages compared to SESAM. Graphene-based SAs are still in need as they have exciting features such as ultrafast recovery time and simple fabrication process that make them an attractive candidate for an SA. Despite the emergence of new material categories of saturable absorber such as topological insulator (e.g. Bi$_2$Se$_3$ [18, 19], Bi$_2$Te$_3$ [20, 21]), transition-metal dichalcogenides (e.g. MoS$_2$ [22], MoSe$_2$ [23]), black phosphorus [24, 25], titanium dioxide [26, 27] and zinc oxide [28], graphene is still relevant for generating ultrafast fiber laser.

In the paper, we report that we have successfully mode-locked a multitude of longitudinal modes in an EDFL using graphene. This passively mode-locked laser was observed to have repetition rates and pulse width which were 8.3 MHz and 1.38 picoseconds respectively, with an optical spectrum centered at 1558.8 nm. Therefore, this experiment demonstrated the feasibility of graphene SA for EDFL mode locking operation and could encourage more development in the photonics field.

2. Experimental Setup

The erbium-doped fiber laser based graphene SA configuration is shown in Figure 1. It consists of 50 cm length of erbium doped fiber model Liekki ER110-4/125 with a peak absorption of 110 dB/m at 1530 nm, a 5 m length of single mode fiber (SMF) and few layer graphene thin film (GTF) based SA. A 974nm laser diode, (Oclaro LC96A74P-20R) was employed as a pump laser. It was spliced to the pump port of a 980/1550 nm wavelength division multiplexer (WDM) while the common port was spliced to 50 cm EDF. A polarization-independent isolator was integrated to ensure uni-directional laser propagation. Afterwards, a polarization controller (PC), GTF saturable absorber, 10-dB output coupler (OC 1) and additional SMF were integrated into the cavity, GTF was sandwiched between two fiber ferrules. GTF fabrication was described in other work [29]. The laser output that was extracted from the cavity and was divided equally by a 3-dB optical coupler (OC2) to enable simultaneous measurements. The laser pulses were characterized using optical spectrum analyzer (OSA) (YOKOGAWA model AQ6373) and a digital oscilloscope (YOKOGAWA model DLM2054). Other characterizations equipment includes radio frequency spectrum analyzer (RFSA) (Anritsu model MS2683A) and autocorrelator (ALNAIR, model HAC200) cavity.
3. Results and Discussion

Self-started mode-locked pulses alongside optical spectrum with Kelly sidebands emerged when pump power reached 80 mW. The spectrum was centered at 1558.8 nm wavelength as shown in Figure 2. From the oscilloscope, a stable pulse train with repetition rate of 8.3 MHz were observed (Figure 3). Using a radio frequency spectrum analyser, the pulse had a fundamental frequency of 8.3 MHz with harmonics every 8.3 MHz (Figure 4). Unlike Q-switched laser, when pump power was increased, no frequency changes were observed. Moreover, the RFSA presents no spectral modulation, indicate a stable ultrafast pulse in EDFL. As shown in Figure 5, by using an autocorrelator, the pulse width was measured to be 1.38 ps (full width at half maximum). In this work, the pulse width could be narrowed down by improving modulation depth of the graphene thin film and by using shorter cavity length.

The Kelly sidebands soliton in this work showed the mode-locked pulse was operated in the net anomalous dispersion regime as discussed by Lau et.al [29]. The generated soliton mode-locking through the interconnection between self-phase modulation and group velocity dispersion has highly stable pulse operation. Therefore, the mode-locked pulse was tested in term of its stability measurement over an hour and the result showed no significant difference in terms of wavelength shift and output power. These indicated the stability of picoseconds ultrafast erbium doped fiber laser utilizing graphene thin film as SA was verified in this work.
Figure 2: Characteristic of ultrafast pulse with 1558.8 nm optical wavelength spectrum at 80mW

Figure 3: Pulse trace with repetition rate of 8.3 MHz by using oscilloscope
4. Conclusion

We have successfully generated an ultrafast mode locked pulses in EDFL by using graphene thin film SA. A stable optical spectrum with Kelly sidebands emerged with central wavelength at 1558.8 nm, repetition
rate of 8.3 MHz, and narrowest pulse duration of 1.38 ps was accomplished. This results prove that graphene can be used as saturable absorber for generating mode-locked fiber laser.

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References

[1] P. Dupriez et al., 2006, Optics Express, 14, (21), 9611-9616.
[2] M. Leigh, W. Shi, J. Zong, J. F. Wang, S. B. Jiang, and N. Peyghambarian, 2007, Optics Letters, 32[8], 897-899.
[3] I. A. Sukhoivanov, S. O. Iakushev, O. V. Shulika, J. A. AndradeLucio, A. Diez, and M. Andres, 2014, Optics Express, 22[24], 30234-30250.
[4] A. Roy, M. Laroche, P. Roy, P. Leproux, and J. L. Augustine, 2007, Optics Letters, 32[22], 3299-3301.
[5] Y. Okamoto, R. Kitada, Y. Uno, and H. Doi, 2008, Journal of Advanced Mechanical Design Systems and Manufacturing, 2[4], 651-660.
[6] W. Shi, M. Leigh, J. Zong, and S. B. Jiang, 2007, 2009, Optics Letters, 32[8], 949-951.
[7] W. Shi et al., IEEE Journal of Selected Topics in Quantum Electronics, 15[2], 377-384.
[8] G. J. Spuhler et al., 2001, Applied Physics B-Lasers and Optics, 72[3], 285-287.
[9] S. X. Xu, W. X. Li, Q. Hao, H. Zhai, and H. P. Zeng, 2008, Chinese Physics Letters, 25[2], 548-551.
[10] H. Ahmad, M. A. M. Salim, S. R. Azzuhri, M. R. K. Soltanian, and S. W. Harun, 2015, Laser Physics, 25[6].
[11] H. Ahmad, M. A. M. Salim, M. R. K. Soltanian, S. R. Azzuhri, and S. W. Harun, 2015, Journal of Modern Optics, 62[19], 1550-1554.
[12] A. Schmidt et al., 2008, Optics Letters, 33[7], 729-731.
[13] Y. Gao et al., 2013, Optics Communications, 286, 261-264.
[14] H. Ahmad, J. M. Semangun, S. R. Azzuhri, M. Z. Zulkifli, N. A. Awang, and S. W. Harun, 2015, Laser Physics, 25[4].
[15] M.A.M. Salim, H. Ahmad, S. Harun, N. Bidin, and G. Krishnan, 2018, Journal of Physics: Conference Series, 1027[1], 012011.
[16] J. Liu, S. D. Wu, Q. H. Yang, and P. Wang, 2011, Optics Letters, 36[20], 4008-4010.
[17] L. Zhang et al., 2012, Laser Physics Letters, 9[12], 888-892.
[18] H. Ahmad, M.A.M. Salim, S. R. Azzuhri, M. Soltanian, and S. Harun, 2015, Laser Physics, 25[6], 065102.
[19] H. Ahmad, M.A.M. Salim, M. Soltanian, S. R. Azzuhri, and S. Harun, 2015, Journal of Modern Optics, 62[19], 1550-1554.
[20] M.A.M. Salim, R. Shaharuddin, M. Ismail, S. Harun, H. Ahmad, and S. R. Azzuhri, 2017, Laser Physics, 27[12], 125102.
[21] M. A. M. Salim, M. Z. Ab Razak, S. R. Azzuhri, M. A. Ismail, F. Ahmad, and S. W. Harun, 2019, Sains Malaysiana, 48[6], 1289-1294.
[22] H. Ahmad, Z. C. Tiu, A. Zarei, M. Suthaskumar, M. A. M. Salim, and S. W. Harun, 2016, Applied Physics B, 122[4], 1-5.
[23] H. Ahmad et al., 2016, Laser Physics Letters, 13[11], 115102.
[24] H. Ahmad, M.A.M. Salim, K. Thambiratnam, S. Norizan, and S. Harun, 2016, Laser Physics Letters, vol. 13[9], 095103.
[25] F. Rashid et al., 2016, Laser Physics Letters, 13[8], 085102.
[26] H. Ahmad et al., 2016, Chinese Optics Letters, 14[9], 091403.
[27] H. Ahmad and M.A.M. Salim, 2017, IEEE Journal of Quantum Electronics, 53[5], 1-6.
[28] H. Ahmad, M.A.M. Salim, M. F. Ismail, and S. W. Harun, 2016, Laser Physics, 26[11], 115107.
[29] K. Lau, F. Muhammad, A. Latif, M. A. Bakar, Z. Yusoff, and M. Mahdi, 2017, Optics & Laser Technology, 94, 221-227.