# Graphene-based, ultrafast Er-doped fiber laser with linearly polarized output pulses

Grzegorz Sobon,[1,*] Jaroslaw Sotor,[1] Iwona Pasternak,[2] Wlodek Strupinski,[2] and Krzysztof M. Abramski[1]

[1]*Laser & Fiber Electronics Group, Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland*
[2]*Institute of Electronic Materials Technology, Wolczynska 133, 01-919 Warsaw, Poland*

Received April 03, 2014; accepted June 29, 2014; published June 30, 2014

**Abstract**—We demonstrate an all-fiber, Er-doped fiber laser mode-locked with a graphene-based saturable absorber. The resonator is designed using only polarization maintaining fibers and components, which allows to achieve a linearly polarized output beam. The laser delivers 595fs long pulses at a 1560nm center wavelength with a 6. nm bandwidth and a 67MHz repetition rate. As a saturable absorber, a graphene-polymer composite was used.

Graphene, the most recently discovered allotrope of carbon, has attracted great attention of the ultrafast laser community in the last three years. Thanks to its unique optical properties like broadband nonlinear absorption, ushort recovery time and high modulation depth, graphene is considered as an universal saturable absorber (SA) for mode-locking of fiber lasers operating at different wavelengths. Since the first demonstrations of Er-doped fiber lasers mode-locked by graphene in 2009 [1-2], a number of setups have been presented, utilizing Erbium [3-10], Ytterbium [11] and Thulium-doped fibers [12-14].

There are several methods of fabricating graphene-based saturable absorbers. The most important include: chemical vapor deposition (CVD), chemical functionalization and mechanical exfoliation. The CVD technique allows to obtain high-quality mono- and multi-layer graphene by epitaxial growth on metallic substrates (e.g. nickel or copper). Such layers might be afterwards transferred onto optical substrates (like mirrors, glass windows, fiber connectors etc.) with the use of polymer support, eg. poly(methyl methacrylate) (PMMA), forming reflective or transmissive saturable absorbers for bulk solid state or fiber lasers [8,10,15]. Graphene flakes might also be obtained by exfoliation of natural graphite via ultrasonication in various organic solvents, like dimethyloformamide (DMF) [16]. Such graphene flakes are often mixed with polymers, e.g. polyvinyl alcohol (PVA) and applied on fiber connectors, allowing efficient mode-locking of Er-doped fiber lasers [4-6]. The historically first method of obtaining graphene, and the obviously simplest one, is based on micro-mechanical cleavage of pure graphite by scotch tape. It allows to obtain multi-layer graphene flakes, which might be transferred onto fiber connectors due to the strong atomic interactions between carbon and $SiO_2$. However, the repeatability of the process is very poor and the number of layers cannot be controlled in any way. Mechanical exfoliation already led to many interesting results, though [16-20].

For many practical applications of a fiber laser it is required to maintain the linear polarization of the output beam. Typically, mode-locked fiber lasers demonstrated in the literature are designed using non-polarization maintaining fibers and components. Thus, the output polarization state is undetermined. Moreover, such lasers are vulnerable to external factors (like vibrations, temperature changes, etc.) and require adjustments of the intra-cavity polarization in order to lock the modes and start the pulsed operation. The only way to provide self-starting mode-locking with long-term stability and vulnerability to environmental factor is to design the cavity using only PM fibers and components. The first and all-PM fiber lasers incorporating graphene were presented by our group [19-20] with the usage of mechanically exfoliated graphene. In this work, we demonstrate an all-fiber, all-PM Er-doped fiber laser, which utilizes a saturable absorber based on CVD-graphene immersed in PMMA polymer support, with a fully controlled number of layers.

The experimental setup is depicted in Fig. 1. The laser is based on a 40cm long erbium doped fiber (Liekki Er80-4/125-PM, EDF), which is counter-directionally pumped by a 980nm laser diode via a filter-type wavelength division multiplexer (WDM), which reflects the 980nm pump radiation and passes the 1560nm lasing signal. In order to make sure that there is only one polarization axis propagating in the laser, a polarization beam-splitter (PBS) is placed inside the cavity. The light is output-coupled from the laser by a 20% PM coupler. The saturable absorber (SA) consists of a graphene-polymer

[*] E-mail: grzegorz.sobon@pwr.wroc.pl

 

composite inserted between two angled fiber connectors. The SA contains two layers of graphene. The details of graphene preparation were described by the authors previously [14-15].

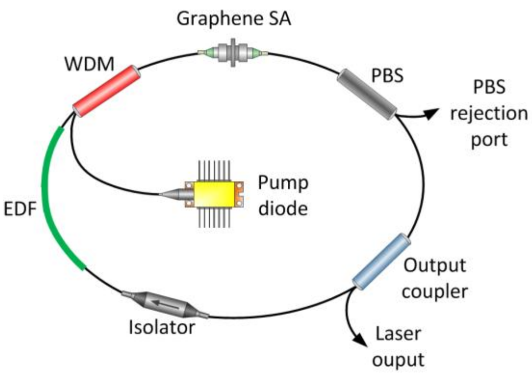


Fig. 1. Experimental setup of the fiber laser.

The performance of the laser was observed using an optical spectrum analyzer (Yokogawa AQ6370B), digital oscilloscope (Hameg HMO3524), 7 GHz radio frequency (RF) spectrum analyzer (Agilent EXA N9010A), Thorlabs PAX5710 polarimeter and an autocorrelator.

Fully stable and self-starting mode-locking was achieved at the pumping power of 40mW. The average output power was 1.14mW. Figure 2 illustrates the recorded optical spectrum of the laser. It is centered at 1560.3nm and has a typical soliton-like shape, which results from the all-anomalous cavity design. The full width at half maximum (FWHM) bandwidth of the emission is 6.3nm.

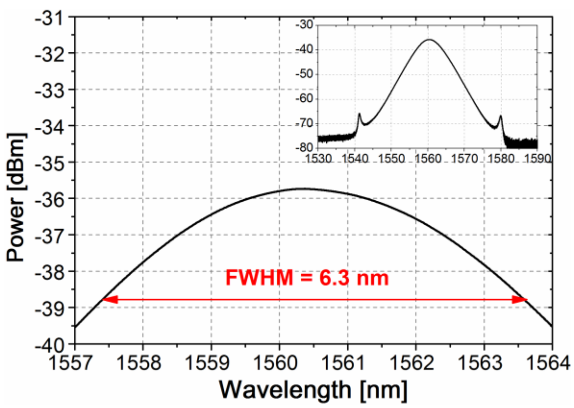


Fig. 2. Optical spectrum of the laser.

The output spectrum could be potentially broader and was not limited by the absorption bandwidth of the graphene saturable absorber. The emission bandwidth could be increased by proper dispersion management or by increasing the pumping power. However, at increased pumping power, Kelly's sidebands observed in the spectrum would be strongly pronounced. The sidebands are related to the periodic disturbance of soliton pulses in the laser resonator. Very intense sidebands may indicate that the laser works unsteadily and the relative intensity noise is high [21]. In our experiment, the laser was optimized to suppress Kelly's sidebands as much as possible in order to obtain high stability and excellent noise properties. The intensity of sidebands is more than 30 dB lower than the central peak of the spectrum, which indicates that cavity dispersion and nonlinearities are properly balanced.

The radio frequency (RF) spectrum measured with a 4MHz frequency span and a 1kHz resolution bandwidth (RBW) is depicted in Fig. 3. The repetition rate of the laser was 67.1MHz The graph inset in Fig. 3 illustrates the RF spectrum recorded in the full available 7GHz frequency span, showing a broad spectrum of harmonics. The electrical signal to noise ratio was higher than 80dB.

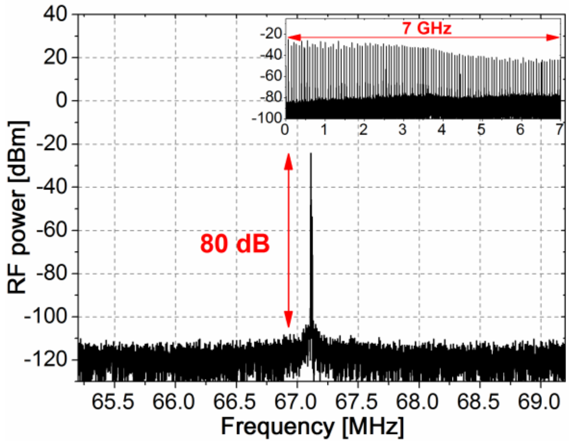


Fig. 3. Measured RF spectrum of the laser.

Figure 4 shows the output pulse train recorded with an oscilloscope. The pulses are equally spaced by 15ns, which corresponds to a 67MHz repetition frequency. No signs of dual-pulsing or parasitic Q-switching were observed. The graph inset in Fig. 4 illustrates the pulse train in a 2μs wide span.

The measured output pulse duration of the laser was 595fs, assuming a $sech^2$ pulse shape. The autocorrelation trace is depicted in Fig. 5. With a 6.3nm FWHM bandwidth (776GHz), the Time-Bandwidth Product (TBP) is equal to 0.46. It means that the pulses are about 32% longer than expected from the transform limit (0.315 TBP for $sech^2$ pulses). If the pulses were transform-limited, they could achieve the duration of 405fs. This slight chirp might be caused by the dispersion of the output fiber (outside the cavity) and by the delivery fiber of the autocorrelator. The pulse energy calculated from the average power is 17pJ, which is comparable to other graphene-based soliton lasers presented so far [1, 15].

 

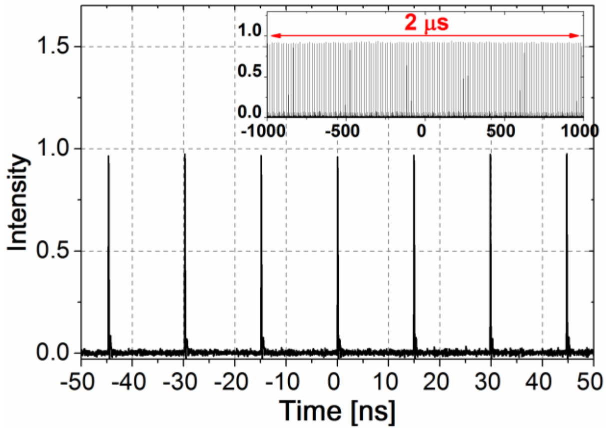


Fig. 4. Oscilloscope trace of the laser output.

In order to confirm the linear polarization of the output beam, we have measured the degree of polarization (DOP) and the azimuth using a polarimeter. The measured DOP was at the level of 99.42% with very small variations over the 60 seconds period. The azimuth of the linear polarization was also very stable with standard deviation at the level of 0.01°. The measurement confirms excellent polarization properties of the presented laser.

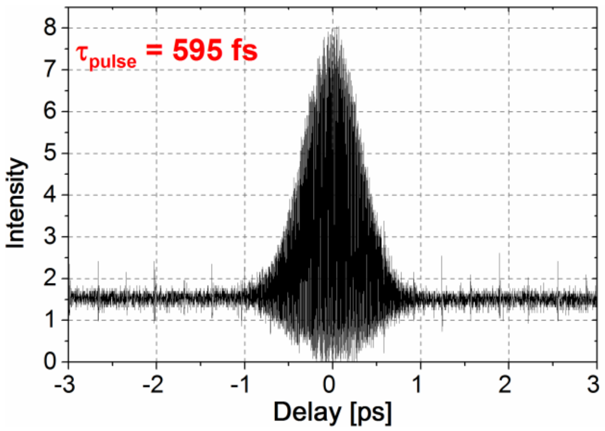


Fig. 5. Autocorrelation trace of the 595 fs output pulse.

In summary, we have demonstrated an Er-doped fiber laser mode-locked by a CVD-graphene/PMMA composite. The laser delivered linearly polarized, sub-600fs pulses centered at a 1560nm wavelength with a 67MHz repetition rate. Such an oscillator can be considered as an excellent seed source for stable, high-power chirped pulse amplifiers.

The work presented in this paper was supported by the National Centre for Research and Development (NCBiR, Poland) under research and development project entitled "Ultrafast graphene-based fiber lasers" UltraGRAPH).

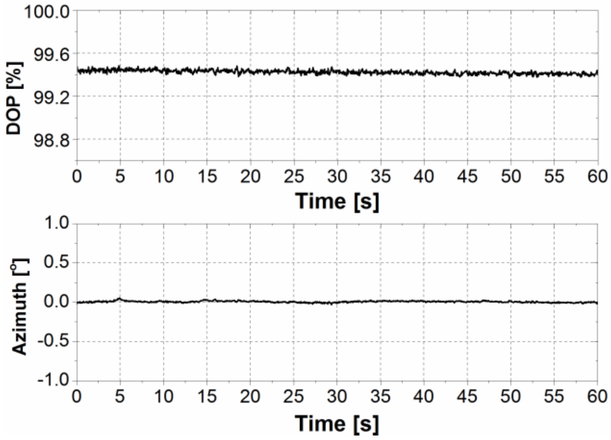


Fig. 6. DOP and azimuth measurement over 1 minute period.

## References


[1] Q.L. Bao, H. Zhang, Y. Wang, Z.H. Ni, Z.X. Shen, K.P. Loh, D.Y. Tang, Adv. Funct. Mater. **19**, 3077 (2009).

[2] T. Hasan, Z. Sun, F. Wang, F. Bonaccorso, P.H. Tan, A.G. Rozhin, A.C. Ferrari, Adv. Mater. **21**, 3874 (2009).

[3] H. Zhang, D.Y. Tang, L.M. Zhao, Q.L. Bao, K.P. Loh, Opt. Expr. **17**, 17630 (2009).

[4] Z. Sun, T. Hasan, F. Torrisi, D. Popa, G. Privitera, F. Wang, F. Bonaccorso, D.M. Basko, A.C. Ferrari, ACS Nano **4** , 803 (2010).

[5] Z. Sun, D. Popa, T. Hasan, F. Torrisi, F. Wang, E. JR Kelleher, J.C. Travers, V. Nicolosi, A.C. Ferrari, Nano Res. **3**, 653 (2010).

[6] D. Popa, Z. Sun, F. Torrisi, T. Hasan, F. Wang, A.C. Ferrari, Appl. Phys. Lett. **97**, 203106 (2010).

[7] H. Zhang, D.Y. Tang, L.M. Zhao, Q.L. Bao, K.P. Loh, B. Lin, S.C. Tjin, Laser Phys. Lett. **7**, 591 (2010).

[8] H. Zhang, Q. Bao, D. Tang, L. Zhao, K. Loh, Appl. Phys. Lett. **95**, 141103 (2009).

[9] J. Xu, S. Wu, H. Li, J. Liu, R. Sun, F. Tan, Q.-H. Yang, P. Wang, Opt. Expr. **20**, 23653 (2012).

[10] P.L. Huang, S. Lin, C. Yeh, H. Kuo, S. Huang, G. Lin, L. Li, C. Su, W. Cheng, Opt. Expr. **20**, 2460 (2012).

[11] X.H. Li, Y.G. Wang, Y.S. Wang, Y.Z. Zhang, K. Wu, P.P. Shum, X. Yu, Y. Zhang, Q.J. Wang, Laser Phys. Lett. **10**, 075108 (2013).

[12] M. Zhang, E.J.R. Kelleher, F. Torrisi, Z. Sun, T. Hasan, D. Popa, F. Wang, A.C. Ferrari, S.V. Popov, J.R. Taylor, Opt. Expr. **20**, 25077 (2012).

[13] Q. Wang, T. Chen, B. Zhang, M. Li, Y. Lu, K.P. Chen, Appl. Phys. Lett. **102**, 131117 (2013).

[14] G. Sobon, J. Sotor, I. Pasternak, A. Krajewska, W. Strupinski, K.M. Abramski, Opt. Expr. **21**, 12797 (2013).

[15] G. Sobon, J. Sotor, I. Pasternak, K. Grodecki, P. Paletko, W. Strupinski, Z. Jankiewicz, K.M. Abramski, J. Lightwave Technol. **30**, 2770 (2012).

[16] A. Martinez, K. Fuse, B. Xu, S. Yamashita, Opt. Expr. **18**, 23054 (2010).

[17] Y.M. Chang, H. Kim, J.H. Lee, Y. Song, Appl. Phys. Lett. **97**, 211102 (2010).

[18] A. Martinez, K. Fuse, S. Yamashita, Appl. Phys. Lett. **99**, 121107 (2011).

[19] G. Sobon, J. Sotor, K.M. Abramski, Laser Phys. Lett. **9**, 581 (2012).

[20] J. Sotor, G. Sobon, K.M. Abramski, Opt. Lett. **37**, 2166 (2012).

[21] M.L. Dennis, I.N. Duling III, IEEE J. Quantum Electron. **30**, 1469 (1994).


 