EPJ Web of Conferences **41**, 10001 (2013)
DOI: 10.1051/epjconf/20134110001

Sub-picosecond Graphene-based Harmonically Mode-Locked Fiber Laser With Repetition Rates up to 2.22 GHz

G. Sobon, J. Sotor, and K.M. Abramski

Laser & Fiber Electronics Group, Wroclaw University of Technology, Wybrzeze Wyspianskiego 27, 50-370 Wroclaw, Poland

Abstract. Passive harmonic-mode locking (PHML) of erbium-doped fiber laser with multilayer graphene is presented. The laser could operate at several harmonics (from 2nd to 21st) of the fundamental repetition frequency of the ring resonator (106 MHz). The highest achieved repetition rate was 2.22 GHz (which corresponds to the 21st harmonic) with 900 fs pulse duration and 50 dB of the supermode noise suppression. The saturable absorber was formed by multilayer graphene, mechanically exfoliated from pure graphite block through Scotch-tape and deposited on the fiber ferrule.

1 Introduction

Since first demonstration in 2009 [1], graphene mode-locked fiber lasers have shown a great potential of generating ultra-short pulse trains with MHz-level repetition rates. Graphene, thanks to its unique optical properties, like ultra-broad tuning range, can be widely used as a saturable absorber for all types of fiber lasers. Other outstanding properties, like very low saturable absorption threshold level and high modulation depth open new possibilities in developing ultrafast mode-locked fiber lasers [2-4]. Unfortunately, repetition frequency of fundamentally mode-locked lasers is strongly limited to several hundreds of MHz. One of the most promising methods to obtain repetition frequencies in the GHz-range is so called passive harmonic mode-locking (PHML). In harmonically mode-locked fiber lasers, in the presence of relatively high pumping power, the single pulse circulating in the cavity can be split into several pulses. In such regime, pulses are usually randomly located in the cavity. However, under certain conditions they can self-arrange to create a stable and well organized pulse train with repetition rates far beyond the fundamental mode spacing [5,6].

In this work we demonstrate harmonic mode-locking in a fiber laser passively mode-locked by graphene saturable absorber. The highest recorded repetition rate was 2.22 GHz, which corresponds to the 21st harmonic of the fundamental cavity frequency (106 MHz resulting from the resonator length). The harmonic mode-locking operation was obtained at tens of miliwatts pumping level.

2 Experimental setup

The graphene mode-locked laser setup is presented in Figure 1. The resonator consists of 30 cm long highly-erbium doped fiber (Liekki Er110), a fiber isolator, 980/1550 single-mode WDM coupler, in-line fiber polarization controller, 10% output coupler and the graphene-based saturable absorber placed between two FC/APC connectors. The laser is pumped by a 980 nm laser diode. Graphite flakes were obtained by precise peeling of a commercially available graphite block (SGL Group) by a sharp blade. Then, the flakes were placed onto a scotch tape and pressed repeatedly to obtain multilayer atomic graphene. Afterwards, graphene sheets were deposited on a standard FC/APC fiber connector (ultrasonically cleaned with isopropyl alcohol) just by pressing the ferrule to the inner side of the tape. Due to strong interaction between graphite and SiO_2, a graphene layer is formed on the end fiber facet. Such connector is then connected with a clean one through an FC/APC adapter and spliced into the laser cavity.

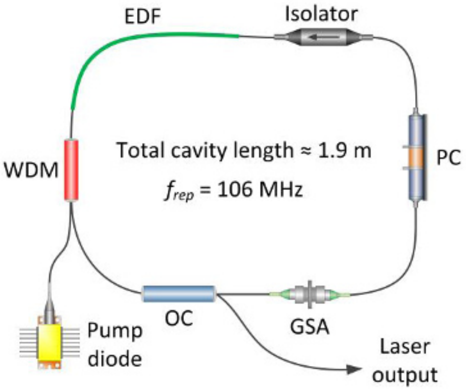
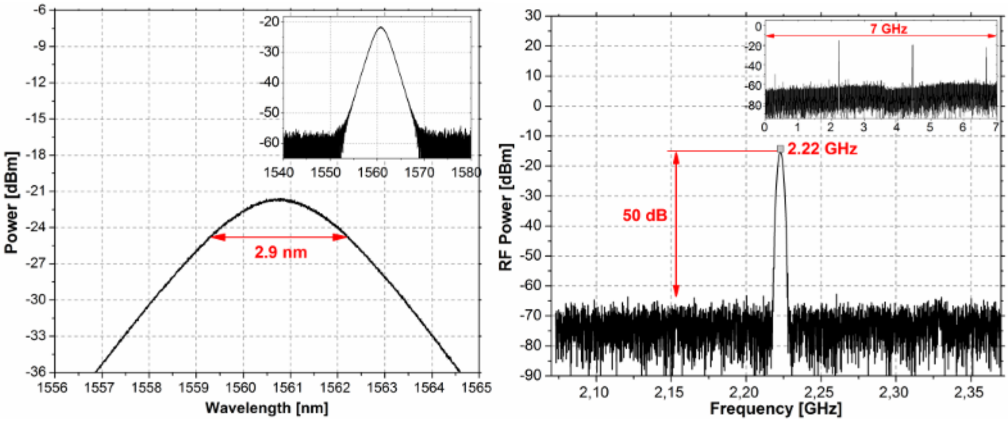


Fig. 1. Graphene mode-locked fiber laser. EDF – erbium doped fiber, PC – polarization controller, OC – output coupler, GSA – Graphene saturable absorber.

3 Experimental results

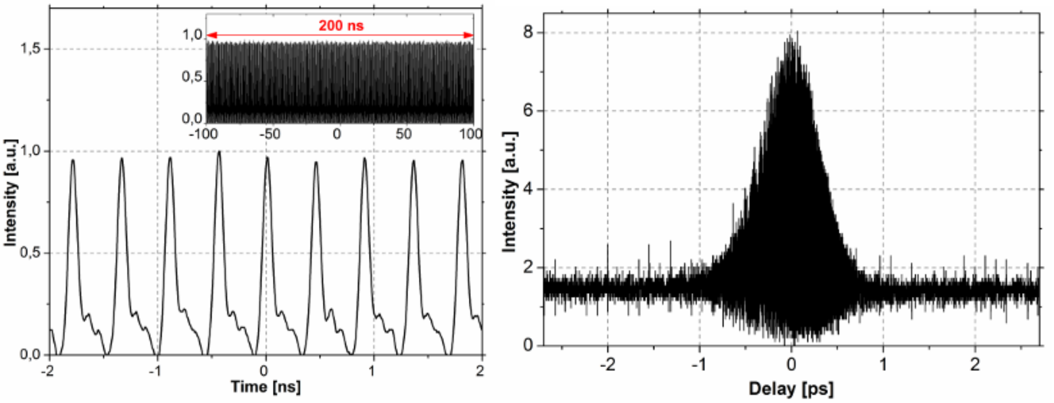
After launching the pump power (at the level of 12 mW) the laser starts to operate in the CW regime. Increasing the pumping to 15 mW results in stable, fundamental mode locking at 106 MHz repetition rate. The harmonic mode-locking operation was obtained with pump power higher than 40 mW (2nd harmonic). The highest stable repetition rate was 2.22 GHz which corresponds to the 21st harmonic of the fundamental repetition frequency. This harmonic was obtained at 230 mW of pumping power and the laser output power was at the level of 9.6 mW. The 21st harmonic optical spectrum with the 2.9 nm FWHM is shown in Fig. 2a. It can be nicely fitted with sech2 shape and has no signs of any CW lasing. The RF spectrum recorded with 2.7 MHz RBW is shown in Figure 2b. Center frequency is set to 2.22 GHz. The supermode suppression was always higher than 50 dB, which is much better than in previously reported harmonically mode-locked lasers based on NPR technique [5,6].



a) b)

Fig. 2. Optical (a) and RF (b) spectra of the laser at 21st harmonic (2.22 GHz).

Figure 3a shows the pulse train with pulses equally spaced by approx. 450 ps, which corresponds to 2.22 GHz repetition rate. Figure 3b shows the 21st harmonic pulse autocorrelation with the pulse duration measured to be 900 fs (assuming sech^2 pulse shape). No signs of pulse braking or pulse-pair generation were observed. With 2.9 nm bandwidth (0.357 THz), the Time-Bandwidth Product (TBP) is equal to 0.321, which is very close to the transform-limit for sech2-shape pulses (0.315).



a) b)

Fig. 3. Recorded pulse train with 4 and 200 ns span (a) and 900 fs pulse autocorrelation (b) at 21st harmonic (2.22 GHz).

4 Summary

In conclusion, we have demonstrated a harmonically mode-locked erbium-doped fiber laser with graphene saturable absorber and highest repetition frequency reported so far (2.22 GHz). The saturable absorber was prepared by Scotch-taping of pure graphite. The presented laser could operate at the 21st harmonic of the fundamental cavity frequency, with near-transform limited sub-picosecond pulses.

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. D. Popa, Z. Sun, F. Torrisi, T. Hasan, F. Wang, A. C. Ferrari, Appl. Phys. Lett. **97**, 203106 (2010)
3. H. Zhang, Q. Bao, D. Tang, L. Zhao, K. Loh, Appl. Phys. Lett. **95**, 141103 (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. G. Sobon, K. Krzempek, P. Kaczmarek, K.M. Abramski, M. Nikodem, Opt. Commun. **284**, 4203 (2011)
6. F. Amrani, A. Haboucha, M. Salhi, H. Leblond, A. Komarov, Ph. Grelu, F. Sanchez, Opt. Lett. **34**, 2120 (2009)