Short Pulse Generation in Erbium-Doped Fiber Lasers Using Graphene Oxide as a Saturable Absorber

Catarina S. Monteiro[1,2][a], Rosa P. Herrera[3,4][b], Susana Silva[1][c] and Orlando Frazão[1][d]

[1]*INESC TEC—Institute for Systems and Computer Engineering, Technology and Science, Rua do Campo Alegre 687, 4150-179 Porto, Portugal*

[2]*Department of Engineering Physics, Faculty of Engineering, University of Porto, Rua Dr. Roberto Frias s/n, 4200-465 Porto, Portugal*

[3]*Department of Electrical, Electronic and Communication Engineering, Public University of Navarra, 31006 Pamplona, Spain*

[4]*Institute of Smart Cities (ISC), Public University of Navarra, 31006 Pamplona, Spain*

Keywords: Fiber Laser, Graphene Oxide, Saturable Absorption.

Abstract: The use of graphene oxide (GO) as a saturable absorber for short pulses generation in an Erbium-doped fiber laser was studied and demonstrated. The saturable absorber consisted of a thin GO film, with a high concentration of monolayer GO flakes, spray-coated on the end face of a ferrule-connected fiber. By including the saturable absorber in the laser cavity and controlling the intra-cavity polarization, the generation of short-pulsed light was achieved under mode-locking and Q-switching operations. Under mode-locking operation, it was observed a pulse train with a fundamental repetition rate of 1.48 MHz, with a working wavelength centered at 1564.4 nm. In the Q-switch operation, a pulse train with a 12.7 kHz repetition rate and a 14.3 µs pulse duration was attained for a 230-mA pump current. Further investigation showed a linear dependence of the repetition rate with the pump power, attaining frequencies between 12.7 and 14.4 kHz.

1 INTRODUCTION

Ultrafast fiber lasers are capable of delivering pulses in the order of pico- or femtoseconds in a compact and align-free structure (Cheng et al., 2020), making these devices a powerful tool for applications in nonlinear optics (M. Liu et al., 2020), precision metrology (Oh & Kim, 2005), industrial applications (Wang et al., 2022), and medical treatments (Hoy et al., 2014), for example. The most typical approach to producing short and ultrashort pulses is through Q-switching and mode-locking. Q-switching and mode-locking can be achieved passively, using a saturable absorber, creating a fiber laser with a more compact and simpler design (Ahmad et al., 2016). To passively initiate the generation of short and ultrashort pulses, different saturable absorber materials and methods have been explored such as the well-established conductor saturable absorber mirrors (SESAMs) (Keller et al., 1996), the nonlinear polarization rotation technique (X. M. Liu & Mao, 2010), or using carbon nanotubes (Set et al., 2004), for example.

More recently, graphene has attracted much attention due to its unique optical and electrical properties such as high carrier mobility, low saturation power, and broadband wavelength tunability (Steinberg et al., 2018). Graphene can be synthesized through chemical vapor deposition or mechanical exfoliation, yielding graphene samples with different physical, optical, and electrical properties. The two techniques present different advantages and disadvantages, but both lack scalability for mass production. Graphene oxide and reduced graphene oxide exhibit comparable properties with faster synthesis methods. In particular, graphene oxide exhibits saturable absorption, which

[a] https://orcid.org/0000-0002-0463-9894
[b] https://orcid.org/0000-0002-6856-9143
[c] https://orcid.org/0000-0001-7555-361X
[d] https://orcid.org/0000-0001-7680-1056

Monteiro, C., Herrera, R., Silva, S. and Frazão, O.
Short Pulse Generation in Erbium-Doped Fiber Lasers Using Graphene Oxide as a Saturable Absorber.
DOI: 10.5220/0011700400003408
In *Proceedings of the 11th International Conference on Photonics, Optics and Laser Technology (PHOTOPTICS 2023)*, pages 78-81
ISBN: 978-989-758-632-3; ISSN: 2184-4364

makes it suitable for ultrafast pulse generation using mode-locking (Zhao et al., 2011). Femtosecond pulse generation has already been demonstrated using GO as a saturable absorber (Huang et al., 2014; Ko et al., 2017; J. Liu et al., 2012; Xu et al., 2012; Yap et al., 2022; Zhou et al., 2012).

This communication demonstrates Q-switching and mode-locking operation using a GO-based saturable absorber. The thin GO film was deposited on the end face of a fiber using spray coating and was placed between two fiber ferrules. The GO thin film was added to the erbium-doped fiber laser cavity and, by controlling the intra-cavity dispersion and polarization state, mode-locking and Q-switching were achieved. The mode-locking operation was studied in the wavelength and temporal domain, attaining a fundamental repetition rate of 1.48 MHz. In the Q-switching regime, a pump power-dependent pulse train was attained with a repetition rate between 12.7 and 14.4 kHz.

2 EXPERIMENTAL CONFIGURATION

The experimental configuration was composed of an erbium-doped fiber amplifier (EDFA), schematically demonstrated in the grey box in Figure 1. The EDFA (IPG Laser HBM, model EAD-1K-C3-W) is capable of outputting a maximum power of 1 W. The isolator of the EDFA guarantees unilateral light propagation, and the polarization controller (Thorlabs FPC030) can adjust the traveling light's polarization state. The output coupler, with a 5% output ratio, enables to monitor the extracted light. The output spectrum and pulse train were attained using an optical spectrum analyzer (OSA – Advantest Q8384) and photodetector (Thorlabs PDA10CS-EC) connected to a 2GHz sampling rate oscilloscope (GWinstek GDS-2304A), respectively. A single-mode fiber (SMF) coil of 100 m was added to the laser ring cavity to control the dispersion and total cavity length. The total length of the ring was measured using an OTDR, attaining an approximated value of 130 m.

The GO film serving as a saturable absorber was deposited on the end face of a fiber terminated with an FC/PC connector using spray coating. The GO solution was acquired from Graphene, in a water suspension with a concentration of 4 mg/mL with a monolayer content greater than 95%. Prior to spray coating, the GO solution was sonicated to decrease the agglomerates of the GO flakes.

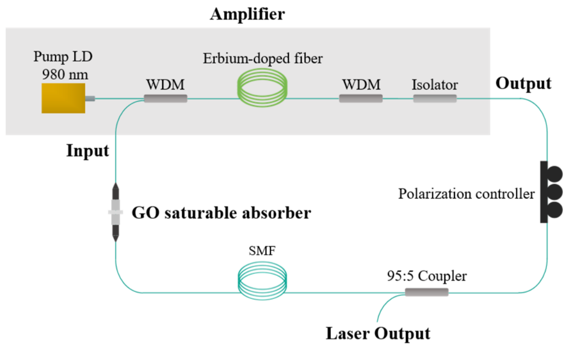

Figure 1: Experimental setup of the EDFL based on graphene oxide saturable absorber.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Mode-Locked Operation

In passive mode-locking operation, the saturable absorber attenuates weak longitudinal modes, while high-intensity modes are passed through it. This stimulates other modes with phase-locking, resulting in the formation of periodic short pulses. To exclude the possibility of self-mode-locking or self-Q-switching, the output spectrum of the cavity with no GO saturable absorber was attained using the OSA. By varying the pump power and changing the polarization of the light traveling in the laser cavity using the polarization controller, no mode-locking was observed as presented in Figure 2, where only the laser's peak is observed with a central wavelength of 1564.4 nm with an FWHM of 1.5 nm. Therefore, no self-start mode-locking operation induced by non-linear polarization rotation was achieved.

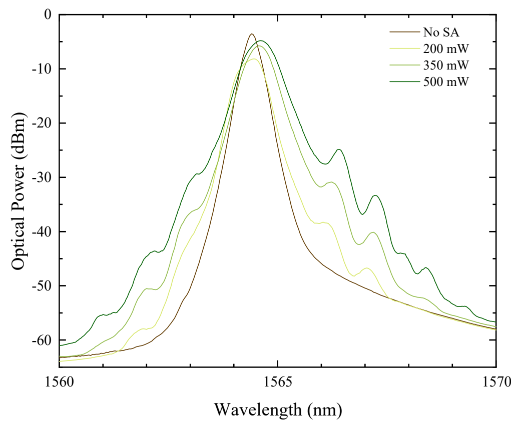

Figure 2: Output spectrum at different pump powers.

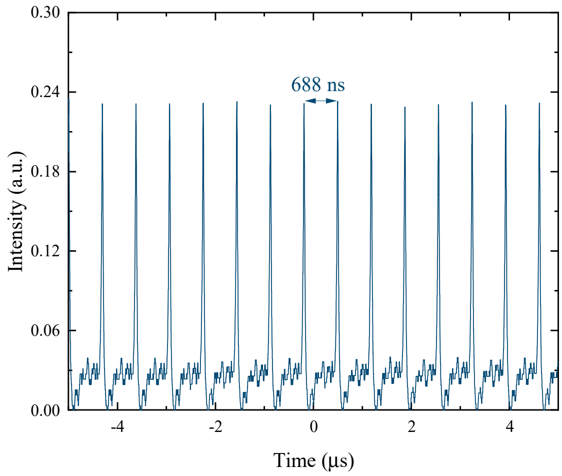

Figure 3: Output pulse train in mode-locking operation.

By introducing the GO saturable absorber into the setup, increasing the pump power to a value greater than 200 mW, and controlling the polarization state, the mode-locking operation was achieved as shown in Figure 2, where Kelly's sidebands start to appear, which are characteristic of the soliton operation of a fiber laser (Bao et al., 2009). The acquired pulse train is presented in Figure 3 with a pulse interval of approximately 688 ns, corresponding to a fundamental repetition rate of 1.48 MHz which is in accordance with the total length of the cavity.

3.2 Q-Switched Operation

In Q-switch operation, the losses of the cavity are temporarily increased by introducing an attenuator that prevents laser action. This will allow a population inversion that far exceeds the case where no attenuator is present. By rapidly decreasing the attenuation, the laser will exhibit gain that far surpasses the losses, leading to the release of the stored energy as a short and intense light pulse (Svelto, 2010).

For the Q-switch operation, the experimental setup was adjusted to reduce the number of fiber connectors. The erbium-doped fiber amplifier was replaced by an in-house amplifier, with a 4 m erbium-doped fiber. Moreover, the SMF coil was removed from the fiber cavity. Adjusting the polarization state, it was possible to observe the Q-switching operation on the laser. Figure 4 presents the typical Q-switching pulse train, achieved for a pump current of 230 mA with a repetition rate of 12.7 kHz and a pulse duration of 14.3 μs.

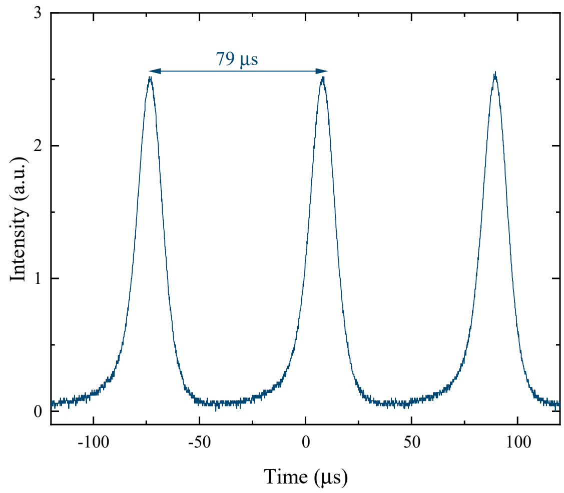

Figure 4: Q-switching operation: pulse train for a pump power of 230 mA, with a repetition rate of 12.7 kHz.

The evolution of the repetition rate of the Q-switched pulses with the pump power was studied for a fixed polarization state. For a pump current between 230 and 250 mA, the frequency of the Q-switched pulses varies between 12.7 and 14.4 kHz as presented in Figure 5.

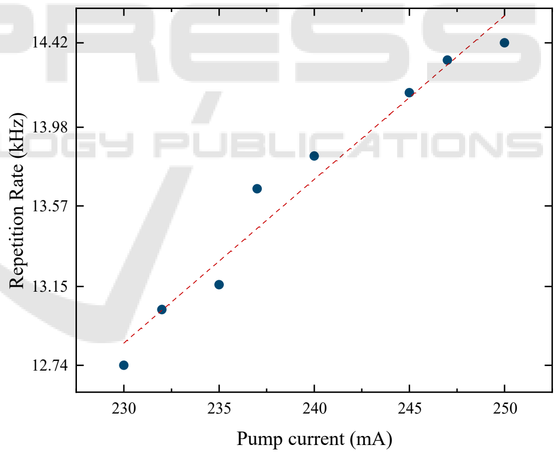

Figure 5: Evolution of the repetition rate with the increase of pump current.

4 CONCLUSIONS

In this work, the generation of short pulses in an erbium-doped fiber laser was studied using GO as saturable absorber. The saturable absorber was spray-coated on an end face of a ferrule-connected fiber, after sonication of the GO solution, avoiding agglomerates of GO flakes. The saturable absorber was inserted on the erbium-doped fiber laser cavity, resulting in both mode-locking and Q-switching operation after intra-cavity polarization control.

Under mode-locking operation, a fundamental repetition rate of 1.48 MHz was attained for pump power values higher than 200 mW for a central wavelength of 1564.4 nm. In the Q-switching operation, short pulses were attained with a repetition rate between 12.7 and 14.4 kHz. At the lower repetition rate, a pulse duration of 14.3 µs was achieved.

REFERENCES

Ahmad, H., Lee, C. S. J., Ismail, M. A., Ali, Z. A., Reduan, S. A., Ruslan, N. E., Ismail, M. F., & Harun, S. W. (2016). Zinc oxide (ZnO) nanoparticles as saturable absorber in passively Q-switched fiber laser. *Optics Communications*, *381*, 72–76. https://doi.org/10.1016/j.optcom.2016.06.073

Bao, Q., Zhang, H., Wang, Y., Ni, Z., Yan, Y., Shen, Z. X., Loh, K. P., & Tang, D. Y. (2009). Atomic-layer craphene as a saturable absorber for ultrafast pulsed lasers. *Advanced Functional Materials*, *19*(19), 3077–3083. https://doi.org/10.1002/adfm.200901007

Cheng, P., Du, Y., Han, M., & Shu, X. (2020). Mode-locked and Q-switched mode-locked fiber laser based on a ferroferric-oxide nanoparticles saturable absorber. *Optics Express*, *28*(9), 13177. https://doi.org/10.1364/OE.391006

Hoy, C. L., Ferhanoğlu, O., Yildirim, M., Kim, K. H., Karajanagi, S. S., Chan, K. M. C., Kobler, J. B., Zeitels, S. M., & Ben-Yakar, A. (2014). Clinical ultrafast laser surgery: Recent advances and future directions. *IEEE Journal on Selected Topics in Quantum Electronics*, *20*(2). https://doi.org/10.1109/JSTQE.2013.2287098

Keller, U., Weingarten, K. J., Kartner, F. X., Kopf, D., Braun, B., Jung, I. D., Fluck, R., Honninger, C., Matuschek, N., & Aus der Au, J. (1996). Semiconductor saturable absorber mirrors (SESAM's) for femtosecond to nanosecond pulse generation in solid-state lasers. *IEEE Journal of Selected Topics in Quantum Electronics*, *2*(3), 435–453. https://doi.org/10.1109/2944.571743

Liu, M., Wei, Z. W., Li, H., Li, T. J., Luo, A. P., Xu, W. C., & Luo, Z. C. (2020). Visualizing the "Invisible" Soliton Pulsation in an Ultrafast Laser. *Laser and Photonics Reviews*, *14*(4), 1–8. https://doi.org/10.1002/lpor.201900317

Liu, X. M., & Mao, D. (2010). Compact all-fiber high-energy fiber laser with sub-300-fs duration. *Optics Express*, *18*(9), 8847. https://doi.org/10.1364/OE.18.008847

Oh, J. S., & Kim, S.-W. (2005). Femtosecond laser pulses for surface-profile metrology. *Optics Letters*, *30*(19), 2650. https://doi.org/10.1364/ol.30.002650

Set, S. Y., Yaguchi, H., Tanaka, Y., & Jablonski, M. (2004). Laser Mode Locking Using a Saturable Absorber Incorporating Carbon Nanotubes. *Journal of Lightwave Technology*, *22*(1), 51–56. https://doi.org/10.1109/JLT.2003.822205

Steinberg, D., Zapata, J. D., De Souza, E. A., & Saito, L. (2018). Mechanically exfoliated graphite onto D-shaped optical fiber for femtosecond mode-locked Erbium-doped fiber laser. *Journal of Lightwave Technology*, *36*(10), 1868–1874. https://doi.org/10.1109/JLT.2018.2793764

Svelto, O. (2010). *Principles of Lasers*. Springer US. https://doi.org/10.1007/978-1-4419-1302-9

Wang, S., Wang, L., Zhang, S., Zheng, H., Zhang, C., Liu, S., Liu, F., & Cheng, G. J. (2022). A low-damage copper removal process by femtosecond laser for integrated circuits. *Vacuum*, *203*(June), 111273. https://doi.org/10.1016/j.vacuum.2022.111273

Zhao, X., Liu, Z. B., Yan, W. B., Wu, Y., Zhang, X. L., Chen, Y., & Tian, J. G. (2011). Ultrafast carrier dynamics and saturable absorption of solution-processable few-layered graphene oxide. *Applied Physics Letters*, *98*(12), 2009–2012. https://doi.org/10.1063/1.3570640

Zhou, Z., Liu, W., Huang, Y., Wang, H., Jianping, H., Huang, M., & Jinping, O. (2012). Optical fiber Bragg grating sensor assembly for 3D strain monitoring and its case study in highway pavement. *Mechanical Systems and Signal Processing*, *28*, 36–49. https://doi.org/10.1016/j.ymssp.2011.10.003.