

## Pulse train stability in passively mode-locked erbium-doped fiber laser with a nonlinear polarization rotation

Nur Ameelia Abdul Kadir, Nurul Alina Afifi Norizan, Azura Hamzah

Department of Electronic Systems Engineering, Malaysia-Japan International Institute of Technology,  
Universiti Teknologi Malaysia, Malaysia

---

### Article Info

#### Article history:

Received Dec 3, 2018

Revised Apr 5, 2019

Accepted Apr 26, 2019

---

#### Keywords:

Erbium-doped

Mode locking laser

Nonlinear polarization rotation

Polarization dependent isolator

Ring cavity

---

### ABSTRACT

A nonlinear polarization rotation technique-based mode-locked erbium-doped fiber laser has been experimentally demonstrated using a 0.75 m long highly concentrated erbium-doped fiber as the gain medium. With unintentional polarization dependent loss induced by twisting single-mode fiber in an intracavity polarization controller, the optical output of the laser shifts from continuous wavelength to modelocked soliton pulse. A stable and cleaner pulse with a repetition rate of 15.32 MHz laser wavelengths and a pulse energy of 0.496 nJ with optical signal-to noise ratio of more than 33 dB are successfully obtained using a simple ring cavity.

Copyright © 2019 Institute of Advanced Engineering and Science.  
All rights reserved.

---

### Corresponding Author:

Nur Ameelia Abdul Kadir,  
Department of Electronic Systems Engineering,  
Universiti Teknologi Malaysia,  
54100, Kuala Lumpur, Malaysia.  
Email: nurameeliaabdulkadir@gmail.com

---

## 1. INTRODUCTION

There has been considerable interest in developing mode-locked fiber lasers for their feasibility in a variety of applications especially in optical sensing, medicine, communication, and measurements [1-4]. Typically, there are several candidates for the mode-locking mechanisms, such as colliding pulse or additive pulse modelocking [5-7] nonlinear saturable absorption mode-locking [8-10], and nonlinear polarization rotation (NPR) mode-locking, [11-13] and etc. Notably, mode-locked fiber lasers due to NPR have been actively studied in the last few years for being simple and efficient tools for ultra-short pulse generation [14, 15]. By using additive mode-locking through NPR, a stable self-mode-locking in rare earth doped fiber lasers have been successfully obtained [16-18]. This type of laser has more tolerance to power damage and stronger design compared to mode-locked lasers based on saturable absorbers (SAs).

The principals involved in mode-locking is as follows: the polarization of a pulse develops nonlinearly along a birefringent fiber that is due to the combined effects of cross-phase and self-phase modulation; those effects are induced on the two orthogonal polarization components, both resulting from optical Kerr effect [19, 20]. A polarizing isolator blocks the low intensity pulse wings and allows the central intense part of the pulse pass by adjusting the polarization controller at the end of the fiber. Based on the orientation of the polarization controller, passive mode-locked can be achieved. Smirnov et al. [15] have demonstrated all-normal-dispersion fiber laser mode-locked with NPR. They characterized qualitatively for three regimes of single pulse generation per round trip. They also studied spectral, compressibility, and temporal features of the pulses produced in all three regimes. Li et al. [21] in a study, described a simple technique based on NPR for the amplitude equalization of high repetition rate pulses generated from a rational harmonic mode-locked fiber ring laser. They obtained amplitude equalized pulses at 10 GHz,

which is the fourth rational harmonic. Besides this, a theoretical study was done by Salhi et al. [20] on erbium-doped fiber laser (EDFL), passively mode-locked by NPR. They investigated theoretically, the properties of the mode-locking of an erbium-doped birefringent fiber laser in a unidirectional cavity containing an optical isolator. In view of a previously reported laser system that was passively modelocked with the cooperation of NPR and saturable absorption, the NPR effect was introduced to improve the pulse shortening [22] while the noise filtering effect induced by a saturable absorber facilitates laser stability [23].

Here, in this paper, we report the demonstration of passively mode-locked erbium-doped fiber laser based on NPR. It was found that the combination of polarization dependent isolator (PDI) together with polarization controller (PC) in the ring cavity helped to generate a stable self-starting soliton mode-locked pulse without using any nonlinear optical element-specifically, saturable absorber (SA)-which can turn the laser's continuous wave output into a train of ultrashort optical pulses.

## 2. CONFIGURATION OF THE MODE-LOCKED EDFL

The schematic configuration of the mode-locked EDFL based on NPR is shown in Figure 1. The laser cavity comprises a 0.75 m high-gain erbium-doped fiber (EDF) as the gain medium, which is forward pumped by a 980 nm laser diode (LD) and backward pumped by a 1550 nm LD. The EDF used in the cavity has a numerical aperture of 0.24, an erbium concentration of 2000 ppm and absorption of 24 dB/m at 1550 nm. Wavelength division multiplexer (WDM, 980/1550) is used in the setup to convey the pumping powers and feedback coupling. Self-started mode-locking is achieved simply by incorporating PDI together with PC and twisting PC in the setup while increasing the pump power. Thus, the nonlinear polarization rotation technique is used to realize the self-started mode locking in the laser cavity. The output of the laser is taken via a 10% fiber coupler while 90% of the light remains oscillating in the ring cavity. The laser is then analyzed simultaneously with an optical spectrum analyzer (Yokogawa, AQ6370D), an oscilloscope (Tektronix, MDO3024) combined with a 5 GHz photodetector (Thorlabs, DET08CFC/M) and an optical power meter, respectively.

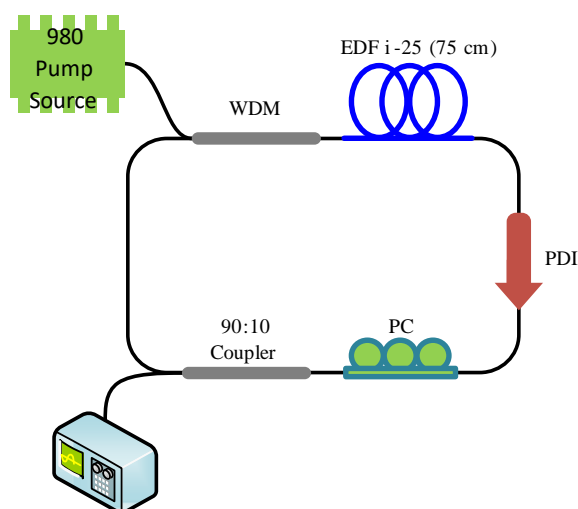


Figure 1. Experimental setup for the mode-locked EDFL

## 3. RESULTS AND ANALYSIS

Figure 2 indicates output power and pulse energy of the laser as a function of pump power within 21.39 to 119.4 mW. Both output power and pulse energy characteristics are observed to increase linearly when the cavity pump power is raised inside the cavity. In order to obtain soliton operation from the laser, the pump power must be tuned to beyond 21.39 mW. The soliton is observed to remain stable until pump power reaches 119.4 mW. The maximum pulse energy is calculated to be 0.496 nJ, that is additionally displayed in Figure 2. The average output power increased linearly with the pump power as the pump power exceeded the threshold. The output power reached 7.61 mW at a maximum pump power of 119.4 mW. From Figure 2, as the pump power is raised from 21.39 to 119.4 mW, the pulse repetition rate remained stable at the frequency of 15.32 MHz.

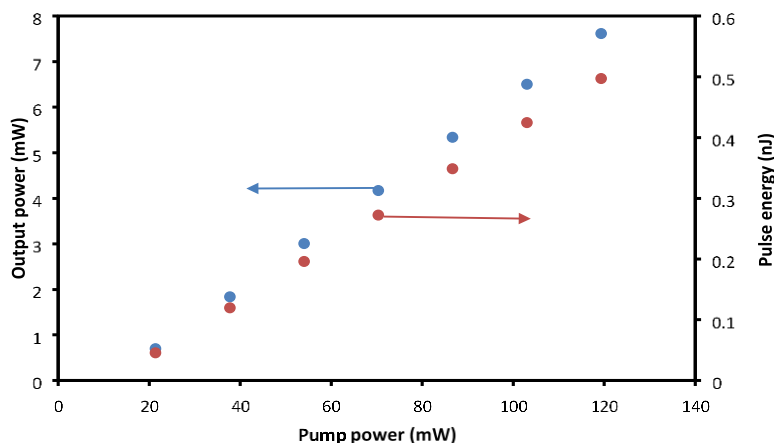


Figure 2. Output power (blue dots) and pulse energy (red dots) versus pump power

Stable self-starting mode-locked pulses are observed by carefully adjusting the PC when the launched pump power is increased to 21.39 mW. Once the mode-locking is achieved by the initial adjustment of the PC, the soliton pulses are self-starting and no longer needed to adjust the PC, even for increased and re-switched pump power. It is worth mentioning that the performance of soliton mode-locking is significantly sensitive to the position of the PC. Slight adjustment of the PC from their optimized positions would lead to continuous wavelength (CW) breakthrough because of the existence of CW path in the oscillator [24]. The corresponding optical spectrum, pulse train, and radio frequency (RF) spectrum are shown in Figure 3 (a), (b) and (c) respectively, which is included with the softcopy of the optical spectrum analyzer and oscilloscope. From Figure 3 (a), we can see that the absence of additional narrow spectral line confirms that the pulses are free of CW components. Note that CW breakthrough generally starts with the Kelly sideband if the PC shifts from the optimum positions. The measured optical spectrum of mode-locked pulsed laser is recorded at the pump power of 119.4 mW with a central wavelength of 1565 nm and 3dB spectral bandwidth of 6 nm. Figure 3 (b) illustrates a typical pulse train of the passive mode-locked laser at maximum input incident pump power of 119.4 mW. As evident in Figure 3 (b), the mode-locked pulsed train has a constant spacing 0.11  $\mu$ s of which translates to a repetition rate of 15.32 MHz. To identify the pulse in detail, the generated pulse is further measured using a radio frequency spectrum analyzer (RFSA) to measure the signal-to-noise ratio (SNR) as shown in Figure 3 (c). From the figure, SNR ratio is obtained as 33 dB at the fundamental repetition rate of 15.32 MHz, thus confirming stability of the pulse.

#### 4. CONCLUSION

In conclusion, a stable self-starting mode-locked pulse train operating at 1565 nm has been successfully demonstrated at threshold pump powers of 21.39 to 119.4 mW as a result of the unintentional PDL induced by twisting the single mode fiber (SMF) in the intracavity PC [25]. The mode-locked pulsed laser based on the NPR technique has produced a repetition rate of 15.32 MHz and pulse energy of 0.496 nJ as the pump power was varied from 21.39 to 119.4 mW. We have initially obtained a soliton operation state of the laser by rising the pump power above the threshold. Then, the pump power has been reduced to a level where only one soliton pulse existed in the cavity. Our experimental results have shown a potential alternative for soliton pulse formation in ultrashort pulse soliton lasers. Future works will investigate the performance of this mode-locked pulse laser based NPR for optical sensor applications with high sensitivity, stability and repeatability.

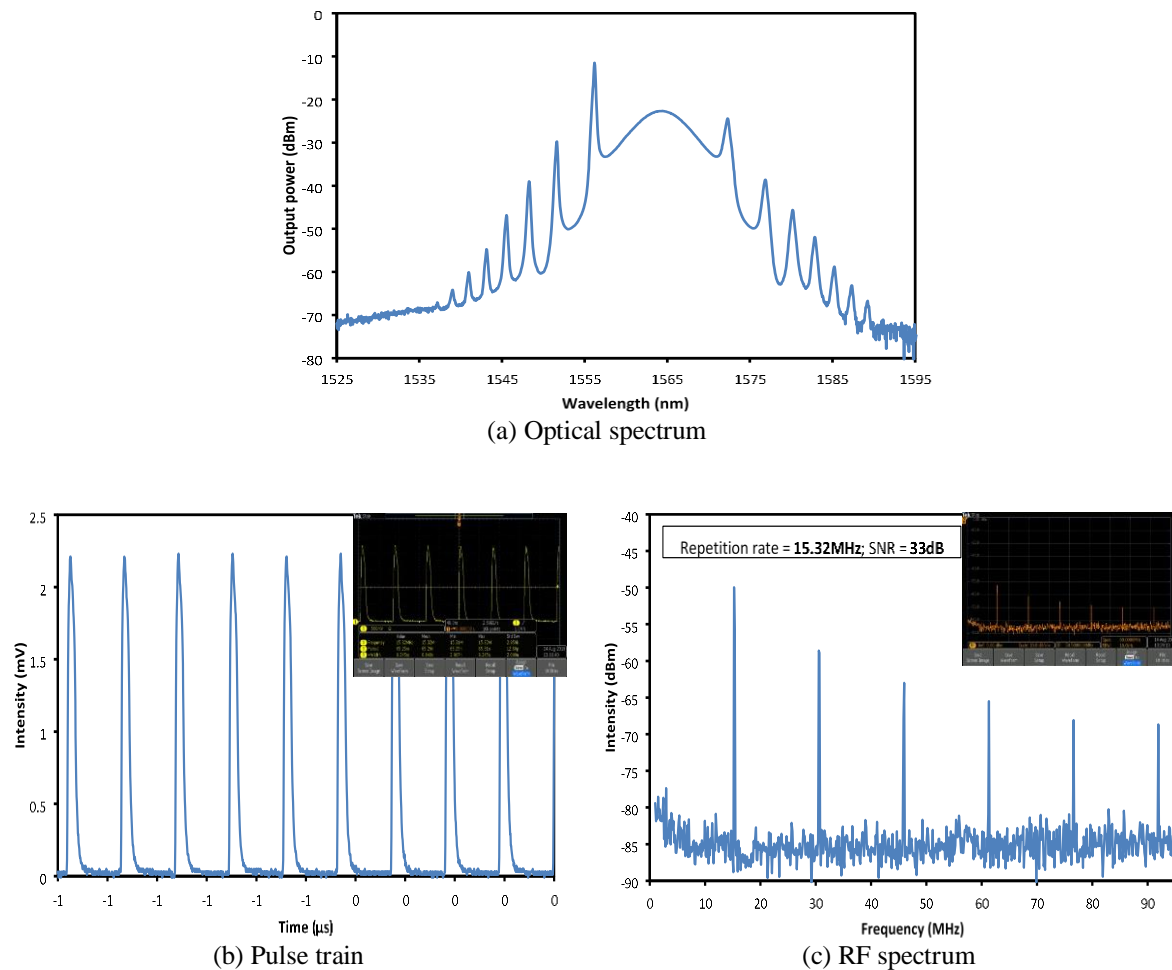


Figure 3. Soliton mode-locked EDFL at 119.4 mW

### ACKNOWLEDGEMENTS

This work was supported in part by Universiti Teknologi Malaysia under Grant Nos Q. K130000.2543.17H26.

### REFERENCES

- [1] Fermann, M.E. and I. Hartl, *Ultrafast fibre lasers*. Nature photonics, 2013. **7**(11): p. 868.
- [2] Popa, D., et al., *Sub 200 fs pulse generation from a graphene mode-locked fiber laser*. Applied Physics Letters, 2010. **97**(20): p. 203106.
- [3] Sun, Z., et al., *Graphene mode-locked ultrafast laser*. ACS nano, 2010. **4**(2): p. 803-810.
- [4] Sun, Z., et al., *A stable, wideband tunable, near transform-limited, graphene-mode-locked, ultrafast laser*. Nano Research, 2010. **3**(9): p. 653-660.
- [5] Haus, H.A., J.G. Fujimoto, and E.P. Ippen, *Structures for additive pulse mode locking*. JOSA B, 1991. **8**(10): p. 2068-2076.
- [6] Liu, X., D. Du, and G. Mourou, *Laser ablation and micromachining with ultrashort laser pulses*. IEEE journal of quantum electronics, 1997. **33**(10): p. 1706-1716.
- [7] Tamura, K., H. Haus, and E. Ippen, *Self-starting additive pulse mode-locked erbium fibre ring laser*. Electronics Letters, 1992. **28**(24): p. 2226-2228.
- [8] Haus, H., *Theory of mode locking with a slow saturable absorber*. IEEE Journal of Quantum Electronics, 1975. **11**(9): p. 736-746.
- [9] Haus, H.A., *Theory of mode locking with a fast saturable absorber*. Journal of Applied Physics, 1975. **46**(7): p. 3049-3058.
- [10] Set, S.Y., et al., *Laser mode locking using a saturable absorber incorporating carbon nanotubes*. Journal of Lightwave Technology, 2004. **22**(1): p. 51.
- [11] Kim, A., J. Kutz, and D. Muraki, *Pulse-train uniformity in optical fiber lasers passively mode-locked by nonlinear polarization rotation*. IEEE Journal of Quantum Electronics, 2000. **36**(4): p. 465-471.

- [12] Matsas, V., et al., *Selfstarting passively mode-locked fibre ring soliton laser exploiting nonlinear polarisation rotation*. Electronics Letters, 1992. **28**(15): p. 1391-1393.
- [13] Wu, J., et al., *Soliton polarization dynamics in fiber lasers passively mode-locked by the nonlinear polarization rotation technique*. Physical review E, 2006. **74**(4): p. 046605.
- [14] Kim, J. and Y. Song, *Ultralow-noise mode-locked fiber lasers and frequency combs: principles, status, and applications*. Advances in Optics and Photonics, 2016. **8**(3): p. 465-540.
- [15] Smirnov, S., et al., *Three key regimes of single pulse generation per round trip of all-normal-dispersion fiber lasers mode-locked with nonlinear polarization rotation*. Optics express, 2012. **20**(24): p. 27447-27453.
- [16] Hamzah, A., et al., *Passively mode-locked erbium doped zirconia fiber laser using a nonlinear polarisation rotation technique*. Optics & Laser Technology, 2013. **47**: p. 22-25.
- [17] Nelson, L., et al., *Ultrashort-pulse fiber ring lasers*. Applied Physics B: Lasers and Optics, 1997. **65**(2): p. 277-294.
- [18] Schröder, J., T.D. Vo, and B.J. Eggleton, *Repetition-rate-selective, wavelength-tunable mode-locked laser at up to 640 GHz*. Optics letters, 2009. **34**(24): p. 3902-3904.
- [19] Lin, Q. and G.P. Agrawal, *Vector theory of cross-phase modulation: Role of nonlinear polarization rotation*. IEEE journal of quantum electronics, 2004. **40**(7): p. 958-964.
- [20] Salhi, M., H. Leblond, and F. Sanchez, *Theoretical study of the erbium-doped fiber laser passively mode-locked by nonlinear polarization rotation*. Physical Review A, 2003. **67**(1): p. 013802.
- [21] Li, Z., et al., *Theoretical and experimental study of pulse-amplitude-equalization in a rational harmonic mode-locked fiber ring laser*. IEEE journal of quantum electronics, 2001. **37**(1): p. 33-37.
- [22] Komarov, A., H. Leblond, and F. Sanchez, *Passive harmonic mode-locking in a fiber laser with nonlinear polarization rotation*. Optics communications, 2006. **267**(1): p. 162-169.
- [23] Wei, X., et al., *A femtosecond hybrid mode-locking fiber ring laser at 409 MHz*. Laser Physics Letters, 2013. **10**(8): p. 085104.
- [24] Li, J., et al., *All-fiber passively mode-locked Tm-doped NOLM-based oscillator operating at 2- $\mu$ m in both soliton and noisy-pulse regimes*. Optics Express, 2014. **22**(7): p. 7875-7882.
- [25] Chen, T.-H., et al., *Unintentional Polarization Dependent Pulsewidth of Graphene Mode-Locked Er-Doped Fiber Lasers*. IEEE Journal of Selected Topics in Quantum Electronics, 2017. **23**(1).

## BIOGRAPHIES OF AUTHORS



Nur Ameelia Abdul Kadir is a Postgraduate student at Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia. She received the Bachelor's degree in Electronics Physic and Instrumentation from Universiti Malaysia Terengganu, Malaysia in 2015 and the Master's from University Malaya, Malaysia in 2017. Currently she is a member for Optical Devices and System Ikhza (ODESY). Her current research interests include pulse generation in fiber laser and sensing applications.



Nurul Alina Afifi Norizan is a Postgraduate student at Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia. She received the Bachelor's degree in Pure Physics from Universiti Teknologi Malaysia, Skudai in 2016. Currently she is a member for Optical Devices and System Ikhza (ODESY). Her current research interests include pulse generation in fiber laser.



Azura Hamzah is a Senior Lecturer at Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia. In MJIIT, she is a Full Member for Optical Devices and Systems Ikhza (ODESY) and an Associate Member for Disaster Preparedness and Prevention Centre (DPPC). She received her Bachelor's degree in Communication Engineering from International Islamic University Malaysia, Malaysia in 2005 and the Master's and PhD degree from Universiti Malaya, Malaysia in 2008 and 2012. Her research interests are in optical amplifier and laser, pulse laser, optical sensor, optical interconnect and rare-earth-doped optical devices. Currently, she is a member for The Institution of Electrical and Electronics Engineers and one of the Secretariat for IEEE Photonic Society Malaysia Chapter.