Dynamic Behavior of a Pump-Modulated Erbium-Doped Fiber Linear Laser with Single Fiber Bragg Grating

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Abstract An experimental analysis of the dynamical behavior of a pump-modulated Erbium-doped fiber laser (EDFL) with single fiber Bragg grating has been carried out and reported in this paper. The linear laser cavity here resembles a Fabry Perot interferometer. While varying the modulation frequency with a consistent signal amplitude and pump power, a wide range of features were observed which include: bifurcation, regions of optical bi-stability, period doubling, intermittently chaotic paths to chaos and chaos. Based on the region of chaos observed around the resonant frequency, the propensity of the laser to be used as a sensor to detect acoustic waves is briefly discussed, as the EDFL displayed tunable sensitive frequency capability.

Keywords EDFL · Pump modulation · Bifurcation

1 Introduction

Erbium-doped fiber lasers (EDFL) are known to have very outstanding features such as single-mode operation, high amplification, self-pulsations, high sensitivity to external disturbances, etc. These characteristics have made them a good laser source for many applications including optical communication, medicine, science and technology, reflectometry, pipeline sensing, intrusion zone identification, airborne acoustic sensing, etc. [1–6]. The characteristic of "high sensitivity to external disturbances" has gained more focus over the years as it leads to nonlinear dynamics during pump or loss modulation [7], which has an immense range of applications. Experimental pump modulation has been carried out on fiber lasers doped with Erbium by various authors [8–20]; however, our configuration is different from theirs and is quite simple and affordable. More so, it is customizable as other optical devices or

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fiber can be attached to the laser set-up to alter the length of the cavity, reflectivity or loss in the cavity [6].

In this paper, a study of the dynamical behavior of a single-mode Erbium-doped fiber laser (EDFL) is carried out and reported. The dynamic behavior of the EDFL is triggered by the laser diode pump modulation. The EDFL having a linear cavity is pump-modulated experimentally and its dynamical behavior is examined. Compared to the linear cavity set-up by other researchers where two reflectors are employed, only one fiber Bragg grating (FBG) is attached to the Erbium-doped fiber sensing arm to serve as a mirror to reflect the photons back to the laser cavity. During pump modulation, bifurcation, optical bi-stability, including period doubling and the intermittently chaotic paths to chaos are observed at various pump modulation frequencies with a constant signal amplitude. When the pump modulation frequency is modulated within a certain range, chaos occurs. Pump modulation is actually an easy and straightforward approach to modulate the laser output power in order to examine the behavior exhibited by regulating the laser diode pump power using a function generator and an oscilloscope. Similar studies have been implemented on the dynamics of Erbium-doped fiber ring lasers in which these behaviors were also exhibited [8–18, 20, 21]. Nevertheless, research on the nonlinear dynamics of fiber lasers doped with Erbium is inexhaustible due to its many evolving potential applications. Based on the behaviors observed, the EDFL has a high propensity to be used as a sensor as it demonstrated high sensitivity at its resonance frequency.

This paper is organized such that: the introduction is presented in Sect. 1 and Sect. 2 gives details of the EDFL experimental set-up. In Sect. 3, the results of the experiments are reported graphically and explained in details; Sect. 4 is the conclusion.

2 Experimental Set-Up of the Pump-Modulated EDFL

The experimental set-up of the EDFL is displayed in Fig. 1 which resembles a Fabry Perot interferometer. The linear laser cavity consists mainly of a 980/1550 nm high-performance wavelength division multiplexer (WDM) coupler and an Erbium-doped fiber (EDF) as an active or gain medium (3 m length, core of 8 μm diameter, clad of 125 μm diameter) all in one box. As part of the laser cavity, a 3 m long bare fiber is attached to the EDF which is called a single-mode fiber (SMF) acting as a sensing arm to detect acoustic waves and vibration. Attached to the other side of the SMF is a single side fiber Bragg grating (FBG), which has a center wavelength of 1550 nm ± 0.3 nm, > 99% reflectivity, > 5 dB SLSR and bandwidth of < 0.3 nm @ 3 dB. The entire laser cavity length is about 10 m from the photodetector end to the FBG end. This cavity design takes less space and is affordable as no expensive devices are required. It should be noted that no polarizer is used in this set-up.

The working principle of our EDFL under pump modulation is very simple. A function generator (GWINSTEK GFG-8020H) is used to modulate the frequency and optical power of the 980 nm pump laser and a digital oscilloscope (MEGURO

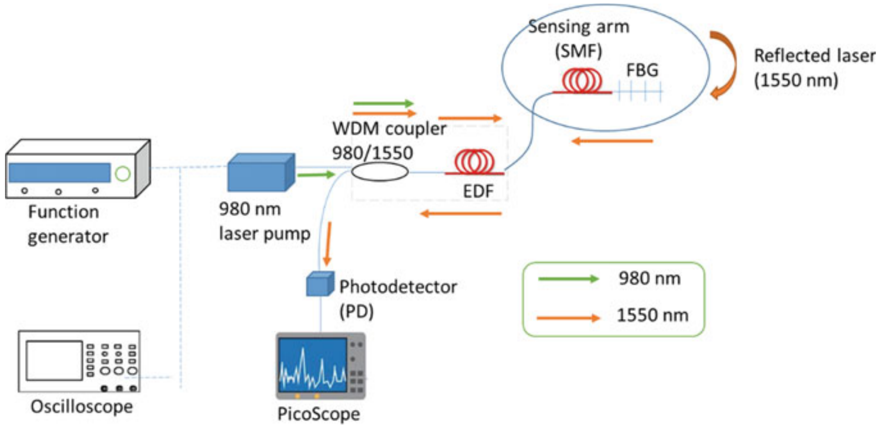

Fig. 1 Experimental set-up for pump modulation

MO-1020, 20 MHz) is used to monitor the modulation wave pattern. The modulation waveform of the pump laser is sinusoidal. A single wavelength 980 nm pump laser diode (Gooch & Housego EM595, with maximum pump power of 245 mW) emits 980 nm photons into the WDM and the WDM couples the photons into the EDF. The Erbium ions in the EDF absorb the photons of 980 nm wavelength and spontaneously emit photons with wavelength ranging from 1520 to 1560 nm. However, only photons of 1550 nm wavelength are reflected by the FBG back to the laser cavity and received by a high-speed photodetector (PD) made by THORLABS (DET08CFC/M). The PD changes the optical output to electrical output, so as to monitor the output light in waveforms on a PC via an oscilloscope (PicoScope 6 (3000 series)). The green and orange arrows in Fig. 1 symbolize the optical path of 980 and 1550 nm wavelengths.

3 Experimental Results

The optical spectrum of the EDFL was viewed using an optical spectrum analyzer (OSA) (Anritsu MS9740A 0.6 – 1.75 μm). With good launched pump power, the laser emission is obtained at 1549.7 nm ≈ 1550 nm, which matches the wavelength of the FBG. With continuous pumping of the laser, the lasing light remains uninterrupted.

After analyzing the optical spectrum of the lasing light, pump modulation experiments were carried out to observe the dynamic behaviors exhibited by the EDFL. During the experiments, optical output of the pump laser diode is modulated by the harmonic signal (A sin ($2\pi f$t)) of the external modulation applied from the function generator to the laser diode driver, where A and f are the modulation amplitude and frequency, respectively [8]. The resonant peak displayed in the electrical frequency spectrum when the pump power is adjusted is the resonant frequency of the laser cavity which increases as the pump power is increased. The EDFL can actually have many resonant frequencies due to the long resonator cavity. Hence, for our pump modulation experiment, the pump power was fixed at 52.6 mW, corresponding to 19 kHz resonant frequency of the laser cavity, and the amplitude (*A*) of the signal was fixed at 0.4 V (corresponding to 33 mW pump power). Direct modulation of the laser diode was then carried out by modulating the frequency from 0 to 45 kHz via the function generator. PicoScope 6 was used in observing the laser optical output features in time and frequency domains. The pump laser output power linearly depends on the current from the laser diode. Maximum peak-to-peak amplitude of the laser intensity was recorded for each modulation frequency variation from 0 to 45 kHz and vice versa to get the graph in Fig. 2b which shows the dynamic behavior of the EDFL.

During frequency modulation, resonant peaks, bifurcation and three regions of optical bi-stability (where three resonant transmission states exist and are unwavering) were attained. On increasing the modulation frequency from 0 to 45 kHz (indicated by a blue line in Fig. 2b), the lasing light exhibited its first resonant peak at 5 kHz and repetitive resonant peaks at 9, 12, 17 and at 29 kHz. When the modulation frequency was decreased from 45 to 0 kHz (indicated by an orange line in Fig. 2b), resonant peaks were also observed but at 6, 9, 12 kHz and 20 kHz causing a delay (hysteresis) between the laser systems' input and output as a result of the alteration in route. The hysteresis curve created three optical bi-stability regions. The second bi-stable region (10–17 kHz) is wider than the first (5–7 kHz) and the third (19–29 kHz) is wider than the second.

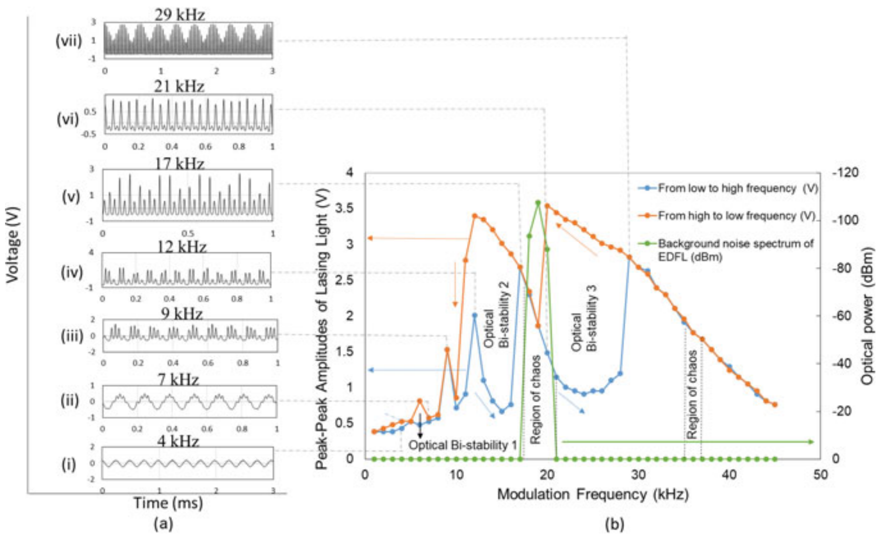

Fig. 2 **a** Time domain plots for the EDFL spectrum at different modulation frequencies; **b** graph showing the dynamical behaviors of the EDFL obtained by sweeping the modulation frequency from 0 to 45 kHz and vice versa

The time domain of the EDFL optical output was captured at different modulation frequencies and plotted in Fig. 2a with dashed lines showing the respective frequencies for each plot from (i) to (vii). When the modulation frequency is below 6 kHz, a lasing waveform with the resemblance of an amplitude modulation is obtained as shown in Fig. 2a (i) for 4 kHz. At 7 kHz (Fig. 2a (ii)), peaks are seen on the crest of each sinusoidal wave which reduces to 2 peaks in each sinusoidal wave at 8 kHz modulation frequency. At 9 kHz to 10 kHz, a period-doubling bifurcation repeating after every 3 long pulses and 1 short pulse is seen (Fig. 2a (iii)). The behavior goes back to 3 peaks on the crest of a sinusoidal waveform at 11 kHz modulation frequency, just as in 7 and 8 kHz. From 12 to 13 kHz, three stable lasing peaks are generated repetitively as shown in Fig. 2a (iv); two long peaks and a small peak. On increasing the pump modulation frequency to 14, 15 and 16 kHz, 2 tiny peaks appear on the crest of a single sinusoidal wave repeatedly. From 17 to 20 kHz, a period-doubling chaotic route observed as resonantly enhanced pulses repeating after a series of pulses exist as shown in Fig. 2a (v) leading to chaos at 21 kHz modulation frequency (Fig. 2a (vi)). Thus, the first region of chaos is marked from 17 to 21 kHz in Fig. 2b. At the region of chaos, the EDFL is most sensitive to external perturbations and forms some high intensity pulses. Chaos is indicated as irregular lasing peaks appearing at a particular frequency or range of frequencies and arises from the interaction of the population inversion with the intensity of the laser cavity [17]. From 22 to 34 kHz modulation frequency, the dynamic behavior changed again to period-doubling bifurcation with a higher order repetition of pulses. Chaos is seen to occur again at 35 kHz to 37 kHz modulation frequency. After the chaotic region, resonantly enhanced higher order repetition pulses leading to stable pulsation are obtained from 38 to 45 kHz. The existence of these routes to chaos and the occurrence of an irregularity after a series of period doubling shows that there is always a tendency for chaos to arise as expected in a pump-modulated EDFL for some variations of the modulation frequency and a constant pump power.

Resonant frequency aids in the characterization of the sensitivity of the EDFL as a sensor to acoustic wave modulation, although this is not the main focus of this paper. At the resonant frequencies of the EDFL, the system tends to oscillate at a maximum amplitude because of the periodic disturbance occurring at the same period of one of its natural frequencies. As said earlier, the resonant frequencies of the laser cavity can be regulated by varying the laser pump power from 0 to 245 mW (maximum limit of the laser diode). For the experiment carried out in this paper, the optical laser pump power was set at 52.6 mW to obtain a resonance frequency of 19 kHz. The background noise spectrum of the EDFL indicating the resonant peak at 19 kHz modulation frequency has been matched into Fig. 2b (indicated by the green line). It is clearly seen that irregular lasing peaks commonly called chaos occurs between modulation frequencies of 17–21 kHz, wherein 19 kHz is the resonance frequency. It can be deduced that at the resonance frequency of 19 kHz, the EDFL has a high propensity to be used as a sensor to detect ultrasonic waves at a low frequency and can thus be used for either gas, water or oil pipeline monitoring and leakage detection which is the proposed use of this sensor. Other possible applications include biomimicking and multi-stable switching. Also, one of the advantages of the EDFL sensor is its tunable sensitive frequency capability for acoustic wave sensing as the distribution of the resonant frequency at various pump power levels indicates a shift to a higher frequency with respect to the pump power increase [6]. Furthermore, theoretical simulation using the rate equations in MATLAB has been carried out and a comparison with the experiments showed similar results and would be published in another article. Similar comparison carried out by other authors actually showed a good agreement between their theoretical and experimental results [7–9, 12, 14].

4 Conclusion

In this paper, pump modulation has been carried out in the EDFL system to aid in the understanding of its behavior when exposed to external disturbances. Pump modulation on the EDFL performed from low to high frequency and from high to low frequency showed the existence of period-doubling bifurcation, intermittently chaotic paths to chaos, chaos and optical bi-stability. The existence of these routes to chaos shows that there is a tendency for chaos to obviously occur in an EDFL. Results from the experiments have also shown that chaos occurs at the resonance frequency of the EDFL which shows that it has a high propensity to be used as a sensor to detect ultrasonic waves at a low frequency and can thus be used for pipeline monitoring and leakage detection.

References

1. Luo L, Chu PL (1998) Optical secure communications with chaotic erbium-doped fiber lasers. J Opt Soc Am B 15:2425–2530
2. Digonnet MJF (2001) Rare Earth Doped Fiber Lasers and Amplifiers, Revised and Expanded, 2nd edn. Marcel Dekker, New York
3. Pua CH, Norizan SF, Harun SW, Ahmad H (2011) Non-membrane optical microphone based on longitudinal modes competition. Sens Actuators A Phys 168(2):281–285. https://doi.org/10.1016/j.sna.2011.04.034
4. Pua CH, Chong WY, Ahmad H (2013) Instantaneous response of wide area intrusion sensor with long haul monitoring capability. IEEE Photonics Tech. Lett 25(23):2255–2258. https://doi.org/10.1109/LPT.2013.2284608
5. Woon SL, Kwan KM, Chong WY, Lin HS, Pua CH (2017) Cascaded acoustic wave sensors based on erbium-doped fibre laser dynamics for intrusion zone identification. IEEE Sensors 17(6):1893–1898. https://doi.org/10.1109/JSEN.2017.2655019
6. Pua CH, Ahmad H, Harun S, De La Rue R (2012) Direct airborne acoustic wave modulation of Fabry-Perot fiber laser (FPFL) over 100 kHz of operating bandwidth. Appl Opt 51(15):2772–2777. https://doi.org/10.1364/AO.51.002772
7. Pua CH, Ahmad H, Harun S (2012) Study of Dual-wavelength mode competition in an Erbium-Doped Fiber Laser (EDFL) produced by acoustic waves. IEEE J Quantum Electron 48(12):1499–1504
8. Pisarchik, A.N., Barmenkov, Y.O., Kir'yanov, A.V.: Experimental characterization of the bifurcation structure in an Erbium-doped fiber laser with pump modulation. IEEE J. Quantum Electron 39(12), 1567–1571 (2003).

9. Pisarchik, A.N., Kir'yanov, A.V., Barmenkov, Y.O.: Dynamics of an erbium-doped fiber laser with pump modulation: theory and experiment. J. Opt. Soc. Am. B 22(10), 2107–2114 (2005). https://doi.org/10.1364/JOSAB.22.002107.
10. Reategui, R.J., Kir'yanov, A.V., Pisarchik, A.N., Barmenkov, Y.O., Il'ichev, N.N.: Experimental study and modelling of coexisting attractors and bifurcations in an Erbium-doped fiber laser with diode-pump modulation. Laser Phys 14(9), 1–5 (2004).
11. Pisarchik AN, Barmenkov YO (2005) Locking of self-oscillation frequency by pump modulation in an erbium-doped fiber laser. Opt Commun 254:128–137. https://doi.org/10.1016/j.optcom.2005.05.028
12. Lacot E, Stoeckel F, Chenevier M (1994) Dynamics of an erbium doped fiber laser. Phy. Rev. A. 49:3997–4008. https://doi.org/10.1364/JOSAB.22.002107
13. Luo L, Tee TJ, Chu PL (1998) Bistability of erbium-doped fiber laser. Opt Commun 146:151–157. https://doi.org/10.1016/S0030-4018(97)00502-6
14. Luo L, Tee TJ, Chu PL (1998) Chaotic behaviour in erbium-doped fiber-ring lasers. J Opt Soc Am B 15(3):972–978. https://doi.org/10.1364/JOSAB.15.000972
15. Kruger TS, Rech PC (2012) Dynamics of an erbium-doped fiber dual-ring laser. Eur Phys J D 66(12):3997–4008. https://doi.org/10.1140/epjd/e2011-20396-4
16. Arellano-Sotelo, H., Kir'yanov, A.V., Barmenkov, Y.O., Aboites, V.: The use of nonlinear dynamics of erbium-doped fiber laser at pump modulation for intra-cavity sensing. Opt Laser Technol 43 132–137 (2011). https://doi.org/10.1016/j.optlastec.2010.05.017.
17. Kumar G, Vijaya R (2015) Dynamical features of loss and pump modulation in an erbium-doped fiber ring laser. J Opt 17(125402):1–9. https://doi.org/10.1088/2040-8978/17/12/125402
18. Sola IJ, Martin JC, Alvarez JM (2002) Non-linear response of a unidirectional erbium-doped fiber ring laser to a sinusoidally modulated pump power. Opt Commun 212:359–369
19. Sola IJ, Martin JC, Alvarez JM (2006) Analytical treatment for the study of an erbium-doped fiber ring laser fed by a sinusoidally modulated pump power. Opt Commun 258:59–66
20. Onubogu NO, Pua CH, Lin HS, Faidz A-R (2020) The dynamic behavior of non-polarized erbium-doped fiber ring. Optik 207(164442):1–8
21. Zhang L, Yang R, Qin JM, Yang LZ (2013) An experimental study of high frequency chaotic dynamics in an erbium-doped fiber ring laser. Laser Phys 23(12):125104. https://doi.org/10.1088/1054-660X/23/12/125104