Experimental investigation on chaos generation in erbium-doped fiber single-ring lasers*

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In this paper, the chaotic behaviors in an erbium-doped fiber (EDF) single-ring laser (EDFSRL) are investigated experimentally by using the loss modulation method. An electro–optic modulator (EOM) made of $LiNbO_3$ crystal is added to the system. Thus, by changing the modulation voltage and the modulation frequency of the EOM, the freedom of the EDFSRL system is increased. The chaotic characteristics of the system are studied by observing the time series and the power spectra. The experimental results indicate that the erbium-doped fiber single-ring laser system can enter into chaos states through period-doubling bifurcation and intermittency routes.

Keywords: erbium-doped fiber single-ring lasers, electro–optic modulator, chaos generation, power spectrum

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1. Introduction

Chaos is an important branch of nonlinear science, and it exists in physics, chemistry, communication, and so on.[1−3] Erbium-doped fiber lasers (EDFLs) have many advantages, such as high gain and low noise, and are applied widely in various fields, such as communication, sensing, spectroscopy, and medicine. The erbium-doped fiber single-ring lasers (EDFSRLs) are class B lasers, and are the second-order autonomous systems. This kind of laser systems can generate chaos behaviors by adding freedom degrees, such as the pump power, the delay time, and the cavity loss. Recently, some experts[4−19] have studied the chaos in EDFLs numerically and experimentally. Boudec *et al.*[4] reported anti-phase dynamics and chaos in self-pulsing EDFLs. Lacot *et al.*[5] investigated the dynamics of an EDFL; Quinton *et al.*[6] studied the fast polarization dynamics of an erbium-doped fiber-ring laser. Luo *et al.*[7] reported the chaotic behavior in erbium-doped fiber-ring lasers; Abarbanel *et al.*[8] reported the chaotic dynamics in erbium-doped fiber-ring lasers; Luo *et al.*[9] investigated experimentally the synchronization chaos in EDFLs; Wang *et al.*[10] reported the synchronization of chaotic systems modulated by another chaotic system in an erbium-doped fiber dual-ring laser system; Zhang *et al.*[11,12] investigated the generalized synchronization of chaos and the controlling hyper-chaos in erbium-doped dual-ring lasers, they[13] also reported the synchronization of chaotic erbium-doped fiber lasers and its application in secure communication; Yan[14] presented a study on the method of controlling chaos in an erbium-doped fiber dual-ring laser via external optical injection and shifting optical feedback light; Fan *et al.*[15] reported the dynamics of an EDFL with optical delay feedback and chaotic synchronization; Liu *et al.*[16,17] presented an experiment of dynamical behaviors in an erbium-doped fiber-ring laser with loss modulation by using acousto–optic modulators (AOMs), they also reported the frequency locking and the chaos in erbium-doped fiber-ring lasers with dual-frequency loss modulation; Yang *et al.*[18] presented the study of chaotic bandwidth in an erbium-doped ring fiber laser. Yang *et al.*[19] investigated dynamical behaviors and the complexity of an erbium-doped fiber dual-ring laser with time-delay feedback.

Chaotic generation in an EDFL is very important due to its applications in secure communication.[13,20−24] In this paper, we will study experimentally the generation of chaos in the EDFSRL by adding

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an electro–optic modulator (EOM) into the system.

2. Experimental system

To study the chaotic generation in the EDFSRL, we use the experiment setup shown in Fig. 1, where the laser is the light source for the system, its output power is 20.9 mW, and its wavelength is 1550.190 nm. C_1 and C_2 are two couplers with the coupling ratio of 90:10. The OAT is an attenuator. The ISO is an optical isolator, it is used to ensure the unidirectional transmission. The EDFA is an erbium-doped fiber amplifier, it is made by Accelink Technologies Co Ltd, its type number is EDFA-PA-20-2-4-FC/PC, it consists of a semiconductor laser providing the pump light with 980-nm wavelength, a coupler, a segment of 26-m erbium-doped fiber, and an ISO placed at the end of the EDFA, the wavelength and the power of the input light signal of this EDFA are 1528 nm–1563 nm and −40 dBm−−10 dBm, respectively. The filter is a narrow bandwidth fiber filter with the wavelength range of 1547 nm–1551 nm. The EOM is an electro–optic modulator, and its bandwidth is 10 GHz. The DC is a direct-current voltage source. The SG is a signal source. The PD is a photo-detector with a bandwidth of 10 GHz, this PD is used to complete the transformation of the optical signal to the electrical signal. The OSC is an oscilloscope (Tektronix TDS7404), and it is used to observe the time series and the frequency spectrum of the electrical signal from the PD.

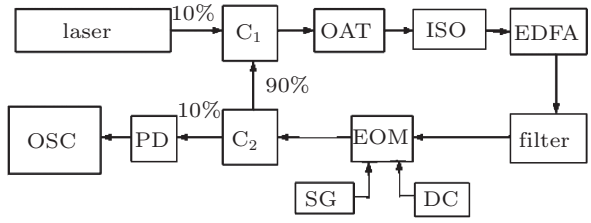


Fig. 1. Experimental setup of the erbium-doped fiber single-ring laser.

3. Experimental results and analysis

Firstly, the dc bias voltage of the EOM is kept at 10 V, and its modulation frequency f is used as the control parameter. When $f = 75$ MHz, from the OSC, the time series and the corresponding fast Fourier transform (FFT) spectra are obtained and shown in Figs. 2(a) and 2(b), respectively. These two diagrams illustrate that the system is in the one period (1P) state. Then the modulation frequency f is reduced. When $f = 68$ MHz and $f = 64$ MHz, the time series and the corresponding FFT spectra are presented in Figs. 2(c), 2(d) and Figs. 2(e), 2(f), respectively. From Fig. 2(c), we can find that the pulse signal has two maximum values approximatively. By comparing Fig. 2(d) with Fig. 2(b), we can see that some new peaks are present in Fig. 2(d), and they lie between the peaks existing in Fig. 2(b). Thus, figures 2(c) and 2(d) show that the system is in the two-period (2P) state. From Fig. 2(e), we can see that the pulse is random, namely, non-periodic. From Fig. 2(f), we can see that the FFT spectra are the broadband background noise. Thus, figures 2(e) and 2(f) show that the system is in the chaotic state. Therefore, figure 2 indicates that this EDFSRL system can generate chaos through the period-doubling bifurcation route by reducing the modulation frequency f of the EOM and keeping its dc bias voltage at 10 V.

Secondly, the modulation frequency of the EOM is kept at 60 MHz, and its dc bias voltage V is taken as the control parameter. When $V = 4$ V, the waveform is shown in Fig. 3, where panel (a) is the time series diagram, and panel (b) is the corresponding FFT spectrum. We compare the pulses and the FFT spectra in Figs. 2(a) and 3(a), and in Figs. 2(b) and 3(b), respectively. It is found that the system's state corresponding to Figs. 3(a) and 3(b) is the three-period (3P) state. Then the bias voltage V is increased. When $V = 6$ V and $V = 10$ V, the time series and the corresponding FFT spectra are shown in Figs. 3(c), 3(d) and Figs. 3(e), 3(f), respectively. We can see that the pulse waveform in Fig. 3(c) is slightly different, namely, slightly intermittent, from that in Fig. 3(a), and the FFT spectrum in Fig. 3(d) is also different from that in Fig. 3(b). Thus, figures 3(c) and 3(d) show that this EDFSRL system is in the slight intermittency state. From Fig. 3(e), we can see that the pulse varies randomly. From Fig. 3(f), we can find that the FFT spectrum is the broadband background noise. Thus, figures 3(e) and 3(f) indicate that the system is in the chaotic state. Therefore, figure 3 illustrates that this EDFSRL system can generate chaos through intermittency chaos by increasing the dc bias voltage V of the EOM and keeping its modulation frequency at $f = 60$ MHz.

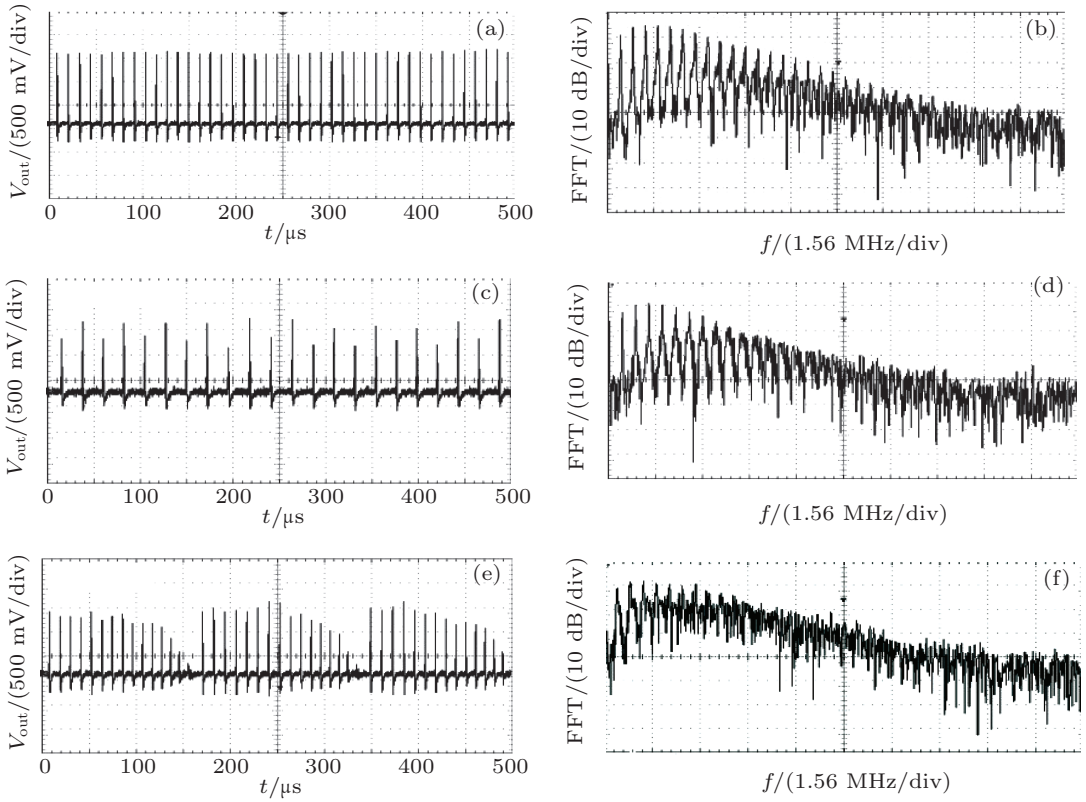


Fig. 2. The time series and the corresponding FFT spectra with different modulation frequencies. Panels (a) and (b): 1P state with 75 MHz; panels (c) and (d): 2P state with 68 MHz; panels (e) and (f): chaos state with 64 MHz.

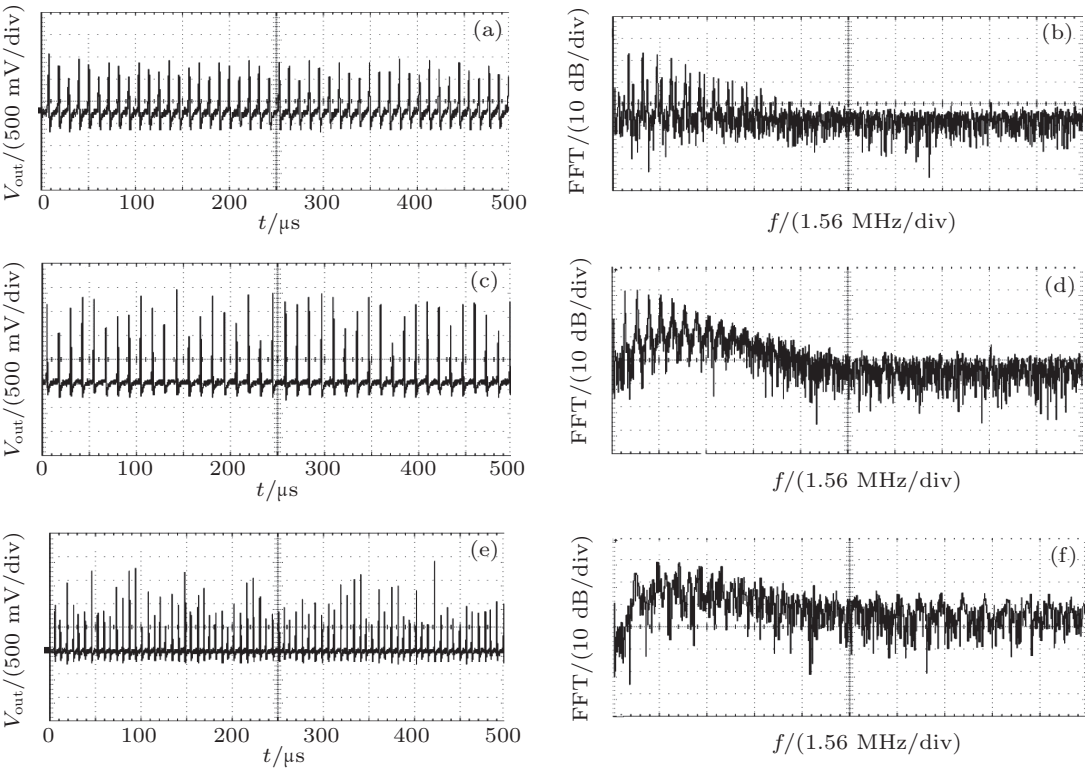


Fig. 3. Time series and the corresponding FFT spectra with different dc bias voltages of the EOM. Panels (a) and (b): 3P state with 4 V; panels (c) and (d): slight intermittency state with 6 V; panels (e) and (f): chaos state with 10 V.

4. Conclusion

We studied experimentally chaotic generation in an EDFSRL by adding an EOM into the system. Experimental results show that two routes of going into chaotic states can co-exist in this EDFSRL system by appropriately adjusting the dc bias voltage and the modulation frequency of the EOM used in this system. When the dc bias voltage of the EOM is kept at 10 V and its modulation frequency is changed from 75 MHz to 64 MHz, we can observe that this system enters the chaos state through the period-doubling bifurcations. When the modulation frequency of the EOM is kept at 60 MHz and its bias voltage varies from 4 V to 10 V, we can see that this system goes into the chaotic state through intermittency. These results will be useful for applying chaos states in an EDFSRL.

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