Chaotic dynamics of erbium-doped fiber laser with nonlinear optical loop mirror

Lingzhen Yang *, Li Zhang, Rong Yang, Li Yang, Baohua Yue, Ping Yang

Institute of Optoelectronic Engineering, Department of Physics and Optoelectronics, Taiyuan University of Technology, Taiyuan, 030024, China

A R T I C L E   I N F O

Article history:
Received 13 April 2011
Received in revised form 20 July 2011
Accepted 10 September 2011
Available online 28 September 2011

Keywords:
Chaos
Fiber laser
Nonlinear optical loop mirror (NOLM)

A B S T R A C T

We experimentally and numerically demonstrate the chaotic dynamics of the erbium-doped fiber laser with a nonlinear optical loop mirror. When the polarization controllers are fixed at an appropriate orientation, we observe that the fiber laser exhibits a period-doubling route to chaos with increasing the pump power in the experiment and simulation. The numerical simulation shows a good agreement with the experimental results. The results show experimentally and numerically that the chaotic dynamics of the erbium-doped fiber laser is related to the polarization state and the pump power of light in the cavity.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Due to its natural confidentiality, anti-interference and non-predictability, chaos has been extensively applied in the fields of secure communication [1], chaotic sensor [2] and imaging encryption [3]. It is well known that the erbium-doped fiber lasers are relatively simple and compact. Chaotic properties of many kinds of fiber lasers have been proposed and demonstrated [4–6]. The basic methods of the chaotic generation in erbium-doped fiber lasers include the pump modulation, the loss modulation, the nonlinear Kerr effect and the nonlinear optical loop mirror (NOLM) [7–13]. The NOLM has been used as fast saturable absorber to passively mode-locked laser oscillators [14] or sagnac interferometer [15]. A.L. Steele numerically analyzed the optical instabilities in a nonlinear optical fiber loop mirror with feedback, and the results showed that the NOLM with feedback can lead to the period-doubling route to chaos [16]. C.A. Merchant theoretically used the NOLM with optical feedback generating chaos [17]. In 2005, Lai W.J. analyzed the dynamics of a NOLM and a nonlinear amplifying loop mirror (NOLM–NALM) fiber ring laser, and they foresaw the possibility of the chaotic operation of the laser [18]. However, the works did not extend further into the chaotic dynamics of NOLM–NALM fiber ring laser.

In this paper, we study the chaotic dynamics of the erbium-doped fiber ring laser with a NOLM without the optical injection by experimental validation and numerical simulation. When the polarization controllers are adjusted to an appropriate position, we can obtain the period-doubling route to chaos with increasing the pump power. The experimental and numerical results show that the chaotic dynamics of fiber laser with NOLM is related to the polarization state and the pump power of the light in the cavity.

2. Experiment

2.1. Experimental setup

The experimental setup of the erbium-doped fiber ring laser (EDFRL) with a NOLM is shown in Fig. 1. The fiber ring cavity consists of a wavelength division multiplexer (WDM), an erbium-doped fiber (EDF) with a length of 9 m, and a polarization independent isolator (ISO). A 980-nm laser diode (LD) with the maximum pump power of 250 mW is used to pump EDF through a 980/1550-nm WDM. The ISO ensures the unidirectional propagation of light. The NOLM constructed with single mode fiber (SMF) is connected together with the ring cavity through a 2 × 2 fiber coupler (70:30, C1). Two polarization controllers (PCs) and a 30-m SMF are inserted inside the NOLM. The PCs are set to change the polarization states of the light waves, and determine the interference in the NOLM. The output of the fiber laser is taken from the 10% output of fiber coupler (C2). The output light in the laser cavity is monitored by a 500 MHz bandwidth and 5 Gbps sampling ratio digital oscilloscope together with a 2 GHz photo detector (PD). The chaotic spectrum is measured with a RF spectrum analyzer.

2.2. Experimental results

The cavity round-trip time of the fiber laser is 208.8 ns corresponding to the loop length of the fiber laser with 40.16 m in our experiment. We adjust the polarization controllers and the pump power to observe the output dynamics of the fiber laser. In order to achieve...
the chaotic output, the PCs are carefully adjusted. When we appropriately select the orientations of the two polarization controllers to an appropriate combination, the period-one, period-two, and quasi-periodicity states are observed separately for the pump power to be 42.8 mW, 45.1 mW, and 46.9 mW, which are shown in Figs. 2–4 respectively. The time series, the power spectra, the autocorrelation traces, and the phase portraits of different oscillation states in Figs. 2–4 show the route of period-doubling to quasi-periodicity states.

The output of the fiber laser begins to enter a chaotic state, when we further increase the pump power to 62.5 mW. The chaos still exists when the pump power is increased to 240.0 mW. The first and second columns of Fig. 5 illustrate the time series, the power spectra, the autocorrelation traces, and the phase portraits for pump powers of 77.0 mW and 240.0 mW respectively.

From the experiment, we find that the chaotic state does exist in a very small region. In addition, if we adjust polarization controllers to other positions, we observe the fiber laser could demonstrate various dynamic characteristics such as multi-pulse, mode-locking.

3. Numerical simulation

3.1. Numerical model

The numerical analysis of the chaotic dynamics of EDFRL with a NOLM is shown in Fig. 8 based on the model of EDFRL proposed by Abarbanel [12] and Lexis [19].

The propagation equation of the electrical field $E(z, t) = \epsilon(z, t) e^{i(k_0 z - \omega_0 t)}$ in the EDFRL can be described by

$$\frac{\partial \epsilon_{x,y}(z, \tau)}{\partial z} = g n(\tau) \epsilon_{x,y} + L_{x,y} \epsilon_{x,y} + N_{x,y} \epsilon_{x,y}.$$  \hspace{1cm} (1)

The retarded time is given by $\tau = t - z/v_g$, where $v_g$ is the group velocity of the waves, $g$ is the gain parameter, $n(\tau)$ population inversion, and $\omega_0$ is the light wave angular frequency.
The linear operator $L_{x,y}$ includes the linear birefringence, group-velocity dispersion (GVD), and gain dispersion

$$L_{x,y} = \pm \frac{ik_0(n_x - n_y)}{2n_0} \left( \pm \frac{\Delta}{n_0 c} \omega \right) - \frac{i}{2} \frac{\Delta}{n_0} \frac{\alpha^2}{n_0} - \frac{g_R(T)\alpha^2 T_2^2}{1 + \alpha^2 T_2^2},$$

where $\Delta = n_0(n_x - n_y)$ is the differential birefringence, $\omega$ is the signal angular frequency, and $T_2$ is the decay time of the fast fluctuations of polarization.

The nonlinear operators are

$$N_x e_x = i\gamma \left\{ \left[ |e_x(z,\tau)|^2 + \frac{2}{3} |e_y(z,\tau)|^2 \right] e_x(z,\tau) \right\},$$

$$N_y e_y = i\gamma \left\{ \left[ |e_y(z,\tau)|^2 + \frac{2}{3} |e_x(z,\tau)|^2 \right] e_y(z,\tau) \right\},$$

where $\gamma$ is the nonlinear coefficient of the fiber.

---

Fig. 5. Chaotic states of the fiber laser with pump powers of 77.0 mW and 240.0 mW. (a) Time series, (b) power spectra, (c) autocorrelation traces, and (d) phase portraits.

Fig. 6. Chaotic spectrum of the fiber laser with pump power of 240.0 mW.

Fig. 7. Output power of the fiber laser versus pump power.
where $R = T$ is the transitivity of the NOLM, $T$ is the transitivity of the NOLM, $P$ is the pump strength, and $Q$ and $\tau$ represent the pump strength and delay to the EDFRL. When the light arrives at the entrance to the cavity, the input electric field is split into two counter propagating fields which return in coincidence to recombine at the coupler. The optical path lengths experienced by the two propagating fields are exactly the same, since they follow the same route but in opposite directions. The transmission equation of the NOLM can be described by

$$p(t + \tau_D) = TP(t),$$

where $T$ is the transitivity of the NOLM,

$$T = 2k(1-2k)(1 + \cos[(1-2k)\gamma_{\text{NOLM}}P(t)])$$

and $\tau_D$ is the round trip time of the NOLM, and $k$ is the coupling ratio. After the light from the NOLM propagates over the round trip time $\tau_D$, it will experience a Jones matrix $\mathbf{J}_\text{PC}$ with the polarization controller, then reenter the main ring.

The dynamics of the EDFRL with NOLM can be described by the evolution equations of electrical field $\varepsilon(t)$ and integrated population inversion $w(\tau) = \int_0^\infty n(z, \tau)dz$. The overall propagation map including all the passive and active parts of the ring is

$$\varepsilon(z = l_A + l_F, \tau + \tau_R) = R\mathbf{J}_\text{PC}TP(t),$$

where $R = \text{diag}(R_x, R_y)$ is the polarization-dependent attenuation, $\tau_R$ is ring round-trip time, $l_A$ is the length of EDF, and $l_F$ is the length of SMF in the whole cavity. Transmission operator is $P(t) = \varepsilon(z = l_A, t)$, $Q$ represents pump strength, and $T_1$ is the lifetime of the excited states.

3.2. Numerical results

We use the following parameters for the simulation unidirectional: $l_A = 9\, \text{m}$, $l_F = 31.16\, \text{m}$, $n_A - n_0 = 1.8 \times 10^{-6}$, $n_0 = 1.46$, $\beta_2 = -20\, \text{ps}^2/\text{km}$, $k = 0.7$, $\gamma = 3 \times 10^{-3}\, \text{W}^{-1}\, \text{km}^{-1}$, $T_1 = 10\, \text{ms}$, $T_2 = 1\, \text{ps}$, and $\tau_R = 200.8\, \text{ns}$. As the orientations of the two polarization controllers are selected to be an appropriate combination, we get the period-doubling route to chaos in numerical simulation. The time series, the power spectra, the autocorrelation traces, and phase portraits of different oscillation states in Figs. 9–11 show the periodic states for the pump power of 41.7 mW, 46.2 mW, and 47.0 mW separately, where the period-one, period-two, and quasi-periodicity states are obtained respectively. Compared with the Figs. 2–4, the time series, the power spectra, the autocorrelation traces, and the phase portraits have a good agreement. If we further increase the pump power to 68.0 mW, the fiber laser will present chaotic state as shown in Fig. 12. The first and second columns of Fig. 5 illustrate the time series, the power spectra, the autocorrelation traces, and the phase portraits for the pump power to be 68.0 mW and 240.0 mW respectively.

4. Discussion

In terms of the procedure of the route of period-doubling, quasi-periodic states to chaotic states in the experiment and simulation, we can find random intensity fluctuations in time series, bandwidth enhancement of power spectra, and randomly distributed dots in the phase portrait. The autocorrelation trances for the pump power of 240 mW are similar to $\delta$ function with some side lobes. The time interval between the two neighboring side lobes is 200.8 ns which is the round-trip time of the cavity corresponding to the length of the EDFRL with NOLM. The cavity round-trip time is estimated as $L/v$, where $L$ is the cavity length and $v = c/n$ is the speed of light in the fiber, $c$ is the speed of light in vacuum, and $n$ is the index of refraction of erbium-doped fiber. We believe that the high side lobes are induced by the repetitive interference of light in the cavity, which suffer a nonlinear phase shift. When the pump power is 240.0 mW, the bandwidth of Fig. 12 is wider than that of Fig. 5, except for the trailing of power spectra in Fig. 5, which are caused by the limitation of bandwidth of the oscilloscope.

In terms of the experimental and numerical results, we can get that the chaotic states are not only related to the pump power but...
also to the polarization state. If we fix the pump power to a certain value which must be higher than the threshold power, the polarization controllers will determine the output states. For different polarization states, we find that the EDFRL with NOLM presents various dynamic characteristics, such as multi-pulse, mode-locking. The chaotic states can be observed in the proper position of the polarization controllers. Consequently, the chaotic generation is related to the polarization state and pump power. It is an intrinsic property of such a nonlinear cavity whose output exhibits the period-doubling route to chaos under larger nonlinear phase shift of light in the cavity [20].

5. Conclusion

We have demonstrated the chaotic dynamics behavior of the EDFRL with a NOLM in numerical simulation and experiment. By changing the pump power and the polarization states in the cavity, the chaotic dynamics has been observed. When the polarization controllers are fixed in a certain state, we can achieve the period-doubling route to chaos without external optical injection as the pump power increasing. The experimental and numerical results

![Fig. 11. Pump power of 47.0 mW for quasi-periodicity state. (a) Time series, (b) power spectrum, (c) autocorrelation trace, and (d) phase portrait.](image)

![Fig. 12. Chaotic states of the fiber laser with pump powers of 68.0 mW and 240.0 mW. (a) Time series, (b) power spectra, (c) autocorrelation traces, and (d) phase portraits.](image)
confirm that the chaotic behaviors of the EDFRL with NOLM are related to the polarization state and the pump power of the light in the cavity.

Acknowledgments

This work is supported in part by the Natural Science Foundation for Young Scientists of Shanxi Province, China and the National Natural Science Foundation of China under Grant Nos. 2008021008 and 60908014.

References