Chaotic generation based on figure-of-eight erbium-doped fiber laser with an optical fiber ring*

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(Received 7 November 2011)

We experimentally demonstrate the chaotic generation in a figure-of-eight erbium-doped fiber laser (F8L) with an optical fiber ring (OFR). With an appropriate combination of polarization controllers, we find that the fiber laser exhibits period-doubling route to chaos, and the chaotic self-synchronous dynamics has a tendency to be reduced significantly. The experimental results show the tendency is related to the interference and the nonlinear phase shift of light in the optical fiber ring. Meanwhile, the chaotic dynamics is related to the polarization state and pump power.

Document code: A **Article ID:** 1673-1905(2012)03-0209-3

DOI 10.1007/s11801-012-1164-6

The erbium-doped fiber (EDF) lasers are very attractive for low threshold, high power, high signal-to-noise ratio, and excellent fiber compatibility. Chaotic generation by the erbium-doped fiber lasers has been studied extensively in the optical communication and sensor[1-3]. But the correlative performance of chaos generated by erbium-doped fiber ring lasers has a certain periodicity[4]. Based on the intensity-dependent phase shift accumulated over a fiber ring, dynamic behaviors of the optical fiber ring (OFR) have been researched[5-8]. The OFR is a simple structure and can be used for retrieving the measured information from the chaotic output of the system[9]. The OFR has the inherent sensitivity for various physical parameters, such as index of refraction, fiber length, and attenuation. So the OFR can be used for improving the properties of all-optical switching[10] and producing the high-speed chaos-based secure communications[11]. The chaotic fiber ring resonator can be used as a sensor for measuring several physical parameters[12]. The single optical ring resonator connected to a Sagnac loop has achieved to tune the filter response with desired bandwidths[13], and the OFR cavity can control the repetition rate[14]. In this paper, we get the chaotic dynamics of figure-of-eight erbium-doped fiber laser (F8L) with an OFR without the external optical injection by experimental performance, and use the OFR for improving the chaotic correlative performance of F8L.

The experimental setup of F8L with an OFR is shown in Fig.1. The F8L is composed of the erbium-doped fiber ring laser with a nonlinear optical loop mirror (NOLM). The erbium-doped fiber ring consists of a wavelength division multiplexer (WDM), an erbium-doped fiber with the length of 9 m, and a polarization independent isolator (ISO). A 980 nm laser diode (LD) with the maximum output 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) to form a F8L, which is framed in dashed lines. The two polarization controllers (PC1, PC2) and a 30 m SMF are inserted inside the NOLM. The PCs are set to change the polarization states of light and determine the interference in the NOLM. Then an OFR is added to the output port of the F8L. The OFR is constructed by connecting the

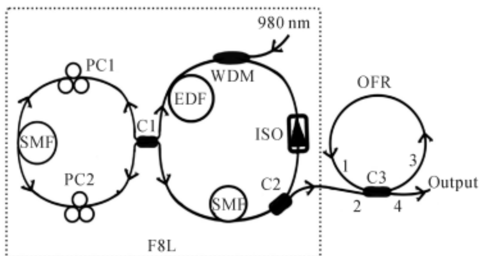

Fig.1 Experimental setup of the F8L with an OFR

* This work has been supported by the National Natural Science Foundation of China (No.61107033), and the Natural Science Foundation for Young Scientists of Shanxi Province of China (No.2008021008).

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output port 3 with the input port 1 by using 50:50 optical fiber coupler (C3). The output light emits from the port 4 of OFR. The output light in the laser cavity is monitored by a digital oscilloscope with bandwidth of 500 MHz and a 2 GHz photodetector.

When we appropriately select the orientations of the two PCs to achieve an appropriate combination, the threshold power is measured to be 33.0 mW. The F8L with an OFR presents period-doubling route to chaos.

Figs.2, 3 and 4 illustrate the period-one, period-two and quasi-periodicity states under the pump power of 42.6 mW, 44.3 mW and 45.4 mW, respectively.

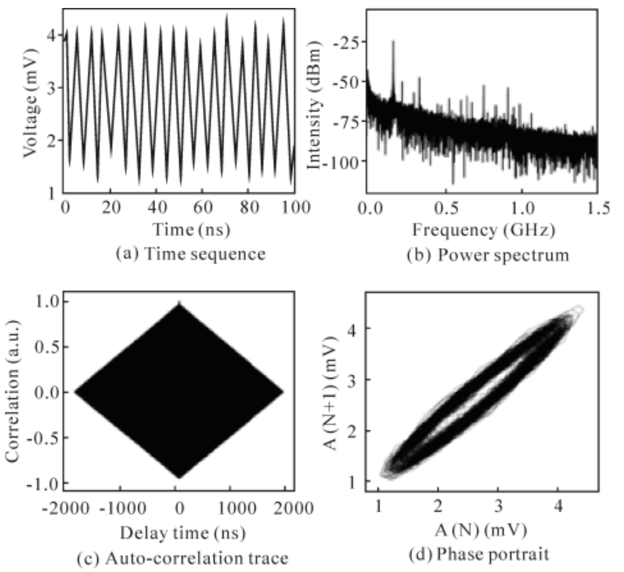

Fig.2 Period-one state under the pump power of 42.6 mW

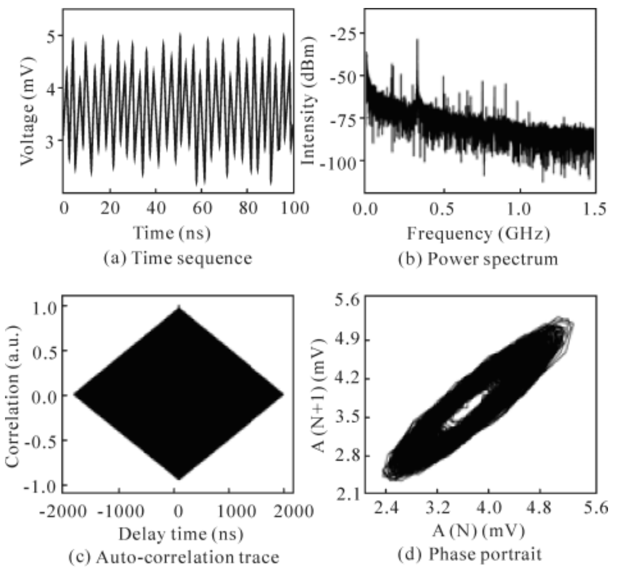

Fig.3 Period-two state under the pump power of 44.3 mW

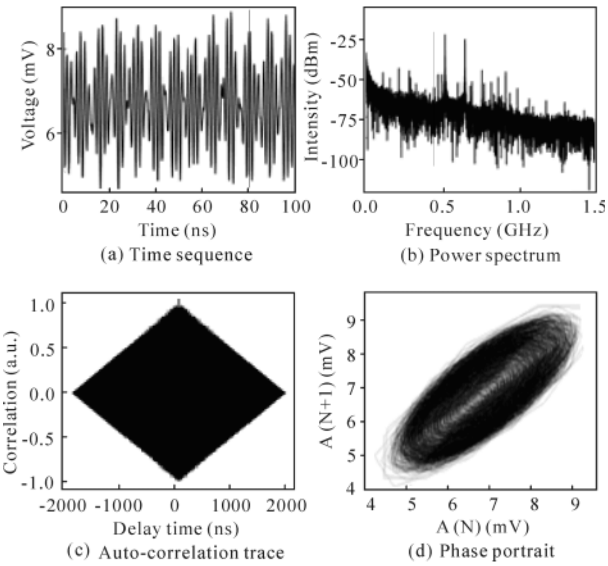

Fig.4 Quasi-periodicity state under the pump power of 45.4 mW

If we further increase the pump power to 56.6 mW and 238.4 mW, the fiber laser can present chaotic state. Figs.5 and 6 illustrate the time sequences, the power spectra, the auto-correlation traces and the phase portraits for the pump power of 56.6 mW and 238.4 mW, respectively.

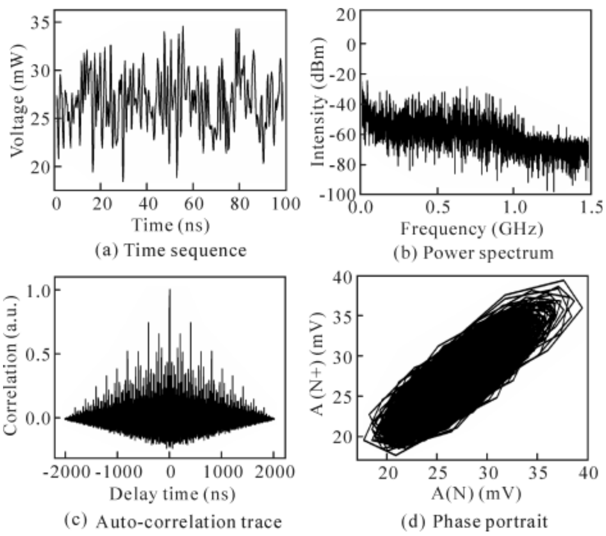

Fig.5 Chaotic states of fiber laser with pump power of 56.6 mW

The procedure of period-doubling, quasi-periodic states to chaotic states shows chaotic dynamics such as random intensity fluctuations and bandwidth enhancement. The auto-correlation trace for the pump power of 238.4 mW in Fig.6 is similar to δ function with some side lobes presenting the self-synchronous dynamics. The time interval between the

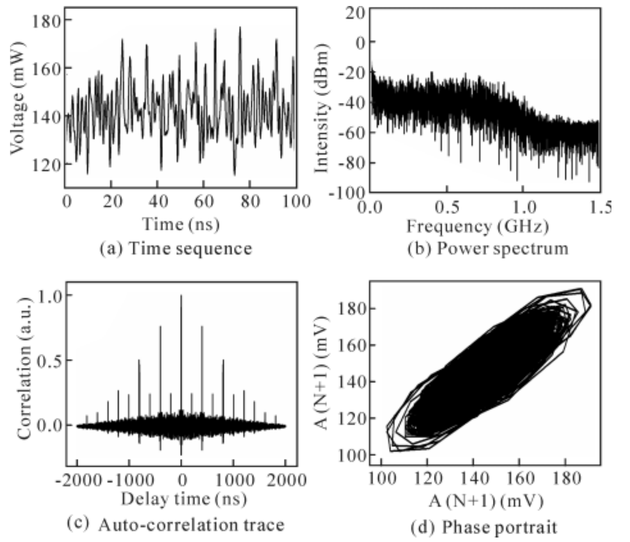

Fig.6 Chaotic states of fiber laser with pump power of 238.4 mW

two neighboring side lobes is 200 ns which is the cavity round-trip time of the F8L corresponding to the length of the F8L. The cavity round-trip time is estimated as L/v, where L is the cavity length and $v = c/n$, c is the speed of light in vacuum, and the refractive index of EDF (i.e., n) is about 1.46. We believe that it is induced by the repetitive interference of light in the cavity suffering the nonlinear phase shift. In addition, the power spectra have the trailing, which is due to the limitation of bandwidth of the digital oscilloscope. From the period-doubling and quasi-periodic states to the chaotic states, chaotic state appears obviously, when the pump power reaches a certain value with a fixed polarization state of PCs. We can conclude that the chaotic state is related to the pump power.

In terms of all the experimental results, we can get that the chaotic states are still related to the polarization state. If we fix a certain value higher than the threshold power of the pump, the polarization state determines the output states. For the different polarization states, we find that the F8L with an OFR presents various dynamic characteristics, such as multi-pulse, mode-locking and self-pulsing. But the chaotic states can be observed in a specific orientation of two PCs. Consequently, the chaotic generation is related to the polarization state and pump power.

In addition, for the pump power of 238.4 mW, we observe that the self-synchronous dynamics of chaos has a tendency to be reduced significantly. The tendency is induced by the interference and the nonlinear phase shift of light in the OFR. The principle scheme of OFR is shown in Fig.7.

The transmission equation of the OFR can be described by[15,16]

$$E_{\mathrm{out}}(t) = \sqrt{1-k}\,E_{\mathrm{in}}(t) - \mathrm{j}\sqrt{k}\,E_1(t-\tau_{\mathrm{R}})\exp[-\mathrm{j}(\phi_0+\phi_{\mathrm{N}})] \quad ,(1)$$

where k is the coupling ratio, ϕ_0 is the linear phase shift,

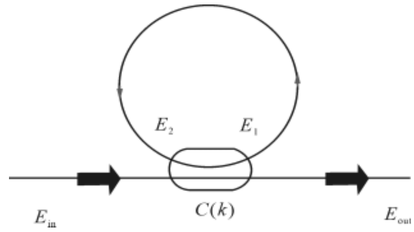

Fig.7 Principle scheme of the OFR

$\tau_{\mathrm{R}}=n_0L/c$ is the round trip time of the NOLM, n_0 is the index of refraction, L is the cavity length and c is the speed of light in vacuum. From Eq.(1), we get the conclusion with certain parameters that the output dynamics is determined by delay time τ_{R} induced by the OFR. The train of chaos $E_1(t-\tau_{\mathrm{R}})$ obtains the nonlinear phase shift ϕ_{N} caused by nonlinear effect, when it travels in the OFR.

After a round-trip time τ_{R}, it can interfere and iterate with $E_{\mathrm{in}}(t)$ in the coupler C. So the self-synchronous dynamics of chaos has a tendency to be reduced after several iterations.

The F8L with an OFR experimentally presents the period-doubling route to chaos. The chaotic self-synchronous dynamics has a tendency to be reduced. The tendency is due to the interference and nonlinear phase shift in the OFR. The experimental results confirm that the dynamics is related to the polarization state, the pump power and the nonlinear effect of light in cavity.

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