

Chaotic dynamics of active optical fiber ring resonator with optical injection

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We experimentally obtain the route from period doubling to chaos in an active optical fiber ring resonator (AOFRR) with optical injection. The results show that the AOFRR is sensitive to external optical injection and demonstrate various dynamic characteristics. Meanwhile, the change of the injection strength can cause the output of the AOFRR to become periodic or chaotic. It can be confirmed that all the dynamic characteristics of the system are due to the interaction of the semiconductor laser with the erbium-doped fiber amplifier (EDFA).

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Chaos has attracted a great deal of research interest due to its potential applications in optical security communication, ranging, radar, and so on^[1–6]. As we know, semiconductor laser is small and integrated, cheap to produce, electrically pumped, and easy to modulate, and it is widely used as carrier-generator in those optical fields. It has been proved experimentally and theoretically that basic methods of the chaotic generation in semiconductor lasers include external optical injection, optical feedback, current modulation, and electro-optical feedback^[7]. In 1993, Liu *et al.* discovered chaotic dynamics in a directly modulated semiconductor laser^[8]. Simpson found that the single-mode semiconductor lasers subjected to external optical injection could exhibit periodic, quasiperiodic, and chaotic output in 2003^[9]. Lin *et al.* investigated numerically nonlinear dynamic characteristics of an optical injected semiconductor laser subjected to optoelectronic feedback^[10]. Tronciu *et al.* studied the dynamics of a semiconductor laser subjected to a double cavity feedback^[11]. At present, chaotic dynamics have still attracted extensive attention^[12,13]. In this letter, a semiconductor laser is connected to an active optical fiber ring resonator (AOFRR) and the chaotic dynamics of the AOFRR are investigated experimentally. Various dynamic phenomena can be observed by changing the injection strength and the polarization state of the light inside the cavity.

Several wavelengths can be used to optically pump an erbium-doped fiber amplifier (EDFA) in order to obtain laser emission. The pump wavelength is fixed at 1553.9 nm and provided by a tunable distributed feedback (DFB) semiconductor laser (WTD LDM5S752). The tunable DFB semiconductor laser is driven by a low-noise current source (Newport 501) and a temperature controller (ILX Lightwave LDT-5412). The experimental setup is shown in Fig. 1. The amplifying medium is a 12-m-long erbium-doped fiber and the total cavity length is about 20 m with the addition of 8 m of passive

optical fiber. The fiber is closed on itself in order to form a ring cavity. To ensure unidirectional operation, an optical isolator is placed inside the ring cavity. The optical isolator is insensitive to polarization. A polarization controller (PC) is used to adjust the polarization state of the light to achieve dynamic output. The pump light from the semiconductor laser is launched into the AOFRR through the optical fiber coupler C1 (99:1). The optical isolator (ISO₁) can prevent backreflected light from entering the DFB laser, while the output couplers (C1 and C2) extract part of the light that circulates inside the ring cavity. Two different output couplers have been used to change the loss in the ring cavity, with coupling ratios of 99:1 and 90:10, respectively. The output coupler C1 is connected to the optical spectrum analyzer (OSA) (Agilent 86140B), while the output emission from C2 is measured with a high-speed photodetector (PD) connected to the input channel of a fast digital oscilloscope (OSC) (Tektronix TDS3052B).

We turn off the pump laser after obtaining laser emission for the high energy in ring cavity, which makes the weak optical injection hardly have any effect on the output. However, C1 and C2 are used to improve the loss inside the cavity and make the whole system cannot

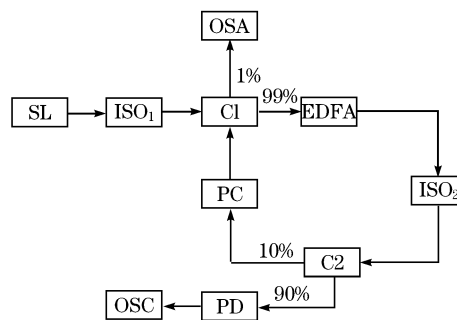


Fig. 1. Experimental setup of the active optical fiber ring resonator with optical injection.

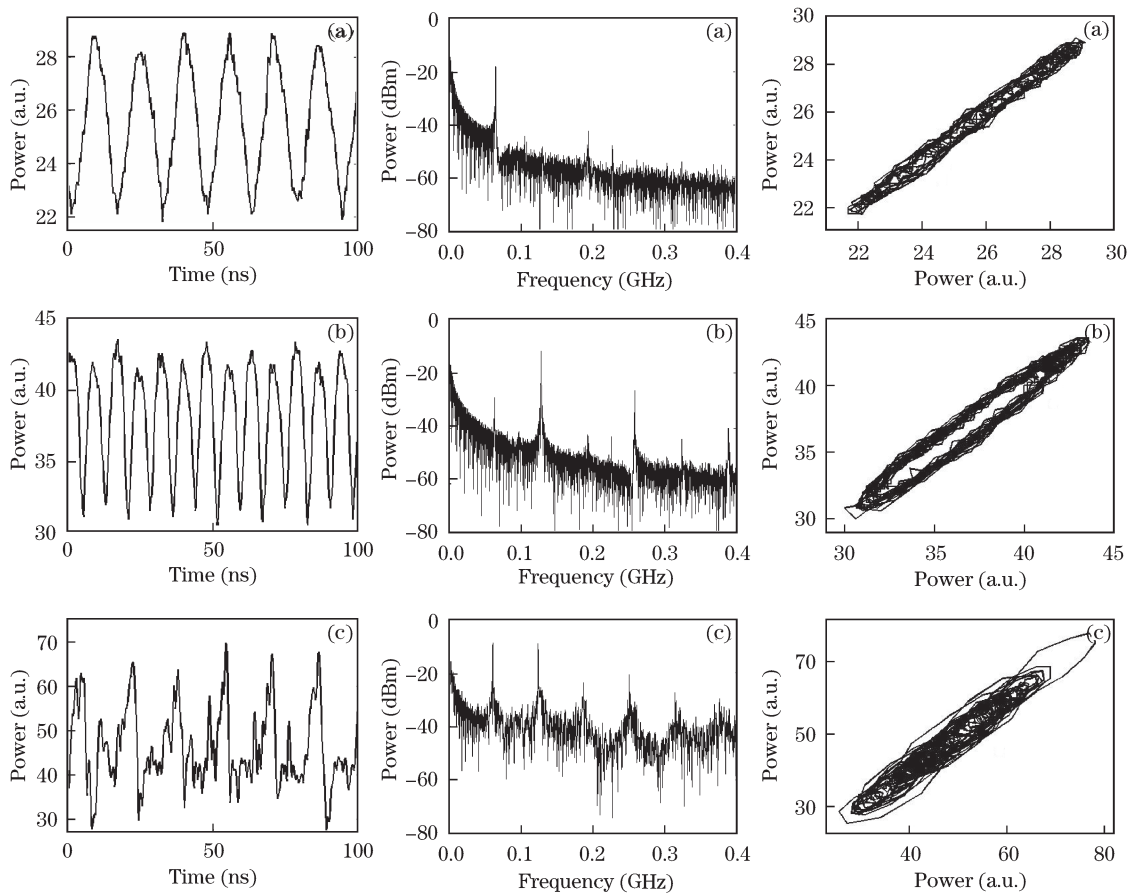


Fig. 2. Time series, power spectra, and phase portraits of different oscillation states showing the route from period-doubling to quasiperiodicity under the injection powers of 1.1, 1.08 and 0.25 mW separately for (a) period-one, (b) period-two, and (c) quasiperiodic states, respectively.

run without it. The optical injection can easily change the dynamic output as a disturbance to the ring resonator.

A characteristic time trace of the total output intensity extracted by the output coupler in the higher loss case (90:10 coupling) is used to characterize this system. Such a procedure shows that the lasing threshold is 0.16 mW. Period-one is observed with a periodicity of ~ 16 ns when the pump current of the EDFA and the temperature of the semiconductor laser are fixed and the injection power is 1.1 mW. This deviates from the cavity round-trip time of our system, which is estimated as L/v , where $L=20$ m 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 the index of refraction of erbium-doped fiber n is about 1.46. We believe that this is induced by the continuous external optical injection as a disturbance to the ring resonator. In this case, the dynamic behaviors of the AOFRR with the optical injection are only determined by the injection power and the polarization state of the light inside the cavity. The injection power can be adjusted by changing the bias current of the semiconductor laser, and the different polarization states can be adjusted by varying the PC. Reducing the injection power to 1.08 mW, we can get period-two whose periodicity is still unrelated to the cavity round-trip time. The quasiperiodicity will be observed when the injection power is down to 0.25 mW,

as shown in the first column of Fig. 2. In the second and last columns, the figures are characteristic frequency traces of the total output intensity and phase portrait according to the first column. In Fig. 2, We can clearly observe the procedure of period-doubling to quasiperiodicity from the time, frequency, and phase.

The output of the AOFRR begins to enter into chaos when the injection power is adjusted to 0.2 mW, and the chaos in Fig. 3 is taken under the injection power of 0.18 mW. The chaotic states can be observed in a very small region in the injection parameter space and careful adjustments of both the strength and the polarization state of injection light are needed to operate the laser in such states. The trailing in the power spectrum of Fig. 3(b) is due to the limitation of bandwidth of the digital oscilloscope. The optical spectrum of Fig. 3(d) shows that the center wavelength of semiconductor laser is near 1553.89 nm while that of the EDFA is 1532.5 nm, and the powers of semiconductor laser and the EDFA are 6.16 and -27.76 dBm separately. The power difference between two peaks is more than 30 dB, so the tubercle of the EDFA is only fluorescence spectrum where its gain is less than the cavity loss and cannot work without optical injection for the high loss in the ring cavity.

The case of fiber ring without EDFA with the injection strength and the polarization state of light inside the cavity is also studied. No chaotic or periodic states

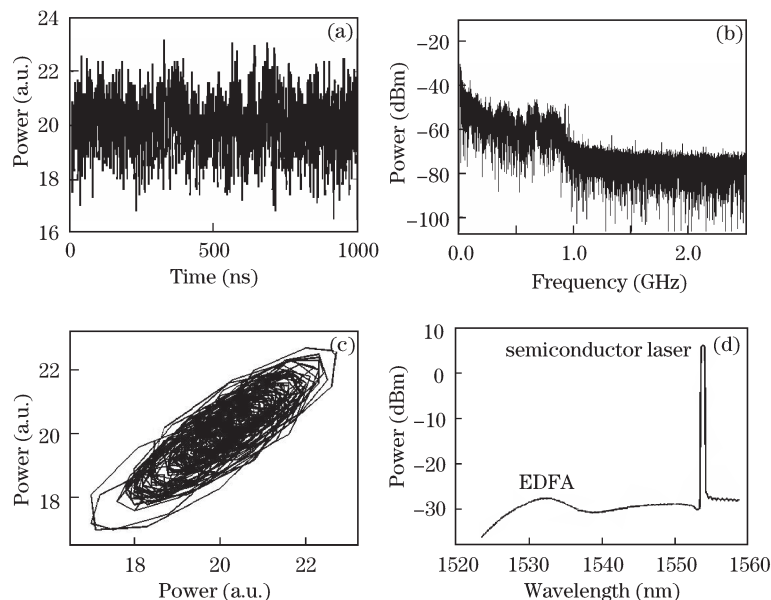


Fig. 3. (a) Time, (b) power spectrum, (c) phase portrait, and (d) optical spectrum of chaos under the injection power of 0.18 mW.

are observed and the power spectrum of the output of fiber ring is continuous without any peak or tubercle at all. Combined with what is previously described, this indicates that the dynamic characteristics of system are due to the interaction between the semiconductor laser and the EDFA.

In conclusion, the dynamic characteristics of AOFRR with optical injection have been experimentally investigated. The dynamic phenomena have been observed by changing the power of the semiconductor laser and the polarization state of the light inside the cavity. Fixing the pump current of the EDFA at 60 mA, reducing the power of the semiconductor laser from 1.1 to 0.18 mW, and adjusting PC at the same time, we can obtain the route from period doubling to chaos. The periodicity deviates from the cavity round-trip time of our system because of the continuous external optical injection as a disturbance to the ring resonator. In addition, it can be confirmed that all the dynamic characteristics of the system are due to the interaction between the semiconductor laser and the EDFA.

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