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Visible details of the period-eight cycle route to chaotic process based on stimulated Brillouin scattering

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ABSTRACT

A period-eight cycle route to chaos has been observed in a stimulated Brillouin scattering (SBS) system for the first time. Since the observation of fine periodic-orbit structure in very short dynamical region of chaotic domain is very difficult, in this work, we design a novel experiment to extend the chaotic domain by injecting light to the end of fiber and adjusting the proportion of stimulated Brillouin backscattering power and pump power, the present result shows the period-eight cycle route to chaotic laser process as well as more details of chaos. Simulations of the route to chaos are also presented.

1. Introduction

In the recent years, nonlinear dynamics of laser system has attracted a great deal of scientific interest since the chaotic behaviors were observed in many standard semiconductor and fiber-based laser systems [1–4]. Chaotic behaviors can be useful for chaos-based security communications [3] and for the fast random bit generation [5–7]. A typical unperturbed laser is a nonlinear oscillator capable of damped periodic oscillation or stationary-state operation. However, this may be changed drastically when the laser is coupled to other lasers subjecting to an external stimulus, such as optical injection or optical feedback [1]. In this case, the laser can undergo a number of bifurcations leading to periodic, quasi-periodic and chaotic oscillations. The understanding of chaotic systems can be considerably improved with the knowledge of their periodic-orbit structure. But the specific process from bifurcation routes to chaos in the fiber has not been shown before, in addition to Yun Liu et al., Tai Hyun Yoon et al. and Lingzhen Yang et al. [8–10]. Their experiments exhibit a period-three cycle and a period-doubling route to chaos, respectively.

Stimulated Brillouin scattering (SBS) is a nonlinear optical effect which can limit the performance of optical transmission systems by reflecting a part of the power launched into an optical fiber. It has been theoretically demonstrated that the Stokes power in SBS exhibits a deterministic fluctuation in time and space under certain conditions of external feedback, Stokes gain and nonlinear refractive index [11,12]. Chaotic SBS generated in the optical fibers has been observed experimentally [12–14]. It has been found that spontaneous Brillouin scattering having a stochastic property is dramatically suppressed in the presence of the feedback pump light, indicating that chaos is generated by the Stokes light. The phenomenon is developed from the bifurcation route to chaos through periodic and quasi-periodic emissions when the external feedback of the pump light from the fiber ends interacts with Stokes waves [15]. One of the explanations about the phenomenon is that the optical Kerr effect introduces a nonlinear optical coupling between the pump and Stokes waves and renders the SBS chaotic dynamics due to the feedback [16]. The dynamics of SBS chaotic process with external feedback of the pump light from the fiber ends is investigated in the beginning of this work. It has been experimentally demonstrated that bifurcation route to chaos through periodicity and quasi-periodicity are as same as the previous results [12]. In this work, chaotic domain is very short so that the higher-order periodic-orbit structure of the chaos is very difficult to be observed. In addition, the pump light power is designed to increase through optical injection in order to expand chaotic dynamical range. Near the threshold power of SBS occurrence, when the injected pump power is adjusted to satisfy the backscattering Stokes power, we verified that bifurcation undergo the period-one, period-doubling, period-four and period-eight cycle route to chaos. The results show that the chaotic dynamics of SBS is related to the Stokes backscattering and the injected pump power.

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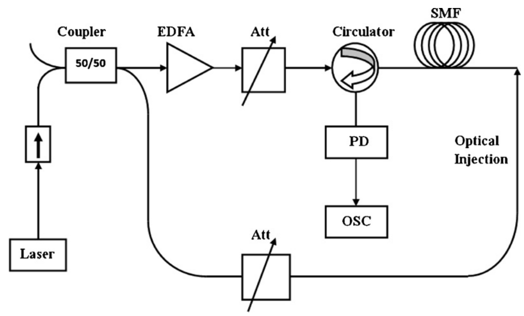

Fig. 1. Experimental setup of the chaos with optical injection.

2. Chaotic experiments

Our experimental setup is shown in Fig. 1. A 10 km length of single mode fiber (SMF) with core diameter $d \approx 9\,\mu\text{m}$ is used as the nonlinear media to generate SBS. Before the pump output power of a tunable semiconductor laser (DL-BF12-CLS101B-S1550) delivering up to ∼10 mW at 1550 nm with line width of ∼50 kHz is launched into the SMF via a three-port optical circulator, which is amplified by an Erbium-doped fiber amplifier (EDFA) to achieve a maximum power around 200 mW. The three-port optical circulator also delivers the output of the fiber to the detection system consists of a photodiode (PhD) and an oscilloscope (OSC). A power meter is used to measure the backward scattering signal of the fiber, which is not shown in Fig. 1. Instead of 4% reflection from the end of the fiber with a 90° cutting angle which is often adopted in previous work [15], optical injection is used as the feedback condition and two optical attenuators (ATT) are used to modulate the proportion of pump power and injected light power. In this experiment, half of the input pump power is injected to the end of the single mode fiber by a coupler (50:50).

In order to achieve the chaotic output, the optical injection must be carefully modulated, through trial and error, we verified that the optimal constant value of the injected light power is 3.6 mW in this experiment. By modulating the input pump power, the evolution of temporal structure towards chaos in period-doubling bifurcation routes is observed as illustrated in Fig. 2, which experiences period-one state (Fig. 2a), period-doubling state (Fig. 2b), period-four cycle state (Fig. 2c) and period-eight state (Fig. 2d) at various initial pump power ranging from 20.23 to 45.68 mW, eventually reaches a chaotic state (Fig. 2e) when the pump power increases to 48.92 mW. We would like to interpret our experimental results about the division of different periodic states here: as the sequence charts are obtained at the same sweep time range of OSC, the number of spikes increases exponentially at the same time interval (around 90 μs) when we enhance the pump power. The corresponding spectra of the Stokes signals are illustrated on the right-hand column of Fig. 2, comparing Fig. 2j with the other four spectra (Fig. 2f–i) of the periodic states, we cannot observe distinct spikes in Fig. 2j when it enters the chaotic state, which is the characteristic of chaotic spectra. To illustrate the various dynamical behavior of SBS system under different injected pump power and backscattering Stokes power more intuitive, we mark them on a fitted curve illustrating the relation between pump power and backscattering Stokes power which is almost linear as shown in Fig. 3. The curve is characterized by six distinct regions: (1) the stably low output state below SBS threshold. The threshold power of Stokes in the SBS process is about 14 mW in this experiment which is also regarded as a reference from period cycles to chaos in the whole experiment; (2) period-one state, with the periodicity approximates 90 μs; (3) period-doubling state; (4) period-four state; (5) period-eight state; (6) chaotic state. The influence of weak feedback on SBS chaos has been experimentally investigated previously in [15], and they believe

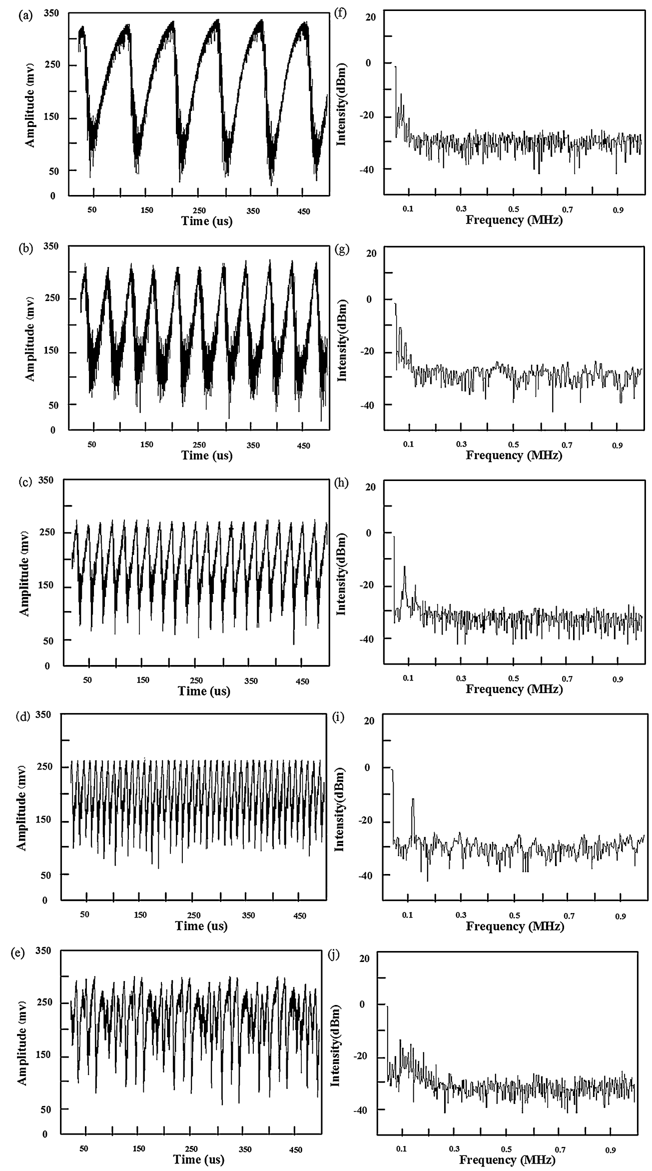

Fig. 2. Time series (left-hand column) and corresponding power spectra (right-hand column) of the Stokes signals, with injected light power: 3.6 mW. The pump power and corresponding averaged output power for each state are as follows: (a, f) Period-one, 20.23 and 5.06 mW; (b, g) period-doubling, 25.36 and 8.51 mW; (c, h) period-four, 41.04 and 19.58 mW; (d, i) period-eight, 45.68 and 21.77 mW; (e, j) chaos, 48.92 and 25.15 mW.

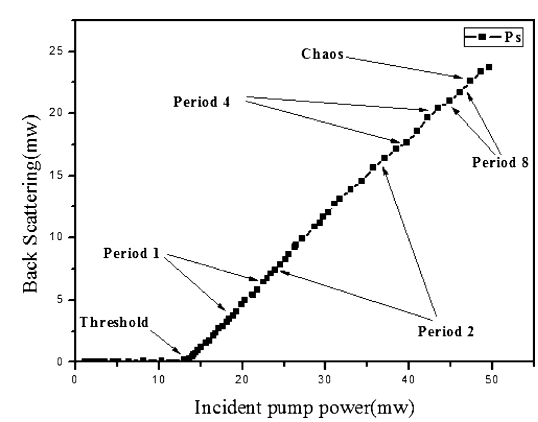

Fig. 3. Backscattering Stokes signal as a function of incident pump power, regions marked with arrows indicate various dynamical states of the SBS systems under different input pump power.