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Experimental observation of stochastic, periodic, and localized light structures in a brillouin cavity system

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ABSTRACT

It has been an important research subject to find new nonlinear optical phenomena. In this paper, we report the experimental observation of stochastic, periodic, and localized light structures in a super long single-mode standard fiber with external optical feedback provided by the fiber end. The end facet reflection provides an analogous Fabry-Perot stimulated Brillouin resonator cavity. By increasing the pump power to exceed stimulated Brillouin scattering threshold, we observed light structures exhibiting extremely rich temporal-pulse characteristics that had never been reported in literature before, including supercontinuum background generation, the localization of periodic optical structure formation, fission, and compression. These optical structures are of period-doubling distribution and have different recurrence rates. What is more interesting is that we have observed sets of low frequency bipolar cycle-pulse trains that is often seen in the electrical field and hardly seen in pure optical system. Real-time specification of dynamical temporal regimes of laser operation may bring new insight into rich underlying nonlinear physics of practical fiber cavity systems. Therefore, some new nonlinear optical phenomena have been observed.

1. Introduction

Stimulated Brillouin scattering (SBS) [1], which is one of the most prominent optical effects, has attracted a great deal of attention since it was first observed in 1964 [2]. Various fundamental and applied aspects of SBS were studied in the past decades [3–9]. However, research in SBS remains a zealously developing area of nonlinear optics with hundreds of papers published annually. A mass of novel technology areas where SBS plays an important role are emerging continuously. These include, for example, high power fiber lasers [10], slow light [11], microfluidic devices [12], SBS in microspheres [13], Brillouin cooling and excitation [14,15], and so on.

Brillouin optics allows the parametric coupling of phonon- and photon-modes in cavities and is studied in a broad variety of fiber laser systems. For this reason, understanding the fundamental physics in the process of pulse generation in Brillouin cavities becomes especially important. SBS in cavity systems may take place through the generation of a backward propagating Stokes wave that carries most of the pump power, once the SBS threshold is reached. Chaos can occur around the SBS threshold when two counterpropagating pump waves are present simultaneously [16]. This instability phenomenon is attributed to the SBS-induced coupling between the counterpropagating pump waves through an acoustic wave. Chaotic light structures are also observed when the backward pump is not launched externally but is generated by the feedback of the forward pump at a reflector [17–19]. Further, the power of generated pulses can be boosted, in conventional Brillouin cavity systems, by lengthening the laser cavity because the pulse power is inversely proportional to the repetition rate [20]. However, long fiber laser systems are known for their complex behavior that a loss of coherence is resulted from phase and amplitude stochasticity. As the laser cavity is lengthened, fully coherent lasing operation grows more and more unstable, eventually leading to the generation of stochastic pulses.

Both the ring-cavity and the Fabry-Perot (F-P) geometries have been used for constructing Brillouin cavity systems, each having its own advantages. The difference between them results from the simultaneous presence of the forward and backward propagating components associated with the pump and Stokes waves. Higher-order Stokes waves are produced through cascaded SBS, a process in which each successive Stokes component pumps the next-order Stokes component after the pump power is large enough to reach the SBS threshold. At the same time, anti-Stokes components are produced through four-wave mixing between copropagating pump and Stokes waves. The number of Stokes and anti-Stokes lines depends on the pump power. For some applications [21,22], tuning of the frequency comb generated inside a Brillouin fiber cavity is desirable.

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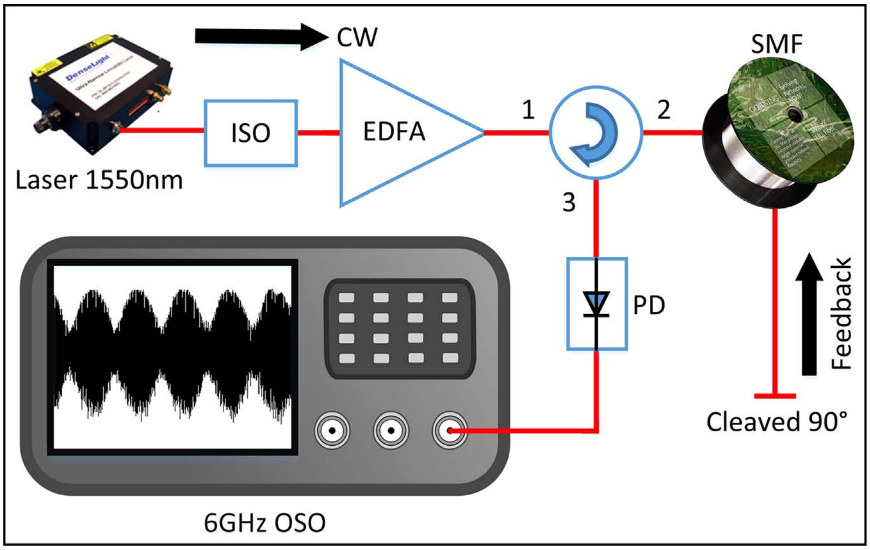

Fig. 1. Schematic of experimental setup. ISO: polarization-insensitive optical isolator. EDFA: Erbium doped fiber amplifier. SMF: single-mode fiber. PD: 12 GHz photodetector. OSO: optical sampling oscilloscope.

In this Letter, a super long standard communication optical fiber has been applied to the SBS system. The fiber end was cleaved at an angle of 90° to construct an analogous F-P cavity system. It should be stressed that this F-P cavity system is different from the conventional F-P cavity system. Only 4% of the pump power can be reflected at the fiber end facet. We discovered in particular, above a certain pump power level, some non-trivial long-scale internal periodicity in stochastic generation of the distinctive Brillouin cavity operating in dynamic temporal regimes. By increasing the pump light power gradually, we observed the 5-, 10-, and 15-period quasi-stationary localized dark and bright structures and their fission processes. Here, we will provide an overall description of temporal mechanism when the incident pump power (ranging from 40 mW to 300 mW) is much higher than SBS threshold power (about 14 mW in our experiment). A large number of new phenomena that have not been reported in literature yet will be presented below.

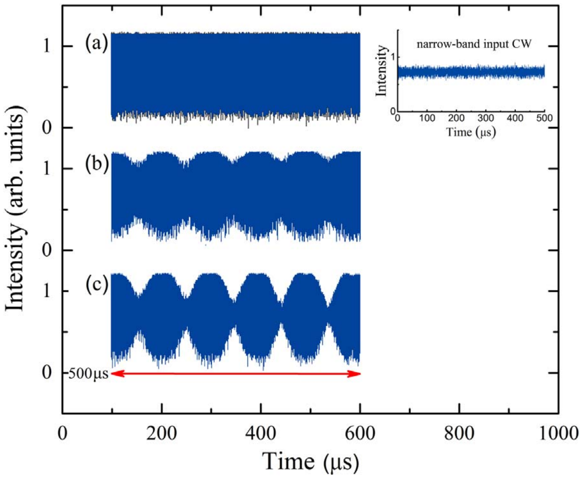

Fig. 2. Evolution of a spontaneous breakup from a SCB to a periodic envelope light train according to the input pump power at (a) 40.64 mW, (b) 45.13 mW and (c) 51.89 mW. The inset in the top right-hand corner of the figure is the narrow-band input CW.

2. Experiments and Results

The experimental setup of our Brillouin cavity is shown schematically in Fig. 1. The pump laser (DL-BF12-CLS101B-S1550) is a linearly-polarized continuous-wave (CW) tunable semiconductor laser emitting at 1550 nm (with a ~50 kHz linewidth). The laser is used as a pump source to provide a variable output power up to ~10 mW. The output is injected into a polarization-insensitive optical isolator (ISO) which avoids backward reflection from the other part of the setup, and is then amplified by the Erbium doped fiber amplifier (EDFA) to achieve a maximum power of around 300 mW before it is injected into a 10 km long single-mode fiber (SMF) via three-port circulator. The SMF with loss coefficient of 0.084 km^{-1} and refractive index of 1.46 as well as core diameter of ~9 μm is used for the SBS generation. One end facet of the SMF is cleaved at an angle of 90° so as to provide ~4% pump optical feedback. The back scattering signal is measured through the circulator by using the power meter. The Brillouin cavity system output is finally monitored by a 6 GHz optical sampling oscilloscope (OSO) with a fast 12 GHz photodetector (PD).

We first performed a measurement of the light signal output power using a power meter to estimate the SBS threshold and found it to be about 14 mW in the experiment. This value is considered as a reference from period cycles to chaos in the preliminary stage of the whole experiment. The waveform of narrow-band input CW is stable when the pump power is below the SBS threshold, which is shown in the inset of the top right-hand corner of Fig. 2. When the pump power reaches ~14 mW (SBS threshold), a temporal structure arises in the backward Stokes scattering signal light. The dynamic evolution of the whole chaotic process in the vicinity of SBS threshold was presented particularly in Ref [23]. Once above the SBS threshold, a class of random bipolar localized light structures can be excited in the presence of the weak feedback.

In the experiment, supercontinuum background (SCB) is generated by enhancing the input pump power to 40.64 mW, and the SCB is shown in Fig. 2(a). Then the evolution of a spontaneous breakup from a SCB to a periodic envelope light train with a 500 μs time window, by enhancing the input pump power, is observed in Fig. 2(b–c). As it can be seen, the SCB begins to split when the input pump power reaches approximately 45.13 mW. The envelope light train is formed completely in P_{in}=51.89 mW. Note that both the repetition rate and width of the non-trivial envelope light train are 100 μs. In the evolution process, an acoustic wave initially generates thermally through the electrostriction [24] in the long fiber. Then the pump light is downshifted in frequency and generates a backward-propagating Stokes wave which experiences exponential amplification at the expense of the pump. Owing to the pump light, the Stokes wave and the pump feedback light comes from fiber end exist at the same time, a variety of complex processes can occur. Degenerate four-wave mixing (FWM), formed as a