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Emission of dark envelopes in a fiber ring laser with net normal cavity dispersion

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Abstract: We report on a novel state of dark pulse emission in a net normal dispersion cavity fiber ring laser. We show both experimentally and numerically that the observed dark pulses are dark envelopes formed as a result of the superposition between a high repetition rate dark pulse train and dark solitons formed in the fiber laser.

OCIS codes: (060.5530) Pulse propagation and temporal solitons; (140.3510) Lasers, fiber; (190.5530) Pulse propagation and temporal solitons

1. Introduction

In nonlinear optics, due to the potential application of optical solitons in future high speed optical communications, studies on optical soliton formation and soliton dynamics have attracted considerable attention. Extensive soliton studies have been focused on the optical solitons formed in single mode fibers (SMFs). It's now well known that the pulse propagation in SMFs is governed by the nonlinear Schrödinger equation (NLSE). Based on it, bright solitons are formed in the anomalous dispersion SMFs, while the dark solitons, which are intensity dips on a CW background, are formed in the normal dispersion SMFs. It has been theoretically shown that dark solitons have less sensitivity to noise and fiber losses as compared with the bright solitons. They are more attractive for the future optical communication and optical signal processing applications. Fiber lasers are a perfect testbed for the experimental study of nonlinear fiber optics. They are also an ideal source for the dark soliton generation. However, there has been less attention on the dark soliton fiber lasers until recent years. Sylvestre *et al.* generated stable dark-soliton-like pulse trains in a fiber laser using the dissipative four-wave mixing method [1]. Zhang and Tang *et al.* reported the spontaneous dark soliton generation in the all-normal dispersion fiber ring lasers [2-4]. Very recently Song *et al.* also reported 280 GHz dark soliton train emission of a fiber laser [5].

The main challenge for the experimental study on the dark solitons is how to detect them. Unlike the bright solitons, whose existence can be easily detected using a photodetector, a dark soliton is an intensity dip embedded in a CW background, if it is too narrow, the conventional low speed detector cannot detect it. With a high speed detector and oscilloscope, the problem could be partially solved [3, 4]. But there is a limitation of the electronic detection systems. For example, the 10%-to-90% rise time of a commonly used 40 GHz photodetector is 9 ps. It means that if the rising or falling edge of a dark pulse is below 9 ps, the photodetector will give a strongly distorted dark pulse with a shallow darkness [6]. This brings a barrier for the experimental study of dark solitons. In this paper, we report on the experimental observation of dark pulse emission of a fiber ring laser and explain its formation mechanism. We point out that if a high frequency modulation and a dark pulse coexist in a normal dispersion cavity fiber laser, they will be automatically shaped into a high repetition dark pulse train and a dark soliton separately. Due to the light field superposition, the dark soliton will form a wide dark envelope embedded in the high repetition rate dark pulse train background. The formation of the broad dark envelope makes a narrow pulse width dark soliton detectable. We have both experimentally and numerically confirmed the existence of this phenomenon.

2. Experimental setup and results

We build a fiber ring laser with average normal cavity dispersion to generate a high repetition dark pulse train and dark solitons. The fiber laser has a cavity configuration as shown in Fig. 1. The fiber ring has a total length of 15.6 m, consisting of a piece of 3 m Erbium doped fiber (EDF) with a group velocity dispersion (GVD) parameter of -48 ps/nm/km, 8.5 m single mode fiber (SMF-28) with a GVD parameter of 18 ps/nm/km and 4.1 m of dispersion compensation fiber (DCF) with a GVD parameter of -4 ps/nm/km. The fiber laser is pumped by a 1480 nm single mode Raman fiber laser whose maximum output power is 5 W. The laser emission is monitored by an electronic detection system consisting of a 40 GHz photo-detector and a 33 GHz bandwidth real-time oscilloscope. The narrowest dark pulse clearly resolvable by our detection system is about 18 ps.

Figure 1. A schematic of the Erbium-doped fiber laser. EDF: Erbium-doped fiber. SMF: Single mode fiber. DCF: Dispersion compensation fiber. WDM: Wavelength division multiplexer. PC: Polarization controller.

By increasing the pumping power to about 2W, where the intracavity fiber laser intensity is about 500 mW, and setting the intra-cavity PC at an appropriate orientation, a stable dark pulse emission state can be achieved, as shown in Fig. 2(a). The dark pulses are randomly distributed in the cavity and repeat themselves at the cavity roundtrip. Besides, the amplitude of dark pulses randomly varies. Fig. 2(b) shows the zoom-in trace of some dark pulses. It clearly tells us that the dark pulses are all well-separated single pulses with an average pulse width of ~ 90 ps. Fig. 2(c) is the corresponding optical spectrum of the laser emission. The spectrum is modulated with a modulation frequency of about 230 GHz. Based on the measured spectrum, the central CW peak is at 1582.7 nm and has a 3-dB bandwidth of about 0.2 nm. Considered as transform-limited pulses, the width of the dark pulses should be ~ 13 ps [2]. In principle, such a narrow dark pulse shouldn't be detected by our measurement system. To understand the dark pulses, we measured the autocorrelation trace of laser output, as shown in Fig. 2(d). The autocorrelation trace shows the existence of a periodic dark pulse train with ~ 220 GHz repetition rate, which matches with the measured spectrum. However, the autocorrelation trace also exhibits pulse peak modulation. Such a peak modulation indicates the existence of some embedded structures in the high repetition pulse trains. Considering the normal dispersion cavity and the easy formation of dark solitons, we conjecture that some dark solitons could be embedded in the high repetition dark pulse train.

Figure 2: A dark pulse emission state of our fiber laser. (a) Oscilloscope trace of the dark pulse emission. (b) Zoom-in of the dark pulse emission trace. (c) The corresponding optical spectrum of the laser emission. (d) Autocorrelation trace of the laser emission.

3. Simulation and discussion

To understand the laser emission, we have numerically simulated the operation of our fiber laser. The simulation is based on numerically solving the Grinzburg-Laudau equation (GLE) of the laser operation. To confirm our idea, we start with a CW initial state whose background is modulated with 200 GHz modulation and a weak dark pulse on the CW background. Other simulation conditions just the same in our experiment. A typical result is shown in Fig. 3(a) and (b). It is shown that an initially periodically modulated CW background is shaped into a stable dark pulse train in the fiber laser. In addition, the weak dark pulse is split into two identical dark pulses. The two dark pulses moved to opposite directions. The moving dark pulses can collide with another. After collision they still remain their pulse

profiles, showing that they have the soliton property. In Fig. 3(b), the simulated fiber laser emission state is presented. The “dark solitons” embed in the dark pulse train are actually dark envelopes. The rising and falling time of the dark envelopes are ~ 12 ps, which is in the detection range of the photodetector. The high repetition rate dark pulse train cannot be resolved by the 40 GHz detector. It is displayed as a noisy CW background. Hence, the dark envelopes would be shown as dark pulses. We also simulate the evolution of dark pulses in fiber laser cavities without formation of high repetition dark pulse train. The results are shown in Fig. 3(c) and (d), where the dark pulses are shaped into narrow dark solitons (~ 3 ps), which can't be resolved by our detection system.

The simulation results well explain the experimental observations. The “dark pulses” observed in experiments are actually dark envelopes, which are formed due to the superposition of dark solitons with a high repetition dark pulse train. Formation of the dark envelopes makes the dark solitons detectable by our electronic detection system.

Figure 3: (a), (b) Simulation results of dark envelope formation, (c), (d) Simulation results of dark soliton formation.

4. Conclusion

In this paper, we have shown the formation of dark envelopes in a fiber laser with net normal cavity dispersion. The formation mechanism of the dark envelope is the superposition of the formed dark solitons with the high repetition dark pulse train. The experimental observations are well supported by the numerical simulation results. This observation provides a new aspect of the dark pulses/solitons in fiber laser, helping to reveal the real physical content behind the experimental observations.

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