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Dark solitons embedded in a stable periodic pulse train emitted by a fiber ring laser

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Abstract

We report on the experimental observation of dark solitons embedded in a stable periodic pulse train emitted by a net normal dispersion cavity fiber laser. Our experimental result shows that in addition of forming in a continuous-wave background, a dark soliton could also be formed in a stable periodic pulse train background. Numerical simulations have well reproduced the experimental result. Moreover, numerical simulations also show that as a result of the periodic pulse train background the formed dark soliton could exhibit a dark pulse envelope that is much broader than its actual pulse width.

1. Introduction

Solitons as a novel stable localized nonlinear structure formed either in the temporal or spatial domain have attracted extensive studies in different branches of physics, such as nonlinear optics, condense matter physics, fluid mechanics and particle physics [1]. In nonlinear optics, study on the temporal soliton formation and soliton dynamics in single mode fibers (SMFs) have attracted considerable attention [2–4], due to the potential applications of the solitons in high speed long-haul optical communications and signal processing. It is now well known that the optical pulse propagation in SMFs is governed by the nonlinear Schrödinger equation (NLSE), and bright solitons are formed in the anomalous dispersion SMFs, while dark solitons that are an intensity dip formed on a continuous-wave (CW) background, are formed in the normal dispersion SMFs. Both the bright and dark soliton formation in SMFs were experimentally observed [5, 6].

Fiber lasers are an excellent testbed for the experimental study on the temporal optical solitons. Although the existence of laser gain and cavity output loss could affect the details of the soliton evolution in a fiber laser, it was found that under appropriate conditions the essential dynamics of the formed solitons was still governed by the NLSE. The bright soliton formation and soliton dynamics in the net anomalous dispersion cavity fiber lasers have been experimentally extensively investigated [7–9]. Recently, the dark soliton formation in net normal dispersion cavity fiber lasers was also experimentally observed. Worth mentioning here that Sylvestre *et al* generated stable dark-soliton-like pulse trains in a fiber laser using a dissipative four-wave mixing method [10]. Zhang *et al* reported spontaneous dark pulse formation in an all-normal dispersion fiber ring laser [11]; Tang *et al* demonstrated the NLSE type dark solitons in an all-normal dispersion fiber laser [12, 13]; Song *et al* reported 280 GHz dark soliton train emission of a fiber laser [14]. Meanwhile, many theoretical work on dark solitons have also been reported [15–17].

A challenge for the experimental study of dark solitons is to detect their existence. Unlike bright solitons, which are an intensity peak that can be detected even with a slow detector, a dark soliton is an intensity dip in a CW intensity background. If a dark soliton is too weak or has too narrow pulse width, it is difficult to detect its existence even with a high speed detection system [18]. Although one could still use the

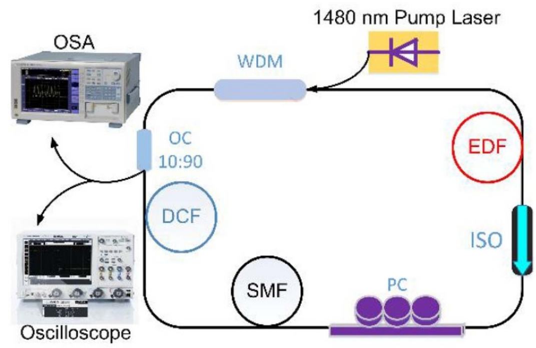

Figure 1. A schematic of the Erbium-doped fiber laser. EDF: Erbium-doped fiber. SMF: single mode fiber. DCF: dispersion compensation fiber. WDM: wavelength division multiplexer. PC: polarization controller. ISO: polarization independent isolator.

autocorrelation method to detect the existence and pulse parameters of stable high repetition rate dark pulse trains [10, 14], to detect a single dark pulse unfortunately the most easy and practical way is still using a high speed electronic detection system [12, 13]. However, the narrowest dark pulse that can be resolved is limited by the bandwidth of the detection system.

In this paper we report on the experimental observation of an interesting dark soliton formation phenomenon in a fiber laser. We found experimentally that a dark soliton could be formed even in a stable high repetition rate periodic pulse train background, instead of a CW background. Numerically simulations have well reproduced the experimental observation. Moreover, numerical simulations also show that the formed dark solitons could exhibit a dark pulse envelope that is much broader than its actual soliton pulse width.

2. Experimental setup and results

Our experiment was conducted on a dispersion-managed fiber ring laser with a cavity configuration as shown in figure 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^{-1} km^{-1}, 8.5 m single mode fiber (SMF28) with a GVD parameter of 18 ps nm^{-1} km^{-1}, and 4.1 m of dispersion compensation fiber (DCF) with a GVD parameter of -4 ps nm^{-1} km^{-1}. The fiber laser is pumped by a 1480 nm single mode Raman fiber laser whose maximum output power is 5 W. A polarization independent isolator (ISO) is inserted in the cavity to force the unidirectional circulation of light in the cavity. In addition, an intra-cavity polarization controller (PC) is used to fine-tune the cavity. A wavelength division multiplexer (WDM) is used to couple the pumping light into the cavity, and a 10% fiber output coupler (OC) is used to output the light. The components used in our experiment have very low polarization dependent loss (PDL) (WDM: 0.01 dB, Isolator: 0.04 dB, Coupler: 0.01 dB), to avoid the unwanted PDL-induced mode locking [19]. The fiber ring cavity is estimated to have an average net normal GVD parameter of 0.5 ps nm^{-1} km^{-1}. Such a low average dispersion helps to lower the threshold of the cavity induced modulation instability, which was used in our experiment to generate the high repetition rate pulse train [14]. The laser emission was monitored by an electronic detection system consisting of a 40 GHz photo-detector and a 33 GHz bandwidth real-time oscilloscope.

We have operated the fiber laser at a pump power of 2 W. Under the pumping the average intra cavity laser beam intensity is about 500 mW. In our experiment we have fixed all other laser parameters but only fine-tuned the intra-cavity PC, which changes the net cavity birefringence. Experimentally, under suitable PC settings single polarization CW laser emission could always be obtained. We attribute the formation of such a single polarization CW laser emission to the polarization instability of the laser operation [20]. Starting from such a single polarization laser operation state, we then slightly tuned the intra-cavity PC orientation. At an appropriate PC orientation, a dark pulse emission state as shown in figure 2(a) could be suddenly formed. The dark pulses obtained had the characters that they were randomly distributed in the cavity, and their pulse intensity also varied randomly. The dark pulse patterns repeated with the cavity roundtrip time, suggesting that they are structurally stable. The features of the dark pulses are well in agreement with those of the dark solitons reported previously [13]. Figure 2(b) shows a zoom-in trace of the dark pulses. Each dark pulse in the cavity had a pulse width of ~30 ps, which is the limitation of our detection system. However, different from the dark solitons observed previously in fiber lasers [12, 13], the laser emission showed an optical spectrum as shown in figure 2(c). The spectrum is similar to that reported

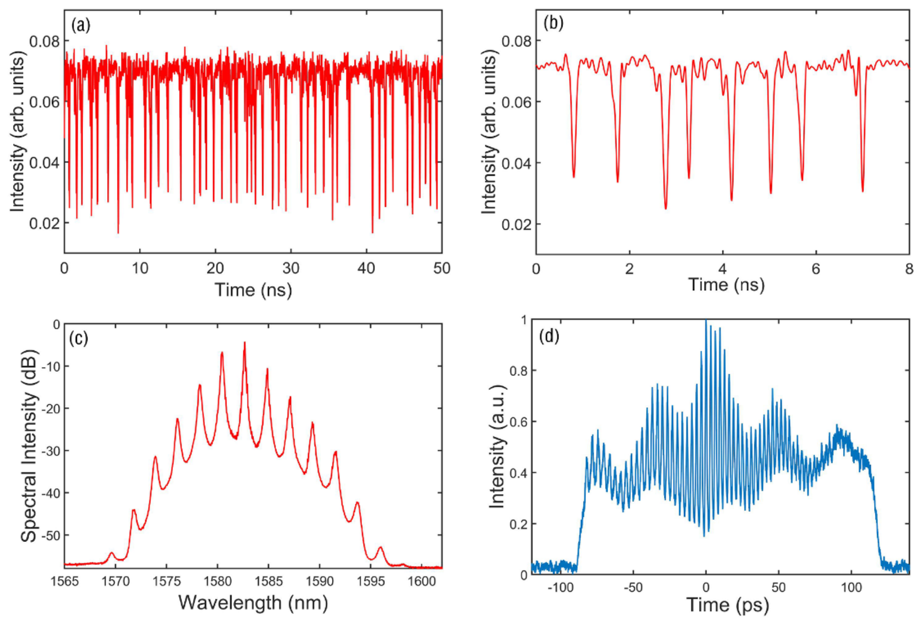

Figure 2. A dark pulse emission state of the fiber laser. (a) Oscilloscope trace of the laser emission. (b) Zoom-in trace of the dark pulses. (c) The corresponding optical spectrum. (d) Autocorrelation trace of the laser output.

in [14], except that all the spectral peaks are now obviously broadened. The spectrum clearly shows that in addition of the dark soliton emission, there is stable high frequency periodic intensity modulation in the laser emission. Based on the separation between the adjacent spectral peaks, the modulation frequency is identified as about 230 GHz. To confirm the existence of the high frequency laser intensity modulation we further measured the autocorrelation trace of the laser emission. The result is shown in figure 2(d). There were indeed obvious high repetition spikes on the autocorrelation trace. The separation of the spikes shows that the pulse train had a repetition rate of 220 GHz, which coincides with that measured from the spectral peak separation. Different from the autocorrelation trace reported in [14], the amplitude of the high repetition spikes on the autocorrelation traces was strongly modulated, suggesting that the intensity of the high repetition rate pulse train is not uniform.

We found that the above experimental result could be well explained if the dark solitons shown in figure 1(a) were embedded in a high repetition rate (220 GHz) pulse train, rather than in a CW background. It is known that as a result of the cavity induced modulation instability, a stable high repetition rate periodic pulse train can be easily formed even in a net normal dispersion cavity fiber laser [14, 21]. Dark soliton formation is an intrinsic feature of the net normal dispersion cavity fiber lasers. Especially, different from the bright soliton formation, dark soliton formation has no threshold [22]. In view of the facts one would expect that under suitable conditions these two effects could simultaneously appear in the same fiber laser. If it is true, limited by the bandwidth of our electronic detection system, only the dark solitons would be detected and displayed in the oscilloscope trace, the high repetition rate pulse train would be filtered away and displayed as a DC background, as shown in figures 2(a) and (b). However, the existence of the high repetition pulse train would be detected by the optical spectrum and autocorrelation trace measurements. Nevertheless, due to the coexistence of the dark solitons the spectral peaks of the high repetition rate pulse train would become broadened, and the autocorrelation traces would be modulated. Following the line one could also estimate the actual dark soliton pulse width based on the spectral peak broadening. The central CW peak of the spectrum shown in figure 2(c) is at 1582.7 nm, and it has a 3 dB bandwidth of about 0.2 nm. Considering that the formed dark solitons are transform-limited pulses, we estimate that their actual width would be about 13 ps.

3. Numerical simulations

We note that the estimated dark soliton pulse width is far narrower than that limited by the bandwidth of our detection system. But we still could experimentally detect them. To understand the experimental phenomenon, especially to clarify why we could experimentally easily detect such a narrow dark soliton with our detection system, we further numerically simulated the laser operation under the experimental conditions. We used a so-called roundtrip model for the simulation [9]. Briefly, we start with a certain weak

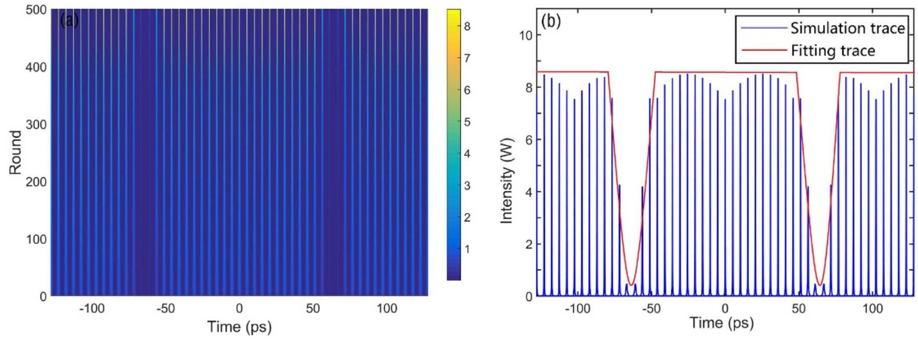

Figure 3. Numerical simulation of dark soliton formation in a high repetition pulse train. (a) Laser emission along the cavity roundtrips; (b) laser emission at a fixed roundtrip.

input light as the initial condition and let the light circulate in the cavity. The light propagation in the cavity fibers is described by the extended Grinzburg–Laudau equation (GLE):

$$i\frac{\partial E}{\partial z}-\frac{\beta_2}{2}\frac{\partial^2 E}{\partial t^2}+\gamma|E|^2E-i\frac{g}{2}E-i\frac{g}{2\Omega_g}\frac{\partial^2 E}{\partial t^2}=0 \tag{1}$$

where E is the complex envelope of the optical field, $\boldsymbol{\beta_2}$ is the group velocity dispersion (GVD) coefficient of the fibers, γ is the nonlinear coefficient. We assumed that all the fibers have the same γ value. And $\boldsymbol{z}$ is the spatial parameter along the fiber and $\boldsymbol{t}$ is the retarded time in a reference frame traveling with the group velocity of light. $\boldsymbol{g}$ is the gain coefficient of the gain fiber and $\boldsymbol{\Omega_g}$ is the effective gain bandwidth. For the undoped fibers $\boldsymbol{g}=0$. $\boldsymbol{g}$ is the saturated gain, which is described as

$$g=\frac{g_0}{1+\int|E|^2dt/E_s} \tag{2}$$

where $\boldsymbol{g_0}$ is the small signal gain coefficient and $\boldsymbol{E_s}$ is the saturation energy of the gain fiber.

We have numerically solved equations (1) and (2) using the spilt-step Fourier method [23] and possibly set the simulation parameters according to the experimental conditions, e.g. a ring cavity length of 15.6 m consisting of 3 m EDF, 8.5 m SMF and 4.1 m DCF, and an average cavity GVD parameter of 0.5 ps nm^{-1} km^{-1}, To simulate the periodic pulse train background, we have used a modulated CW as the initial condition. Based on our previous works, a modulated CW in a normal dispersion cavity fiber laser will be shaped into a high repetition rate dark pulse train [14]. We added weak dark pulses in the modulated CW background, which always evolve into dark solitons in the laser cavity. To compare with our experimental results, we have deliberately set the modulation frequency at 200 GHz and the width of the added dark pulses at about 13 ps. We have used the periodic boundary condition for our simulations. To keep the boundary condition we added two tanh-shaped dark pulses in the simulation window.

Either the saturated gain g or the saturation energy $\boldsymbol{E_s}$ was used as the control parameter. This corresponds to experimentally change the pump strength. Figure 3(a) shows a typical stable laser emission state obtained under the parameters that the small signal gain coefficient $\boldsymbol{g_0}=5000\ \mathrm{km}^{-1}$, gain saturation energy $\boldsymbol{E_s}=20$ pJ, effective gain bandwidth $\boldsymbol{\Omega_g}=10$ nm, and a calculation window of 256 ps. Selection of those parameters resulted in an intra cavity power of 500 mW, which matches our experimental value. As expected, the initial periodically modulated weak CW background is shaped into a stable periodic dark pulse train with a pulse repetition rate of 200 GHz in the cavity, and each of the initial dark pulses are shaped into a dark soliton, as shown in figure 3(a).

Figure 3(b) shows the simulated laser emission with time. Obviously, the laser emits a high repetition rate periodic pulse train with the 'dark solitons' embed in it. In figure 3(b) we have also sketched the envelope of the dark solitons. The width of the envelopes is about 25 ps. We note that either the periodic pulse train state or the dark soliton state individually is a stable state of the laser operation [13, 14]. The above numerical simulations further show that the states could even simultaneously exist in a fiber laser. The numerical result well confirmed our explanation on the experimental results.

Numerically we also simulated the dark soliton formation in the same fiber laser but in a CW background. To this end we have kept all the laser parameters and the initial dark pulse input the same but removed the high frequency modulation. The result is shown in figure 4. Again, stable dark soliton operation state was obtained. However, compared with the case shown in figure 3, where the dark solitons are embedded in a periodic pulse train background, the dark solitons formed have pulse width of 13 ps. The

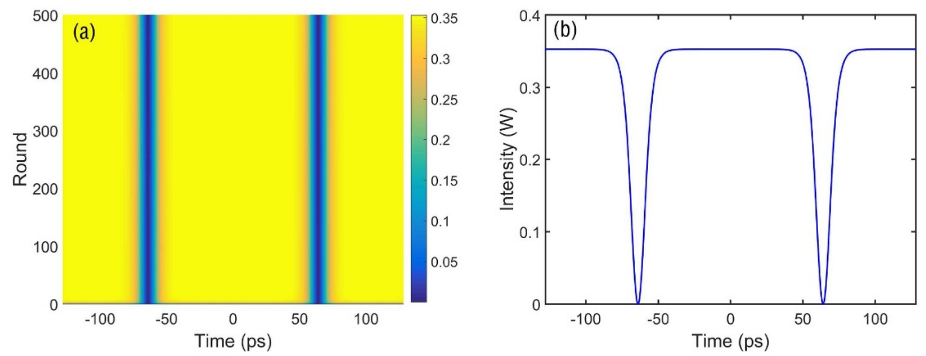

Figure 4. Numerical simulation of dark soliton formation in a CW background. (a) Laser emission along the cavity roundtrips; (b) laser emission at a fixed roundtrip.

result shows that a dark soliton would exhibit a much broader dark pulse envelope in a periodic pulse train background than its actual pulse width.

4. Discussion

It is now well-known that, like the bright soliton formation in the anomalous dispersion SMFs, dark soliton formation is an intrinsic feature of nonlinear light propagation in the normal dispersion SMFs. However, different from the bright soliton formation that is a threshold effect, the dark soliton formation is threshold-less. Because of the feature of the dark solitons and the unavoidable existence of various perturbations, strong light propagation in normal dispersion SMFs should be prone of dark soliton formation. The same should also apply for the case of light circulation in high power fiber lasers with net normal cavity dispersion. Nevertheless, so far only a few experimental observations on the dark soliton formation in fiber lasers have been reported. As mentioned in the introduction, the main challenge for the experimental observation of dark solitons is how to detect them. Obviously one has to appropriately design the cavity and select the laser operation conditions so that the formed dark solitons are within the range of the electronic detection system.

Based on the results of numerical simulations, one could also understand why in our experiment the dark solitons whose pulse width is far narrower than the detector bandwidth limited pulse width could be detected. The reason is that the dark solitons were formed in a high repetition rate pulse train background. As revealed by the numerical simulations, a dark soliton formed in a stable periodic pulse train background could exhibit a much broader pulse envelope than its actual pulse width, which would be easier to be detected. We note that the formation of such a broader dark envelope is purely a visual effect, whose formation mechanism could be traced back to the Moiré pattern [24]. In addition, compared with a DC background, a periodic pulse train background also favors the dark pulse detection.

We had shown dark soliton formation in CW background of a fiber laser previously [13]. Our current experiment further demonstrated that dark solitons could even be formed in a stable periodic pulse train background. In a fiber laser due to the cavity induced modulation instability [14, 21], a strong CW oscillation can be easily destabilized into a periodic pulse train. However, contrary to our understanding, the destabilization of CW background does not affect the dark soliton formation.

5. Conclusion

In conclusion, we have first experimentally observed dark soliton formation in a stable periodic pulse train in a net normal dispersion cavity fiber laser. The stable high repetition rate pulse train is formed in our fiber laser as a result of the cavity induced modulation instability effect, and the dark soliton formation is an intrinsic effect of the net normal dispersion cavity fiber lasers. Although each of the effects was observed previously, to our knowledge, the coexistence of them in the same laser simultaneously has never been reported before. Our experimental result shows once again that the dark soliton formation in fiber laser is a robust effect. The experimental observation is further confirmed by the numerical simulations. Our numerical simulations have shown not only that dark solitons can be formed in a periodic pulse train background, but also that a narrow dark soliton could exhibit a much broader pulse envelope in a periodic pulse train background. The destabilization of a CW background into a periodic pulse train does not destroy the dark soliton formation.

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