

Observation of anti-dark solitons in fiber lasers

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Abstract: We report on the numerical simulation and experimental observation of anti-dark solitons in fiber lasers. The anti-dark solitons were obtained in the net normal near zero dispersion regions where the third-order dispersion plays a role.

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1. Introduction

Theoretical studies on the soliton formation in SMFs have revealed that near the zero group velocity dispersion, a new form of so-called anti-dark solitons could be formed [1, 2]. An anti-dark soliton could be seen as a weak dark soliton with reversed amplitude. Its formation is a feature of the NLSE at the near zero group velocity dispersion, where the third-order dispersion also plays a role. However, there is still no report on the experimental observation of the anti-dark solitons in optical fibers. In this talk we report on the first experimental observation of anti-dark solitons in a fiber laser. Besides, results of the numerical simulations are also presented.

2. Theoretic background and numerical simulations

The light propagation in SMFs at normal near zero GVD is described by the normalized NLSE of the form:

$$i \frac{\partial u}{\partial z} - \frac{1}{2} \frac{\partial^2 u}{\partial t^2} + |u|^2 u = i \frac{\beta_3}{6} \frac{\partial^3 u}{\partial t^3} \quad (1)$$

where β_3 is the normalized 3rd order dispersion coefficient of the fiber. Under the small amplitude approximation, Eq. (1) has the solution [1]:

$$u(z, t) = [u_0 + a(z, t)] \exp[iu_0^2 z + i\phi(z, t)] \quad (2)$$

where $a(z, t)$ is a small amplitude and has the form

$$a(z, t) = -u_0 \frac{\mu^2 (\gamma + 4\sigma)}{2(\gamma + \sigma)} \text{sech}^2 Z \quad (3)$$

where $\mu = \varepsilon/u_0$, ε is an arbitrary value, $\sigma = \pm 1$, $\gamma = \frac{3}{\beta_3 u_0}$, $Z \approx \mu u_0 (t - u_0 \sigma z)$ and

$$\phi(Z) = [\sigma \mu (\gamma + 4\sigma) / (\gamma + \sigma)] \tanh Z + \phi_0 \quad (4)$$

where ϕ_0 is an arbitrary phase factor. In Eq. (3), the sign of $a(z, t)$ could either be positive or negative depending on the parameter selections. As firstly shown by Kivishar *et al* [1, 2], the positive and negative $a(z, t)$ refers to the anti-dark and dark soliton solutions, respectively. For example, for $\sigma = -1$, $1 < \gamma < 4$, anti-dark solitons are formed, while for $\sigma = 1$, $\gamma > -1$ or $\gamma < -4$, dark solitons are formed.

We firstly show the numerical simulation results of the anti-dark soliton formation in a net normal near zero dispersion fiber laser cavity. The simulation is based on numerically solving the GLE using the split-step Fourier method.

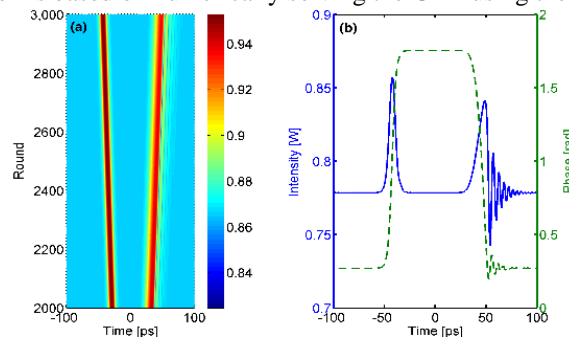


Figure 1. (a) Formation of a stable anti-dark soliton from an initial small intensity peak. (b) The state at the 3000th cavity roundtrip. The blue solid (green dashed) line is the intensity (phase) of the light, respectively.

The initial state of the simulation is a small amplitude peak on the CW background. As we can see in the simulation results shown in Fig. 1, the initial one peak breaks up into two pulses. The pulse on the right is unstable and will disappear at last, meanwhile, the left pulse is very stable and its width and amplitude never change during the propagation. Therefore we can conclude this pulse has been evolved into an anti-dark soliton. In the simulation, we also find that the stable anti-dark solitons are only observed in a small region near the net zero dispersion point. Besides, the anti-dark soliton can be only stable under relatively high light intensity and its width decreases with the increasing of light intensity.

3. Experimental results

Our experiment setup is a typical fiber ring laser. The fiber ring has a total length of 12.1 m, consisting of a piece of 3 m Erbium doped fiber (EDF) with a group velocity dispersion (GVD) parameter of -48 ps/nm/km, 8.2 m single mode fiber (SMF-28) with a GVD parameter of 18 ps/nm/km and 0.9 m dispersion compensation fiber (DCF) with a GVD parameter of -4 ps/nm/km. The fiber laser is estimated to have a near zero dispersion. It is pumped by a 1480 nm Raman fiber laser whose maximum output power is 5 W. By increasing the pumping power to about 800 mW, by tuning the intra-cavity polarization controller, stable anti-dark soliton emission can be achieved, as shown in Fig. 2.

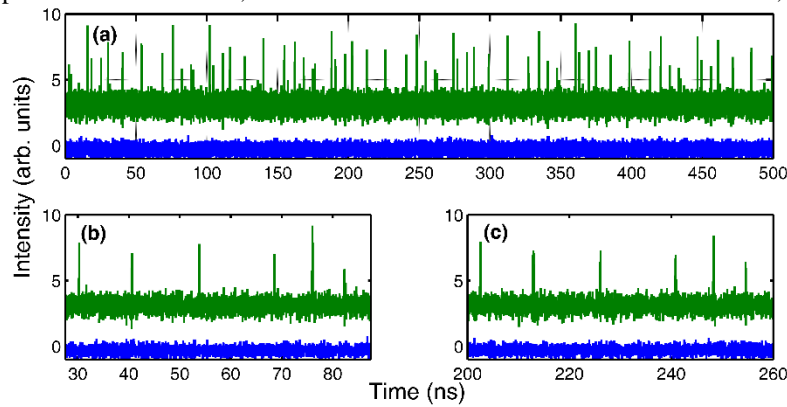


Figure. 2: Anti-dark pulse emission recorded in several cavity roundtrips. (a) The full experiment trace, (b)&(c) Comparison between the anti-dark soliton emission trace between two cavity roundtrips.

The experimental result clearly shows the anti-dark solitons are spontaneously formed on the CW background. Besides we show the anti-dark soliton emission traces of two different cavity round trips in Fig. 2(b) and (c). By comparing these two trace, we can find the anti-dark pulses repeated themselves with the cavity roundtrip, clearly showing that they are very stable in the cavity and exclude the possibility of random intensity fluctuations of the laser emission. The amplitude of the anti-dark solitons differs with each other, which is a typical character of those solitons based on the third-order dispersion, such as the vector solitons supported by the third-order dispersion [3].

In our experiment, we also changed the length of DCF to tune the net dispersion of the fiber laser cavity. Just the same as the simulation results, anti-dark solitons can only appear under a very small dispersion regime, which makes this experiment very challenging. Besides the anti-dark soliton state, the formation of dark solitons and coexistence of dark and anti-dark soliton states are also observed in the experiment. It confirms that fiber laser is a perfect testbed for study of NLSE based nonlinear phenomenon.

4. Conclusion

In conclusion, using a fiber ring laser we have first experimentally confirmed the existence of NLSE anti-dark solitons formed in the normal near zero group velocity dispersion regime. The properties of anti-dark solitons formed in a fiber laser cavity are numerically studied and the simulation results fit very well with the experimental observations.

5. Reference

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