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Observation of antisymmetric dispersion-managed solitons in a mode-locked laser

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Abstract

We report experimental evidence of antisymmetric solitons in a mode-locked fiber laser with a strong dispersion map. A dispersion-managed soliton breathes as it traverses the dispersion map, and the antisymmetric dispersion-managed soliton can be considered a tightly-bound soliton pair with π phase difference between the component solitons. The antisymmetric soliton is only observed at particular values of the net cavity dispersion.

A dispersion-managed (DM) soliton is a soliton solution of a transmission line with segments of alternating normal and anomalous dispersion. The DM soliton has a breathing temporal profile, which is close to a Gaussian profile, in contrast to the static hyperbolic secant profile of a soliton of the ordinary nonlinear Schrödinger equation (NLSE). Scientists also recognized that a DM transmission system can support different forms of solitons, which can be considered higher-order DM solitons.

The first prediction of a second-order DM soliton was presented by Pare [1]. This solution is well-approximated by a chirped, odd Hermite-Gaussian (HG) temporal profile of the electric field:

$$E(t) = A_o \frac{a^3}{(a^2 - iD)^{3/2}} t e^{-\frac{t^2}{2(a^2 - iD)}}. \quad (1)$$

D designates the group-velocity dispersion (GVD). The intensity profile exhibits two temporal (and spectral) peaks with π phase difference ($\Delta\phi$) between them. Such a pulse has been referred to as an antisymmetric dispersion-managed (ASDM) soliton. The ASDM soliton can also be interpreted as a pair of bound DM solitons with $\Delta\phi = \pi$ and an appropriate separation [1]. The solution can therefore be modeled as a pair of chirped Gaussian pulses:

$$E(t) = A_o \frac{t_o}{\sqrt{t_o^2 - iD}} \left(e^{i\pi - \frac{t^2}{2(t_o^2 - iD)}} + e^{-\frac{(t-s)^2}{2(t_o^2 - iD)}} \right). \quad (2)$$

The component pulses are separated by s . Both analytic expressions are equally good approximations, in the sense that they are successfully used as the *ansatz* in treatments of ASDM solitons by the variational approximation [1]. As an odd HG pulse (Eq. 1) propagates in a dispersive medium, the pulse broadens, but maintains its shape. As a result, the ratio of the separation between component pulses and the duration of one pulse remains

constant, with the value $s/\Delta t = 1.73$. The separation between the component pulses in the bound-soliton model requires another independent parameter, which might be viewed as a disadvantage in theoretical modeling of experiments. However, the bound-soliton model allows for convenient analysis of solutions with phase differences other than π between pulses. In this letter, both models are used. The bi-soliton [2] and the temporal soliton molecule [3] are related to the ASDM soliton. Distinct focuses and approaches lead to distinct terminologies, but a bi-soliton with $\Delta\varphi = \pi$ and a temporal soliton molecule refer to fields that are identical in their essential features.

Bound solitons in passively mode-locked lasers have been studied extensively. Motivated by the theoretical predictions of the Ginzburg-Landau equation (GLE) [4,5], bound solitons were observed in solid state [6] and soliton fiber lasers [7]. Since then, a variety of bound solitons have been observed in fiber lasers. Bound solitons with $\Delta\varphi = \pi$ would seem to be closely similar to the ASDM soliton, but they evolve in fundamentally-different ways. Bound solitons of the GLE are static solutions with fixed pulse duration and separation everywhere in the cavity. Experimentally-observed pulse separations are typically ~ 10 times the pulse duration. This phenomenon is consistent with the theoretical prediction of bound pair formation with slightly-overlapping solitons [4]. In contrast, the ASDM soliton is a bound pair of breathing DM solitons. As the ASDM soliton propagates, it is quite possible for the (chirped) pulse duration to become much larger than the pulse separation. Even though chirped DM solitons overlap substantially, the temporal intensity is zero at the center of the two pulses owing to $\Delta\varphi = \pi$. Bound solitons were also observed in a stretched-pulse fiber laser [8]. Bound DM solitons with $\Delta\varphi = \pi$ were observed, but the separation was ~ 3 times larger than that of the ASDM soliton [9]. Although many aspects of these bound pulses were elucidated, ASDM soliton evolution in a laser has not been observed experimentally to date.

In addition to their fundamental importance, ASDM solitons may be relevant to applications. The potential importance of the ASDM soliton in optical telecommunication has been pointed out. The data transmission rate and the timing jitter can be improved significantly by the use of ASDM solitons [2, 10]. Recently, the generation of ASDM solitons in a fiber laser with a strong dispersion map was predicted in numerical simulations [11].

Here we report evidence of ASDM solitons in a passively mode-locked fiber ring laser. Under appropriate conditions, the laser generates pulses that are consistent with the properties of bound DM solitons with $\Delta\varphi = \pi$ and an appropriate separation. These only occur within a narrow range of net cavity dispersion values.

The experimental setup is similar to that of [12]. The laser cavity contains 4.1 m of single-mode fiber (SMF) followed by 60 cm of Yb-doped fiber and another 1.3 m of SMF. All fibers have normal dispersion and a 6- μm core diameter. After the fiber section, nonlinear polarization evolution (NPE) provides self-amplitude modulation. The main output (output 1) is taken directly from a polarizing beam splitter, which is the NPE ejection port. A double-pass grating pair provides anomalous dispersion, and the net cavity GVD is -0.038 ps^2 . The cavity setup is slightly different from a conventional dispersion map since the anomalous-dispersion segment is linear. However, DM soliton evolution is observed in the given cavity [13], as expected considering that the evolution of a DM soliton can be understood as nearly-linear propagation. Thus, ASDM solitons should be possible in such a cavity. The repetition rate is 30 MHz. A 1% coupler is placed at the middle of the fiber segment to monitor the evolving spectrum. The output pulse train is monitored with a photodetector that can resolve features as short as $\sim 300 \text{ ps}$, and the pulse autocorrelation (AC) is monitored for delays up to $\sim 100 \text{ ps}$.

Operation of the laser to generate fundamental DM solitons (*i.e.*, the lowest-order symmetric soliton) is obtained easily by adjusting the waveplates. The bound state of DM solitons, which matches the description of the ASDM soliton [1], is produced by adjusting the pump power and waveplates carefully. The experimental features of this state are shown in Fig. 1. The power spectrum develops a pronounced (~ 15 dB) dip in the center. The pulse from the main output is positively chirped, as indicated by the AC of Fig. 1(b). The pulse is dechirped to the Fourier-transform limit by a grating pair that provides dispersion of -0.042 ps^2 . This value implies that the pulse reaches minimum pulse duration at two points in the cavity, one in the anomalous-dispersion segment and one in the normal-dispersion segment, as expected for a DM soliton. The dechirped interferometric AC with three peaks (Fig. 1(c)) indicates a doubly-peaked intensity profile. The component pulses are 145 fs in duration and ~ 350 fs apart. $\Delta\phi = \pi$ between the pulses is confirmed in the fringes of the AC (Fig. 1(d)). With ~ 100 mW pump power, the output power is 10 mW, which corresponds to 0.3 nJ pulse energy.

A complete characterization of the electric field of this type of pulse is desirable. In particular, verification of the phase difference between the bound pulses would be valuable. Second harmonic generation frequency-resolved optical grating (SHG FROG) is available in our laboratory, but it cannot resolve the phase difference, owing to the fundamental phase ambiguity in the measurement technique [14]. Hause *et al.* recently developed a technique to retrieve the intensity and phase of this kind of pulse, but a sophisticated experimental setup is required [15]. In the absence of a direct measurement, we decided to compare the experimental measurements to calculated ACs of bound DM solitons (Eq. 2) that have been subjected to varying amounts of dispersion. Theoretical ACs are created by substituting the experimentally-observed parameters $t_o = 87$ fs, $s = 350$ fs into Eq. 2 and varying the GVD parameter D . These are compared to experimental results in Fig. 2.

The tails of tightly-bound DM solitons overlap. The intensity in the overlapping region, which influences the AC trace, is sensitive to the phase difference. For example, ACs with $\Delta\phi = \pi/2$ (Fig. 2(a) and (b) insets) are quite different from those with $\Delta\phi = \pi$. With $\Delta\phi = \pi$, the theoretical AC has three clear lobes, with near-zero intensity between lobes. The experimental AC, which matches very well with the theoretical AC envelope (Fig. 2(b)), shows the expected behavior with close to zero intensity between lobes (Fig. 1(c and d)). The temporal profile of the chirped pulse directly from the fiber cavity can be calculated. By adding $D = 0.042 \text{ ps}^2$ (GVD to dechirp the pulse), pulses are stretched to ~ 815 fs, with ~ 350 -fs separation. Even though the pulses overlap significantly, due to $\Delta\phi = \pi$, the temporal intensity profile shows two separate envelopes with 355-fs duration and 630-fs separation. The calculated value of $s/\Delta t \sim 1.77$ agrees very well with value (1.73) appropriate to the odd HG pulse. For the dechirped pulses, $s/\Delta t \sim 2.41$, which does not agree as well but is still reasonably close to the theoretical value. Again, the calculated AC of bound chirped Gaussian pulses matches very well with the measured AC trace (Fig. 2(a)). From the good agreement between the calculated ACs and the measured traces (Fig. 2(a and b)), we conclude that $\Delta\phi \sim \pi$ and the separation between pulses is as expected for the HG pulse. The ACs of the pulse chirped external to the laser (Fig. 2(d)) also match the calculated ACs (Fig. 2(c)). The measured pulse shape, $\Delta\phi \sim \pi$, value of $s/\Delta t$, and observed evolution are all consistent with the properties of the ASDM soliton [1].

ASDM solitons are only observed with the net cavity GVD in a narrow range, within $\pm 0.005 \text{ ps}^2$ of -0.038 ps^2 . In contrast, ordinary DM solitons are produced by this laser over a wide range of anomalous dispersion. Extensive searches for the ASDM soliton pulses were made at each dispersion value, but the ASDM soliton was only found in the stated narrow range. Similar investigations were performed with other fiber lasers in our laboratory, with a similar conclusion: although solitons can be generated for a wide range of dispersions,

ASDM solitons only seem to form near a single dispersion value that is particular to the details of the laser. We have been unable to observe the ASDM soliton solution in numerical simulations, which otherwise account well for many properties of modelocked fiber lasers. The limited range of stability of the ASDM soliton is consistent with the work of Ablowitz *et al.*, who employed a higher-order, multi-scale asymptotic analysis [16] to show that higher-order solutions of the DM NLSE exist only at particular parameter values.

To summarize, we observe ASDM solitons in a Yb-doped fiber laser with a strong dispersion map. All of the features of the pulse are consistent with the predicted properties of ASDM solitons. The ASDM soliton fiber laser is a realization of an interesting soliton in a feedback system. Future work could attempt to explain why the ASDM soliton is observed only at specific dispersion values, which is currently unresolved.

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Fig. 1.

Experimental result: (a) main output spectrum (dotted: output 2 spectrum), (b) chirped interferometric AC, (c) dechirped interferometric AC, (d) grey rectangular region in (c), periodic vertical lines indicate the period of fringes.

Fig. 2.

(a) Chirped interferometric AC and (b) dechirped AC; grey: experimental ACs of Fig. 1, black: calculated AC envelope for bound Gaussian pulses, insets: calculated AC envelopes with $\pi/2$ phase difference, (c) calculated intensity ACs for chirped bound Gaussian pulses; bottom: $D = 0$, middle: $D = -0.05 \text{ ps}^2$, top: $D = -0.07 \text{ ps}^2$, (d) experimental intensity ACs of chirped pulses with the same GVD values as in (c).