Observation of bound states of solitons in a passively mode-locked fiber laser

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We report on an experimental observation of bound states of solitons in a passively mode-locked fiber soliton ring laser. The observed bound solitons are stable and have discrete, fixed soliton separations that are independent of the experimental conditions.

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Bound states of solitons known as high-order soliton solutions of the nonlinear Schrödinger equation (NLSE) have been extensively studied [1–5]. A bound state of solitons of the NLSE is formed because two or more fundamental solitons coexist, and they have the same velocity and locate at the same position. Recently, another form of bound solitons has also been theoretically predicted [6] to exist in nonlinear dynamical systems such as the Ginzburg-Landau equation [7,8], and the coupled nonlinear Schrödinger equations [9]. In contrast, the formation of these bound solitons is due to a direct interaction between the solitons, and the propagation of them is characterized by the fact that the solitons have discrete, fixed separations.

It is well known that the dynamics of passively mode-locked fiber soliton lasers can be well modeled by the complex Ginzburg-Landau equation [10,11]. The same equation also describes the soliton propagation in the long-distance optical transmission lines [12–13]. It would be expected that the predicted bound states of solitons could be observed in these systems. However, to the best of our knowledge, so far no bound states of solitons of this form have been experimentally confirmed in the systems.

Two effects in optical fibers are detrimental to the formation of the predicted bound states of solitons. One is the Raman effect. Theoretical studies have shown that a strong Raman effect destroys the bound solitons [6]. Another one is the random-phase variations of the solitons, which causes random soliton interactions. Although in fiber soliton lasers, the influence of the Raman effect can be significantly reduced by the effect of laser gain dispersion [14], no efficient way has been found to suppress the random relative phase variations between solitons. In this paper, we report on an experimental observation of bound states of solitons in a passively mode-locked fiber soliton laser. We confirm experimentally the existence of stable bound states of solitons with discrete, fixed soliton separations.

Our experiment is conducted on a passively mode-locked fiber soliton ring laser. A schematic of the laser configuration is shown in Fig. 1. The laser cavity is about 10 m long, which comprises of a 4-m long 2000 ppm erbium-doped fiber with a group velocity dispersion of about -10 ps/nm km and two pieces of 3-m-long single-mode dispersion-shifted fiber, whose group velocity dispersion is -1 ps/nm km. The nonlinear polarization rotation technique [15] is used to achieve the self-started mode locking in the laser. To this end, a polarization-dependent isolator together with two polarization controllers is used to adjust the polarization of light in the cavity. The polarization-dependent isolator and the polarization controllers are mounted on a 7-cm-long fiber bench, with which accurate polarization adjustments can be easily obtained. The laser is pumped by a pigtailed $In_xGa_{x-1}AsP$ semiconductor diode of wavelength 1480 nm. Two output ports, one locates before the erbium-doped fiber, and the other one after, have been used to outlet the soliton pulses out of the laser cavity. The output of the laser is taken via two 10% fiber couplers and analyzed with an optical spectrum analyzer (HP 70 004A) and a commercial optical autocorrelator (Inrad 5-14-LDA).

Multiple soliton operations can be easily achieved in a passively mode-locked fiber soliton laser. However, due to the unavoidable environmental perturbations and the interaction between soliton and dispersive waves, the phases of the solitons vary randomly, which causes a random interaction between the solitons. To experimentally suppress the random soliton phase variations, we have developed a novel intracavity phase-locking technique to synchronize the random-phase change of solitons. To this end, we build up a very

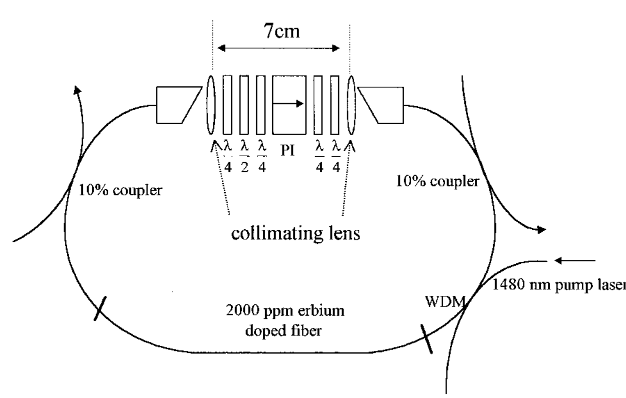

FIG. 1. A schematic of the fiber soliton laser setup. λ/4, quarter-wave plate; λ/2, half-wave plate; PI, polarization-dependent isolator.

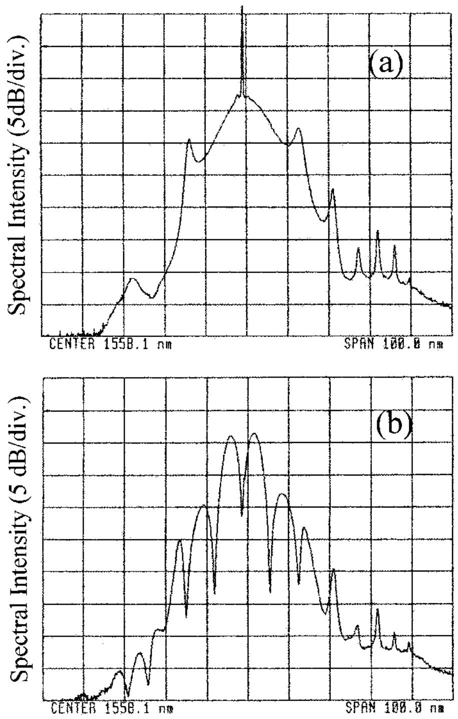

FIG. 2. Typical soliton spectra of the laser observed. (a) Soliton spectrum with the coexistence of a strong cw component. (b) Spectrum of a bound state of soliton.

strong (cw) laser field in the laser cavity, which coexists with the solitons. By carefully setting the cw mode-frequency position in the soliton spectrum, a phase locking between one of the dynamical modes of the solitons and the cw mode takes place automatically. In this way, the phase variations of all the solitons in the laser cavity can be synchronized to those of the cw mode except for an arbitrary phase constant. Details of the phase-locking principle and techniques will be reported elsewhere [16].

Bound states of soliton are observed in our laser after that the random relative-phase variations between the solitons are suppressed. Figure 2 shows a typical spectrum of a bound state of solitons observed. For comparison, we have also shown the soliton spectrum of the laser before the solitons are bound together. Except for the coexistence of a strong cw spectral component in the center of the soliton spectrum, the spectrum shown in Fig. 2(a) has typical characteristics of those also observed in other fiber soliton lasers. Specifically, the sidebands caused by the periodic perturbations of the laser gain and losses are clearly seen. The spectrum of the bound solitons shown in Fig. 2(b) is strongly modulated, which is a direct consequence of a very close soliton separation in the time domain. The spectral modulation has a rather symmetric structure with a dip in the center, indicating that the phase difference between the bound solitons is roughly pi as predicted theoretically in [6,7,9]. Although bound states of a zero phase difference between the solitons have also been theoretically predicted, in all of our experiments no such bound states of solitons have been observed. A strong cw component is necessarily required to get the bound state of solitons, however, once the solitons are bound, we can reduce the cw mode strength by reducing the pump power.

In our laser, the pulse duration of the fundamental soliton is about 310 fs when measured after the erbium-doped fiber and assuming a sech-form pulse profile, and 340 fs measured before it. The variation of the soliton pulse duration along the laser cavity is due to the average soliton effect of the laser [17]. The soliton separation between the bound solitons shown in Fig. 2(b) is measured to be about 1160 fs. Two methods have been used to work out the soliton separation. One is that we first measure the period of the soliton spectral modulation, and then calculate the pulse separation based on the spectral modulation frequency. The other one is to directly measure the soliton pulse separation by using an optical autocorrelator. Within the experimental error range, both methods have given the same value, showing that the spectral modulation observed in Fig. 2(b) is actually a result of the closed soliton separation. The pulse separation of the bound solitons is roughly 3.5 times of the soliton pulse duration, suggesting strongly that the state of bound solitons is formed due to the direct interaction between the solitons.

We emphasize that the observed bound states of solitons are very stable. Although in our experiment no effort has been taken to reduce the environmental perturbations, which are in fact quite strong in our experiments. Once the bound state is obtained, it can remain there for several hours. Changing the experimental conditions such as the pump power, etc., does not change the soliton separation and their phase relationship. Another significant feature of the observed bound solitons is that no matter how we change the experimental conditions, such as changing the wave plates' orientations and stressing the fibers, as long as the bound states of solitons are obtained, the bound solitons will always have the same discrete, fixed separations that in our laser are either 1160 or 2280 fs. No other values of soliton separations have been observed. Fixed, discrete soliton separations are another characteristic of the bound states of solitons predicted in [6,7,9]. Again, our experimental results confirm the property of the bound solitons. However, we point out that in our experiment, the observed soliton separations have almost a fixed relationship of a factor of 2, which although is well in agreement with the theoretical prediction of the coupled nonlinear Schrödinger equations model [9], the phase relationship between the observed bound states does not have a pi phase change. While considering that the solitons in our laser are in fact not exactly the nonlinear Schrödinger equation solitons but the complex Ginzburg-Landau equation solitons, this discrepancy could then be explained.

To check if the soliton separation varies periodically along the laser cavity, as in the case of bound solitons of NLSE, we have measured the soliton spectra and pulse separations at each of the two laser output ports. Figure 3 shows a comparison of the measured soliton autocorrelation traces. Both traces give exactly the same soliton separation. At different positions of the laser cavity, the soliton spectral modulation becomes slightly asymmetric, indicating a small relative phase change between the solitons. This small phase change could, however, be attributed as a result of the average soliton effect of the laser. Despite the fact that the individual soliton pulse duration itself varies along the laser cav-

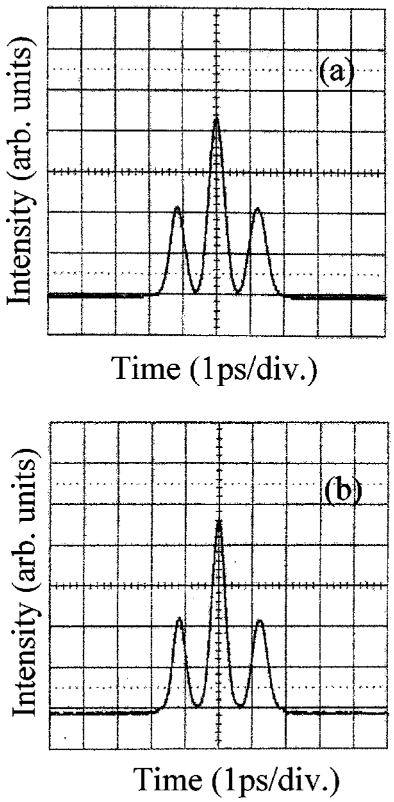

FIG. 3. Autocorrelation traces measured at the two output ports of the laser. (a) Measured before the gain medium. (b) Measured after the gain medium.

ity, the soliton separations between the bound solitons remain constant, which is in good agreement with the theoretical predictions [6,7,9].

In a previous paper we have shown that, by carefully adjusting the pump power, one can create (or destroy) the soliton in the laser cavity one by one [18]. We found that the number of the bound states of solitons can also be controlled in the same way. However, in the case of bound solitons, instead of a single-soliton pulse being created (or destroyed), a soliton pair in the form of bound states will be created (or destroyed). In particular, when multiple solitons coexist in

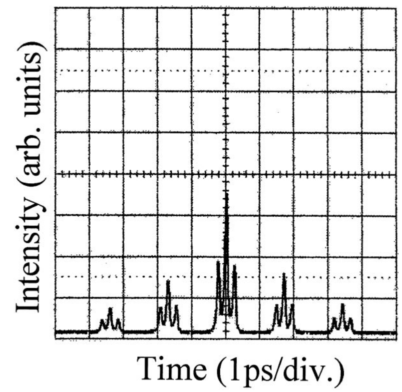

FIG. 4. A typical autocorrelation trace showing the coexistence of multiple-bound solitons.

the laser cavity, in the stable state only bound states of soliton are observed. Solitons in the laser cavity will automatically pair together and form bound states of solitons. To demonstrate this feature, we show in Fig. 4 a long scan of the autocorrelation traces. Within the scan range, there are three pairs of solitons. We have further studied each of these three pairs of solitons in detail. We found that each of them forms a bound state of solitons, and in particular, all of the bound states of solitons have exactly the same soliton separation and phase relationship. However, the separations between the bound states of solitons are not fixed. We observed that when a new pair of solitons was generated or an existing pair was destroyed, the separations between the bound states of solitons changed.

In conclusion, we have experimentally observed a type of bound states of solitons in a passively mode-locked fiber soliton laser. The observed bound states of solitons are characterized as being very stable, and have discrete, fixed soliton separations. Comparing the pulse separation of the bound solitons with that of the individual soliton pulse duration, it shows that the formation of the observed bound solitons is due to a direct interaction between the solitons in the laser. All of these properties of the observed bound solitons are in good agreement with those of theoretical predictions. This is experimental evidence of bound states of soliton of this form observed in a passively mode-locked fiber laser.

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