PHYSICAL REVIEW E **70**, 067602 (2004)

Bound twin-pulse solitons in a fiber ring laser

B. Zhao, D. Y. Tang, and P. Shum
School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore

X. Guo and C. Lu
Institute for Infocomm Research, Singapore

H. Y. Tam
Department of Electrical Engineering, Hong Kong Polytechnic University, Kowloon, Hong Kong
(Received 29 December 2003; published 20 December 2004)

Bound states of twin-pulse solitons were experimentally observed in a passively mode-locked fiber ring laser. Similar to those of single-pulse solitons, the bound states of twin-pulse solitons are marginally stable and occur at some fixed, quantized soliton separations. Our experimental investigations revealed that the formation of such bound states might be resulted from the dispersive wave mediated long-range soliton interaction in the laser.

DOI: 10.1103/PhysRevE.70.067602 PACS number(s): 42.65.Tg, 42.81.Dp, 42.65.Re, 42.55.Wd

Soliton operation is a generic feature of passively mode-locked ultrashort pulse fiber lasers and has been intensively investigated [1,2]. A typical characteristic of the lasers is that multiple soliton pulses can coexist in the cavity, and they all have exactly the same properties: the same pulse profile and pulse energy, which is known as the soliton energy quantization effect [1]. Solitons in the laser can also interact with each other. Depending on the concrete mechanism of interaction, various forms of stable soliton distribution have been observed, such as the soliton bunching, quasiharmonic and harmonic mode locking [2,3].

Conventionally, soliton operation of a fiber laser is modeled by the extended nonlinear Schrödinger equation, and the soliton pulses observed have a single-pulse intensity profile. Recently, we have experimentally demonstrated a novel form of twin-pulse solitons in passively mode-locked fiber ring lasers [4]. The twin-pulse solitons were found to have the characterization that their intensity profiles have a double-peak shape with fixed, discrete peak separations. So far the exact formation mechanism of the twin-pulse solitons in the lasers is still not very clear, which needs to be further investigated. Nevertheless, numerical simulations on the soliton operation of the lasers did demonstrate the existence of such a soliton profile [5], which suggested that it could be another intrinsic state of the laser emission. In addition, extended experimental investigations on the twin-pulse solitons have revealed properties of the solitons such as the energy quantization, pump power hysteresis [6], quasi-harmonic and harmonic mode-locking [7], which are exactly the same as those of the conventional single-pulse solitons in the laser.

In this Brief Report we further report on the experimental observation of bound states of the twin-pulse solitons. We show that depending on the initial conditions, multiple twin-pulse solitons could bind together, forming various stable bound states. Bound states of twin-pulse solitons with different soliton separations, and the coexistence of bound twin-pulse solitons are experimentally observed. Like the bound states of the conventional single-pulse solitons, the soliton separations of the twin-pulse solitons also exhibit a certain fixed relationship.

The fiber laser configuration we used is similar to that reported in Ref. [4]. Briefly, it has a ring cavity of about 5.5 m long that comprises of a 3.5 m erbium-doped fiber with a group velocity dispersion parameter of about 10 ps/(nm km), a piece of 1 meter single-mode dispersion-shifted fiber, whose group velocity dispersion parameter is about 2 ps/(nm km), and another piece of 1 meter standard telecom fiber (SMF28), whose group velocity dispersion parameter is 18 ps/(nm km). The nonlinear polarization rotation technique is used to achieve the self-started mode locking of the laser. For this purpose a polarization dependent isolator together with two polarization controllers, one consists of two quarter-wave plates and the other two quarter-wave plates and one half-wave-plate, 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 to easily and accurately control the polarization of the light. The laser is pumped by a pigtailed $In_{1-x}Ga_xAs_yP_{1-y}$ semiconductor diode of wavelength 1480 nm. The output of the fiber laser is taken via a 10% fiber coupler and analyzed with an optical spectrum analyzer (ANDO AQ6317B) and a commercial optical autocorrelator (APE PulseScope 50). A 50 GHz wide bandwidth sampling oscilloscope (Agilent 86100A) and a 25 GHz photodetector (New Focus 1414FC) are used to study the soliton evolution in the laser cavity.

Soliton operation of the laser can be easily achieved by increasing the pump power beyond the mode-locking threshold and by appropriately adjusting the orientation of the wave-plates. In our experiment depending on the setting of the wave-plates, either the conventional single-pulse soliton operation or a twin-pulse soliton operation can be obtained, respectively. The single-pulse solitons have a pulse width (FWHM) of about 340 fs, and the twin-pulse solitons have a profile of two pulses with a fixed peak-to-peak separation of about 930 fs. Figure 1 shows the optical spectrum and the

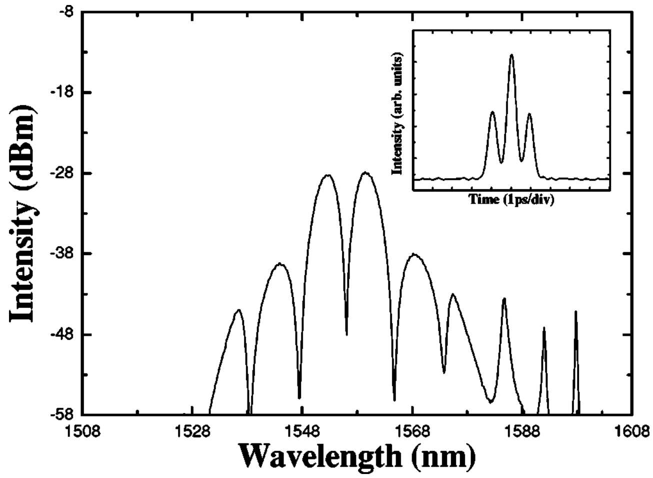

FIG. 1. Optical spectrum of the twin-pulse soliton operation of the laser. The inset is the corresponding autocorrelation trace. The separation between the twin peaks is about 930 fs.

corresponding autocorrelation trace of the laser output with only one twin-pulse soliton in the cavity. Clearly both from the autocorrelation trace and the optical spectrum it is to see that the two pulses in a twin-pulse soliton have very close pulse separation. The almost symmetric soliton spectrum with a deep dip in the center further suggests that the optical phase difference between the two pulses is about π.

Like the single-pulse solitons, multiple twin-pulse solitons can also coexist in the laser cavity. Especially, when the separations between the twin-pulse solitons are large so that there is no strong mutual interaction between them, each of the twin-pulse soliton exhibits exactly the same pulse profile and pulse energy [6]. As an example we show in Fig. 2 the oscilloscope trace of the laser operation when multiple twin-pulse solitons coexist in the cavity. The round trip time of our laser is about 26 ns. It is to see that 8 twin-pulse solitons irregularly distributed in the cavity. The twin-pulse solitons are far apart from each other, each has the same pulse height. Comparing the soliton spectra of the laser output under such

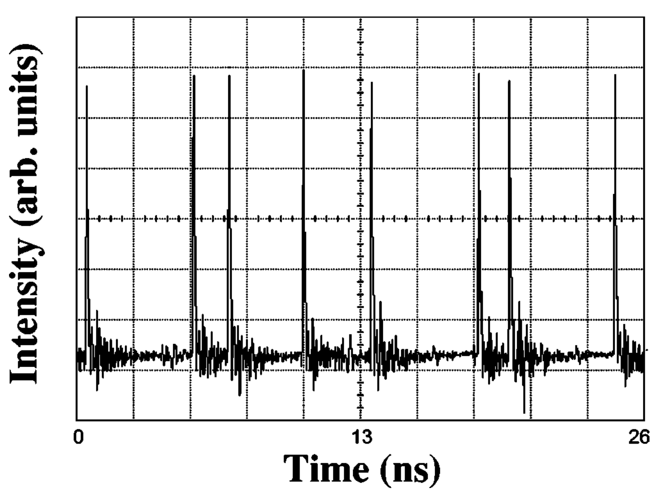

FIG. 2. A typical oscilloscope trace of multiple twin-pulse soliton operation of the laser. The cavity round trip time is 26 ns. There are 8 twin-pulse solitons far apart from each other in the cavity.

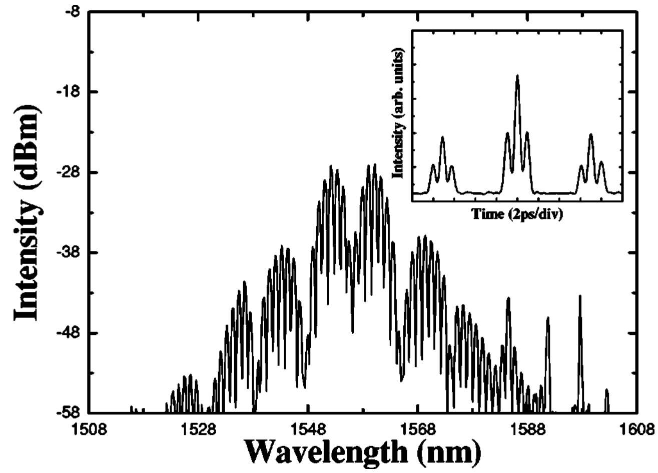

FIG. 3. The optical spectrum and corresponding autocorrelation trace when a bound state of two twin-pulse solitons exists in the cavity. The separation between the two twin-pulse solitons is around 6.8 ps.

multiple twin-pulse soliton operation with that when only one twin-pulse soliton is in the cavity, there is no visible difference on their spectral profiles except that the spectral strength for the case of the multiple twin-pulse solitons is stronger. Correspondingly, their autocorrelation traces are also the same except for an intensity increase in the case of multiple twin-pulse solitons. This property is also exactly the same as observed for the multiple single-pulse soliton operation of fiber lasers. We note that in the oscilloscope trace shown in Fig. 2, each spike has actually a twin-pulse structure. However, limited by the resolutions of the photodetector (25 GHz) and the oscilloscope, the real pulse profile cannot be displayed on the oscilloscope. However, the twin-pulse nature of the oscilloscope spikes can be measured by their autocorrelation traces and optical spectra.

Just like the single-pulse solitons, when the separation between two twin-pulse solitons is small, they interact with each other. Under certain conditions stable bound states of twin-pulse solitons are observed in the laser. Figure 3 shows the optical spectrum and autocorrelation trace of one of such states. From the autocorrelation trace it is to see that two twin-pulse solitons are binding together with a separation of about 6.8 ps. The bound state is also evidenced by the measured optical spectrum. A stable spectral modulation with a period of about 1.2 nm, which corresponds exactly to the measured soliton separation of 6.8 ps, is clearly visible on the twin-pulse soliton spectrum. Other bound states of twin-pulse solitons with different pulse separations are also observed in our experiments. Figure 4 shows a bound state of twin-pulse solitons with soliton separation of about 12.8 ps. This separation corresponds to an optical spectral modulation of about 0.63 nm. It is to note that with the use of a large scan range of the autocorrelator (APE PulseScope 50), the detailed twin-pulse structure of each soliton cannot be clearly resolved on the autocorrelation trace. But as we decrease the scan range to show only the center peak, the same autocorrelation trace as shown in Fig. 1 is obtained, confirming that each individual solitons are actually twin-pulse soli-

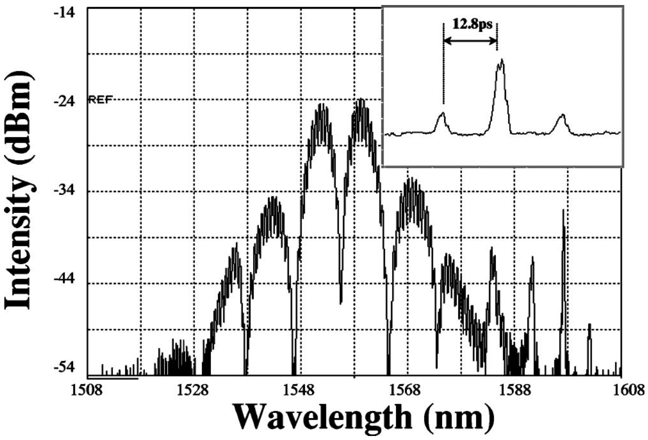

FIG. 4. The optical spectrum and corresponding autocorrelation trace when a bound state of two twin-pulse solitons of around 12.8 ps soliton separation exists in the cavity.

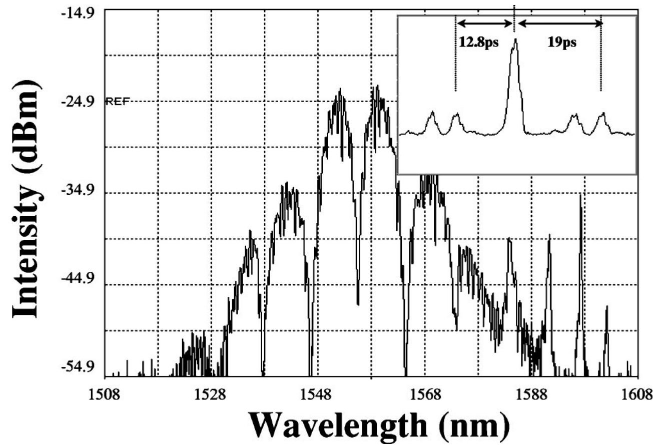

FIG. 6. Coexistence of two bound twin-pulse solitons with different soliton separations in cavity. The inserted autocorrelation trace shows there are two bound states in cavity: one with a pulse separation of 12.8 ps, and another 19 ps.

tons. Figure 5 shows the corresponding oscilloscope trace of Fig. 4. Unlike that in Fig. 2, the pulse height in Fig. 5 is no longer uniform. There is a pulse whose height is almost twice of that of the others, which is the bound twin-pulse solitons. Here again since the photodetector and the sampling oscilloscope are not fast enough to resolve such a short separation, the bound state of the twin-pulse solitons can only be displayed as a pulse of extra height in the oscilloscope trace. In Fig. 5, altogether 5 twin-pulse solitons coexist with one bound twin-pulse soliton pair in the cavity.

Coexistence of bound twin-pulse solitons with different soliton separations has also been observed in the laser. Figure 6 shows the optical spectrum and autocorrelation trace of such a state. From the autocorrelation trace there are two bound states of twin-pulse solitons coexist in the laser cavity, one with a pulse separation of about 12.8 ps and the other of about 19 ps. Due to the coexistence of the two different bound solitons, the corresponding optical spectrum no longer exhibits clear periodic modulation as those observed in Fig. 3 and Fig. 4. The corresponding oscilloscope trace of the state shows that there are two bound solitons and 3 separate twin-pulse solitons in the cavity. Apart from the bound states of two twin-pulse solitons, we have also experimentally obtained bound states of three twin-pulse solitons. Figure 7 shows the spectrum and autocorrelation trace of such a case. The optical spectrum exhibits a similar modulation as those shown in Fig. 3, while the autocorrelation trace exhibits five peaks with equal peak-to-peak separation of about 6.8 ps, suggesting that three twin-pulse solitons are binding together with equal soliton-to-soliton separations. To confirm it, we have also simultaneously checked the oscilloscope trace, which shows that one bound twin-pulse soliton triplet, together with 2 separate twin-pulse solitons that are far away to the triplet, is in the cavity.

Experimentally we found that the appearance of bound states of solitons depends strongly on the initial condition of the laser operation. All the bound states of soliton are stable in the sense that if the laser parameters are fixed, they can remain there for several hours. However, if any of the laser parameters is changed, e.g., the pump power or the orientations of the wave-plates is slightly changed, the bound states may be destroyed. Another feature of the bound states is that their pulse separations exhibit roughly discrete, quantized

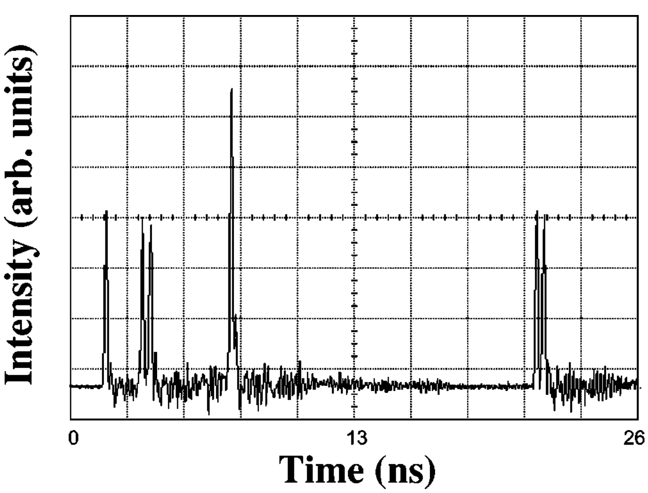

FIG. 5. The corresponding oscilloscope trace of Fig. 4.

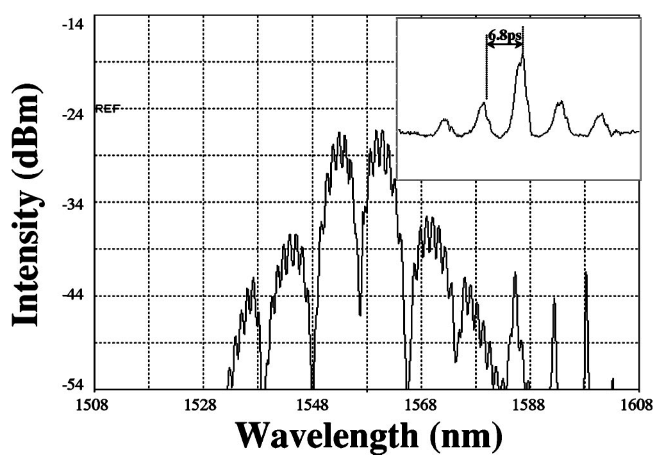

FIG. 7. A bound state of three twin-pulse solitons. Three twin-pulse solitons bind together with a separation of 6.8 ps in between.

values (6.8 ps, 12.8 ps, and 19 ps). In our experiments we have frequently obtained bound twin-pulse solitons under different operation conditions, e.g., different pump power and wave-plate orientations, but all the observed bound states have one of these separations, which strongly suggested that a certain fixed mechanism exists that contributes to the formation of the bound solitons.

It is unlikely that the observed bound solitons are formed due to the direct soliton interaction. Previous studies on the solitons interaction have shown that the direct soliton interaction could be neglected if the soliton separation is larger than 5 pulse-widths [8]. The observed soliton separations of the bound solitons are far bigger than that value. A possible mechanism is that they are formed through the dispersive wave mediated long-range soliton interaction in the laser. It is well known that a soliton circulating in the laser cavity endures periodically gain and loss perturbations, and will consequently periodically reshapes itself and sheds energy into linear dispersive waves. Socci *et al.* have analyzed the long-range soliton interaction induced by the dispersive waves in periodically amplified fiber links [9]. They found that the radiative dispersive waves could introduce periodical interactions between solitons depending on their initial pulse separations. They also anticipated that bound soliton states could be formed at certain pulse separations. Malomed has also theoretically studied bound soliton formation through emission and absorption of radiation [10]. He pointed out that either pair or a whole array of solitons could be pinned by their common radiation field with marginal stability. In particular, the bound states of solitons have fixed discrete soliton separations. Experimentally, bound states of single-pulse solitons were already observed in passively mode-locked fiber soliton lasers. For instance, Seong and Kim have reported the bound states of single-pulse solitons in a figure-of-eight laser [11]. In our laser, we have also frequently observed bound single-pulse solitons. However, to the best of our knowledge, this is the first experimental observation of the bound states of twin-pulse solitons. The observed bound states exhibit exactly the same properties as those of single-pulse solitons.

We have experimentally studied the soliton interaction in our laser and found that, though other mechanisms such as the laser gain recovery [12] and acoustic effect [13] may also introduce weak long-range soliton interaction in the laser, the dispersive wave mediated soliton interaction is the strongest one, which plays an essential role on the formation of various modes of the soliton operation of the lasers. Experimentally we found that depending on the pumping strength, the dispersive waves can form a modulated quasi-cw pedestal around the solitons with an extent of about 500 ps. If the separation between two solitons is shorter than that value, they will interact with each other mediated through their dispersive waves. Not only the bound states of solitons are formed as a result of this long-range soliton interaction, we believe that the formation of the soliton bunching observed in fiber soliton lasers could also be attributed to a result of this soliton interaction.

In conclusion, we have experimentally observed bound states of twin-pulse solitons in a passively mode-locked fiber soliton ring laser. Both bound twin-pulse soliton pairs and bound twin-pulse soliton triplet are observed. Experimentally we also found that bound solitons with different soliton separations can coexist in a laser cavity, indicating that the formation of the state is not determined by the cavity property. Similar to the bound states of single-pulse solitons, the observed bound twin-pulse solitons are marginally stable and the soliton separations of different bound twin-pulse solitons exhibit fixed, discrete values.

[1] A. B. Grudinin, D. J. Richardson, and D. N. Payne, Electron. Lett. **28**, 67 (1992).
[2] D. J. Richardson, R. I. Laming, D. N. Payne, V. J. Matsas, and M. W. Phillips, Electron. Lett. **27**, 1451 (1991).
[3] R. P. Davey, N. Langford, and A. I. Ferguson, Electron. Lett. **27**, 1257 (1991).
[4] D. Y. Tang, W. S. Man, H. Y. Tam, and P. D. Drummond, Phys. Rev. A **64**, 033814 (2001).
[5] D. Y. Tang, B. Zhao, D. Y. Shen, C. Lu, W. S. Man, and H. Y. Tam, Phys. Rev. A **66**, 033806 (2002).
[6] B. Zhao, D. Y. Tang, P. Shum, Y. D. Gong, C. Lu, W. S. Man, and H. Y. Tam, Appl. Phys. B: Lasers Opt. **77**, 585 (2003).
[7] B. Zhao, D. Y. Tang, P. Shum, W. S. Man, H. Y. Tam, Y. D. Gong, and C. Lu, Opt. Commun. **229**, 363 (2004).
[8] W. H. Loh, A. B. Grudinin, V. V. Afanasjev, and D. N. Payne, Opt. Lett. **19**, 698 (1994).
[9] L. Socci and M. Romagnoli, J. Opt. Soc. Am. B **16**, 12 (1999).
[10] B. A. Malomed, Phys. Rev. E **47**, 2874 (1993).
[11] N. H. Seong and Dug Y. Kim, Opt. Lett. **27**, 1321 (2002).
[12] J. N. Kutz, B. C. Collings, K. Bergman, and W. H. Knox, IEEE J. Quantum Electron. **34**, 1749 (1998).
[13] A. N. Pilipetskii, E. A. Golovchenko, and C. R. Menyuk, Opt. Lett. **20**, 907 (1995).