Experimental observation of transitions of different pulse solutions of the Ginzburg-Landau equation in a mode-locked fiber laser

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Transitions between different types of pulse solutions of the Ginzburg-Landau equation (GLE) have been studied experimentally in a mode-locked fiber laser. It is demonstrated that the different pulses corresponding to different solutions of the GLE can be generated in a single mode-locked laser. Dispersion-managed solitons, dissipative solitons, and similaritons can be emitted depending on parameters such as the pulse intensity, the linear cavity phase-delay bias, and the birefringence effect in the cavity. The three nonlinear waves show different features, especially the spectral shapes and dynamics accompanying pump power scaling. Also, our study implies that integrable systems and dissipative systems can be switched in a mode-locked fiber laser. This phenomenon reveals properties of the GLE which are not only scientifically interesting but also valuable for practical applications of mode-locked fiber lasers.

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I. INTRODUCTION

Passively mode-locked fiber lasers have been developed extensively since 1992 [1,2]. Different types of nonlinear waves exist in mode-locked fiber lasers. Among these, nonlinear Schrödinger solitons (NSSs) [3,4], dispersion-managed (DM) solitons, dissipative solitons (DSs), and similaritons [5] draw much attention because of their practical applications. The Ginzburg-Landau equation (GLE) can be used to describe these different pulses in mode-locked lasers effectively. Usually, different pulses have to be generated in different laser cavities to obtain the coefficients of the GLE, especially the net dispersion. NSSs exists in cavities with anomalous dispersion, and DM solitons are generated in cavities consisting of segments of anomalous and normal dispersion. DSs exists in all normal- as well as anomalous-dispersion cavities. In the following, the DS is taken to be the one in normal-dispersion cavities. A numerical study implies that DM solitons and similaritons can be switched in a net positive- dispersion cavity by adjusting the gain parameter [6]. Also, a transition between similaritons and DSs was predicted numerically in a laser by using a filter [7]. It is thus intuitive that it might be possible to get different pulses in a fixed dispersion map, i.e., a single laser. Nevertheless, there has been no experimental observation so far, to our knowledge. Recently, Oktem *et al*. [8] reported a new mode-locking regime, in which, solitons and similaritons are emitted at different positions of the same laser. However, up to date, we know of no experiments demonstrating transitions between different solutions of the GLE.

In this work, we construct a fiber laser to study the GLE experimentally. DM solitons, similaritons, and DSs can be observed in one laser depending on parameters such as the pulse intensity, the linear phase delay, and the birefringence of the fiber cavity. The DM solitons, similaritons, and DSs can be distinguished because of their different spectral shapes. Furthermore, the spectral width of DSs increases with pump power, which is consistent with the theoretical predictions [9,10]. This is quite different from the case of DM solitons. Haus *et al*. havre shown theoretically that the spectral width of DM solitons decreases with gain increment [11]. We also prove this relation for DM solitons experimentally.

Although transitions between different pulses have been theoretically studied, the experimental observations are lagging, since it is a challenge to relate the coefficients of the GLE to the physical parameters in a real system. Whether varying the coefficients of the GLE can control the solutions in a real system is still an open question. Here our observation demonstrates this possibility. The experimental study can not only give a better understanding of the formation mechanisms of these different pulses in mode-locked lasers but also provide insight into GLE systems. The method is also likely to be applicable to other nonlinear systems governed by the GLE, including vegetation clustering in arid lands, Bose-Einstein condensates in cold atoms, and binary fluid convection. Transitions between different solutions in mode-locked fiber lasers imply similar counterparts in these systems.

II. EXPERIMENTAL DESIGN AND SETUP

DM solitons exist in dispersion-managed cavities. They have been extensively studied in laser cavities around zero net dispersion. However, theoretically they can also be generated with large net positive dispersion [12]. Previously, zero net dispersion was adopted to generate sub-100-fs pulses [13–15]. DM solitons with large positive dispersion are rarely studied. DSs exist in all normal-dispersion cavities and can also be found in dispersion-managed cavities with large net positive dispersion; this has been shown by both theory [16] and experiments [10,17], and can be explained by the stability of DSs under anomalous-dispersion perturbations [16]. As a result, DM solitons and DSs may coexist in a cavity with strong net positive dispersion. Recently, spectrum modulation of DSs caused by modulation instability has been observed and studied [18]. Spectral sidebands are present in the spectrum,

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which limit the pulse duration. The sidebands can be used to measure the cavity dispersion. A method to eliminate the sidebands was also proposed, and nearly pedestal-free pulses were generated.

The GLE can describe various nonlinear systems. Different pulse solutions of the GLE exist, and one was first predicted in Ref. [19]. In terms of mode-locked fiber lasers, the GLE is found to be the governing equation when the laser is mode locked by nonlinear polarization rotation (NPR) [20]. Recently, the equation has been explicitly given as a function of the parameters of the laser [20]:

$$i\psi_z+\frac{D}{2}\psi_{tt}+\psi|\psi|^2 = i\delta\psi+i\beta\psi_{tt}+i\varepsilon\psi|\psi|^2+i\mu\psi|\psi|^4, \tag{1}$$

where ψ is the electric field envelope, z and t denote the distance and retarded time, and D is the net cavity dispersion.

$$\beta = \frac{g_0}{\omega_g^2|\beta_2|}, \tag{2}$$

$$\delta = Lg_0 + \ln|\theta\cos 2\alpha_3 \cos\alpha|, \tag{3}$$

$$\varepsilon = -\frac{1}{3}\sin 2\alpha_2 \tan\alpha, \quad \mu = -\frac{1}{9}\frac{\sin^2 2\alpha_3}{2\cos^2\alpha}, \quad \alpha = 2\alpha_2 - \alpha_1 - \alpha_3, \tag{4}$$

where β_2 is the second-order group-velocity dispersion, g_0 is the linear gain, ω_g is the bandwidth of the gain medium, and α_1, α_2, and α_3 denote the angles between one eigenaxis of each of the plates 1, 2, and 3 and the passing axis of the polarizer [20]. In Eqs. (2) and (3), β denotes the gain dispersion and δ is the net gain. Both of them depend on the linear gain. In experiments the linear gain can be varied by changing the saturation energy of the gain through adjusting the pump power [21], which results in tuning β and $\delta \cdot \varepsilon$ and μ represent cubic and quintic absorption terms, respectively. β, δ, ε, and μ represent dissipative terms [21].

Dissipative terms are not necessary in generating DM solitons [22,23], and the GLE is reduced to the nonlinear Schrödinger equation. The formation mechanism of DM solitons is dominated by the Kerr effect and linear dispersion [22]. When the pump power is increased to a threshold, DM solitons cannot be sustained in the laser due to their limited energy. Increasing the pump power will not amplify the pulse, and background noise becomes appreciable instead, which can distort the pulse. However, it is well known that DSs can contain much larger energy than DM solitons. As a result, DSs can be generated when DM solitons are destroyed, given that the net dispersion is strong for DS generation. In other words, the solution of the GLE is transmitted from DM solitons to DSs whose formation mechanisms are based on nonlinearity, dispersion, and dissipative terms. Thus, there is a pump power threshold for switching from DM solitons to DSs, which can be determined by experiments. A numerical study also implies that DM solitons can be switched to other types of pulse by gain adjustment [6].

Similaritons can be generated by putting an initial pulse of arbitrary intensity profile in an amplifier with normal dispersion [24]. However, in a laser, a filter must be added to make the pulse evolution self-consistent [8,25]. Furthermore, infinite bandwidth of the gain fiber is needed to generate similaritons. A filter can limit the bandwidth of the pulse so that when it propagates in the gain fiber the gain bandwidth can be treated as infinite, and the spectrum of the pulse will resemble that of the similaritons. It has also been confirmed numerically [7] that DSs can be switched to similaritons as long as the spectral width of the DSs is decreased to a threshold value by using a filter. NPR based on fiber components acts not only as a mode locker but also as a tunable spectral filter. The bandwidth induced by the birefringence of the fiber can be changed continuously through tuning polarization controllers (PCs) [26,27], which makes similariton generation possible.

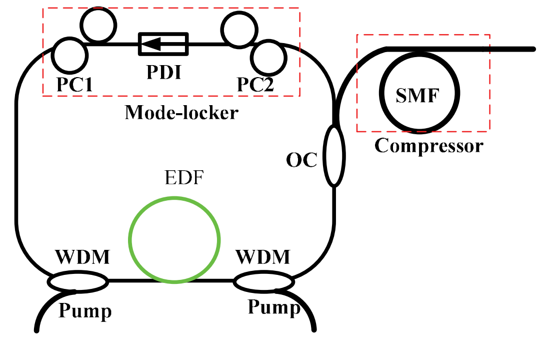

FIG. 1. (Color online) Experimental configuration of the laser.

To meet these requirements, we constructed a fiber laser consisting of segments of anomalous and normal dispersion, but with large net positive dispersion. As shown in Fig. 1, the laser cavity is made of a 250 cm Erbium-doped fiber (EDF) with group-velocity dispersion (GVD) of -51 ps/(nm km) at 1550 nm, which is pumped bidirectionally by two 976 nm laser diodes through two wavelength division multiplexers (WDMs). The 10:90 optical coupler (OC) is used to output the laser signal. For reducing anomalous dispersion, the OC is made of dispersion-shifted fiber (DSF), as is the fiber wrapped around the two PCs. The two WDMs are made of Nufern 980 fiber. The GVD parameters of the fibers are 7 (DSF) and 4.5 (Nufern 980 fiber) ps/(nm km) at 1550 nm. The polarization-dependent isolator (PDI) is pigtailed by a single-mode fiber (SMF) with GVD of 17 ps/(nm km) at 1550 nm. However, the length of SMF is minimized to only 15 cm, and thus the anomalous dispersion of PDI can be neglected. The net dispersion is 0.12 ps^2. In principle, this dispersion parameter can meet the requirement of generating different pulse solutions of the GLE in one mode-locked laser. A compressor made of SMF can be used to compress the pulse through the cutback method.

III. EXPERIMENTAL RESULTS AND DISCUSSION

Mode locking was initiated by NPR. We studied the laser features under a weak light field first. A Gaussian-type spectrum is observed when the laser is mode locked at the pump threshold of 100 mW. Figure 2 is the observed spectrum with 9 nm width and its Gaussian fitting (red dotted line). It is well known that the spectral width of DM solitons decreases with increase in the net dispersion [11,28]. The spectral width (9 nm) is much smaller than that of typical

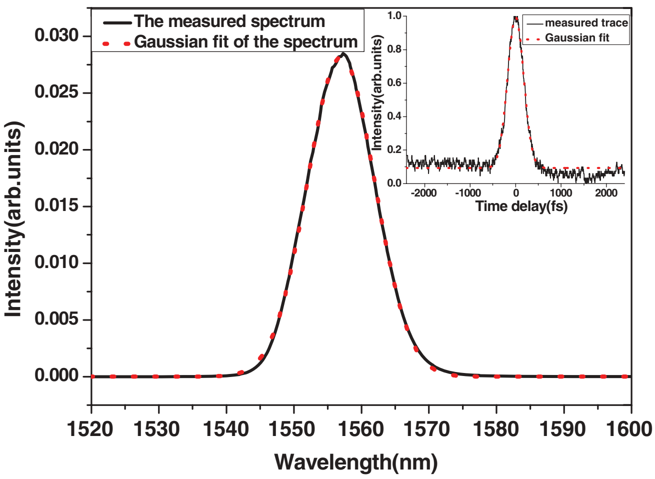

FIG. 2. (Color online) The spectrum and autocorrelation trace (inset) of the DM solitons (solid black line) and the Gaussian fit (dotted red line).

DM solitons (60 nm) as the net dispersion in our laser is nearly an order of magnitude larger than in the usual lasers. The inset of Fig. 2 is the autocorrelation trace, and the pulse duration is 355 fs assuming a Gaussian shape. DM solitons can be distinguished from others by their Gaussian-type spectrum [11]. In Fig. 2, the spectrum is fitted by a Gaussian function quite well, indicating that this is a DM soliton. Furthermore, the time-bandwidth product is 0.4, close to the 0.44 for Gaussian pulses. Theoretically, it has been shown that the spectral width of DM solitons decreases with gain increment [11]; the following experiment also demonstrates this characteristic of DM solitons. The pump power is increased at intervals of 3 mW. Remarkably, as shown in Fig. 3, the spectral width decreases continuously, and the shape is still Gaussian. Noise becomes obvious at about half the maximum pump power. As seen in Fig. 4, the width decreases from 13 to 2 nm when the pump power is tuned from 100 to 315 mW. Further increase in the pump power destroys mode locking, and a continuous wave appears in the spectrum as a spike, as shown in the inset of Fig. 4.

As mentioned above, there is a pump power threshold for switching from DM solitons to DSs. The experiment finds that

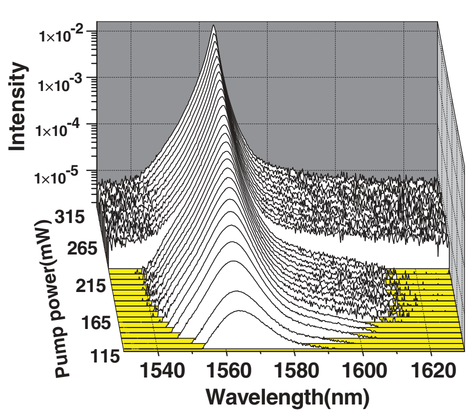

FIG. 3. (Color online) The spectral scaling of DM solitons with pump power.

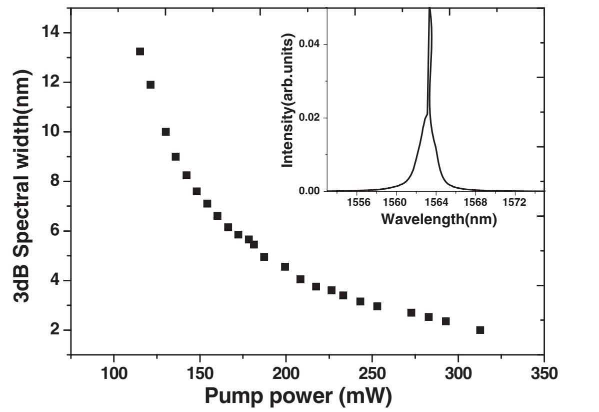

FIG. 4. The spectral width scaling with pump power and the spectrum of the cw (inset).

this threshold is just the one where DM solitons are destroyed at the pump power of 319 mW. Adjusting the PCs can generate another nonlinear wave after the DM solitons are destroyed. Figure 5 shows the spectrum of the observed new nonlinear wave, which is steep at the edges and has a dip in the top. Such a spectrum is characteristic of DSs [10,29]. The pump power of 319 mW is the threshold of the transition between DM solitons and DSs. In other words, it is the critical value that makes the governing equation of the laser system change from the nonlinear Schrödinger equation to the GLE. The inset of Fig. 5 shows the autocorrelation trace of the DS pulses. The pulse width is 192 fs after compression by the SMF. The second maximum in the trace is caused by third-order dispersion.

Kalashnikov and Apolonski [9] and Cabasse *et al.* [10] theoretically predicted that the spectral width of a DS increases with increase in the pump power. Clearly, the experimental result in Fig. 6 proves this conclusion. The spectral width increases with pump power increment without changing shape, which is opposite to the case of DM solitons. Comparing these different features of DSs and DM solitons, we get a qualitative understanding about them. The light field gets stronger as the pump power increases, which causes DM solitons to switch to DSs. However, due to the stability of DM solitons, they can be broadened in the time domain to decrease the peak intensity

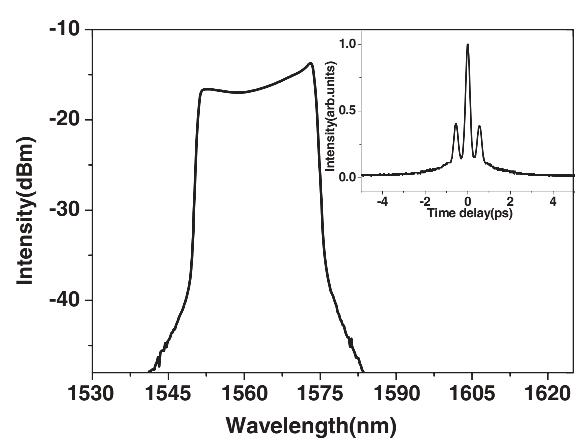

FIG. 5. The spectrum and autocorrelation trace (inset) of the DS.

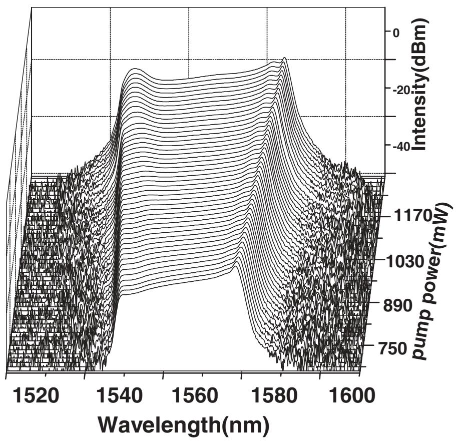

FIG. 6. Pulse spectrum of DS scaling with pump power.

through narrowing the spectral width. Thus, the spectral width of DM solitons decreases with increase in the pump power. The minimum spectral width of a DS in the laser is about 25 nm; they are much wider than DM solitons (13 nm maximum). This indicates that gain dispersion becomes more important than DM solitons in the pulse-shaping mechanism [10], considering the gain bandwidth of the EDF (30 nm). Gain dispersion as well as other dissipative terms cannot be neglected; they play important roles in DS generation.

The fiber components used to form NPR mode-locking technology also constitute a filter with tunable bandwidth. On slightly tuning one PC paddle clockwise (counterclockwise), the spectral width increases (decreases) without changing shape when a DS is generated. Remarkably, when the spectral width of a DS decreases to a certain value (∼30 nm), the spectral shape suddenly changes, as shown in Fig. 7 (solid black line). Compared to the spectrum of the DS, the dip in the top is shallower and the steep edges become smoother. Considering the formation mechanism, this may be an amplifier similariton. In Fig. 7, the spectrum is well fitted by a parabolic function (the dotted red line). The parabolic spectrum is the distinguishing shape of similaritons [8,30–33].

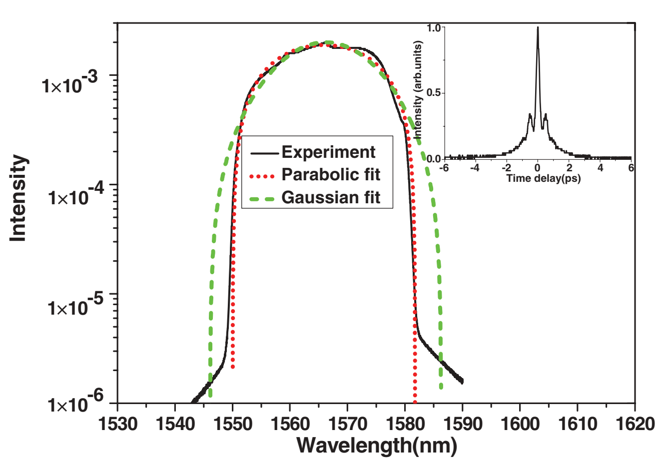

FIG. 7. (Color online) The measured spectrum of similaritons (solid black line), and Gaussian (dashed green line) and parabolic (dotted red line) fits. The inset shows the autocorrelation trace.

A Gaussian fitting (the dashed green line) is also present for comparison. We thus claim that the pulses are similaritons. The inset of Fig. 7 shows the autocorrelation trace, and the pulse width is 197 fs. It should be noted that the gain in the amplifier also plays an important role in similariton generation [34]. Decreasing the spectral width of the DS to a minimum by PC tuning will not generate similaritons if the total pump power is lower than a certain threshold value (backward pump 49 mW, forward pump 546 mW). However, if the pump power is then increased above the threshold, DSs change to similaritons without PC adjustment. Thus, we have experimentally demonstrated that both the gain of the amplifier and the bandwidth of the filter play important roles in generating similaritons, which is consistent with the theoretical studies [34,35].

Finally, different solutions of the GLE are observed in a laser. DM solitons governed by the nonlinear Schrödinger equation occur in integrable systems. DSs and similaritons occur in dissipative systems. Transitions between them indicate that integrable and dissipative systems can be switched from one to the other in a laser. A numerical study showed that the two systems can be switched by parameter scaling in an equation [36], as has been demonstrated in this experiment. In terms of passive mode locking, our study shows that switching between different operational regimes of mode locking can occur in a mode-locked fiber laser. The pump power, linear phase-delay bias, and the birefringence of the fiber play important roles in the switching. These parameters should be taken seriously in mode-locked fiber lasers.

Pulses of different intensity profiles were found in separate systems previously, but the relations between them are unclear. Our study demonstrates that different pulses are indeed related to each other. Additionally, in all anomalous-dispersion regimes, two types of pulse have been found to date. One is the sech soliton, and the other is the square soliton [1,37,38] which is a kind of DS. Previously, they were generated in different laser systems. Guided by our study, they may also be generated in the same laser. This work is currently under way.

IV. CONCLUSION

In conclusion, we observe three type of pulses in a mode-locked fiber laser. The different formation mechanisms of pulses are shown in the same laser. Our study demonstrates some properties of GLEs, and shows experimentally that the coefficients of the GLE can be controlled to make the laser transfer between different solutions in the same system, which will stimulate and perhaps clarify the corresponding studies in other systems governed by GLEs. Furthermore, that the three different kinds of pulse can be emitted in just one laser makes the laser very attractive for applications.

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