280 GHz dark soliton fiber laser

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We report on an ultrahigh repetition rate dark soliton fiber laser. We show both numerically and experimentally that by taking advantage of the cavity self-induced modulation instability and the dark soliton formation in a net normal dispersion cavity fiber laser, stable ultrahigh repetition rate dark soliton trains can be formed in a dispersion-managed cavity fiber laser. Stable dark soliton trains with a repetition rate as high as ~280 GHz have been generated in our experiment. Numerical simulations have shown that the effective gain bandwidth limitation plays an important role on the stabilization of the formed dark solitons in the laser.

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Since first predicted in 1973 [1], the dark soliton formation in single mode fibers (SMFs) has been extensively investigated [2]. Like the bright soliton formation in the anomalous dispersion SMFs, the dark soliton formation is an intrinsic feature of the nonlinear light propagation in the normal dispersion SMFs. It is a result of the natural balance between the fiber dispersion and the nonlinear Kerr effect. However, numerically as well as theoretically it was shown that the dark soliton propagation in SMFs is less sensitive to noise and fiber losses than the bright solitons [3,4]. The dark solitons are promising for future optics telecommunication and optical signal processing applications.

The dark soliton formation in SMFs was first experimentally observed by Emplit *et al.* [5]. Weiner *et al.* reported experimental observation of dark soliton formation initialed either by an odd-symmetry or an even-symmetry dark pulse [6]. Taking advantage of the dark soliton formation and stability in the normal dispersion SMFs, various techniques for the generation of highrepetition rate dark soliton trains were also proposed [7–9]. Richardson *et al.* have demonstrated 100 GHz repetition rate dark soliton train generation in a dispersion decreasing fiber (DDF) through the nonlinear conversion of a beat signal [7]. Based on the same principle, Atieh *et al.* proposed to use a comb-like dispersion profile fiber structure to replace the DDF, to overcome the manufacturing problem of the DDF. They demonstrated the generation of a dark soliton train with a 47.6 GHz repetition rate [8]. Sylvestre *et al.* generated stable high-repetition rate dark soliton trains in a fiber laser using the dissipative four-wave mixing method. They used a Fabry–Perot (FP) filter together with a bandpass filter in their fiber laser to achieve the dissipative four-wave mixing, and generated dark soliton pulses with a repetition rate of ~15 GHz, which was determined by the free spectral range of the FP filter used [9]. Recently, Zhang and co-workers also reported dark soliton formation in an all-normal dispersion fiber laser [10,11]. However, due to the thresholdless feature of the dark soliton formation, the dark solitons were randomly formed and the number of dark solitons in the cavity was uncontrolled.

In this Letter we report a novel technique for the generation of ultrahigh repetition rate dark soliton trains in a fiber laser. Ultra-high repetition rate bright soliton fiber lasers were reported previously [12,13]. The key for generating high repetition rate pulses in the fiber lasers is the self-induced modulation instability (MI) effect. Although there is no MI in the normal dispersion SMFs, due to the cavity effect self-induced MI could still occur in normal dispersion fiber cavities [14]. Here we propose to use a dispersion-managed fiber laser with a net normal dispersion cavity to generate ultrahigh repetition rate dark soliton trains. We found numerically that using the combined effect of the cavity-induced MI and the dark soliton formation in a net normal dispersion cavity fiber laser, not only could high repetition rate dark solitons be formed, but also the formed dark soliton trains are stable if the effective gain bandwidth of the laser is appropriately selected. With this technique we have experimentally successfully generated stable dark soliton trains with a 280 GHz repetition rate.

We first show the working principle of the proposed technique numerically. The light circulation in a unidirectional fiber ring cavity is governed by the following equation [15]:

$$i\frac{\partial u}{\partial z} - \frac{\beta_2}{2}\frac{\partial^2 u}{\partial t^2} + \gamma|u|^2 u - i\frac{g}{2}u - i\frac{g}{2\Omega_g^2}\frac{\partial^2 u}{\partial t^2} = 0, \qquad (1)$$

where u is the slowly varying amplitude of the light field, β_2 is the average cavity dispersion parameter, γ is the nonlinearity of the fiber, g is the effective laser gain coefficient, and Ω_g is the effective bandwidth of the laser gain. To derive the equation it has been assumed that the light field is in resonance with the cavity and the cavity length is far shorter than the dispersion and nonlinear length of the light in the cavity. The gain saturation of the laser is described by

$$g = \frac{g_0}{1 + \int |u|^2 \mathrm{d}t / E_s}, \qquad (2)$$

where g_0 is a small signal gain and E_s is the saturation energy. For the simplicity of numerical simulations, the above equation is further normalized with $L_{\mathrm{NL}} = 1/\gamma P_0$, $L_d = T_0^2/|\beta_2|$, $U\sqrt{P_0} = u$, $\eta = \mathrm{sgn}(\beta_2)$, $\xi = z/L_d$, $\tau = t/T_0$, $N^2 = L_d/L_{\mathrm{NL}} = 1$. Eq. (1) then has the form:

$$i\frac{\partial U}{\partial \xi}-\frac{\eta}{2}\frac{\partial^2 U}{\partial \tau^2}+|U|^2U-i\frac{G}{2}U-i\frac{G}{2\Omega^2}\frac{\partial^2 U}{\partial \tau^2}=0, \qquad (3)$$

where $G=gL_d=g_0L_d/(1+\int|U|^2\mathrm{d}\tau/I_s)$, $\Omega=\Omega_gT_0$, $I_s=E_s/(P_0T_0)$ are the normalized gain coefficient, bandwidth, and saturation energy, respectively.

Equation (3) has exactly the same form as the extended Ginzburg–Landau equation. Hence it is easy to understand that as far as the net cavity dispersion is in the normal dispersion regime, an intensity dip in the cavity will eventually evolve into dark solitons [6]. In a fiber laser there are plenty of sources that could generate such an initial intensity dip. Therefore, uncontrolled dark soliton generation always occurs in the laser cavity, which causes complicated dark soliton operation of a fiber laser [11].

The challenge now is how to generate controlled dark soliton formation in a fiber laser and stabilize the formed dark solitons. We found that by using a dispersion-managed cavity fiber laser with net normal cavity dispersion and appropriately selecting the effective gain bandwidth, stable high repetition rate dark soliton trains could be generated. A dispersion-managed cavity is made of both normal and anomalous dispersion fibers. Due to the average low cavity dispersion the self-induced MI has a low threshold [13]. The MI introduces an initial high frequency intensity modulation on the light circulating in the cavity. As the light is circulating in a net normal dispersion fiber cavity, based on Eq. (3), instead of forming an ultrahigh repetition rate bright soliton train, the intensity modulation will be shaped into an ultrahigh repetition rate dark soliton train.

To validate the above analysis we have numerically simulated such an MI dark soliton fiber laser. We considered an unidirectional ring fiber cavity made of a piece of 3 m erbium-doped fiber with a group velocity dispersion (GVD) parameter of −48 ps/km/nm, and a piece of the standard SMF with a group velocity GVD parameter of 18 ps/km/nm. The averaged cavity dispersion parameter is $\beta_2=0.65\ \mathrm{ps}^2/\mathrm{km}$, and $\gamma=3\ \mathrm{W}^{-1}\,\mathrm{km}^{-1}$. We choose $T_0=1$ ps, $P_0=0.2$ W, $\Omega=3.75$, which refers to a 30 nm gain bandwidth, and $E_s=2$ pJ. Through appropriately setting the linear cavity losses and the gain parameter, a stable operation state of the fiber laser can always be obtained. We then simulated the MI effect of the cavity by artificially introducing a weak field of $U(0,\tau)=U_0\cos(2\pi\Delta\nu)$ as an initial perturbation. It was found numerically that if the gain bandwidth is appropriately selected, a stationary dark-pulse train is automatically formed in the cavity. Figure 1 shows a typical result numerically obtained.

Figures 1(a) and 1(b) show the temporal intensity and phase profile of the stationary dark-pulse train formed. The phase of the dark-pulse train reveals a π phase jump in the center of each pulse, which indicates that the dark pulses are dark soliton. The autocorrelation trace of the dark-pulse train is shown in Fig. 1(c). We note that a similar equation was used by Sylvestre *et al.* to simulate the dark soliton train formation in their fiber laser and similar results were also obtained [8]. However, we need it to point out that the working principle of the two systems is different. Unlike the results of Sylvestre *et al.*, where the

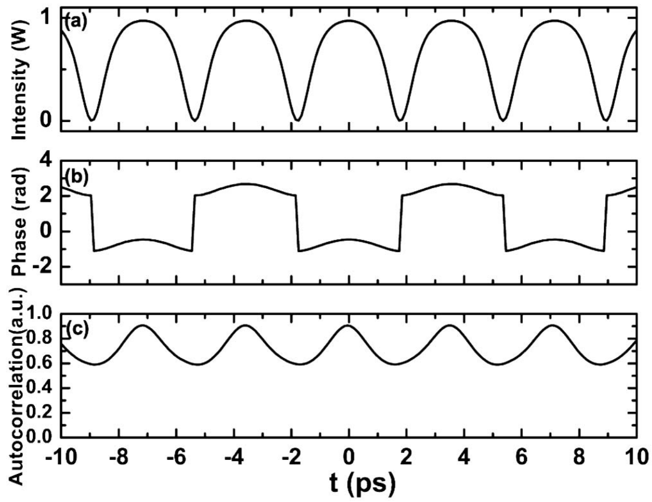

Fig. 1. Numerically calculated (a) temporal intensity, (b) phase profile, and (c) corresponding autocorrelation trace of the dark pulse train. $U_0=0.1$, $\Delta\nu=0.14$, $G=400$, and cavity loss is 10%.

four-wave mixing between two optical fields was used to generate the dark pulses, we have used the self-induced MI of the cavity. In addition, there was no physical bandpass filter in our cavity. Instead the effective gain bandwidth of the erbium-doped fiber played the role in our laser. In the numerical simulation we noticed that even without the gain bandwidth limitation, dark pulses could still be formed. However, the pulses are unstable. Their intensities vary periodically with the propagation distance. Under the effective gain bandwidth limitation, a stable dark soliton train could always be formed. The result indicates that the dark solitons are a kind of dissipative dark soliton. In Fig. 2(d), we also showed the corresponding spectrum of the stationary pulse train shown in Fig. 1(a). It shows that a large number of harmonics are generated.

Guided by the numerical simulation, we further designed an erbium-doped dispersion-managed cavity fiber laser as shown in Fig. 3. The fiber laser had a dispersion-managed cavity with a length of 15.6 m. Among the cavity

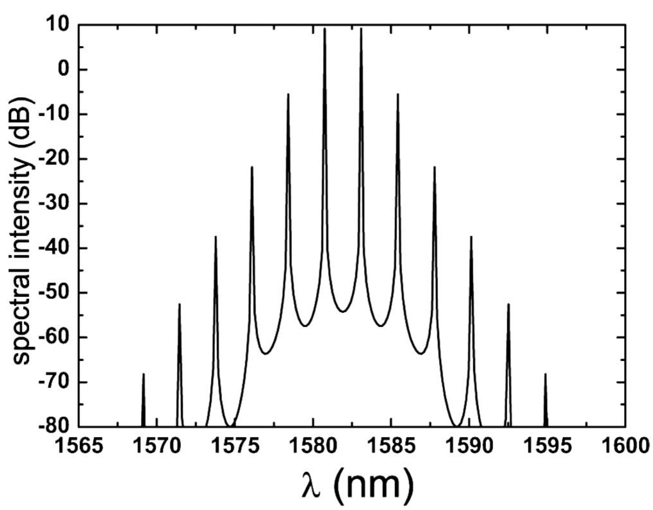

Fig. 2. Optical spectrum (central wavelength, 1582 nm) of the dark pulse train shown in Fig. 1(a).

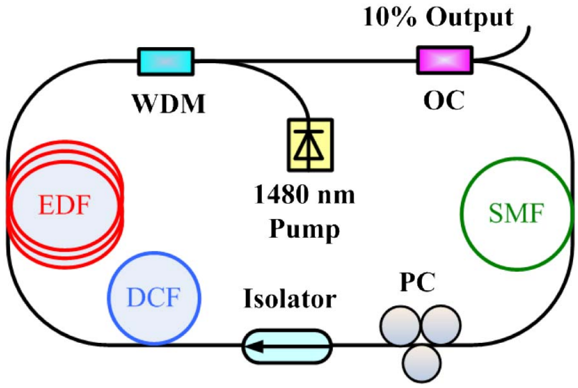

Fig. 3. Schematic of the fiber laser. SMF, single-mode fiber; DCF, dispersion compensating fiber; PC, polarization controller; EDF, erbium-doped fiber; WDM, wavelength-division multiplexer; OC, optical coupler.

fibers a piece of 3 m erbium-doped fiber (OFS80) with a GVD parameter of −48 ps/nm/km was used as the gain medium. To reduce the MI threshold, a segment of standard SMF with a GVD parameter of 18 ps/nm/km was added into the cavity. In addition, 4.1 m dispersion shifted fiber with a GVD parameter of −4 ps/nm/km was added into the cavity to make sure that the total cavity operates in the normal dispersion regime. A polarization independent isolator was employed in the cavity to force the unidirectional operation of the ring cavity, and an intracavity polarization controller (PC) was used to fine tune the linear cavity birefringence. A 10% output coupler was used to output the laser emission. The laser was pumped by a high power fiber Raman laser source (KPS-BT2-RFL-1480-60-FA) of wavelength 1480 nm. The pump laser can deliver a maximum pump power as high as 5 W.

We have operated the fiber laser in the single polarization emission state. This was achieved experimentally through appropriately setting the orientation of the intracavity PC. Under strong intracavity light intensity due to the polarization instability effect the laser then oscillated in a single polarization state. Experimentally it was observed that the self-induced MI appeared at a pump power of ~1 W, characterized by the appearance of weak spectral modulations on the optical spectrum. The spectral modulation frequency varied with the intracavity light intensity. At a pump power of 2 W, which corresponds to ~500 mW intracavity power, a state of stable high repetition rate dark pulse train was obtained, as shown in Fig. 4. Figure 4(a) shows the intensity autocorrelation trace of the dark pulse train. Stable autocorrelation pulses are visible on top of a strong continuous wave background and the pulse train is over the whole scan range of the autocorrelator, which is typical for the high repetition rate dark pulses [7,9]. Based on the measured autocorrelation trace the dark pulse train had a repetition rate of ~285 GHz. The FWHM of the autocorrelation pulses is ~1.4 ps. If a sech^2 pulse profile is assumed, the dark pulse has a width of ~910 fs. Figure 4(b) shows the corresponding optical spectrum. The separation of the adjacent spectral peaks is $\Delta\nu = 280$ GHz, which coincides with the result obtained from the autocorrelation trace. Like the numerically calculated optical spectrum,

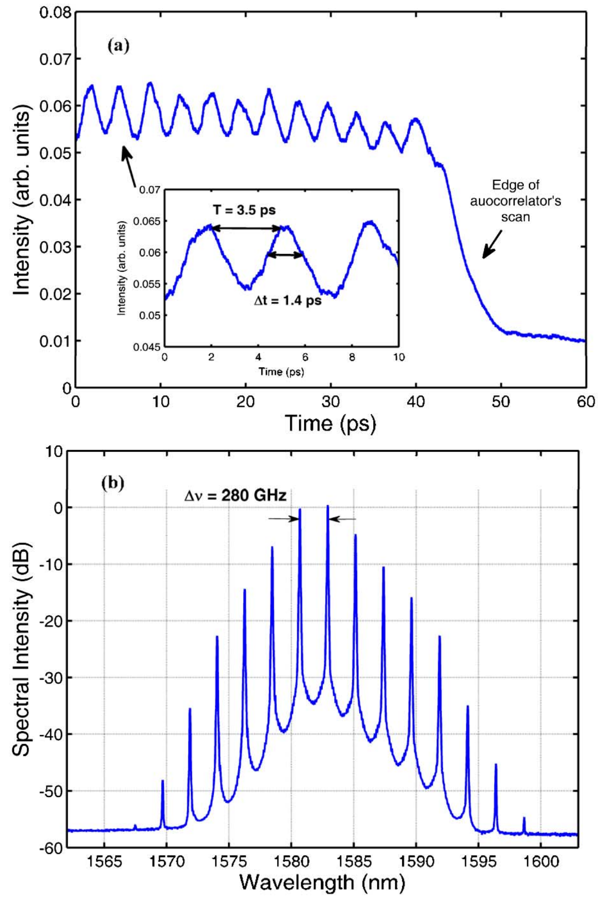

Fig. 4. (a) Measured autocorrelation trace of the dark soliton pulse train. Inset: zoom-in of the autocorrelation trace; (b) the corresponding optical spectrum.

the experimentally measured spectrum shows an obviously symmetric profile, which is a characteristic of the dark soliton trains formed in fiber lasers [7,9].

The frequency of maximum gain in an MI process is given by [15]

$$\Omega_M^2 = \frac{2\gamma P_0}{|\beta_2|}, \tag{4}$$

where P_0 is the average power. Taking $\beta_2 = 0.65\ \mathrm{ps}^2/\mathrm{km}$, $\gamma = 2\ \mathrm{W}^{-1}\ \mathrm{km}^{-1}$ and $P_0 = 500$ mW in our laser, the estimated MI frequency is $\nu_m = 279$ GHz, which is well in agreement of the measured ~280 GHz. In our experiment the high repetition rate dark soliton train was very stable. Once formed, the state could be maintained for hours. When the pump power was changed, stable dark soliton trains with other repetition rates were also experimentally obtained, which shows that it is an intrinsic feature of the fiber laser.

In summary, we have proposed a novel method to generate a stable high repetition rate dark soliton train in a fiber laser. Our approach is based on the combined effects of cavity self-induced MI, the dark soliton formation in a net normal dispersion fiber cavity, and the dark soliton train stabilization by the effective gain bandwidth effect. Preliminary experimental study has demonstrated stable 280 GHz dark soliton trains. We believe such an ultrahigh repetition rate dark soliton train may find practical applications in optical communications systems and optical signal processing systems.

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References

1. A. Hasegawa and F. Tappert, Appl. Phys. Lett. **23**, 171 (1973).
2. Y. S. Kivshar, IEEE J. Quantum Electron. **29**, 250 (1993).
3. W. Zhao and E. Bourkoff, Opt. Lett. **14**, 703 (1989).
4. Y. Chen and J. Atai, Opt. Lett. **16**, 1933 (1991).
5. P. Emplit, J. P. Hamaide, F. Reynaud, C. Froehly, and A. Barthelemy, Opt. Commun. **62**, 374 (1987).
6. A. M. Weiner, J. P. Heritage, R. J. Hawkins, R. N. Thurston, E. M. Kirschner, D. E. Leaird, and W. J. Tomlinson, Phys. Rev. Lett. **61**, 2445 (1988).
7. D. J. Richardson, R. P. Chamberlin, L. Dong, and D. N. Payne, Electron. Lett. **30**, 1326 (1994).
8. A. K. Atieh, P. Myslinske, J. Chrostowski, and P. Galko, Opt. Commun. **133**, 541 (1997).
9. T. Sylvestre, S. Coen, P. Emplit, and M. Haelterman, Opt. Lett. **27**, 482 (2002).
10. H. Zhang, D. Y. Tang, L. M. Zhao, and X. Wu, Phys. Rev. A **80**, 045803 (2009).
11. D. Y. Tang, L. Li, Y. F. Song, L. M. Zhao, H. Zhang, and D. Y. Shen, Phys. Rev. A **88**, 013849 (2013).
12. E. Yoshida and M. Nakazawa, Opt. Lett. **22**, 1409 (1997).
13. C. J. S. de Matos, D. A. Chestnut, and J. R. Taylor, Opt. Lett. **27**, 915 (2002).
14. M. Haelterman, S. Trillo, and S. Wabnitz, Opt. Lett. **17**, 745 (1992).
15. G. P. Agrawal, *Nonlinear Fiber Optics* (Academic, 2007).