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Enhanced stability of dispersion-managed mode-locked fiber lasers with near-zero net cavity dispersion by high-contrast saturable absorbers

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We experimentally investigate the stability of dispersion-managed mode-locked fiber lasers using carbon-nanotube-based saturable absorbers (SAs) with different modulation depths. An unstable operation region of the mode-locked fiber laser with near-zero net cavity dispersion is observed, where the laser produces random pulse burst rather than stable pulse train. Through the implementation of high-contrast SAs in the laser, the unstable region is found to be shrunk by ~31.3% when the modulation depth of the SAs increases from 6.4% to 12.5%. The numerical simulation is consistent with the experimental observation. © 2013 Optical Society of America

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Passively mode-locked fiber lasers have emerged as one of the best pulsed light sources for a broad range of applications, including optical communication, frequency metrology, microscopy, and micromachining [1]. In particular, dispersion-managed mode-locked fiber lasers consisting of anomalously or normally dispersive fibers present an attractive design to produce stretched pulses with excellent performance [2–4]. Previous reports have demonstrated that the best performance of output pulses, in terms of large spectral bandwidth and low timing jitter, can be achieved by managing the net cavity dispersion ($\beta_{\text{net}}^{(2)}$) of the fiber laser approaching zero [5–8]. In a dispersion-managed mode-locked fiber laser, the spectral filtering induced by the limited gain bandwidth plays an important role as the spectrum broadens when $\beta_{\text{net}}^{(2)}$ approaches zero, which affects the laser stability [9]. Since the loss experienced by the pulse with a large spectral bandwidth is greater than that by continuum wave (CW) due to spectral filtering, CW could break through the pulse and cause instabilities [10]. Numerical studies have figured out that there is an unstable region in 1.55- μm dispersion-managed mode-locked fiber lasers near zero $\beta_{\text{net}}^{(2)}$, where stable output pulses cannot be obtained [11]. Such an unstable region is also found in reported experimental works, and this limits the achievement of stable mode-locking with $\beta_{\text{net}}^{(2)}$ toward zero [9,12,13]. One solution to compensate for such spectral filtering loss is to adopt saturable absorbers (SAs) with more absorption to CW than to high-intensity pulses in the laser cavities [10]. Theoretical studies have predicted that SAs with large modulation depth can assist fiber lasers in obtaining stable mode-locking around zero $\beta_{\text{net}}^{(2)}$ [14]. However, it is not yet experimentally or numerically confirmed how much of $\beta_{\text{net}}^{(2)}$ can be pushed toward zero $\beta_{\text{net}}^{(2)}$ for stable mode-locking by SAs with different modulation depths.

For the investigation of the influence of the SAs on mode-locked fiber lasers, semiconductor-based SAs are one of the good candidates to obtain mode-locked fiber lasers with predefined modulation depth and stable

operation [14–17]. Recently, it has been shown that dispersion-managed mode-locked fiber lasers incorporating carbon-nanotube-based SAs (CNT-SAs) can generate pulses with a pulse width of ~74 fs and a spectral bandwidth of ~63 nm when $\beta_{\text{net}}^{(2)}$ is -0.003 ps^2 [18]. In this Letter, we experimentally investigate the stability of a dispersion-managed mode-locked fiber laser with $\beta_{\text{net}}^{(2)}$ near zero using CNT-SAs with different modulation depths. Experimental results show that the unstable region of the laser could be shrunk by ~31.3% when the modulation depth of the SA increases from 6.4% to 12.5%. Numerical analysis is also performed to investigate the dispersion-managed mode-locked fiber laser with different modulation depths of SAs, which is consistent with the experimental observation. The obtained results are not merely applicable to dispersion-managed mode-locked fiber lasers incorporating CNT-SAs, but also could be a general guidance for lasers using similar kinds of SAs.

Figure 1 shows the experimental setup of a dispersion-managed mode-locked fiber laser incorporating CNT-SAs. The 7.32 m long erbium-doped fiber (EDF) with group velocity dispersion parameter ($\beta^{(2)}$) of $+23.4 \text{ ps}^2/\text{km}$ is pumped by a 976 nm pump laser via a 980/1550-nm wavelength division multiplexing

Fig. 1. Experimental setup of dispersion-managed mode-locked fiber laser incorporating CNT-SA. WDM coupler, wavelength division multiplexing coupler; EDF, erbium-doped fiber; PC, polarization controller; SMF, single-mode fiber.

(WDM) coupler. The EDF has a mode field diameter of $\sim 5.9 \mu\text{m}$ and a peak absorption of $\sim 6 \text{ dB/m}$ at 1530 nm . The WDM coupler comes with a 0.66 m long HI1060 fiber pigtail with $\beta^{(2)}$ of $+20 \text{ ps}^2/\text{km}$. A polarization-insensitive optical isolator is applied to ensure unidirectional propagation of the light in the cavity. The 80/20 coupler extracts 20% of the optical power from the laser cavity as the laser output. A fiber-based polarization controller (PC) is included for optimizing the mode-locking condition. The CNT-SA is constructed by connecting two fixed connection/physical contact connector ends, in which one of the connector ends is deposited with CNTs by an optically driven deposition method [19]. The CNTs are prepared by a bulk production method called high-pressure CO conversion, and are well dispersed in dimethylformamide solvent through the purification process [20]. Two CNT-SAs with modulation depths of 12.5% and 6.4% are employed in this Letter, exhibiting nonsaturable losses of 47% and 28.1%, respectively. $\beta_{\text{net}}^{(2)}$ is changed ranging from -0.31 to $+0.04 \text{ ps}^2$ by shortening the length of standard single mode fiber (SMF) in the laser cavity.

Figure 2(a) shows the measured spectra of the developed fiber laser incorporating CNT-SA with modulation depth of 12.5%. When the laser operates with net anomalous dispersion ($\beta_{\text{net}}^{(2)} = -0.297 \text{ ps}^2$), the self-started mode-locking can be achieved at a relatively low pump power of $\sim 4 \text{ mW}$. The strong Kelly sidebands are superimposed on the spectrum, which indicates that the laser operates in the conventional soliton regime [21]. The single pulse generation is confirmed by the corresponding RF spectrum as well as the autocorrelation trace. Such laser produces pulses with pulse width of $\sim 640 \text{ fs}$, spectral bandwidth of $\sim 4.9 \text{ nm}$, and single-pulse energy of $\sim 14 \text{ pJ}$. When the relative amount of negative to positive dispersion fiber is reduced by shortening the length of the SMF ($\beta_{\text{net}}^{(2)} = -0.158 \text{ ps}^2$), the Kelly sidebands are found to gradually move away from the center

wavelength while the spectrum turns into a Gaussian-like shape associated with spectrum broadening. The relatively clean spectrum indicates that the laser transits into the dispersion-managed soliton regime (or stretched-pulse) [2]. The laser produces pulses with pulse width of $\sim 450 \text{ fs}$, spectral bandwidth of $\sim 6.8 \text{ nm}$, and single-pulse energy of $\sim 11.2 \text{ pJ}$ under pump power of $\sim 4 \text{ mW}$. By further increasing $\beta_{\text{net}}^{(2)}$ to -0.114 ps^2 , the spectrum changes to a nearly triangular shape, showing a weak CW spike on the center wavelength. Under this condition, the laser only produces the random pulse burst, rather than the stable pulse train, no matter how the pump power and the state of the PC are adjusted. When $\beta_{\text{net}}^{(2)}$ is increased to be normal dispersion ($\beta_{\text{net}}^{(2)} = +0.029 \text{ ps}^2$), a spectrum with a rectangular shape can be observed by adjusting the PC under pump power of $\sim 17 \text{ mW}$. The laser generates pulses with pulse width of $\sim 50 \text{ ps}$, spectral bandwidth of $\sim 8.6 \text{ nm}$, and single-pulse energy of $\sim 86 \text{ pJ}$. The pulse width can be further compressed outside the laser cavity to $\sim 870 \text{ fs}$ using an SMF with an optimized length of $\sim 536 \text{ m}$. The steep edges of the spectrum and the highly chirped pulse imply that the mode-locked fiber laser operates in the dissipative soliton regime [22].

For comparison, the experiment is repeated using the same fiber laser incorporating a CNT-SA with modulation depth of 6.4%, as shown in Fig. 2(b). The operation of the laser transits from the conventional soliton with relatively large net anomalous dispersion ($\beta_{\text{net}}^{(2)} = -0.301 \text{ ps}^2$) into the dissipative soliton with net normal dispersion ($\beta_{\text{net}}^{(2)} = +0.039 \text{ ps}^2$), while tending to be unstable as $\beta_{\text{net}}^{(2)}$ approaches zero ($\beta_{\text{net}}^{(2)} = -0.165 \text{ ps}^2$). Figure 3(a) plots the spectral bandwidth against net cavity dispersion for lasers with two different CNT-SAs. When the absolute value of $\beta_{\text{net}}^{(2)}$ is close to zero, the spectral bandwidth gradually increases and then sharply decreases. The significant decrease in the spectral bandwidth is a reflection of the unstable operation of the laser. For the fiber laser incorporating the CNT-SA with modulation depth of 6.4%, the unstable region is found to be in the range of $-0.233 \text{ ps}^2 < \beta_{\text{net}}^{(2)} < +0.039 \text{ ps}^2$. On the other hand, for the case of CNT-SA with modulation depth of 12.5%, the unstable region of the laser is measured in the range of $-0.158 \text{ ps}^2 < \beta_{\text{net}}^{(2)} < +0.029 \text{ ps}^2$. The results show that

Fig. 2. Experimental results of the output spectra of dispersion-managed mode-locked fiber lasers with different net cavity dispersion using CNT-SAs with modulation depths of (a) 12.5% and (b) 6.4%.

Fig. 3. Plots of output for (a) spectral bandwidth and (b) pulse width against net cavity dispersion of dispersion-managed mode-locked fiber lasers using CNT-SAs with different modulation depths.

the unstable region in the dispersion-managed mode-locked fiber laser could be shrunk by $\sim 31.3\%$ when the modulation depth of SAs increases from 6.4% to 12.5%. Figure 3(b) shows the pulse width versus $\beta_{\text{net}}^{(2)}$ in the net anomalous dispersion region. The pulse width decreases as $\beta_{\text{net}}^{(2)}$ approaches zero. The shortest pulse width is obtained around 450 fs, with $\beta_{\text{net}}^{(2)}$ of -0.158 ps^2 , when the CNT-SA with modulation depth of 12.5% is applied.

Numerical simulation is performed to qualitatively analyze the role of SAs in dispersion-managed mode-locked fiber lasers. The numerical model is similar to the experimental setup shown in Fig. 1. A piece of gain fiber is connected to a HI1060 fiber. The length of SMF after the SA is adjusted to manage $\beta_{\text{net}}^{(2)}$. Light propagation within each fiber section can be modeled by the modified nonlinear Schrödinger equation [23],

$$\frac{\partial A(\xi, T)}{\partial \xi} + \frac{i}{2} \left(\beta_{\text{net}}^{(2)} + ig \frac{1}{\Omega_g^2} \right) \frac{\partial^2 A(\xi, T)}{\partial T^2} = i\gamma |A(\xi, T)|^2 A(\xi, T) + \frac{g}{2} A(\xi, T), \quad (1)$$

where $A(\xi, T)$ is the envelope of the field, ξ is the propagation coordinate, T is the time scaled to the pulse duration, $\beta_{\text{net}}^{(2)}$ is the group velocity dispersion parameter, γ is the nonlinear parameter, and Ω_g is the gain bandwidth. The gain g is given by

$$g = g_0 / (1 + P_{\text{ave}} / P_{\text{sat}}), \quad (2)$$

where g_0 is the small signal gain, P_{sat} is the gain saturation power, and P_{ave} is the average power of the pulse train. The intensity-dependent transmittance $T(I)$ of the SA is expressed by

$$T(I) = 1 - (a_0 / (1 + I / I_{\text{sat}}) + a_{\text{ns}}), \quad (3)$$

where I is the instantaneous intensity of the pulse, I_{sat} is the saturation intensity of SA, a_{ns} refers to the nonsaturable loss, and a_0 is the modulation depth, which also accounts for transmission contrast of SAs. Provided that L refers to the fiber length and i denotes each fiber section, the net cavity dispersion $\beta_{\text{net}}^{(2)}$ can be given by

$$\beta_{\text{net}}^{(2)} = \sum_i L_i \times \beta_i^{(2)}. \quad (4)$$

The cavity parameters used in the simulation are summarized in Table 1. The gain bandwidth is $\Omega_g = 5.5 \text{ THz}$. In order to investigate specifically the influence of the modulation depth on the stability of dispersion-managed mode-locked fiber lasers, only a_0 and L_{SMF} are changed

Table 1. Summary of Simulation Parameters^a

Fiber Type	$\beta_{\text{net}}^{(2)}$ (ps ² /km)	γ (W ⁻¹ km ⁻¹)	L (m)	g_0	P_{sat} (mW)
EDF	+23.4	2.69	7.32	2	5
HI1060	+20	1.5	0.66	0	0
SMF	-22	1.06	Var.	0	0

^aEDF, erbium-doped fiber; SMF, single-mode fiber; Var., variable.

while the other parameters are kept constant. I_{sat} is set to be 10 MW/cm^2 , referring to the typical value of CNT-based SAs [24]. a_{ns} is assumed to be 15%, corresponding to the minimum nonsaturable loss of CNT-SAs with a desirable modulation depth obtained in our experiments [19]. The numerical model is solved with a standard split-step Fourier algorithm.

Figure 4 shows the numerical results of the laser with $a_0 = 12.5\%$ at different $\beta_{\text{net}}^{(2)}$. For $\beta_{\text{net}}^{(2)} = -0.172 \text{ ps}^2$, the Kelly sidebands are superimposed on the spectrum as shown in Fig. 4(a), which could be explained by the periodic perturbations such as gain, filtering, and loss [21]. Figure 4(e) shows the corresponding pulse fitted by a sech^2 -profile, which exhibits a negligible frequency chirp across the duration. Such chirp-free pulse is a result of the phase cancellation between the anomalous dispersion and the self-phase modulation. For $\beta_{\text{net}}^{(2)} = -0.028 \text{ ps}^2$, the spectrum exhibits a wide spectral bandwidth as illustrated in Fig. 4(b). The corresponding pulse shows a Gaussian profile with a short pulse width and a purely linear frequency chirp as given in Fig. 4(f). The up-chirp is due to the output after the normal dispersion gain fiber. Further increasing $\beta_{\text{net}}^{(2)}$ to $+0.02 \text{ ps}^2$, an output spectrum with steep edges can be observed, as shown in Fig. 4(c). The corresponding pulse is highly chirped with a relatively wide pulse width, as plotted in Fig. 4(g), confirming that the laser operates in the dissipative soliton regime.

Figure 4(d) simulates the spectrum of the laser with $\beta_{\text{net}}^{(2)}$ of -0.001 ps^2 . A small CW spike is superimposed on the center wavelength of the spectrum, while no stable pulse can be maintained in the time-domain.

Fig. 4. Numerical results of output spectra of dispersion-managed mode-locked fiber lasers with net cavity dispersion of (a) -0.172 ps^2 , (b) -0.028 ps^2 , and (c) $+0.02 \text{ ps}^2$. (e), (f) and (g) are the corresponding temporal pulses shown together with the frequency-chirps; (d) is the output spectrum of the laser with net cavity dispersion of -0.001 ps^2 ; and (h) is the evolution of the spectral bandwidth and the peak power against the number of round trips in the cavity.

Fig. 5. (a) Plot of temporal pulse evolution against the number of round trips in the laser when net cavity dispersion is -0.001 ps^2 . (b) Spectral bandwidth against net cavity dispersion for lasers incorporating different SAs with modulation depths of 6.4%, 12.5%, and 20%.

Although it is difficult to estimate precisely the parameters from the real laser cavity, one can find general agreement with the experimental observation. Figure 4(h) plots the evolution of the spectral bandwidth and the peak power of the pulse against the cavity round trip. In the beginning, the initial pulse from the amplified spontaneous emission noise is reshaped by the SA, and followed by amplification via gain fiber, which enhances the peak power of the pulse. Subsequently, the spectrum broadens due to self-phase modulation. As the spectral bandwidth gets wider, the spectral filtering due to the finite gain bandwidth plays an increasingly important role that, in turn, increases the loss experienced by the pulses. When the loss deviates substantially and cannot be caught up by the cavity gain, the peak power of pulse is correspondingly decreased. As a result, the weak nonlinear effect is insufficient to support the broadband mode-locking and the instabilities grow.

Figure 5(a) shows the pulse evolution in the laser with $\beta_{\text{net}}^{(2)}$ of -0.001 ps^2 . The initial seed is an arbitrary weak pulse. After hundreds of cavity round trips, the built-up pulse is gradually shed away. In order to reshape the pulse to achieve a desirable peak power, a SA with large modulation depth is necessary. Figure 5(b) shows the spectral bandwidth against $\beta_{\text{net}}^{(2)}$ for the lasers with different modulation depths of SAs. The unstable region of the laser can be shrunk by $\sim 36\%$ when a_0 is changed from 6.4% to 12.5%. In the case of a SA with a_0 of 20%, the laser can operate in a stable mode-locking state across the entire dispersion region. It is observed that for a large a_0 , the spectral bandwidth tends to decrease near zero $\beta_{\text{net}}^{(2)}$. This implies that the residual saturable absorption could contribute to the cavity loss, which might decrease the threshold for Q-switching instability [25]. In order to obtain laser mode-locking with a minimum unstable region, a_0 is optimized at 16% for the given cavity parameters. Since the same $\beta_{\text{net}}^{(2)}$ can be designed by various combinations of fibers, we also numerically analyze the dispersion-managed mode-locked fiber laser with a short-length cavity. The relationship between the spectral bandwidth and $\beta_{\text{net}}^{(2)}$ for the laser with different a_0 shows a similar trend to Fig. 5(b). Note that the unstable region of the fiber laser with $a_0 = 12.5\%$ can also be minimized by setting the gain bandwidth to 12.5 THz. This further verifies that the origin of the instabilities is related to the strong spectral filtering.

In conclusion, we investigate the stability of dispersion-managed mode-locked fiber lasers with net cavity dispersion near zero by using CNT-SAs with different modulation depths. Experimental results demonstrate that the unstable region of the dispersion-managed mode-locked fiber laser can be reduced by $\sim 31.3\%$ when the modulation depth of SAs increases from 6.4% to 12.5%. A SA with a large modulation depth can assist a laser cavity to stabilize the mode-locking operation. The simulated result is consistent with the experimental observation, which can be a general guidance for similar dispersion-managed mode-locked fiber laser systems.

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References

1. M. E. Fermann and I. Hartl, *IEEE J. Sel. Top. Quantum Electron.* **15**, 191 (2009).
2. H. A. Haus, K. Tamura, L. E. Nelson, and E. P. Ippen, *IEEE J. Quantum Electron.* **31**, 591 (1995).
3. D. Y. Tang and L. M. Zhao, *Opt. Lett.* **32**, 41 (2007).
4. F. Ö. Ilday, F. W. Wise, and T. Sosnowski, *Opt. Lett.* **27**, 1531 (2002).
5. D. Ma, Y. Cai, C. Zhou, W. Zong, L. Chen, and Z. Zhang, *Opt. Lett.* **35**, 2858 (2010).
6. L. Nugent-Glandorf, T. A. Johnson, Y. Kobayashi, and S. A. Diddams, *Opt. Lett.* **36**, 1578 (2011).
7. Y. Song, K. Jung, and J. Kim, *Opt. Lett.* **36**, 1761 (2011).
8. Y. Song, C. Kim, K. Jung, H. Kim, and J. Kim, *Opt. Express* **19**, 14518 (2011).
9. K. Kieu and F. W. Wise, in *Conference on Lasers and Electro-Optics/International Quantum Electronics Conference*, OSA Technical Digest (CD) (Optical Society of America, 2009), paper CML3.
10. F. X. Kärtner, J. A. der Au, and U. Keller, *IEEE J. Quantum Electron.* **4**, 159 (1998).
11. S. Chouli, J. M. Soto-Crespo, and P. Grelu, *Opt. Express* **19**, 2959 (2011).
12. N. Nishizawa, Y. Nozaki, E. Itoga, H. Kataura, and Y. Sakakibara, *Opt. Express* **19**, 21874 (2011).
13. Y. Nozaki, N. Nishizawa, E. Omoda, H. Kataura, and Y. Sakakibara, *Opt. Lett.* **37**, 5079 (2012).
14. R. Herda and O. G. Okhotnikov, *IEEE J. Quantum Electron.* **40**, 893 (2004).
15. S. Yamashita, *J. Lightwave Technol.* **30**, 427 (2012).
16. J. Lim, K. Knabe, K. A. Tillman, W. Neely, Y. Wang, R. A. Correa, F. Couny, P. S. Light, F. Benabid, J. C. Knight, K. L. Corwin, J. W. Nicholson, and B. R. Washburn, *Opt. Express* **17**, 14115 (2009).
17. M. Zhang, E. J. R. Kelleher, A. S. Pozharov, E. D. Obraztsova, S. V. Popov, and J. R. Taylor, *Opt. Lett.* **36**, 3984 (2011).
18. D. Popa, Z. Sun, T. Hasan, W. B. Cho, F. Wang, F. Torrisi, and A. C. Ferrari, *Appl. Phys. Lett.* **101**, 153107 (2012).
19. H. H. Liu, Y. Yang, and K. K. Chow, *Opt. Express* **21**, 18975 (2013).
20. K. K. Chow, S. Yamashita, and S. Y. Set, *Opt. Lett.* **35**, 2070 (2010).
21. L. E. Nelson, D. J. Jones, K. Tamura, H. A. Haus, and E. P. Ippen, *Appl. Phys. B* **65**, 277 (1997).
22. P. Grelu and N. Akhmediev, *Nat. Photonics* **6**, 84 (2012).
23. G. P. Agrawal, *Nonlinear Fiber Optics*, 4th ed. (Academic, 2009).
24. S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, *IEEE J. Sel. Top. Quantum Electron.* **10**, 137 (2004).
25. C. Hönninger, R. Paschotta, F. Morier-Genoud, M. Moser, and U. Keller, *J. Opt. Soc. Am. B* **16**, 46 (1999).