Dark pulse generation in fiber lasers incorporating carbon nanotubes

H. H. Liu and K. K. Chow*

School of Electrical and Electronic Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore
*kkchow@ntu.edu.sg

Abstract: We demonstrate the generation of dark pulses from carbon nanotube (CNT) incorporated erbium-doped fiber ring lasers with net anomalous dispersion. A side-polished fiber coated with CNT layer by optically-driven deposition method is embedded into the laser in order to enhance the birefringence and nonlinearity of the laser cavity. The dual-wavelength domain-wall dark pulses are obtained from the developed CNT-incorporated fiber laser at a relatively low pump threshold of 50.6 mW. Dark pulses repeated at the fifth-order harmonic of the fundamental cavity frequency are observed by adjusting the intra-cavity polarization state.

OCIS codes: (160.4330) Nonlinear optical materials; (060.3510) Lasers, fiber.

References and links

1. H. Zhang, D. Y. Tang, L. M. Zhao, and X. Wu, "Dark pulse emission of a fiber laser" Phys. Rev. A **80**, 045803 (2009).
2. J. Schröder, S. Coen, T. Sylvestre, and B. J. Eggleton, "Dark and bright pulse passive mode-locked laser with in-cavity pulse-shaper" Opt. Express, **18**, 22715-22721 (2010).
3. W. Zhao and E. Bourkoff, "Generation, propagation, and amplification of dark solitons" J. Opt. Soc. Am. B **9**, 1134-1144 (1992).
4. C. Milián, D. V. Skryabin, and A. Ferrando, "Continuum generation by dark solitons" Opt. Lett. **34**, 2096-2098 (2009).
5. X. Wang, P. Zhou, X. Wang, and Z. Liu, "2 µm bright–dark pulses in Tm-doped fiber ring laser with net anomalous dispersion" Appl. Phys. Express **7**, 022704 (2014).
6. D. Y. Tang, L. Li, Y. F. Song, L. M. Zhao, H. Zhang, and D. Y. Shen, "Evidence of dark solitons in all-normal-dispersion-fiber lasers" Phys. Rev. A **88**, 013849 (2013).
7. H. Zhang, D. Tang, L. Zhao, and X. Wu, "Dual-wavelength domain wall solitons in a fiber laser" Opt. Express **19**, 3525-3530 (2011).
8. Q. Y. Ning, S. K. Wang, A. P. Luo, Z. B. Lin, Z. C. Luo, and W. C. Xu, "Bright–dark pulse pair in a figure-eight dispersion-managed passively mode-locked fiber laser" IEEE Photon. J. **4**, 1647-1562 (2012).
9. J. Zhao, P. Yuan, and S. Ruan, "Observations of three types of pulses in an erbium-doped fiber laser by incorporating a graphene saturable absorber" Appl. Opt. **52**, 8465-8470 (2013).
10. L. Y. Wang, W. C. Xu, Z. C. Luo, W. J. Cao, A. P. Luo, J. L. Dong, and H. Y. Wang, "Dark pulses with tunable repetition rate emission from fiber ring laser" Opt. Commun. **285**, 2113-2117 (2012).
11. V. A. Margulis, "Theoretical estimations of third-order optical nonlinearities for semiconductor carbon nanotubes" J. Phys. Condens. Matter. **11**, 3065-3074 (1999).
12. S. Yamashita, "A tutorial on nonlinear photonic applications of carbon nanotube and graphene" J. Lightw. Technol. **30**, 427-447 (2012).
13. S. Y. Set, H. Yaguchi, Y. Tanaka, and M. Jablonski, "Ultrafast fiber pulsed lasers incorporating carbon nanotubes" IEEE J. Sel. Top. Quantum Electron. **10**, 137-146 (2004).
14. K. K. Chow, S. Yamashita, and Y. W. Song, "A widely tunable wavelength converter based on nonlinear polarization rotation in a carbon-nanotube-deposited D-shaped fiber" Opt. Express **17**, 7664-7669 (2009).
15. K. K. Chow and S. Yamashita, "Four-wave mixing in a single-walled carbon-nanotube-deposited D-shaped fiber and its application in tunable wavelength conversion" Opt. Express **17**, 15608-15613 (2009).
16. K. Kashiwagi and S. Yamashita, "Deposition of carbon nanotubes around microfiber via evanescent light" Opt. Express **17**, 18364-18370 (2009).

17. H. Dong, P. Shum, M. Yan, J. Q. Zhou, G. X. Ning, Y. D. Gong, and C. Q. Wu, "Measurement of Mueller matrix for an optical fiber system with birefringence and polarization-dependent loss or gain" Opt. Commun. **274**, 116-123 (2007).
18. D. Y. Tang, L. M. Zhao, B. Zhao, and A. Q. Liu, "Mechanism of multisoliton formation and soliton energy quantization in passively mode-locked fiber lasers" Phys. Rev. A **72**, 043816 (2005).
19. S. Q. Chen, C. J. Zhao, Y. Li, H. H. Huang, S. B. Lu, H. Zhang, and S. C. Wen, "Broadband optical and microwave nonlinear response in topological insulator" Opt. Mater. Express **4**, 587-596 (2014).
20. H. Zhang, S. B. Lu, J. Zheng, J. Du. S. C. Wen, D. Y. Tang, and K. P. Loh, "Molybdenum disulfide (MoS2) as a broadband saturable absorber for ultra-fast photonics" Opt. Express **22**, 7249-7260 (2014).
21. C. J. Zhao, Y. H. Zou, Y. Chen, Z. T. Wang, S. B. Lu, H. Zhang, S. C. Wen, and D. Y. Tang, "Wavelength-tunable picosecond soliton fiber laser with Topological Insulator: Bi_2Se_3 as a mode locker" Opt. Express **20**, 27888-27895 (2012).

---

1. Introduction

Dark pulse operation of lasers has emerged as an attractive topic in laser physics with respect to bright pulses in recent years [1, 2]. Dark pulses are defined as a train of intensity dips in the intensity of a continuous wave (CW) background of the laser emission. Numerical simulations have found that dark pulses are less sensitive to fiber loss and more stable in the presence of noise compared with bright pulses, which have potential applications in long distance communication [3, 4]. To date, there have been experimental demonstrations of dark pulse emission from fiber lasers operating at various center wavelengths [1, 5]. The formation of dark pulse in fiber lasers is believed to be an intrinsic feature no matter that the laser has either net anomalous dispersion or net normal dispersion [6]. Generally, the mechanism of fiber lasers with net anomalous dispersion to produce dark pulses can be explained by domain-wall theory, in which two leasing beams originated from two-Eigen operation states of fiber lasers are coupled incoherently with each other [7]. Such two-Eigen operation states of lasers can be achieved by managing either the two orthogonal polarization states of the lasers or two separated wavelengths induced by intra-cavity birefringent filter [1, 8]. The produced two light beams are coupled through the nonlinear effect of optical fibers, and the lasers typically require the pump threshold for formation of dark pulse to be around 100 mW [5, 9]. In order to further enhance the cross-coupling effect between the two lasing beams and make the dark pulse generation easily, a medium with high nonlinearity is required. Previous report has shown that by introducing a piece of highly nonlinear fiber into the laser cavity, the pump threshold of laser for dark pulse generation can be reduced down to 43.4 mW [10]. Recently, carbon nanotubes (CNTs) exhibiting strong third-order nonlinear susceptibility promise significant value in pulsed lasers and nonlinear optics [11, 12]. The imaginary-part of third-order nonlinear susceptibility which is responsible for nonlinear absorption enables CNTs as saturable absorber (SAs) in fiber lasers for pulse generation [13]. On the other hand, the real-part of third-order nonlinear susceptibility of CNTs is responsible for optical Kerr effect making CNTs as a nonlinear medium. Theoretical studies have predicted that the nonlinearity of CNTs is almost eight-order magnitude larger than that of standard single mode fiber [12], and recent demonstrations have confirmed that a very short-length of CNT-deposited device has a comparable Kerr nonlinearity to a relative long-length of highly nonlinear fiber [14, 15].

In this paper, we demonstrate the generation of dark pulses in a CNT-incorporated erbium-doped fiber ring laser with net anomalous dispersion for the first time. CNTs are deposited on a side-polished fiber by optically-driven deposition method. With the help of large Kerr nonlinearity in the CNT-deposited side-polished fiber, dark pulses are generated from the CNT-incorporated fiber laser at a relatively low pump threshold of 50.6 mW. The dark pulses repeated at the fifth-order harmonic of fundamental cavity frequency can be obtained by adjusting the polarization state of laser cavity.

2. Design and fabrication of CNT-deposited side-polished fiber

The working principle of a CNT-deposited side-polished fiber is based on the interaction of CNTs with the evanescent field of propagating light in the fiber. The CNTs in our experiment are made by a bulk production method called high-pressure CO conversion (HiPCO). The average diameter of CNTs is around 1 nm. The prepared CNT powder is homogeneously dispersed in deionized water with 2% sodium dodecyl surfate (SDS) surfactant. Figure 1(a) shows the schematic diagram of CNT deposition along a side-polished fiber by optically-driven deposition method. A polarized continuous-wave output from a 1550 nm laser diode is amplified to be around 19 dBm by an erbium-doped fiber amplifier (EDFA). The side-polished fiber in this work is a commercial product made from standard single-mode fiber with a polished region length of 17 mm. It has insertion losses of about 0.1 and 56 dB when putting in air and refractive-index-matching oil, respectively. The polished region of the fiber is covered by a droplet of the prepared CNT solution on a glass slide. A polarization controller (PC) is adopted to adjust the evanescent field of light and trigger the deposition of CNT particles. The movement of CNTs towards the fiber in the presence of light can be explained by optical trapping and heat convection effect [16]. In the experiment, the deposition process lasts for 35 min and the fiber device is finished by drying up and put on another clean glass slide. Figure 1(b) shows the microscopic image of the side-polished region of the fiber from the top view and a CNT-layer is clearly observed on the fiber. An additional insertion loss of 1.2 dB is measured for the fabricated CNT-deposited side-polished fiber compared to a bare side-polished fiber. In our previous work using similar side-polished fibers, the effective nonlinear coefficient of the CNT-deposited fiber can be as high as 563.7 $W^{-1}km^{-1}$ measured by four-wave mixing [15]. The polarization dependent loss (PDL) of CNT-deposited side-polished fiber is characterized by a system described in [17]. A tunable laser source with center wavelength of 1550 nm is applied to emit completely polarized light with stable polarization state. It is followed by a computer-controlled PC and an in-line polarimeter (Thorlabs IPM 5300) to generate and monitor appropriate input Stokes parameters. Another polarimeter after the fiber under test is used to record the output Stokes parameters. By setting the input at four pre-determined polarization states, a 4×4 Muller matrix of fiber under test can be measured and PDL is derived from the Muller matrix [17]. By using this system, the PDL of the prepared CNT-deposited side-polished fiber is calculated to be 0.5 dB.

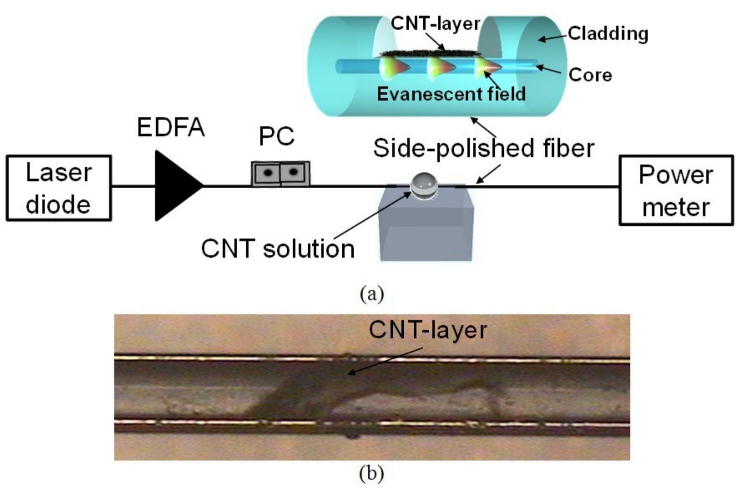

Fig. 1. (a) Experimental setup for optically-driven deposition of carbon nanotubes (CNTs) on a side-polished fiber. EDFA: erbium-doped fiber amplifier, PC: polarization controller; and (b) microscopic image of the side-polished fiber deposited with CNT-layer from the top view.

3. Experiments on dark pulses generation

Figure 2 shows the experimental setup of a CNT-incorporated fiber laser. The prepared CNT-deposited side-polished fiber is directly spliced into fiber laser cavity. A 976 nm laser diode is used to pump a 0.6-m-long erbium-doped fiber (EDF: LIEKKI Er110) with a group velocity dispersion (GVD) parameter β_2 of +0.012 ps^2/m through a 980/1550 nm wavelength-division multiplexer (WDM) coupler. The pigtailed WDM coupler comes with a 0.35-m-long HI1060 fiber with a β_2 of +0.02 ps^2/m. The rest of fibers in the laser cavity are standard single mode fibers, and the total cavity length is about 13.2 m with a net cavity dispersion of -0.255 ps^2. An optical isolator with wavelength range of 1530-1570 nm is applied to ensure unidirectional propagation of the laser beam. A fiber-based PC is used to adjust and optimize the cavity linear birefringence. 10% of the optical power is extracted from the cavity as an output through a 90/10 coupler. The output optical spectrum and pulse train are characterized simultaneously by an optical spectrum analyzer with a resolution of 0.01 nm and an oscilloscope together with a 2 GHz photodetector, respectively.

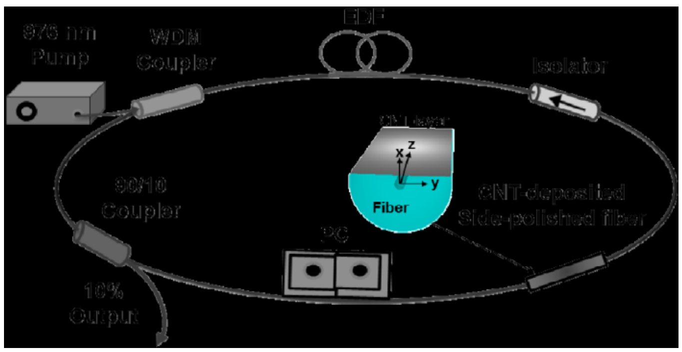

Fig. 2. Experimental setup of an all-fiber ring-configuration fiber laser incorporated with CNT-deposited side-polished fiber. WDM: wavelength division multiplexer; EDF: erbium-doped fiber; and PC: polarization controller.

The CW emission from the laser occurs at a pump power of 28.2 mW and the self-started mode-locking of the constructed laser is achieved at a pump power of 38.9 mW. The corresponding average output power is measured to be 0.858 mW. Figure 3(a) shows that bright pulses are circulating in the cavity with a round-trip time of 64.1 ns which is corresponding to the cavity fundamental frequency of 15.6 MHz. Figure 3(b) gives the output optical spectrum and the center-wavelength is located at 1565.58 nm with a 3-dB bandwidth of 0.1 nm. By keeping the operation conditions and increasing the pump power up to 50.6 mW, dark pulses are found to circulate in the cavity repeated at 15.6 MHz as shown in Fig. 3(c), indicating that the laser is shifted away from the mode-locking regime. An additional wavelength component appears in the output optical spectrum as shown in Fig. 3(d). Although no obvious polarizer is incorporated in the cavity, the slightly residual polarization asymmetry of the used components such as the side-polished fiber can cause the formation of a linear artificial birefringent filter. The existence of the artificial birefringent filter can result in the multi-wavelength within the effective laser gain bandwidth. As pump power increases, the intra-cavity power becomes large. The cross-phase coupling between the dual-wavelength emission is subsequently enhanced that could form the domain-wall dark solitons [7].

Comparative experiments are further conducted where the CNT-deposited side-polished fiber is replaced by a bare side-polished fiber under optimized polarization states. Even though the pump power is pushed up to 260 mW, only continuous wave emission is obtained. Since CNTs are believed to exhibit strong third-order susceptibility, Kerr nonlinearity is

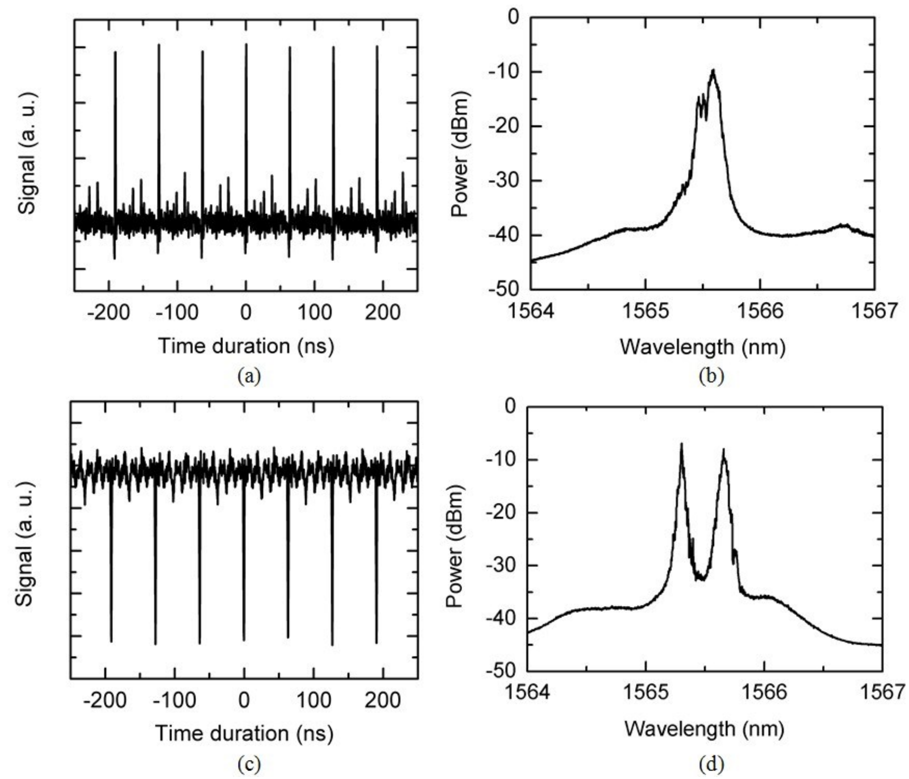

Fig. 3. Outputs from the CNT-incorporated fiber laser showing (a) the bright pulse and (b) its corresponding optical spectrum at a pump power of 38.9 mW; (c) the dark pulse and (d) its corresponding optical spectrum at a pump power of 50.6 mW.

highly enhanced by the CNT-deposited side-polished fiber and the induced cross-phase coupling is power-dependent [14]. Figure 4 shows the pump-induced transformation of single bright pulse into dark pulse from the constructed fiber laser within a cavity round-trip time. Before bright pulse is changed to dark pulse, the laser inevitably goes through the middle state that emits bright-dark pulse under pump power of 42.7 mW. The corresponding optical spectrum of laser is given in the inset of Fig. 4. Such bright-dark pulse contains a bright pulse followed by a dark pulse with almost equal amplitude and propagates stably through cross-coupling effect [8]. In the experiment, the transformation of bright pulse into dark pulse can be reversed by decreasing the pump power.

The pump-induced transformation of bright pulse into dark pulse from the CNT-incorporated fiber laser is further confirmed by changing the polarization state of laser cavity. When the pump power is fixed at 38.9 mW, by carefully adjusting the PC, period-doubling bifurcation of pulses is observed in the laser due to soliton energy quantization effect [18]. Five bright pulses are circulating in one round-trip time which corresponds to a repetition rate of 78 MHz as shown in Fig. 5(a). Once the pump power is increased up to 50.6 mW, dark pulses repeated at the fifth-order harmonic of fundamental cavity frequency are obtained. The results confirm the operation of dark pulse generation from the constructed fiber laser. Figure 5(b) records its output optical spectra under different pump powers, revealing that the laser operates in the dual-wavelength profile. Here, the optical spectrum of dark pulses is broader than that of bright pulses due to the relatively stronger pump strength. As the operation state of laser is both power-dependent and polarization-dependent, the polarization scrambling could induce the drift of operation wavelength and pulse separation. In practical implementation, the laser should be well packaged in order to weaken sharp vibration of polarization state. The experimental evidence of the existence of dark pulses in carbon-nanotube-incorporated fiber laser might be applicable for graphene-like two-dimensional materials and topological insulators embedded in fiber lasers for dark pulse generation, provided that these new nano-materials exhibit large nonlinearity [19-21].

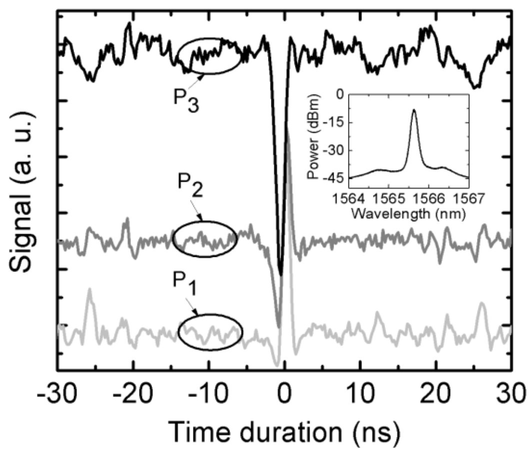

Fig. 4. Transformation of single bright pulse into dark pulse, the curves refer to pulse trains under different pump powers: P_1=38.9 mW, P_2=42.7 mW and P_3=50.6 mW. The inset shows the output optical spectrum of laser under a pump power of 42.7 mW.

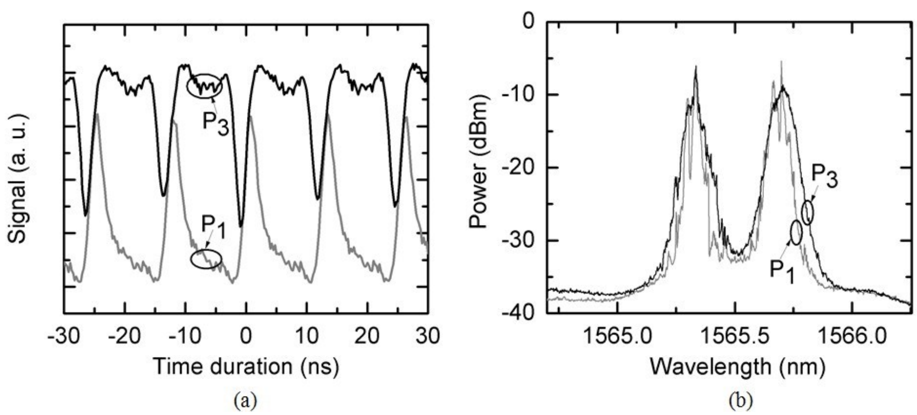

Fig. 5. (a) Output pulse trains and (b) the corresponding optical spectra showing the transformation of multiple bright pulses into dark pulses per cavity round-trip time under pump powers: P_1=38.9 mW and P_3=50.6 mW.

4. Conclusion

In summary, we have demonstrated the generation of dark pulses from a CNT-incorporated erbium-doped fiber ring laser for the first time. CNTs are deposited on side-polished fibers by optically-driven deposition method. With the help of the large nonlinearity from CNTs, dark pulse emission could be observed at relatively low threshold pump strength. Moreover, dark pulses repeated at the fifth-order harmonic of cavity fundamental frequency are demonstrated.

Acknowledgments

This work was partially supported by Academic Research Fund Tier 2 Grant (ARC26/14) of Ministry of Education (MOE), Singapore.