Observation of Bright-Dark Soliton Pair in a Fiber Laser With Topological Insulator

Bo Guo, Yong Yao, Jia-Jun Tian, *Member, IEEE*, Yu-Feng Zhao, Shuai Liu, Meng Li, and Ming-Ran Quan

***Abstract*— The bright-dark soliton pair in a passively mode-locked fiber laser based on the topological insulator: Bi_2Se_3/polyvinyl alcohol (PVA) film in the proper polarization state and the pump power is experimentally demonstrated. By carefully adjusting the pump power and the polarization state, the bright-dark soliton pair could be easily observed. Furthermore, it is found experimentally that the formation of the bright-dark soliton pair is mainly due to the polarization effect based on the high nonlinear effect of topological insulator: Bi_2Se_3/PVA film. We also demonstrate that the pulse shape of the bright-dark soliton pair can be affected by the total net cavity dispersion in the fiber laser.**

***Index Terms*— Fiber laser, passive mode-locking, topological insulator, bright-dark soliton pair.**

I. INTRODUCTION

THE soliton formed in single mode fibers, which was predicted in 1973 and firstly observed in 1981, attracted considerable attention due to their versatile applications in optical communication, optical continuum generation and optical-processing system [1]. Since 1991, various passive mode-locking schemes, such as the nonlinear polarization rotation [2], nonlinear amplifying loop mirror [3], semiconductor saturable absorber mirror [4], carbon nanotubes [5], graphene [6], [7], topological insulators [8], and MoS_2 [9], [10], have been used to realize the soliton operation. So far, several kinds of soliton have been observed in the optical fiber system, such as bright soliton, dark soliton [11], similariton [12], dissipative soliton [13], and so on. Interestingly, dark-dark, bright-bright, even dark-bright soliton pairs may also exist due to the interactions between the solitons, according to the soliton theory in [1]. Later, the dark-bright soliton pair was indeed theoretically demonstrated in Kerr-type nonlinear medium [14], [15] and was experimentally observed in the optical fiber system [16]. As we know, the bright-dark pulse pair could be generated by the cross-phase modulation (two or more optical pulses) or polarization effect (only one optical pulse) [1]. In 2012, Ning *et al.* reported on the bright-dark pulse pair caused by the cross-phase modulation in a figure-eight dual-cavity passively mode-locked fiber laser [17]. However, there is rare paper reporting on the bright-dark soliton pair formed in a single-cavity passively mode-locked fiber laser based on the polarization effect until now.

Recently, a rising two-dimensional layer-by-layer material: topological insulators (TIs), characterized by a robust metallic edge or surface state and a narrow band-gap bulk topological insulating state, have gained great scientific and technical attention in physics, chemistry and material fields [18]. Similar to the graphene saturable absorber (SA), the TIs have been found to be another potential and efficient candidate for mode-locked [19]–[23] or Q-switched [24]–[27] fiber lasers due to their excellent saturable absorption nature. In 2012, Zhao *et al.* firstly demonstrated the stable soliton pulses with 1.57 ps in an erbium-doped fiber laser based on the TI: Bi_2Se_3 SA [8]. In 2014, Liu *et al.* reported on the generation of optical pulse with ~660 fs in a fiber laser by using a PVA-based TI:Bi_2Se_3 SA [23]. It should note that, however, only bright soliton was obtained in these fiber lasers, there is no bright and dark soliton were simultaneously observed. Therefore, it would be interesting to know whether the bright soliton and dark soliton could coexist in the fiber lasers with a TISA.

In this letter, we propose and demonstrate the generation of bright-dark soliton pair due to the polarization effect in a passively mode-locked fiber laser based on the TISA. By properly adjusting the pump power and the polarization state, the bright-dark soliton pair could be stably initiated. We also discuss the effect of the total net cavity dispersion on the pulse shape of the bright-dark soliton pair. This letter provides the first example of the simultaneous existence of both dark soliton and bright soliton based on the polarization effect in a passively mode-locked fiber laser with a TISA.

II. TISA PREPARATION AND CHARACTERISTICS

Currently, the high-quality TI: Bi_2Se_3/PVA film used in our experiment was obtained by the liquid-phase exfoliation/ spin-coating method [26], as shown in Fig. 1(a). First, we synthesized the Bi_2Se_3 crystal from Bi_2O_3 powder and Se powder through the hydrothermal method. Then, the as-synthesized Bi_2Se_3 powders were added into the N-methyl-2-pyrrolidone solution and 24 hours by ultrasound to produce the well-dispersed TI: Bi_2Se_3 suspension. Thereafter, we put some PVA powder into the TI: Bi_2Se_3 solution with ultrasonic agitation for 2 hours. Finally, we sprayed the TI: Bi_2Se_3/PVA suspension onto a glass substrate by the spin-coating method and dried in an oven to obtain the TI: Bi_2Se_3/PVA film.

Before transferring the TI: Bi_2Se_3/PVA film into the laser cavity, we firstly characterized its thickness (~25 μm) and crystalline structure with an alpha-step profiler (Surface

Manuscript received October 15, 2014; revised December 28, 2014; accepted January 6, 2015. Date of publication January 12, 2015; date of current version March 2, 2015. This work was supported in part by the National Natural Science Foundation of China (61107036) and in part by the Guangdong Province Shenzhen Municipal Science and Technology Plan (Projects 2010B090400306, JC201105160592A, JC201105160524A, and JCYJ20140417173156106).

The authors are with the School of Electronic and Information Engineering, Shenzhen Graduate School, Harbin Institute of Technology, Shenzhen 518055, China (e-mail: guobo512@163.com; yaoyong@hit.edu.cn; jiajuntian@gmail.com; ef6270@163.com; lsblue1@gmail.com; 18688719810@163.com; quanmingran@163.com).

Color versions of one or more of the figures in this letter are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/LPT.2015.2390212

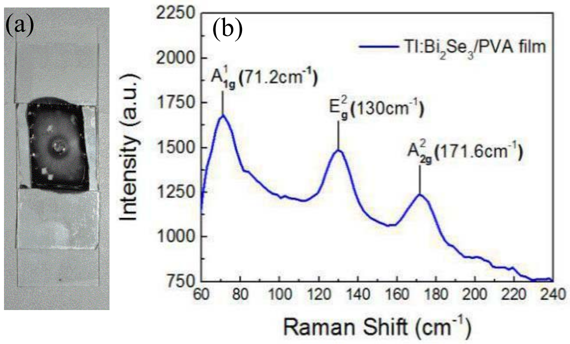

Fig. 1. (a) The photograph and (b) the Raman spectrum of the TI: Bi_2Se_3/PVA film.

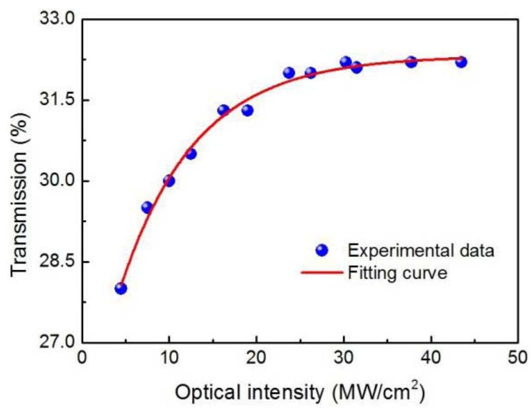

Fig. 2. The nonlinear transmission characteristic of the TISA.

Profiler P-10, KLA-Tencor) and a Renishaw inVia micro-Raman system (Renishaw Inc., New Mills, U.K.), respectively. Fig. 1(b) depicts the Raman spectra of the TI: Bi_2Se_3 in the range of 60-240 cm^{-1} using the 514 nm excitation line at room temperature. Three typical Raman peaks, corresponding to A^1_{1g}($\sim$71.2 cm^{-1}), E^2_g ($\sim$130 cm^{-1}) and A^2_{1g} ($\sim$171.6 cm^{-1}), are consistent with the previously reported Raman spectra of the TI: Bi_2Se_3 [23]. Clearly, the TI: Bi_2Se_3 nanosheets keep their crystalline structure well even though they are embedded into PVA matrix. Next, the TI SA parameters, such as saturation intensity ($\sim$25 MW/cm^2) and modulation depth ($\sim$3.8%) were determined by the open-aperture Z-scan technique performed in an experimental setup similar to that in [25], as shown in Fig. 2. Furthermore, the inserting loss of the mode-locker is about 2.9 dB, was measured by a power meter.

III. Experimental Setup

The experimental setup of our proposed fiber laser is sketched in Fig. 3. The laser cavity consists of a piece of $\sim$ 5 m highly doped Erbium-doped fiber (Core active L-900, EDF) with dispersion parameter of ~ -16.3 ps/(km·nm) and peak absorption of 14.5 dB/m at 1530 nm and $\sim$185 m single mode fiber (SMF) with dispersion parameter of 18 ps/(km·nm). The total net cavity dispersion is ~ -4.15 ps^2. A fiber-pigtailed 976 nm laser diode (980-500-B-FA, LD) via a fused 980/1550 wavelength-division multiplexer (WDM) is used to pump source and a 10:90 optical coupler (OC) is employed to extract the output of the laser beam. A polarization independent isolator (ISO) and a polarization controller (PC) were used to force the unidirectional operation of the ring cavity and adjust the polarization state of the propagation light, respectively. The optical performance of the pulse was monitored by an optical spectrum analyzer (ANDO, AQ-6317B) with spectral resolution of 0.01 nm, a photo-detector (Thorlabs PDA 2GHz) combined with a 1 GHz mixed oscilloscope (Tektronix MDO4054-6, 5 GHz/s) and a power meter.

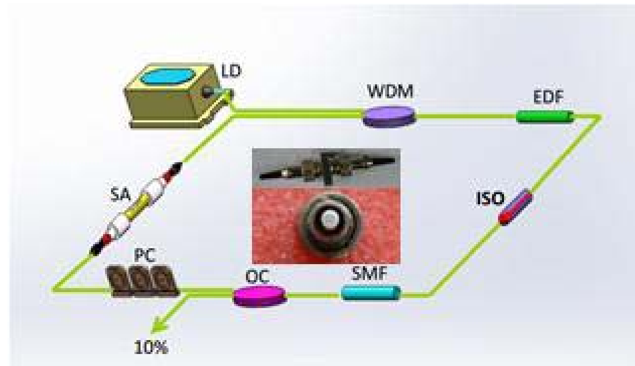

Fig. 3. The experimental setup of our proposed fiber laser. Inset: top, the photograph of the mode-locker; bottom, the photograph of the pigtail with the TI: Bi_2Se_3/PVA film (gray color).

IV. Experimental Results and Discussions

First, we test the operation characteristics of the fiber laser without incorporating the TI: Bi_2Se_3/PVA film. By adjusting the pump strength and the cavity polarization state in a wide range, there is neither mode-locking nor dual-wavelength pulses generation, which exclude the possibility of self-mode-locking of the laser and the Fabry-Perot cavity effect of the mode-locker. Next, a small piece of sample ($\sim$1×1 mm^2), was cut from the TI: Bi_2Se_3/PVA film, spliced into one of the two optical connectors in the laser cavity and formed a mode-locker, as shown inset of the Fig. 3. Continuous wave operation started at a pump power of about 15 mW and the self-started mode-locking occurred at about 25 mW. A series of experiments show that the stable bright-dark soliton pair can be easily obtained by rotating the PC carefully.

Here, we focus our discussion on the optical characteristics of the bright-dark soliton pair at the pump power of 97.3 mW in our proposed fiber laser. By properly adjusting the PC, the typical optical spectrum of optical pulse is obtained, as shown in the Fig. 4(a). Clearly, we almost didn't observe the Kelly sidebands, this may be attributed to the spectral filtering effect which caused by the combination of the polarization of polarization controller and intra-cavity birefringence of SMF. Interestingly, the spectrum shows an M-shape profile, which is similar to the previous report [2], implying that the formation of the pulse may be also associated with the cavity feedback and the gain competition. By adjusting the oscilloscope triggering level above or below the noise, bright or dark pulse could be observed, respectively. Surprisingly, the bright pulse and the dark pulse could be observed simultaneously by properly adjusting the oscilloscope triggering level, as depicted in Fig. 4(b). Based on the soliton theory in [1], we call it bright-dark soliton pair, which exhibits the shape-preserving property of soliton over a long time. This pulse train has a period of 920.8 ns, which matches with the cavity roundtrip time, thus verifies the mode-locking operation of the fiber laser. Fig. 4(c) shows its corresponding single pulse profile of the bright-dark soliton pair. Clearly, for

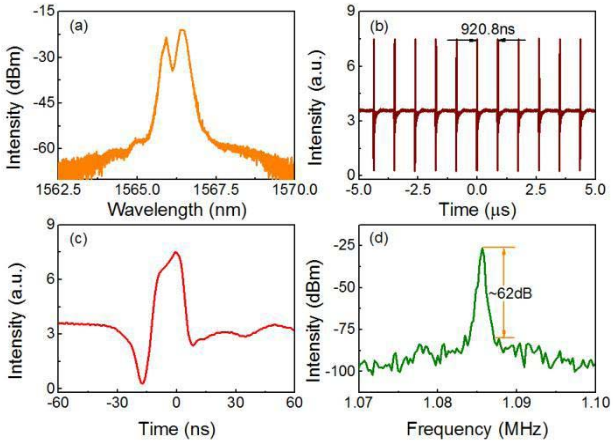

Fig. 4. Typical optical characteristics of the bright-dark soliton pair at the pump power of 97.3 mW. (a) the output optical spectrum; (b) the pulse train; (c) the corresponding single pulse profile of the bright-dark soliton pair and (d) the corresponding RF spectrum.

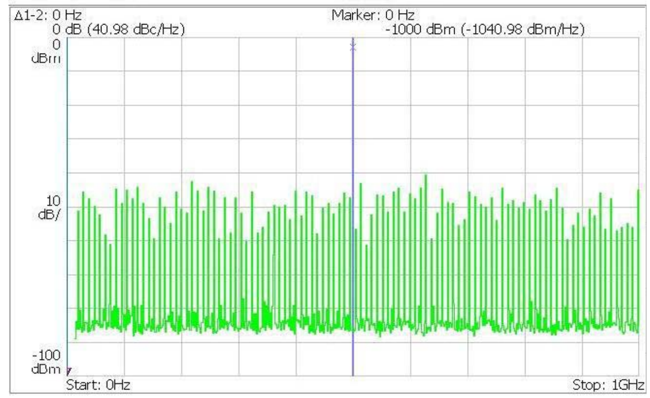

Fig. 5. The RF spectrum of the bright-dark soliton pair measured in wider frequency range (1GHz).

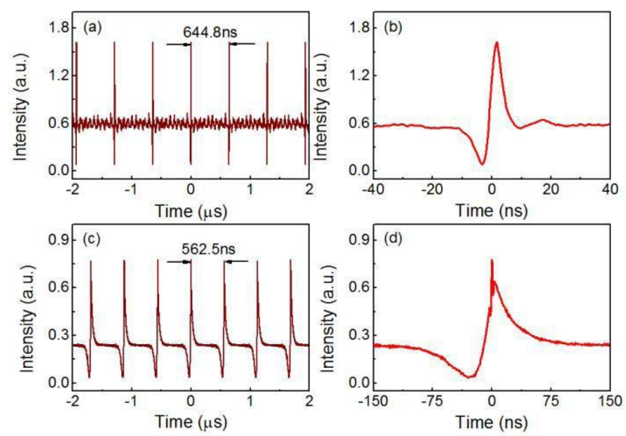

Fig. 6. Typical time-domain characteristics of the bright-dark soliton pair with different length of the single mode fiber (a) the pulse train and (b) the corresponding single pulse profile of the bright-dark soliton pair when $L_{SMF} = 132.5$ m, $\beta_{2,cavity} = \sim{-2.94}$ ps^2; (c) the pulse train and (d) the corresponding single pulse profile of the bright-dark soliton pair when $L_{SMF} = 115$ m, $\beta_{2,cavity} = \sim{-2.54}$ ps^2.

the bright soliton and the dark soliton, it shows an asymmetric profile with different pulse intensity and pulse width, which is different from the symbiotic solitary-wave pairs in the previous reports [16], [17]. This may be caused by the high-order nonlinear effect of the TI: Bi_2Se_3/PVA film. Here, the μm-scale film can be viewed as the high-nonlinear fiber at the same pump power, benefits from its giant nonlinear refractive index of 10^{-14} m^2/W (almost six orders of magnitude larger than that of bulk dielectrics) [28]. As we know, due to the slow response time of our photodetector and sampling oscilloscope, the single oscilloscope trace could not reflect the real pulse duration for the ultrafast pulses. Therefore, a commercial optical autocorrelator (FR-103XL) was used to measure the pulse-width of the bright-dark soliton pair. Surprisingly, no autocorrelation trace was obtained. Meanwhile, we noticed that there was no autocorrelation trace observed in [16] either. So, we think it should be attributed to the inherent feature of the bright-dark soliton pair in the fiber laser.

To investigate the stability of the bright-dark soliton pair, we also measured its radio frequency (RF) spectrum, as depicted in Fig. 4(d). Its fundamental peak, located at the cavity repetition rate of 1.086 MHz, has a signal-to-noise ratio of ~62 dB, indicating good stability and further confirming the mode-locking operation of the bright-dark soliton pair. To investigate the long-term stability of the bright-dark soliton pair, we measured its RF spectrum in wider frequency range, as shown in Fig. 5. The wide-band RF spectrum shows a little spectral modulation, the reason could be interpreted as follows. Unlike single-wavelength mode-locking, the dual-wavelength operation exhibits two fundamental repetition rates corresponding to two mode-locked states. The intensities of two RF peaks have small fluctuations due to their different net cavity dispersion, and thus the power of each mode-locked operation varies slightly.

Notably, for the bright-dark soliton pair in Fig. 4(c), the shape profile of the bright pulse deviated seriously from that of conventional soliton, implying that, the dynamics of the bright-dark soliton pair may be affected by the cavity dispersion base on the dispersion theory in [1]. Therefore, we consider the effect of the total net cavity dispersion ($\beta_{2,cavity}$) on the pulse shape profile of the bright-dark soliton pair by only adjusting the length of the single mode fiber (L_{SMF}) in the proposed laser cavity. To this end, we shorten L_{SMF} from ~185 m to ~132.5 m, even ~115 m, the bright-dark soliton pair still exists, as depicted in Fig. 6. Clearly, the shape of the bright-dark soliton pair becomes smoother and more closer the conventional soliton though still asymmetric. Interestingly, compared with bright pulse, dark pulse shows better stability and less influence of the cavity dispersion, as shown in Fig. 4(c), Fig. 6(b) and Fig. 6(d). So, we believe that the total net cavity dispersion has important effect on the formation and dynamics of the bright-dark soliton pair. In experiment, we also test that the damage threshold of the mode-locker is about 200 mW and observe the harmonic mode-locking of the bright-dark pair. Finally, we remove the mode-locker, there is no bright-dark soliton pair observed no matter how adjust the triggering level, pump strength and the cavity polarization state in a wide range.

To understand why the bright-dark soliton pair could be formed in our laser, we notice that Manakov had once theoretically studied the propagation of a single optical pulse in high birefringent fibers using a set of coupled nonlinear Schrödinger equations [29]. They pointed that a dark pulse on the slow axis and a bright pulse on the fast axis could simultaneously

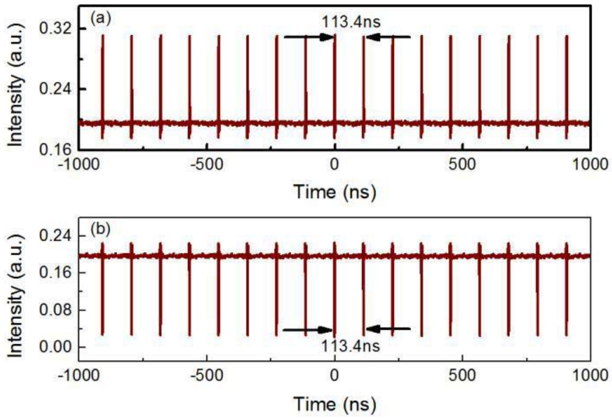

Fig. 7. Separated measurement of the pulse train of the bright-dark soliton pair under the external cavity rotatable polarizer. (a) the bright soliton; (b) the dark soliton when $L_{SMF} = 18.3$ m, $\beta_{2,cavity} = \sim -0.32$ ps^2.

propagate without distortion over long time. As we know, TI: Bi_2Se_3 shows a giant nonlinear refractive index [28], which can naturally induce a high nonlinear effect to generate the bright-dark soliton pair in our laser cavity. In order to further verify the polarization characteristics of the bright–dark soliton pair, an external cavity rotatable polarizer is used to observe the alteration of the soliton pair profile. Through rotating the polarizer from 0° to 90°, the bright and dark soliton could be eliminated in turn, as shown in Fig. 7, which is similar to [17]. Therefore, we believe that the passively mode-locked fiber laser with a TISA can support a pair of solitons which composed of one dark soliton and one bright soliton in the proper polarization states and pump power.

Finally, the two-dimensional materials deposited microfibers were demonstrated to be the good candidates of highly-nonlinear photonic device in fiber lasers [20], [30]. We hope the bright-dark soliton pair could be also observed by them in the future research.

V. Conclusion

In conclusion, we have experimentally demonstrated a bright-dark soliton pair in a passively mode-locked fiber laser based on polarization effect with a topological insulator saturable absorber. By properly adjusting the pump power and the polarization state, the bright-dark soliton pair could be stably initiated. Furthermore, it is found experimentally that the formation of the bright–dark soliton pair is mainly due to the polarization effect based on the high nonlinear effect of TI: Bi_2Se_3. In addition, we also discuss the effect of the cavity dispersion on the pulse shape of the bright-dark soliton pair. We hope the propagation and interaction mechanism of the bright-dark soliton pair will be well discussed in the future research.

References

[1] G. P. Agrawal, *Nonlinear Fiber Optics*, 5th ed. San Francisco, CA, USA: Academic, 2013.

[2] H. Zhang *et al.*, "Dual-wavelength domain wall solitons in a fiber ring laser," *Opt. Exp.*, vol. 19, no. 4, pp. 3525–3530, Feb. 2011.

[3] Q.-Y. Ning *et al.*, "Vector nature of multi-soliton patterns in a passively mode-locked figure-eight fiber laser," *Opt. Exp.*, vol. 22, no. 10, pp. 11900–11911, May 2014.

[4] P. Li *et al.*, "Tunable picosecond SESAM mode-locking ytterbium-doped double-clad LMA PCF oscillator," *Opt. Commun.*, vol. 317, pp. 62–66, Apr. 2014.

[5] C. Mou *et al.*, "All-fiber polarization locked vector soliton laser using carbon nanotubes," *Opt. Lett.*, vol. 36, no. 19, pp. 3831–3833, Oct. 2011.

[6] H. Zhang *et al.*, "Graphene mode locked, wavelength-tunable, dissipative soliton fiber laser," *Appl. Phys. Lett.*, vol. 96, no. 11, p. 111112, Mar. 2010.

[7] S. Huang *et al.*, "Tunable and switchable multi-wavelength dissipative soliton generation in a graphene oxide mode-locked Yb-doped fiber laser," *Opt. Exp.*, vol. 22, no. 10, pp. 11417–11426, May 2014.

[8] C. Zhao *et al.*, "Wavelength-tunable picosecond soliton fiber laser with topological insulator: Bi_2Se_3 as a mode locker," *Opt. Exp.*, vol. 20, no. 25, pp. 27888–27895, Dec. 2012.

[9] H. Zhang *et al.*, "Molybdenum disulfide (MoS_2) as a broadband saturable absorber for ultra-fast photonics," *Opt. Exp.*, vol. 22, no. 6, pp. 7249–7260, Mar. 2014.

[10] H. Liu *et al.*, "Femtosecond pulse erbium-doped fiber laser by a few-layer MoS_2 saturable absorber," *Opt. Lett.*, vol. 39, no. 15, pp. 4591–4594, Aug. 2014.

[11] H. Zhang, D. Y. Tang, L. M. Zhao, and X. Wu, "Dark pulse emission of a fiber laser," *Phys. Rev. A*, vol. 80, no. 4, p. 045803, Oct. 2009.

[12] J. M. Dudley, C. Finot, D. J. Richardson, and G. Millot, "Self-similarity in ultrafast nonlinear optics," *Nature Phys.*, vol. 3, no. 9, pp. 597–603, Mar. 2007.

[13] P. Grelu and N. Akhmediev, "Dissipative solitons for mode-locked lasers," *Nature Photon.*, vol. 6, no. 2, pp. 84–92, Feb. 2012.

[14] Z. Chen, M. Segev, T. H. Coskun, D. N. Christodoulides, Y. S. Kivshar, and V. V. Afanasjev, "Incoherently coupled dark-bright photorefractive solitons," *Opt. Lett.*, vol. 21, no. 22, pp. 1821–1823, Nov. 1996.

[15] Z. H. Musslimani and J. Yang, "Transverse instability of strongly coupled dark–bright Manakov vector solitons," *Opt. Lett.*, vol. 26, no. 24, pp. 1981–1983, Dec. 2001.

[16] Y. Meng *et al.*, "Bright-dark soliton pairs emission of a fiber laser," in *Proc. Commun. Photon. Conf. Exhibit.*, Nov. 2011, pp. 1–6.

[17] Q.-Y. Ning *et al.*, "Bright–dark pulse pair in a figure-eight dispersion-managed passively mode-locked fiber laser," *IEEE Photon. J.*, vol. 4, no. 5, pp. 1647–1652, Oct. 2012.

[18] X.-L. Qi and S.-C. Zhang, "Topological insulators and superconductors," *Rev. Modern Phys.*, vol. 83, no. 4, pp. 1057–1110, Oct. 2011.

[19] F. Bernard *et al.*, "Towards mode-locked fiber laser using topological insulators," in *Nonlinear Photon. OSA Tech. Dig.*, Jun. 2012, pp. 1–3, paper NTh1A.5.

[20] Z.-C. Luo *et al.*, "2 GHz passively harmonic mode-locked fiber laser by a microfiber-based topological insulator saturable absorber," *Opt. Lett.*, vol. 38, no. 24, pp. 5212–5215, Dec. 2013.

[21] M. Jung *et al.*, "A femtosecond pulse fiber laser at 1935 nm using a bulk-structured Bi_2Te_3 topological insulator," *Opt. Exp.*, vol. 22, no. 7, pp. 7865–7874, Apr. 2014.

[22] J. Sotor *et al.*, "Mode-locking in Er-doped fiber laser based on mechanically exfoliated Sb_2Te_3 saturable absorber," *Opt. Mater. Exp.*, vol. 4, no. 1, pp. 1–6, Jan. 2014.

[23] H. Liu *et al.*, "Femtosecond pulse generation from a topological insulator mode-locked fiber laser," *Opt. Exp.*, vol. 22, no. 6, pp. 6868–6873, Mar. 2014.

[24] Y. Chen *et al.*, "Large energy, wavelength widely tunable, topological insulator Q-switched erbium-doped fiber laser," *IEEE J. Sel. Topics Quantum Electron.*, vol. 20, no. 5, Sep./Oct. 2014, Art. ID 900508.

[25] Z. Luo *et al.*, "1.06 μm Q-switched ytterbium-doped fiber laser using few-layer topological insulator Bi_2Se_3 as a saturable absorber," *Opt. Exp.*, vol. 21, no. 24, pp. 29516–29522, Dec. 2013.

[26] L. Sun *et al.*, "Preparation of few-layer bismuth selenide by liquid-phase-exfoliation and its optical absorption properties," *Sci. Rep.*, vol. 4, p. 4794, Apr. 2014.

[27] Z. Luo *et al.*, "Topological-insulator passively Q-switched double-clad fiber laser at 2 μm wavelength," *IEEE J. Sel. Topics Quantum Electron.*, vol. 20, no. 5, Sep./Oct. 2014, Art. ID 0902708.

[28] S. Lu *et al.*, "Third order nonlinear optical property of Bi_2Se_3," *Opt. Exp.*, vol. 21, no. 2, pp. 2072–2082, Jan. 2013.

[29] S. V. Manakov, "On the theory of two-dimensional stationary self-focusing of electromagnetic waves," *J. Experim. Theoretical Phys.*, vol. 38, no. 2, pp. 248–253, Mar. 1974.

[30] A.-P. Luo *et al.*, "Microfiber-based, highly nonlinear graphene saturable absorber for formation of versatile structural soliton molecules in a fiber laser," *Opt. Exp.*, vol. 22, no. 22, pp. 27019–27025, Nov. 2014.