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Dissipative soliton generation with sidebands using Bismuth Telluride (Bi_2Te_3) in erbium doped fiber laser

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ABSTRACT

In this work, the demonstration of dissipative soliton (DS) was observed in erbium doped fiber laser (EDFL) using of Bismuth Telluride (Bi_2Te_3) nanosheets saturable absorber (SA). The prepared SA was deposited on a fiber ferrule using optical deposition method. Interestingly, the DS generatered was accompanied with sidebands and the number of sidebands grew with laser diode pump power. Sidebands were observed as a result of modulation instability (MI) process, which arises from the interaction between DS and nonlinear gain in the fiber laser cavity. Signal to noise ratio (SNR) of 58 dB was attained, confirming the stability of the generated pulse. This work proved the capability of Bi_2Te_3 as SA for generating DS with sidebands in an EDFL.

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1. INTRODUCTION

Optical pulses are the fundamental feature in applications spanning across different fields [1]–[3]. Optical solitons have unique features where they can propagate long distance while maintaining their shape. As such, optical solitons are under intense research, owning to prospective application particularly in optical communication and optical signal processing [4], [5]. Researchers often consider fiber lasers as the nonlinear platform to conduct their studies on the formation, dynamics and evolution of optical soliton. Additionally, the optical pulse generated from fiber lasers offers high beam quality, high efficiency, and compact in structure. Various kinds of soliton pulse are revealed using this platform such as conventional soliton [6], [7], bound soliton [8], [9], vector soliton [10], [11], dissipative soliton (DS) [12], [13] and dissipative soliton resonance (DSR) [14], [15]. Each of these solitons have their own distinct characteristics, for instance conventional solution possesses unique Kelly sidebands while DSR appears as rectangular shaped pulse in the time domain where its pulse width increases linearly with pump power.

On the other hand, DS is characterized with steep edges and flat top spectrum. Apart from dispersion and nonlinearity, the formation of DS is also influenced by gain and loss in the system. In regard to this, pulse energy of DS can be increased by 1~2 orders of magnitude compared to conventional soliton [16]. Besides, DS usually has large chirp and its pulse width can be further compressed. Till date, DS are demonstrated in fiber lasers using various methods, such as nonlinear polarization rotation (NPR) [17], [18], nonlinear optical loop mirror (NOLM) [19], [20], multimode interference (MMI) structure [21], and real saturable absorbers (SAs) graphene [22]–[24], transition metal dichalcogenide (TMD) [25], topological insulator (TI) [26], [27], back phosporus (BP) [28], MXene [29], and organic material [30]. This shows that generation of DS in fiber laser is well established and is still actively undertaken by researchers.

Many works on DS covering from 1-2 um were published. One remarkable work was demonstrated by Wang *et al.* [26]. In his work, a very wide DS up to 3 dB bandwidth of 51.62 nm using Bismuth Telluride (Bi_2Te_3) sandwiched in between fiber ferrule. Interestingly, DS with sidebands were observed by some group of researchers. This kind of spectrum is rather eccentric reported by [31]–[33] on DS with sidebands using NPR technique. These observations were indeed quite rare, but it was proven by theoretical simulations, confirming that it was possible to have sidebands on DS. The sidebands on DS are not Kelly sidebands, even though it appeared to be similar. In the simulation conducted by Xu *et al.* [32], the angle of polarization controller was controlled by increasing the angles of pulses and the fast axis of polarization maintaining fiber (PMF) could enhance modulation instability (MI), which subsequently resulted in sidebands on DS. In this work, we experimentally demonstrate similar work, DS which comes along with sidebands on the spectrum using TI Bi_2Te_3 as SA. The obtained DS spectrum was centred at 1558.8 nm, with 3 dB bandwidth of 17.6 nm. Up to four pairs of sidebands were imposed on the DS spectrum at the maximum available pump power. Up to date, majority published works were centered on conventional soliton using TI Bi_2Te_3 as SA. In contrast to these studies, our work showcased novel observation with TI Bi_2Te_3 SA, by demonstrating DS with sidebands. Hence our findings provide new insights on nonlinear optical behavior of Bi_2Te_3 in DS with sidebands pulse shaping in an erbium doped fiber laser (EDFL).

2. MATERIAL PREPARATION AND EXPERIMENTAL SETUP

In this work, Bi_2Te_3 thin film is used as SA. First of all, 5 mg of Bi_2Te_3 were dissolved 50 ml of isopropyl alcohol in a hot plate stirrer. The solution was stirred for 24 hours using a magnetic stirrer. Once uniform dispersion is achieved, the mixture was subjected to ultrasonication for 6 hours to produce Bi_2Te_3 composite. Later, it was put into ultrasonic bath (Branson 2510, 40 kHz) to obtain stable composite solution. The SA has modulation depth of 41.4% and non-saturable absorption of 10% by using dual optical power meter technique. It has linear absorption of 15% near 1550 nm region. The prepared Bi_2Te_3 was attached to the end of fiber ferrule using optical deposition method. The details of material preparation and characterization can be referred to [34].

Figure 1 shows the experimental configuration for the proposed DS generation with sidebands in EDFL. The 3 m long erbium doped fiber (EDF) was excited with a 980 nm laser diode via 980/1550 nm wavelength division multiplexer (WDM). The EDF used had dispersion of -21.64 ps/(nm•km) at wavelength of 1550 nm. The rest of the cavity consisted of 14 m long single mode fiber (SMF-28), with dispersion 17 ps/(nm•km). Light polarization in the fiber laser cavity was fine tuned using a three paddles polarization controller, while an isolator was used to enforce unidirectional light oscillation. 5% of light was extracted out from the laser cavity for analysis with optical spectrum analyzer (OSA, Yokogawa AQ6370B), oscilloscope (LeCroy, 352A), radio frequency spectrum analyzer (RFSA, Anritsu MS2683A) and autocorrelator. The remaining 95% of light was re-circulated into the cavity. The total cavity length was estimated close to17 m, with the laser cavity operated in the anomalous dispersion region.

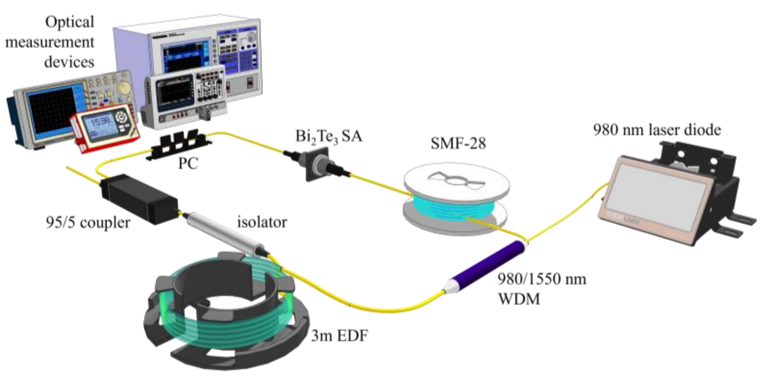


Figure 1. Experimental set up of mode-locked DS EDFL

3. RESULTS AND DISCUSSION

The laser diode pump power gradually increased to 155.4 mW and upon adjusting the polarization of light accordingly, mode-locking behavior became evident. Figures 2(a) to (c) illustrates the evolution of optical spectrum of mode-locked laser at various pump powers. The optical spectrum is centered at 1558.8 nm. Steep edges and flat top spectrum could be observed throughout the increment of pump powers from 155.4 mW to 185.5 mW, while maintaining the orientation of PC. This affirmed that the obtained mode-locked pulse was DS, formed in the anomalous dispersion cavity. The formation of steep edges is attributed to strong spectral filtering (SF) effect. The 3 dB bandwidth at pump power of 185.5 mW was measured at 17.6 nm. Besides the steep edges and flat top, stokes and anti stokes sidebands were noticeable on the spectrum, which is rather unusual. These sidebands reminiscent Kelly sidebands. Generally, Kelly sidebands are imposed on the conventional soliton due to phase matching conditions. Even though the sidebands appeared alike to Kelly sidebands, but the formation differs. MI is a nonlinear phenomenon, induced by the nonlinear gain in the laser cavity and the appropriate orientation of PC contributed to the formation of these sidebands [33]. Moreover, parametric process such as four wave mixing (FWM) and cross phase modulation (XPM) could also lead to sidebands generation in a dissipative system. These sidebands were examined to be more intense, and the number increased and with the rise of pump power. From 155.4 mW to 185.5 mW, the number of sidebands grew from one pair to four pairs. Similar works were validated by [31]–[33] where they examined DS with sidebands as well in their work. Observation on this work is also consistent with the work demonstrated by Tang *et al.* [35]. Longer wavelengths travel slower in the presence of anomalous dispersion. Small perturbations on the DS envelope can lead to the growth of sidebands through MI.

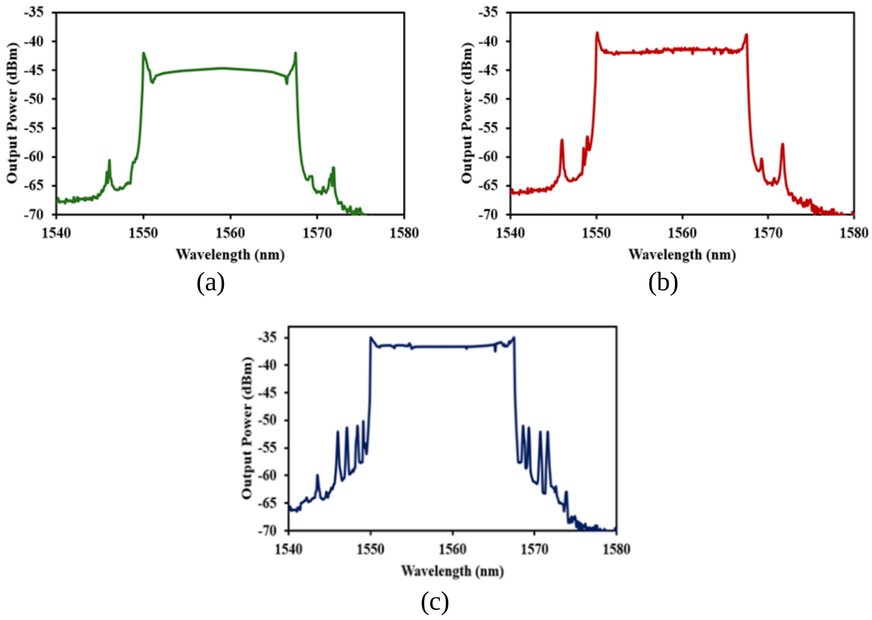
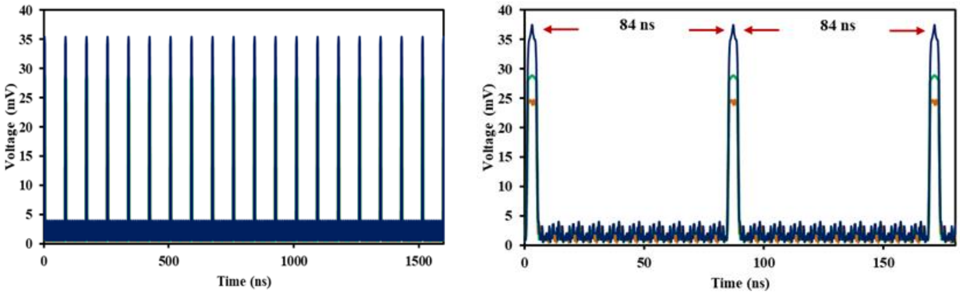


Figure 2. DS optical spectrum at pump power of; (a) 155.4 mW, (b) 170.8 mW, and (c) 185.5 mW

Figure 3(a) depicts the repetition rate of the DS taken at 185.5 mW. The intensity of the oscillation trace was stable at laboratory environment. Figure 3(b) illustrates the enlarged view on the oscillation signal. The spacing between oscillations was measured at 84 ns and it translated to repetition rate of 11.9 MHz. Referring to Figure 4, the pulse width was revealed at 5.2 ps when it was measured using autocorrelator. The signal to noise ratio (SNR) of pulse was determined at 58 dB, and it signified that the pulse was stable. The maximum measured output power was approximately 2.8 mW. On the other hand, Figure 5 illustrates SNR of 58 dB, at pulse operating frequency of 11.9 MHz. This signifies that the pulse is stable in the laboratory environment.

Table 1 shows the compilation of studies on typical DS generation based on TI. Most of the DS emissions emission were centred at 1550 nm. The broadest 3 dB bandwidth was 39.95 nm, with pulse width 4.72 ps, using Bi_2Te_3. All the reported work were the typical DS with steep edges and flat top spectrum. In our work, the performance of DS pulse laser was comparable to others, but the DS generated had sideband imposed on the spectrum. MI from the nonlinear gain, parametric process and precise orientation of light polarization contributed to the formation of sidebands on DS.



(a) (b)

Figure 3. Oscillation trace of DS with sidebands at the pump power of 185.5 mW; (a) time span of 1500 ns and (b) time span of 150 ns

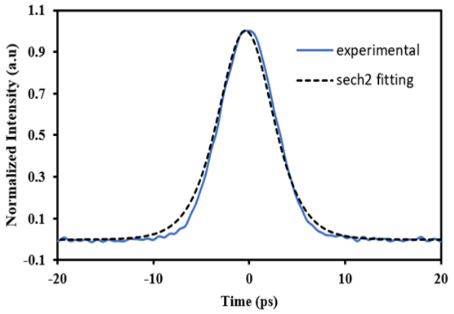


Figure 4. Measured pulse width with autocorrelator at the pump power of 185.5 mW

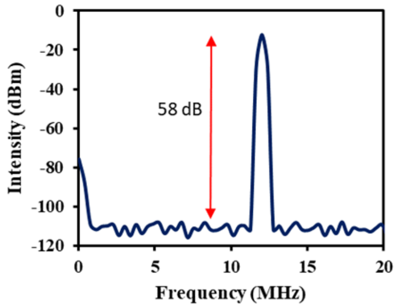


Figure 5. SNR of pulse measured at 58 dB

Table 1. Comparison of DS with TI

Center wavelength and 3 dB bandwidth	TI	Integration method	Repetition rate and pulse width	References
1559 nm, 26 nm	Bi_2Se_3	PCF	7.04 MHz, 7.564 ps	[36]
1560 nm, 34 nm	Sb_2Te_3	D shaped fiber	25.38 MHz, 167 fs	[37]
1571 nm, 39.95 nm	Bi_2Te_3	Fiber ferrule	10.71 MHz, 4.72 ps	[26]
1057.82 nm, 3.69 nm	Bi_2Te_3	Fiber ferrule	1.44 MHz, 230 ps	[38]
1558 nm, 17.6 nm	Bi_2Te_3	Fiber ferrule	11.9 MHz, 5.2 ps	This work

4. CONCLUSION

We demonstrated flat top DS with sidebands using homemade Bi_2Te_3, with spectrum centred at 1558 nm. Fundamental pulse repetition rate and pulse width were determined at 11.9 MHz and 5.2 ps, respectively. The precise tuning of light polarization and the nonlinear gain in the fiber laser resulted in the creation of sidebands. The number of sidebands and intensity grew as the pump power was raised. This work provided some insights on sidebands formation on DS using Bi_2Te_3. Moving forward, we will focus on the investigation of sidebands generation with orientation of PC and fiber length. Extension of current work will provide depper insights into the underlying physics of sidebands generation in DS and broaden the scope of potential applications for Bi_2Te_3 based DS fiber laser.

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