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Q-Switched Erbium Doped Fiber Laser Incorporating Antimony (III) Telluride in Polyvinyl Alcohol as Saturable Absorber

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ABSTRACT

In this paper, we demonstrated a Q-switched erbium doped fiber laser (EDFL) incorporating Antimony (III) Telluride (Sb_2Te_3) in polyvinyl alchohol (PVA) as passive saturable absorber. The saturable absorber was fabricated by dissolving Antimony (III) Telluride powder into PVA solution and dry in the ambient temperature for 48 hours. Then, 1 mm^2 x 1 mm^2 Sb_2Te_3-PVA film based saturable absorber were sandwiched in between FC/PC ferrule for Q-switched laser generation. The stable and self-started Q-switched laser operates at center wavelength 1560 nm with 3 dB bandwidth of 0.23 nm. The laser operates at pump power of 29.3 mW until 84.9 mW with repetition rate of 20.99 kHz to 89.29 kHz and pulse width of 13.95 µs to 5.10 µs. At maximum pump power, the laser able to achieve pulse energy of 62.72 nJ and high signal to noise ratio of 71.4.

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1. INTRODUCTION

The development in the generation of Q-switched fiber laser give a huge momentum in wide range of applications especially in remote sensing, range finding, laser processing and optical communications [1]. This Q-switched laser can be realized into two categories which is active or passive techniques. In active technique, an optical modulator is required to modulate the loss in the cavity. This technique enables a high stability pulse, high power and narrow pulse duration [2]. On the other hand, in the passive technique, losses are automatically modulatesd by incorporating a saturable absorber. Many types of saturable absorbers are intensively investigated, including semiconductor saturable absorber (SESAM), carbon nanotubes (CNT) and 2D materials [3]. However, SESAM's are rather costly, complex in fabrication, operates in narrow band and requires long recovery time. Besides that, CNT's are cost effective and easy to fabricate, but operates at a particular wavelength thus requiring bandgap tuning by controlling the chirality and diameter [3].

Q-switching typically is a technique to generate a short pulse by sudden switching loss of the cavity Q-factor or cavity loss. By means, switching happens when the gain achieve a maximum energy and saturates, then suddenly switches from high states to low states in the form of short and intense pulse. This phenomenon can only be realized in the presence of saturable absorber. Thus, the saturable absorber are required to have a certain optical bandgap to allow the light absorption and electron transition for pulse generation. 2D materials are excellent candidates as saturable absorber. 2D material family consists of several materials group, which is graphene, transition metal dichalcogenides (TMD), black phosphorus (BP) and topological insulator (TI) which offers distinct, unique optical properties thus opening up ~~a~~ new opportunities for fiber laser applications [2].

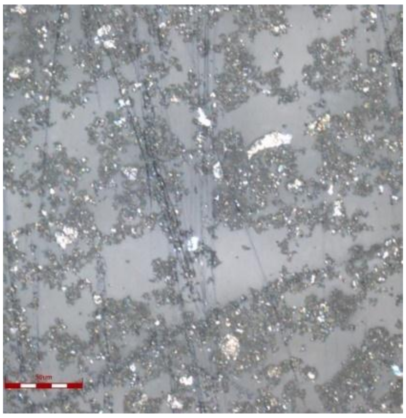
Antimony (III) Telluride (Sb_2Te_3) is one of the significant 2D material which lies in the TI's group. Unlike two of its other family member which is Bismuth (III) Selenide and Bismuth (III) Telluride, Antimony (III) Telluride have not been receiving as many attention as it deserves, especially in Q-switched regime. Antimony (III) Telluride have a narrowed optical bandgap, approximately 0.2 eV [4] which is ~~s~~ suitable as saturable absorber. There are several reported works on Antimony (III) Telluride as a saturable absorber using various techniques. Boguslawski et al. was able to generate a pulse laser using a liquid phase exfoliated method by dissolving the bulk Antimony (III) Telluride crystal into chitosan solution [4]. The Antimony (III) Telluride-chitosan solution were dropped on the side polished fiber for pulse generation. Though it has advantages in terms of deposition precision, this method causes the device to be highly sensitive to polarization. This can largely effect the produced pulsed if not controlled properly. In addition, Sotor et al. proposed a mechanical exfoliation technique from bulk Antimony (III) Telluride and was able to achieve more than 55 dB signal to noise ratio [5-6] in mode locking regime. However, this technique requires tedious works and the thickness of the exfoliated layer is rather hard to be controlled. Besides, it also causes a great number of material losses.

Thus, in this paper we proposed a method by dispersing Antimony (III) Telluride powder into a polyvinyl alcohol (PVA) as host polymer to developed Antimony (III) Telluride-polyvinyl alcohol (Sb_2Te_3-PVA) based passive saturable absorber. Using this method, concentration and thickness of the SA can be controlled. This method is easier to fabricate, with high repeatability and scalable production possibility. The developed Antimony (III) Telluride- polyvinyl alcohol based saturable absorber is sandwiched in between fiber-optic connector/physical contact (FC/PC) for a stable pulse generation in Q-switched regime.

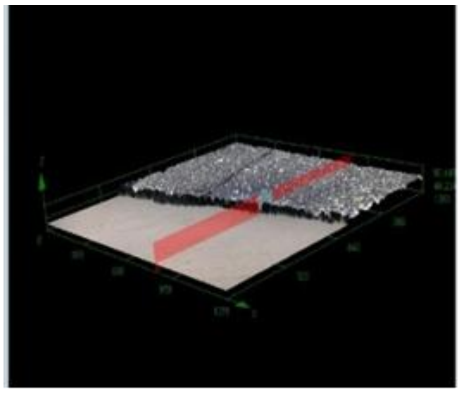
2. RESEARCH METHOD

2.1. Saturable Absorber Preparation

The polyvinyl alcohol which is a water soluble synthetic polymer was dissolved in De-Ionized (DI) water with the aid of a magnetic stirrer at room temperature to obtain a polyvinyl alcohol solution. Antimony (III) Telluride-polyvinyl alcohol based saturable absorber were prepared by dissolving 10 mg of Antimony (III) Telluride powder (Sigma-Aldrich, -325 mesh, 99.96% trace metal basis) into 5 ml of polyvinyl alcohol solution by ultra-sonication technique for 90 minutes, followed by centrifugation for 10 minutes at 2000 rpm to produce a stable Antimony (III) Telluride- polyvinyl alcohol suspension. Then, the Antimony (III) Telluride- polyvinyl alcohol suspension were decanted into a 14.4 cm^3 petri dish and kept in a dry cabinet at ambient temperature for 48 hours. The surface and the thickness of developed Antimony (III) Telluride-polyvinyl alcohol film based passive saturable absorber was observed and measured using 3D measuring laser microscopes (Olympus, LEXT OLS4100). The surface of the Antimony (III) Telluride- polyvinyl alcohol film consist of randomly distributed Antimony (III) Telluride powder with the measured thickness of 34 μm as shown in Figure 1(a) and Figure 1(b).



(a)



(b)

Figure 1. (a) Microscope Image of Sb_2Te_3-PVA Film (b) Thickness Measurement of Sb_2Te_3-PVA Film

2.2. Experimental Setup

The experimental setup of the proposed Q-switched EDFL is shown in Figure 2. The laser cavity are comprised of 980 nm laser diode, 980/1550 nm wavelength division multiplexing (WDM), 2.6 m long Erbium doped fiber (EDF), an optical isolator, 80/20 optical coupler and the newly developed Antimony (III) Telluride- polyvinyl alcohol based passive saturable absorber. The laser was pump by a 980 nm laser diode through the WDM. An EDF with peak absorption of 45 dB/m at 1531 nm was used to excite the 980 nm light to 1550 nm wavelength. An optical isolator was used to allow for unidirectional light propagation. The output were tapped out using 80/20 coupler where 80% of light oscillates in the cavity and 20% used for output measurement. The output was measured using an optical spectrum analyzer (OSA), a digital oscilloscope, an optical power meter and a radio frequency spectrum analyzer (RFSA). The Antimony (III) Telluride-polyvinyl alcohol based saturable absorber was cut into 1 mm^2 x 1 mm^2 and sandwiched in between FC/PC fiber ferrule for pulse laser generation.

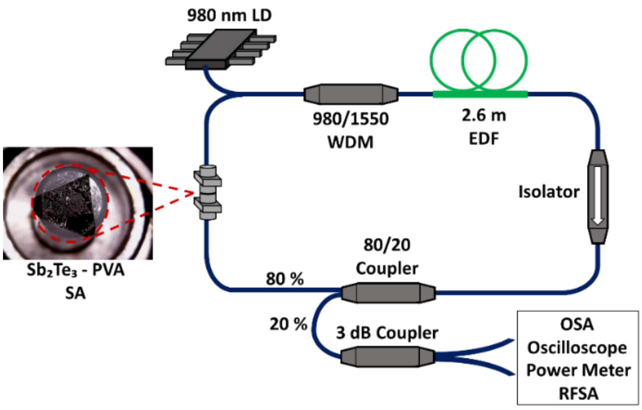


Figure 2. Laser Cavity Configuration Setup

3. RESULTS AND ANALYSIS

The Q-switching operation were observed at initial pump power of 29.3 mW and was held stable until the pump power reaches 84.9 mW. When the pump power was tuned exceeding 84.9 mW, the pulse started to get distorted and eventually diminished. To confirm the pulse generated were directly associated with the newly fabricated saturable absorber and not subject to the nonlinear polarization rotation (NPR) in the cavity, the saturable absorber were removed resulting in no observable pulse as the pump power was tuned over a wide range. Figure 3 shows the optical spectrum at 84.9 mW. The laser operates at a central wavelength of 1560 nm with a 3 dB spectral bandwidth of 0.23 nm due to the spectral broadening induced by the Antimony (III) Telluride-polyvinyl alcohol saturable absorber

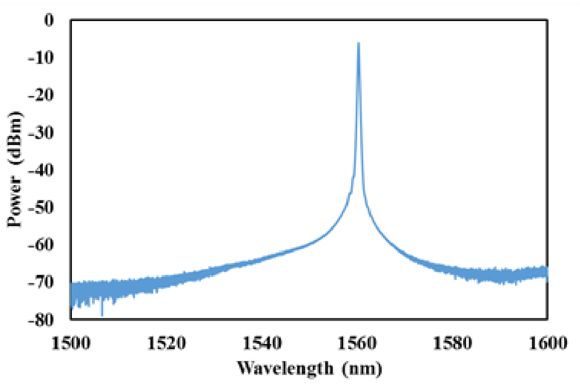


Figure 3. Optical Spectrum at Pump Power of 84.9 mW

Figure 4 (a) displays the typical oscilloscope trace of Q-switched laser at maximum pump power of 84.9 mW. The figure shows a uniform pulse with no distinct amplitude variation. The pulse duration at full width half maximum showsn in Figure 4(b) are 5.1 µs and pulse-to-pulse separation of 11.2 µs.

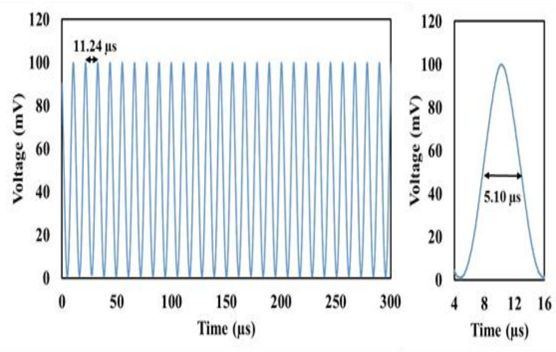


Figure 4. (a) Typical Oscilloscope Traces (b) Single Pulse at Pump Power of 84.9 mW

Figure 5 shows the repetition rate and pulse duration as a function of pump power. The repetition rates were observed to increase from 21.0 kHz to 89.3 kHz as the pump power was increased from 29.3 mW until 84.9 mW. On the contrary, the pulse width was decreased from 14.0 µs to 5.1 µs when the pump power was increased. The increase in pump power provides more photons channeled to the saturable absorber resulting in faster saturation of the saturable absorber, thus emitting more light. Thus, the repetition rates become faster and pulse width is narrowed.

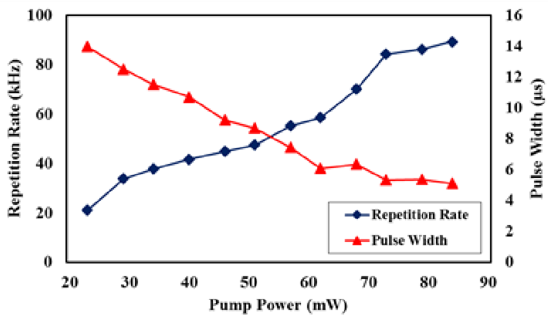


Figure 5. Repetition Rate and Pulse Width as a Function of Pump Power.

Figure 6 shows the output power and pulse energy as a function of pump power. The output power increases directly proportional to the increasing pump power, from 0.9 mW up to 5.6 mW. Same goes to pulse energy, increased from 46.2 nJ to 67.4 nJ at pump power of 62.7 mW and decreased as the pump power was increased beyond 62.7 mW. The increasing of repetition rate and decreasing pulse width can creates an intense pulse allowing increased pulse energy. The proposed works produce a wide range of tunable repetition rate from 20.99 kHz to 89.30 kHz which is better than Bismuth (III) Selenide (Bi_2Se_3) [8,9] and Bismuth (III) Telluride (Bi_2Te_3) [7,10] based saturable absorber. The shortest single envelope of 5.1 µs is shorter than 27.3 µs as reported in [9] using Bismuth (III) Selenide Bi_2Se_3 and 12.74 µs employing Bismuth (III) Telluride [7].

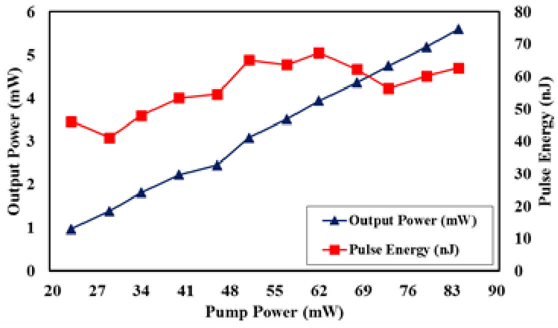


Figure 6. Output Power and Pulse Energy as a Function of Pump Power.

Figure 7 depicts the output of RFSA at fundamental repetition rate of 89.3 kHz. The recorded signal to noise ratio of the Q-switched laser is 71.4 dB showing that the laser have a good stability due to high signal to noise ratio. The signal to noise ratio (SNR) of 71.4 dB is higher than other reported works of topological insulators (Tis) based saturable absorber [8-10].

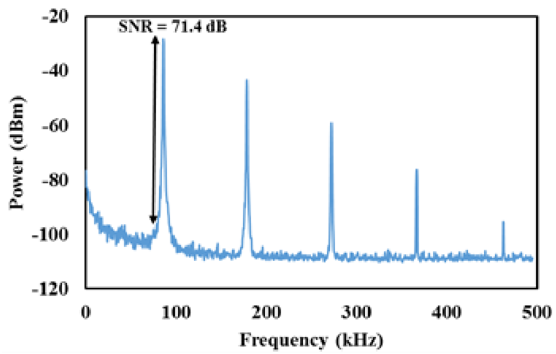


Figure 7. Signal to Noise Ratio at Fundamental Repetition Rate of 89.3 kHz

Table 1. Comparison of the Laser Performance Using Different Topological Insulator based Saturable Absorber in Q-Switched Regime

SA	λ (nm)	Pp min. (mW)	Pp max. (mW)	RR (kHz)	PW (s)	AOP (mW)	PE max. (nJ)	SNR (dB)	Ref.
Bi_2Te_3	1567.1	43	201.7	3.3-12.7	12.74 μ	3.5	278.8	-	[7]
Bi_2Te_3	1589.1	67	238.5	2.1-12.8	13 μ	19.5	1.525	36.4	[10]
Bi_2Te_3	1543.3	30	210.0	12.6-177.7	217 n	1.3	7.5	-	[11]
Bi_2Se_3	974.0	9.3	150.1	6.2-40.1	4.9 μ	1.6	39.8	50	[8]
Bi_2Se_3	1530.0	60	100.0	26.1-36.6	27.3 μ	-	6.1	58	[9]
Sb_2Te_3	1560. 0	29.3	84.9	20.9-89.2	5.10 μ	5.6	62.7	71.4	This Work

SA – Saturable absorber, Pp – pump power, RR- repetition rate, PW- pulse width, AOP-average output power, PE- pulse energy, SNR – Signal to noise ratio, Bi2Te3- Bismuth (III) Telluride, Bi2Se3- Bismuth (III) Selenide, Sb2Te3- Antimony (III) Telluride.

4. CONCLUSION

As a summary, Q-switched Erbium-doped fiber laser (EDFL) incorporating Antimony (III) Telluride- polyvinyl alcohol (Sb_2Te_3-PVA) as passive saturable absorber was demonstrated in this manuscript. The saturable absorber was prepared by dissolving Antimony (III) Telluride powder into polyvinyl alcohol solution. The Antimony (III) Telluride- polyvinyl alcohol suspension was decanted into a petri dish and left dry in the ambient for 48 hours. The saturable absorber was deposited in between the fiber-connector/physical contact (FC/PC) with fiber connector to generate pulse laser. The stable Q-switched laser operates on threshold input pump power of 29.3 mW and was sustained until 84.9 mW. The laser operates at center wavelength of 1560 nm. As the pump power increased, the repetition rate was increased and pulse width decreased. The highest pulse energy were achieved at 67.4 nJ at input pump power of 62.7 mW. The output power was directly proportional to the input pump power. The recorded signal to noise ratio (SNR) of 71.4 dB shows the high stability of the generated pulse which is also the highest recorded signal to noise ratio reported among topological insulator based passive saturable absorber.

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