Microsecond Pulse Generation using Bismuth Salenide as Saturable Absorber in 1.5 µm Region

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Abstract. A Q-switched Erbium-doped fiber laser (EDFL) was demonstrated utilizing Bismuth Salenide (Bi₂Se₃) as a saturable absorber. The saturable absorber (SA) is fabricated by mixing directly the Bismuth Salenide (Bi₂Se₃) into polyvinyl alcohol (PVA) aqueous solution to form a thin film. The SA is integrated into EDFL cavity to achieve a stable Q-switched at center wavelength of 1559.8 nm. The peak power is a steady increasing pattern from 2.52 mW to 3.21 mW as the pump power is increased from 86.1 mW to 116.6 mW. The highest pulse energy obtained was 36.9 nJ at the pump power of 116.6 mW.

1. Introduction

Pulsed laser has received tremendous focus among researchers within the field of laser because it plays crucial roles in wide selection of applications including optical communication, optical sensing, materials processing technology, life sciences, precision mechanics, national defence science and etc [1-3]. There are two techniques to realize pulsed laser which are active and passive. The latter is more favourable due to few advantages including ease of preparation, high flexibility and high efficiency. The generation of pulsed laser via passive means is highly dependent on the implementation of material as a saturable absorber inside a laser cavity. Recent years, many materials were implemented inside laser cavity to initiate pulsed laser such as semiconductor saturable absorber mirrors (SESAMs) [4] and carbon nanotubes (CNTs) [5].

For SESAMs, pulsing method require additional devices such as mirror, lenses and U-bench units which introduce extra losses to the cavity. Therefore, researcher starts to use carbon-based materials to generate pulsed laser. CNTs, which seems very promising in terms of electron mobility exhibit ultra-fast recovery time (< 1 ps) and wide absorption spectrum (1-2 µm) [6]. However, tenability of wavelength for CNTs are dependable on it shapes and sizes, thus provide complexity for pulse generation. For instance, structural, morphological and alignment control needed to be establish for the purpose of band gap alteration for CNTs [7]. Thus, 2-dimensional carbon allotrope (graphene) is introduced due to excellent electronic and optical properties. In terms of saturable absorption ability, graphene provide significant improvement compare to CNTs. Hexagonal honeycomb lattice of graphene exhibit wide-band operation due to its ultrafast recovery time (~200 fs) and point band gap structure [8]. However, graphene exhibits low modulation depth, typically lower than 2 % per layer. Since then, few Dirac-like materials are introduced as SA in laser cavity (Bi₂Se₃, Bi₂Te₃). Previously, Q-switched fiber lasers were demonstrated using Bismuth (III) Telluride (Bi₂Te₃) as a saturable
In this paper, we demonstrate a Q-switched fiber laser based on Bismuth (III) Salenide (Bi$_2$Se$_3$) as SA to generate laser in 1.5 micro region.

2. Preparation and Optical Characterisation of Bi$_2$Se$_3$ SA.

The commercially available few-layer Bi$_2$Se$_3$ powder with molecular weight of 654.84 g/mol was used to prepare the SA in this experiment. To prepare the host polymer, 1 g of polyvinyl Alcohol (PVA) (Sigma Aldrich) is dissolved in 120 ml de-ionized (DI) water with the aid of a magnetic stirrer at room temperature. Next, 14 mg of Bi$_2$Se$_3$ powder was mixed with 3 ml of the PVA solution before they are thoroughly mixed using a magnetic stirrer for three hours. Then the Bi$_2$Se$_3$-PVA solution was placed in ultrasonic bath for 10 minutes to make sure the Bi$_2$Se$_3$ material fully binds with the PVA. After that, the Bi$_2$Se$_3$ suspension was carefully poured onto petri dishes to avoid trapping any air bubble and is left to dry at room temperature for 48 hours to form Bi$_2$Se$_3$-PVA composite film.

Figure 1(a) shows the field emission scanning electron microscopy (FESEM) image of the fabricated Bi$_2$Se$_3$ film. As shown in the figure, the Bi$_2$Se$_3$ film has a high density of micro-rods and micro-grains, which can be clearly viewed on the substrate surface and distributed randomly on the substrate surface. These micro-rods and micro-grains are in irregular shapes with an average size of 0.3 to 1.66 μm. Figure 1(b) illustrates the absorbance spectrum of the prepared Bi$_2$Se$_3$-PVA film in the range of 200 nm to 1100 nm. The figure attests a constant absorbance for the Bi$_2$Se$_3$-PVA film which indicates that it possesses a broadband resonance wavelength like graphene. Figure 1(c) shows the Raman spectrum of the fabricated Bi$_2$Se$_3$-PVA film. The spectrum indicates three distinct peaks at 67 cm$^{-1}$, 126 cm$^{-1}$, and 170 cm$^{-1}$, which can be assigned to the A$_{1g}$, E$_{2g}$ and A$_{2g}$ vibrational modes, respectively. The nonlinear optical response property for the Bi$_2$Se$_3$ film was also investigated to confirm its saturable absorption characteristic by applying dual optical power meter techniques. The pulse input source used a mode-locked fiber laser, which has femtosecond output pulse with a 17 MHz repetition rate and a 900 fs pulse duration, which the output power is approximately 5 mW. Figure 1(d) shows the transmission characteristic of the Bi$_2$Se$_3$ SA, which was fitted using the following simple saturable absorption model equation:

$$\text{Transmittance (%) } = 100 \times \left(1 - \frac{I}{I_0}\right)$$
\[ T(I) = 1 - a_0 \exp\left(\frac{I}{I_{\text{sat}}}\right) - a_{\text{ns}} \]  

where \( T(I) \), \( a_0 \), \( I \), \( I_{\text{sat}} \) and \( a_{\text{ns}} \) stand for the transmission, modulation depth, input intensity, saturation intensity, and non-saturable absorption, respectively. The modulation depth, non-saturable absorption and saturation intensity were measured to be approximately 15.9 %, 77 % and 50 MW/cm², respectively as shown in Figure 1(d).

3. Experimental setup

Figure 2 shows the experimental setup of the erbium doped fiber laser with Bi₂Te₃ as a saturable absorber. The ring cavity consists of a 2.4 m long erbium doped fiber (EDF) as the active medium, a 980/1550 nm wavelength-division multiplexer (WDM), an optical isolator, a Bi₂Se₃ based SA, and a 90:10 output coupler. The Bi₂Se₃ as a SA is sandwiched between two FC/PC fiber connectors and inserted into the fiber cavity. The insertion loss of the SA is measured to be around 2 dB at 1550 nm. It is pumped by the 980 nm laser diode via a 980/1550 nm WDM. Isolator is located between coupler and gain medium to allow light travel in a one direction. The output of the laser is tapped out of the cavity through a 90:10 output coupler, which allows 10% of the output to be extracted for analysis.

4. Results and Discussion

In the experiment, the EDFL started to generate pulse at threshold pump power of 86.1 mW. As the pump power is further increased, the Q-switching operation was maintained up to 116.6 mW. Figure 3 shows the comparison of the output spectrum of the proposed EDFL with and without using Bi₂Se₃ as a SA at the pump power of 116.6 mW. As seen, the operating wavelength of the laser shifted to the left by 1.2 nm from 1561.0 nm to 1559.8 nm with the incorporation of the SA. The wavelength shift and higher intensity obtained by the proposed Q-switched EDFL is due to the integration of Bi₂Se₃ based SA device inside the cavity. The output spectrum with SA (solid line) was measured at 1559.8 nm. Without the SA, the ring cavity operates in a continuous wave (dotted line) method and output spectrum at 1561.0 nm.
Figure 3. Output spectrum of the EDFL with and without Bi₂Se₃ as a SA at pump power of 175 mW

The stable pulse trains with different repetition rate were observed when the pump sources were progressively increased from 86.1 mW to 116.6 mW. The EDFL started to produce a Q-switched pulse at threshold pump power of 86.1 mW. Figures 4 (a) shows typical oscilloscope trace of the Q-switched pulse train at the pump power of 116.6 mW. It shows the peak-to-peak duration of 11.49 μs, which is equal to the repetition rate of 87.03 kHz. Figure 4 (b) shows a single envelope of the Q-switching pulse at pump power of 116.6 mW. The pulse is observed to have an almost symmetric shape with a pulse width of approximately 5.11 μs.

Figure 4. (a) Oscilloscope pulse train at 116.6 mW pump power (b) a single envelop of the Q-switched at power pump of 116.6 mW

Figure 5 shows the relationship between the repetition rate and the pulse width against the pump power. The repetition rate of the proposed Q-switched EDFL can be tuned from 84.08 to 87.03 kHz as the pump power is raised from 86.1 to 116.6 mW. In the meantime, the pulse width reduces from 5.41 μs to 5.11 μs as the pump power is increased within the same range.
Figure 5. Repetition rate and pulse width of Q-switched EDFL within 86.1 mW to 116.6 mW.

Figure 6 illustrates the relationship between the pulse energy and the peak power as the function of the pump power. The peak power is showing a steadily increasing pattern from 2.52 mW to 3.21 mW as the pump power is increased from 86.1 mW to 116.6 mW. The highest pulse energy obtained was 36.9 nJ at the pump power of 116.6 mW.

The radio frequency (RF) spectrum analyser at pump power of 116.6 mW was measured. Figure 7 shows the RF spectrum of the Q-switched laser output of the pumping sources. It shows a stable repetition rate of 87.03 kHz and peak to background ratio of about 60 dB. This indicates stable pulses are produced by our laser cavity.
5. Conclusion
An EDFL is proposed and demonstrated using Bi\textsubscript{2}Se\textsubscript{3} as a passive saturable absorber (SA). Bi\textsubscript{2}Se\textsubscript{3} film is sandwiched between two FC/PC fiber connector to analyze the performance of erbium doped fibre laser based on Bi\textsubscript{2}Se\textsubscript{3} as a saturable absorber. Without SA, the ring cavity operates in a continuous wave regime with output spectrum at 1561.0 nm. By inserting SA, the EDFL operates at 1559.8 nm. The lasers was self-started and generate stable pulse train by changing the pump power from 86.1 mW to 116.6 mW with repetition rate that can be tuned from 84.08 to 87.03 kHz. It operated at 1559.8 nm wavelength, which was slightly red-shifted from the CW laser without the SA due to insertion loss of the SA device. The spectral broadening was also observed due to self-phase modulation effect inside the laser cavity. The RF spectrum showed the signal noise to ratio of about 60 dB, which indicates Q-switched operates with an excellent stability. The output power increases from 2.52 to 3.21 mW as the pump power increased from 86.1 mW to 116.6 mW. The maximum pulse energy of 36.9 nJ was obtained at pump power of 116.6 mW. The lowest pulse width of 5.11 μs was also obtained at pump power of 116.6 mW.

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