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Q-switching in EDFL Cavity using Ti_3AlC_2 as Saturable Absorber

Suziana Omar, Baktiar Musa*, Sulaiman Wadi Harun, Norizan Ahmed, Nur Farhanah Zulkipli, Zulzilawati Jusoh, and Husna Abdul Rahman

***Abstract*— In this paper, Titanium Aluminium Cloride (Ti_3AlC_2) is used as a saturable absorber (SA) to generate Q-switched pulses in an erbium-doped fibre laser (EDFL) cavity. The Ti_3AlC_2 film was prepared based mixing the material with polyvinyl alcohol (PVA) solution. It was added into the laser cavity by sandwiching the film between two fiber ferrules. By controlling the cavity's loss and gain, a stable Q-switched operation was achieved. When the pumping power was increased from 58.88 to 97.62 mW, the repetition frequency was increased from 59.52 to 67.52 kHz, resulting in the shortest pulse width of 3.3 µs. The Q-switched EDFL operated at a centre wavelength of 1560 nm, had a maximum pulse energy of 138.76 nJ, and a slope efficiency of 9.36 percent. The results demonstrate that Ti_3AlC_2 can be used as a SA for realizing a laser device for various applications including optical communications.**

***Index Terms*— Q-switched, 2D material,saturable absorber.**

I. Introduction

THE saturable absorption mechanism was used to generate laser pulses based on Q-switching mechanism. Once the beam enters the fibre laser cavity and reaches the saturable absorber (SA), the photons are absorbed by the electron contained within the SA, allowing the electron to leap to a higher energy state. The saturation of SA allows the generation of pulses in kHz regime. In recent years, the research interests are surged in this topic due to their utility in a variety of industrial applications, including spectroscopy, sensing and medicine [1,2]. Extensive researches have also been conducted to improve their speed and efficiency.

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Suziana Omar, Baktiar Musa, Norizan Ahmed and Zulzilwati Jusoh are from School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA, Cawangan Terengganu, Kampus Dungun, 23000 Dungun, Terengganu, Malaysia (email: suzia5374@uitm.edu.my and baktiar@uitm.edu.my).

H. A. Rahman is from School of Electrical Engineering, College of Engineering, Universiti Teknologi MARA (UiTM), 40450 Shah Alam, Selangor, Malaysia. (e-mail: husna232@uitm.edu.my).

N. F. Zulkipli and S. W. Harun are from Photonics Engineering Laboratory, Department of Electrical Engineering, University of Malaya, Kuala Lumpur 50603, Malaysia. (e-mail: swharun@um.edu.my).

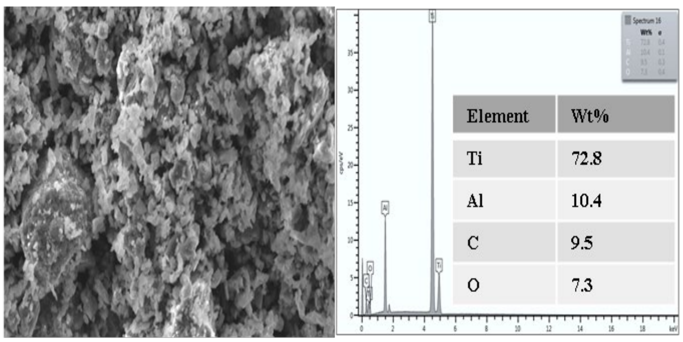
*Corresponding author
Email address: baktiar@uitm.edu.my

Q-switched fibre lasers are advantageous for a variety of applications, including laser cutting, remote sensing, and medical [3]. Fiber lasers combine high beam quality with cost-effective technology, and as a result, numerous papers have been published on this subject in recent years [4]. Numerous techniques, including nonlinear polarisation rotation (NPR) [5,6], semiconductor saturable absorber (SESAMs) [7-9], carbon nanotubes (CNTs) [10-11], and graphene [12], have been demonstrated to generate Q-switched fibre lasers with saturable absorber (SA). When low light is absorbed, the light intensity increases. However, these SAs have inherent weaknesses that limit their effectiveness as SAs due to factors such as high sensitivity to the environment, complex optical alignment, complex fabrication process, or narrow operating bandwidth [13,14]. Recently, due to their graphene-like electronic band structure, topological insulators, black phosphorous, and transition metal dichalcogenides (TMDs) have been investigated [15]. TMD materials have garnered the most interest for short pulse generation among 2D nanomaterials due to their complementary electronic properties [16]. MXene, a newly synthesised 2D material, has also recently been the subject of an extensive study [17,18]. However, its parent phase, the MAX phase (layered metal carbides and nitrides), has not been fully explored in terms of its ability to generate near-infrared pulses. To be precise, the MAX phase (bulk) is an early version of MXene (2D) before A-group elements (such as aluminium) were removed from the composition. It is as exceptional as its precursor in terms of electrical conductivity, thermodynamic stability of nanolaminates, high damage tolerance at room temperature, mechanical strength, and oxidation resistance [19,20].

Titanium Aluminum Carbide (Ti2AlC) is the MAX phase family's first material. It demonstrates efficiency in the 1.55-m region with a 2:1:1 composition [13]. We investigate the potential of a MAX phase Ti_3AlC_2 material as a SA for operation in 1.5 µm region. Here, a Ti_3AlC_2 thin film is prepared by embedding its compound into polyvinyl alcohol (PVA). The film is inserted into an erbium doped fibre (EDFL) cavity through a sandwich-structured fiber-ferrule device. By increasing the pump power from 55.88 mW to 97.62 mW, a stable Q-switched pulse train is formed at 1560 nm.

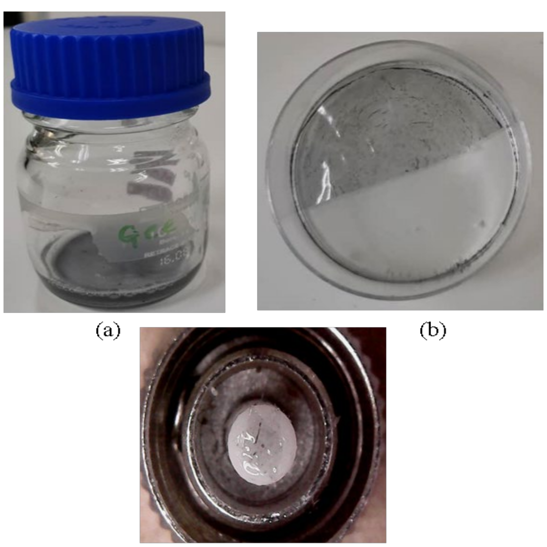
II. Characterization and Preparation of SA

Field-emission scanning electron microscopy (FESEM) and energy dispersive spectroscopy (EDS) were used to characterise the Ti_3AlC_2 thin film. The FESEM image of the film is shown in Fig. 1(a), which indicates the Ti_3AlC_2 particles has a size in a range from a few to tens of micrometres. The elemental composition of Ti_3AlC_2 was determined using energy-dispersive X-ray spectroscopy (EDX) as shown in Fig. 1(b). The EDX analysis indicates few strong peaks that corresponding to titanium (Ti), aluminium (Al), and carbon (C). This proved that the film consists of Ti_3AlC_2 elements. The Ti_3AlC_2 thin film was synthesised by mixing Ti_3AlC_2 powder with a solution of polyvinyl alcohol (PVA). To begin, 1 gram of polyvinyl alcohol (PVA) powder was dissolved in 120 ml distilled water. A magnetic stirrer was used to stir the mixture at 300 rpm for approximately 24 hours on a hotplate set to 200°C. Following that, the PVA solution was poured into a clean beaker along with 10mg of Ti_3AlC_2 powder. After 24 hours of stirring at room temperature, the Ti_3AlC_2 PVA solution was obtained. Following that, a two-hour ultrasonication was used to remove any particles that had not been consumed.



(a) (b)

Fig. 1.Characteristics of Ti_3AlC_2 film based saturable absorber (a) FESEM image (b) EDX analysis



(a) (b) (c)

Fig. 2. Preparation of Ti_3AlC_2 film based saturable absorber (a) Ti_3AlC_2 solution that fully dissolved (b) peeling Ti_3AlC_2 thin film that dried in a petri dish (c)Ti_3AlC_2 film on the ferrule

Fig. 2(a) shows the prepared Ti_3AlC_2 PVA solution [21]in a 25ml bottle.The fully dissolved solution was then poured onto a petri dish. It was allowed to dry at room temperature for at least 48 hours to form a Ti_3AlC_2 thin film as shown in Fig. 2. (b). This film was peeled and cut to a dimension of 1 mm x 1 mm from the petri dish in order to be used as a SA. The concentration of the SA film in relation to its thickness is a critical parameter for pulse generation in passively Q-switched fiber laser. As illustrated in Fig. 2(c), the thin film is placed on a fibre ferrule for pulse generation. To avoid damaging the film SA, the Q-switched operation was carried out at a low or moderate pump power.

III. Experimental Arrangements

In this work, we used an Erbium-doped fibre laser (EDFL) cavity to test the SA as shown in Fig. 3. The Erbium-doped fiber (EDF) was pumped in forward direction by a 980nm laser diode through a 980/1550nm Wavelength Division Multiplexer (WDM) to provide gain to the cavity. It has a length of 2.4 m long with a mode field diameter of 5.8 m and a fibre diameter of 125.4 m at 980nm. A polarization-independent isolator (PI-ISO) was used in the ring cavity, ensuring only unidirectional light and preventing light from moving backward inside the laser cavity. A Ti_3AlC_2 film was placed inside the cavity through a sandwich-structured fiber-ferrule device to function as a Q-switcher. Index matching gel was utilised to adhere a Ti_3AlC_2 SA thin film to the surface of a fiber-ferrule. SA generates Q-switched laser pulses by continuously modulating the cavity's Q-factor. An optical output coupler with a 90/10 split ratio was used to harvest 10% of the lasing output while returning 90% of the lasing within the laser cavity through the WDM's 1550 nm port. The output of the laser cavity was linked to an oscilloscope (GWINSTEK: GDS-3352) for analysis and a 7.8GHz radio frequency (RF) spectrum analyzer (ANRITSU, MS2683A) for measurement of the output pulse train. To capture the output power at various pump power and the laser spectrum an optical power meter (Thorlabs PM 100D) and 0.02 nm resolution optical spectrum analyzer (OSA, Yokogawa AQ6370C) were respectively used.

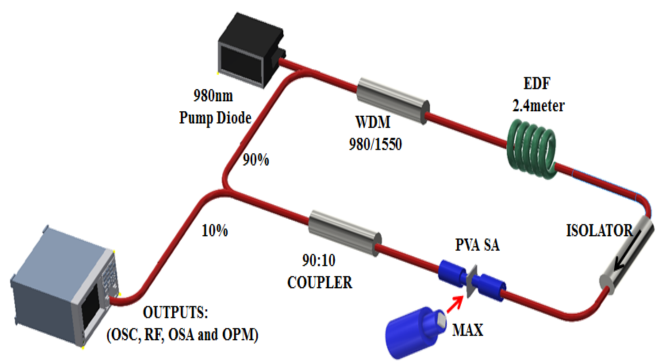


Fig. 3. Schematic diagram of the Q-switched fiber laser utilizing Ti_3AlC_2 PVA as saturable absorber.

IV. Results and Discussion

Passively Q-switched pulses are generated and remained stable as the pump laser diode's input power was adjusted within 55.88 to 97.62 mW. The output spectrum of the Q-switched EDFL is illustrated in Fig. 4, as it was measured by an OSA at a pump power of 97.62 mW within a span 100 wavelength range of 1510 nm to 1610 nm. Inset figure shows the enlarged spectrum, indicating that the laser peaked at 1560 nm. The stability of pulses at the 97.62 nm pump power was also measured using an RF spectrum analyzer as demonstrated in Fig. 5. The RF spectrum has recorded numerous harmonics over a wideband frequency range within a span of 1000 kHz. At 67.02 kHz fundamental frequency, the generated Q-switched signal has a signal-to-noise ratio (SNR) of 67.93 dB. The result indicates the exceptional Q-switching stability.

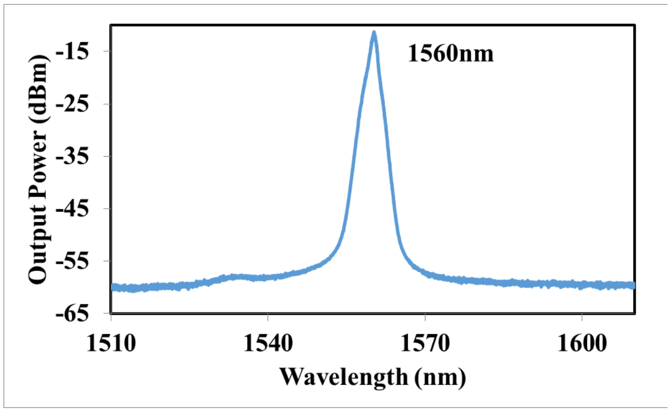


Fig 4. Output spectrum of Q-switched Ti_3AlC_2 at pump power of 97.62mW

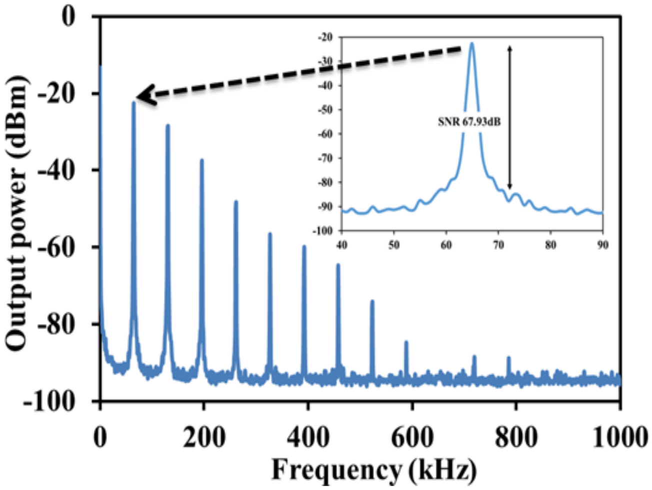
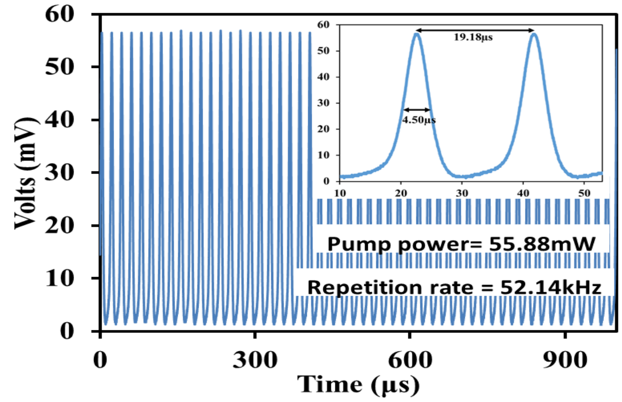
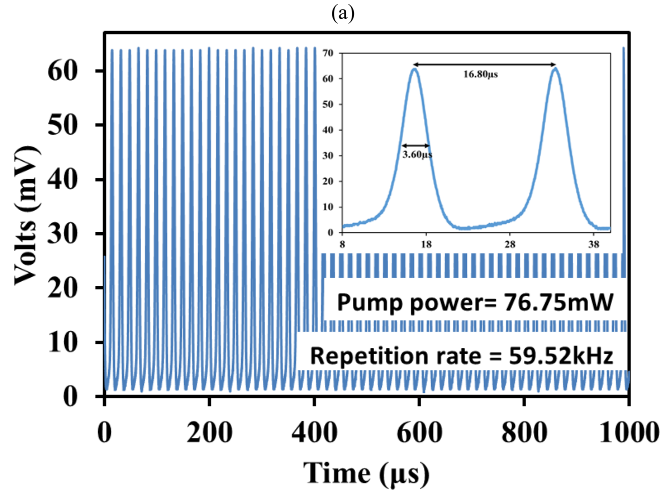


Fig 5. RF spectrum at 97.62 mW

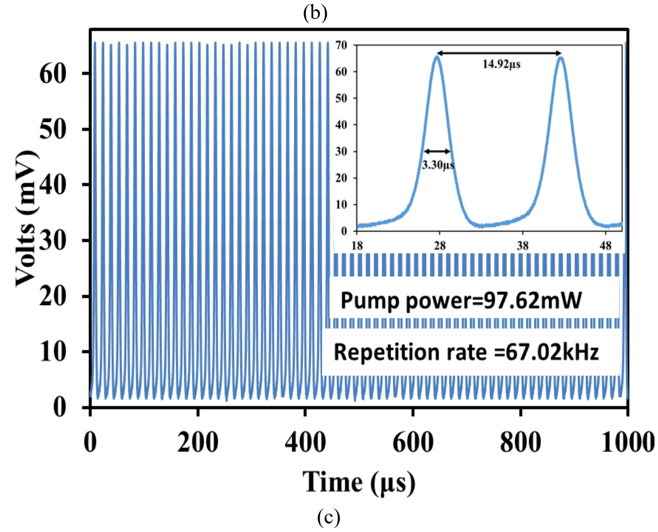
The Q-switching pulse trains were stable and maintained a uniform distribution throughout the pump power range of 55.58 to 97.62 mW as shown in Fig. 6. Fig. 6 (a) depicts a simple Q-switched laser pulse train obtained from the digital oscilloscope trace when the pump power was set to 55.58 mW. The pulse train is repeated at a frequency of 52.14 kHz. As the power of the input pump was increased to 76.75 mW and 97.62 mW, the repetition rate was also improved to 59.52 kHz and 67.52 kHz as shown in Figs. 6 (b) and (c), respectively. The pulse duration, on the other hand, reduces with the increase pump power. All the pulse trains are stable and uniform, which indicates the stability of the Q-switching operation. As we increased the pump power to greater than 97.6 mW, the Q-switching pulses became unstable and then disappeared. The laser was converted to CW operation up to the maximum pump power of 200 mW. However, the Q-switching operation was regained as the pump power was reduced back to below 97.62 mW. This indicates that the damage threshold of the SA film is higher than the maximum power of the pump of 200 mW. These findings indicate that MAX phase Ti_3AlC_2 is a viable SA material for Q-switching application especially at low pumping strengths.



(a)



(b)



(c)

Fig 6. Oscilloscope pulse train at three different pump powers of (a) 55.88mW (b) 76.75mW (c) 97.62mW

The evaluation of pulse energy, average output power, repetition rate, and pulse width as functions of pump power, are carried out and the results are summarised in Figs. 7 and 8. The average output power increased steadily from 5.41mW to 9.30mW, as illustrated in Fig. 7, which plots the output power and pulse energy against the pump power. At a pump power of 97.62mW, the highest pulse energy of 138.76 nJ was obtained.

The pulse repetition rate and pulse width are plotted against the pump power in Fig. 8. The pulse rate increased from 52.14 to 67.02kHz as the output power of the pump increased from 55.88 to 97.62 mW, while the pulse width decreased from 4.5 to 3.3s. The linear relationships are typical for a Q-switched laser since the amount of energy delivered to the cavity was incraesed as the pump power increases until the SA becomes saturated.

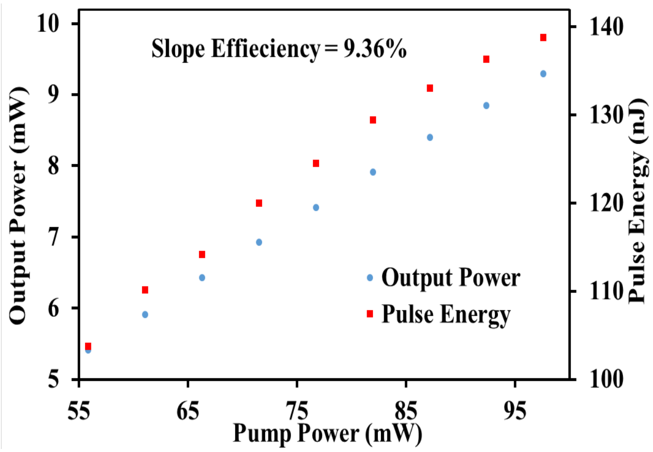


Fig 7. Output characteristics within 55.88mW to 97.62 mW of pump power of pulse energy and average output power.

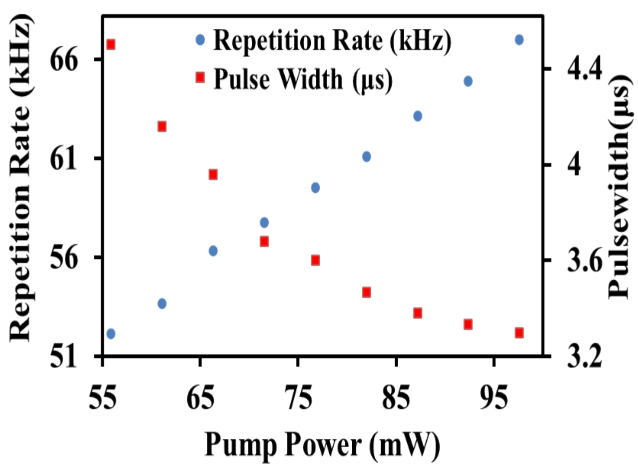


Fig 8. Output characteristics within 55.88mW to 97.62 mW of pump power: of repetition rate and pulsewidth

The proposed laser in this work is capable of producing a stable Q-switching output, indicating that a passive SA based on Ti_3AlC_2 has been successfully developed. Additionally, with Ti_3AlC_2, significant photonics application potential exists. The output performance of the proposed Ti_3AlC_2 SA is observed to be comparable with other SAs as shown in Table 1. This table summarizes the performance of various SA for Q-switching.

V. Conclusion

The Q-switched pulse generation was demonstrated in an EDFL cavity using Ti_3AlC_2 film-based SA. Self-starting and stable Q-switched pulse trains were obtained and operated at a center wavelength of 1560 nm. The pulses have a shortest pulse width of 3.3 μs and a maximum o pulse energy of 138.76 nJ. The pulse frequencies are tunable between 52.14 and 67.02kHz as the pump power varies between 55.88 and 97.62 mW. In the 1.5 µm wavelength region, the laser exhibits excellent Q-switching performance.

TABLE I
= Comparison of output performance by different SAs for passive Q-switching

Materials of SA	Max. Pulse Energy (nJ)	Repetition Rate (kHz)	Max. Output Power (mW)	Min. Pulse Width (μs)	Refs
Eu_2O_3	162	60.1-68.6	11.1	3.6	[16.]
Wse_2	33.2	49.6	1.23	3.1	[22.]
Ws_2	28.9	50.26-67.2	28.9	1.94	[23.]
Ti_3C_2Tx	125	70.67 ~ 96	12	2.31	[24.]
Ti_2AlC	22.58	16.14 ~ 27.45	0.62	4.88	[25.]
$TiSe_2$	79.28	24.5-73.79	5.85	1.31	[26.]
Ti_3AlC_2	138.76	59.52 ~ 67.52	9.30	3.3	This work

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