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Passively Q-switched Erbium-doped Fiber Laser Based on Iron Disulfide as a Saturable Absorber

N. Ahmed, N.F. Zulkipli, S. Omar, Z. Jusoh, H.A. Rahman, B. Musa and S.W. Harun

Abstract— **This work highlights the demonstration of a passively Q-switched pulse laser with iron disulfide (FeS_2) as a saturable absorber in near-infrared region. The FeS_2 saturable absorber is fabricated using liquid exfoliation method. A small piece of the FeS_2-SA film is incorporated into the erbium-doped fiber laser ring cavity resulting in stable repetition rate from 80.4 kHz to 88.5 kHz. The laser delivered a pulse duration that decreases from 12.43 µs to 11.3 µs. By tuning the power pump from 125.2 mW to 166.4 mW, maximum output power and pulse energy are recorded at 2.2 mW and 24.8 nJ respectively. Therefore, this work reveals that FeS_2 has good nonlinear saturable absorption properties to produce a stable pulse at 1559.8 nm central wavelength.**

Index Terms—**erbium-doped fiber laser, iron sulfide, Q-switching, saturable absorber.**

I. Introduction

THE short pulse fiber lasers generated from a passive Q-switcher still offers a tremendous applications such as material cutting [1], oral and maxillofacial surgery [2] and optical communications [3]. To date, many researchers prefer passive techniques rather than active since it is more flexible , cost effective and compact. This technique requires a nonlinear absorptions material known as saturable absorber, that is capable to modulate the Q-factor of fiber ring laser and then generates pulse train as short as femtoseconds [4]. In early 1990s, semiconductor saturable absorber mirrors (SESAMs) had led the work as a Q-switcher followed by graphene that was discovered in 2004. Both materials have been making outstanding debut for years. However, the limitations on the operating bandwidth and high cost with a complex fabrication of SESAMs [5] and a small modulation depth per layer of graphene [6], hinder the potential of these saturable absorber (SA).

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Thus far, various types of materials have been actively explored such as single-wall carbon nanotubes (SWCNTs) [7][8][9] and quantum dots (QDs) [10][11][12]. In addition, recent research trend shows a growing interest in two-dimensional (2D) materials such as transition metal dichalcogenides (TMDs) (e.g., MoS_2, $MoSe_2$, WS_2), transition metal oxides (TMOs) (e.g., TiO_2, ZnO, NiO), topological insulators(BiSb, Bi_2Te_3, Bi_2Se_3) and black phosphorus (BP).

The demonstrations of Q-switched lasers of MoS_2 [13], Ws_2 [14], TiO_2 [15], Er_2O_3 [16], Bi_2Se_3 [17] and BP [18] had verified complementary properties of these 2D materials that can initiate Q-switching pulsation. These remarkable properties of 2D materials have stimulated a significant research interest in searching for a novel Q-switcher that can lead to high performance lasers. Moreover, 2D materials shared many similar properties such as Pauli blocking induced saturable absorption as well as ultrafast relaxation time, and high optical nonlinearity [19]. Pyrite (FeS_2) or formally known as iron disulfide, has great potential to be directed towards photonic applications. It has a bandgap of $\approx$ 0.95 eV with a high optical absorption capacity [20]. The crystal structure with unique electrical and optical properties of FeS_2 have been widely used for the applications in solar cell material [21] and photodetectors [22]. The above investigations have clearly shown the feasibility of this material, hence, the potential of FeS_2 in the applications of photonic devices must be explored.

This article demonstrates a passively Q-switched erbium-doped fiber laser using FeS_2-based SA. FeS_2-SA thin film was fabricated using liquid-phase exfoliation method which offers simplicity and low cost. The thin film was successfully incorporated into the erbium-doped fiber laser ring cavity and was able to operate a Q-switched with an average output power of 2.2 mW. The repetition rate was tuned from 80.4 kHz to 88.5 k Hz and a decreasing pulse width that varies from 12.43 µs to 11.3 µs was obtained. The central wavelength of 1559.8 nm was observed under a maximum input pump power of 166.4 mW. This indicates that FeS_2-SA is indeed a promising Q-switcher in pulsed laser applications.

II. IRON DISULFIDE FILM PREPARATION AND OPTICAL CHARACTERIZATION

The concentration with thickness of the SA film is the essential parameter for pulse generation in passive optical fibers. The preparation of FeS_2 film was started by dissolving 1 gram of polyvinyl alcohol (PVA) powder into 120 ml of distilled water. A magnetic stirrer was used to stir the mixture for about 24 hours at 100°C temperature. 50 ml of the prepared PVA solution is mixed with 15 mg of FeS_2 powder as illustrated

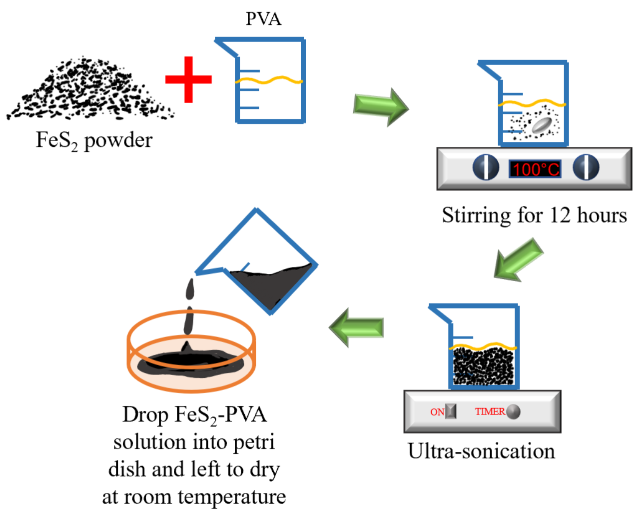

Fig. 1. FeS_2-SA preparation.

in Fig. 1. The mixture was further stirred at 300 rpm speed for 12 hours. In liquid-phase exfoliation (LPE) method, a high intensity of ultra-sonication by applying a sound energy higher than 20 kHz is required to create microbubbles and forces in order to break the van der Waals force between molecules, or in other words, remove particles that are not absorbed. The ultra-sonication bath was applied for 1 hour. Finally, FeS_2-PVA solution was left to dry at room temperature in a petri dish and used for characterizations.

A sample of FeS_2-SA is characterized using field emission scanning electron microscopy (FESEM), as shown in Fig. 2.

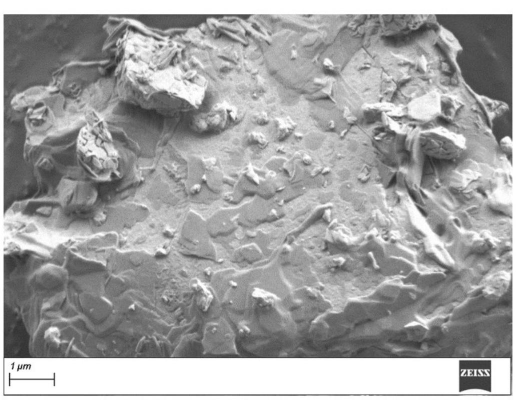

Fig. 2. FESEM image.

The energy dispersive X-ray spectroscopy (EDS) profile in Fig. 3 testifies the presence of Iron and Sulfur elements in the film. Fig. 4 depicts the linear absorption measurement of FeS_2-SA. The absorption of 5.6 dB occurs at 1559.8 nm. A technique known as a twin-balanced detector measurement were performed in order to measure the nonlinear optical absorption. From the profile shown in Fig. 5, FeS_2-based SA has a modulation depth, a saturable intensity, and a nonsaturable absorption of 4.8 %, 0.11 MW/cm2 and 12.7 %, respectively.

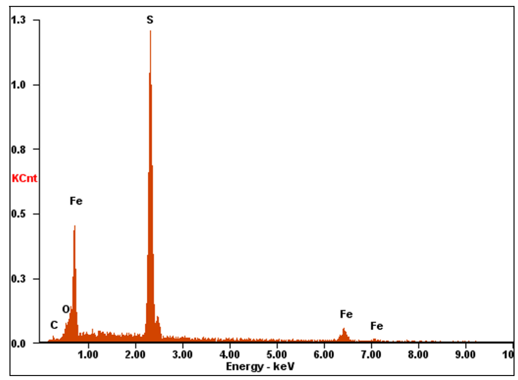

Fig. 3. EDS profile of FeS_2-SA

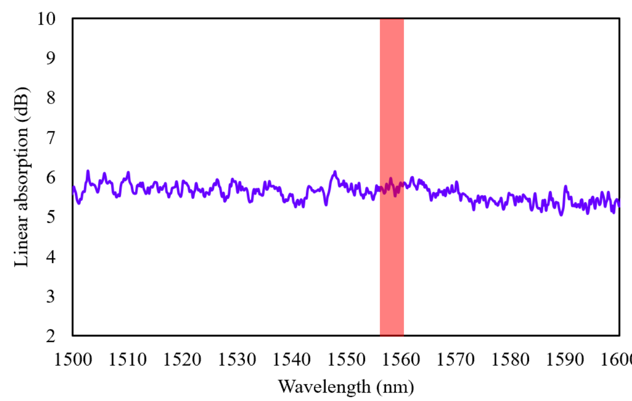

Fig. 4. Linear absorption measurement.

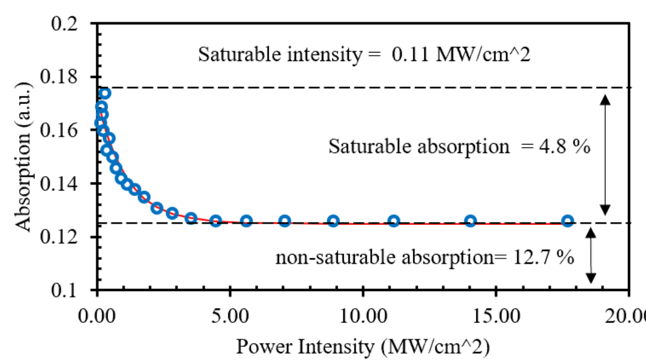

Fig. 5. Nonlinear optical profile of FeS_2-SA.

III. ERBIUM-DOPED FIBER LASER (EDFL) SETUP

Fig.6. described the configuration of all-fiber ring cavity setup of the EDFL with FeS_2 based SA. The input for the EDF

was pumped from a 980 nm laser diode via a 980/1550 nm wavelength-division multiplexing (WDM). A 2.4 m long erbium-doped fiber (EDF) with a coefficient of absorption of 23.9 dB/m at 979 nm, a numerical aperture (NA) of 0.24, a fibre diameter of 125.4 µm and a core diameter of 5.8 µm was used as the gain medium. An isolator (ISO) was positioned after the EDF to ensure unidirectional signal propagation. FeS_2-SA was deposited into the optical fiber ferrule, as shown in Fig. 7.

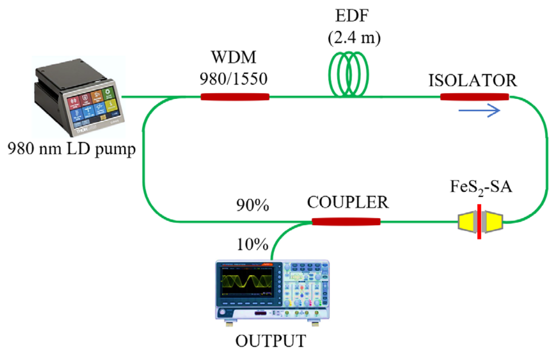

Fig. 6. Ring cavity setup of the EDFL Q-switched.

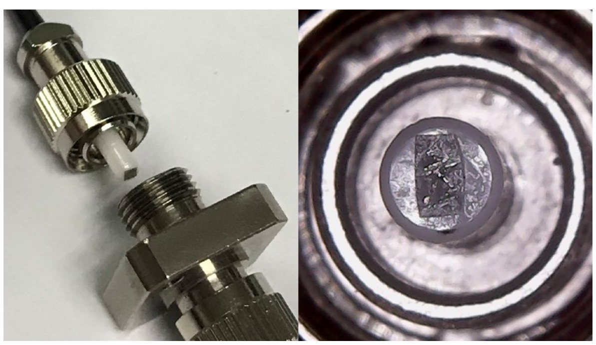

Fig. 7. FeS_2 film on fiber ferrule.

The SA continually modulates the Q-factor of the cavity and generates Q-switched laser pulses. A 3dB coupler was applied at the end of the ring cavity to extract 10% of the lasing output while the rest was recirculated within the cavity via the 1550 nm port of the WDM. The passive Q-switching output spectrum resulted from the FeS_2-SA was measured using an optical spectrum analyzer with a 0.03 nm resolution. A 500-MHz digital oscilloscope and a radio frequency spectrum analyzer (RFSA) were used to observe the stability and quality of the Q-switched pulse traces. The output power of the developed EDFL was measured using an optical power meter (OPM).

IV. Q-switched EDFL Performances

When FeS_2-SA film was incorporated into the ring cavity, a stable Q-switching was observed at pump power, starting at 125.2 mW. The Q-switched lasing appeared stable when the pump power was continuously increased to 166.4 mW. It was observed that when the pump power was increased to higher pump power for more than 20 minutes, the pulse laser was still stable with no damage. This incident indicates that the laser operates below the damage threshold thus verifies that FeS_2 is a good SA. As illustrated in Fig.8, the EDFL Q-switched laser operates at a central wavelength of 1559.8 nm. The signal to noise ratio (SNR) at maximum pump power of 166.4 mW in Fig.9, indicates a stable RF spectrum regime of Q-switched laser at 55 dB. Fig. 10 depicts the Q-switched pulse train at 166.4 mW pump power and 88.5 kHz of repetition rate.

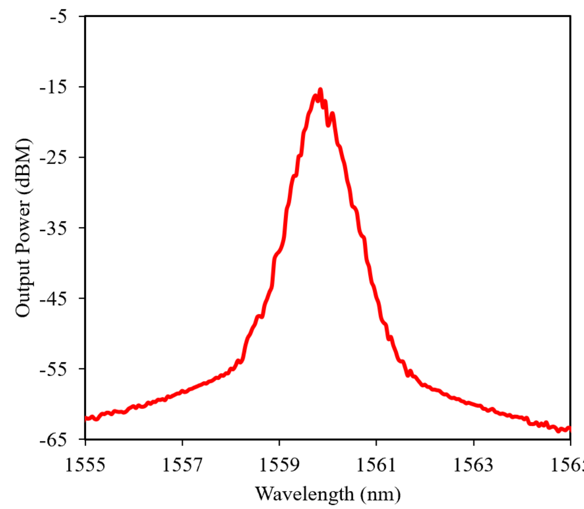

Fig. 8. The output spectrum.

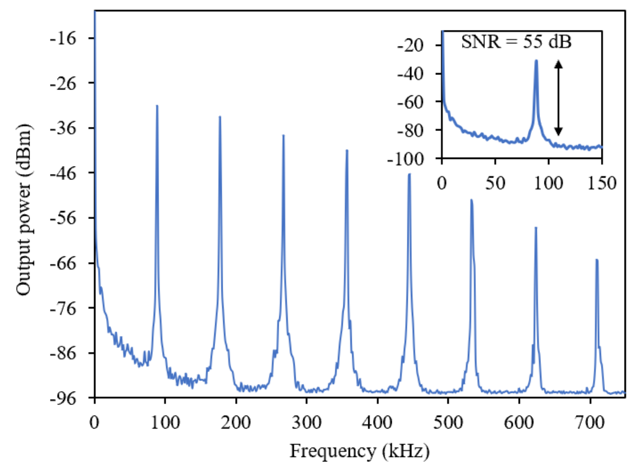

Fig. 9. RF spectrum at 166.43 mW of pump power.

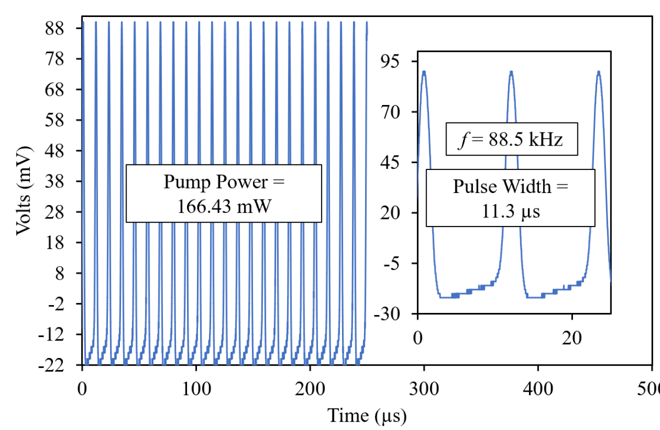

Fig. 10. Stability of pulse train at a pump power of 166.43 mW

As shown in Fig. 11, increasing the pump power in the range of 125.2 mW to 166.4 mW, increases the repetition rate from 80.4 kHz to 88.5 kHz and decreases the pulse duration from 12.4 µs to 11.3 µs. The figure shows a typical pattern of a passive Q-switched performance. The measured pump power against pulse energy and output power is depicted in Fig. 12. The output power increases steadily with a slope efficiency of 1.5%, showing the same increasing pattern with the pulse energy. The highest output power and pulse energy were recorded at 2.2 mW and 24.8 nJ respectively. This work's proposed laser is capable of delivering a Q-switched output that has high stability, high pulse repetition rate and high pulse energy, thus confirming that the developed passive EDFL with FeS_2-SA has a significant potential in photonics applications.

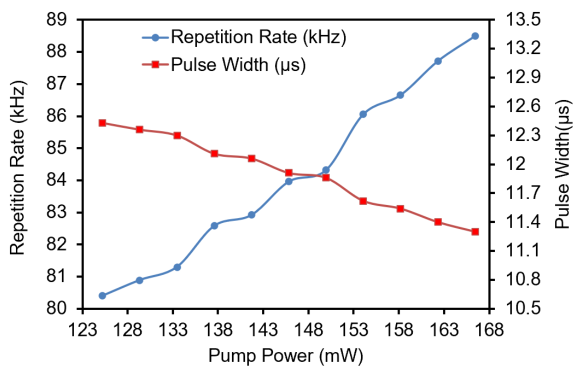

Fig. 11. Repetition rate and pulse width of the input laser.

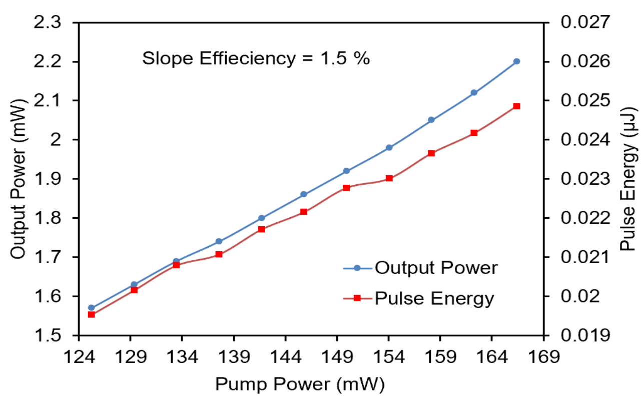

Fig. 12. Average power and peak pulse power of the input laser versus pump power.

Table I shows the comparison of output performance by different SAs in Q-switched EDFL. Optimization of EDFL ring cavity and nonlinear saturable absorption properties such as saturable intensity and modulation depth, should provide further improvements in performance.

TABLE I
COMPARISON OF OUTPUT PERFORMANCE BY DIFFERENT SAs IN Q-SWITCHED EDFL

Saturable absorber	SNR (dB)	Max. pulse repetition rate (kHz)	Max. pulse energy (nJ)	Ref.
Wse_2	46.7	49.6	33.2	[23]
PbS	63	38.7	10.6	[24]
CdSe	47	64	1.16	[25]
WSSe	57.8	61.8	7.31	[26]
FeS_2	55	88.5	24.8	This work

V. CONCLUSION

This work proves that FeS_2 based saturable absorber prepared by LPE method has succeeded in generating a Q-switched laser pulse at a central wavelength of 1559.8 nm. A small piece of FeS_2-SA thin film, in conjunction with EDFL, produced a laser pulse that started at pump power from 125.2 mw to 166.4 mw. The repetition rate is recorded from 80.4 kHz to 88.5 kHz. As pulse width decreases from 12.43 µs to 11.3 µs, the maximum pulse energy of 24.86 nJ and maximum output power of 2.2 mw are obtained. The non-saturable absorbance, modulation depth and saturation intensity of FeS_2 are 12.7%, 4.8% and 0.11 MW/cm^2 respectively. These results reveal that FeS_2-SA has promising potential in pulsed laser applications.

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REFERENCES

[1] P. Gautam and K. K. Singh, “Experimental investigation and modeling of heat affected zone and surface roughness in erbium-doped fiber laser cutting of CFRP composite,” *Mater. Today Proc.*, vol. 5, no. 11, pp. 24466–24475, 2018.
[2] T. J. Sawisch, *Oral Surgery for the General Practitioner*, First Edit. Copyright © 2011 by Mosby, Inc., an affiliate of Elsevier Inc., 2010.
[3] T. Krishnaswamy Subramaniam, “Erbium Doped Fiber Lasers for Long Distance Communication Using Network of Fiber Optics,” *Am. J. Opt. Photonics*, vol. 3, no. 3, p. 34, 2015.
[4] C. Xu *et al.*, “MXene (Ti 3 C 2 T,” vol. 361, no. 8, pp. 255–266, 2020.
[5] W. Abdulkhaleq, S. Abdulhameed, I. A. M. Alani, and M. H. M. Ahmed, “Magnesium oxide (MgO) thin fi lm as saturable absorber for passively mode locked erbium-doped fi ber laser,” *Opt. Laser Technol.*, vol. 115, no. January, pp. 331–336, 2019.
[6] A. K. Geim and K. S. Novoselov, “The rise of graphene,” *Nanosci. Technol. A Collect. Rev. from Nat. Journals*, pp. 11–19, 2009.
[7] Y. G. Wang, S. Y. Cheng, P. T. Tai, and J. Tang, “Saturable absorber at 940 nm using single wall carbon nanotubes deposited by vertical evaporation technique,” *Optik (Stuttg).*, vol. 123, no. 4, pp. 348–351, 2012.
[8] S. Absorber, “Tunable Passively Q -switched Erbium-Doped,” *Technology*, vol. 22, no. 1, pp. 2009–2011, 2010.
[9] Y. W. Song, S. Yamashita, and S. Maruyama, “Single-walled carbon nanotubes for high-energy optical pulse formation,” *Appl. Phys. Lett.*, vol. 92, no. 2, pp. 1–4, 2008.
[10] Y. Fu *et al.*, “Low- and high-order nonlinear optical properties of Ag 2 S quantum dot thin films,” *Nanophotonics*, vol. 8, no. 5, pp. 849–858, 2019.
[11] L. Yun *et al.*, “PbS quantum dots as a saturable absorber for ultrafast laser,” *Photonics Res.*, vol. 6, no. 11, p. 1028, 2018.
[12] J. Du *et al.*, “Phosphorene quantum dot saturable absorbers for

ultrafast fiber lasers," *Sci. Rep.*, vol. 7, no. January, pp. 1–10, 2017.
[13] N. N. Razak, M. Yasin, Z. Zakaria, A. A. Latiff, and S. W. Harun, "Q-switched fiber laser with a tungsten disulfide saturable absorber prepared by the drop casting method," *Photonics Lett. Pol.*, vol. 9, no. 3, pp. 103–105, 2017.
[14] H. Ahmad *et al.*, "Passively Q-switched erbium-doped fiber laser at C-band region based on WS_2 saturable absorber," *Appl. Opt.*, vol. 55, no. 5, p. 1001, 2016.
[15] H. Ahmad, Z. A. Ali, and M. A. Ismail, "C-Band Q-Switched Fiber Laser Using Titanium Dioxide (TiO 2) As Saturable Absorber C-Band Q-Switched Fiber Laser Using," vol. 8, no. 1, 2016.
[16] M. F. Baharom, N. F. Zulkefli, M. B. H. Mahyuddin, A. A. Latiff, A. R. Muhammad, and S. W. Harun, "Erbium Oxide as new Saturable Absorber for Short-Pulse Generation at 1.55-micron region," *J. Phys. Conf. Ser.*, vol. 1151, no. 1, 2019.
[17] Z. Yu *et al.*, "High-repetition-rate Q-switched fiber laser with high quality topological insulator Bi_2Se_3 film," *Opt. Express*, vol. 22, no. 10, p. 11508, 2014.
[18] Z. Qin *et al.*, "Black phosphorus as saturable absorber for the Q-switched Er:ZBLAN fiber laser at 28 µm," *Opt. Express*, vol. 23, no. 19, p. 24713, 2015.
[19] K. Wu *et al.*, "High-performance mode-locked and Q-switched fiber lasers based on novel 2D materials of topological insulators, transition metal dichalcogenides and black phosphorus: review and perspective (invited)," *Opt. Commun.*, vol. 406, no. February, pp. 214–229, 2018.
[20] D. Banjara, Y. Malozovsky, L. S. Franklin, and D. Bagayoko, "First-principles studies of electronic, transport and bulk properties of pyrite FeS2," *AIP Adv.*, vol. 8, no. 2, 2018.
[21] G. S. Chandrawat, J. Tripathi, A. Sharma, J. Singh, S. Tripathi, and J. Chouhan, "Study of structural and optical properties of FeS2 nanoparticles prepared by polyol method," *J. Nano- Electron. Phys.*, vol. 12, no. 2, pp. 2–5, 2020.
[22] S. Liu *et al.*, "Phase-pure iron pyrite nanocrystals for low-cost photodetectors," *Nanoscale Res. Lett.*, vol. 9, no. 1, pp. 1–7, 2014.
[23] B. Chen, X. Zhang, C. Guo, K. Wu, J. Chen, and J. Wang, "Tungsten diselenide Q-switched erbium-doped fiber laser," *Opt. Eng.*, vol. 55, no. 8, p. 081306, 2016.
[24] X. Sun, B. Zhou, W. Zhao, T. Wang, and C. Mou, "Passively Q-switched Erbium-doped fiber lasers using PbS polystyrene film as saturable absorber," *ICOCN 2017 - 16th Int. Conf. Opt. Commun. Networks*, vol. 2017-Janua, pp. 1–2, 2017.
[25] A. H. A. Rosol *et al.*, "Cadmium Selenide Polymer Microfiber Saturable Absorber for Q-Switched Fiber Laser Applications," *Chinese Phys. Lett.*, vol. 34, no. 9, 2017.
[26] H. Ahmad, Z. C. Tiu, and S. I. Ooi, "Passive Q -switching in an erbium-doped fiber laser using tungsten sulphoselenide as a saturable absorber," *Chinese Opt. Lett.*, vol. 16, no. 2, pp. 1–5, 2018.

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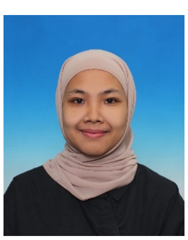

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