A wide-band and tunable Q-switched erbium-doped fiber (EDF) laser operating at 1560.5 nm with a tungsten ditelluride (WTe₂) saturable absorber (SA) is demonstrated. The semi-metallic nature of WTe₂ as well as its small band gap and excellent nonlinear optical properties make it an excellent SA material. The laser cavity uses an 89.5 cm long EDF, pumped by a 980 nm laser diode as the linear gain while the WTe₂ based SA generates the pulsed output. The WTe₂ based SA has a modulation depth, non-saturable loss and saturation intensity of about 21.4%, 78.6%, and 0.35 kW/cm² respectively. Stable pulses with a maximum repetition rate of 55.56 kHz, narrowest pulse width of 1.77 µs and highest pulse energy of 18.09 nJ are obtained at the maximum pump power of 244.5 mW. A 56 nm tuning range is obtained in the laser cavity, and the output is observed having a signal to noise ratio (SNR) of 48.5 dB. The demonstrated laser has potential for use in a large number of photonics applications.

Pulsed lasers are highly desirable laser sources that are typically realized in the form of mode-locked¹ and Q-switched lasers² that can be further classified as either active³ or passive⁴ systems. Active pulsed laser is accomplished through the use of acousto-optic⁵ and electro-optic modulators⁶ among other technique to generate pulses. This approach gives significant control over the various parameters of the generated pulses, but at the cost of a bulky and expensive setup. Normally, passive pulse laser can be typically achieved through the use of saturable absorbers (SAs)⁷,⁸. This approach, while providing less control over the output parameters of the generated pulses, is advantageous in that it allows for compact and cost-effective fiber laser cavities to be designed⁹. Topological insulators (TIs) such as bismuth selenide (Bi₂Se₃)¹⁰, bismuth telluride (Bi₂Te₃)¹¹, black phosphorus¹²,¹³, perovskite¹⁴, as well as carbon-based materials such as carbon nanotubes (CNTs)¹⁵ and graphene¹⁶ are amongst the various materials that have shown great potential as SAs in order to produce pulses in erbium-doped fiber (EDF) laser cavities. This is because the afore-mentioned groups of materials exhibits a larger non-linear-optical response¹⁷ as well as exceptional optical properties that include a large absorption coefficient, low defect density and long carrier lifetimes¹⁸. Besides that, the thin 2D structure of these materials give it an advantage in terms of unique photonic, magnetic, and electronic properties that is crucial for pulsed laser generation¹⁹.

Q-switched pulse generation has long been the focus of research efforts due to its advantageous intrinsic characteristics that include long pulses with higher pulse energies and durations²⁰, which is highly desirable for applications in material processing, remote sensing, range finding, and medicine²¹–²³. Furthermore, Q-switching is easier to induce as compared to mode-locking²⁴, which would require delicate balancing between the dispersion and nonlinearities in the laser cavity²⁵. As such, Q-switching is generally the preferred method of obtaining pulses in a laser cavity. Recently, researchers have focused their attention towards the exploration of transition metal dichalcogenide (TMD) group of materials in generating Q-switched pulses at broadband wavelengths. As SAs, TMD have significant advantages that include strong absorption²⁶, high nonlinear optical response, optical fiber compatibility and ease of fabrication²⁷. Luo et al.³⁰ demonstrated passively Q-switched Ytterbium (Yb), Erbium (Er) and Thulium (Tm) fiber lasers using a molybdenum disulfide (MoS₂) film as an SA, and their findings show that few-layer MoS₂ films have significant potential as broadband SAs operating at the near to mid-infrared regions. Furthermore, Zhang et al.³¹ demonstrated the use of tungsten disulfide (WS₂) to passively Q-switch...
EDF and Yb-fiber laser cavities. The WS\textsubscript{2} based SA is capable of generating Q-switched pulses with microsecond durations and kilohertz repetition rates at lasing wavelengths of 1030 and 1558 nm, demonstrating the potential for WS\textsubscript{2} as an SA in ultrafast photonic applications.

Tungsten ditelluride (WTe\textsubscript{2}) is another member of the TMD family and is a unique material as it is associated to a rising class of Weyl semimetals. This makes them highly promising for future applications as electronic, spintronic, and optoelectronic devices\textsuperscript{32,33} and also as a potential candidate for quantum spin Hall insulator materials\textsuperscript{34}. Even though WTe\textsubscript{2} belongs to the TMD family, its uniqueness arises from the additional structural distortion caused by the W atoms forming zigzag chains in a quasi-one-dimensional arrangement\textsuperscript{35}. Furthermore, the small overlap between the valence band and conduction band of WTe\textsubscript{2} results in an almost gapless band; as small as 0.7 eV\textsuperscript{36} compared to other TMD materials which typically have band gaps of more than 1 eV\textsuperscript{37}. As such, WTe\textsubscript{2} is more suitable for applications in near-infrared systems such as photodetectors, communications devices and in the area of ultrafast optics. WTe\textsubscript{2} was also been found to have unique characteristics such as a high unsaturated magneto-resistance (MR) as well as good superconducting behaviour while under high pressure\textsuperscript{38} which makes WTe\textsubscript{2} quite attractive for nano-electronic applications\textsuperscript{39}. In addition to that, the very fast relaxation of photocarriers makes WTe\textsubscript{2} suitable for generating Q-switched pulses\textsuperscript{40}. In a study conducted by Wang \textit{et al.}\textsuperscript{40}, an ultrafast pulse was successfully generated in a mode-locked thulium-doped fiber laser through the use of magnetron-sputtering deposited WTe\textsubscript{2} as an SA. Stable soliton pulses with pulse durations of 1.25 ps and average output powers of 39.9 mW were obtained at a central wavelength of 1915.5 nm. Similarly, Koo \textit{et al.}\textsuperscript{41}, developed passively mode-locked ultrafast lasers at 1556.2 nm using defective, bulk-structured WTe\textsubscript{2} microlakes as an SA. They discovered that the structural dimensionality does not critically influence the saturable absorption performance of WTe\textsubscript{2}.

In this work, WTe\textsubscript{2} is demonstrated as a wideband SA in a passively Q-switched EDFA operating at the 1.5 μm region. The WTe\textsubscript{2} SA has a modulation depth of 21.4% and saturation intensity of ~0.35 kW/cm\textsuperscript{2}. Stable Q-switched pulses are obtained at a central lasing wavelength of 1560.5 nm, which can be tuned over a range of 56 nm from 1522 nm to 1578 nm. The proposed SA would have significant benefits and potential to be used in various applications.

Characterization of a Tungsten Ditelluride (WTe\textsubscript{2}) - Based SA

Figure 1(a) shows the morphology of the WTe\textsubscript{2} layer as obtained from a Hitachi SU8220 field-emission scanning electron microscope (FESEM) under x13k magnification. From the figure, it can be seen that the WTe\textsubscript{2} nanoparticles have a flake-like morphology and tend to stack together to form thicker flakes. Figure 1(b) shows the energy dispersive X-ray (EDX) profile of the WTe\textsubscript{2} sample, with signal peaks associated only with the tungsten (W) and tellurium (Te) elements observed. This shows both the formation of WTe\textsubscript{2} sample as well as its purity. The inset of Fig. 1(b) shows the area of the WTe\textsubscript{2} sample from which the scan was obtained, as well as the weight and atomic percentage of the two elements which are 0.91% and 42. 15%, for W and 0.87% and 57.85% for Te respectively.

An NT MDT atomic force microscope (AFM) is used to measure the thickness of the WTe\textsubscript{2} film. The location of the WTe\textsubscript{2} film surface that was chosen for the thickness measurement is denoted by the blue line. The obtained AFM image is shown in Fig. 1(c), and it can be seen that the WTe\textsubscript{2} sample used in this work consists of about six individual layers stacked together. Figure 1(d) gives the height profile of WTe\textsubscript{2} film projected within the blue line. Six steps can be counted on the height profile, which gives the estimated thickness of the WTe\textsubscript{2} film to be six layers. The green line represents the position of one WTe\textsubscript{2} layer, with the thickness of a single layer estimated to be about 35.6 nm. As such, the overall thickness of the sample is estimated to be 213.6 nm. Further characterization of the WTe\textsubscript{2} sample is also carried out using a Renishaw inVia Raman microscope linked with a 532 nm line from a doubled Nd:YAG laser as the excitation source. As displayed in Fig. 1(e), two distinct Raman peaks are seen in the Raman spectrum of WTe\textsubscript{2}. The peaks located at 163 and 211 cm\textsuperscript{-1} can be assigned to the in-plane A\textsubscript{1g} and A\textsubscript{1h} modes of WTe\textsubscript{2}, respectively\textsuperscript{42,43}.

The SA assembly is formed by sandwiching a small piece of the WTe\textsubscript{2}-PVA between two optical fiber patchcords. A small amount of index matching gel is placed on the surface of the optical fiber patchcord, on which the WTe\textsubscript{2}-PVA piece is then placed. Using a fiber adaptor, another patchcord is joined to the first, thus forming the SA assembly. A white light source is linked to the SA as to obtain the linear optical transmission characteristics of the WTe\textsubscript{2} assembly. A black light from the SA assembly is observed from 1200 nm to 1600 nm using a Yokogawa AQ6370C optical spectrum analyser (OSA) with an average transmission (T) of 92.64% observed at 1560 nm as in Fig. 2(a). The obtained data is inserted into the saturation model equation\textsuperscript{44}:

\[
\alpha(I) = \frac{\alpha_s}{1 + I/I_{sat}} + \alpha_{ns},
\]

where \(\alpha_s\), \(I\), \(I_{sat}\), and \(\alpha_{ns}\) refer to the modulation depth, input intensity, saturation intensity, and non-saturable loss respectively. The relative parameters for the WTe\textsubscript{2} SA are obtained based from the resulting fitted curve as given in Fig. 2(b), with the modulation depth, saturation intensity and non-saturable loss of the WTe\textsubscript{2} SA being ~ 21.4%, 0.35 kW/cm\textsuperscript{2}, and 78.6%, respectively. The insertion loss of the WTe\textsubscript{2} SA is measured to be approximately 0.31 dB.

Experimental Setup

Figure 3 shows the schematic of the passively Q-switched ring cavity EDF laser. The laser cavity uses a 980 nm laser diode (LD) as the pump source with a maximum output power of 244.5 mW and injected into the cavity via the 980 nm port of a 980/1550 nm wavelength-division multiplexer (WDM). The output of the WDM is connected to a 89.5 cm long EDF which has a dopant concentration, absorption, mode field diameter, and numerical aperture of 2000 ppm, 16 dB/m at 1530 nm, 9.5 μm at 1550 nm and 0.13, respectively. The EDF serves as the gain

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media, and is connected to an optical isolator as well as an optical tunable bandpass filter (TBPF) with a tuning range of 80 nm and a resolution of 1 nm. The signal now reaches the WTe₂ based SA, and an 80:20 optical coupler is used to obtain 20% of the signal. The 80% port of the coupler is connected to the 1550 nm port of the WDM, thereby closing the optical cavity. Polarization controllers (PCs) are not included in the design of the cavity as Q-switched pulses can be observed immediately with the incorporation of the WTe₂ based SA into the laser cavity and without any further optimization of the propagating signal. Therefore, adding a PC would not improve the performance of the cavity, and will instead induce additional insertion losses to the cavity.

Figure 1. (a) FESEM image, (b) EDX spectrum, (c) AFM image, (d) Lateral height measurement, and (e) Raman spectrum for few layers WTe₂.
Results and Discussion

When operating without the WTe$_2$ SA, no pulsed outputs can be detected, thus confirming that the generation of pulses is due solely to the SA and not arising from other optical phenomena. With the WTe$_2$ SA in the cavity, continuous wave (CW) operation is obtained at a threshold pump power of 77.43 mW while Q-switching begins at a threshold pump power of 124.9 mW. Pulsing is observed to continue steadily until the maximum pump power of 244.5 mW is reached. The pulse characteristics of the Q-switched EDF laser at a pump power of 244.5 mW are shown in Fig. 4. The optical spectrum of the pulses is given in Fig. 4(a), where the central wavelength is determined to be 1560.5 nm with a 3-dB bandwidth of 1.55 nm. The oscilloscope trace of the Q-switched pulses is given in Fig. 4(b), whereby the generated pulses have a peak-to-peak pulse interval of 18.86 μs that corresponds to a repetition rate of 55.56 kHz. In Fig. 4(c), the single pulse profile has a full width at half maximum (FWHM) duration of 1.77 μs. Based on the RF spectrum, a frequency of 55.56 kHz is observed in Fig. 4(d), with the pulses having an average signal-to-noise ratio (SNR) of about 48.5 dB. This indicates that the generated Q-switched pulses are highly stable, and comparable to that of other similar systems$^{45,46}$.

Figure 5(a) shows the oscilloscope traces of the output pulses obtained at four different pump powers. It can be seen from the figure that the repetition rate increases while the spacing between pulses decreases as the pump power is increased. These trends are characteristic of Q-switching operation. The repetition rate and pulse width as a function of pump power is given in Fig. 5(b) and shows the repetition rate increasing from 38.39 kHz to 55.56 kHz when the pump power is increased from 124.9 mW to 244.5 mW. At the same time, the pulse width decreases from 3.67 μs to 1.77 μs, with a sharp decrease in the pulse width before a pump power of 236.5 mW and a slower decrease after it. The slower decrease of the pulse width at the higher pump powers is attributed to the change in the saturable-absorption property of the WTe$_2$ SA from parasitic continuous waves that can partially bleach it$^{47}$. As shown in Fig. 5(c), the variation of the output power and pulse energy against the pump power
shows a generally rising trend, rising from 0.28 mW to 1.01 mW and 7.31 nJ to 18.09 nJ, respectively as the pump power is pushed to the maximum. However, as can be seen from the figure, a decrease in the average output power is observed at a pump power of 204.8 mW, before the average output power continues to rise normally against the increasing pump power. This sudden decrease in power is a result of a kink in the output power of the LD as the drive current increases. This causes the output power from the fiber laser to drop slightly, then continue to increase normally as the drive current increases. Another possibility as put forward by Adel48 is that when the drive current increased, this causes an increase in the temperature of the laser diode, and shifts the lasing wavelength away from the peak absorbing wavelength of 974 nm. This reduces the absorption occurring in the EDF, thus lowering the output power of the fiber laser. Further increasing the drive current of the LD will increase the pump power and cause the output power of the fiber laser to increase in tandem, as would be expected.

Figure 6 gives the RF spectra as captured over a span of 60 minutes at a pump power of 221 mW. No significant changes in the SNR value over the time period can be observed, with the average SNR value being ~48.5 dB. Based on the inset of Fig. 6, no frequency drifting can be observed with the frequency remaining constant at about ~53.8 kHz throughout the observation period. These results indicate the high stability of the proposed laser and also that there is no significant degradation of the WTe2 SA’s performance throughout its operation period.

Figure 7(a) shows the optical spectra of the tunable wavelength output obtained at a constant pump power of 194.2 mW. From the figure, no Q-switching operation can be observed below the wavelength of 1522 nm or beyond the wavelength of 1578 nm, giving the laser a tuning wavelength of 56 nm. Figure 7(b) shows the repetition rates against different wavelengths, and from the figure it can be seen that there is a gradual increase in the repetition rate as the wavelength is tuned from 1522 to 1532 nm. In general, the high repetition rate at the larger gain region of the cavity is due to lower cavity losses. This happens as a result of the more rapid bleaching of the SA which is due to faster population inversion/depletion rates49. Above a wavelength of 1532 nm, the variation of repetition rate trend follows the amplified spontaneous emission (ASE) spectrum of the laser, as the inset of Fig. 7(b), from which the EDF’s gain profile is obtained50. The variation of the pulse width of the Q-switched laser output over the same wavelength tuning range is given in Fig. 7(c). From the figure, it can be seen that the pulse width increases from 1.3 μs to 2.6 μs over the increasing wavelength range. This is attributed to the different wavelength regions experiencing different gains, and as such variations in the repetition rate and pulse width that correspond to the gain curve of the cavity.

A comparison of the passively Q-switched fiber laser in this work against other similar systems using different SAs is given in Table 1. From the table, it can be seen that the proposed laser of this work using the WTe2-PVA
Figure 5. (a) Passively Q-switched pulse trains at the pump powers of 124.9 mW, 166.6 mW, 194.2 mW, and 221 mW, respectively, (b) repetition rate and pulse width and (c) output power and pulse energy.

Figure 6. Stability performance of the passively Q-switched EDF laser within 60 minutes recorded using RFSA at a constant pump power of 221 mW.
film based SA generates Q-switched pulses with the narrowest pulse width. Furthermore, the threshold pump power for Q-switching to occur in this system is lower compared other similar systems. Overall, the output performance of the proposed laser system is comparable and at some points is better than that in previous reports, thus confirming the applicability of WTe$_2$ as an SA for Q-switched pulse generation at the C-band region. The excellent photoresponse behaviour possessed by tellurium (Te) allows for good pulsed laser performance to the realized.

Figure 7. (a) Superimposed optical spectra of the tunable EDF laser at different wavelengths, (b) the repetition rate of Q-switching against the tunable lasing wavelength at constant pump power of 194.2 mW (Inset: ASE spectrum), and (c) the pulse width versus lasing wavelength.

| Saturable absorber | Operation wavelength (nm) | Tunable wavelength range (nm) | Pump power range (mW) | Pulse width (μs) | Repetition rate (kHz) | Maximum pulse energy (nJ) | Ref. |
|--------------------|---------------------------|-------------------------------|-----------------------|-----------------|---------------------|--------------------------|-----|
| MoSe$_2$ - PVA     | 1560                      | —                             | 570–720               | 4.04–6.506      | 60.724–66.847       | 369.5                    | 50  |
| WSe$_2$ - PVA      | 1560                      | —                             | 280–720               | 4.063–9.182     | 46.281–85.365       | 484.8                    | 50  |
| MoWSe$_2$          | 1554                      | —                             | 99–245                | 6.80–1.90       | 26–48               | 11.80                    | 53  |
| MoS$_2$ - PVA      | 1565                      | 17.40–134.30                  |                       | 23.20–5.40      | 6.50–27             | 63.20                    | 40  |
| MoS$_2$ - PVA      | 1560                      | 1519.6–1567.7                | 18.9–227.1            | 26.7–3.3        | 8.77–43.47          | 160                      | 40  |
| LPE Chitosan/MoS$_2$ | 1561.5                  | 1510–1580                     | 135.4–280.5           | 1.68 – 1.02     | 57.3–79.4           | 43.69                    | 40  |
| WS$_2$             | 1568.4                    | 1530–1570                     | 89.07–280.5           | 4.16–2.6        | 27.52–61.81         | 7.31                     | 40  |
| MoS$_2$ - PVA      | 1562                      | 22.4–102.0                    | 59.1–30.4             | 16.9–32.8       | 57.9                |                          | 40  |
| WTe$_2$            | 1531                      | 212–630                       | ~2.3–0.583            | 144.7–240       | 58.625              |                          | 60  |
| SnS                | 1560                      | 275–500                       | —                     | 36.36–65.19     | —                   |                          | 60  |
| BP                 | 1988                      | —                             | 1.78                  | 19.25           | 7840                |                          | 60  |
| WTe$_2$ - PVA      | 1560.5                    | 1522–1578                     | 124.9–244.5           | 3.67–1.77       | 38.39–55.56         | 18.09                    | 68  |

Table 1. Passively Q-switched fiber laser operating at 1.5 μm by different SAs. MoS$_2$ = Molybdenum disulfide, MoSe$_2$ = Molybdenum diselenide, WSe$_2$ = Tungsten diselenide, MoWSe$_2$ = Molybdenum tungsten diselenide, WS$_2$ = Tungsten sulfide selenide, SnS = Tin Sulfide, BP = Black phosphorus.
Methods

Preparation of a Tungsten Ditelluride (WTe2) - Based SA. Solution casting is used to fabricate the WTe2 film with a polyvinyl alcohol (PVA) polymer thin film host. The WTe2 solution is purchased from 2D Semiconductors at 99.99% purity while the PVA at MW~31,000 powder is obtained from Sigma Aldrich. Approximately 100 mg of the PVA powder is slowly added into 10 ml of deionized water (DIW) at 60 ºC and stirred continuously for 2 hours using a magnetic stirrer. A homogeneous WTe2 solution is obtained by treating the purchased WTe2 solution with a bath sonicator for a period of 30 minutes. Approximately 2 ml of the homogeneous 1 mg/mL WTe2 solution is added drop by drop into a beaker containing 8 ml of the 10 mg/mL PVA solution while stirring. The mixture is stirred continuously for another 15 minutes at 60 ºC. Finally, the mixture is poured into a glass petri dish and heated in an oven for 2 hours at 60 ºC, and the WTe2/PVA film is carefully removed from the petri dish after being allowed to cool down to room temperature.

Laser characterization. Analysis of the sample signal is done using the Yokogawa AQ6370C OSA as well as a Yokogawa DLM2054 oscilloscope (OSC) with a 1 GHz photodetector. An Anritsu MS2683A radio frequency spectrum analyzer (RFSA) and a Thorlabs optical power meter (OPM) are used to monitor the output spectra for further analysis.

Conclusion

In this work, a broadband WTe2-based SA is demonstrated for the passive generation of Q-switched pulses in the C-band region. A stable Q-switched output is achieved at a threshold pump power of 124.9 mW with a central wavelength of 1560.5 nm. By increasing the pumping power from 124.9 mW to 244.5 mW, the repetition rate rises from 38.39 kHz to 55.56 kHz while the pulse width decreases from 1.77 µs to 0.77 µs. The proposed laser system exhibits wide-band tunability of up to 56 nm from 1522 nm to 1578 nm, and is highly stable with no significant fluctuation in frequency observed over an operation period of 60 minutes with average SNR values of 48.5 dB. The obtained experimental results imply that WTe2 has a great potential as SA and the proposed laser system can be used as a pulse tunable laser source for various optical telecommunications and measurement applications.

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The authors declare no competing interests.

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Author contributions
Harith Ahmad proposed the study and designed the experiment. Hissah Saedoon Albaqawi performed the fiber laser experiments and wrote the manuscript. Norazriena Yusoff prepared the WTe2 films, performed the material characterization and contributed to writing of the manuscript. Chong Wu Yi contributed to data analysis.

Competing interests
The authors declare no competing interests.
