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Theoretical and experimental studies on a Q-switching operation in an erbium-doped fiber laser using vanadium oxide as saturable absorber

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Abstract

We introduce theoretical analysis for a passively Q-switching operation in an erbium-doped fiber laser (EDFL) with a saturable absorber (SA). Peak power, repetition rate, and pulse duration have been calculated as functions of pump power and cavity length. The simulation results are compared with the passively Q-switched EDFL demonstrated using vanadium oxide (V²O₅) as SA. The nonlinear saturable absorption of the V²O₅-SA is characterized by a modulation depth of 7% with a saturation intensity of 71 MW cm⁻². This is the first demonstration of a fiber laser based on a V²O₅-SA that introduces new opportunity for photonic applications. The introduced theoretical model could be highly useful for understanding and improving Q-switched EDFLs based on a SA.

Keywords: fiber laser, Q-switching, passive saturable absorber

(Some figures may appear in colour only in the online journal)

1. Introduction

Passive Q-switching is a kind of cost-effective technique to generate giant optical pulses. In passive Q-switching, the loss modulation can be obtained by a nonlinear optical element in the cavity whose loss is intensity dependent. This element is called the saturable absorber (SA). The SA is a nonlinear optical component (modulator) whose modulation depth is controlled by the optical pulse itself. Among the materials that can be used as SA, we find dyes, semiconductor saturable absorber mirrors (SESAMs) [1], graphene, and carbon nanotubes (CNTs) [2–4]. Lately, transition metal dichalcogenides such as molybdenum disulfide (MoS₂) and tungsten disulfide (WS₂), topological insulators, and black phosphorous (BP) have shown good potential as SAs for pulse laser applications [5–8]. Very recently, transition metal oxide nanoparticles such as zinc oxide (ZnO), titanium dioxide (TiO₂), cobalt oxide (Co₃O₄), and nickel oxide (NiO) [9–13] have been demonstrated as SAs in Q-switched fiber lasers. Transition metal oxides represent a class of materials that exhibit nonlinear optical properties. Over the past few decades, transition metal oxides have been intensively investigated not only due to their optical nonlinearity, but also their mechanical strength, thermal and chemical stability. For instance, several metal oxide films show a large nonlinear optical response with a third-order nonlinear susceptibility in the range between 10⁻⁸ and 10⁻⁷ esu.

Vanadium oxides are one of the most important transition metal oxides. There are a series of oxides that form from vanadium which are commonly available as VO, V₂O₅, VO₂ and
V$_2$O$_5$. The most important of these oxides is V$_2$O$_5$ and it is the most stable member of the series [14]. The nonlinear optical absorption characteristics of V$_2$O$_5$ have been studied in [15]. In this paper, we theoretically study the passively Q-switching operation in an erbium-doped fiber laser (EDFL) cavity based on a SA and the simulation results are compared to our experimental work on a Q-switched EDFL based on V$_2$O$_5$ thin film as SA.

### 2. Theoretical model

The numerical investigations of the Q-switching operation are based on the coupled rate equations of the laser system with the saturable absorption dynamics of the SA material. In this model, the laser system is considered as a ring cavity, as shown in figure 1, that consists of a 3-meter-long erbium-doped fiber (EDF) representing the gain medium with 125 µm cladding and 4 µm core diameters, passive fiber (SMF-28), and SA. The cavity is pumped by a 980 nm laser diode via a fused 980/1550-nm wavelength division multiplexer. In order to preserve the unidirectional light operation, we used an isolator (ISO). The output pulsed laser is extracted via a 9/5 fiber output coupler.

Here, we consider the SA as a nonlinear optical material (semiconductor thin film). The saturable absorption of such nonlinear optical material can be described by its optically induced carrier densities as [16]

$$\alpha(N_a) = \frac{\alpha_s}{1 + N_a/N_{sa}} + \alpha_{NS}. \quad (1)$$

Here, $\alpha_s$ denotes the small-signal saturable absorption (modulation depth of SA), $N_a$ refers to the photocarrier density of the SA, $N_{sa}$ refers to the saturation photocarrier density and $\alpha_{NS}$ is the non-saturable absorption coefficient.

The photo-carrier density of the SA is described by

$$\frac{dN_a}{dt} = \frac{I\alpha(N_a)}{h\nu} - \frac{N_a}{\tau_{sa}} \quad (2)$$

where $\tau_{sa}$ is the SA carrier recombination time which can be altered via the fabrication of material.

The dynamics of population in the laser system can be described by the following equations [16–18]:

$$\frac{d\phi}{dt} = \frac{\phi}{t_r} \left( 2\sigma_{ex}n_pL - 2\alpha(N_a)L_{sa} - \ln \left( \frac{1}{R} \right) - \delta \right) \quad (3)$$

$$\frac{dn_a}{dt} = W_p - \gamma \sigma_{ex} c \phi n_k - \frac{n_k}{\tau_g} \quad (4)$$

$$\frac{dN_a}{dt} = c \phi \alpha(N_a) - \frac{N_a}{\tau_{sa}} \quad (5)$$

where $\phi$ denotes the photon density inside the laser cavity and $n_p$ represents the population inversion density. $L$ is the length of the active fiber, $L_{sa}$ is the thickness of the SA, $c$ is the speed of light, and $t_r$ refers to the round-trip transit time of the cavity. $R$ is the output-coupling ratio and $\delta$ is the dissipative optical loss of the cavity while $\gamma$ is the inversion reduction factor. $W_p$ is the pumping power, $A$ is the effective doping area of the active fiber and $h\nu$ is the laser photon energy.

The Q-switching operation of the proposed laser system is studied by solving the above coupled rate equations using the Runge–Kutta method. EDF was chosen as the active medium and the numerical calculations have been done using the following parameters: $\sigma_{ex} = 2 \times 10^{-25} m^2$, $\tau_g = 10^{-2} s$, $\gamma = 1.8$, $\delta = 0.4$, $N_{sa} = 2.4 \times 10^{27} m^{-3}$, $\tau_{sa} = 0.1$ ns, $\alpha_{NS} = 0.4$, $\alpha_s = 0.1$, $L_{sa} = 10 \mu m$, $A = 1.26 \times 10^{-11} m^2$, $L = 3$ m, and $R = 0.95$.

### 3. Simulation analysis of Q-switching operation

With pumping, the erbium ions’ population in the excited energy level of the active fiber increases, generating photons inside the cavity. A part of these photons is absorbed by the SA which increases the photo carrier density $N_p$ and this introduces a high loss inside the cavity making the laser system operate below the lasing threshold. The absorption ability of the SA gets saturated when a sufficient amount of the population is accumulated at its excited level (the photocarrier density reaches almost its maximum value). With continuous pumping, the laser system is allowed to overcome the threshold and lasing is realized. The cavity is Q-switched at the time when the inverted population $n_p$ reaches its maximum

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**Figure 1.** Fiber cavity configuration of the Q-switched EDFL.

- $\sigma_{ex}$ is the stimulated emission cross-sectional area of the gain medium and $\tau_g$ denotes the spontaneous decay time of the upper laser level of the gain medium.
- The pump rate of the active medium $W_p$ is approximated as

$$W_p = \frac{P_p}{h\nu AL} \quad (6)$$

where $P_p$ is the pumping power, $A$ is the effective doping area of the active fiber and $h\nu$ is the laser photon energy.

- The output pulse energy $E_{out}$ and peak power $P_{out}$ can be approximated by [1, 19–21]

$$E_{out} = \frac{h\nu AL}{\tau_r} \ln \left( \frac{1}{R} \right) \int_0^{\phi_{max}} \phi(t) dt \quad (7)$$

$$P_{out} = \frac{h\nu AL}{\tau_r} \ln \left( \frac{1}{R} \right) \phi_{max} \quad (8)$$

where $\phi_{max}$ is the maximum photon density in the laser cavity.
value and the photon density $\phi$ continues to grow up, leading to a pulse whose peak occurs some time after switching. The inverted population density corresponding to the peak of the photon density pulse is approximately $7.8 \times 10^{23}$ m$^{-3}$ as shown in figure 2(a), which is the same as the critical population inversion $n_{gc}$. As the photon number in the cavity grows via stimulated emission, the population inversion will drop from its initial value to the final value left after the pulse is over. Simultaneously, the decay rate of the excited energy level of the SA suppresses the absorption and thus the population of the SA excited energy level decreases and when the population drops to a certain level, the absorption (due to the SA) dominates again which increases the photocarrier density until the SA excited level becomes saturated again.
and consequently sequential pulses are generated (the recovery of the SA allows Q-switching to start a new round trip). Figure 2(c) shows the time behavior of the photocarrier density of the SA.

During each pulse formation, the inversion falls from its initial value (before Q-switching) to a final value (after the Q-switched pulse). The population inversion is then restored to its initial value by the pumping process before the following Q-switching process. Since the time taken to restore the inversion is approximately equal to the upper state lifetime \( \tau_g \), the time between two successive pulses should be equal to or shorter than \( \tau_g \). Actually, if the time between two successive pulses is much longer than the upper state lifetime, most of the available inversion will be lost via spontaneous decay. Hence, Q-switched pulsed lasers’ repetition rate is typically a few kHz.

4. Q-Switching performance of the \( \text{V}_2\text{O}_5 \)-SA based laser

First, vanadium oxide (\( \text{V}_2\text{O}_3 \)) was synthesized by chemical reaction as reported in [22]. In a typical synthesis, 20 g of \( \text{NH}_4\text{VO}_3 \) (Sigma Aldrich, Malaysia) was dissolved in 500 ml of deionized water. After that, 0.1 g of Triton X-100 surfactant was added in the above solution under constant stirring at 90 °C for 60 min in order to complete the emulsification. Concentrated \( \text{HNO}_3 \) (35% Merck) was then added dropwise in the above mixture to acidify the solution. The dark brown precipitates were formed overnight, which were collected and washed with deionized water in order to remove acid and traces of surfactant. The precipitates were dried in a hot air oven at 90 °C for 12 h. Finally, dried powder was crushed and calcined at 500 °C for 5 h in a box furnace at a heating and cooling rate of 25 °C min\(^{-1}\) to obtain yellowish-brown \( \text{V}_2\text{O}_5 \). Second, the structural crystallinity and phase purity of \( \text{V}_2\text{O}_5 \) were investigated by x-ray diffraction (XRD) as shown in figure 3(a). As shown in the figure, \( \text{V}_2\text{O}_5 \) displays sharp peaks at the 2θ value of 15.4, 20.3, 21.7, 26.2, 31, 32.4, 34.4, 47.4 and 51.3 which correspond to the lattice planes of (2 0 0), (0 1 0), (1 1 0), (1 0 1), (3 1 0), (0 1 1), (3 0 1), (6 0 0) and (0 0 2), respectively. All diffraction peaks for \( \text{V}_2\text{O}_5 \) can be indexed as an orthorhombic crystal phase (space group P m n 21, PDF 96-101-1226) without showing any impurity. The surface morphology of the prepared \( \text{V}_2\text{O}_5 \) was then investigated.
by field emission scanning electron microscopy (FESEM). Figure 3(b) displays the FESEM image of V$_2$O$_5$ which shows the tubular shape of V$_2$O$_5$.

The synthesized V$_2$O$_5$ was integrated with a polymer in order to fabricate V$_2$O$_5$ SA thin film. 1.0 g of polyethylene glycol (PEO) was dissolved in 120 ml of deionized water and then stirred for 2 h at a constant temperature of 50 °C in order to obtain a uniform transparent solution. Subsequently, an appropriate amount of the prepared V$_2$O$_5$ was added into the PEO solution and kept under constant stirring for a further 2 h to obtain homogenous slurry. Finally, the solution mixture containing the V$_2$O$_5$-PEO composite was cast onto the Teflon petri and dried in a vacuum oven at 60 °C for 24 h to obtain light yellow solid thin film.

The nonlinear saturable absorption of the V$_2$O$_5$-SA film was then determined using the twin-detector technique with an illumination source of a homemade mode-locked fiber laser with a repetition rate of 15 MHz and pulse width of 0.9 ps centered at 1554 nm. The absorption at various input intensities was recorded and plotted as shown in figure 3(c), after fitting using the following saturation model [23]:

$$T(I) = 1 - q_0 \exp \left(- \frac{I}{I_{sat}} \right) - q_{ns}$$  (9)

where $T(I)$ is the transmission, $q_0$ is the modulation depth of the SA which represents the maximum change in absorption, $I$ is the input intensity, $I_{sat}$ is the SA saturation intensity, and $q_{ns}$ is the non-saturable absorption. The saturation intensity and modulation depth of the V$_2$O$_5$-SA were determined to be 71 MW cm$^{-2}$ and 7%, respectively.

The experimental result of the Q-switched EDFA based on the V$_2$O$_5$-SA is obtained using the same configuration used in the theoretical model as shown in figure 1. A 350 MHz oscilloscope combined with a 1.2 GHz photo-detector, optical power meter, and an optical spectrum analyzer (OSA) with a spectral resolution of 0.07 nm were used simultaneously to monitor the output laser.

The EDFA cavity started to generate a continuous-wave laser at a pump power of 20 mW. A stable Q-switched operation was observed when the pump power had exceeded 35 mW. Figure 4(a) shows the output spectrum of the Q-switched EDFL at a 165 mW pump power with a center wavelength of 1565 nm and 3 dB bandwidth of 1.12 nm. The oscilloscope trace of the pulse trains obtained at the pump power of 165 MW is shown in figure 4(b). It is observed that the typical pulse train shows a stable Q-switching operation with no fluctuations. Figure 4(c) shows the single pulse temporal profile at the pump power of 165 mW with a full width at half maximum of 5.6 µs. In order to confirm that the Q-switched pulses are attributed to the V$_2$O$_5$-SA, the fiber connector fiber ferrule with V$_2$O$_5$ film was replaced with a common clean ferrule. In this case, no Q-switched pulses were observed on the oscilloscope even when the pump power was adjusted over a wide range. This verified that the V$_2$O$_5$-SA was responsible for the Q-switching operation of the EDFL. In order to investigate the stability of our Q-switched pulse, the degree of suppression of the adjacent harmonics through the corresponding radio-frequency (RF) spectrum is obtained as shown figure 4(d). The RF spectrum shows that the fundamental frequency of our fiber laser cavity was obtained at 60 kHz and the side modes were suppressed by about 55 dB (signal-to-noise ratio (SNR)), confirming the stability of the pulse [24].

In order to further study the characteristics of the output Q-switched pulses, the effect of the pump power on the pulse...
duration and repetition rate has been investigated, as shown in figures 5(a) and (b). As the pump power increases the SA excited energy level needs less time to get into saturation and more time to get out, leading to a higher repetition rate and shorter pulse duration. The figure shows a good agreement between the experimental and simulation results. Furthermore, the output peak power was also calculated at different pump powers and the result is shown in figure 5(c). As shown in the figure, the output peak power increases with increasing the pump power which is in line with the simulation results. This means that when the pump power increases, the energy stored in the gain medium increases and this leads to an increase of the output peak power.

The output characteristics of the pulse change following changing the cavity length are as shown in figure 6. This was realized by increasing the length of the passive fiber while the length of the active fiber is kept constant. We observed that the pulse duration increases as the cavity length increases while the peak power decreases. This happens because the life time of the photon in the cavity $\tau_0$ is proportional to the cavity length $L_c$; $\tau_0 \approx t_r/ (\delta - \ln(R))$ and $t_r = nL_c/c$ [25] where $t_r$ is the round-trip time of the cavity, and the repetition rate is approximately equal to $\kappa/\tau_0$ [26] where $\kappa$ is a constant; this explains the decay in the repetition rate and thus also the peak power. After a certain cavity length, the variation becomes less sensitive compared to that of the pump power.

It is observed that the theoretical results for the proposed Q-switched laser model are in agreement with our experimental results. The very little quantitative difference between the experimental and theoretical results is due to the following reasons. In the experimental setup a wavelength division multiplexer and ISO have been used which have not been taken into account in the simulation. In addition, some of the parameters used in the theoretical model have been estimated (are not exactly equal to the real values) for the V$_2$O$_5$ thin film which acts as the Q-switcher.

Compared to other SA materials used in fiber lasers, V$_2$O$_5$ is more abundant and easy to synthesize with low cost. In addition, it has very appropriate modulation depth (7%) and saturation intensity (71 MW cm$^{-2}$) with a high damage threshold. Table 1 summarizes the performance of our V$_2$O$_5$-SA and compares it with the performance of other SA materials used in the previous works [12, 27–39]. For example, the V$_2$O$_5$-SA produced pulses with narrower repetition rates compared to those generated by Bi$_2$Se$_3$, SnS$_2$, and graphene-based SAs. Compared to MoSe$_2$, Bi$_2$Te$_3$, ReS$_2$, gold nanorods, and BP-based SAs, the proposed V$_2$O$_5$-based Q-switched laser operated at a wider tuning range.

5. Conclusion

We studied theoretically the passively Q-switching operation in the EDFL cavity and successfully demonstrated a passively Q-switched fiber laser using the V$_2$O$_5$-SA with results in high agreement with the proposed theoretical model. The effects of pump power and cavity length on the performance of the laser have been investigated. It is found that the pump power is a main factor which governs the output performance of the laser system while the cavity length effect is not high compared to the pump power effect. The generated output pulses based on the V$_2$O$_5$-SA whose nonlinear saturable absorption is characterized by a modulation depth of 7% with saturation intensity of 71 MW cm$^{-2}$ have a repetition rate ranging from around 20 kHz to 60 kHz, and a pulse width decreasing from 12 $\mu$s to 5.6 $\mu$s when the pump power increases from 55 mW to 165 mW. The introduced theoretical model could be highly useful for understanding and improving passively Q-switched EDFLs based on various SAs. The experimental results verified that the V$_2$O$_5$ has an excellent potential as an effective SA to generate a passively Q-switched fiber laser.

<table>
<thead>
<tr>
<th>SA</th>
<th>Modulation depth/saturation intensity (MW/cm$^2$)</th>
<th>Wavelength (nm)</th>
<th>Output power/pump power (mW)</th>
<th>Pulse width ($\mu$s)</th>
<th>Repetition rate (kHz)</th>
<th>Ref.</th>
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</thead>
<tbody>
<tr>
<td>V$_2$O$_5$</td>
<td>7%/71</td>
<td>1565</td>
<td>1.6/165</td>
<td>5.6</td>
<td>60</td>
<td>Our work</td>
</tr>
<tr>
<td>NiO</td>
<td>39%/0.025</td>
<td>1561.2</td>
<td>1.68/95</td>
<td>5.2</td>
<td>52.18</td>
<td>[12]</td>
</tr>
<tr>
<td>Fe$_2$O$_4$</td>
<td>8.2%/25</td>
<td>1560</td>
<td>0.8/110</td>
<td>3.2</td>
<td>33.3</td>
<td>[27]</td>
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<tr>
<td>Bi$_2$Se$_3$</td>
<td>4.3%/11</td>
<td>1565.0</td>
<td>22.35/360</td>
<td>1.9</td>
<td>940</td>
<td>[28]</td>
</tr>
<tr>
<td>Bi$_2$Te$_3$</td>
<td>30%/</td>
<td>1543.2</td>
<td>0.045/120</td>
<td>9.5</td>
<td>12</td>
<td>[29]</td>
</tr>
<tr>
<td>MOS$_2$</td>
<td>2.1%/129.4</td>
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<td>1.31/100</td>
<td>12.9</td>
<td>21.8</td>
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<td>WS$_2$</td>
<td>2.5%/148.2</td>
<td>1560</td>
<td>6.41/650</td>
<td>4.1</td>
<td>71.2</td>
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<td>WSe$_2$</td>
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<td>1560</td>
<td>3.16/500</td>
<td>4.8</td>
<td>66.8</td>
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<td>1549.8</td>
<td>44.1/229</td>
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<td>37.1</td>
<td>[31]</td>
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<td>1564.5</td>
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<td>PbS quantum dot</td>
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<td>1562.7</td>
<td>19.4/128.7</td>
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<td>ReS$_2$</td>
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<td>1557.3</td>
<td>0.4/120</td>
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<td>SnS$_2$</td>
<td>3.15%/65</td>
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<td>9.33/637</td>
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<td>233</td>
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<tr>
<td>BP</td>
<td>18.5%/10.7</td>
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<td>1.48/110</td>
<td>13.2</td>
<td>10.42</td>
<td>[36]</td>
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<td>1561.9</td>
<td>8.37/46.75</td>
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<td>17.1</td>
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<td>[38]</td>
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<td>Graphene</td>
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Acknowledgments

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