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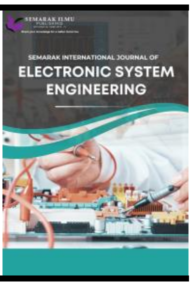

Generation of a Q-Switched Erbium-Doped Fiber Laser using MXene V_2CTx as Saturable Absorber

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ABSTRACT

Fiber laser generation is widely studied for applications in telecommunications and industrial processes, yet enhancing laser performance, especially with effective saturable absorbers (SAs), remains a challenge. This research focuses on using MXene V_2CTx film as a saturable absorber to generate Q-switched fiber lasers. A passive fiber laser was developed using a solution casting method to fabricate the MXene V_2CTx SA. When pump power was increased from 50.66 to 149.79 mW, stable Q-switched pulses at 1530 nm were achieved, with a maximum repetition rate of 93.41 kHz, a pulse width of 3.24 µs, and a pulse energy of 48.82 nJ. These findings demonstrate that MXene V_2CTx is effective in producing stable Q-switched fiber lasers, offering potential for enhanced laser performance in various applications.

1. Introduction

Fiber lasers have emerged as indispensable tools in various scientific, industrial, and medical applications due to their exceptional properties, including high efficiency, compactness, and excellent beam quality as stated by several authors [1-5]. These lasers use optical fibers as their gain medium, ensuring robust performance, easy heat dissipation, and low maintenance compared to conventional solid-state or gas lasers. Among fiber lasers, erbium-doped fiber lasers (EDFLs) are particularly noteworthy for their operation in the telecommunication window around 1.55 µm, making them ideal for optical communication, remote sensing, and biomedical imaging as highlighted by these authors [6,7]. These capabilities align with several Sustainable Development Goals (SDGs), such as SDG 9 (Industry, Innovation, and Infrastructure) by driving advancements in communication technologies and SDG 3 (Good Health and Well-being) through biomedical innovations.

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The core of an EDFL lies in the Erbium-doped fiber (EDF), which serves as the active medium. The unique energy levels of Erbium ions (Er^{3+}) enable efficient amplification of light in the C-band region, aligning perfectly with low-loss regions in optical fibers as discussed by Srivastava *et al.,* [8]. This property, combined with the potential for long gain media in a compact format, makes EDFLs highly attractive. Moreover, when EDFLs are operated in a pulsed mode, they offer enhanced peak powers and are particularly suited for applications such as micromachining, spectroscopy, and nonlinear optics discussed by Deepak *et al.,* [9].

Recent developments in laser technology have focused on improving the efficiency, cost-effectiveness, and environmental impact of these systems, addressing SDG 12 (Responsible Consumption and Production). One widely used technique to generate pulsed output is Q-switching, which modulates the quality factor (Q) of the laser cavity to store and then release energy in the form of intense short pulses. Active Q-switching employs external modulators, such as acousto-optic or electro-optic devices, to control the intracavity loss. As stated by Paschotta [10] in his book, while this approach provides precise control over the pulse parameters, it often requires additional electronics and increases system complexity. In contrast, passive Q-switching offers a simpler and more compact solution by incorporating saturable absorber materials that modulate their transmission intensity-dependent behavior directly into the laser cavity supported by various studies [11-13].

MXenes, a family of two-dimensional (2D) transition metal carbides, nitrides, and carbonitrides, have recently gained significant attention as advanced saturable absorbers for passive Q-switching studied by Dhamodharan *et al.,* [14]. Among these, V_2CTx (Vanadium Carbide MXene) stands out for its exceptional nonlinear optical properties, broadband absorption, and fast recovery time. The inherent advantages of MXene materials, such as high chemical stability, tunable electronic properties, and ease of integration into fiber lasers, position them as promising alternatives to traditional saturable absorbers like graphene or transition-metal dichalcogenides supported by studies conducted by several researches [15-21]. These innovations contribute to SDG 7 (Affordable and Clean Energy) by promoting energy-efficient technologies in photonics.

This paper explores the generation of Q-switched pulses in an erbium-doped fiber laser using MXene V_2CTx as a saturable absorber. By leveraging the superior properties of MXene, we demonstrate a highly efficient and stable laser system capable of producing high-quality pulses. The results underline the potential of MXene-based saturable absorbers to revolutionize pulsed laser systems, paving the way for advanced applications in photonics and beyond. This work not only addresses emerging technological demands but also underscores the role of innovative materials in advancing sustainable and impactful technologies.

2. Methodology

MXene-PVA was synthesized by combining polyvinyl alcohol (PVA) (Sigma-Aldrich, Malaysia) with V_2CTx (Sigma-Aldrich, Malaysia). PVA was chosen as the host polymer due to its excellent film-forming properties, high tensile strength, ease of emulsification, and water solubility, making it ideal for thin-film preparation. The film was fabricated using a 1:1 ratio of PVA to MXene powder.

As illustrated in Figure 1, an all-fiber configuration was employed to construct the erbium-doped fiber laser (EDFL) ring cavity, with the V_2CTx-PVA-based saturable absorber (SA) as the primary component. The active gain medium in the laser system was a 1.8 m erbium-doped fiber (EDF) with a numerical aperture (NA) of 0.23 and a core/cladding diameter of 4 µm/125 µm. Pumping was achieved using a 980 nm diode laser, which was connected to the EDF via a 980/1550 nm wavelengthdivision multiplexer (WDM). To ensure unidirectional propagation of the oscillating laser within the ring cavity, an optical isolator was placed at the output end of the EDF.

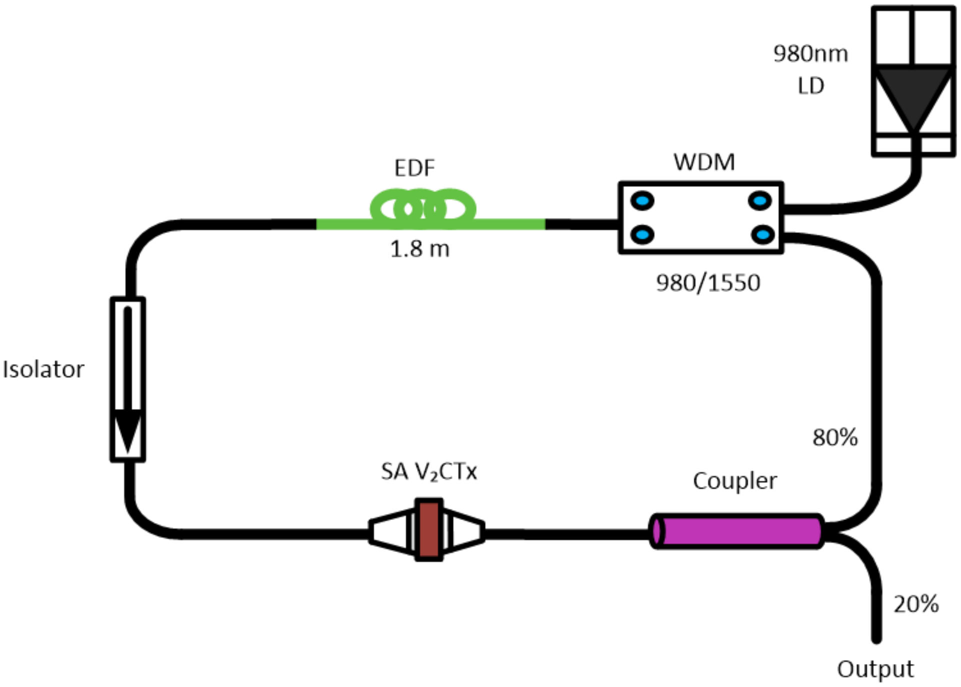

Fig. 1. EDFL ring cavity setup

The Q-factor of the cavity was dynamically modulated by the SA film, which adjusted the intra-cavity losses automatically. The laser loop was completed through an 80:20 optical coupler, which split the laser output, directing 20% of the light for spectral analysis and recycling 80% back into the cavity. The performance and quality of the Q-switching signals were characterized using a suite of diagnostic tools, including a photodetector, a radio frequency spectrum analyzer (RFSA, Anritsu, MS2683A, Tokyo, Japan), a digital oscilloscope (GW Instek, GDS-3502, 500 MHz bandwidth, Seoul, Korea), and an optical spectrum analyzer (OSA, Anritsu, MS9710C, Tokyo, Japan). These instruments were used to analyze the laser's optical properties and validate its output performance.

3. Results

At the initial stage of the experiment, the erbium-doped fiber laser (EDFL) was operated without the inclusion of a saturable absorber (SA) to evaluate its fundamental operating characteristics and to investigate the potential for pulse generation through nonlinear polarization. However, despite increasing the pump power and cavity polarization, only continuous-wave (CW) laser operation was observed. Subsequently, the V_2CTx film saturable absorber was incorporated into the cavity. Under these conditions, the CW laser transitioned to Q-switched pulse operation at a pump power of 50.66 mW. The Q-switched pulses remained stable up to a pump power of 149.79 mW, operating at a wavelength of 1531.6 nm as shown in Figure 2, which aligns with the expected emission wavelength of the EDFL. Beyond this threshold, further increases in pump power caused the Q-switched pulses to become unstable, reverting to CW operation. However, when the pump power was reduced below 149.79 mW, the Q-switched pulses reappeared and regained stability.

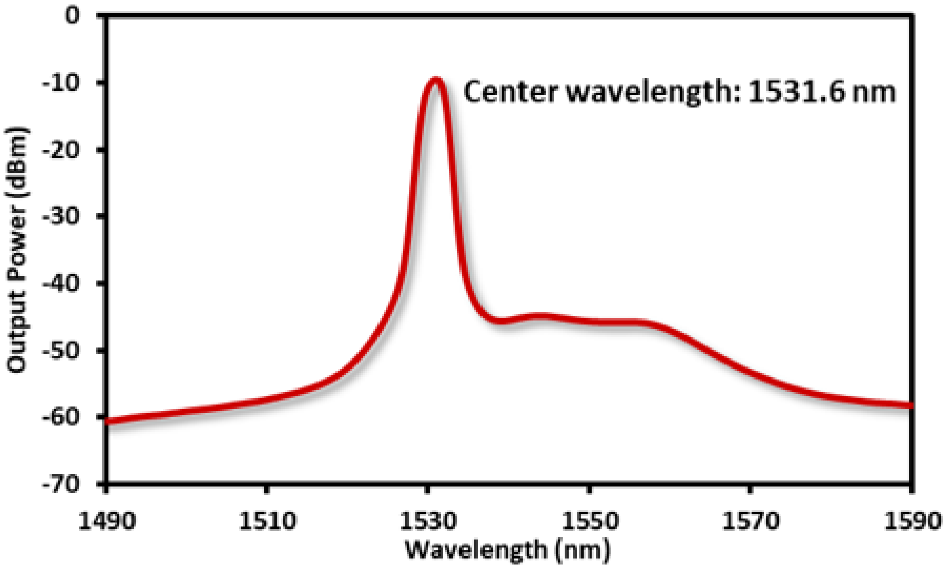

Fig. 2. Output spectrum

Figure 3 illustrates the Q-switched pulse trains at various pump powers. The temporal profiles of the pulses are consistent across the range of pump powers, displaying no irregularities or distortions. This consistency is a key indicator of stable Q-switched pulse operation under the experimental conditions.

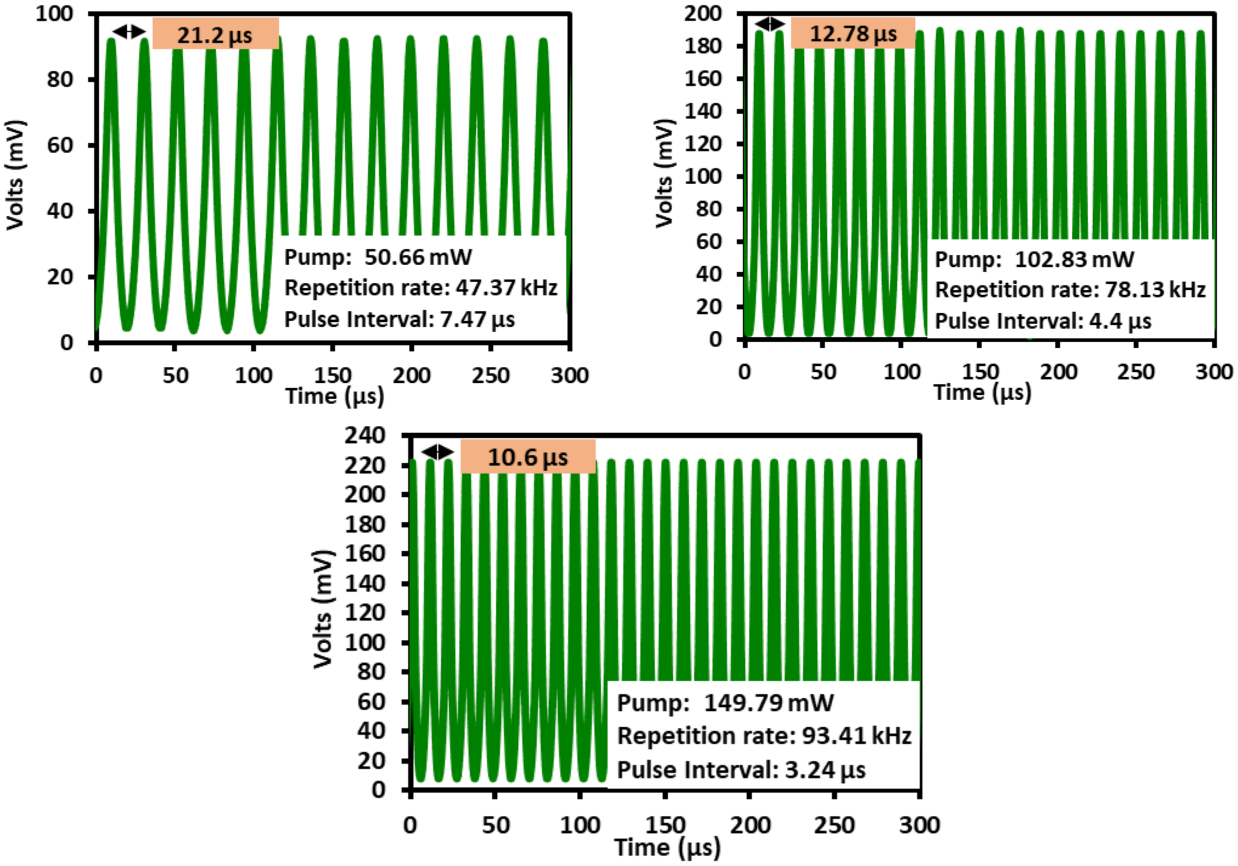

Fig. 3. Oscilloscope pulse train

Figure 4 and 5 presents the analysis of pulse energy, average output power, repetition rate, and pulse width as functions of pump power. Figure 4 illustrates the relationship between pulse repetition rate and pulse width with respect to pump power. As the pump power increased from 50.66 mW to 149.79 mW, the pulse width decreased from 7.47 µs to 3.24 µs, while the repetition rate rose from 47.37 kHz to 93.41 kHz. The observed trends indicate a stable and consistent Q-switching process, as evidenced by the absence of significant fluctuations in either the repetition rate or pulse width across the range of pump powers.

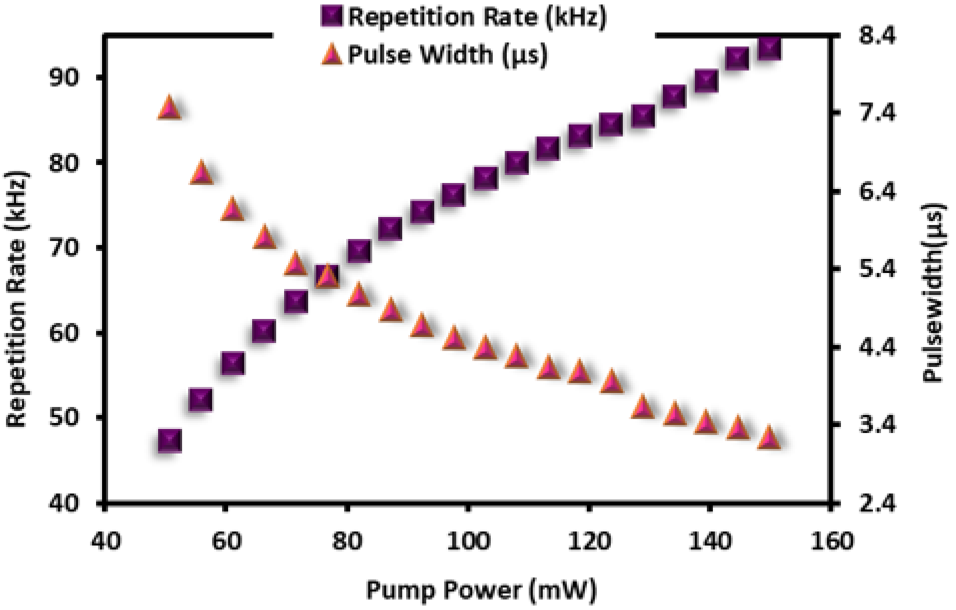

Fig. 4. Repetition rate against pulse width

Figure 5 shows that the average output power increased linearly with pump power, from 0.88 mW to 4.56 mW. The highest pulse energy, 48.82 nJ, was achieved at the maximum pump power of 149.79 mW. These linear trends are characteristic of Q-switched lasers, where the energy transferred to the cavity increases with pump power until the saturable absorber becomes fully saturated.

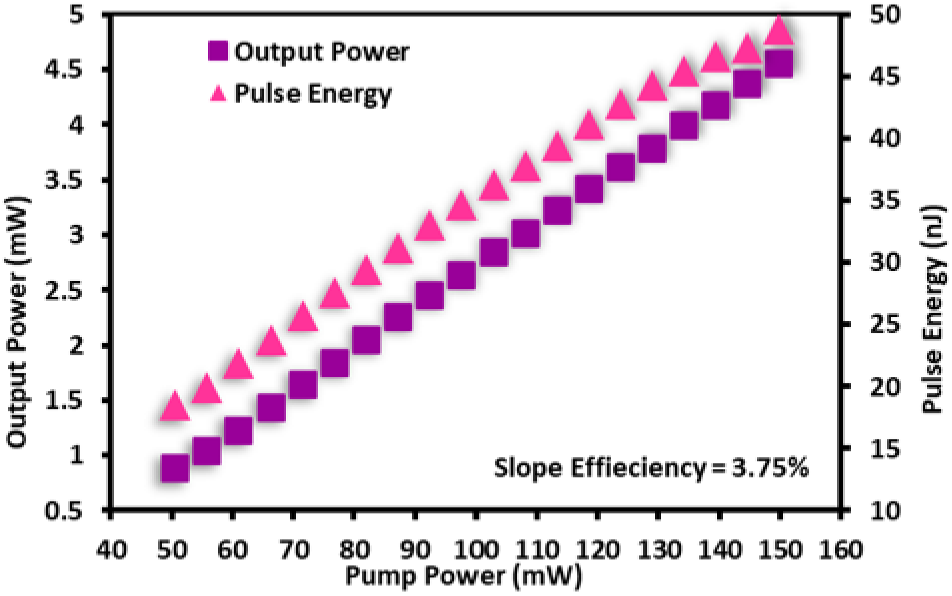

Fig. 5. Output power against pulse energy

At the maximum pump power, the RF spectrum, shown in Figure 6, reveals multiple harmonics with a fundamental frequency of 93.41 kHz. The RF signal-to-noise ratio (SNR) at this frequency exceeds 50 dB, further confirming the stability of the Q-switching operation. Additionally, the inset of Figure 6 shows a single sharp peak at the pulse repetition frequency, with minimal sidebands or harmonics, providing further evidence of the pulse's stability and consistency.

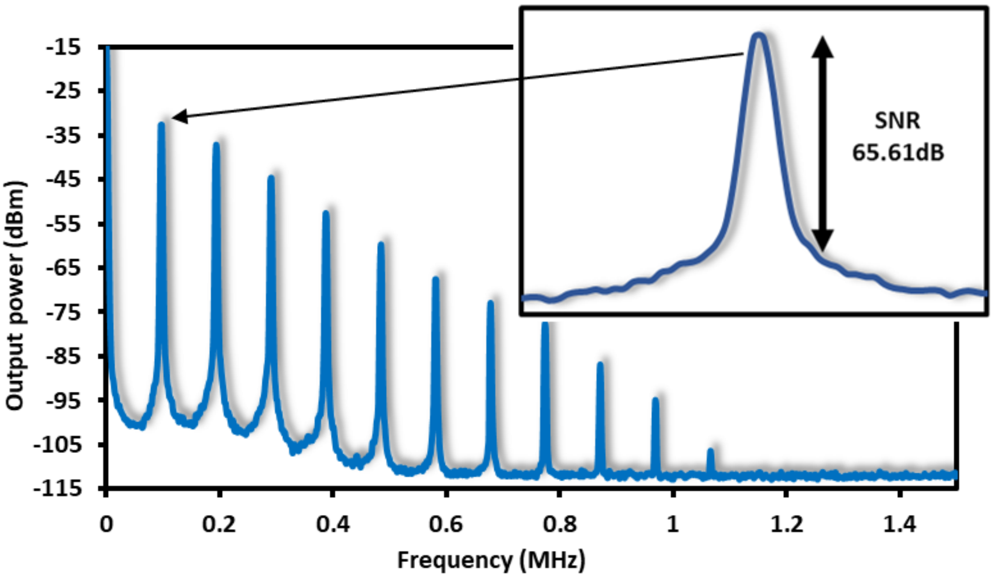

Fig. 6. RF spectrum

4. Conclusions

In this study, MXene V_2CTx film has been successfully demonstrated as an effective saturable absorber for the generation of Q-switched fiber lasers. The results highlight the material's potential to enhance laser performance, achieving stable pulses with a maximum repetition rate of 93.41 kHz, a pulse width of 3.24 µs, and a pulse energy of 48.82 nJ under pump powers ranging from 50.66 to 149.79 mW. These findings underline the capability of MXene V_2CTx as a viable and efficient SA, paving the way for its integration into advanced fiber laser systems for telecommunications and industrial applications. Future research could explore further optimization of MXene-based SAs to extend their operational parameters and broaden their applicability in diverse laser systems.

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