Q-SWITCHED AND MODE-LOCKED ERBIUM DOPED PULSED FIBER LASER USING MOLYBDENUM TITANIUM ALUMINUM CARBIDE AS SATURABLE ABSORBER

MUHAMMAD AIZAT ZAIM BIN ZAINI

MASTER OF SCIENCE IN ELECTRONIC ENGINEERING

2025

Faculty of Electronics & Computer Technology and Engineering

Q-SWITCHED AND MODE-LOCKED ERBIUM DOPED PULSED FIBER LASER USING MOLYBDENUM TITANIUM ALUMINUM CARBIDE AS SATURABLE ABSORBER

Muhammad Aizat Zaim bin Zaini

Master of Science in Electronic Engineering

2025

Q-SWITCHED AND MODE-LOCKED ERBIUM DOPED PULSED FIBER LASER USING MOLYBDENUM TITANIUM ALUMINUM CARBIDE AS SATURABLE ABSORBER

MUHAMMAD AIZAT ZAIM BIN ZAINI

A thesis submitted
in fulfillment of the requirements for the degree of
Master of Science in Electronic Engineering.

Faculty of Electronics & Computer Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2025

DECLARATION

I declare that this thesis entitled "Q-switched and Mode-locked Erbium Doped Pulsed Fiber Laser using Molybdenum Titanium Aluminum Carbide as Saturable Absorber" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : MUHAMMAD AIZAT ZAIM BIN ZAINI

Date : 25-07-2025

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of Master of Science in Electronic Engineering.

Signature : ....

Supervisor Name : ANAS BIN ABDUL LATIFF

Date : 25-JUL-2025

DEDICATION

This thesis is dedicated to my beloved parents (Zaini Tumian and Muna Al Aisri @ Alasri), whose unwavering love, sacrifices, and endless support have been my guiding light throughout this journey. Your belief in me, even during the most challenging times, has been my greatest source of strength. This achievement is as much yours as it is mine.

To my family, siblings, and loved ones, thank you for standing by me with patience and encouragement. Your prayers and kindness have carried me through every obstacle.

Lastly, to all those who strive for knowledge and pursue their dreams, may this work inspire you to persevere and never give up, no matter how difficult the path may seem.

ABSTRACT

This research focuses on the main limitations in existing saturable absorber (SA) materials, specifically their low optical damage thresholds, complex fabrication processes, and limited compatibility with high-power and flexible fiber laser configurations. To overcome these challenges, the study investigates Molybdenum Titanium Aluminum Carbide (Mo_2TiAlC_2), a MAX phase material as a saturable absorber for pulsed fiber laser applications. A Mo_2TiAlC_2-PVA thin film was fabricated using the solvent casting method and characterized using Field Emission Scanning Electron Microscopy (FESEM) and Energy Dispersive X-ray Spectroscopy (EDX) to confirm its structural and elemental properties. Optical measurements revealed a modulation depth of 2.8 % and a saturable intensity of 0.2 kW/cm^2, indicating its suitability for nonlinear photonic applications. The thin film was integrated into an erbium-doped fiber laser (EDFL) to demonstrate both Q-switched and mode-locked operations. In Q-switched operation, the laser achieved repetition rates from 31.1 kHz to 66.83 kHz, with pulse widths ranging from 13.45 µs to 6.35 µs as pump power increased. The maximum output power and pulse energy were 6.56 mW and 98.16 nJ, respectively, with a signal-to-noise ratio (SNR) of 58 dB. For mode-locking, the cavity was integrated with 150 m and 200 m of single-mode fiber (SMF) to study dispersion effects. The 150 m SMF setup achieved a repetition rate of 1.257 MHz with a pulse width of 357 ns, while the 200 m of SMF generated 0.9524 MHz and 493.2 ns, respectively. Both configurations maintained stable mode-locking, with output powers above 11 mW and pulse energies up to 11.55 nJ. These outcomes validate the effectiveness of Mo_2TiAlC_2 as a saturable absorber, combining strong nonlinear response with thermal stability and simple fabrication. The study concludes that Mo_2TiAlC_2-PVA thin films are a practical and high-performing alternative to conventional SA materials for ultrafast fiber laser systems.

LASER GENTIAN BERDENYUT TERPUTUS DAN TERKUNCI MODE BERASASKAN ERBIUM DENGAN MOLYBDENUM TITANIUM ALUMINIUM KARBIDA SEBAGAI PENYERAP TEPU

ABSTRAK

Kajian ini fokus atas batasan utama dalam bahan penyerap tepu yang sedia ada terutamanya ambang kerosakan optik yang rendah, proses fabrikasi yang kompleks, dan ketidakserasian dengan konfigurasi laser gentian berkuasa tinggi dan fleksibel. Bagi mengatasi cabaran ini, kajian ini menilai keberkesanan Molibdenum Titanium Aluminium Karbida (Mo_2TiAlC_2) sejenis bahan fasa MAX, sebagai penyerap tepu untuk aplikasi laser gentian berdenyut. Filem nipis Mo_2TiAlC_2-PVA telah difabrikasi menggunakan kaedah larutan tuangan dan pencirian dengan menggunakan Mikroskopi Imbasan Elektron Pancaran Medan (FESEM) dan Spektroskopi Sinar-X Penyerakan Tenaga (EDX) untuk mengesahkan struktur dan komposisi elemennya. Pengukuran optik menunjukkan kedalaman modulasi sebanyak 2.8 % dan keamatan penyerap tepu sebanyak 0.2 kW/cm^2, menunjukkan kesesuaian dalam aplikasi fotonik tak linear. Filem nipis ini kemudian diintegrasi ke dalam rongga laser gentian berpandukan erbium (EDFL) berdemonstrasi untuk Q-switch dan mode-lock. Dalam operasi Q-switch, laser mencapai kadar pengulangan antara 31.1 kHz hingga 66.83 kHz, dengan lebar denyutan antara 13.45 µs hingga 6.35 µs bergantung pada kuasa pam. Kuasa keluaran maksimum dan tenaga denyutan masing-masing ialah 6.56 mW dan 98.16 nJ, dengan nisbah isyarat kepada hingar (SNR) sebanyak 58 dB. Untuk mode-lock, gentian mod tunggal (SMF) sepanjang 150 m dan 200 m digunakan untuk mengkaji kesan penyebaran. Konfigurasi 150 m mencapai kadar pengulangan 1.257 MHz dengan lebar denyutan 357 ns, manakala 200 m mencapai 0.9524 MHz dan 493.2 ns. Kedua-dua konfigurasi menunjukkan kestabilan mode-lock, dengan kuasa keluaran melebihi 11 mW dan tenaga denyutan hingga 11.55 nJ. Hasil kajian ini mengesahkan keberkesanan Mo_2TiAlC_2 sebagai penyerap tepu yang berprestasi tinggi, stabil secara termal, dan mudah difabrikasi. Kajian ini menyimpulkan bahawa filem nipis Mo_2TiAlC_2-PVA merupakan alternatif praktikal dan berdaya saing kepada bahan SA konvensional dalam system laser gentian ultra pantas.

ACKNOWLEDGEMENT

First and foremost, I would like to express my deepest gratitude to Allah SWT, the Most Merciful and Most Compassionate, for granting me the strength, patience, and guidance to complete this thesis. Without His blessings, this journey would not have been possible.

I am profoundly grateful to my supervisors, Associate Professor Ir. Dr. Anas Abdul Latiff and Ir. Ts. Dr. Mohd Fauzi Ab Rahman, for their invaluable guidance, unwavering support, and insightful feedback throughout this research. Their expertise, encouragement, and patience have been instrumental in shaping this thesis and my growth as a researcher. I am truly fortunate to have had the opportunity to learn under their mentorship.

I would also like to extend my sincere thanks to the faculty members and staff of the Photonics Engineering Research Group (PERG) at Universiti Teknikal Malaysia Melaka (UTeM) and Universiti Malaya (UM) for their assistance and support. Special thanks to Mohammad Effendy Abidin for their technical guidance and access to laboratory facilities, which were essential for the successful completion of this work.

This research was made possible through the support of PERTAM Sdn. Bhd. under the Industrial Grant INDUSTRI/PSSB/FKEKK/2022/I00079. I am sincerely grateful for the financial assistance and industrial collaboration that significantly contributed to the successful execution of this project.

To my beloved family, especially my parents (Zaini Tumian and Muna Al Aisri @ Alasri), and my siblings (Muhammad Abdul Rauf Zaim, Siti Aishah Zaim, and Siti Arifal Afzal Zaim), thank you for your endless love, prayers, and encouragement. Your sacrifices and belief in me have been my driving force throughout this journey. I am forever indebted to you for your unwavering support.

My heartfelt gratitude goes to my friends and colleagues, particularly (Ahmad Muzammil Roslizar, Mohd Adzimnuddin Mohd Nor Azami, Ilyana Amalin Zainal Roslan, Nur'in Batrisyia Mohd Faizu, and Izzah Hazirah Zainal), for their companionship, motivation, and shared laughter during both challenging and rewarding times. Your support has made this journey more meaningful and enjoyable.

This thesis is a culmination of the efforts, guidance, and support of many individuals. To all who have contributed directly or indirectly, I extend my deepest appreciation. Thank you for being part of this significant chapter in my life.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

$0D$	-	Zero-dimensional
$1D$	-	One-dimensional
$2D$	-	Two-dimensional
$3D$	-	Three-dimensional
ASE	-	Amplified Spontaneous Emission
BP	-	Black Phosphorus
CW	-	Continuous Wave
EDF	-	Erbium-doped Fiber
$EDFLs$	-	Erbium-doped Fiber Lasers
EDX	-	Energy Dispersive X-ray
FBG	-	Fiber Bragg Grating
$FESEM$	-	Field Emission Scanning Electron Microscopy
$HDFLs$	-	Holmium-doped Fiber Lasers
LD	-	Laser Diode
Mo_2TiAlC_2	-	Molybdenum Titanium Aluminum Carbide
OPM	-	Optical Power Meter
OSA	-	Optical Spectrum Analyzer
PVA	-	Polyvinyl Alcohol
RFA	-	Radio Frequency Analyzer
SAs	-	Saturable Absorbers
SBS	-	Stimulated Brillouin Scattering
$SESAMs$	-	Semiconductor Saturable Absorber Mirrors

SMF	-	Single-mode Fiber
SRS	-	Stimulated Raman Scattering
TBP	-	Time Bandwidth Product
$TDFLs$	-	Thulium-doped Fiber Lasers
TIs	-	Topological Insulators
$TMDs$	-	Transition Metal Dichalcogenides
VOA	-	Variable Optical Attenuator
WDM	-	Wavelength Divison Multiplexer

LIST OF SYMBOLS

h	-	Plank’s Constant
v	-	Photon’s Frequency
E_1	-	Ground State
E_2	-	Excite State
C	-	Speed of Light
τ	-	Pulse Width
T	-	Pulse Period
f_o	-	Fundamental Frequency

LIST OF APPENDICES

LIST OF PUBLICATIONS

The followings are the list of publications related to the work on this thesis:

M. A. Z. Zaini, M. F. A. Rahman, A. A. Latiff, M. F. M. Rusdi, I. A. Z. Roslan, and S. W. Harun, 2024. Nanosecond Pulse Generation with Molybdenum Titanium Aluminum Caribide (Mo_2TiAlC_2) Deposited onto D-shaped Fiber. *Nonlinear Optics, Quantum Optics*, vol. 60, pp. 71-84
(SCOPUS - Atomic and Molecular Physics, and Optics).

M. A. Z. Zaini, M. F. A. Rahman, A. A. Latiff, M. F. M. Rusdi, I. A. Z. Roslan, and S. W. Harun, 2024. Passsive Q-switched Pulse Fibre Laser with Molybdenum Titanium Aluminum Carbide (Mo_2TiAlC_2) Saturable Absorber. *Journal of Modern Optics*, vol. 70, pp. 661-672 (WOS-SCIE OPTICS (Q4)).

CHAPTER 1

INTRODUCTION

1.1 Background

Fiber lasers have revolutionized the field of photonics and optoelectronics, serving as essential tools in various applications such as materials processing, medical diagnostics, telecommunications, and scientific research. Their unique advantages, including high efficiency, compact design, and excellent beam quality, have driven their widespread adoption and continuous development (Limpert et al., 2006; Richardson et al., 2010). Central to the functionality of fiber lasers is their ability to produce pulsed outputs, which are essential for applications requiring precise energy delivery, high peak power, or ultrafast temporal resolution.

The generation of pulsed laser output is primarily achieved through techniques such as Q-switching and mode-locking. These methods enable the manipulation of the laser cavity's gain and loss dynamics, resulting in the production of pulses with varying durations and repetition rates. Q-switching typically produces microsecond pulses with high energy per pulse, while mode-locking generates ultrashort pulses in the picosecond or femtosecond range (Yap et al., 2022). These distinct characteristics make Q-switching and mode-locking complementary techniques, each tailored to specific application domains.

Passive techniques for inducing pulsed laser output, particularly those utilizing saturable absorbers, have garnered significant attention due to their simplicity and effectiveness. A saturable absorber is a material whose optical absorption decreases with increasing light intensity, allowing for passive modulation of intracavity laser dynamics. The emergence of novel saturable absorber materials has been pivotal in advancing pulsed laser technology. Among these materials, two-dimensional (2D) substances like graphene and transition metal dichalcogenides (TMDs) have been extensively studied for their remarkable nonlinear optical properties and broad tunability (Jhon et al., 2021). However, these materials often face challenges such as limited optical damage thresholds, which can restrict their performance and practical implementation.

Saturable absorber structures are important in the generation of pulsed laser systems, with various configurations to enhance performance across different applications (Debnath et al., 2021). Various saturable absorber structures have been developed to optimize light-matter interaction and enhance pulse generation efficiency. These include semiconductor saturable absorber mirrors (SESAMs), thin films, tapered fibers, optical deposition, and D-shaped fibers. Each saturable absorber's structure offers distinct advantages in terms of fabrication, integration, and performance. SESAMs provide reliable and customizable absorption properties, while thin films are favored for their fabrication simplicity and broadband operation. Tapered and D-shaped fiber increase evanescent field exposure for stronger interaction with absorber materials (Steinberg et al., 2018). This research investigates thin film saturable absorber using novel 3D materials, aiming to improve the performance and durability of pulsed fiber lasers in high-power applications.

1.2 Problem Statement

The development of high-performance pulsed fiber lasers is increasingly limited by the shortcomings of current saturable absorber materials. While passive techniques using SAs are attractive for their simplicity and compactness, widely used materials such as graphenes and transition metal dichalcogenides (TMDs) suffer from low optical damage thresholds, restricting their use in high-power laser applications. Other alternatives, like black phosphorus (BP) and topological insulators (TIs), present challenges, including poor environmental stability and complex fabrication requirements, respectively (Lee et al., 2019a; Kong et al., 2011; Wood et al., 2014).

In addition to material limitations, many high-performance SAs demand expensive and complex fabrication methods, such as molecular beam epitaxy or ion implantation, which require large-scale or cost-effective deployment in fiber laser systems (Lau et al., 2022a). Furthermore, achieving stable mode-locked pulse, particularly when incorporating additional fiber elements like single-mode fiber spools remain underexplored. These configurations can affect pulse stability and performance, especially when combined with novel SA materials (Cheng et al., 2020; Wang et al., 2022a).

Given these challenges, there is a need for new SA materials that can operate at high intensities, simple design, and cost-effective to fabricate. This research focuses on these research gaps by investigating MAX phase thin film saturable absorber, which offer strong nonlinear optical properties, excellent thermal stability, and a straightforward fabrication process. The study further evaluates pulse performance under varying fiber length to assess the potential of this material system in practical ultrafast laser applications.