PASSIVELY Q-SWITCHED FIBRE LASER GENERATION FOR MID INFRARED USING ALUMINIUM-BASED MAX PHASE MATERIALS

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MASTER OF SCIENCE IN ELECTRONIC ENGINEERING

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Faculty of Electronic and Computer Technology and Engineering

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DECLARATION

I declare that this thesis entitled “Passively Q-Switched Fibre Laser Generation For Mid Infrared Using Aluminium-Based Max Phase Materials” 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 : Amal Muaz Bin Mohd Nasir

Date : 30 May 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	: Ir. Ts. Dr. Mohd Fauzi Bin Ab Rahman
Date	: 1 Jun 2025

DEDICATION

To my beloved parents and my family,

Your unwavering support, boundless love, and constant encouragement have been the guiding lights of my academic journey. Your sacrifices, patience, and belief in my abilities have shaped both my academic pursuits and the essence of who I am today. Your commitment to my dreams has been a beacon of hope and inspiration, propelling me forward even in adversity. Your faith in my potential and unconditional love have been the pillars of strength upon which I have built my aspirations. Your support, understanding, and encouragement have been my constant companions, providing solace in times of uncertainty and joy in moments of triumph. Your belief in me has instilled the courage to pursue my dreams relentlessly, knowing I have your unwavering support and love guiding me.

This thesis is dedicated to each of you with the deepest gratitude and appreciation for your support, love, and sacrifices that have enriched my academic journey beyond measure. Your presence in my life is a testament to the power of family, and I am eternally grateful for the love, encouragement, and belief in my abilities you have given me.

ABSTRACT

Pulsed fibre lasers are increasingly vital in modern photonics due to their compactness, efficiency, and high peak power, supporting applications in sensing, imaging, and materials processing. Among pulse generation techniques, passive Q-switching is preferred for its simplicity and low cost. However, identifying saturable absorbers (SAs) that are stable, efficient, and compatible with mid-infrared operation remains a challenge. This study explores the integration of aluminium-based MAX phase materials; Molybdenum Titanium Aluminium Carbide ($Mo_2Ti_2AlC_2$) and Titanium Aluminium Nitride (Ti_4AlN_3), as SAs for passively Q-switched erbium-doped fibre lasers (EDFLs) operating near 1.55 µm. The MAX phase materials were dispersed in polyvinyl alcohol (PVA) to form homogeneous films via drop-casting. Each film was sandwiched between standard fibre ferrules and inserted into a ring-cavity EDFL for passive Q-switching. Optical characterisation of the materials revealed suitable absorption and modulation properties for Q-switch operation. The $Mo_2Ti_2AlC_2$-PVA film exhibited a linear absorption of 1.5 dB and enabled self-started Q-switching with pulse durations from 21.7 µs to 8.9 µs and repetition rates from 20.45 kHz to 40.40 kHz, achieving a maximum output power of 1.1 mW and pulse energy of 27.2 nJ. In comparison, the Ti_4AlN_3-PVA film showed a modulation depth of 17% and produced pulses at 1559.4 nm with a minimum duration of 5.75 µs at 59.2 kHz, yielding a peak output power of 2.34 mW and pulse energy of 39.5 nJ. These results confirm the effectiveness of aluminium-based MAX phase materials as practical SAs for mid-infrared fibre lasers. Their strong nonlinear absorption, thermal stability, and ease of integration offer a promising solution for the

development of compact, stable, and high-performance pulsed laser systems in emerging photonic applications.

PENJANAAN LASER GENTIAN Q-TUKAR PASIF UNTUK INFRAMERAH PERTENGAHAN MENGGUNAKAN BAHAN FASA MAX BERASASKAN ALUMINIUM

ABSTRAK

Laser gentian berdenyut semakin penting dalam bidang fotonik moden kerana reka bentuknya yang padat, cekap, dan mampu menghasilkan kuasa puncak tinggi, yang sesuai untuk aplikasi seperti penderiaan, pengimejan, dan pemprosesan bahan. Dalam kalangan teknik penjanaan denyutan, pensuisan-Q secara pasif menjadi pilihan kerana reka bentuknya yang ringkas dan kos yang rendah. Walau bagaimanapun, pembangunan penyerap tepu (saturable absorber, SA) yang stabil, cekap dan sesuai untuk operasi dalam kawasan inframerah pertengahan masih menjadi cabaran. Kajian ini meneroka penggunaan bahan fasa MAX berasaskan aluminium; Molybdenum Titanium Aluminium Carbide ($Mo_2Ti_2AlC_2$) dan Titanium Aluminium Nitride (Ti_4AlN_3), sebagai SA untuk laser gentian beradunan erbium (EDFL) yang disuis-Q secara pasif pada panjang gelombang sekitar 1.55 µm. Bahan fasa MAX ini disebatikan dalam larutan polivinil alkohol (PVA) dan dibentuk menjadi filem seragam melalui teknik tuangan titisan (drop-casting). Filem yang terhasil disisipkan di antara ferul gentian dan dimasukkan ke dalam rongga gelang laser EDFL. Pencirian optik menunjukkan sifat serapan dan modulasi yang sesuai untuk operasi suis-Q. Filem $Mo_2Ti_2AlC_2$-PVA menunjukkan serapan linear sebanyak 1.5 dB dan membolehkan pensuisan-Q bermula sendiri dengan lebar denyutan antara 21.7 µs hingga 8.9 µs serta kadar pengulangan antara 20.45 kHz hingga 40.40 kHz, menghasilkan kuasa keluaran maksimum 1.1 mW dan tenaga denyutan 27.2 nJ. Filem Ti_4AlN_3-PVA pula menunjukkan kedalaman modulasi 17% dan menghasilkan denyutan stabil pada 1559.4 nm dengan lebar *minimum 5.75 µs pada kadar 59.2 kHz, menghasilkan kuasa maksimum 2.34 mW dan tenaga denyutan 39.5 nJ. Keputusan ini mengesahkan keberkesanan bahan fasa MAX berasaskan aluminium sebagai SA yang praktikal untuk laser gentian inframerah pertengahan. Sifat penyerapan tidak linear yang kukuh, kestabilan terma, dan kemudahan integrasi menunjukkan potensi besar bahan ini dalam pembangunan sistem laser berdenyut yang stabil, padat dan berprestasi tinggi untuk aplikasi fotonik masa hadapan.*

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LIST OF ABBREVIATIONS

BP	-	Black Phosphorus
EDF	-	Erbium-doped Fibre
EDFA		Erbium-doped Fibre Amplifier
EDFL	-	Erbium-doped Fibre Laser
EDS	-	Energy Dispersive Spectroscopy
EDX	-	Energy-Dispersive X-Ray
FESEM	-	Field Emission Scanning Electron Microscopy
FTKEK	-	Fakulti Teknologi Dan Kejuruteraan Elektronik Dan Komputer
FWHM	-	Full Width Half Maximum
LAP	-	Linear Absorption Profile
$Mo_2Ti_2AlC_2$	-	Molybdenum Titanium Aluminium Carbide
RBW	-	Resolution Bandwidth
SA	-	Saturable Absorber
SAs	-	Saturable Absorbers
SESAMs	-	Semiconductor Saturable Absorber Mirrors
TI	-	Topological Insulators
Ti_4AlN_3	-	Titanium Aluminium Nitride
TMD	-	Transition Metal Dichalcogenide
UTeM	-	Universiti Teknikal Malaysia Melaka
XRD	-	X-Ray Diffraction

LIST OF SYMBOLS

E	-	Pulse Energy
f	-	Pulse Repetition Rate / Pulse Frequency
P_{avg}	-	Pulse Average Power
P_{peak}	-	Pulse Peak Power
t	-	Pulse Period

LIST OF APPENDICES

LIST OF PUBLICATIONS

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

Nasir, A.M.M., Latiff, A.A., Anuar, S.A., Muhammad, A.R., and Rahman, M.F.A., 2023a. Passively Q-switched fiber laser utilizing molybdenum titanium aluminum carbide ($Mo_2Ti_2AlC_2$) for pulsed laser generation. *Optik*, 273, pp. 170439.

Nasir, A.M.M., Rahman, M.F.A., Anuar, S.A., Latiff, A.A., Rosol, A.H.A., and Al-Masoodi, A.H.H., 2023b. Generation of Q-switched erbium-doped fiber laser using MAX phase titanium aluminum nitride Ti_4AlN_3. *Optik*, 295, pp. 171488.

CHAPTER 1

INTRODUCTION

1.1 Background

Fibre laser technology has undergone significant advancements over the decades, transforming from a research novelty into a cornerstone of modern industry and science. The evolutionary trajectory of fibre lasers highlights key milestones that have shaped their development. In the 1960s, the foundational work on laser technology paved the way for subsequent innovations. By the 1980s, the introduction of optical fibres doped with rare-earth elements enabled the creation of fibre lasers, marking a breakthrough. During the 1990s, fibre lasers became commercially viable, gaining attention for their efficiency and reliability. The 2000s witnessed the emergence of high-power fibre lasers, which found applications in diverse fields such as industrial manufacturing and medical therapies. By the 2010s, advanced materials and techniques, including Q-switching, were integrated into fibre lasers, further enhancing their performance and applicability. Today, ongoing innovations, particularly in novel materials such as MAX phase compounds, are driving the next phase of development in fibre laser systems.

The evolution of fibre lasers is characterized by continuous improvements in power output, beam quality, and cost-effectiveness. These advancements have made fibre lasers indispensable tools in manufacturing, telecommunications, and medicine, enabling unprecedented levels of precision and efficiency. Key technological enhancements include the optimization of doping processes in optical fibres and the simplification of system designs to reduce maintenance and operational costs.

At the heart of fibre laser technology lies the utilization of optical fibres doped with rare-earth elements such as erbium, ytterbium, neodymium, or thulium. These elements play a critical role in amplifying light, thereby enabling laser operation. The core components of a fibre laser system include the active fibre, which is doped with rare-earth materials to facilitate light amplification, and the pump source, which provides the necessary energy to excite the active medium. Additionally, optical isolators are employed to prevent feedback interference, while optical couplers are used to direct the laser output for specific applications. These components work in harmony to deliver the high-performance characteristics that define fibre lasers.

Q-switching represents a pivotal advancement in laser technology, enabling the generation of short, high-intensity pulses. This technique significantly enhances the peak power of lasers, making them suitable for applications that require concentrated energy bursts. The process involves the rapid modulation of the laser cavity's quality factor (Q), which determines the efficiency of energy storage and release. By transitioning the Q-factor from low to high, a substantial amount of energy can be stored and subsequently released in a powerful pulse.

There are four primary types of Q-switching: mechanical, acousto-optic, electro-optic, and passive. Among these, passive Q-switching, which relies on saturable absorbers (SAs), is particularly noteworthy. These absorbers become transparent at high light intensities, enabling automatic modulation of the laser output without external control.