UNIVERSITI PUTRA MALAYSIA

LINEAR CAVITY MULTIWAVELENGTH THULIUM-DOPED FIBER LASER INCORPORATING A HIGHLY NONLINEAR FIBER

ROZLINDA BINTI RADZALI

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Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Master of Science

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Chairman: Muhammad Hafiz Bin Abu Bakar, PhD
Faculty: Engineering

2-μm laser generation has attracted intense research interest due to its ability to fulfill shorter wavelength needs such as laser cutting and surgery whilst providing eye-safer operation. Additionally, in applications such as light detection and ranging (LIDAR), sensing, spectroscopy, and material processing, certain materials interact better in 2-μm wavelength band, thus delivering better accuracy and precision in the results. In recent times, the constant need for more data or information has evoked exploration on the use of 2-μm region as an expansion to the optical fiber communication band, further promoting interest in 2-μm thulium-doped fiber lasers. One major issue in multiwavelength thulium-doped fiber laser (MWTDFL) however, is the high loss of silica in that region. This consequently impedes the generation of high gain that is essential in producing multiple channels. Resultantly, most works had to resort to complex nonlinear structure in order to address this issue, thus lessening the feasibility of translating these laser devices into industrial applications.

This work proposed a simple thulium-doped fiber laser configuration capable of generating multiwavelength output. A linear cavity configuration was employed for this purpose with two loop mirrors confining the oscillation for the thulium-doped fiber induced gain. An optical interleaver was included to generate the multiwavelength seed signal, allowing four distinct lasing peaks to be observed albeit with instability to the two lower power peaks. The work then progressed to the integration of highly nonlinear fiber (HNLF) within the structure. A 500-m section of HNLF was spliced in the laser setup to investigate its performance. The presence of HNLF helped to increase the number of output channels to 22 and 35 lasing lines in 10-dB and 20-dB bandwidth respectively with optical signal to noise ratio as high as 30-dB. Maximum output power observed is 0.406 mW. The high nonlinearity from the presence of HNLF induced four-wave mixing (FWM) effect which assisted gain distribution allowing higher channel count to be produced. The stability of the HNLF-integrated MWTDFL was then investigated. This experiment was performed by observing the multiwavelength laser spectrum every 5 minutes for a total time span of one hour at the maximum pump power of 2000 mW.

Based on the findings, the laser exhibited power fluctuations of less than 1.325-dB, with the worst value recorded at shorter wavelength region due to the lower net gain profile. Maximum wavelength dithering of 0.12 nm was also observed thanks to the use of physical multiwavelength selector. In summary, the work has demonstrated the use of a simple linear cavity design to generate multiwavelength output achieved by integrating a section of HNLF within the cavity without complex nonlinear-based structure. High channel count was generated with minimal fluctuation to the peak power and wavelength. The success of this work can elevate the status of MWTDFL as a feasible candidate for industrial applications requiring 2-µm laser band.

Abstrak tesis dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Sarjana Sains

LASER GENTIAN TERDOP THULIUM PELBAGAI PANJANG GELOMBANG RONGGA LINEAR MENGGABUNGKAN GENTIAN SANGAT TAK LINEAR

Oleh

ROZLINDA BINTI RADZALI

Januari 2017

Pengerusi: Muhammad Hafiz Bin Abu Bakar, PhD
Fakulti: Kejuruteraan

Penjanaan laser 2-µm telah menarik perhatian dalam penyelidikan kerana kelebihannya dalam memenuhi keperluan panjang gelombang yang lebih pendek seperti pemotongan laser dan pembedahan disamping itu, penggunaannya yang lebih selamat untuk mata. Tambahan pula, dalam aplikasi seperti pengesanan cahaya dan meliputi (LIDAR), rangsangan, spektroskopi dan pemprosesan bahan, bahan-bahan tertentu dilihat lebih baik dalam panjang gelombang laser 2-µm. Lantaran itu, hasil yang lebih baik dapat diperolehi yang meliputi ketepatan dan perinciannya. Baru-baru ini, penerokaan dalam panjang gelombang 2-µm telah menjadi keperluan yang berterusan untuk data dan maklumat jika dipanjangkan kepada gentian optik komunikasi, disamping ia merupakan tarikan dalam 2-µm tulium-terdop gentian laser. Walaubagaimanapun, masalah utama dalam laser gentian terdop thulium pelbagai panjang gelombang (MWTDFL) ialah silika mengalami kehilangan yang sangat tinggi dalam kawasan ini. Oleh itu, ini telah mengakibatkan terhalang dari menghasilkan generasi yang sangat berganda untuk penghasilan saluran yang berbilang-bilang. Akibatnya, kebanyakan kerja-kerja penyelidikan menghasilkan kompleks struktur yang tidak linear dalam menyelesaikan isu ini. Oleh itu, kemungkinan ini telah mengurangkan penggunaan peranti laser untuk aplikasi dalam industri.

Tesis ini mencadangkan laser gentian terdop thulium yang mampu menghasikan pelbagai panjang gelombang dengan menggunakan struktur yang mudah. Satu konfigurasi rongga linear dengan menggunakan dua gelung cermin dimana aliran ayunan laser dihadkn untuk merangsang gandaan gentian terdop thulium. Interleaver optik digunakan untuk menghasilkan isyarat pelbagai panjang gelombang yang menghasilkan empat puncak las yang berbeza dengan ketidakstabilan pada dua puncak kuasa yang terendah. Kerja ini kemudiannya berkembang dengan memperkenalkan gentian yang sangat tidak linear (HNLF) dalam struktur. HNLF sepanjang 500 meter disambungkan untuk mengkaji pretasinya dalam struktur laser. Kehadiran HNLF telah membantu meningkatkan hasil saluran kepada 22 dan 35 garisan laser dalam jalur lebar 10 dB dan 20 dB masing masing

dengan nisbah setinggi 30 dB. Hasil kuasa keluaran tertinggi ialah 0.406 mW. Malahan, dengan kehadiran sangat tidak linear daripada HNLF menggalakkan kesan daripada pergaulan empat gelombang (FWM) dimana membantu pengagihan dalam penghasilan kiraan saluran yang lebih tinggi. Seterusnya, kestabilan HNLF yang berintegrasi dengan MWTDFL dikaji. Eksperimen ini telah dijalankan dengan memerhatikan pelbagai panjang gelombang laser spektrum setiap 5 minit untuk jumlah tempoh masa satu jam pada kuasa pam maksimum 2000 mW. Berdasarkan keputusan menunjukkan turun naik kuasa laser yang kurang daripada 1.325 dB, dengan nilai yang paling teruk dicatatkan pada kawasan sebelah panjang gelombang yang lebih pendek kerana medium gandaan yang lebih rendah. Turun naik panjang gelombang maksimum iaitu pada 0.12 nm juga diperhatikan dengan bantuan pemilih fizikal pelbagai panjang gelombang. Ringkasnya, kerja yang ditunjukkan menggunakan bentuk rongga linear yang mudah untuk menghasikan pelbagai panjang gelombang dengan integrasi sebahagian daripada HNLF dalam rongga tanpa kompleks struktur linear. Bilangan saluran yang tinggi telah dihasilkan dengan turun naik yang minimum dalam kuasa puncak dan panjang gelombang. Kejayaan karya ini mungkin boleh meningkatkan MWTDFL sebagai pilihan untuk aplikasi dalam industri yang memerlukan 2-µm laser.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Master of Science. The members of the Supervisory Committee were as follows:

Muhammad Hafiz Abu Bakar, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Amirah Abdul Latif, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Member)

Mohd. Adzir Mahdi, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Member)

____
ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

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Signature:	
Name of Chairman of Supervisory Committee:	Dr. Muhammad Hafiz Abu Bakar
Signature:	
Name of Member of Supervisory Committee:	Dr. Amirah Abdul Latif
Signature:	
Name of Member of Supervisory Committee:	Prof. Dr. Mohd Adzir Mahdi

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LIST OF ABBREVIATIONS

ASE	Amplified spontaneous emission
BEFL	Brillouin Erbium fiber laser
BTFL	Brillouin Thulium fiber laser
BP	Brillouin pump
CPM	cross-phase modulation
DSF	Dispersion shifted fiber
DWDM	Dense division wavelength multiplexing
FUT	Fiber under test
EDF	Erbium-doped fiber
EDFA	Erbium-doped fiber amplifier
EDFL	Erbium-doped fiber laser
FWM	Four wave mixing
FBG	Fiber brag grating
FSR	frequency spacing range
HG-HNLF	Highly Germania highly nonlinear fiber
HNLF	Highly nonlinear fiber
LIDAR	Light detection and ranging
LD	Laser diode
MWFL	Multiwavelength fiber laser
MWTDFL	Multiwavelength thulium-doped fiber laser
MZI	Machzender interference
NPR	Nonlinear polarization rotation
NALM	Nonlinear amplifier loop mirror

OPM	Optical power meter
OSNR	Optical signal noise to ratio
OSA	Optical spectrum analyzer
PC	Polarization controller
PM-TDF	Polarization maintaining-thulium doped fiber
PMF	Polarization maintaining fiber
SBS	Stimulated Brillouin-scattering
SRS	Stimulated Raman-scattering
SMF	Single mode fiber
SPM	self-phase modulation
SMSR	side mode suppression ratio
TBF	Tunable bandpass filter
TDF	Thulium-doped fiber
TLS	Tunable laser source
Tm	Thulium
TDFL	Thulium-doped fiber laser
WDM	Wavelength division multiplexing
YDF	Yterbium-doped fiber
YDFL	Yterbium-doped fiber laser

CHAPTER 1

INTRODUCTION

1.1 Overview

Over the past few years, light emission in wavelength range around 2-µm has been actively explored owing to their multiple applications, such as in Light detection and ranging (LIDAR), gas sensing systems and direct optical communications [1][2][3]. The bandwidth is of particular interest as it resides in the 'eye safer' range for human [4]. Additionally, certain materials have better absorption or interaction within that region thus enabling accurate spectroscopy measurement [5] and efficient material processing [6]. Rare earth elements such as thulium and holmium are capable of emission around 2-µm leading to their use as gain medium for laser generation within that band [7].

Thulium in particular, possesses remarkable properties since it can be directly excited with commercially available laser diodes at wavelength of approximately 800 nm. In contrast, adequate laser operation of holmium can only be achieved with excitation of laser at 1.9-µm or by utilizing an energy transfer process from thulium or ytterbium [8]. Thulium-based laser also offers high output power in the 2-µm wavelength region whilst minimizing temperature and water absorption issues inherent to its rival rare earth element; holmium [9].

Optical fiber-based thulium laser is an increasingly attractive device, due to its ability to be employed in conventional 2-µm band applications whilst also maintaining its coupling simplicity for optical fiber communication systems. The realization of Thulium-doped fiber laser (TDFL) with multiple lasing lines can further encourage deployment of systems in 2-µm bandwidth. Over the last decade, a number of studies have investigated the expansion of wavelength division multiplexing (WDM) communication scheme to 2-µm regions [10]. Such system will require the availability of 2-µm laser source with high channel count and stability in order to address the increasing demand for data. In addition, the flexibility accorded by having a laser with multiple channels of different wavelength will be highly beneficial for spectroscopy purposes.

1.2 Problem Statement and motivation

Despite numerous research proposals on multiwavelength TDFL (MWTDFL), high silica fiber loss in its operating region remains a challenging issue in the generation of 2-µm output. This drawback is further emphasized in multiwavelength laser generation due to the need for high gain to ensure stable multiple lasing lines output. In order to address this issue, many methods have been proposed to alleviate the limitation in multiwavelength thulium-doped fiber laser (MWTDFL). However, the proposals typically employ complex procedural and operational designs that may hinder adoption of 2-µm systems.

1.3 Aim and objectives of work

The aim of this project is to design and develop a simple MWTDFL with high channel count and stable output. Specific objectives supporting this aim are:

1. To design and develop linear cavity MWTDFL.
2. To integrate highly nonlinear fiber (HNLF) in the aforementioned structure.
3. To investigate the stability of the HNLF-integrated MWTDFL and its impact on the channel count.

1.4 Scope of work

The scope of study in this research work is summarized in Figure 1.1 This research work focuses on the design and development of an optical fiber laser. The wavelength range in focus is in 2-µm wavelength band utilizing emission from rare-earth doped fiber gain medium. Thulium-doped fiber is the gain medium of choice and the laser system is designed for multiwavelength channel generation. The use of nonlinearity effects in fiber is explored in order to generate stable MWTDFL.

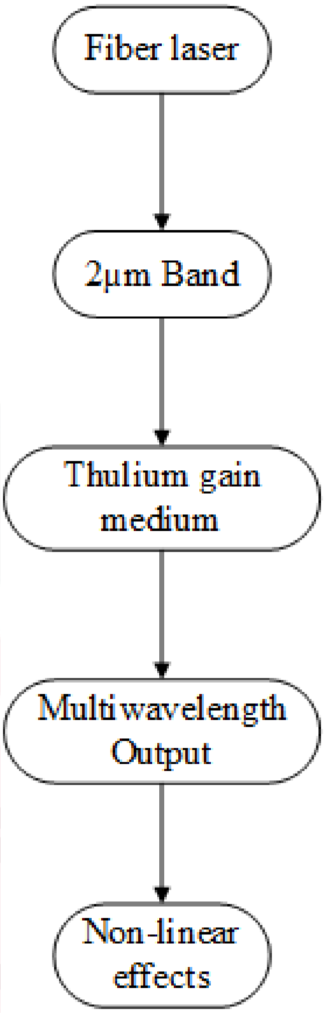

Figure 1.1: Scope of work in generating stable MWTDFL

1.5 Organization of thesis

The introduction section of this work is presented in Chapter 1. This chapter gives an overview of 2-µm laser systems and its status within the optical field of research. Problem statement and objectives of the study are elucidated as well. The direction of this project is presented in the scope of work as well as the thesis organization.

In chapter 2, literature review relevant to this research project is discussed. A brief theoretical outlook relevant to the proposed system is provided in this chapter. Subsequently, a review of past studies leading to the current state of the art in MWTDFL is presented.

The methodology employed in this work as well as findings and their discussions are detailed out in Chapter 3. Outcome from the experimental work performed according to the methodology is presented, analyzed, and discussed. Data obtained from the experiment is properly illustrated and described to highlight the research findings.

Finally, the main results are gathered and highlighted in Chapter 4 to emphasize the completion of all the research objectives. Conclusions are drawn out and recommendations for future work are provided in this chapter as well.

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BIODATA OF STUDENT