UNIVERSITI PUTRA MALAYSIA

SINGLE LONGITUDINAL MODE FIBER LASER WITH INTEGRATION OF GALLIUM-ERBIUM CO-DOPED FIBER

NOR HAFIZAH BINTI MOHAMED HALIP

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By

NOR HAFIZAH BINTI MOHAMED HALIP

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

Single longitudinal mode (SLM) lasers have gained much attention because of its ability to generate narrow linewidth output with low phase noise necessary for applications in optical communication and sensing. The generation of SLM in fiber laser is highly desirable due to its excellent performance and coupling simplicity. The issue however, is the complexity imposed by the inherently long cavity length and doped fiber gain medium, which lead to small free spectral range (FSR) and broad gain bandwidth.

The experimental work presented in this thesis demonstrates SLM operation using Ga-EDF as gain medium together with several mode filtration techniques in the laser setup. High Erbium ion concentration in the fiber leads to high gain coefficient allowing short gain medium length to be used hence reducing the cavity length and widening the FSR. Ring cavity configuration employing optimum Ga-EDF length of 2 m was employed as the base structure. In order to suppress and filter the multi longitudinal modes, tunable bandpass filter (TBF), sub-ring structure and cascaded dissimilar fiber taper were utilized in this laser system. Each of the filter mechanism was tested individually within the laser cavity to assess its performance. Once the performance of each filter was obtained, all of them were deployed into the laser system. Ultimately, the 1561.47 nm SLM output was able to achieve a narrow linewidth laser of 1.19 kHz with output power of 1.814 mW and optical signal-to-noise ratio of 55.37 dB. Additionally, the stability and tunability of the laser were investigated. The laser can be tuned from 1522 nm to 1563 nm by tuning the TBF and 0.16 dB of power fluctuation was observed in duration of one hour.

Evidently, the use Ga-EDF is feasible and significant for SLM operation thanks to its high gain coefficient. Simple mode selectors such as TBF, sub-ring cavity and dissimilar cascaded tapered fiber are influential as longitudinal mode eliminator. The findings from this study highlighted the attractiveness of high dopant co-doped fiber as gain medium for various laser configuration. Among the works that had been proposed by researchers, to the best of our knowledge, this is the first SLM laser demonstration utilizing Ga-EDF as the gain medium.

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

LASER GENTIAN MOD MEMBUJUR TUNGGAL BERINTEGRASIKAN GALLIUM-ERBIUM CO-DOPAN GENTIAN OPTIK

Oleh

NOR HAFIZAH BINTI MOHAMED HALIP

Disember 2016

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

Laser mod membujur tunggal (SLM) sering mendapat perhatian berdasarkan keupayaannya menghasilkan lebar garis sempit berserta fasa hingar rendah yang penting untuk aplikasi komunikasi optikal dan penderiaan. Penghasilan SLM dalam gentian optik laser amat dikehendaki berikutan prestasinya yang bagus dan penggandingan yang mudah. Masalah yang timbul adalah struktur kompleks yang disebabkan kepanjangan kaviti dan gentian dopan medium ganda yang seterusnya membawa kepada julat spektrum bebas yang kecil dan kelebaran lebar jalur.

Hasil penyelidikan kerja tesis ini berdasarkan operasi SLM yang menggunakan Ga-EDF sebagai medium ganda beserta beberapa teknik penapis mod di dalam penyediaan laser. Kepekatan ion Erbium didalam gentian optik membawa kepada tinggi ganda pekali yang membenarkan penggunan medium ganda yang pendek boleh digunakan dan hasilnya dapat mengurangkan panjang kaviti dan melebarkan FSR.

Konfigurasi kaviti membulat dengan kehadiran panjang optimum Ga-EDF sebanyak 2 m telah digunakan dalam struktur asas. Demi menyekat dan menapis multimod, penapis boleh laras (TBF), struktrur submembulat dan gentian optik tirus berlata tak simetri digunakan didalam sistem laser. Setiap mekanisme penapis telah diuji secara individu didalam kaviti laser to mengkaji prestasinya. Setelah prestasi setiap penapis berjaya diperolehi, kesemua penapis mod digabungkan dalam sistem laser. Hasilnya, 1561.47 nm SLM boleh mencapai lebar garis sempit sebanyak 1.19 kHz dengan kuasa output 1.814 mW dan 55.37 dB nisbah isyarat-hingar. Kestabilan dan penalaan laser juga dikaji. Laser boleh di tala dari 1522 nm sehingga 1563 nm dengan menyelaraskan TBF dan 0.16 dB kuasa turun naik diperhatikan dalam tempoh satu jam.

Penggunaan GA-EDF boleh dilaksana dalam operasi SLM berdasarkan pekali ganda yang tinggi. Penapis-penapis mod mudah iaitu, TBF, kaviti sub-membulat dan gentian optik tirus berlata tak simetri berperanan sebagai penghapus mod membujur. Hasil penyelidikan ini menyerlahkan daya penarik gentian dopan tinggi dengan gandingan dopan sebagai medium ganda dalam pelbagai konfigurasi laser. Penyelidikan ini merupakan SLM laser yang pertama dihasilkan dengan penggunaan Ga-EDF sebagai medium ganda.

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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)

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

Amirah Binti Abd Latif, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
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School of Graduate Studies
Universiti Putra Malaysia

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Signature: ______________________

Name of Chairman of Supervisory Committee: Dr. Muhammad Hafiz Abu Bakar

Signature: ______________________

Name of Member of Supervisory Committee: Prof. Dr. Mohd Adzir Mahdi

Signature: ______________________

Name of Member of Supervisory Committee: Dr. Amirah Binti Abd Latif

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LIST OF ABBREVIATIONS AND SYMBOLS

ASE	Amplified Spontaneous Emission
BEFL	Brillouin Erbium Fiber Laser
BFL	Brillouin Fiber Laser
C- Band	Conventional – wavelength Band (1530 nm to 1565 nm)
CM-FBG	chirped moirȇ FBG
CW	Continuous Wave
dB	Decibel
dBm	Decibel miliWatt
DFB	Distributed Feedback Laser
EDF	Erbium Doped Fiber
EDFA	Erbium Doped Fiber Laser Amplifier
EDFL	Erbium Doped Fiber Laser
FBG	Fiber Bragg Grating
FFP-TF	Fiber Fabry-Perot Tunable Filter
FSR	Free Spectral Range
Ga-EDF	Gallium Co-Doped Erbium Doped Fiber
GHz	Giga Hertz
kHz	Kilo Hertz
L - Band	Long – wavelength Band (1565 nm to 1625 nm)
m	Meter
mW	mili Watt
MZ	Mach-Zehnder
OSA	Optical Spectrum Analyzer
OSNR	Optical Signal-To-Noise Ratio
PM-PGFBG	Polarization-Maintaining Phase-Gap Fiber Bragg Grating

S - Band	Short – wavelength Band (1460 nm to 1530 nm)
SA	Saturable Absorber
SBS	Stimulated Brillouin Scattering
SI-FBG	superimposed fiber Bragg gratings
SRS	Stimulated Raman-Scattering
SLM	Single Longitudinal Mode
SMF	Single Mode Fiber
TBF	Tunable Bandpass Filter
TDF	Thulium-Doped Fiber
TLS	Tunable Laser Source
YDF	Ytterbium-Doped Fiber

CHAPTER 1

INTRODUCTION

1.1 Overview

Single longitudinal mode (SLM) laser is a single frequency laser with a narrow optical emission spectrum. A narrow linewidth laser has many advantages such as low phase noise and ultra-long coherent length. These advantages produce output of high spectral purity and the laser will also exhibit low intensity noise. Currently, SLM fiber laser has emerged as an attractive alternative compared to other SLM laser systems. It is more compact, easy to integrate in optical systems, cost effective, and offers tunability options. Hence, SLM fiber laser offers a lot of potential applications in optical fiber communication, sensing, and spectroscopy.

Optical fiber-based SLM laser is generated using conventional fiber laser configuration plus a number of SLM operation-specific components. In that regards, the confinement and oscillation occur in optical fiber cavity incorporating gain supplying mechanism such as nonlinear effects or rare-earth doped fiber. Doped fiber gain medium is the typical method of gain generation due to its high gain efficiency and various rare-earth dependent emission wavelength. Rare-earth elements of choice include neodymium, dysprosium, ytterbium and erbium, with erbium extensively explored due to its operation in the conventional optical communication band. SLM erbium-doped fiber laser (EDFL) is highly sought after as a method to mitigate the impact of dispersion in optical fiber communication [1].

Several fiber laser system configurations have been proposed to achieve SLM output. Basic linear or ring cavity design integrating numerous filter types is typically used to ensure only one longitudinal mode propagates in the cavity and also for laser stabilization. Some mode filter mechanisms used is fiber Bragg gratings (FBG) [2], [3], Fabry-Perot interferometer [4] and unpumped erbium-doped fiber (EDF) as saturable absorber [2].

1.2 Problem Statement and Motivation

Generation of SLM output in EDFL is difficult due to the long fiber cavity length that produces output with small free spectral range (FSR). This is further compounded by the need for lengthy gain medium to excite sufficient gain for the lasing process. One possible method to address this issue is through the use of high dopant concentration erbium-doped fiber (EDF) that will allow elevated gain generation from short gain medium length. However, the issue with high dopant concentration EDF is clustering of erbium ions leading to degradation of power and gain efficiency due to quenching. Bismuth and other heavy metal ions such as Aluminum and Germanium as well as

Gallium (Ga) are employed as co-dopant in such fiber to the ion clustering issue. Gallium-erbium co-doped fiber (Ga-EDF) is one of the more recent fibers investigated for such purpose but there has been no attempt to employ Ga-EDF as gain medium in any laser devices, raising a question mark on its feasibility.

1.3 Aim and Objective

In this research, a configuration capable of producing narrow linewidth SLM output is designed to investigate the performance of Ga-EDF as a laser gain medium. In general, the aim of this research is to produce a narrow linewidth SLM output using Ga-EDF as a gain medium. In specific, the objectives of this thesis are:

i. To design and develop a fiber laser with Ga-EDF as the gain medium
ii. To generate SLM output from the proposed Ga-EDF fiber laser.
iii. To investigate the tunability and stability of the proposed laser.

To the best of our knowledge, this would be the first time an investigation is performed on the ability of Ga-EDF as a gain medium for lasing and SLM output generation.

1.4 Scope of Work

The scope of work in the research is summarized in Figure 1.1. In general, this study looks into the design and development of an optical fiber-based laser. Ring cavity is chosen compared to linear cavity because of the ability to produce more stable SLM laser system and in principle, ring cavity allows lower phase noise and correspondingly smaller linewidth. Gain is an essential component for laser generation thus in this work, rare-earth doped fiber is chosen as the gain medium. Ga-EDF is selected for this work due to its ability to produce high gain in short fiber length at 1.5 µm conventional communication band, which ultimately contributes to shorter laser cavity length essential for wider longitudinal mode FSR. The Ga-EDF will be optimized first in terms of length in order to find the most suitable length of the gain medium in the laser configuration. The aim of this step is to find the shortest length of Ga-EDF to be used and yet provide sufficient amount of power to the setup. This is important as the specific laser operation proposed in this work is for SLM output. Therefore, the main focus of this work will revolve around methods and structural optimizations essential to attaining SLM lasing within a Ga-EDF fiber laser. The performance of the SLM fiber laser will be discussed in terms of RF beating modes, optical spectrum, OSNR, linewidth of laser, stability and the tunability of the fiber laser system.

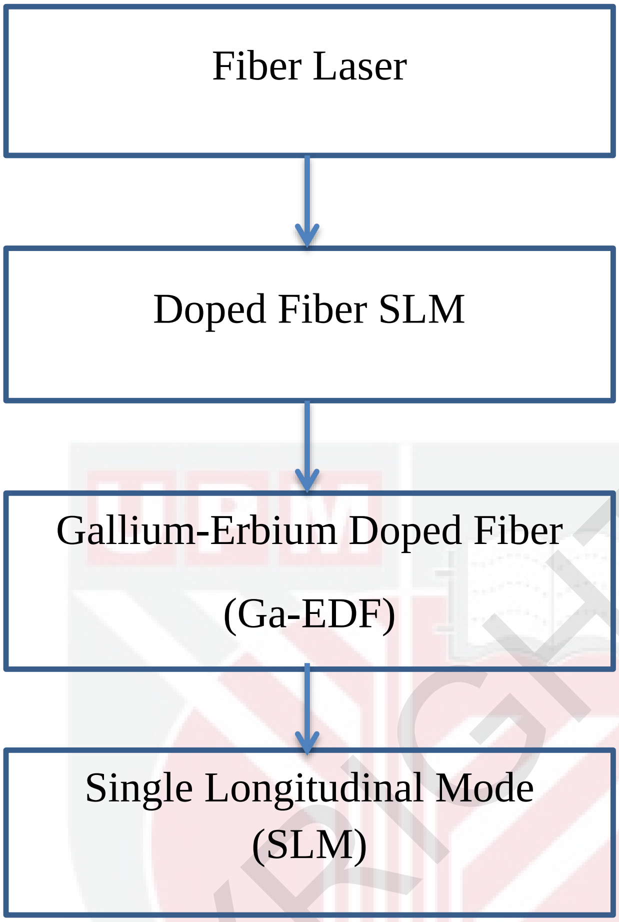

Figure 1.1: Scope of work

1.5 Organization of The Thesis

The organization of this thesis is explained as following:

Chapter 1 consists of the introduction and overview of SLM laser, especially fiber-based laser. The issues with SLM fiber laser is highlighted together with the aim and objectives that are shaped from those issues. The scope of work and thesis organization are also included in this chapter.

Chapter 2 introduces the underlying theory behind SLM operation. This includes thorough discussion on related innovative studies in the generation of SLM fiber lasers.

Chapter 3 combines the methodology used in this work and the result obtained from the whole process. Overview of the laser design and explanation on how it operates are provided. All the findings are discussed and analyzed in this chapter.

Finally, in chapter 4, the conclusions of the research are drawn and all the important results are highlighted. Recommendations for future work are also given at the end of this chapter.

REFERENCES

[1] H. Ahmad, M. Dernaika, O. M. Kharraz, M. Alimadad, M. F. Ibrahim, K. S. Lim, S. W. Harun "A tuneable, power efficient and narrow single longitudinal mode fibre ring laser using an inline dual-taper fibre Mach–Zehnder filter," *Laser Phys.*, vol. 24, no. 8, p. 85111, Aug. 2014.

[2] Z. Fan, X. Zeng, C. Cao, Z. Feng, Z. Lai, and W. Dang, "Novel structure of an ultra-narrow-bandwidth fibre laser based on cascade filters: PGFBG and SA," *Opt. Commun.*, vol. 368, pp. 150–154, 2016.

[3] S. Feng, S. Lu, W. Peng, Q. Li, T. Feng, and S. Jian, "Tunable single-polarization single-longitudinal-mode erbium-doped fiber ring laser employing a CMFBG filter and saturable absorber," *Opt. Laser Technol.*, vol. 47, pp. 102–106, 2013.

[4] X. Wang, T. Zhu, L. Chen, and X. Bao, "Tunable Fabry-Perot filter using hollow-core photonic bandgap fiber and micro-fiber for a narrow-linewidth laser., *Opt. Express*, vol. 19, no. 10, pp. 9617–25, May 2011.

[5] F. G. Smith, *Optics and Photonics : An Introduction Second Edition*; Wiley . 2007.

[6] K. Thyagarajan, *Fiber Optic: 1st Edition*; Cambridge University Press, 1998.

[7] R. Tyson, *Adaptive Optics Engineering Handbook*,; CRC Press. 10. 1999.

[8] P. C. Becker, N. a. Olsson, J. R. Simpson, and I. P. Kaminow, *Erbium-Doped Fiber Amplifiers: Fundamentals and Technology*.; Academic Press 1999.

[9] H. Ahmad, C. S. J. Lee, M. A. Ismail, Z. A. Ali, S. A. Reduan, N. E. Ruslan, M. F. Ismail, and S. W. Harun, "Zinc oxide (ZnO) nanoparticles as saturable absorber in passively Q-switched fiber laser," *Optics Commun.*, vol. 381, pp. 72–76, 2016.

[10] B. Zhang, Q. Song, G. Wang, Y. Gao, Q. Zhang, M. Wang, and W. Wang, "Passively Q-switched Nd:GdTaO4 laser by graphene oxide saturable absorber," *Opt. Eng.*, vol. 55, no. 8, 2016.

[11] Y. Zhang, C. Yang, Z. Feng, H. Deng, M. Peng, Z. Yang, and S. Xu, "Dual-wavelength passively q-switched single-frequency fiber laser," *Opt. Express*, vol. 24, no. 14, p. 16149, Jul. 2016.

[12] International Telecommunications Union, *Optical Fibres, Cables and Systems*,;ITU Publisher, 2009.

[13] A. Jain, N. Chandra, A. Anchal, and P. Kumar K, "Tunable multiwavelength mode-locked fiber laser using intra-cavity polarization and wavelength dependent loss," Optics & Laser Techn., vol. 83, pp. 189–194, 2016.

[14] Z. C. Tiu, A. Zarei, H. Ahmad, and S. W. Harun, “Multi-wavelength mode-locked erbium-doped fiber laser with photonic crystal fiber in figure-of-eight cavity,” *Optik - Int. Journal for Light and Electron Optics* vol. 127, no. 15, pp. 5894–5898, 2016.

[15] C. Jin, S. Yang, X. Wang, H. Chen, M. Chen, and S. Xie, “Stable Mode-Locked Nanosecond Chirp-Free Pulse Generation With Ultra-Narrow Bandwidth,” *IEEE Photonics Technol. Lett.*, vol. 28, no. 12, pp. 1352–1355, Jun. 2016.

[16] H. J. R. Dutton, “Understanding Optical Communications,” *Int. Tech. Support Organ.*, vol. 1, pp. 1–638, 1998.

[17] B. E. A. Saleh and M. C. Teich, *Fundamentals of photonics*.; Wiley-Interscience, 2007.

[18] S. Yin, *Fiber Optic Sensors, Second Edition*, CRC Press. 2002.

[19] C.-H. Yeh, T. T. Huang, H.-C. Chien, C.-H. Ko, and S. Chi, “Tunable S-band erbium-doped triple-ring laser with single-longitudinal-mode operation,” *Opt. Express*, vol. 15, no. 2, p. 382, Jan. 2007.

[20] G. P. Agrawal, *Nonlinear Fiber Optics: 5th Edition*.; Academic Press 2001.

[21] J. a Miragliotta, “Analytical and Device-Related Applications of Nonlinear Optics,” *Johns Hopkins Appl. Tech. Dig.*, vol. 16, no. 4, pp. 348–356, 1995.

[22] X. P. Cheng, P. Shum, C. H. Tse, J. L. Zhou, M. Tang, W. C. Tan, R. F. Wu, and J. Zhang, “Single-Longitudinal-Mode Erbium-Doped Fiber Ring Laser Based on High Finesse Fiber Bragg Grating Fabry–PÉrot Etalon,” *IEEE Photonics Technol. Lett.*, vol. 20, no. 12, pp. 976–978, Jun. 2008.

[23] G. P. Agrawal, *Fiber-optic communication systems: 4th edition*.; Wiley, 2010.

[24] M. C. Paul, A. Dhar, S. Das, M. Pal, S. K. Bhadra, A. M. Markom, N. S. Rosli, A. Hamzah, H. Ahmad, and S. W. Harun, “Enhanced Erbium-Zirconia-Yttria-Aluminum Co-Doped Fiber Amplifier,” *IEEE Photonics J.*, vol. 7, no. 5, 2015.

[25] N. K. Dutta, *Fiber Amplifiers and Fiber Lasers,;* World Scientific. 2014

[26] K. P. W. Dissanayake, H. A. Abdul-Rashid, A. Safaei, A. Oresegun, N. Shahrizan, N. Y. M. Omar, Z. Yusoff, M. I. Zulkifli, S. Z. Muhamad-Yassin, K. A. Mat-Sharif, and N. Tamchek, “Fabrication and characterization of a Gallium co-doped Erbium optical fiber,” *Proc. ICP 2014 - 5th Int. Conf. Photonics 2014*, pp. 113–115, 2015.

[27] Hewlett-Packard engineers and scientists, *Fiber Optic Test and Measurement*.; Prentice Hall, 1998.

[28] Z. You, Y. Wang, J. Xu, Z. Zhu, J. Li, H. Wang, and C. Tu, “Single-longitudinal-mode Er:GGG microchip laser operating at 27 μm,” *Opt. Lett.*, vol. 40, no. 16,

p. 3846, Aug. 2015.

[29] Yi Liu, Mingjiang Zhang, Peng Wang, Lan Li, Yuncai Wang, and Xiaoyi Bao, "Multiwavelength Single-Longitudinal-Mode Brillouin–Erbium Fiber Laser Sensor for Temperature Measurements With Ultrahigh Resolution," *IEEE Photonics J.*, vol. 7, no. 5, pp. 1–9, Oct. 2015.

[30] Y. Zhou, P. C. Chui, K. K. Y. Wong, and S. Member, "Multiwavelength Single-Longitudinal-Mode Ytterbium-Doped Fiber Laser," *IEEE Photonics Tech. Lett* vol. 25, no. 4, pp. 385–388, 2013.

[31] F. Yan, W. Peng, S. Liu, T. Feng, Z. Dong, and G. K. Chang, "Dual-Wavelength Single-Longitudinal-Mode Tm-Doped Fiber Laser Using PM-CMFBG," *IEEE Photonics Technol. Lett.*, vol. 27, no. 9, pp. 951–954, 2015.

[32] Z. Fan, X. Zeng, C. Cao, Z. Feng, Z. Lai, and W. Dang, "Novel structure of an ultra-narrow-bandwidth fibre laser based on cascade filters: PGFBG and SA," *Opt. Commun.*, vol. 368, pp. 150–154, Jun. 2016.

[33] F. T. Passband, "Manual tunable bandpass filter.", DiCon Fiberoptics

[34] C.-H. Yeh, H.-Z. Chen, J.-Y. Chen, and C.-W. Chow, "Use of fiber Bragg grating (FBG) for stable and tunable erbium-doped fiber ring laser with single-longitudinal-mode (SLM) output," *Laser Phys.*, vol. 25, no. 11, p. 115101, Nov. 2015.

[35] S. Feng, S. Lu, W. Peng, Q. Li, T. Feng, and S. Jian, "Tunable single-polarization single-longitudinal-mode erbium-doped fiber ring laser employing a CMFBG filter and saturable absorber," *Opt. Laser Technol.*, vol. 47, pp. 102–106, 2013.

[36] T. Feng, F. Yan, S. Liu, Y. Bai, W. Peng, S. Tan, "Switchable and tunable dual-wavelength single-longitudinal-mode erbium-doped fiber laser with special subring-cavity and superimposed fiber Bragg gratings," *Laser Phys. Lett.*, vol. 11, no. 12, p. 125106, Dec. 2014.

[37] Y. Cheng, J. T. Kringlebotn, W. H. Loh, R. I. Laming, and D. N. Payne, "Stable single-frequency traveling-wave fiber loop laser with integral saturable-absorber-based tracking narrow-band filter," *Opt. Lett.*, vol. 20, no. 8, p. 875, Apr. 1995.

[38] B. Yin, S. Feng, Y. Bai, Z. Liu, and S. Jian, "Switchable Dual-Wavelength SLM Fiber Laser Using Asymmetric PMFBG Fabry–Perot Cavities," *IEEE Photonics Technol. Lett.*, vol. 27, no. 12, pp. 1281–1284, Jun. 2015.

[39] B. Yin, S. Feng, Z. Liu, Y. Bai, and S. Jian, "Single-frequency and single-polarization DFB fiber laser based on tapered fbg and self-injection locking," *IEEE Photonics J.*, vol. 7, no. 3, 2015.

[40] T. Zhu, X. Bao, and L. Chen, "A Single Longitudinal-Mode Tunable Fiber Ring Laser Based on Stimulated Rayleigh Scattering in a Nonuniform Optical Fiber,"

J. Light. Technol., vol. 29, no. 12, pp. 1802–1807, Jun. 2011.

[41] Y. Gao, J. Sun, G. Chen, and H. Xie, "Single-longitudinal-mode BEFL incorporating a Bragg grating written in EDF," *Opt. Commun.*, vol. 345, pp. 125–128, 2015.

[42] K. P. W. Dissanayake, H. A. Abdul-Rashid, A. Safaei, A. Oresegun, N. Shahrizan, N. Y. M. Omar, Z. Yusoff, M. I. Zulkifli, S. Z. Muhamad-Yassin, K. A. Mat-Sharif, and N. Tamchek, "Fabrication and characterization of a Gallium co-doped Erbium optical fiber," in *2014 IEEE 5th International Conference on Photonics (ICP)*, 2014, pp. 113–115.

[43] S. Feng, Q. Mao, Y. Tian, Y. Ma, W. Li, and L. Wei, "Widely Tunable Single Longitudinal Mode Fiber Laser With Cascaded Fiber-Ring Secondary Cavity," *IEEE Photonics Tech. Lett.* vol. 25, no. 4, pp. 323–326, 2013.

[44] C. H. Yeh, T. T. Huang, H. C. Chien, C. H. Ko, and S. Chi, "Tunable S-band erbium-doped triple-ring laser with single-longitudinal-mode operation," *Opt. Express*, vol. 15, no. 2, pp. 382–386, 2007.

[46] Y. Mustapha Kamil, M. H. Abu Bakar, M. A. Mustapa, M. H. Yaacob, A. Syahir, and M. A. Mahdi, "Sensitive and Specific Protein Sensing Using Single-Mode Tapered Fiber Immobilized With Biorecognition Molecules," *IEEE Photonics J.*, vol. 7, no. 6, 2015.

[47] B. Yin, S. Feng, Z. Liu, Y. Bai, and S. Jian, "Tunable and switchable dual-wavelength single polarization narrow linewidth SLM erbium-doped fiber laser based on a PM-CMFBG filter," *Opt Express*, vol. 22, no. 19, pp. 22528–22533, 2014.

[48] X. Cheng, P. Shum, and C. Tse, "Single-longitudinal-mode erbium-doped fiber ring laser based on high finesse fiber Bragg grating Fabry–Perot etalon," *Photonics Res.*, vol. 20, no. 12, pp. 976–978, 2008.

[49] T. Feng, F. Yan, S. Liu, Y. Bai, W. Peng, and S. Tan, "Switchable and tunable dual-wavelength single-longitudinal-mode erbium-doped fiber laser with special subring-cavity and superimposed fiber Bragg gratings," *Laser Phys. Lett.*, vol. 11, no. 12, p. 125106, 2014.

[50] J. Zhou, A. Luo, Z. Luo, X. Wang, X. Feng, and B. Guan, "Dual-wavelength single-longitudinal-mode fiber laser with switchable wavelength spacing based on a graphene saturable absorber," *Photonics Res.*, vol. 3, no. 2, pp. 21–24, 2015.

BIODATA OF STUDENT

Nor Hafizah Binti Mohamed Halip was born in Selangor, Malaysia, in 1991. She received her Bachelor's Degree in Computer and Communication System from Universiti Putra Malaysia (UPM) in 2014.

She is now pursuing her Master's Degree in Photonics Engineering at Universiti Putra Malaysia (UPM). She is a member of The Optical Society (OSA) and IEEE Photonics society.

LIST OF PUBLICATION

Published paper

N. H. Mohamed Halip, N. S. Isa, A. A. Latif, M. A. Mahdi, and M. H. Abu Bakar, "Asymmetric fiber taper for narrow linewidth comb filter," vol. 78, no. 3, pp. 117–121, Mar. 2016.