UNIVERSITI PUTRA MALAYSIA

HYBRID RAMAN-ERBIUM RANDOM FIBER LASER

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HYBRID RAMAN-ERBIUM RANDOM FIBER LASER

By

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

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

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December 2017

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In random distributed feedback fiber laser (RDB-FL), Rayleigh scattering (RS) is utilized as random feedback mechanism in the lasing cavity. Random feedback mechanism works by scattering the propagating light; increasing the path of the light. Once optical gain exceeds total intracavity loss, random lasing is commenced. Owing to the weak, long, and continuous random scattering centers, the cavity length of the laser is boundless; allowing cavity length to be varied accordingly. Despite the outstanding traits of RDB-FL, it requires a high amount of power to achieve threshold.

In this research, an enhanced hybrid configuration of the RDB-FL based on the integration of 80 km of single mode fiber (SMF) and erbium-doped fiber (EDF) in an open-ended linear cavity is proposed. The laser is powered by a single 1455 nm Raman pump through the ends of the laser cavity. The proposed architecture is named as hybrid erbium random fiber laser (HRFL) based on its fundamental operation; the hybrid amplification of Raman and EDF gain assisted by RS feedback. The HRFL utilizes the same pump source to initiate stimulated Raman scattering (SRS) and excite the erbium ions. The Stokes signal produced by SRS then acts as a signal to the EDF. A conventional RDB-FL is first designed and developed to determine the optimum pumping scheme and range of cavity length that can cater for SMFs with different Raman gain coefficients. Two types of SMF are tested, which are SMF-28e fiber and TrueWave REACH single mode fiber (TW). It was found that cavity length of 77-91 km and inward pumping scheme are the optimum conditions to achieve high slope efficiency and low threshold. EDF is then integrated to the developed configuration to construct the HRFL. The length of EDF is also varied to observe the spectral and power performance.

The HRFL output is stable lasing peak at wavelength 1555-1565 nm with 38 % slope efficiency and 260 mW threshold power. Intriguingly, it is discovered that by using an appropriate EDF length, dual lasing peak can be obtained without the aid of any reflectors/filters. The HRFL not only managed to amplify the 2nd Raman gain peak (1565 nm), but also the 3rd Raman gain peak (1595 nm), producing a dual peak laser in between the C-band and the L-band. To minimize the high disparity between the dual peaks, the HRFL is enhanced by modifying the architecture. Balanced dual peaks with peak discrepancy of 0.16 dB is achieved at maximum peak power of -10.66 dBm.

The advantage of the HRFL is the dispensable need for a unique pump wavelength, compared to other HRFLs employing EDF that have used separate pumps to power the SMF and EDF. The proposed configuration also has a lower threshold condition by a factor of 5 compared to HRFLs utilizing SRS and higher power conversion efficiency compared to other HRFLs employing EDF. It is believed that the novelty of this research work lies within the use of a simple open-ended cavity design to produce single and dual peak lasing.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk Ijazah Doktor Falsafah

LASER GENTIAN RAWAK HIBRID RAMAN-ERBIUM

Oleh

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Dalam laser gentian maklum balas tersebar secara rawak (RDB-FL), serakan Rayleigh (RS) digunakan sebagai mekanisma maklum balas secara rawak dalam rongga laser. Mekanisma maklum balas secara rawak berfungsi dengan menyebarkan cahaya rambatan; yang meningkatkan panjang laluan cahaya. Setelah gandaan cahaya melebihi jumlah kerugian intra-rongga, laser rawak terhasil. Disebabkan oleh pusat penyebaran rawak yang lemah, panjang dan berterusan, ini membolehkan panjang rongga laser tidak terbatas dan boleh diubah sewajarnya. Walaupun ciri-ciri RDB-FL menonjol, ia memerlukan kuasa yang tinggi untuk mencapai kondisi ambang.

Dalam kerja penyelidikan ini, konfigurasi hibrid RDB-FL yang berasaskan integrasi 80 km gentian mod tunggal (SMF) dengan gentian dop-erbium (EDF) dalam rongga linear terbuka dicadangkan. Laser ini menggunakan kuasa pam Raman 1455 nm yang disalurkan dari kedua-dua hujung rongga laser. Skema yang dicadangkan ini dinamakan gentian laser rawak hibrid (HRFL) berdasarkan prinsip operasinya, iaitu hibrid penguatan Raman dan gandaan EDF terbantu oleh maklum balas RS. HRFL ini menggunakan sumber pam yang sama untuk merangsang rambatan Raman (SRS) dan ion erbium. Isyarat Stokes yang dihasilkan oleh SRS kemudian bertindak sebagai isyarat kepada EDF.

Pertama sekali, RDB-FL konvensional direka dan dibangunkan untuk menentukan skema pam optimum dan panjang rongga yang boleh memenuhi keperluan SMF dengan koefisien gandaan Raman yang berbeza. Dua jenis SMF diuji, iaitu gentian SMF-28e dan gentian TrueWave REACH (TW). Telah didapati bahawa panjang rongga sebanyak 77-91 km dan skema pam ‘ke dalam’ adalah kondisi optimum untuk mencapai kecekapan penukaran kuasa tinggi dan kondisi ambang yang rendah. EDF kemudian diintegrasikan kepada konfigurasi RDB-FL yang dibangunkan untuk

membina HRFL. Panjang EDF juga divariasikan untuk pemerhatian prestasi spektrum dan kuasa.

Output sistem HRFL ini ialah puncak laser yang stabil di jarak gelombang 1555-1565 nm dengan 38 % kecekapan penukaran kuasa dan 260 mW kondisi ambang. Yang menariknya, dengan penggunaan panjang EDF yang sesuai, dua puncak jarak gelombang laser boleh dihasilkan tanpa memerlukan penggunaan reflector/penapis. Sistem hibrid ini bukan sahaja menguatkan puncak Raman yang kedua (1565 nm), malah juga yang ketiga (1595 nm). Ini secara tidak langsung menghasilkan dua puncak laser yang jarak gelombangnya berada dalam jalur-C dan jalur-L. Untuk meminimumkan perbezaan yang tinggi antara dua puncak ganda itu, HRFL dipertingkatkan dengan mengubah skema nya. Dua puncak ganda seimbang dengan perbezaan 0.16 dB dicapai pada puncak maksimum -10.66 dBm.

Kelebihan HRFL ini ialah ketidakperluan terhadap pam jarak gelombang khas, berbanding dengan HRFL lain menggunakan EDF yang memerlukan pam yang berbeza jarak gelombangnya untuk memberi kuasa kepada SMF dan EDF secara berasingan. Konfigurasi yang dicadangkan ini juga mempunyai kondisi ambang yang lebih rendah sekurang-kurangnya faktor 5 berbanding HRFL yang telah dilaporkan menggunakan SRS sebagai kaedah penguatan. Konfigurasi yang dicadangkan ini juga mempunyai kecekapan penukaran kuasa yang lebih tinggi berbanding HRFL yang telah dilaporkan menggunakan gandaan EDF. Adalah dipercayai bahawa kerja penyelidikan ini sesuatu yang baru kerana reka bentuknya yang ringkas dan terbuka untuk menghasilkan satu atau dua puncak jarak gelombang laser.

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I certify that a Thesis Examination Committee has met on 21 December 2017 to conduct the final examination of Nadiah Husseini binti Zainol Abidin on her thesis entitled "Hybrid Raman-Erbium Random Fiber Laser" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This is to confirm that:

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ASE	Amplified spontaneous emission
CW	Continuous wave
C-band	Conventional – wavelength band (1530 nm to 1565 nm)
DCF	Dispersion compensated fiber
EDF	Erbium-doped fiber
ESA	Excited state absorption
FBG	Fiber Bragg grating
HNLF	Highly nonlinear fiber
HRFL	Hybrid Erbium Random Fiber Laser
LD	Laser diode
L-band	Long – wavelength band (1565 nm to 1625 nm)
NZ-DSF	Non-zero dispersion-shifted fiber
OSNR	Optical signal to noise ratio
PCF	Photonic crystal fiber
PMF	Polarization maintaining fiber
RF	Radio-Frequency
RPU	Raman pump unit
RDB-FL	Random distributed feedback fiber lasers
RS	Rayleigh scattering
SWR	Selective wavelength reflector
S-band	Short – wavelength band (1460 nm to 1530 nm)
SMF	Single mode fiber
SMF-28e	SMF-28e single mode fiber
SHB	Spectral hole burning

SBS	Stimulated Brillouin scattering
SBS	Stimulated Raman scattering
TW	TrueWave REACH single mode fiber
TOF	Tunable optical filter
UHNA	Ultrahigh numerical aperture
WDM	Wavelength division multiplexer
YDF	Ytterbium-doped fiber

CHAPTER 1

INTRODUCTION

1.1 Overview

Optical communication system have come a long way since the first invention of lasers in the 1960s. As they say, great things come in small packages and fiber laser systems utilizing hair-thin optical fibers, have transformed the field as a whole. The advancement of this technology has made it a vital solution in the age of internet. The rapid pace of laser development study also compels it to be a very prominent tool in multiple ever-changing fields such as the medical field, industrial, military weapon and information technology (IT).

The operation of a basic fiber laser is based on the exploitation of resonant feedback and stimulated emission to produce a high intensity light beam of the signal photons. The excitation of the fiber gain medium occurs through optical pumping. The interaction of incoming signal photons with the excited gain medium creates stimulated emission. Meanwhile, to achieve feedback, components which function as reflectors are fixed at both ends of the fiber cavity to produce a linear resonator. As light oscillates back and forth in the resonator, the total gain exceeds the cavity loss and lasing is achieved [1].

Utilizing optical fiber as laser gain media is immensely practical; it takes little amount of space as it can be coiled, and shield the propagating light from environmental and electrical damage. It also features large gain bandwidth that supports the growing demand of optical transport. However, the drawback of traditional fiber lasers is that it is hard to design, and its construction requires precision. Besides that, the traditional laser cavity poses limitation on transmission length as signal attenuation adds up over long distances and diminishes the signal. To alleviate the issue, repeaters or amplifiers are often used but this comes at a price of lower signal to noise ratio and contributes to very costly configuration.

Random fiber laser is introduced as an alternative to traditional fiber laser. Before the emergence of random fiber laser, optical scattering was regarded as undesirable in the conventional fiber laser scheme as it would remove photons from its respective lasing modes [2]. However, in disordered gain media, multiple scatterings support laser oscillation and amplification [3]. This provides a route for random lasers to operate without a classical resonator or mirrors [2]–[6] enabling random fiber lasers to be constructed without a precise and costly configuration. In 2010, the concept of random distributed feedback fiber lasers (RDB-FL) was first reported by Turitsyn et al. [7]–[10]. Random lasing in the optical fiber was achieved by utilizing multiple scattering in an inhomogeneous amplified medium to achieve resonance, where the intrinsic inhomogeneity of the refractive index (Rayleigh scattering) of the optical fiber provides random distributed scattering along the cavity. The continuous random feedback allows the cavity length to be varied accordingly for short or long distance signal transmission. In RDB-FL, amplification was attained via stimulated Raman scattering (SRS). SRS is an attractive choice of gain for the RDB-FL as it is the leading candidate for large capacity transmission systems. Its gain integral over large distances amount to several dBs which prevents signal degradation [11]. Besides that, SRS can materialize in any type of optical fiber, with or without rare earth dopants. It also features with wavelength tunability by pump wavelength control and a broad spectral bandwidth over 40 THz wide.

1.2 Problem statement

The current situation with random fiber laser employing SRS is that it features a high threshold condition, which is due to the low gain coefficient of Raman and the weak feedback from Rayleigh scattering. The high threshold condition of random fiber laser limits the potential applications that can be engineered, especially in circumstances where low power is the ideal. Not only that, the components within the laser is expected to be durable at very high optical power, heightening the total cost of the system. The use of hybrid gain by introducing auxiliary gain medium such as erbium-doped fiber (EDF) has been suggested. EDF has high gain coefficient and wide bandwidth which coincides with the minimum loss area of SMF. However, this comes at the expense of an additional pump or reflector-based cavity enhancements incorporated within the system. Hence, there is a significant need for a simpler SRS-based random fiber laser employing EDF with low threshold condition to minimize the issues aforementioned.

1.3 Research objectives

This research aims to achieve a hybrid erbium random fiber laser with low threshold condition through the manipulation of pumping schemes, cavity length, and EDF length. This study aims to produce said performance with simplest configuration possible. The objectives of this study are outlined as the following:

i. To investigate the optimum pumping scheme and cavity length of conventional Raman-based RDB-FL.
ii. To investigate RDB-FL with EDF integration using designed pumping scheme and cavity length for performance enhancement.
iii. To design and develop enhanced HRFL architecture to obtain balanced multi-wavelength peaks.

1.4 Research scope

The scope of work for this experimental investigation is illustrated in Figure 1.1. In a broader perspective, the study focuses into the design and development of a fiber-based laser. The fiber laser in question is mirrorless whereby the gain medium is unbounded by reflectors but is still able to achieve resonance. This mirrorless laser is known as random fiber laser. A new hybrid design of the random fiber laser is proposed based on the combination of single mode fiber (SMF) and erbium-doped fiber (EDF). The scheme is powered by a single pump source in an open ended linear cavity. The proposed scheme employs SRS to convert the pump radiation assisted by Rayleigh scattering for cavity feedback. Residual pump and SRS generation are utilized as second-order pump and signal source to the EDF, eliminating the need to separately power the EDF. The pumping scheme and cavity length will be optimized first while employing different types of SMF in conventional random fiber laser. The optimized design is then integrated with EDF to make the hybrid random fiber laser. The result analysis from the investigation of hybrid scheme is revised to make appropriate changes in the design to obtain improved power performances.

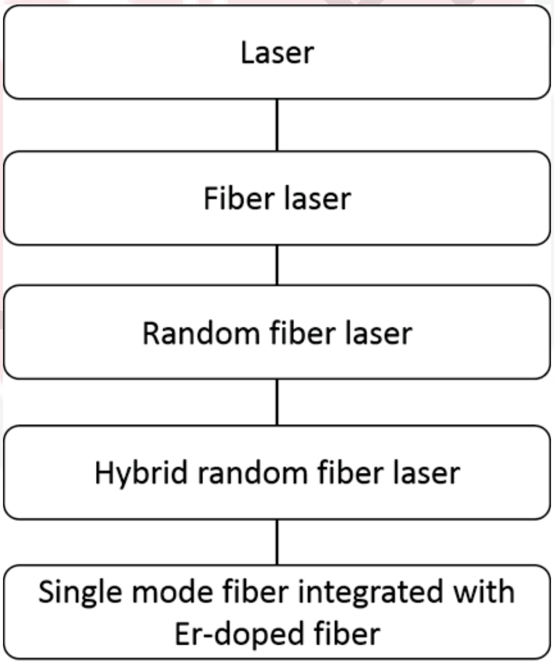

Figure 1.1 : Research scope.

1.5 Organization of thesis

The thesis is divided into six chapters as the following:

Chapter 1 describes the background research of the study. It briefly mentions on traditional lasers versus random fiber lasers, the reported hybrid erbium random fiber laser configurations, the gaps in the prior study, and motivations behind the research.

Chapter 2 explains the basic theory behind traditional Raman fiber lasers and erbium-doped fiber laser. An overview of random distributed feedback fiber laser, its principle of operation, and the role of stimulated Raman scattering and Rayleigh scattering is also presented with supporting literatures. Finally, this chapter introduces hybrid random fiber lasers, discusses the reported hybrid schemes not exclusive to EDF, and reviews reported hybrid erbium random fiber lasers designs in more detail with regards to its performance.

Chapter 3 examines the performance of the conventional random distributed feedback fiber lasers with different single mode fibers as the gain medium, cavity lengths, and pumping schemes. The best pumping scheme with acceptable cavity length range is summarized based on the result analysis.

Chapter 4 delivers the experimental investigation of two sets of hybrid random fiber laser. The first set explores the performance of integration of LSL EDF with TrueWave REACH single mode fiber while the second set of LSL EDF with SMF-28e single mode fiber. The results of each set are presented and discussed as to which is the more viable configuration to produce intended outcomes.

Chapter 5 is a subsequent step from Chapter 4 where it investigates the determined configuration with multiple proposed add-on architectures to enhance the performance of the laser. The chapter further describes the architecture's merits and demerits from one design to the next based on the analysis of the results. A final design of the intended outcome is reached and critically analyzed.

Chapter 6 provides a conclusion to the research work, the research contributions, and recommendations for future work.

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