DUAL-WAVELENGTH RANDOM FIBER LASER INCORPORATING MICRO-AIR CAVITY

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By

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Almost one decade ago, a newborn fiber laser with simplified version called random distributed feedback fiber laser (RDFB-FL) has been a spotlight among the photonic research community. Despite of the natural behavior of Rayleigh scattering as a fundamental loss for propagating light in optical fibers, it can be utilized as a distributed mirror in ultra-long fiber laser. In this case, the mechanism of feedback is termed as random which leads to the development of RDFB-FL. However, the absence of physical feedback devices require a very high power to overcome total cavity losses to be a laser. In this research work, a simple linear cavity half open ended of random fiber laser (HOCRFL) consists of 36 km TrueWave RS fiber (TW) incorporating micro-air cavity (MAC) is proposed. The MAC is constructed by adjusting the air-gap distance between two optical fibers that produce multiple fringes based on the Fabry-Pérot cavity. At the same time, this MAC enhances the reflectivity to improve the overall laser performance. For MAC characterizations, the transmission loss increases while reflectance, transmittance and channel spacing decrease with the increment of air-gap distances. The best MAC location in the fiber laser cavity is at the opposite end of the output port and the optimum pumping configuration of HOCRFL is the bidirectional scheme. From the optimization of MAC air-gap distance from 100 µm to 1000 µm, smaller air-gaps (100 µm to 400 µm) are preferable for high pump power operation near 2 W while larger air-gaps (500 µm up to 1000 µm) are suitable for low pump power operation below 1.5 W. Based on the findings, it is found that the 200 µm and 600 µm air-gap distance produce the best lasing performance for these two separate pump power regions. The former air-gap distance generates dual-wavelength laser at 1552.48 nm and 1557.04 nm with 18.79 dB and 18.73 dB optical signal-to-noise ratio (OSNR), respectively. On the other hand, for the 600 µm air-gap distance, the dual-wavelength lasers occur at 1553.86 nm and 1555.75 nm with 14.69 dB and 13.73 dB OSNR. In comparison between these two air-gap distances, the 200 µm air-gap distance has better OSNR. However, its critical power (pump power that generate the best lasing performance) of 1987 mW is higher than 1240 mW obtained from 600 µm air-gap distance. It is believed that the novelty of this work lies within the use of simple architecture of MAC in linear cavity random fiber laser to dual-emission peak wavelength.

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

LASER GENTIAN RAWAK DWI-PANJANG GELOMBANG MENGGABUNGKAN RONGGA UDARA MIKRO

Oleh

NORITA BINTI MOHD YUSOFF

Mei 2019

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Hampir satu dekad yang lalu, laser gentian yang baru muncul dengan versi mudah dipanggil laser gentian maklum balas tersebar secara rawak (RDFB-FL) telah menjadi tumpuan di kalangan komuniti penyelidikan fotonik. Walaupun perilaku semulajadi Rayleigh berselerak sebagai kehilangan asas untuk menyebarkan cahaya dalam gentian optik, ia boleh digunakan sebagai cermin teragih dalam laser gentian ultra-panjang. Dalam kes ini, mekanisme maklum balas disebut sebagai rawak yang membawa kepada pembangunan RDFB-FL. Walau bagaimanapun, ketiadaan peranti maklum balas fizikal memerlukan kuasa yang sangat tinggi untuk mengatasi jumlah kerugian rongga untuk menjadi laser. Dalam kerja penyelidikan ini, sebuah rongga linear yang separuh terbuka dengan laser gentian rawak (HOCRFL) terdiri daripada 36 km gentian TrueWave RS (TW) yang menggabungkan rongga udara mikro (MAC) dicadangkan. MAC dibina dengan melaraskan jarak jurang udara antara dua gentian optik yang menghasilkan pelbagai pinggiran berdasarkan rongga Fabry-Pérot. Pada masa yang sama, MAC ini meningkatkan pemantulan untuk meningkatkan prestasi laser secara keseluruhan. Untuk pencirian MAC, kehilangan transmisi semakin meningkat sementara pemantulan, transmisi dan jarak saluran menurun dengan kenaikan jarak jurang udara. Lokasi MAC terbaik di rongga laser gentian adalah bertentangan dengan pot pengeluaran dan konfigurasi pam optimum HOCRFL adalah skema dwi-arah. Dari pengoptimuman jarak jurang udara MAC dari 100 μm hingga 1000 μm, jurang udara yang lebih kecil (100 μm hingga 400 μm) lebih baik untuk operasi kuasa pam yang tinggi berhampiran 2 W manakala jurang udara yang lebih besar (500 μm sehingga 1000 μm) adalah sesuai untuk operasi kuasa pam yang rendah di bawah 1.5 W. Berdasarkan penemuan ini, didapati jarak 200 μm dan 600 μm jurang udara menghasilkan prestasi laser terbaik bagi kedua-dua kawasan kuasa pam berasingan. Bekas jarak jurang udara menjana laser dwi-jarak gelombang pada 1552.48 nm dan 1557.04 nm dengan 18.79 dB dan 18.73 dB nisbah isyarat-ke-bunyi (OSNR) optik. Sebaliknya, untuk 600 μm jarak rongga udara, laser dwi-jarak gelombang berlaku pada 1553.86 nm dan 1555.75 nm dengan 14.69 dB dan 13.73 dB OSNR. Sebagai perbandingan antara dua jarak

jurang udara ini, jarak udara 200 µm udara mempunyai OSNR yang lebih baik. Walau bagaimanapun, kuasa kritikal (kuasa pam yang menghasilkan prestasi laras terbaik) 1987 mW adalah lebih tinggi daripada 1240 mW yang diperolehi dari jarak rongga udara 600 µm. Adalah dipercayai bahawa kebaharuan kerja ini terletak dalam penggunaan seni bina mudah MAC dalam rongga linear laser gentian rawak ke panjang gelombang puncak dwi-pelepasan.

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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:

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LIST OF ABBREVIATIONS

ASE	Amplified spontaneous emission
BS	Brillouin Stokes
CW	Continuous wave
EDF	Erbium doped fiber
FBG	Fiber Bragg grating
FLM	Fiber-loop mirror
FPI	Fabry-Pérot Interferometer
FSR	Free spectral range
FWM	Four wave mixing
HOCRFL	Half-open cavity random fiber laser
ISO	Isolator
MAC	Micro-air cavity
MLFL	Mode-locked fiber laser
MOCRFL	Mirrorless open cavity random fiber laser
MWBRFL	Multiwavelength Brillouin-Raman fiber laser
MWEDFL	Multiwavelength erbium doped fiber laser
MWFL	Multiwavelength fiber laser
MWRFL	Multiwavelength random fiber laser
MZI-FP	Mach Zehnder Interferometer-Fabry Pérot
NPR	Nonlinear polarization rotation
OC	Optical coupler
OPM	Optical power meter
OSA	Optical spectrum analyzer
OSNR	Optical signal-to-noise ratio
PCF	Photonic crystal fiber
PMF	Polarization maintaining fiber

RDFB-FL	Random distributed feedback fiber laser
RFL	Random fiber laser
RPU	Raman pump unit
RS	Rayleigh scattering
SBS	Stimulated Brillouin scattering
SLM	Sagnac loop mirror
SMF	Single mode fiber
SRS	Stimulated Raman scattering
TW	TrueWave RS fiber
WDM	Wavelength division multiplexer

CHAPTER 1

INTRODUCTION

1.1 Introduction

Light properties have been extensively applied since the first demonstration of laser in 1960s. Figure 1.1 depicts a basic laser system requires three main components, specifically an optical pump source to induce population inversion, an active medium with a certain energy levels and optical resonator to introduce optical feedback [1]. Laser action consists of three continuous processes, namely the absorption of energy to occupy the upper levels, followed by the initial photons generation via spontaneous emission and the generation of coherent laser output from stimulated emission as illustrated in Figure 1.2 [1]. There are several types of laser which are described based on the gain medium, namely gas (carbon dioxide), solid state (ruby laser), dye (rhodamine 6G in liquid solutions), semiconductor and excimer laser.

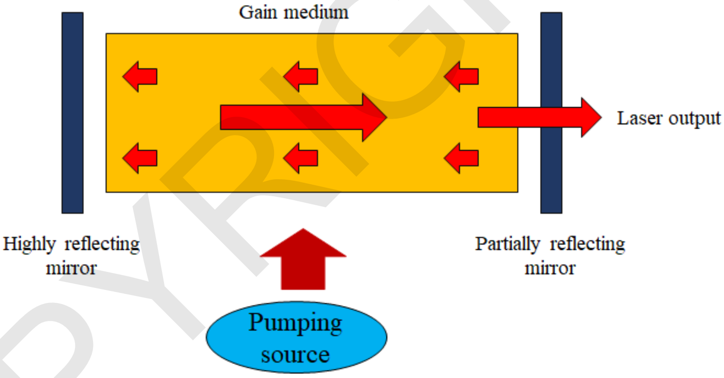
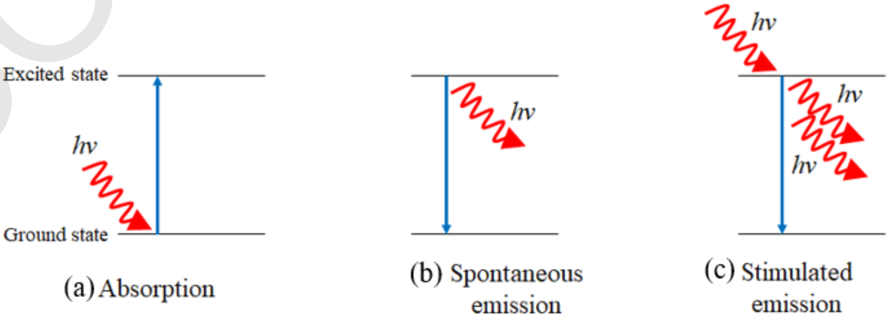


Figure 1.1: Basic laser components [2].



(a) Absorption

(b) Spontaneous emission

(c) Stimulated emission

Figure 1.2: (a) Absorption, (b) spontaneous emission and (c) stimulated emission of laser [2].

In the last 50 years, optical fiber has been utilized as a laser gain medium. Optical fibers make use of total internal reflection phenomenon inside the two different refractive index media (core and cladding) to guide light propagation. It is a promising waveguide and highly efficient compared to other lasers in the aspect of beam quality, stability, high power operations and thermal management. Optical fiber technologies have been adopted in various fields such as medical, communication and military [3]. Furthermore, optical fibers have the capability to send the information at a superior rate over very long distances, with minimal loss and higher bandwidth compared to copper cables [4]. Moreover, the installation of optical fiber is simpler than metal-based cables because it is light weight, relatively smaller in diameter and easier to handle. In addition, optical fiber is nonconductive in nature, thus the transmitted signal is not disrupted by electromagnetic interference (EMI) like radio frequency interference (RFI) [4]. On the other hand, the optical fiber can be engineered for laser applications by utilizing stimulated Raman scattering (SRS) [5].

A basic regular laser, also known as conventional Raman fiber laser needs a gain medium and a pair of reflectors to form a cavity [6]. In this case, the gain medium is the optical fiber itself. When this optical fiber is injected with high intensity light, SRS is naturally induced. In general, the common reflectors used in the basic laser system are fiber Bragg gratings (FBGs) and fiber-loop mirror (FLM). The reflection of FBG is restricted at specific wavelength, and can force the laser system to operate at single longitudinal mode. The spectral bandwidth of the laser system is determined by its properties [7]. On the other hand, FLM is constructed by using either 3 dB optical coupler or circulator which reflect the laser light but transmit the pump radiation [7].

In 1966, the concept of random laser was introduced by Ambartsumyan et al. [8]. Random fiber laser (RFL) is different from regular laser where it does not require any physical reflectors in the laser cavity for light feedback. The light feedback mechanism comes from the multiple scatterings in disordered media. In the last few years, the first invention of random distributed feedback fiber laser (RDFB-FL) has attracted a great attention among research community due to the simple structure and comparable power performance to the conventional laser [9]. Although at some aspects the performance of RFLs is much superior than conventional ones, the uncontrollable randomness nature of laser restricts its practical usage. Many research works have been done to boost up the performance of this laser such as the study of the point reflector’s reflectivity in high power forward pumped RFL system [10], powerful narrow linewidth using tunable fiber laser and FBG [11], high efficiency RDFB-FL utilizing short phosphosilicate fiber [12], [13], linearly polarized RDFB-FL [14], variation of pump coupling ratios in ultra-long Raman based RDFB-FL [15] and forward pumped RDFB with record of high power [16]. In this research work, the investigation on dual wavelength RFL is proposed, where micro-air cavity (MAC) is implemented in an open ended cavity. The MAC is constructed based on the parallel alignment of two flat angled fibers. Based on the published work in [17], MAC is chosen due to its simple structure, low fabrication cost, and the ability to induce strong effect of Fresnel reflections inside the laser cavity.

1.2 Problem statement

RFL based on Raman gain suffer from high threshold condition due to the low Raman gain coefficient in silica fiber and weak feedback of Rayleigh scattering (RS) in the absence of reflectors [6]. Many efforts have been done to induce the passive feedback and subsequently lower down the threshold level which includes various types of reflectors utilized at one side of the laser cavity [10], [18], [19]. The main objective is to increase the reflectivity in addition to the RS feedbacks. For instance, tunable mirror using variable optical attenuator (VOA) in 3 dB coupler in [10] and polarization maintaining fiber (PMF) based Lyot filter in single mode laser cavity in [18]. However, the addition of these components increases the laser cavity complexities and at the same time, induces additional loss to the cavity. MAC offers an alternative solution to reduce the threshold level along with multiwavelength spectrum generation owing to the fact that it functions as both reflective mirror and comb filter [17], [20]–[22]. To date, the integration of MAC technique is limited to two types of fiber laser schemes; multiwavelength fiber lasers (MWFLs) [17], [20], [21], [23], [24] and mode-locked fiber laser (MLFL) [22]. There is still no report on MAC deployment in Raman based RFL systems. Hence, this research work proposes the study on the lasing performance characteristics of RFL integrated with MAC.

1.3 Objectives of the research

1) To evaluate the performance of mirrorless open cavity random fiber laser (MOCRFL) with various pumping schemes.
2) To investigate the effect of MAC on half-open cavity random fiber laser (HOCRFL) performance with variation in micro-air gap distances.

1.4 The scope of the research

Figure 1.3 illustrates the scope of the research that will be investigated in this research work. The MOCRFL is investigated first by concentrating on the pumping schemes; forward, backward and bidirectional. Then, the impact of MAC on the lasing performance is studied by integrating it in RFL architectures. Besides the reflectivity, the research work also focuses on the multiwavelength generation in HOCRFL incorporating MAC. There are many works that have been reported on half-open cavity with the utilization of various type of reflectors to generate different output spectrum such as tunable [25], cascaded [12], [26], multiwavelength [18], [27]–[29], Q-switched [30] as well as narrowband laser [11]. MWFLs have been in the spotlight in the recent years due to their reliable applications such as dense wavelength division multiplexing (DWDM), spectroscopy and fiber sensor [29]. In this work, the dual function of MAC (as reflective mirror and comb filter) in Raman based RFL is proposed to achieve multiwavelength laser, which simultaneously eliminates the complexity of the laser system in comparison to the previous reported works [18], [29], [31]–[34].

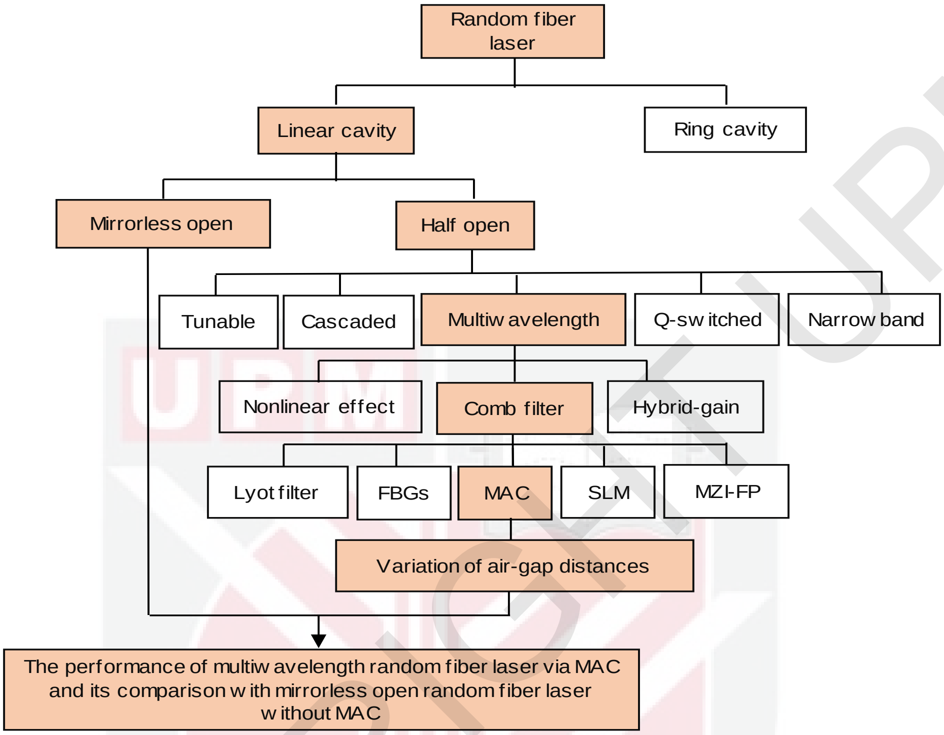


Figure 1.3: The scope of research

1.5 Thesis organization

This thesis is divided into five chapters. Chapter 1 describes an overview of laser and fiber laser. The chapter proceeds by highlighting the issues faced by RFL, followed by the objectives as a solution from those issues. Lastly, the scope of this research work and thesis organization is also discussed in this chapter. Chapter 2 presents the theoretical concept of gain and feedback in Raman fiber laser which leads to the first demonstration of RDFB-FL. The next subchapters cover a review on MWFLs, the reported techniques used for multiwavelength random fiber lasers (MWRFLs), the basic theory of MAC technique and subsequently the overview on the integration of this technique in laser systems. Chapter 3 elaborates on the methodology and principle of operation for experimental works on MOCRFL. The spectral and lasing characteristics of MOCRFL are investigated and discussed to get the basic understanding on the performance of MOCRFL with different pumping schemes. Chapter 4 presents the detail investigation on the effect of pumping architectures, MAC locations as well as variation of air-gap distances from 100 μm to 1000 μm in HOCRFL with the deployment of MAC. Chapter 5 will encapsulate the conclusion of the research and the recommendations for future works.

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