MULTI-WAVELENGTH BRILLOUIN FIBER LASER BY UTILIZING FIBER BRAGG GRATING

by

AMIRA ZAKIAH BINTI MALEK
(1330111111)

A thesis submitted in fulfillment of the requirements for the degree of
Master of Science in Microelectronic Engineering

School of Microelectronic Engineering
UNIVERSITI MALAYSIA PERLIS

2017

THESIS DECLARATION FORM
UNIVERSITI MALAYSIA PERLIS

DECLARATION OF THESIS

Author's full name	:	AMIRA ZAKIAH BINTI MALEK
Date of birth	:	17^{th} JANUARY 1990
Title	:	MULTI-WAVELENGTH BRILLOUIN FIBER LASER BY UTILIZING FIBER BRAGG GRATING
Academic Session	:	……………

I hereby declare that this thesis becomes the property of Universiti Malaysia Perlis (UniMAP) and to be placed at the library of UniMAP. This thesis is classified as:

☐ **CONFIDENTIAL** (Contains confidential information under the Official Secret Act 1972)*

☐ **RESTRICTED** (Contains restricted information as specified by the organization where research was done)*

■ **OPEN ACCESS** I agree that my thesis is to be made immediately available as hard copy or on-line open access (full text)

I, the author, give permission to the UniMAP to reproduce this thesis in whole or in part for the purpose of research or academic exchange only (except during a period of _____ years, if so requested above).

Certified by:

____________________	____________________
SIGNATURE	**SIGNATURE OF SUPERVISOR**
900117-06-5128	DR NOR AZURA MALINI BINTI AHMAD HAMBALI
(NEW IC NO. / PASSPORT NO.)	**NAME OF SUPERVISOR**
Date :22^{th} MAY 2017	Date : 22^{th} MAY 2017

***NOTES**: If the report is CONFIDENTIAL or RESTRICTED, please attach with the letter from the organization with period and reasons for confidentially or restriction.

ACKNOWLEDGEMENT

Alhamdulillah, first and foremost, I would like to take this opportunity to express my sincere appreciation to everyone who were involved in my Master Project, either directly or indirectly, and have aided me through the difficulties and crucial times. Though I had a tough time, with the help of caring, understanding and helpful people, I have managed to finish this report. This Master Project has truly been an educational and significant experience for me.

A special thank goes to my beloved husband, Mr. Azmeer Zairee bin Omar and my father Mr. Malek bin Deraman for their constant support during my research project. The encouragement and motivation they have shown in me is my greatest source of inspiration. I also would like to convey my special gratitude towards my respectful supervisor, Dr. Nor Azura Malini binti Ahmad Hambali. The supervision that she gave truly helps the progression and smoothness of the Master Project. I am forever grateful for being welcomed into your group. Your time, patience, and interest in my work have never gone unnoticed. The cooperation is indeed much appreciated. Not forget, great appreciation goes to my co-supervisor, Dr. Mohamad Halim bin Abdul Wahid that helped me from time to time during the project. I would like also to acknowledge with much appreciation for staff of School of Microelectronics Engineering, Mr. Mohd Azarulsani Bin Md. Azidin who gave his critical comments and constructive suggestions for my project and final report. My many thanks also go to all my fellow friends for their patience, cooperation and assistance provided in completing my Master Project. The whole project really brought us together to appreciate the true value of friendship and respect each other. Also, not forgetting my family members who always been there through my ups and downs during the completion of this project. Their ideas,

suggestions, advice and guidance have really helped me to improve and realize the objective of this Master Project.

Thank you.

TABLE OF CONTENTS

CHAPTER 4 RESULTS AND DISCUSSION

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

SBS	Stimulated Brillouin scattering
BS	Brillouin Stokes
BP	Brillouin pump
SMF	Single mode fiber
MWBFL	Multi-wavelength Brillouin fiber laser
BFL	Brillouin fiber laser
EDFA	Erbium doped fiber amplifier
DWDM	Dense wavelength division multiplexing
MWBEFL	Multi-wavelength Brillouin-Erbium fiber laser
MWBRFL	Multi-wavelength Brillouin Raman fiber laser
EDF	Erbium doped fiber
SRS	Stimulated Raman scattering
DCF	Dispersion compensating fiber
FBG	Fiber Bragg grating
OSNR	Optical signal to noise ratio
BEFL	Brillouin Erbium fiber laser
BRFL	Brillouin Raman fiber laser
SPM	Self-phase modulation
XPM	Cross phase modulation
FWM	Four wave mixing
MWEDFL	Multi-wavelength Erbium doped fiber laser
WDM	Wavelength division multiplexer
OSA	Optical spectrum analyser

PCF	Photonic crystal fiber
HNLF	Highly nonlinear fiber
TLS	Tunable laser source
SSMF	Standard single mode fiber

LIST OF SYMBOLS

nm	Nanometer
mW	Miliwatt
dBm	dB relative to a miliwatt
dB	Decibel
km	Kilometer
ms	Millisecond
%	Percentage
GHz	Gigahertz
v_A	The acoustic velocity in the gain medium
λ_p	The pump wavelength
n	The fiber refractive index
E_1	Energy potential of the ground state
E_2	Energy potential of the excited state
h	Planck's constant
v	Frequency of the photon
$\alpha_p \approx \alpha_s \equiv \alpha$	Fiber losses are nearly the same for the stoke waves
$\omega_p \approx \omega_s$	Small value of the Brillouin shift
g_B	Brillouin gain coefficient
α	Fiber loss coefficient
I_s	BS signal intensity
I_p	BP signal intensity
G_B	The unsaturated Brillouin gain
L	Fiber length

A_{eff}	Effective core area of the fiber
I_p (0)	Pump signal intensity at the initial condition
b_0	The portion of the input pump power that is converted to the BS power
g_0	Small signal gain that is associated with the SBS process
Er^{3+}	Erbium ion
n_1	High refractive index
n_2	Low refractive index
λ_B	Back-reflected light
R	Final reflectance
l	Length of the grating
k	Characteristic of FBG parameter
λ	Operating wavelength
Δn	Amplitude of the index variation
kHz	Kilohertz

Pelbagai Gelombang Gentian Brillouin Laser Dengan Menggunakan Gentian Bragg

ABSTRAK

Sebuah rongga cincin pelbagai panjang gelombang gentian Brillouin laser dengan menggunakan gentian Bragg dimanipulasikan untuk meningkatkan penghantaran atau kadar data dalam komunikasi gentian optik terutamanya di dalam sistem pemultipleksan pembahagian panjang gelombang tumpat. Gabungan kesan berselerak Brillouin dan pembalik cahaya di dalam gentian Bragg telah meningkatkan penjanaan pelbagai gelombang untuk menghantar maklumat yang banyak pada waktu yang sama. Tatarajah rongga cincin telah dieksperimen dengan menggunakan pelbagai panjang gentian mod tunggal di mana ianya bertindak sebagai medium bagi mendapatkan keuntungan Brillouin dan seterusnya merangsang kesan Brillouin berselerak. Kuasa pam Brillouin dilaraskan dari 8 dBm kepada 18 dBm dengan menaikkan kuasa sebanyak 1 dBm secara berperingkat ke dalam sistem laser. Lima panjang gentian mod tunggal yang berbeza sepanjang 8 km, 9 km, 10 km, 11 km and 12 km beserta sembilan nisbah gandingan pengeluaran dari 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% dan 90% telah dioptimumkan untuk menjana lebih banyak keluaran isyarat. Secara keseluruhannya, keputusan menunjukkan penyiasatan mengenai ambang kuasa Brillouin untuk isyarat Brillouin Stokes yang pertama bergantung kepada panjang gentian mod tunggal and nisbah gandingan pengeluaran. Ambang kuasa Brillouin terendah sebanyak 8 dBm direkodkan apabila 10%, 20%, 30% and 40% daripada nisbah gandingan pengeluaran serta 10 km panjang gentian mod tunggal digunakan ke dalam rongga cincin manakala ambang kuasa Brillouin yang paling tinggi sebanyak 12 dBm dicatatkan dengan menggunakan 8 km panjang gentian mod tunggal pada 60%, 70%, 80% dan 90% nisbah gandingan pengeluaran. Selain daripada itu, sehingga maksimum 38 isyarat Brillouin Stokes bersama-sama dengan 16.00 dB purata nilai optik isyarat kepada nisbah hingar direkodkan pada 1550 nm untuk pelbagai panjang gelombang Brillouin pam apabila pam Brillouin dilaraskan sehingga 18 dBm telah dimasukkan ke dalam rongga cincin. Sebanyak 90% optimum nisbah keluaran gandingan dan 10 km gentian mode tunggal telah digunakan dalam menghasilkan generasi pelbagai panjang gelombang. Kekurangan pemilihan panjang gelombang adalah berdasarkan oleh ciri-ciri gentian Bragg itu sendiri. Generasi pelbagai panjang gelombang hanya berlaku dalam lingkungan 1544 nm hingga ke 1556 nm untuk pam Brillouin panjang gelombang mengikut 3 dB jalur lebar 5 nm daripada gentian Bragg. Pendek kata, prestasi projek yang lebih baik terhasil daripada pelbagai gelombang gentian Brillouin laser dengan menggunakan gentian Bragg di mana generasi pelbagai panjang gelombang yang paling berkesan dihasilkan dengan menggunakan 10 km medium keuntungan Brillouin.

Multi-Wavelength Brillouin Fiber Laser By Utilizing Fiber Bragg Grating

ABSTRACT

A ring cavity multi-wavelength Brillouin fiber laser by utilizing fiber Bragg grating is evolved to increase the transmission or data rate in the optical fiber communication especially in dense wavelength division multiplexing system. The combination of stimulated Brillouin scattering effect and fiber Bragg grating's reflectivity enhances the multi-wavelength generation in order to transmit a lot of information at the same time. A ring cavity configuration has been experimental demonstrated with different single mode fiber lengths in which act as a Brillouin gain medium in stimulated Brillouin scattering effect. The amplified Brillouin pump power of 8 dBm to 18 dBm with a step increment of 1 dBm was applied in the laser system. Five different single mode fiber lengths of 8 km, 9 km, 10 km, 11 km and 12 km with nine output coupling ratios of 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90% were optimized to generate more output signals. Overall, the results showed that the investigation of Brillouin threshold power for first Brillouin Stokes signals was critically depends on the selective single mode fiber lengths and output coupling ratios. The lowest Brillouin threshold power of 8 dBm was achieved when 10%, 20%, 30% and 40% of the output coupling ratio at 10 km of single mode fiber was applied into the ring cavity while the highest Brillouin threshold power of 12 dBm was recorded by using 8 km of single mode fiber with 60%, 70%, 80% and 90% of output coupling ratios. Besides that, up to maximum 38 generated Brillouin Stokes signals with 16.00 dB of average optical signal to noise ratio value were recorded at 1550 nm of Brillouin pump wavelength when high amplified Brillouin pump power of 18 dBm was injected into the ring cavity. An optimum output coupling ratio of 90% and 10 km of single mode fiber were utilized in producing the multi-wavelength generation. The wavelength selectivity based on the Fiber Bragg Grating's properties constrains the tuning range ability of this laser system. The multi-wavelength generation only occurred within 1544 nm to 1556 nm of Brillouin Pump wavelength according to the 3 dB bandwidth of 5 nm of the fiber Bragg grating. In short, the better performance of multi-wavelength Brillouin Fiber Laser by utilizing fiber Bragg grating was successfully demonstrated whereby the most multi-wavelength generation produced at 10 km of the effective Brillouin gain medium.

CHAPTER 1

INTRODUCTION

In this chapter explains an overview of the fiber optic communication system and its application in order to understand the whole concept of this research work. The topics were divided into different view such as overview, problem statement, aim and motivation, objectives and scopes of work. The demand of optical fiber for more communication application also deeply explained at the end of this chapter.

1.1 Overview

Generally, the invention based on the fiber optic communication system is mainly known as a technology of transmitting the desired amount of data or information from one location to another by propagating light pulses through an optical fiber (Dike & Ogbe, 2013). Prior to the innovation of the fiber optics, worldwide communication utilizes copper wire as a main medium for communication (Personick, Rhodes, Hanson & Chan, 1980). However, this electrical transmission is not relevant today especially for a long haul communication due to the limitation of huge size and the difficulties of installation (Agrawal, 2002).

Over many decades, fiber optic has tremendously transformed the telecommunication industry in many aspects and offers the reliable data innovation for internet users either in terms of global coverage or data rates (Kinlin, 2006). This growth is due to the development of a wide tuning range of the fiber laser system which offers almost unlimited bandwidth at higher speed (Ahmad et al., 2012). As the interest for data transfer expands, this situation increased the great opportunity to more research and investigation on new applications and technologies.

Since the first investigation of stimulated Brillouin scattering (SBS) effect has been studied in 1964 by (Chiao, Townes & Stoicheff, 1964), the deployment of light for fiber optic communication received vigorous attentions as the future direction communication system. It is well known that SBS is principally caused by the propagation of back-reflected optical signal. The back-reflected signal is downshifted and normally called as Brillouin Stokes (BS) signal, resulted when the injected Brillouin pump (BP) power exceeds a certain level namely as threshold condition. It is important to realize that the downshifted frequency was usually produced at a constant spacing of 0.08 nm at 1550 nm of BP wavelength from the injected BP signal in the case of a standard single mode fiber (SMF). Once the laser system attained the above threshold condition, the BP power has slightly transferred to the first BS signal. Thus, the BS signal power is depends by the material of gain medium in which allow the propagation of light.

In the past few years, the integration of the narrow linewidth Brillouin laser was implemented in the multi-wavelength Brillouin fiber laser (MWBFL) system and its applications. However, the Brillouin gain is typically very low to achieve high performance of multi-wavelength generation in the Brillouin fiber laser (BFL) operation. Thus, additional of optical amplifier such as an Erbium doped fiber amplifier (EDFA) is necessary to counter the transmission attenuation especially in a long haul optical telecommunication. Alternatively, with its narrow linewidth signal, the MWBFL system offers a lot of advantages for applications such as optical metrology (Subías, Heras, Pelayo, & Villuendas, 2009), fiber-optic sensor (Smith, Zarinetchi & Ezekiel, 1991), high-resolution spectroscopy (Schneider & Schille, 1997), gyroscopes

(Zarinetchi, Smith & Ezekiel, 1981), interferometric sensing (Geng et al., 2006), narrow bandwidth amplification (Ferreira, Rocha & Pinto, 1994), dense wavelength division multiplexing (DWDM) system (Mansor et al., 2011) and other optical fiber communications.

After development of MWBFL system, it also has led to the subsequent studies of multi-wavelength Brillouin-erbium fiber laser (MWBEFL) system (Rahman, Nurdik & A. Rahim, 2014) and multi-wavelength Brillouin Raman fiber laser (MWBRFL) system (Toor, Ahmad Hambali, Abdul-Rashid & Yusof, 2014). These techniques have been widely studied as a prominent method in order to generate a high number BS signal and lower threshold power. However, the major drawback of wavelength tunability and the competition of oscillating modes (self-lasing cavity) at the peak of Erbium doped fiber (EDF) caused the output instability in MWBEFL structure. In this situation, the presence of self-lasing cavity modes constrained the generation of multi-wavelength and output power. Hence, a sufficient amount of BP power is highly needed to suppress the self-lasing cavity modes before entering into the BEFL system. This interference of self-lasing cavity modes are mainly produced by the natural effect of light waves from the EDF. Therefore, this technique is only efficient when the BP wavelength is injected beyond of this free-running EDF laser bandwidth.

Meanwhile, the spectral broadening mechanism of laser modes in the MWBRFL system limits the number of lasing signals. It is important to highlight that the spectral broadening appears within the range of Raman peak gain. The formation of noises in the Raman gain spectrum indicated that the BS signals are not able to suppress the noises from the stimulated Raman scattering (SRS). Another special type of fiber, such as dispersion compensating fiber (DCF) is needed to enhance the Raman gain since the stability of multi-wavelength generation is difficult to obtain. In the MWBRFL system, the multi-wavelength generation is constrained and only available at the certain Brillouin and Raman pump source (Guy, Chernikov & Taylor, 1998; Zamzuri, Mahdi, Ahmad, Md Ali & Al-Mansoori, 2007).

In order to rectify these limitations, the implementation of MWBFL system utilizing Fiber Bragg Grating (FBG) is highly needed to produce a high number of multi-wavelength generations at a selected wavelength. The combination process of SBS effect and FBG's reflectivity at a center BP wavelength of 1550 nm are blended in this proposed ring cavity laser system. The optimization of different output coupling ratios and fiber lengths are utilized throughout the investigation to minimize the cavity loss in the structure. Even though the utilization of MWBFL system has not been considered seriously before due to low generation of multi-wavelength, this limitation gives the aim and motivation to find another alternative by incorporated with FBG and hence increases the scattering effect in the main gain medium.

1.2 Problem statement

The development and innovation of ring cavity fiber lasers through the years expanded and brought the revolution in the optical communication system and sensing applications. The requirement for an increment in output power for these applications has been developed extensively. This prompted the execution of numerous vital parameters such as cavity loss, number BS signals and optical signal to noise ratio (OSNR) value.

Several investigations of different type optical structure in the laser system have been developed in order to overcome the limitation of generating BS signals and output power (Parvizi et al., 2010; Shirazi et al., 2008; Shirazi, Biglary, Harun, Thambiratnam

& Ahmad, 2008). Recently, linear (bidirectional propagation) and ring cavity (unidirectional propagation) had been extensively studied in the long haul optical communication system (Ajiya, Mahdi, Al-Mansoori, Mokhtar & Hitam, 2009; Rahman, Hitam, Al-Mansoori, Abas & Mahdi, 2011). However, from the previous research on the reversed-S-shaped ring cavity, the laser system constrained a high cavity loss when only 11 BS signal at 1550 nm of BP wavelength was reported in (Rahman, Hitam, Al-Mansoori, Abas & Mahdi, 2011). Therefore, a better solution must be undertaken in this study in order to improve the cavity loss. Of the various structures, the ring cavity received considerable attention because of their appealing low cavity loss, high power efficiency, and low threshold power. This ring cavity can operate in both light propagations namely as clockwise and anti-clockwise direction. The ring cavity is realized by forming a loop constructed together with an optical coupler, Brillouin gain medium and doped fiber. Normally, the cavity loss in the laser system is optimized by different output coupling ratios and determined by percentage of output power. Therefore, to properly address this issue an employment of FBG's reflectivity in the ring cavity offers a direct impact to produce generation of MWBFL as well as reduces the cavity loss in the laser system.

Moreover, a higher number BS signal is another important parameter to achieve an efficient MWBFL system in order to transmit a lot of information at the same time. To attain this condition, the replacement from previous researches work with the hybrid technique MWBFL by utilizing FBG has reduced the cavity loss and subsequently generates a higher number BS signal in the ring cavity. The reflectivity and selective wavelengths of FBG enhances the SBS effect in the Brillouin gain medium and hence takes into consideration to produce large number BS signals. Following that, the cavity loss also has a direct impact on the quality BS signals in term of OSNR value. The