UNIVERSITI PUTRA MALAYSIA

INVESTIGATION OF DIFFERENT CONFIGURATIONS FOR SINGLE AND DOUBLE SPACING MULTI-WAVELENGTH BRILLOUIN-RAMAN FIBER LASER

GHAZALEH MAMDOOHI

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By

GHAZALEH MAMDOOHI

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

December 2014

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This thesis is dedicated to:

my dearest patient husband,

and my beloved parents

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

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GHAZALEH MAMDOOHI

December 2014

Chairman: Mohd Adzir bin Mahdi, PhD
Faculty: Engineering

The work in this thesis focuses on generation of multi-wavelength Brillouin-Raman fiber laser (MBRFL) with single and double frequency Brillouin spacing shift. Three main configurations have been proposed to accomplish this aim. These are achieved based on the stimulated Brillouin scattering (SBS), stimulated Raman scattering (SRS), and stimulated Rayleigh scattering (SRLS). In all architectures, dispersion compensating fiber (DCF) is utilized as a nonlinear Brillouin-Raman gain medium. Firstly, a new MBRFL utilizing enhanced nonlinear amplifying fiber loop (NAFL) design is proposed and demonstrated to produce adjustable 10 and 20 GHz wavelength spacing. We developed a detailed theoretical analysis, which represents a good foundation on which operation of MBRFL with 10 and 20 GHz spacing is satisfied. By proper adjustments of splitting ratio, the wavelength interval can be adjusted, thus improving the laser performance. Utilizing 50/50 coupler offers 443 flat amplitude channels with 10 GHz spacing and 16.5 dB average Stokes optical signal-to-noise ratio (S-OSNR). On the other hand, 1/99 coupler is desirable for multiple Stokes combs with 20 GHz spacing in which 221 lasing lines with an average 25 dB S-OSNR are generated. The employment of a mirror at the end of this cavity, which is dubbed as the nonlinear amplifying loop mirror (NALM) design is responsible for initiation of lower threshold for SBS effect that leads to the excellent results. A total of 28 channels with 10 GHz spacing and an average 17 dB S-OSNR are achieved when the Raman pump power (RPP) is fixed at only 300 mW. This is the most efficient 10 GHz MBRFL reported at very low RPP through a simple configuration. The second configuration is proposed to generate a MBRFL with 20 GHz spacing via forward pumping scheme. The setup is arranged in a linear cavity by employing 7.2 and 11 km DCF in addition to a 30 cm Bismuth oxide erbium-doped fiber (Bi-EDF). It is found that incorporating 11 km DCF with Bi-EDF results in multiple Brillouin Stokes signals with outstanding OSNR. In this case, a total of 186 Brillouin Stokes combs with -13.5 dBm Stokes peak power (SPP) and an average 28 dB S-OSNR are produced. These results are achieved when Brillouin pump (BP) power of -2.6 dBm , BP wavelength of 1545 nm , and RPP of 900 mW are injected into the cavity. However, characteristics improvement of MBRFL with 20 GHz spacing in terms of channels count, SPP, and wavelength operation is

another aim of this work which is successfully accomplished by introducing the third configuration. In this structure, incorporation of Raman pump source with a set of couplers with various ratios leads to different Brillouin Stokes lines features. The optimization of multi-wavelength laser operation is done with proper adjustments of coupling ratio, BP wavelength, BP power, and RPP. The results demonstrate that the best S-OSNR performance is satisfied at coupling ratio of 50/50. When setting the RPP to 1000 mW, 212 flat amplitude Stokes lines with -10 dBm SPP and an average 27.5 dB S-OSNR are achieved. In this case, the BP power and its corresponding wavelength are set at -2.6 dBm and 1543 nm respectively. Moreover, this configuration reveals the highest peak power discrepancy between odd- and even-order Stokes lines (22.5 dB) in comparison with other configurations with 20 GHz spacing.

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

SIASATAN TERHADAP KONFIGURASI-KONFIGURASI BERBEZA UNTUK TUNGGAL DAN BERKEMBAR PADA LASER GENTIAN BRILLOUIN-RAMAN BERBILANG SALURAN

Oleh

GHAZALEH MAMDOOHI

Decimber 2014

Pengerusi: Mohd Adzir bin Mahdi, PhD
Fakulti: Kejuruteaan

Kerja penyelidikan ini memfokus kepada penghasilan laser gentian Brillouin-Raman berbilang saluran (MBRFL) dengan anjakan selang Brillouin berfrekuensi tunggal dan berkembar. Tiga konfigurasi utama telah disyorkan dalam kerja penyelidikan ini. Ianya dicapai berdasarkan penyerakan Brillouin terangsang (SBS), penyerakan Raman terangsang (SRS), dan penyerakan Rayleigh terangsang (SRLS). Di dalam semua binaan, gentian gantian penyebaran (DCF) digunakan sebagai sebuah media pengganda Brillouin-Raman tidak lurus. Pertamanya, sebuah MBRFL yang baru menggunakan rekaan geluang gentian gandaan tidak lurus (NAFL) termaju telah disyorkan dan didemonstrasikan untuk menghasilkan selang saluran boleh-ubah iaitu 10 dan 20 GHz. Kami juga telah membangunkan suatu analisis teori yang terperinci, di mana ianya adalah suatu penemuan yang bagus, yang mana operasi MBRFL dengan selang 10 dan 20 GHz adalah memuaskan. Dengan pengubahan yang betul terhadap nisbah pecahan, selang saluran boleh diubah, seterusnya meningkatkan prestasi laser. Menggunakan pengganding 50/50 menawarkan selang-selang amplitud rata sejumlah 443 garisan laser dengan 10 GHz dan hampir kepada nilai 16.5 dB untuk nisbah isyarat-kepada-kebisingan optik Stokes (S-OSNR). Selain daripada itu, pengganding 1/99 diperlukan untuk sesikat Stokes berbilang dengan selang 20 GHz, di mana bilangan saluran sejumlah 221 dengan S-OSNR bernilai 25 dB telah dihasilkan. Penggunaan cermin pada hujung kaviti ini di gelar sebagai rekaan cermin gelung gandaan tidak lurus (NALM) dan bertanggungjawab untuk penghasilan nilai ambang yang lebih rendah untuk kesan SBS yang membawa kepada keputusan yang bagus. Sejumlah 28 saluran dengan selang 10 GHz dan purata S-OSNR bernilai 17 dB telah dicapai apabila kuasa pam Raman (RPP) ditetapkan pada 300 mW sahaja. Ia merupakan laporan MBRFL untuk 10 GHz yang paling efisien pada RPP yang paling rendah berdasarkan kepada konfigurasi yang ringkas. Konfigurasi kedua mensyorkan penghasilan suatu MBRFL dengan selang 20 GHz melalui skim pengepaman hadapan. Penyediaan ini disusun dalam kaviti lurus dengan menggunakan DCF yang panjangnya 7.2 dan 11 km, dengan penambahan gentian erbium-terdop Bismuth teroksida (Bi-EDF) yang panjangnya 30 cm. Menggunakan Bi-EDF berserta DCF yang panjangnya 11 km, didapati isyarat Stokes Brillouin berbilang dengan OSNR yang bagus terhasil. Dalam kes ini,

sejumlah 186 sesikat Stokes Brillouin dengan kuasa puncak Stokes (SPP) bernilai -13.5 dBm dan S-OSNR bernilai 28 dB telah dihasilkan. Keputusan ini dicapai apabila kuasa pam Brillouin (BP) adalah -2.6 dBm, saluran BP adalah 1545 nm, dan RPP adalah 900 mW dimasukkan ke dalam kaviti. Akan tetapi, peningkatan ciri MBRFL dengan selang 20 GHz dari segi pengiraan saluran, SPP, dan operasi saluran adalah matlamat lain dalam kerja peneyelidikan ini, yang mana telah berjaya dicapai dengan memperkenalkan konfigurasi ketiga. Dalam struktur ini, kemasukan sumber pam Raman dengan set pengganding pelbagai nisbah menunjukkan kepada sifat garisan Stokes Brillouin yang berbeza. Pengoptimuman operasi laser berbilang saluran dapat dicapai dengan pengubahan nisbah penggandingan, saluran BP, kuasa BP dan RPP. Keputusan ini menyatakan bahawa prestasi S-OSNR terbaik telah dicapai pada nisbah penggandingan 50/50. Apabila RPP ditetapkan pada 1000 mW, 212 garisan Stokes amplitud rata dengan SPP bernilai -10 dBm dan purata S-OSNR bernilai 27.5 dB telah diperolehi. Dalam kes ini, kuasa BP ditetapkan kepada -2.6 dBm, manakala panjang gelombang saluran BP ditetapkan kepada 1543 nm. Selain itu, konfigurasi ini mendedahkan bahawa perbezaan kuasa puncak tertinggi di antara garisan Stokes pada susunan ganjil dan genap adalah bernilai 22.5 dB dalam perbandingan dengan konfigurasi lain dengan selang 20 GHz.

ACKNOWLEDGEMENTS

All grace and thanks belongs to Almighty Allah for giving me the strength, courage, and determination for completing this work, Alhamdulillah.

I would like to express my sincere gratitude to my supervisor Prof. Mohd Adzir bin Mahdi for his guidance, advice, and encouragement in the completion of this study. His professional review helped me to further improve the thesis.

Special thanks dedicated to my supervisory committee member, Dr. Makhfudzah Bt. Mokhtar, Dr.Hanif Yaacob, and Dr.Abdul Rahman Sarmani for their motivations and encouragements.

I would like to express my deepest gratitude to my beloved husband, Behnam Kheradmand, for his endless support during 7 years studying beside him.

Last but not least I am proud and grateful to my beloved parents and my parents in law for being so helpful and supportive through my studies.

APPROVAL

I certify that a Thesis Examination Committee has met on 18th December 2014 to conduct the final examination of Ghazaleh Mamdoohi on her thesis entitled "Investigation of different configurations for single and double spacing multi-wavelength Brillouin–Raman 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.

Members of the Thesis Examination Committee were as follows:

Nor Kamariah bt. Noordin, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Salasiah bt. Hitam, PhD
Faculty of Engineering
Universiti Putra Malaysia
(Internal Examiner)

Md Zaini bin Jamaludin, PhD

Professor
Faculty of Engineering
Universiti Tenaga Nasional (UNITEN)
(External Examiner)

Meil Grogory Raphael Broderick, PhD

Professor
Faculty of Physics
University of Auckland
(External Examiner)

_____

NORITAH OMAR, PhD.
Assoc. Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia
Date:

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

Mohd Adzir bin Mahdi, PhD
Professor
Faculty of Engineering
Universiti Putra Malaysia
(Chairman)

Makhfudzah Bt Mokhtar, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Mohd Hanif Yaacob, PhD
Senior Lecturer
Faculty of Engineering
Universiti Putra Malaysia
(Member)

Abdul Rahman Sarmani, PhD
Senior Lecturer
Faculty of Science
Universiti Putra Malaysia
(Member)

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LIST OF ABBREVIATIONS

AGC	Asiah Glass Company
Al_2O_3	Alumina
ASE	Amplified Spontaneous Emission
BWP	Backward Pumping
Bi-EDF	Bismuth Oxide Erbium-Doped Fiber
BiDP	Bidirectional Pumping
Bi_2O_3	Bismuth Oxide
BFL	Brillouin Fiber Laser
BP	Brillouin Pump
BS	Brillouin Stokes
BSL	Brillouin Stokes Lines
BEFL	Brillouin-Erbium Fiber Laser
BRFL	Brillouin-Raman Fiber Laser
C	Circulator
CW	Clockwise
CCW	Counter-Clockwise
CR	Coupling Ratio
DWDM	Dense Wavelength Division Multiplexing
DCF	Dispersion Compensating Fiber
DSF	Dispersion Shifted Fiber
EDF	Erbium-Doped Fiber
EDFL	Erbium-Doped Fiber Laser
EDFA	Erbium-Doped Fiber Amplifier
Er^{+3}	Erbium
1^{st} BSL	First Brillouin Stokes Line
FWP	Forward Pumping
FWM	Four-Wave Mixing
GeO_2	Germanium Oxide
HNLF	Highly Nonlinear Fiber
I	Isolator
La	Lanthanum
LEAF	Large Effective Area Fiber
M	Mirror
MBEFL	Multi-wavelength Brillouin-Erbium Fiber Laser
MFL	Multi-wavelength Fiber Laser
MBRFL	Multi-wavelength Brillouin-Raman Fiber Laser
MBSS	Multiple Brillouin Stokes Signals
NAFL	Nonlinear Amplifying Fiber Loop
NALM	Nonlinear Amplifying Loop Mirror
NOLM	Nonlinear Optical Loop Mirror
NPR	Nonlinear Polarization Rotation
OA	Optical Amplifier
OPM	Optical Power Meter
OSNR	Optical Signal-to-Noise Ratio
OSA	Optical Spectrum Analyzer
RFL	Raman Fiber Laser

RPG	Raman Peak Gain
RPP	Raman Pump Power
RPU	Raman Pump Unit
RLBS	Rayleigh Backscattering
2^{nd} BSL	Second Brillouin Stokes Line
SiO_2	Silicon Oxide
Si-EDF	Silicon oxide Erbium-Doped Fiber
SPM	Self-Phase Modulation
SMF	Single Mode Fiber
SBS	Stimulated Brillouin Scattering
SRS	Stimulated Raman Scattering
SRLS	Stimulated Rayleigh Scattering
SLC	Stokes Lines Count
S-OSNR	Stokes-Optical Signal-to-Noise Ratio
SPP	Stokes Peak Power
TLS	Tunable Laser Source
WDM	Wavelength Division Multiplexing
WSC	Wavelength Selective Coupler
XPM	Cross-Phase Modulation
YFL	Ytterbium Fiber Laser

CHAPTER ONE

INTRODUCTION

1.1 Introduction

There is currently an increasing demand for transmission bandwidth used for dense wavelength-division-multiplexing (DWDM) optical communication systems as resulted from the remarkable advancement both in the data traffic and the internet [1-2]. DWDM has a potential transmission system with large number of closely spaced channels through optical fiber. In addition, employment of optical amplifiers for regenerating the multi-channel light wave without requiring to demultiplexing of individual channels makes a revolution in multi-wavelength optical system designs. This makes a demand for multi-wavelength light source. In order to fulfill such a demand, using the multi-channel laser source has turned into a noticeable and conceivable solution. Multi-wavelength fiber lasers are highly desirable for the cost and size reduction, improvement of system integration and their compatibility with optical communication networks. Researchers have focused their efforts on producing a multi-wavelength fiber laser (MFL) which is able to generate a higher number of channels with precise wavelength spacing between them. In the past few years, generating multi-wavelength based on nonlinear effects are one of the attractive approaches which were mostly designed in a single or hybrid technology. The single configuration means that only a single-technology has been deployed for this purpose such as the ones based on Brillouin fiber laser (BFL) [3-4], erbium-doped fiber laser (EDFL) [5-6], Raman fiber laser (RFL) [7-8], ytterbium fiber laser (YFL) [9], and others. However, this type of BFL suffers from a limitation in output power due to the small coefficient of the Brillouin gain. Moreover, the EDFL or RFL have some drawbacks, mainly resulting from few laser Stokes line count (SLC) and non-flattened laser Stokes spectra. These features have forced the researchers to explore the hybrid technology. Hybrid-gain configuration is another nonlinear-based multi-wavelength fiber laser which is more attractive due to its ability to generate more multi-wavelength laser. This type of configuration combines Brillouin and other gains for generating multiple wavelengths. Brillouin-Erbium fiber laser (BEFL) in ring and linear cavity have attracted many interests [10-14]. The BEFL operation is also extremely sensitive to resonance detuning between the pump laser frequency and the Brillouin cavity mode [12, 15]. However, the homogeneous nature of its gain medium limits the bandwidth and amplitude envelope profiles of the output multi-wavelength Brillouin-Erbium fiber laser (MBEFL) comb spectrum [16]. Since the number of wavelengths that can be generated in a fiber laser is critical as it is directly proportional to the transmission system capacity. Hence, a new configuration of hybrid multi-wavelength Brillouin–Raman fiber laser (MBRFL) has been regarded as a potential and prosperous solution with several important advantages. These include stable multi-wavelength operation at room temperature and the extremely broad workable wavelength band nearly without limitation. This technique was first proposed by B. Min et al. at 2001 [17] in which the narrow linewidth Brillouin gain is integrated with broad bandwidth Raman gain to generate hundreds of channels. Later on K.D. Park et al. [18-19] have studied the dynamic and threshold features of Brillouin Stokes lines (BSL) generation in Raman

fiber amplifier. Multiple-wavelength Brillouin-Raman fiber lasers having ring and linear cavity configurations have been demonstrated in [20-21]. These two studies used highly nonlinear fiber (HNLF) and dispersion shifted fiber (DSF) as a Brillouin-Raman gain medium which represent 20 and 75 Stokes lines as well as the roughly 10.5 GHz spacing for both configurations correspondingly. A. K. Zamzuri et al. recommended architectures for MBRFL which employ two feedback mirrors at the both ends of the cavities [22-23]. Moreover, they have studied the contribution of Rayleigh scattering on Brillouin comb line generation and the effect of spectral broadening on Stokes-optical signal-to-noise ratio (S-OSNR) [24-26]. Another MBRFL is also proposed by Wu et al. [27] which is performed in a half-open cavity and capable of creating uniform Stokes combs with 210 channels. Furthermore, Sonee Shargh et al. [28] have demonstrated a simple linear cavity MBRFL with a single Raman pump wavelength and employed large effective area fiber (LEAF) with the aim of the S-OSNR enhancement. Other report that accomplished a MBRFL with a double-pass structure and are able to produce a comb fiber laser with more than a few hundred of Stokes lines with 10 GHz spacing is also introduced by [29]. Despite these advantages, the main drawbacks associated with these lasers are their lower average output power and the non-uniformed Brillouin combs. Current research performed by Wang et al. with the aim of enhancing the flatness of the Brillouin Stokes lines utilizing only a single Raman pump [30]. Although, over 500 Stokes lines have been produced across 40 nm bandwidth, it suffers from very low S-OSNR of 12.5 dB and low output power. This is the highest number of channels acquired from a single Raman pump source reported until now. All of the aforementioned reported assessments are designed to attain multiple wavelengths with single wavelength spacing (10 GHz). Despite the research success, these techniques are not feasible as they are either very costly, or not well suited for practical application. In addition, due to the spectral broadening effect at higher pump power, the quality of Stokes lines in terms of optical signal-to-noise ratio (OSNR) is deteriorated [25]. As a result, together with the disadvantages existing in 10 GHz MBRFL the needs to explore alternative MBRFL sources have been increased.

1.2 Motivation

As discussed in the previous section, several MBRFL with 10 GHz wavelength spacing through different kinds of cavity configurations have been reported [17-18, 20-24, 27-30]. Nevertheless, these laser structures with low S-OSNR and narrow channel spacing is not practical for DWDM applications as it is difficult to demultiplex the channels at the receiver end. Thus, another design offering higher spectrum performances in terms of flatness, output peak power, and S-OSNR must be considered for MBRFL with 10 GHz spacing. However, the problem associated with the narrow wavelength spacing can be addressed by the development of MBRFL with wider spacing between BSL. In the earlier work [31], a MBRFL in a ring cavity with 22 GHz wavelength spacing is reported which is able to produce only 16 lines with a 11.7 dB S-OSNR. Although a MBRFL with double wavelength spacing has been realized, the exploitation of higher wavelength numbers with wider bandwidths and average excellent S-OSNR have been rarely demonstrated. Therefore, an alternative setup that improves MBRFL performance with double wavelength spacing (20 GHz) is also preferable. In this thesis, two different linear

cavity configurations are designed to achieve this objective. Moreover, in order to provide design flexibility and functionality, it is desirable to demonstrate a MBRFL source with an adjustable wavelength spacing (10 and 20 GHz spacing) with excellent performances to be more feasible for DWDM systems. Because the current DWDM systems have different channels spacing based on their specific applications. To achieve this, a new cavity design of MBRFL that utilizes a nonlinear amplifying fiber loop (NAFL) is proposed. In addition, further advancement in this cavity is performed as an alternative source for generation of MBRFL with 10 GHz spacing. The advantages of developing this configuration are due to its operation at very low Raman pump power (RPP) which permits the generation of multiple Brillouin Stokes signals (MBSS) with good performances.

1.3 Problem Statements

Even though MBRFL is an excellent approach to generate hundreds of Stokes line, it still has the following problems,

i. Lower value of S-OSNR for both 10 and 20 GHz spacing.
ii. Multi-frequency pump sources or multi-gain media requirement when high count, flattened multi-Stokes lines are needed.
iii. There is no report on generating MBRFL with adjustable wavelength spacing.
iv. Generation of a few MBSS with 10 GHz spacing and acceptable OSNR are achieved at the expense of high RPP and complex design.
v. There is no study on generation of 20 GHz MBRFL with higher number of channels and good S-OSNR values reported.

In addition, an amplified spontaneous emission (ASE) noise and spectral broadening are two main drawbacks which impact on the MBRFL spectrum performances in terms of SLC and S-OSNR. In this doctoral research, all the aforementioned issues are addressed in the linear cavity MBRFL.

1.4 Objectives of This Research Work

Based on the problem statements stated in the earlier sections, there are some objectives needed to be realized and fulfilled in this research. The statements below are the objectives that are going to be achieved:

i. To design a new MBRFL configuration with adjustable wavelength spacing (10 and 20 GHz spacing) with high number of channels and S-OSNR using only a single Raman pump source.
ii. To design and develop a simple MBRFL with 10 GHz spacing with ability of generating MBSS at very low RPP.
iii. To design and develop a simple MBRFL source with a 20 GHz spacing and enhance its spectral combs in terms of SLC, S-OSNR, SPP, and wavelength operation.

1.5 Scope of Research Work

Figure 1.1 shows the scope of works covered in this doctoral research. This work focuses on the MBRFL, which can be divided based on the wavelength spacing. The objective of this thesis is to propose and demonstrate simple configurations for MBRFL with single and double Brillouin frequency spacing shift. However, the main motivation is to design configurations for generating MBRFL with 20 GHz spacing. In this work, all configurations are based on linear cavity due to many advantages such as higher numbers of channels, wider multi-wavelength bandwidth, and higher S-OSNR in comparison with the ring cavity structures. A new structure for MBRFL with an adjustable 10 and 20 GHz spacing is realized by employing an enhanced NAFL design. Moreover, generation of more channels number with a reasonable S-OSNR at very low RPP has been successfully achieved by employing a mirror at the end of the NAFL design which dubbed as a nonlinear amplifying loop mirror (NALM). In addition, utilizing forward pumping (FWP) scheme and a new structure which involves various pump power distributions in forward-backward directions named as a bidirectional pumping (BiDP) scheme is also proposed. In all configurations, by varying the Brillouin pump (BP) power, BP wavelength, and RPP, their detail performances; namely SLC, wavelength operation, spectral combs and S-OSNRs are analyzed thoroughly. Finally, the output of the proposed architectures is compared to the prior works in terms of the SLC, S-OSNR, Stokes peak power (SPP), and RPP.

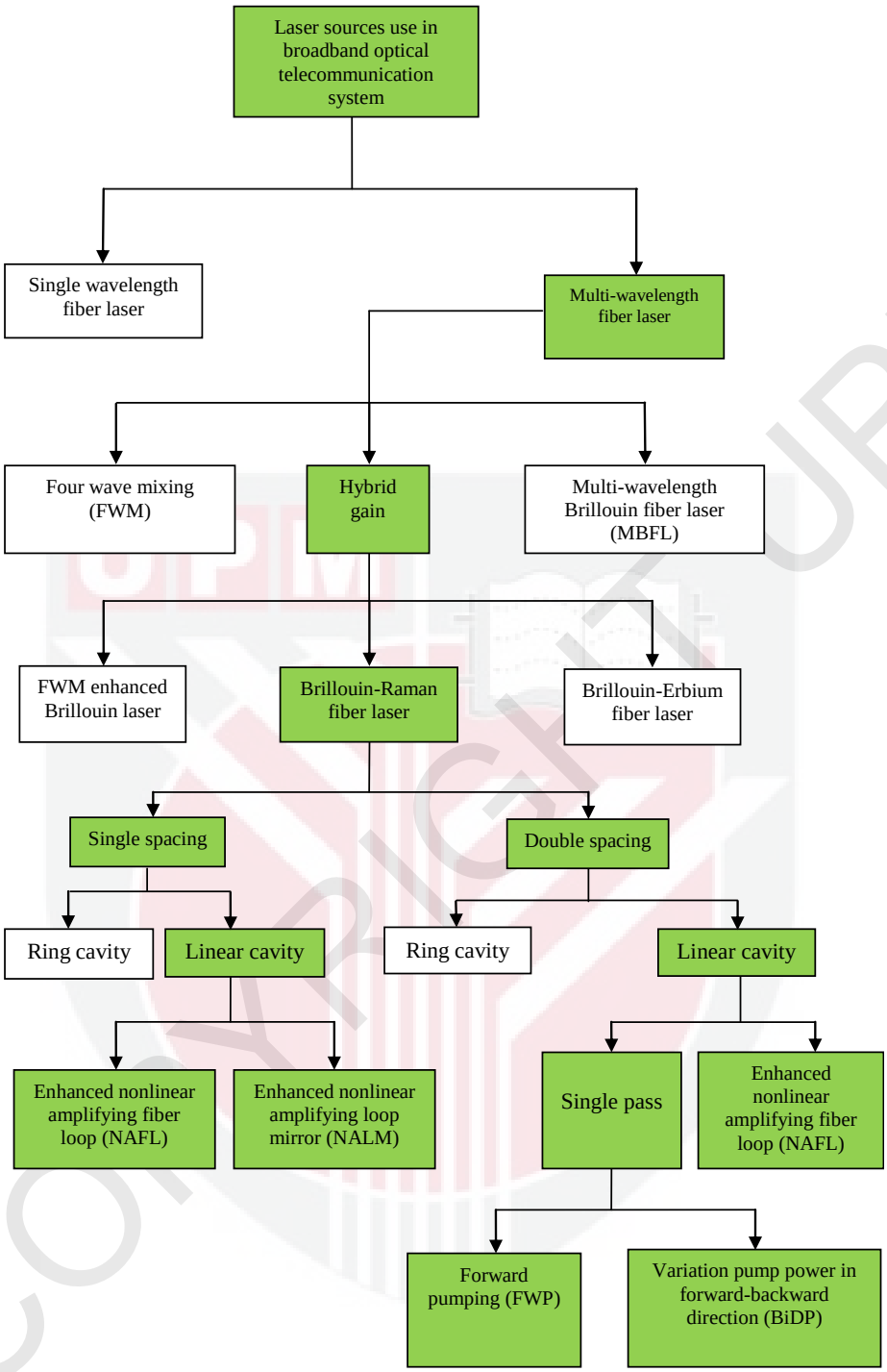

Figure 1.1: Scope of doctoral research.

1.6 Research Methodology

The methodology of this research is presented in Figure 1.2. Briefly, the thesis works are conducted through an experimental process that involves analysis of the optical parameters of generated MBSS as SLC, S-OSNR, SPP, and wavelength operation. Three main architectures are investigated which include enhanced NAFL and NALM designs in Chapter 3 and FWP-MBRFL, and BiDP-MBRFL in Chapter

4. In Chapter 3, a new design of NAFL with different set of couplers is demonstrated to achieve adjustable 10 and 20 GHz spacing operation. To realize this, a theoretical analysis is developed first which agrees well with the experimental results. By proper adjustment of coupling ratios, and optimization of laser parameters, MBRFL with 10 and 20 GHz spacing is satisfied with good characteristics. By employing a mirror at the one end of this configuration that dubbed as a NALM, multiple channels with 10 GHz spacing and a reasonable S-OSNR at very low RPP has been successfully accomplished. In Chapter 4, a simple linear cavity configuration through FWP scheme is arranged by employing 7.2 and 11 km DCFs in addition to a 30 cm Bismuth oxide erbium-doped fiber (Bi-EDF). This is done to achieve MBRFL with 20 GHz spacing with good lasing characteristics. Although 20 GHz spacing MBSS with good features is achieved, to enhance the lasing combs characteristics in terms of SLC, S-OSNR, SPP, and wavelength operation a new configuration of BiDP that implements a variable pumping scheme in backward and forward directions is also demonstrated. This scheme offers MBRFL with 20 GHz spacing and excellent performance. For all configurations, the effect of different input parameters including BP power, BP wavelength, and RPP on output spectra are studied experimentally. The trends of the Raman gain profile before launching the BP signal into the cavity are analyzed as well. For all configurations, the SLC and S-OSNR are measured when the Brillouin pump wavelength is selected at 1555 nm, while the RPP is varied from 800 mW to 1000 mW. In addition, the optical features of generated laser comb spectrum such as SLC are investigated when the BP power is varied from -2.6 to 5 dBm when the RPP is varied from 800 to 1000 mW. The wavelength operation is also investigated for all structures. The RPP is optimized to produce a flat amplitude MBRFL comprising maximum number of channels with high S-OSNR. Consequently, the outputs of each proposed configurations are measured by optical spectrum analyser (OSA). It is noted that the threshold of first Brillouin Stokes line is measured for all configurations when the RPP, BP power and BP wavelength are set at 1000 mW, 5 dBm and 1555 nm respectively. Finally, after analyzing experimental results from all configurations, the results that meet the thesis objectives are considered.

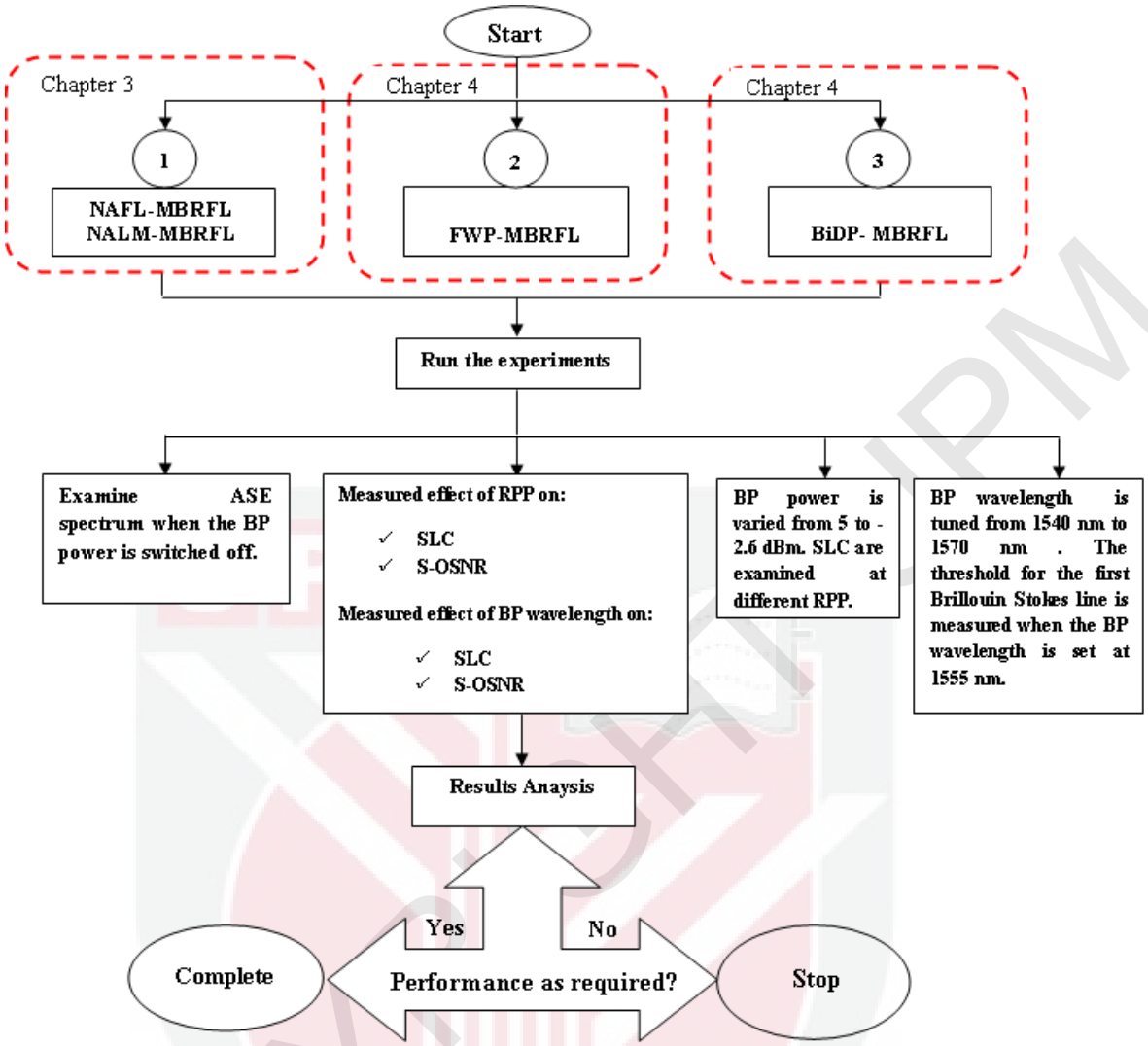

Figure 1.2: Research methodology flow-chart.

1.7 Thesis Overview

This thesis comprehensively studies the performance parameters of three proposed linear MBRFL sources, which employs dispersion compensating fiber (DCF) as the Brillouin-Raman gain medium. In general, this thesis consists of five chapters. Chapter 1, which is this current chapter, gives a general introduction of the topics and defines the context of the work.

Chapter 2 introduces an overview background on the basic concepts of nonlinear fiber optics effects and explains the theoretical backgrounds of nonlinear optical loop mirror (NOLM) and NALM. Moreover, principle operation of MBRFL generation and review of previous works on MBRFL generation is briefly discussed at the end of this chapter.

Chapter 3 proposes new configuration of NAFL for generating MBRFL with adjustable wavelength spacing. It started with the theoretical analysis of the NALM.

Afterward, experimental results are explained where good agreement is found with the theoretical results. The spectral characteristics of this cavity at optimized coupling ratios are studied thoroughly. In addition, by employing a mirror at one end of the NAFL design, generating a high number of lasing lines with a reasonable S-OSNR at very low RPP has been successfully satisfied.

Chapter 4 is devoted to the generation of MBRFL with 20 GHz spacing which includes two linear cavities through FWP and BiDP schemes. The setup implemented via FWP scheme arranged with different DCF lengths in addition to a 30 cm Bi-EDF. The influences of varying several parameters such as RPP, BP power, and BP wavelength on spectra features of all cavity arrangements are studied thoroughly. In order to enhance the characteristics of MBSS in terms of SLC, SPP, and wavelength operation, a simple configuration by employing various coupling ratios is constructed to provide different pump power distributions along the fiber longitudinal structure. By optimization pumping ratios, and BP characteristics, the lasing characteristics are improved. This scheme strongly offers a few advantages specially enhanced feasibility and simplicity due to the utilization of only one RPU.

The finding of this work is summarized and concluded in Chapter 5. The performances of the proposed configurations in contrast to each other and prior works are detailed in this chapter. Moreover, it includes the contribution of this thesis and the recommendation for further research work is also presented in this chapter.

REFERENCES

[1] M. Yamada, "Overview of wideband optical fiber amplification technologies," *NTT Tech. Rev.*, vol. 2, pp. 34-37, 2004.

[2] J. Hecht, "The First Half-Century of Laser Development," *Laser Tech.*, vol. 7, pp. 20-25, 2010.

[3] J. Geng, *et al.*, "Highly stable low-noise Brillouin fiber laser with ultranarrow spectral linewidth," *IEEE Photon. Technol. Lett.*, vol. 18, pp. 1813-1815, 2006.

[4] R. Parvizi, *et al.*, "Multi-wavelength Brillouin fiber laser using dual-cavity configuration," *Laser Phys.*, vol. 21, pp. 205-209, 2011.

[5] Q. Mao and J. W. Y. Lit, "Switchable multi-wavelength erbium-doped fiber laser with cascaded fiber grating cavities," *IEEE Photon.Technol. Lett.*, vol. 14, pp. 612-614, 2002.

[6] S. W. Harun, *et al.*, "Mult-wavelength erbium-doped fiber laser assisted by four wave mixing effect," *Laser Phys. Lett.*, vol. 6, pp. 813-815, 2009.

[7] Y.-G. Han, *et al.*, "Multi-wavelength Raman fiber-ring laser based on tunable cascaded long-period fiber gratings," *IEEE Photon.Technol. Lett.*, vol. 15, pp. 383-385, 2003.

[8] A. K. Abeeluck, *et al.*, "High-power supercontinuum generation in highly nonlinear, dispersion-shifted fibers by use of a continuous-wave Raman fiber laser," *Opt. Lett.*, vol. 29, pp. 2163-2165, 2004.

[9] W. Guan and J. R. Marciante, "Dual-frequency operation in a short-cavity ytterbium-doped fiber laser," *IEEE Photon. Technol. Lett.*, vol. 19, pp. 261-263, 2007.

[10] Z. Zhang, *et al.*, "Tunable self-seeded multi-wavelength Brillouin-erbium fiber laser with enhanced power efficiency," *Opt. Express*, vol. 15, pp. 9731-9736, 2007.

[11] Y. J. Song, *et al.*, "Tunable multi-wavelength Brillouin-erbium fiber laser with a polarization-maintaining fiber Sagnac loop filter," *IEEE Photon. Technol. Lett.*, vol. 16, pp. 2015-2017, 2004.

[12] M. H. Al-Mansoori and M. A. Mahdi, "Tunable range enhancement of Brillouin-erbium fiber laser utilizing Brillouin pump preamplification technique," *Opt. Express*, vol. 16, pp. 7649-7654, 2008.

[13] M. H. Al-Mansoori and M. A. Mahdi, "Multi-wavelength L-band Brillouin-Erbium comb fiber laser utilizing nonlinear amplifying loop mirror," *J. Lightwave Technol.*, vol. 27, pp. 5038-5044, 2009.

[14] Y. G. Shee, *et al.*, "Multi-wavelength Brillouin-erbium fiber laser with double-Brillouin-frequency spacing," *Opt. Express*, vol. 19, pp. 1699-1706, 2011.

[15] M. Ajiya, *et al.*, "Broadly tunable multiple wavelength Brillouin fiber laser exploiting erbium amplification," *J. Opt. Soc. Am. B.*, vol. 26, pp. 1789-1794, 2009.

[16] Y. J. Song, *et al.*, "Self-seeded multi-wavelength Brillouin-erbium fiber laser," *Opt. Lett.*, vol. 30, pp. 486-488, 2005.

[17] B. Min, *et al.*, "Flat amplitude equal spacing 798-channel Rayleigh-assisted Brillouin-Raman multi-wavelength comb generation in dispersion

compensating fiber," *IEEE Photon. Technol. Lett.*, vol. 13, pp. 1352-1354, 2001.
[18] K.-D. Park, *et al.*, "Dynamics of cascaded Brillouin-Rayleigh scattering in a distributed fiber Raman amplifier," *Opt. Lett.*, vol. 27, pp. 155-157, 2002.
[19] K.-d. Park, *et al.*, "Threshold features of a Brillouin Stokes comb generated in a distributed fiber Raman amplifier," *Opt. Lett.*, vol. 28, pp. 1311-1313, 2003.
[20] Y.-g. Liu, *et al.*, "Stable room-temperature multi-wavelength lasing oscillations in a Brillouin-Raman fiber ring laser," *Opt. Commun.*, vol. 281, pp. 5400-5404, 2008.
[21] J. W. Lou, *et al.*, "Brillouin fibre laser enhanced by Raman amplification," *Electron. Lett.*, vol. 40, pp. 1044-1046, 2004.
[22] A. K. Zamzuri, *et al.*, "Brillouin-Raman comb fiber laser with cooperative Rayleigh scattering in a linear cavity," *Opt. Lett.*, vol. 31, pp. 918-920, 2006.
[23] A. K. Zamzuri, *et al.*, "Flat amplitude multi-wavelength Brillouin-Raman comb fiber laser in Rayleigh-scattering-enhanced linear cavity," *Opt. Express*, vol. 15, pp. 3000-3005, 2007.
[24] A. K. Zamzuri, *et al.*, "Contribution of Rayleigh scattering on Brillouin comb line generation in Raman fiber laser," *Appl. Opt.*, vol. 49, pp. 3506-3510, 2010.
[25] A. K. Zamzuri, *et al.*, "OSNR variation of multiple laser lines in Brillouin-Raman fiber laser," *Opt. Express*, vol. 17, pp. 16904-16910, 2009.
[26] A. K. Zamzuri, *et al.*, "Spectral variation in Brillouin-Raman fiber laser," in *Communications and Photonics Conference and Exhibition (ACP)* 2009, pp. 1-2.
[27] H. Wu, *et al.*, "Flat amplitude multi-wavelength Brillouin–Raman random fiber laser with a half-open cavity," *Appl. Phys. B.*, vol. 112, pp. 467-471, 2013.
[28] R. Sonee Shargh, *et al.*, "OSNR enhancement utilizing large effective area fiber in a multi-wavelength Brillouin-Raman fiber laser," *Laser Phys. Lett.*, vol. 8, pp. 139-143, 2011.
[29] R. S. Shargh, *et al.*, "Improvement of comb lines quality employing double-pass architecture in Brillouin-Raman laser," *Laser Phys. Lett.*, vol. 8, pp. 823-827, 2011.
[30] Z. Wang, *et al.*, "Broadband flat-amplitude multi-wavelength Brillouin-Raman fiber laser with spectral reshaping by Rayleigh scattering," *Opt. Express*, vol. 21, pp. 29358-29363, 2013.
[31] N. A. M. A. Hambali, *et al.*, "Multi-wavelength Brillouin-Raman ring-cavity fiber laser with 22-GHz spacing," *Laser Phys.*, vol. 21, pp. 1656-1660, 2011.
[32] M. F. Ferreira, *Nonlinear effects in optical fibers* vol. 2: John Wiley & Sons, 2011.
[33] Q. Lin, *et al.*, "Nonlinear optical phenomena in silicon waveguides: modeling and applications," *Opt. Express*, vol. 15, pp. 16604-16644, 2007.
[34] J. Hecht and L. Long, *Understanding fiber optics*: Prentice Hall Upper Saddle River, NJ, 2002.
[35] G. P. Agrawal, *Nonlinear fiber optics*: Academic press, 2007.
[36] Y.-R. Shen, "The principles of nonlinear optics," *New York, Wiley-Interscience*, 1984.

[37] E. L. Buckland and R. W. Boyd, "Electrostrictive contribution to the intensity-dependent refractive index of optical fibers," *Opt. Lett.*, vol. 21, pp. 1117-1119, 1996.
[38] N. J. Doran and D. Wood, "Nonlinear-optical loop mirror," *Opt. Lett.*, vol. 13, pp. 56-58, 1988.
[39] G. New, *Introduction to Nonlinear Optics*: Cambridge University Press, 2011.
[40] R. W. Boyd, *Nonlinear optics*: Academic press, 2003.
[41] B. Batagelj, *et al.*, "Use of four-wave mixing in optical fibers for applications in transparent optical networks," in *Proceedings of 6th International Conference on Transparent Optical Networks*, 2004, pp. 215-220.
[42] I. Neokosmidis, *et al.*, "New techniques for the suppression of the four-wave mixing-induced distortion in nonzero dispersion fiber WDM systems," *J. Lightwave Technol.*, vol. 23, pp. 1137 - 1144, 2005.
[43] R. Tkach, *et al.*, "Four-photon mixing and high-speed WDM systems," *J. Lightwave Technol.*, vol. 13, pp. 841-849, 1995.
[44] S. A. Babin, *et al.*, "Four-wave-mixing-induced turbulent spectral broadening in a long Raman fiber laser," *J .Opt.Soc. Am. B.*, vol. 24, pp. 1729-1738, 2007.
[45] J. Hagen, *et al.*, "Numerical modeling of intracavity spectral broadening of Raman fiber lasers," *IEEE Photon. Technol. Lett.*, vol. 19, pp. 1759-1761, 2007.
[46] S. P. Singh and N. Singh, "Nonlinear effects in optical fibers: Origin, management and applications," *Prog. Electromagn Res.*, vol. 73, pp. 249-275, 2007.
[47] E. P. Ippen and R. H. Stolen, "Stimulated Brillouin scattering in optical fibers," *Appl. Phys. Lett.*, vol. 21, pp. 539-541, 1972.
[48] S. W. Harun, *et al.*, "Multi-wavelength source using a Brillouin fiber laser," *J. Nonlinear Opt. Phys.* , vol. 17, pp. 199-203, 2008.
[49] P. T. Rakich, *et al.*, "Giant enhancement of stimulated Brillouin scattering in the subwavelength limit," *Phys. Rev. X.*, vol. 2, pp. 011008-, 2012.
[50] K. Shiraki, *et al.*, "SBS threshold of a fiber with a Brillouin frequency shift distribution," *J. Lightwave Technol.*, vol. 14, pp. 50-57, 1996.
[51] R. H. Stolen, *et al.*, "Raman oscillation in glass optical waveguide," *Appl. Phys. Lett.*, vol. 20, pp. 62-64, 1972.
[52] C. Headley and G. Agrawal, *Raman amplification in fiber optical communication systems*: Academic Press, 2005.
[53] S. Namiki, *et al.*, "Challenges of Raman amplification," *IEEE. Proc.*, vol. 94, pp. 1024-1035, 2006.
[54] R. G. Smith, "Optical power handling capacity of low loss optical fibers as determined by stimulated Raman and Brillouin scattering," *Appl. Opt.*, vol. 11, pp. 2489-2494, 1972.
[55] J. Bromage, *et al.*, "Raman Amplifiers and Oscillators in Telecommunications," *MN Islam, Springer Verlag*, 2003.
[56] G. Agrawal, *Applications of nonlinear fiber optics*: Access Online via Elsevier, 2001.
[57] B. Nelson, *et al.*, "All-optical Gbit/s switching using nonlinear optical loop mirror," *Electron. Lett.*, vol. 27, pp. 704-705, 1991.
[58] M. E. Fermann, *et al.*, "Nonlinear amplifying loop mirror," *Opt. Lett.*, vol. 15, pp. 752-754, 1990.

[59] D. J. Richardson, *et al.*, "Very low threshold Sagnac switch incorporating an erbium doped fibre amplifier," *Electron. Lett.*, vol. 26, pp. 1779-1781, 1990.
[60] Y.-G. Han, *et al.*, "Multi-wavelength Raman-fiber-laser-based long-distance remote sensor for simultaneous measurement of strain and temperature," *Opt. Lett.*, vol. 30, pp. 1282-1284, 2005.
[61] S. Pan and J. Yao, "Frequency-switchable microwave generation based on a dual-wavelength single-longitudinal-mode fiber laser incorporating a high-finesse ring filter," *Opt. Express*, vol. 17, pp. 12167-12173, 2009.
[62] Y.-G. Han, *et al.*, "Wavelength-spacing tunable multiwavelength erbium-doped fiber laser based on four-wave mixing of dispersion-shifted fiber," *Opt. Lett.*, vol. 31, pp. 697-699, 2006.
[63] X. Feng, *et al.*, "Stable and uniform multi-wavelength erbium-doped fiber laser using nonlinear polarization rotation," *Opt. Express*, vol. 14, pp. 8205-8210, 2006.
[64] Z. Zhang, *et al.*, "Multi-wavelength fiber laser with fine adjustment, based on nonlinear polarization rotation and birefringence fiber filter," *Opt. Lett.*, vol. 33, pp. 324-326, 2008.
[65] L. Zhan, *et al.*, "160-line multi-wavelength generation of linear-cavity self-seeded Brillouin-erbium fiber laser," *Opt. Express*, vol. 14, pp. 10233-10238, 2006.
[66] A. Loayssa, *et al.*, "Applications of optical carrier Brillouin processing to microwave photonics," *Opt. Fiber Technol.*, vol. 8, pp. 24-42, 2002.
[67] Z. Y. Liu, *et al.*, "Tunable multi-wavelength erbium-doped fiber laser with a polarization-maintaining photonic crystal fiber Sagnac loop filter," *Laser Phys. Lett.*, vol. 5, pp. 446-448, 2008.
[68] S. Pan, *et al.*, "Multi-wavelength erbium-doped fiber laser based on inhomogeneous loss mechanism by use of a highly nonlinear fiber and a Fabry-Perot filter," *Opt. Express*, vol. 14, pp. 1113-1118, 2006.
[69] J. Tang, *et al.*, "Tunable multi-wavelength generation based on Brillouin-erbium comb fiber laser assisted by multiple four-wave mixing processes," *Opt. Express*, vol. 19, pp. 14682-14689, 2011.
[70] M. R. Shirazi, *et al.*, "Multi-wavelength Brillouin-Raman fiber laser generation assisted by multiple four-wave mixing processes in a ring cavity," *Laser Phys.*, vol. 23, pp. 075108-075116, 2013.
[71] N. Ahmad Hambali, *et al.*, "Singlewavelength ring-cavity Brillouin-Raman fiber laser," *Laser Phys. Lett.*, vol. 7, pp. 454-457, 2010.
[72] N. Ahmad Hambali, *et al.*, "L-band multi-wavelength Brillouin–Raman fiber laser utilizing the reverse-S-shaped section," *J. Nonlinear Opt. Phys. Mat.*, vol. 23, pp. 1450026 -1450036, 2014.
[73] Z. Zhang, *et al.*, "Research of distributed optical fiber Raman gain amplifier," in *Asia-Pacific Optical and Wireless Communications Conference and Exhibit*, 2001, pp. 54-56.
[74] L. L Grüner-Nielsen, *et al.*, "Dispersion compensating fibers," *Opt. Fiber Technol.*, vol. 6, pp. 164-180, 2000.
[75] A. K. Abass, *et al.*, "Characteristics of multi-wavelength L-band Brillouin-Raman fiber laser under forward and backward pumped environment," *Appl. Opt.*, vol. 52, pp. 3764-3769, 2013.
[76] H.-P. Gong and Z.-X. Zhang, "The Amplification Effect on Rayleigh Scattering and SBS in 25Km distributed fiber Raman Amplifier," in *Optical Fiber Sensors Conference*, 2008, pp. 1-4.

[77] M. Pang, *et al.*, "Rayleigh scattering-assisted narrow linewidth Brillouin lasing in cascaded fiber," *Opt. Lett.*, vol. 37, pp. 3129-3131, 2012.
[78] M. Mehendale, *et al.*, "Effect of Raman amplification on stimulated Brillouin scattering threshold in dispersion compensating fibres," *Electron. Lett.*, vol. 38, pp. 268-269, 2002.
[79] M. R. Shirazi, *et al.*, "Effects of different Raman pumping schemes on stimulated Brillouin scattering in a linear cavity," *Appl. Opt.*, vol. 47, pp. 3088-3091, 2008.
[80] A. Kobyakov, *et al.*, "Stimulated Brillouin scattering in Raman-pumped fibers: A theoretical approach," *J. Lightwave Technol.*, vol. 20, pp. 1635-1643, 2002.
[81] S. P. N. Cani, *et al.*, "Raman amplifier performance of dispersion compensating fibers," in *Microwave and Optoelectronics Conference* 2003, pp. 553-558.
[82] M. Mehendale, *et al.*, "Stimulated Brillouin scattering in Raman-amplified dispersion compensating fibers," in *Optical Fiber Communication Conference and Exhibit, OFC*, 2002, pp. 560-561.
[83] S. Boscolo, *et al.*, "Design of Raman-based nonlinear loop mirror for all-optical 2R regeneration of differential phase-shift-keying transmission," *IEEE J. Quantum Electron.*, vol. 42, pp. 619-624, 2006.
[84] J. Bromage, "Raman amplification for fiber communications systems," *J. Lightwave Technol.*, vol. 22, pp. 79-, 2004.
[85] Y. K. Kwok, *Applied complex variables for scientists and engineers*, Taylor & francis ed.: Cambridge University Press, 2002.
[86] H. S. Kasana, *Complex variables: theory and applications*: PHI Learning Pvt. Ltd., 2005.
[87] S. G. Krantz, *Function theory of several complex variables*: Wiley New York, 1982.
[88] R. S. Shargh, *et al.*, "Effect of Raman pump direction on conventional multi-wavelength Brillouin-Raman fiber laser," in *3rd International Conference on Photonics (ICP)*, 2012, pp. 184-186.
[89] S. A. Babin, *et al.*, "Turbulence-induced square-root broadening of the Raman fiber laser output spectrum," *Opt. Lett.*, vol. 33, pp. 633-635, 2008.
[90] S. A. Babin, *et al.*, "Turbulent broadening of optical spectra in ultralong Raman fiber lasers," *Phys. Rev. A.*, vol. 77, pp. 0338031-0338035, 2008.
[91] S. Ohara and Y. Kuroiwa, "Highly ytterbium-doped bismuth-oxide-based fiber," *Opt. Express*, vol. 17, pp. 14104-14108, 2009.
[92] H. Ahmad, *et al.*, "Bismuth-based erbium-doped fiber as a gain medium for L-band amplification and Brillouin fiber laser," *Laser Phys.*, vol. 20, pp. 716-719, 2010.
[93] Y. Fujimoto and M. Nakatsuka, "Optical amplification in bismuth-doped silica glass," *Appl. Phys. Lett.*, vol. 82, pp. 3325-3326, 2003.
[94] Z. Tong, *et al.*, "Theoretical investigation and optimization of bi-directionally pumped broadband fiber Raman amplifiers," *Opt. Commun.*, vol. 217, pp. 401-413, 2003.
[95] J. C. Bouteiller, *et al.*, "Dual-order Raman pump," *IEEE Photon. Technol. Lett.*, vol. 15, pp. 212-214, 2003.
[96] J. Bromage, *et al.*, "WDM transmission over multiple long spans with bidirectional Raman pumping," *J. Lightwave Technol.*, vol. 22, pp. 225-232, 2004.