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Department of Electrical-Electronic Engineering

WIDELY FIBER LASER COMB BANDWIDTH BASED ON FOUR WAVE MIXING PROCESS ASSISTED BY MULTIWAVELENGTH BRILLOUIN ERBIUM FIBER LASER

Master Thesis

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Supervisor
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Yoğun Dalga Boyu Bölmeli Çoğullama (DWDM) iletişim sistemlerinde, çok dalga boylu Brillouin fiber lazer (MBFL) ve çok dalga boylu Brillouin erbium fiber lazer (MBEFL), yoğun lazer dalga boyu aralığı sağlaması nedeniyle önemli optik kaynaklardır. Uyarılmış Brillouin saçılması (SBS) ve dört dalgalı karıştırma (FWM) gibi çok dalga boyu üretimi elde etmek için birçok teknik gösterilmiştir. BEFL ve FWM'yi aynı boşlukta birleştirmek, oluşturulan çok dalga boylu stokes hatlarının sayısını artırır ve ayarlanabilirliği iyileştirir. Bununla birlikte, boşluk içinde faz uyumunu sağlamanın zorluğu ve optik güç bileşenlerinin sınırlamaları, üretilen lazer çizgilerinin ayarlanabilirliğini ve sayısını azaltır. Bu nedenle, bu sorunu önlemek için, FWM etkisinin kavite dışında gerçekleşmesi gerekir. Bu tezde, Brillouin Stokes çizgileri ile güçlendirilmiş dört dalgalı karıştırma tarafından oluşturulan geniş bir Çok Dalga Boylu fiber lazer deneysel olarak sunulmaktadır. İç boşluk, doğrusal boşluk ve boşluktan çoklu dört dalgalı karıştırma deneyimleri içinde art arda uyarılmış Brillouin saçılmasının iki doğrusal olmayan fenomenini birleştirir. Brillouin kazancını artırmak ve lazer tarak ayarlanabilirliğini iyileştirmek için boşluk içinde yüksek BP gücü ve ön amplifikasyon tekniği uygulanır. Ek olarak, geniş bir ayarlanabilirlik elde etmek için dört dalgalı karıştırma tarafında geniş bir emisyon tepe noktası olan C+L'ye sahip erbiyum katkılı bir fiber kullanılır. Sonuçlar, Brillouin Stokes hatlarının FWM'ye yardımı nedeniyle üretilen Stokes hatlarının sayısının etkin bir şekilde arttığını göstermektedir. 0.075 nm'lik tek bir Brillouin boşluğu ile 1580 nm'lik L-bant bölgesinde 9 nm spektral aralık içinde 120'ye kadar Stokes hattı elde edilir. 1550 ile 1600 nm arasında 50 nm'lik ayarlanabilir bir aralık kaydedilir.

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Istanbul – 2022

DECLARATION

I hereby declare that in the preparation of this thesis, scientific ethical rules have been followed, the works of other persons have been referenced in accordance with the scientific norms if used, there is no falsification in the used data, any part of the thesis has not been submitted to this university or any other university as another thesis.

Sumaya Muneer Jasim AL-DALWASH

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The thesis study of Sumaya Muneer Jasim AL-DALWASH titled as WIDELY FIBER LASER COMB BANDWIDTH BASED ON FOUR WAVE MIXING PROCESS ASSISTED BY MULTIWAVELENGTH BRILLOUIN ERBIUM FIBER LASER has been accepted as MASTER THESIS in the department of ELECTRICAL-ELECTRONIC ENGINEERING by out jury.

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Director of the Institute

SUMMARY

In dense wavelength division multiplexing (DWDM) communication systems, the multiwavelength Brillouin fiber laser (MBFL) and multiwavelength Brillouin erbium fiber laser (MBEFL) are essential optical sources due to providing dense laser wavelength spacing. Many techniques are demonstrated to achieve multiwavelength generation, such as stimulated Brillouin scattering (SBS) and four-wave mixing (FWM). Combining BEFL and FWM in the same cavity increases the number of the generated multiwavelength stokes lines and improves tunability. However, the difficulty of achieving the phase-matching inside the cavity and the limitations of the optical power components reduce the tunability and number of generated laser lines. So, to avoid this problem, the FWM effect should occur outside the cavity. A broadly Multiwavelength fiber laser created by Brillouin stokes lines boosted four-wave mixing is experimentally presented in this thesis. It combines two nonlinear phenomena of successive stimulated Brillouin scattering within the internal cavity, linear cavity, and the multiple four-wave mixing experiences out of the cavity. The high BP power and pre-amplification technique are implemented inside the cavity in order to enhance the Brillouin gain and improve the laser comb tunability. In addition, an erbium-doped fiber with a broad emission peak, C+L, is used in the four-wave mixing side to achieve tunability widely. The results show that the number of the generated stokes lines is effectively enhanced due to the Brillouin stokes lines' assistance to the FWM. Up to 120 stokes lines within 9 nm spectral range in the L-band region of 1580 nm with a single Brillouin space of 0.075 nm are achieved. A tunable span of 50 nm from 1550 to 1600 nm is recorded.

Keywords : Brillouin Erbium Fiber Laser, Four wave mixing (FWM), Highly Nonlinear Fiber (HNLA).

ÖZET

Yoğun Dalga Boyu Bölmeli Çoğullama (DWDM) iletişim sistemlerinde, çok dalga boylu Brillouin fiber lazer (MBFL) ve çok dalga boylu Brillouin erbium fiber lazer (MBEFL), yoğun lazer dalga boyu aralığı sağlaması nedeniyle önemli optik kaynaklardır. Uyarılmış Brillouin saçılması (SBS) ve dört dalgalı karıştırma (FWM) gibi çok dalga boyu üretimi elde etmek için birçok teknik gösterilmiştir. BEFL ve FWM'yi aynı boşlukta birleştirmek, oluşturulan çok dalga boylu stokes hatlarının sayısını artırır ve ayarlanabilirliği iyileştirir. Bununla birlikte, boşluk içinde faz uyumunu sağlamanın zorluğu ve optik güç bileşenlerinin sınırlamaları, üretilen lazer çizgilerinin ayarlanabilirliğini ve sayısını azaltır. Bu nedenle, bu sorunu önlemek için, FWM etkisinin kavite dışında gerçekleşmesi gerekir. Bu tezde, Brillouin Stokes çizgileri ile güçlendirilmiş dört dalgalı karıştırma tarafından oluşturulan geniş bir Çok Dalga Boylu fiber lazer deneysel olarak sunulmaktadır. İç boşluk, doğrusal boşluk ve boşluktan çoklu dört dalgalı karıştırma deneyimleri içinde art arda uyarılmış Brillouin saçılmasının iki doğrusal olmayan fenomenini birleştirir. Brillouin kazancını artırmak ve lazer tarak ayarlanabilirliğini iyileştirmek için boşluk içinde yüksek BP gücü ve ön amplifikasyon tekniği uygulanır. Ek olarak, geniş bir ayarlanabilirlik elde etmek için dört dalgalı karıştırma tarafında geniş bir emisyon tepe noktası olan C+L'ye sahip erbiyum katkılı bir fiber kullanılır. Sonuçlar, Brillouin Stokes hatlarının FWM'ye yardımı nedeniyle üretilen Stokes hatlarının sayısının etkin bir şekilde arttığını göstermektedir. 0.075 nm'lik tek bir Brillouin boşluğu ile 1580 nm'lik L-bant bölgesinde 9 nm spektral aralık içinde 120'ye kadar Stokes hattı elde edilir. 1550 ile 1600 nm arasında 50 nm'lik ayarlanabilir bir aralık kaydedilir.

Anahtar Kelimeler : Brillouin Erbium Fiber Lazer, Dört dalga karıştırma (FWM), Yüksek Düzeyde Doğrusal Olmayan Fiber (HNLA).

TABLE OF CONTENTS

SUMMARY i
ÖZET ii
TABLE OF CONTENTS iii
ABBREVIATIONS vii
LIST OF TABLES viii
LIST OF FIGURES ix
PREFACE x
INTRODUCTION 1

CHAPTER ONE

PURPOSE OF THE THESIS

1.1. Background 3
1.2. Problem Statement 4
1.3. Objectives of this Study 5
1.4. The work's Scope 5
1.5. Thesis Layout 6

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1. Nonlinear Phenomena in Optical Fiber 8
2.2. Stimulated Brillouin Scattering 10
2.2.1. Principles of Stimulated Brillouin Scattering 10
2.2.2. Stimulated Brillouin scattering fundamentals 11
2.3. Four Wave Mixing 14
2.3.1. Four Wave Mixing Principles 14
2.3.2. Four Wave Mixing (FWM) Signal Generation 15
2.3.3. Previous Works of Four Wave Mixing (FWM) 18

2.4. Phase matching 18
2.5. Type of Optical Fibers 20
2.6. Multi-wavelength Fiber Laser (MFL) 21
2.7. Review on Multi-wavelength Brillouin Erbium Fiber Laser 21
2.8. Review on using Highly Non-Linear Fiber 25

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Introduction 29
3.2. General Flow of Designing a Multi-wavelength Fiber Laser 29
3.3. Equipment and Components 30
3.4. General Research Methodology 33

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1. Introduction 36
4.2. Experimental Setup 36
4.3. Results and Discussions 37
4.3.1. The Generated Stokes Lines Enhancement 37
4.3.2. Improving Tunability 42
4.4. Results Comparison 46

CHAPTER FIVE

CONCLUSIONS AND FUTURE WORK

5.1. Conclusion 47
5.2. Recommendation for further work 47

REFERENCES 49

ABBREVIATIONS

BEFL	**:**	Brillouin Erbium Fiber Laser
BFL	**:**	Brillouin Fiber Laser
BP	**:**	Brillouin Pump
DCF	**:**	Dispersion Compensation Fiber
DWDM	**:**	Dense Wavelength Division Multiplexing
EDF	**:**	Erbium Doped Fiber
EDFA	**:**	Erbium Doped Fiber Amplifier
EDFL		Erbium Doped Fiber Laser
FWM	**:**	Four Wave Mixing
HNLF	**:**	Highly Nonlinear Fiber
ISO	**:**	Optical Isolator
MBEFL	**:**	Multiwavelength Brillouin Erbium Fiber Laser
MBFL	**:**	Multiwavelength Brillouin Fiber Laser
MDM	**:**	Mode Division Multiplexing
MFL	**:**	Multi-wavelength Fiber Laser
OSA	**:**	Optical Spectrum Analyzer
OSNR	**:**	Optical Signal to Noise Ratio
PC	**:**	Polarization Controller

PCF	**:**	Photonic Crystal Fiber
SBS	**:**	Stimulated Brillouin Scattering
SMF	**:**	Single Mode Fiber
SRS	**:**	Stimulated Raman Scattering
TLS	**:**	Tunable Laser Source
WDM	**:**	Wave Division Multiplexing

LIST OF TABLES

Table 1. Components and equipment used in the experimental study 31

Table 2. The comparison of setups performance 46

LIST OF FIGURES

Figure 1. Flow chart of the proposed study. 6

Figure 2. Nnonlinear effects in fiber optics 9

Figure 3. Brillouin pump depletion and the process of stokes signal generation 10

Figure 4. A high level explanation of SBS in optical fibers. 12

Figure 5. The interaction among the BP, Stokes field and acoustic wave in SBS….13

Figure 6. four- wave mixing with (a) nondegenerate and (b) degenerate. 14

Figure 7. General flow of designing a multi-wavelength fiber laser 30

Figure 8. General research flowchart. 35

Figure 9. The proposed setup of combination BEFL cavity and FWM block. 37

Figure 10. The free running modes 38

Figure 11. BEFL spectra for different 1480 nm pump powers and b) output spectra after FWM blook versus 1480 nm pump powers. 40

Figure 12. a) The output spectra at different BP power and optimal pump power of 500 mW b) output spectra after FWM block. 42

Figure 13. Fiber laser spectra at various BP wavelength at the optimum values of BP and 1480 nm pump power. 43

Figure 14. Output fiber laser spectra at different BP wavelength within tuning range band of 50 nm.. 44

Figure 15. The output spectra at the optimal conditions: a) Brillouin Stokes lines without FWM block, b) fiber laser in the presence of FWM block. 45

PREFACE

During this thesis's preparation and writing process, I would like to thank my esteemed professor Assoc. Prof. Dr. Indrit MYDERRİZİ and Assoc. Prof. Dr. THAMER FAHAD AHMED AL-MASHHADANI for their great efforts.

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INTRODUCTION

A multiwavelength fiber laser is implemented to support dense wavelength division multiplexing communication systems since it provides dense laser wavelength spacing. Many techniques are demonstrated to achieve multiwavelength generation, such as phase modulation (J. Sun, 2007), nonlinear optical mirror (Al-mansoori & Mahdi, 2009), stimulated Brillouin scattering (SBS) (Thamer Fahad Al-Mashhadani et al., 2019); (Harun et al., 2008), and four-wave mixing (FWM) (Al-Alimi et al., 2013) (Tang, Sun, Chen, et al., 2011). A combination of nonlinear SBS gain and a linear erbium-doped fiber (EDF) gain in the same cavity is reported to achieve Brillouin-erbium fiber laser (BEFL) (M. K. S. Al-Mashhadani et al., 2020); (Tiu et al., 2016); (Mohammed Hayder Al-Mansoori et al., 2009); (Thamer Fahad Al-Mashhadani et al., 2020). Low threshold power and rigid Brillouin frequency shift are the main advantages that made such fiber lasers widely available. Through decades, BEFLs have been developed using different ring and linear cavity designs (Y. ge Liu et al., 2008); (Tian et al., 2011); (T. F. Al-Mashhadani et al., 2013); (Thamer Fahad Al-Mashhadani et al., 2014). Some of these studies are conducted to enhance the laser tunability (T. F. Al-Mashhadani et al., 2013). Others are presented to enhance the number of generated stokes lines (Thamer Fahad Al-Mashhadani et al., 2014). Four wave mixing is a nonlinear phenomenon that causes both red (stokes) and blue (anti-stokes) to shift in inserted two pump signals. It is suggested as another technique to produce multiple fiber sources. Many designs combine the SBS and FWM phenomena in the same cavity to increase the number of the generated multiwavelength stokes lines (Zhou et al., 2019); (P. Wang et al., 2019). However, the limitations of the optical power components cause a reduction of the FWM occurrence and tunability efficiency. In addition, the difficulty of achieving phase matching inside the cavity leads to lower efficiency.

In this study, an MBEFL assisted FWM process by combining the stimulated Brillouin scattering and four wave mixing phenomena in one design is presented. The Brillouin stokes comb cavity (internal cavity) is formed according to the conventional linear cavity with a Brillouin pump (BP) pre-amplification technique. The FWM effect within the external cavity is achieved by an EDFA2 and a section of a Highly Non-Linear Fiber (HNLF). The EDFA2 section is used to achieve a broad emission peak within the C+L bands so that the generated Brillouin comb can be tuned throughout a wide tuning range.

CHAPTER ONE
PURPOSE OF THE THESIS

1.1. Background

Optical fiber communication technology has been widely adopted in telecommunication networks system. In optical fiber transmission, an optical wave has been utilized as an optical carrier. Using this optical fiber as a transmission medium rather than the traditional copper cable is due to its significant advantages, which are not affected by external environments such as temperature, humidity, and rain. Besides, it presents low signal transmission loss, good security, and tunable bandwidth capacity. To enhance the transmission bandwidth per single optical fiber, a dense wavelength division multiplexing system has been used in the optical network system throughout the previous decade. DWDM systems are suitable for the setup, which transmits multiple optical signals at different wavelengths in the same optical fiber. (Mohammed H. Al-Mansoori & Mahdi, 2008)

Basically, in DWDM technology, there are three different techniques to increase the transmitted capacity per fiber; the first technique depends on the increment of the bit rate per channel while increasing the total transmission bandwidth represents the basis of the second technique. To avoid the complicated dispersion compensation technique, the third technique, which is the best among them, appears with its narrow channel spacing that allows increasing the number of the transmitted channels with low electrical circuits speed. In other words, in this technique, the DWDM system is effectively increasing the bandwidth per single optical fiber as the total system bandwidth is the sum of the bit rates of each different wavelength channel.

The use of an optical signal as an optical source has been around since 1960. The (SBS) nonlinear effect has been investigated in 1964 (Chiao et al., 1964). Since then, researchers' attention has turned to the impact of SBS. The nonlinear process (SBS) results from the interaction between the pump light and the acoustic wave inside the optical fiber (D. COTTER, 1982). A new Stokes light signal is generated with 0.08 nm (10GHz) down frequency-shifted related to the pump light wavelength through the

Doppler Effect. In the past decade, the SBS effect in optical fiber has been employed to propose several important applications such as fiber laser (Smith et al., 1991), optical sensing (K. Kalli et al., 1991), and optical filtering (Lin et al., 2000). The most important application of the SBS effect is to generate Brillouin fiber laser (BFL) with narrow linewidth sources (Kyriacos Kalli & Jackson, 1995).

Multiwavelength BFL sources, which have the essential qualities of rigid frequency shifting and extremely narrow linewidth, might be considered one of the appealing solutions for boosting the DWDM systems (Debut et al., 2001); (Stépien et al., 2002); (Norcia et al., 2004)). Achieving multi-wavelength generation in the BFL cavity is not easy because the small induced Brillouin gain within the fiber makes the cavity losses compensation insufficient. Therefore, additional gain sources are added inside the BFL cavity to compensate for the cavity losses and generate higher multiwavelength Brillouin stokes lines.

To produce Brillouin/Erbium fiber lasers,(Cowle & Stepanov, 1996) proposed a hybrid MBEFL that combined the nonlinear Brillouin gain (inside the optical fiber) and the linear Erbium gain (in Erbium-doped fiber) in the same laser cavity. This proposed cavity successfully increased the bandwidth within the optical communication system by increasing the number of channels.

1.2. Problem statement

Multiwavelength fiber laser is implemented to support (DWDM) communication systems since it provides dense laser wavelength spacing. Several researchers proposed a combination of BEFL and FWM in the same cavity to increase the number of the generated multiwavelength stokes lines. However, FWM occurrence inside the cavity and the tunability efficiency may be influenced by the limitations of the optical power components. In addition, the laser efficiency may reduce due to the difficulty of achieving the phase-matching inside the cavity. So, the FWM process should occur outside the cavity of the Brillouin laser comb. To achieve such a design, several EDF amplifier sections that expense high pump power using different pump power units in addition to a tunable filter that adds more cost to the design are required.

In such a design, two factors affect the generated laser lines tunability; the EDFA before the FWM process and the tunability of the laser comb generated by the Brillouin cavity. All that limits the tunability of the laser lines to the C-band region.

Using a short single-mode fiber (SMF) length raises the SBS threshold. In order to achieve sufficient introduced power to the Brillouin gain medium, large EDFAs' gain may be needed.

1.3 Objectives of this Study

This thesis aims to design and develop a multiwavelength fiber laser assisted FWM process that combines the (SBS) and (FWM) phenomena into a single design. The Brillouin stokes comb cavity (internal cavity) is formed according to the conventional linear cavity with the Brillouin pump (BP) pre-amplification technique. An EDFA2 and a section of HNLF at the internal cavity's output port create the FWM effect within the external cavity. The following are the main research aims for the entire study:

1. Design and evaluate MBEFL, with a high stokes number, assisted by the FWM process via combining the two nonlinear phenomena (SBS and FWM) in one design.
2. Achieve broad emission peak within C+L bands so that the generated Brillouin comb can be tuned over a wide tuning range.
3. Reduce the number of EDFAs and pump power units in the system as much as possible.

1.4 The Work's Scope

The primary purpose of this study is to design a multiwavelength fiber laser with a high stokes number and a wide tuning range. To achieve this aim, the proposed design combined the two nonlinear phenomena of successive (SBS) within the internal cavity, linear cavity, and the (FWM) experiences outside of the cavity. The flow chart of the design realized within the scope of this research is given in Figure 1.

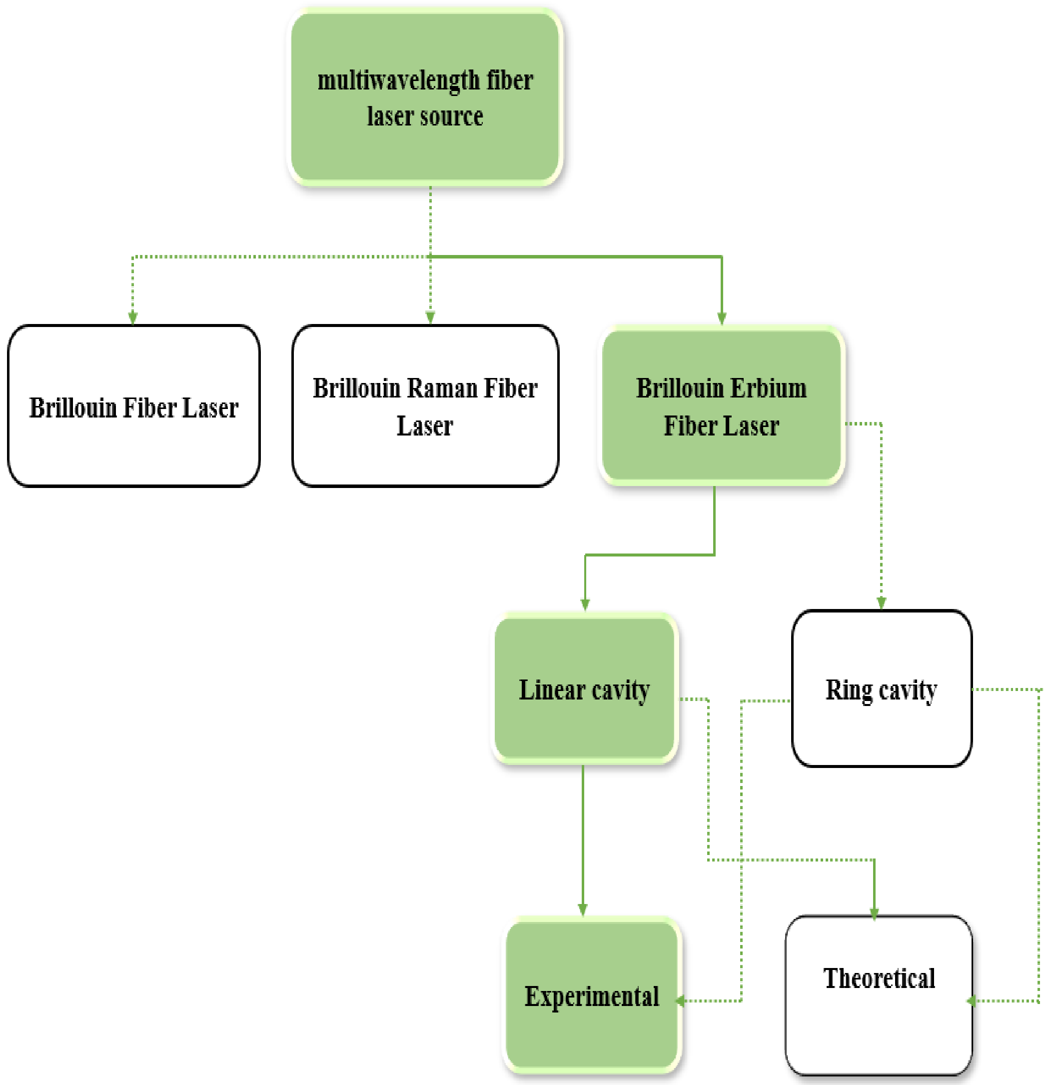


Figure 1. Flow chart of the proposed study.

1.5 Thesis Layout

This thesis is composed of five chapters.

Chapter 1: It provides a background for optical communication systems and the development of the DWDM system. Also, this chapter discusses the problem statement, objectives of the study, and scope of the research work.

Chapter 2: This chapter includes reviews on multiwavelength fiber laser development, MBEF, and the types of optical fibers focusing on the use of HNLF. It also shows the theoretical development of the SBS and FWM effects and explains the basic concept of these two phenomena in optical fiber. The essential condition for coherent nonlinear optical processes, phase-matching, is also discussed in this chapter.

Chapter 3: Presents the general research methodology flow chart for the experimental study conducted in this thesis. It also produces the input design parameters and performance parameters using helpful flowcharts.

Chapter 4: Shows the experimental setup of the proposed MBEFL cavity and discusses the experimental results in terms of the number of generated stokes lines and tunability.

Chapter 5: Based on the obtained results, it highlights the main research conclusions.

CHAPTER TWO

THEORETICAL BACKGROUND AND LITERATURE REVIEW

2.1 Nonlinear Phenomena in Optical Fiber

Due to rapid development in nonlinear optical applications, Maiman produced the Ruby laser in 1960 (Maiman, 1960). Since then, many types of research have focused on theoretical explanations of non-linear phenomena ((Franken et al., 1961); (Kaiser & Garrett, 1961); (Terhune et al., 1962); (Armstrong et al., 1962); (C. C. Wang & Racette, 1965); (C. H. Sun et al., 2007))

There are two types of nonlinear phenomena in an optical fiber: elastic and inelastic. If there is no energy exchange between the media and the incident light, this type is elastic. The refractive index of the material varies depending on the type of input signal and the incident light's intensity, resulting in nonlinear phenomena such as self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM).

Inelastic phenomena, such as stimulated Brillouin scattering and stimulated Raman scattering, occur when energy is exchanged between the medium and the incident light. Brief descriptions of some of these nonlinear effects are summarized in Figure 2.

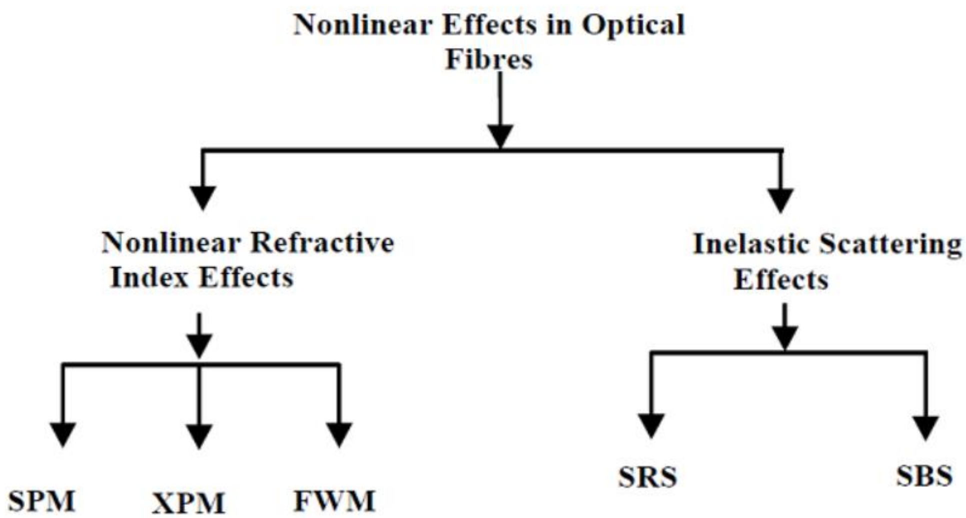


Figure 2. Nonlinear effects in fiber optics

(i) Four Wave Mixing (FWM)

When three channels propagate in the same medium, a fourth channel is generated with the frequency of the three channels added together. These three channels' power is also suppressed at the same time. This process represents the formation of the FWM effect. More details are discussed in Section 2.3.

(ii) Stimulated Raman Scattering (SRS)

A phonon is a quantum atomic cell's early-stage excitation. In the case of using optical fiber, two types of phonons known as optical and acoustic phonons are generated. The SRS effect occurs when incident light collides with an optical phonon, resulting in energy transfer and losing some of the incident light's power. As a result, a new shorter wavelength known as stokes is created. The newly created wavelength has a negative absorption coefficient, allowing the incoming signal to acquire gain. Depending on the nature of the nonlinear medium, the frequency difference between the incident or pump wavelength and the newly created signal is approximately 100 nm (13 THz).

(iii) Stimulated Brillouin Scattering (SBS)

The phenomenon of stimulated Brillouin scattering is caused by the collision of an incident signal with an acoustic phonon. The acoustic phonon is created when positive and negative ions swing together like a moving grating as the electric field propagates. Any photon colliding with this acoustic phonon generates signals with different frequencies. The difference between the incident frequencies and the acoustic phonon frequency, which is approximately 12 THz due to varying medium and electric field source factors, determines the generated frequency. The mechanism of stimulated Brillouin scattering is briefly described in Section 2.2. ((Diament P., 1990); (Binti Norizan S. F. (2014))

2.2 Stimulated Brillouin Scattering

2.2.1 Principles of Stimulated Brillouin Scattering

An electrostriction process of a dielectric medium produces stimulated Brillouin scattering. The medium's refractive index is shifted by a high electric field, causing it to become an acoustic phonon and behave like a moving grating. Brillouin scattering is the backward scattering generated by the collision between the incident light and acoustic wave, as shown in Figure 3.

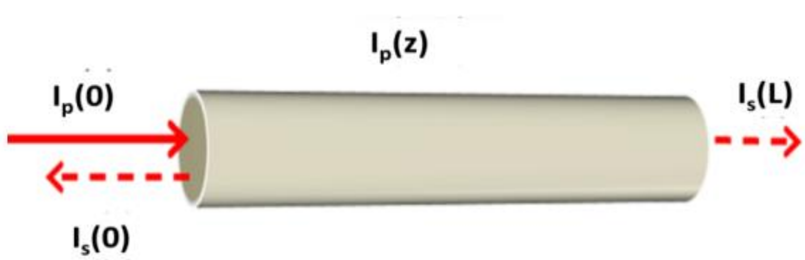


Figure 3. Brillouin pump depletion and the process of stokes signal generation

Brillouin pump (BP) is the name given to the powerful light source that causes the nonlinear effect, while stokes or anti-stokes is the name given to the backscattered signal, depending on the frequency shift. The nonlinear interaction of the Brillouin pump and the stokes wave is controlled by the coupled equations below:

$$\frac{dIp}{dz} = -g_{\boldsymbol{B}}\, I_p\ I_s - \alpha I_p \qquad (1)$$

$$\frac{dIs}{dz} = -g_{\boldsymbol{B}}\, I_p\, I_s + \alpha I_s \qquad (2)$$

The Brillouin pump and stokes intensities are I_p and I_s, respectively, and the Brillouin gain coefficient is g_B. The process repeats until the present stokes power is inadequate to generate a new stokes. During this continuous operation, multiple signals with slightly differing frequencies (f_s) than the Brillouin pump frequency (f_{BP}) are generated.

$$f_s = 2n\, c\, v_a / f_{BP} \qquad (3)$$

where n denotes the group refractive index, c denotes the light velocity, and indicates the acoustic speed. (Binti Norizan S. F. (2014)

2.2.2 Stimulated Brillouin scattering fundamentals

In SMF, the SBS property is summarized as shown in Figure 4. Injecting a high-powered single-wavelength signal into the fiber and satisfying the condition of exceeding the Brillouin threshold power causes the signal to propagate to the output with lowered power due to fiber loss. Also, this process transfers energy to a newly created Brillouin backscattered signal that is frequency downshifted (upshifted in wavelength).

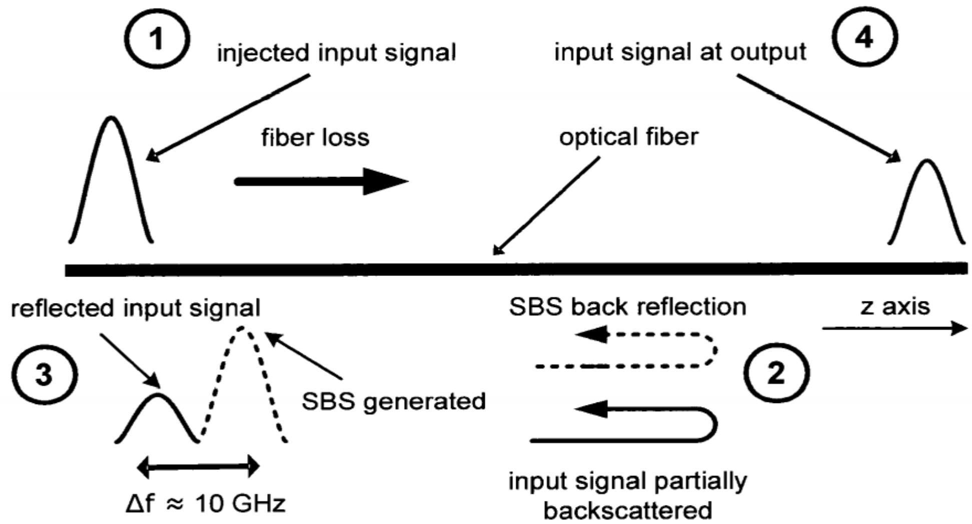


Figure 4. A high-level explanation of SBS in optical fibers

The SBS process can be conventionally defined as a non-linear interaction between the pump, also known as the BP, and stokes fields via an acoustic wave, as shown in Figure 5. To explain the process in more depth, electrostriction is the technique through which the Brillouin pump generates an acoustic wave. The refractive index of the optical fiber is affected by the fluctuating wave pattern of this acoustic wave, resulting in a pump-induced index grating that scatters the pump light via Bragg diffraction. Due to the Doppler effect, the scattered light has a frequency shift because the grating moves at the acoustic velocity ν_A (Agrawal, 2007a).

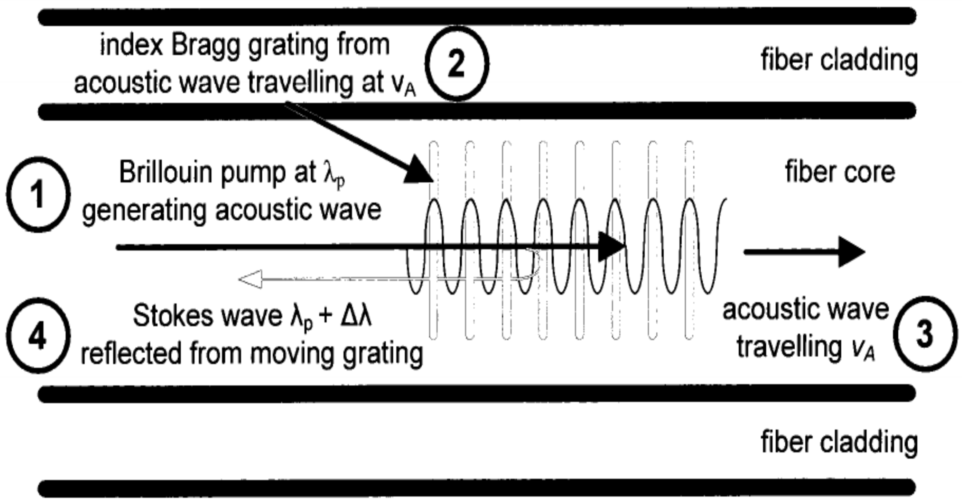


Figure 5. The interaction among the BP, Stokes field and acoustic wave in SBS

Quantum mechanically, SBS can be regarded as a pump photon that is simultaneously converted into a stokes photon and an acoustic phonon. Because energy and momentum must be preserved, the three waves' frequencies and wave vectors must be conserved as well, based on their relationship.

$$\Omega_B = \omega p - \omega s, \; k_A = k_p - k_s \tag{4}$$

where ωp and ωs represent the frequencies, and k_p and k_s represent the wave vectors of the pump and stokes waves, respectively. Furthermore, the acoustic wave's frequency $\Omega\beta$ and the wave vector k_A comply with the classic dispersion relation:

$$\Omega_B = v_A\,|k_A| \sim 2v_A\,|k_p\,|\,sin(\theta/2) \tag{5}$$

where θ is the angle between the Brillouin pump and the stokes field and it is assumed $k_s \sim k_p$. This demonstrates that the frequency shift of the stokes wave is affected by the scattering angle; particularly, Ω_B is maximum in the backward direction (when $\theta = \pi$) and disappears in the forward direction ($\theta = 0$). This illustrates that in optical fibers, when only backward and forward propagation is allowed, SBS occurs in the backward direction, with the Brillouin shift provided by

$$v_B = \frac{\Omega_B}{2\pi} = 2n_p\, \nu_A/\lambda_p \qquad (6)$$

where $k_p = 2\pi\, n_p \nu_A /\, n_p$ and n_p is the effective mode index at the pump wavelength λ_p. Typically in SMF, ν_A= 5.96 km/s and n_p= 1.45, resulting in v_B= 11.1 GHz for λp = 1.55 μm. (Hayder, A. 2008)

2.3 Four Wave Mixing

2.3.1 Four-Wave Mixing Principles

There are several nonlinear refraction effects, and one of them is four-wave mixing which originates from third-order susceptibility. When two signals interact, a third signal known as an idler is produced. FWM effect classified to non-degenerate and degenerate FWM. The simultaneous propagation of three signals with frequencies $\omega 1$, $\omega 2$, and $\omega 3$ inside the fiber induces $(\chi\ 3\ )$ to generate a fourth signal with frequency $\omega 4$. The relation $\omega 4 = \omega 1 \pm \omega 2 \pm \omega 3$ connects this fourth signal to other frequencies, and these frequencies are non-degenerate FWM. While the degenerated FWM type can be produced by the interaction of three components represented by $\omega 3 = \omega 1 + \omega 1 - \omega 2$. Nondegenerate FWM is significantly easier to generate the idler than degenerate FWM, as illustrated in Figure 6 (a and b). (Binti Norizan S. F. (2014)

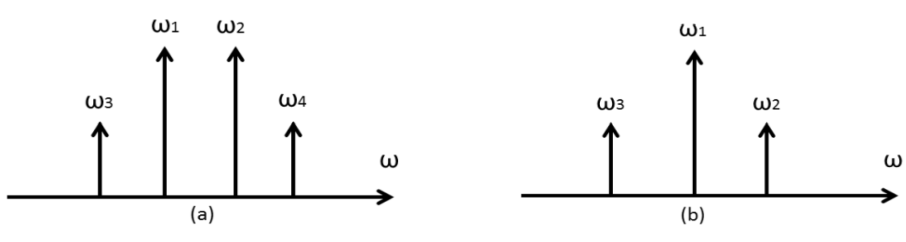


Figure 6. Four-wave mixing with (a) nondegenerate and (b) degenerate

The pump and the signal are the two wavelengths that form the non-degenerate FWM. The power of the created extra signal, $PFWM$, also termed as FWM signal (Inoue, et al. 1992 and Yamamoto, et al. 1997), is represented by:

$$P_{FWM}(L\ ,\Delta\beta)=\eta(\ \Delta\beta)\gamma^2\ L_{eff}^2\ P_p^2 P_s\ \exp(-\alpha\, L)\quad (7)$$

where γ denotes the nonlinear coefficient, $Leff$ denotes the effective length of the fiber, which is given by

$$L_{eff}\ =\ 1\ \propto\ (1\ -\ e\ -\propto L\ )\qquad (8)$$

the absorption coefficient is α, Ps and Pp are the power of the signal and pump respectively, L length of the fiber, while $\eta(\Delta\beta)$ represents FWM efficiency in terms of phase mismatching $\Delta\beta$. FWM efficiency is defined as the ratio of FWM power to FWM power when $\Delta\beta$ equals zero.

$$\eta(\ \Delta\beta) = \frac{PFWM(\Delta\beta,L)}{PFWM(\Delta\beta=0,L)}\qquad (9)$$

In the production of multiwavelength fiber lasers, four-wave mixing is a smart strategy. (Binti Norizan S. F. (2014)

2.3.2 Four-Wave Mixing Signal Generation

Theoretically, FWM is generated if two input signals have been launched in the same optical fiber. FWM is a functional interaction between waves that achieves the phase matching. Photon pairing in a high radiation beam after scattering the host material initiates energy transfer. For high FWM gain, the whole energy of the photon must be preserved because of the limiting material resonances. When it appears in pulse fiber lasers and pulse fiber amplifiers, the induced power transfer from the main pump beam to the spectral sidebands of FWM begins to be restricted in order to maintain high spectral brightness. Another need for effective FWM is the preservation of total photon momentum, which is defined as the phase-matching condition and is expressed as:

$$\Delta k\ =\ 2\emptyset_0\ -\ \emptyset_1 + \emptyset_2 = 0\qquad (10)$$

$\emptyset i$ represents the phase shift and expressed as:

$$\emptyset i = \frac{2\pi\, n_{eff}(\lambda i)}{\lambda i} + \emptyset_{NL}\,(i) \quad (11)$$

the symbols $\Delta k, \lambda i$, $n_{eff}(\lambda i)$, and $\emptyset_{NL}\,(i)$represent the phase shift, wavelength, fiber refractive index, and non-linear phase shift for each beam, respectively.

FWM in optical fiber offers a wide range of uses. FWM can be used for wavelength conversion, phase conjugation, supercontinuum creation, and optical samplers (Agrawal, G.P. (2001) (Inoue & Kawaguchi, 1998). The use of phase conjugation in optical communication systems will be employed to compensate for dispersion [(Zhang & Jørgensen, 1997); (Zacharopoulos et al., 1999); (Ciaramella et al., 2001) (Iannone, E., Matera, F., Mecozzi, A., and Settembre, M. (1998); (Watanabe et al., 1993); (Gnauck et al., 1993)].

The nonlinear response of linked electrons in a medium to an applied optical field is the most significant aspect of an applied parametric operation. The parametric process is divided into two categories based on its susceptibility: second order and third order. FWM is derived from 3rd-order susceptibility and is a 3rd-order nonlinearity x^3.

Because the process of 3rd-order that differs from that of 2nd-order is permitted in all mediums, the FWM is clearly noticeable. The basic concept of optical mixing is highly related to the FWM concept. (Binti Norizan S. F. (2014). The formation of two photons is responsible for the formation of this effect. When single or multiple waves are dispersed, other photons with various frequencies are created, which enforces the conservation of both total momentum and energy during the parametric interaction, resulting in the FWM. FWM is a useful technique method for creating new waves. In the electric field, the harmonic oscillation of bound electrons under the effect of an external field created by total polarization induced by electric dipoles is still not linear and is based on

$$P = \varepsilon_0\,(x^1.E + x^2{:}\,EE + x^3 \vdots\, EEE + \dots) \quad (12)$$

where P represents absolute polarization, ε_0 represents permittivity in vacuum, $x^j = (j = 1,2,3, \dots)$ represents the j^{th} order susceptibility, and E represents the electric field. The third harmonic generation, nonlinear refraction, and FWM are all caused by the third order susceptibility x^3. The majority of nonlinear effects in optical fiber are caused by nonlinear refraction, which is the intensity-dependent on the refractive index. The total index of refraction, ῆ, can be computed using the following formula:

$$\tilde{\eta}\; n(\omega) + n_2 \,|\, E|^2 \qquad (13)$$

where $n(\omega)$ is the linear component, $|E|^2$ is the optical intensity within the fiber, and n_2 is the nonlinear-index coefficient in respect to the third order susceptibility, x^3 given as:

$$n_2 = \frac{3}{8n} Re(x^3) \qquad (14)$$

only one component of third-order susceptibility x^3,of four order tensors contributes to the refractive index, where the real part denotes by Re, and the optical field is regarded linearly polarized. x^3's third-order susceptibility can change the polarization characteristics of optical input through nonlinear birefringence. Consider four linearly polarized waves moving along the same axis and oscillate at frequencies ω_1 , ω_2 , ω_3 and ω_4. The total electric field is calculated as:

$$E = \frac{1}{2}\, \hat{x} \sum_{j=1}^{4} E_j \; exp[i\; (k_j\, z - \omega_j\, t) + c.c. \qquad (15)$$

where k_j represents the constant of propagation, E_j $(j = 1,2,3\; and\; 4)$, i is the wave number, ω_j represents the frequency $(j = 1,2,3, and\; 4)$, $k_j\, (j = 1,2,3, and\; 4)$, and t is time. Supposing four waves spread in the same direction, the definition for third-order polarization is:

$$P_{NL} = \varepsilon_0 x^3 \vdots \mathrm{EEE} \qquad (16)$$

where P_{NL} represents induced nonlinear polarization, ε_0 represents the permittivity of vacuum, x^3 represents third-order susceptibility, and E represents the electric field. The nonlinear polarization form that is induced can be written as:

$$P_{NL} = \frac{1}{2}\, \hat{x} \sum_{j=1}^{4} P_j \; exp[i\; (k_j\, z - \omega_j\, t) + c.c. \qquad (17)$$

Two additional frequencies are created by inserting two frequency components into a coupler (Binti Norizan S. F. (2014). In general, the M number cross mixing products to be generated for the N number of wavelengths of the input signal can be estimated as follows:

$$M = \frac{N^2}{2}(N - 1) \qquad (18)$$

Because the FWM phenomenon is affected by the three optical fiber parameters: length, dispersion, and nonlinearity coefficient, and because these parameters are more efficient in the HNLF, it is preferable to use the HNLF in designing MBEFL cavities. (X. Liu et al., 2005). In longer fibers, the non-uniformity of the fiber is critical for decreasing the efficiency of the FWM process (Stolen et al., 1974).

The strategy of combining the BEFL and multiple FWM considerably enhances the number of lasing lines when compared to conventional BEFL. Furthermore, collecting the help of many FWM can improve energy transfer efficiency from high-peak-power lines to low-peak-power lines. The resulting multi-wavelength fiber lasing has a flatter spectrum and more comb lines.(P. Wang et al., 2019)

2.3.3 Previous Works of Four Wave Mixing (FWM)

Recently, wide applications in optical communication are based on the principle of the four-wave mixing effect. The FWM is used to convert wavelengths with a wide range of tunability and spacing. (Awang et al., 2010). The FWM signals were also shown experimentally in 2013 as the proper approach for generating multi-wavelength in SMF and the HNLF to study lasing stability in the MFL scope. (Han et al., 2006). In 2016, the FWM technique was applied to microfiber to improve phase-matching parameters (Khudus et al., 2016).

2.4 Phase matching

The development of a four-wave mixing technology for wavelength conversion requires phase matching. For coherent nonlinear optical processes like parametric amplification and frequency conversion, phase matching is important because it allows nonlinear sources to combine creatively, leading to more effective emissions. On the other hand, phase mismatch prohibits microscopic nonlinear sources from efficiently combining, leading to disruptive interference and, consequently, bad performance. (Binti Norizan S. F. (2014)

Phase matching refers to a collection of techniques used to produce efficient nonlinear interactions in a medium. An optical transmission system ensures that the correct phase relationship between the interacting waves is established along the propagation direction. If that condition is satisfied, the amplitude contributions to the product wave from different positions would be in phase at the nonlinear crystal's end (Stolen et al., 1974).

The most frequent method for obtaining phase matching in nonlinear crystals is birefringence phase matching, in which birefringence is employed to erase the phase mismatch. This technique is available in various forms: In sum-frequency generation, for example, type I phase matching means that the two fundamental beams have the same polarization perpendicular to the sum frequency wave. In type II phase matching, the two fundamental beams have different polarization directions. In addition, that can be useful when the birefringence is relatively high (overcompensating the dispersion in a type I scheme) or the tiny phase velocity mismatch.

The distinction between types I and II also refers to frequency doubling and degenerate or non-degenerate parametric amplification processes. The various polarization structures may have a variety of practical applications, such as combining multiple nonlinear conversion stages or intra-cavity frequency doubling. (Binti Norizan S. F. (2014)

A powerful technique is quasi-phase-matching, in which no real phase matching occurs. Still, a large conversion efficiency can be achieved in a crystal where the nonlinearity's sign (or intensity) varies periodically.

The interacting waves' group velocities are still not matched in general at the phase match stage; there is a group velocity mismatch, which restricts the duration of interaction for pulses and the range of the spectrum. Furthermore, phase matching only works for a limited number of angles beams. The angular phase-matching bandwidth is the term referring to this range of angles. (Binti Norizan S. F. (2014)

2.5 Optical Fiber Types

An optical fiber is a waveguide that allows an optical signal to be transmitted from a transmitter to a receiver. Fiber optics have grown in variety to meet the modern market demands, particularly in communication technologies. It is ideal for gigabit transmitting and beyond because of its high bandwidth capacity and low attenuation properties.

Its features like suitability for long-distance data transmission, the wide bandwidth despite its small diameter, and lightweight make the optical fiber effective for a wide range of applications.

The SMF is the most well-known and widely utilized optical fiber. An SMF permits light propagation in one mode across the fiber channel. A few-mode fiber (FMF) is an optical fiber that allows a small number of modes to propagate. In the last few years, the advent of FMF for mode division multiplexing (MDM) has attracted growing attention, which has been identified as a possible approach for increasing network system data-carrying capacity (Richardson et al., 2013). Because FMFs are more resistant to mode coupling than a regular multi-mode fiber, they have proven to be a suitable medium. A typical multi-mode fiber has a larger core diameter than SMF. They perform similarly to SMF in terms of dispersion and loss. This fiber can be utilized in a single-mode operation, where all data is transmitted in only one of the spatial modes throughout the fiber due to the lack of mode interaction (Yaman et al., 2010).

Another type of fiber is the highly non-linear fiber (HNLF). The appearance of HNLF led to new nonlinear effects. SMF is used to make this sort of fiber. The HNLF's ultrafast nonlinear response is the primary benefit of employing it as a nonlinear medium. This nonlinear property can be employed in ultrafast signal processing and switching. Fast pulse expansion causes its low magnitude in the normal-dispersion regime (Agrawal, 2007b).

The HNLF can induce the FWM condition because of its large nonlinear coefficient. As a result, mixing HNLF with MBEFL can stimulate the FWM effect, causing each Brillouin stoke to operate as an FWM pump, amplifying the preceding and following first-order Brillouin stoke, equalizing the MBEFL's output power, and broadening the output spectrum. (Zhou et al., 2019).

2.6 Multiwavelength Fiber Laser (MFL)

Lasers are categorized depending on their time-domain as continuous-wave lasers and pulse wave lasers. It is separated into single wavelength laser and multiwavelength fiber laser in the wavelength domain.

The phenomenon of multi-wavelength is a nonlinear phenomenon caused by light wave interference in a waveguide (Harun et al., 2009). Using a fiber ring laser system, multi-wavelength lasing is achieved (An et al., 1999); (Pan et al., 2006)].

Various applications necessitate the use of single-mode laser oscillations. For example, by simultaneously sending separate optical waves at different wave division multiplexing WDM wavelengths. WDM has been used to raise the capacity of a fiber communication network. One widely used WDM wavelength standard is the International Telecommunication Union (ITU) standard, which requires WDM wavelengths of distinct optical waves to match ITU grid frequencies. As a result, each laser transmitter must only operate in one mode at a single WDM wavelength. Precision spectroscopic measurements and short nonlinear optical processes are two further applications for single-mode laser oscillations (Binti Norizan S. F., 2014).

2.7 Review on Multi-wavelength Brillouin Erbium Fiber Laser

The limited Brillouin gain inside the cavity resulted in limitations in the generated stokes lines. For that, many studies have attempted to increase the number of stokes by increasing the gain inside the cavity and executing a hybrid fiber laser. The use of two gain mediums in the same cavity was demonstrated. (Cowle & Stepanov, 1996). MBEFL is achieved by combining the nonlinear gain from the SBS effect inside the SMF with the linear gain from the EDF.

The purpose of MBEFL is to obtain an extra linear gain that compensates for cavity losses and improves the generated stokes lines. To avoid gain saturation and allow good cavity performance, the balance between these two gains (nonlinear and linear) is essential. Combining these two gains media allows generating a high number of stokes lines with 10 GHz or about 0.088 nm spacing at room temperature (Park et al., 2000). In designing MBEFL, three major factors must be considered: the number of generated stokes lines, laser cavity tunability, and lasing cavity threshold. The number of stokes lines generated by the hybrid gain cavity is the essence of the MBEFL's emergence. The tuning range is defined as the wavelength of the Brillouin pump at which no self-lasing cavity modes are recorded at the output laser comb. Threshold lasing power is defined as the amount of pump power required to produce the first stoke in MBEFL (Mohammed Hayder Al-Mansoori et al., 2009).

Improving the Brillouin erbium fiber laser setups became an important research field to increase the number of the generated laser lines and enhance efficiency. At first, (Cowle & Stepanov, 1996) produced a schematic design that obtained a low tuning range of 2 nm at 1532nm and a high Brillouin stokes power of 10 mW with a downshifting frequency of 10 GHz. Using a ring cavity structure, up to 6 stokes lines were obtained in this setup. The number of stokes lines was increased, and up to 30 stokes lines were generated. This increase in stokes lines was attributed to the cavity structure, which allows for amplifying both the generated stokes line and the high order stokes line in both directions (Cowle et al., 1997). The unequal output of stokes power was the downside of this design.

The optimization of BP power has been presented by (H. Kim, K. Kim, 1998). It is proved in this setup that by decreasing the BP power, the number of the generated stokes lines was increased. The EDFA section was inserted in the feedback section of the laser cavity, and up to 4 stokes lines were generated. Many optical elements were used in this setup, increasing the complexity and cost of the suggested design compared to low stokes lines generation. Twin cavity BEFL with bidirectional operation has been proposed by (Abd-Rahman et al., 2000). Up to 24 stokes lines with channel spacing of 11 GHz at 1560 nm were obtained. In the same year, dual-cavity BEFL was also proposed to enhance the stokes lines generations (Park et al., 2000). Up to 30 stokes lines with 11 GHz channel spacing were achieved. An internal complex feedback configuration was included to enhance the operation of ring cavity BEFL. An additional active EDF section was used to amplify the subsequent BP power (generated Brillouin stokes lines), which generated the next Brillouin stokes line. This setup was efficient to produce up to 53 Brillouin stokes lines. The uniformity in shape for all generated stokes lines was observed.

An MBEFL design utilized a bi-directional oscillation provided by two fiber loop mirrors at both ends of the laser cavity. The efficiency of bi-directional amplification in the EDF exhibited a low threshold operation of 5.5 mW pump power of 980 nm to create the first Brillouin stokes. Up to 18 stokes line was generated (M. H. Al-Mansoori et al., 2004). In a ring cavity, the Sagnac loop filter method was employed to achieve up to 12 stokes lines with a tuning range of 14.5 nm (Song et al., 2004). The same year, a ring setup using a fiber laser as the Brillouin pump was created, resulting in a widely tunable MBEFL system with a tuning range of up to 36.7 nm (Abdullah et al., 2004) .

In 2005, the double-pass pre-amplifier technique was used to enhance the tunability of the linear cavity. This was achieved by injecting high Brillouin pump powers to saturate the Erbium gain in the laser cavity. Up to 2 stoke lines with a high tuning range of 60 nm were achieved (M. H. Al-Mansoori, Abd-Rahman, et al., 2005). Then in the same year, a novel technique of producing a multiwavelength laser source was described utilizing a direct injection Brillouin pump in the linear cavity. Up to 22 stable output lasers with 10.88 GHz line spacing were obtained (M. H. Al-Mansoori, Abdullah, et al., 2005).

Using a double pass amplification in the Erbium medium, up to 43 stable output channels with a spacing of 10.88GHz was achieved. The stokes signal was tuned over 10.56 nm from 1547.40 to 1557.96 nm (M. H. Al-Mansoori et al., 2006). A multiple wavelength L-band Brillouin-erbium comb fiber laser with intra-cavity pre-amplified Brillouin pump power technique at low pumping powers was demonstrated. The laser structure achieved a low threshold power. It produced up to 33 stokes lines at 50 mW and 0.042 mW of 1480 nm pump and BP powers, respectively (Mohammed H. Al-Mansoori & Mahdi, 2008).

Then, an efficient MBEFL with a pre-amplified Brillouin pump within a Fabry-Perot cavity was used. In this laser structure, the fiber Bragg grating filter was used as one of the fiber loop mirrors; up to 25 stable Brillouin stokes lines were generated with channels spacing of 0.088 nm (Nasir et al., 2008). The same year, an efficient MBEFL within ring cavity was presented, utilizing broadband fiber Bragg grating as cavity feedback. Only 0.2 dBm of Brillouin pump and 70 mW of the 980 nm LD powers were consumed to generate 31 output channels with a constant spacing of 0.088 nm (M. N.

Mohd Nasir et al., 2008). After that, a clean output spectrum without any spurious self-lasing cavity modes was recorded, and its maximum output power reached 20 mW with 10 laser lines at a spacing of 0.089 nm. A tuning range of 14.8 nm was achieved at the Brillouin pump power of 3.25 mW and the 980-nm pump power of 20 mW (Samsuri et al., 2008).

A novel multiwavelength L-band BEFL utilizing a nonlinear amplifying loop mirror was produced. The proposed fiber laser structure has a low threshold power of roughly 10 mW to generate the first Brillouin stokes signal. With a spacing of 0.089 nm, the total number of 27 stokes signals was obtained. At a BP power of 3.5 mW and a pump power of 30 mW at 1480 nm, a tunable range of 11 nm (1600 nm - 1611 nm) was accomplished. (Mohammed Hayder Al-Mansoori, 2009). Then, a double-pass pre-amplifier technique in the linear cavity was demonstrated. The proposed novel setup produced up to 30 channels at 40 and 0.035 mW of 1480 nm pump and BP powers, respectively, with low threshold power of 15.9 mW. A wide tuning range of 14 nm was achieved (Mohammed Hayder Al-Mansoori et al., 2009). After that, in the same year, (Mohd Narizee Mohd Nasir et al., 2009) utilized 100 m of PCF and a tunable band-pass filter within the pre-amplified BP configuration to generate 14 Brillouin stokes lines. The laser system operated at a BP power of 7dBm and 980nm LD power of 200mW. A wide tuning range of 29nm was obtained.

Meanwhile (Ajiya et al., 2009) reported uni- and bi-directional propagation of Brillouin pump and Brillouin Stokes signals with an EDF gain. The effect of these setups on the output parameters' performance in terms of lasing threshold, number of stokes generation, and tuning range of the generated output channels was studied. The 46.8 nm tuning range of the uni-directional amplifier was superior to the 23 nm tuning range of the bi-directional amplifier. The bi-directional amplifier configuration produced 13 output channels vs. six output channels from the uni-directional amplifier setup at the same pump powers.

In 2012, a tunable wideband MBEFL was demonstrated (Almusafer et al., 2012). A tunable band-pass filter and a pre-amplified Brillouin pump technique were utilized in the ring laser cavity. Up to 6 stokes lines were tuned over C and L bands with constant wavelength spacing of 0.174 nm. A tuning range for 80 nm from 1530 nm to 1610 nm was achieved. The generated laser comb showed good stability with high peak power of -10 dBm. In the same year, an efficient L-band multiple wavelength BEFL was demonstrated (M. H. Al-Mansoori et al., 2012). An optical mirror was connected to the cavity side, while the other was connected to the amplified fiber loop mirror. The BP signal was pre-amplified in the cavity structure before being injected into the SMF. Up to 54 stokes lines numbers were generated at 33 mW of 1480 nm pump power.

2.8 Review on using Highly Non-Linear Fiber

The HNLF is one of the important optical fibers made by using the SMF. The appearance of HNLF led to new nonlinear effects. The HNLF's ultrafast nonlinear response, which may be exploited in ultrafast switching and signal processing, is the primary benefit of employing it as a nonlinear medium (Agrawal, 2007b). The HNLF can induce the FWM condition because of its large nonlinear coefficient. As a result, mixing HNLF with MBEFL can stimulate the FWM effect, causing each Brillouin stoke to operate as an FWM pump, amplifying the preceding and following first-order Brillouin stoke, equalizing the MBEFL's output power, and broadening the output spectrum (Zhou et al., 2019). Therefore, much research has been conducted on the use of HNLF.

In 2011, Tang et al. demonstrated an experimental method for creating a stable and tunable multiwavelength comb fiber laser using a configuration with a 135-m HNLF (Tang, Sun, Zhao, et al., 2011). To enhance the EDFA's performance, a 3-dB coupler was used to divide the 1480 pump laser into two parts (P1 and P2). Up to about 150 lasing lines with a 0.075 nm spacing were created using cascaded SBS and multiple FWM operations. A 6-nm tuning range (1562-1568 nm) was obtained. In 2012, Al-Alim et al. demonstrated a ring MBEFL cavity using an 800 m-long HNLF (Ahmad, Al-Alimi, Abas, Mokhtar, et al., 2012). At the highest Brillouin pump (BP) output of 16.7 dBm, the total number of the generated laser lines was 51 (36 odd and 15 even) with a channel spacing of 0.15 nm. In the same year, a piece of 2 Km HNLF was utilized as a gain medium in conjunction with a figure of eight cavity design to generate 15 stokes channels and 14 anti-stokes channels with 0.154 nm spacing along with a tuning range of 41nm (1526.5 to 1567.5 nm.) (Ahmad, Al-Alimi, Abas, Harun, et al., 2012).

A tunable multiwavelength Brillouin-erbium fiber laser (MBEFL) with a wide tuning range of 40 nm was constructed by Al-Alimi et al. (Al-Alimi et al., 2013). The laser was created in this configuration between a double pass amplification box and a 2015 m HNLF operating as a virtual mirror, removing the reflective physical mirror from one side of the laser structure. Through cascading stimulated Brillouin scattering and producing a FWM process inside the HNLF, up to 150 stokes lines were created. Tonghui Liu et al. demonstrated in 2016 a multiwavelength erbium-doped fiber laser with narrow wavelength spacing (0.1nm) based on FWM by inserting a high fineness Fabry–Perot filter (F–P filter) and a 500 m HNLF into the cavity. This double-pass structure produced up to 40 stokes lines spanning 1563.7 nm to 1567.6 nm (T. Liu et al., 2016). The FWM process suppressed the mode competition in the EDFL. In 2017, A. W. AL-ALIMI et al. reported an experimental demonstration of wide bandwidth and flat multiwavelength BEFL. The design consisted of the ring cavity with FWM assistance (primary cavity) and the Brillouin mirror with feedback (secondary cavity) to produce 200 channels tuned over 16 nm spectral with a flatness of 4.65 dB. The 500 m HNLF put in the primary cavity served as the seed provider via FWM processes in this design. In contrast, the inclusion of the secondary cavity provided Rayleigh components for the oscillating signals (Al-Alimi et al., 2017).

In 2018, Saleh et al. created a multiwavelength erbium-doped fiber laser (EDFL) based on random distributed feedback using a 25-km-long single-mode fiber (RDFB). The random EDFL consisted of a half-opened linear cavity with a mirror at one end and the RDFB of the SMF at the other (Saleh et al., 2018). The instability generated by the RDFB and cascaded stimulated Brillouin scattering in the laser cavity was successfully minimized by the FWM effect in a 2-km-long highly nonlinear fiber. At a pump power of 350 mW, the experimental results showed the creation of 24 steady laser lines. The influence of the HNLF on the laser cavity was summarized in two points. The first point illustrated the improvement of the laser oscillation. The second point focused on the progression of the output spectrum in the case of including and removing the HNLF. By including the HNLF, two primary spikes occurred in the spectrum, 0.08 nm apart at 50 mW pump power. In contrast, in the HNLF absence and at the same pump power, the

Brillouin stokes component was not observed. That meant the presence of HNLF broadened the wavelength range.

It was possible to create a broadband multi-wavelength Brillouin laser with an operational wavelength of about 100 nm (1500–1600nm) (Li et al., 2018). The frequency separation of 9.28 GHz was created by cascaded FWM in the dual-wavelength Brillouin fiber laser cavity utilizing 500 m HNLF. Firstly, cascading Brillouin scattering, and four-wave mixing were used to build multi-wavelength Brillouin lasers with an operating wavelength range of 20 nm (1554–1574 nm) utilizing a single continuous-wave laser as the pump source. Then, the operating wavelength range of the multi-wavelength Brillouin lasers was raised to 100 nm when pumped by two continuous-wave lasers with adequate frequency separation.

A switchable multi-wavelength erbium-doped fiber laser (EDFL) was suggested in 2019 based on a two-mode fiber (TMF) with core offset architecture and the FWM (Zhao et al., 2020). Splicing a portion of TMF with two sections of SMF yielded the suggested filter. The output wavelengths could be single, dual, or triple wavelengths by altering the polarization controller (PC) due to the filter spectra's features and wavelength competitions. The FWM was built with 120 m of highly nonlinear fiber to minimize strong gain competition (HNLF). The number of output lasers was increased due to the intensity-dependent gain induced by FWM. The outputs might be quadruple, quintuple, septuple, and decuple wavelength by changing the PC. Using the HNLF to introduce the FWM, the number of the generated laser lines was improved to six within 30 dB. However, due to the inadequate nonlinear accumulation given by HNLF, the output flatness was unacceptable.

A half-open cavity multi-wavelength Erbium–Brillouin random fiber laser (MW-EBRFL) with a section of HNLF was developed as a tunable and switchable multi-wavelength Erbium–Brillouin random fiber laser (MW-EBRFL) (F. Wang & Gong, 2020). Because of its high nonlinear coefficient, high Brillouin gain coefficient, and high Rayleigh scattering (RS) coefficient, a shorter HNLF could produce strong random distributed feedback and a large SBS gain. A high-power erbium-doped fiber amplifier (HP-EDFA) and an optical attenuator were used to create an optical fiber amplifier loop

(OFAL) to compensate for the significant loss of HNLF. This OFAL was utilized to magnify the Brillouin pump and provide cascade feedback on each order of stokes lasing emission as the following order's BP was created. The suggested MW-EBRFL was able to produce stokes lines that tuned over 36 nm tuning range. Moreover, this MW-EBRFL accomplished switchable multi-wavelength generation of 11th order stokes by adjusting the HP-EDFA pump power, resulting in a rising wavelength.

Using 100 m of HNLF to arouse FWM (Zhou et al., 2019), a setup was achieved to investigate the effects of FWM on the stability and uniformity of MBEFL. Sixteen laser lines with a 0.084 nm wavelength spacing were obtained within a 3 dB bandwidth. Using HNLF, the number of output channels and the threshold power were increased, and the output of the fiber laser became more stable and uniform compared to the same MBEFL without HNLF due to the FWM effect in preventing cross-gain saturation in the cavity.

(P. Wang et al., 2019) used Brillouin-comb-assisted FWM to construct a wide-spectrum multi-wavelength fiber laser. The laser's function was based on a combination of the SBS and multiple FWM processes outside the cavity. Brillouin-comb assistance was a practical approach to improving the FWM process and increasing the number of lines in the experiments. The properties of multi-wavelength fiber lasing were assessed before and after utilizing HNLF concerning EDFA3 output power, TSL wavelength, and input comb line number. More than 110 lines were obtained in a 10-nm spectral range with 0.09 nm wavelength spacing. The multi-wavelength fiber laser was very stable at both operating wavelengths and output power. The tunability of this multi-wavelength fiber laser was greatly improved by introducing a tunable filter into the cavity. The total line number was still larger than 110 across the entire tunable range of 30 nm (1540-1570 nm). The disadvantages of this configuration were that the tunability of the generated laser lines was mainly dependent on the EDFA3 and the tunability of the laser comb of the Brillouin cavity. Therefore, the tunability of the laser lines was limited to the C-band region (1540-1570 nm). Besides that, using a small SMF length of 1km led to increasing the SBS threshold value and, subsequently, high EDFA1 and EDFA2 gains were required to achieve sufficient inserted power into the Brillouin gain medium.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1 Introduction

This chapter states the research method for measuring and observing the experimental investigation for the proposed MBEFL. Via flow charts, the general research methodology and the experimental flow of the proposed setup are included in this chapter, besides the flow chart that considers all the design variables and input parameters. This chapter also discusses the general research and designing process, components, and equipment employed in the proposed MBEFL setup. Finally, an explanation of the experimental examination of the multiwavelength fiber laser with the multiple four-wave mixing cavity is included.

3.2 General Flow of Designing a Multi-wavelength Fiber Laser

The general research flow of designing a multi-wavelength fiber laser is depicted in Figure 7. The bold lines show the flow of the research procedures. This work discusses a multiwavelength fiber laser based on the FWM process assisted by a multiwavelength Brillouin erbium fiber laser.

A traditional linear cavity BEFL boosted four-wave mixing is experimentally demonstrated. For the linear cavity performance parameter, the effect of the two nonlinear phenomena of successive SBS within the internal linear cavity and multiple FWM experiences outside of the cavity is investigated. In this work, the proposed BEFL is analyzed and developed. During the research, many output parameters are investigated: stokes threshold power, stokes signal power, number of generated stokes lines, and tuning range.

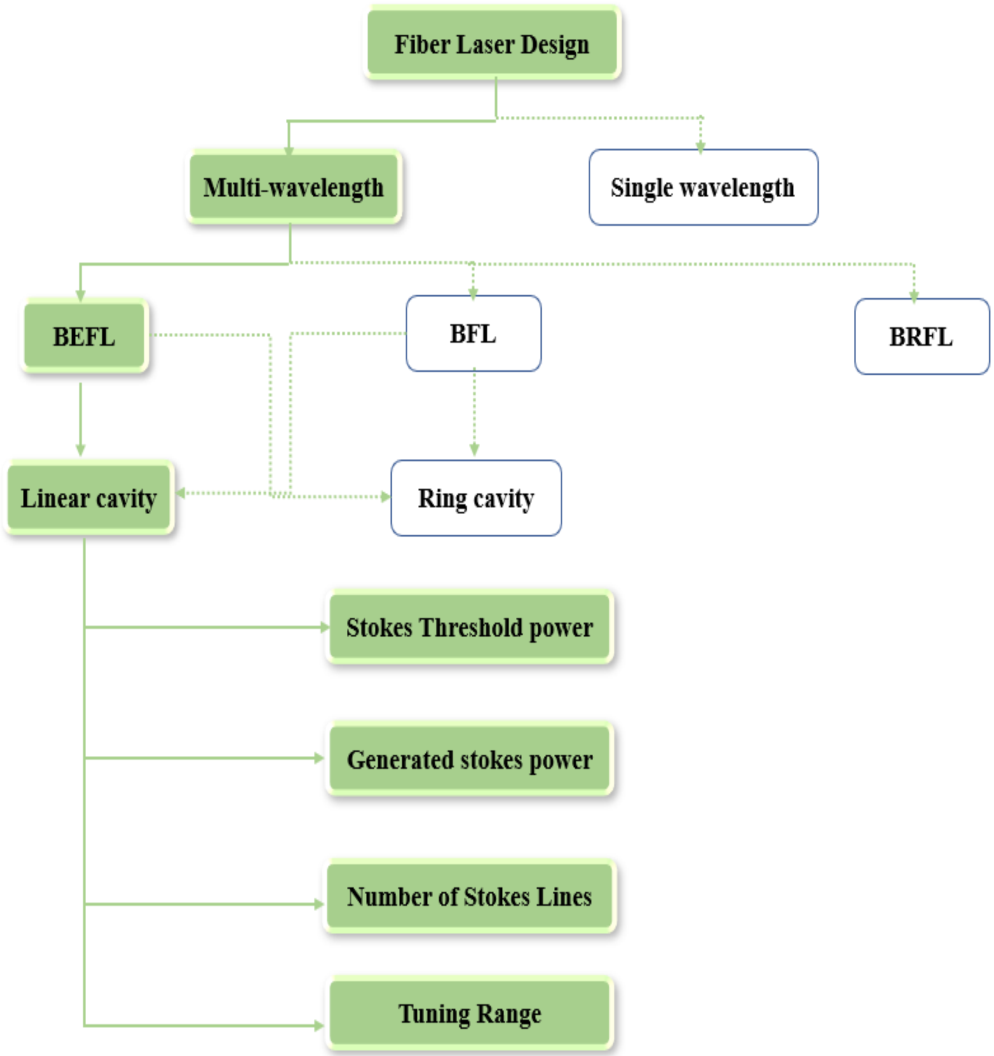


Figure 7. The general flow of designing a multi-wavelength fiber laser

3.3 Equipment and Components

Optical spectrum analyzer (OSA) is utilized to record the output spectrum, threshold power, and the generated stokes signals. A tunable laser source (TLS) provides a BP power signal. To prevent any reflection back into the TLS, an optical isolator (OI) is utilized. In addition, a dispersion compensation fiber (DCF) is used as a Brillouin gain medium. Two EDFA sections are used; in the internal cavity, the injected BP experiences a pre-amplification through EDFA1 before it is inserted into the Brillouin gain medium (DCF). While the EDFA2 section and the standard HNLF are used in the external cavity to achieve the FWM process. Two optical circulators, Cir1 and Cir2, with a wide optical band of 1520-1620 nm, are used as Brillouin erbium cavity resonators. All the optical equipment and components utilized in the experimental setup, measurements, observation, and data collection are listed in Table 1.

Table 1. Components and equipment used in the experimental study.

Equipment and components	General specifications	
Optical spectrum analyzer (OSA)	Measurement wavelength range	600 to 1750 nm
	Wavelength linearity	± 0.01 nm (1520-1580 nm)
	Wavelength reproducibility	±0.005 (for one minute)
	Maximum wavelength resolution	0.03nm
External Tunable laser sources (TLS)	Resolution accuracy	± 5%
	Wavelength resolution	0.001 nm
	Maximum power wavelength	+14.5 dBm
	Relative wavelength accuracy	≤ ± 0.01 nm
	Wavelength range	150 nm (1480-1630 nm)
Erbium Doped Fiber-M12 (EDF)	Numerical Aperture	0.21 - 0.24
	Absorption (dB/m)	11.0 – 13.0 @980nm
	16.0 – 20.0 @1531nm	
	Attenuation (dB/km)	≤10 @1200nm
	Length	3 m
EDF type Er30/110	Length	10 m
Dispersion compensation fiber (DCF)	Model number	DCM-80
	Designed for	SMF-28, (ITU G.652)
	Chromatic Dispersion	-1360±10 ps/nm
	Fiber Length	6 km

	Insertion Loss 9.0 ± 0.5dB
2x2 Optical Coupler	Coupling Ratio 50:50 Center Wavelength 1550 nm Minimum Bandwidth ±40 nm
1x2 Optical Coupler	Coupling Ratio 10:90 Center Wavelength 1550 nm Minimum Bandwidth ±40 nm
Optical circulator	Operating Wavelength 1460nm-1620nm Isolation (dB) Port 2 to Port 1: 50dB minimum Insertion Loss (dB) Port 1 to Port 2: 0.8dB maximum Return Loss (dB) 55dB minimum
Optical isolator	Center wavelength: 1550nm Isolation bandwidth: $\pm 30nm$ insertion loss: 0.6dB
Wavelength division multiplexer (WDM)	Input Fiber [2] Wavelength 1300nm - 1515nm Input Fiber [3] Wavelength 1520nm - 1620nm Output Fiber [1] 1300-1515nm / 1520-1620nm Insertion Loss: [1] to [3] 0.30dB typical Insertion Loss: [1] to [2] 0.30dB typical Input and output Fiber Type SMF-28, 250um
1480 nm pump laser diode (LD)	Fiber-coupled power = 500 mW Output power: 500mW

Highly nonlinear fiber (HNLF)	Chromatic dispersion coefficient ~ 0.60 ps/nm/Km at 1550nm Zero-Dispersion Wavelength (ZDW) = ~ 1495nm Nonlinear Coefficient =~ 10.7 /W/Km at 1550nm Length = 200m

3.4 General Research Methodology

Figure 8 illustrates the general research approach setup used in this thesis. This work studies the effect of the FWM process on the laser comb tunability and the number of generated stokes improvements. The MBEFL cavity consists of internal and external cavities. The internal cavity consists of a linear cavity that incorporates the BP pre-amplification technique through EDFA1 before it is inserted into the Brillouin gain medium to achieve a wider tuning range of the obtained Brillouin stokes lines. On the other hand, the external cavity consists of an EDFA2 section and standard HNLF in order to achieve the FWM process. The characteristics of the achieved fiber laser lines in the cases of with and without FWM process are investigated under the conditions of different 1480 nm pump powers, different BP wavelengths, and BP power variation.

Firstly, the conventional linear cavity with Brillouin pump pre-amplification technique adjusts powers of BP and 1480 pump and the BP wavelength. After that, the self-lasing cavity modes are recorded in the absence of BP power and FWM block. Then, for the case of un usage of the FWM block, the input parameters of the setup: TLS power, BP power, 1480 pump power, and wavelengths are adjusted as well as the properties of EDFA1 to generate a coherent Brillouin Stokes comb. Before being introduced into the Brillouin gain medium (DCF), the injected BP within the internal cavity experiences pre-amplification through EDFA1.

For the FWM block usage case, after setting the EDFA2 and HNLF properties, the generated Brillouin stokes comb is injected into the external cavity in order to achieve the FWM effect.

In order to achieve good tunability, flatness, and more stoke lines, the EDFA's sections' type and length are tuned carefully. By changing and setting the BP and 1480 pump powers, the optimum output parameters, such as the number of the generated stokes lines, tuning range, and laser cavity threshold, are adjusted. If the output is satisfactory, the process continues until the gains and losses are equal. If it is not, the flow must be repeated from the beginning to design the appropriate MBEFL.

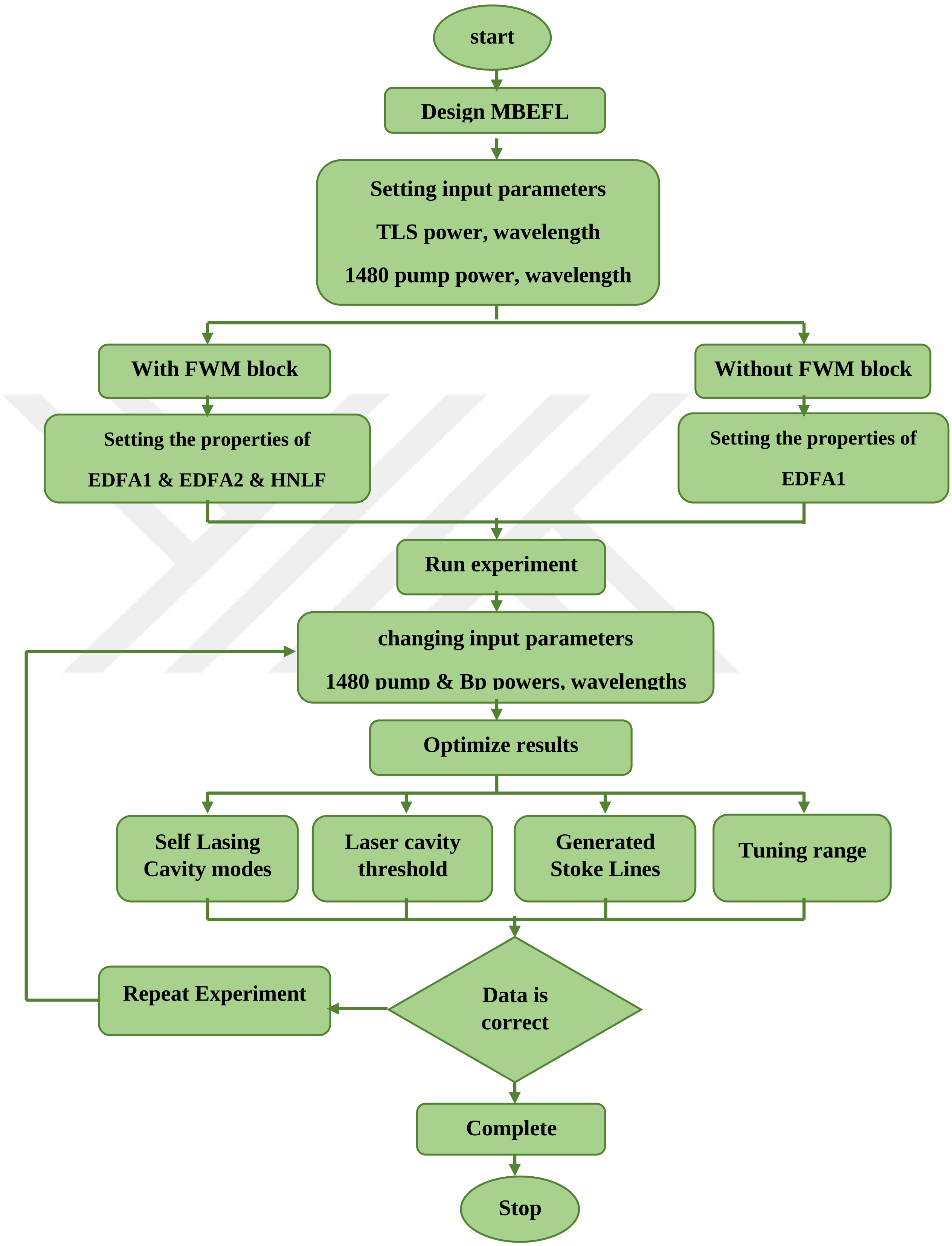


Figure 8. General research flow chart.

CHAPTER FOUR

EXPERIMENTAL RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents an MBEFL assisted four wave mixing process by combining the SBS and FWM phenomena into one design. The Brillouin Stokes comb cavity (internal cavity) is formed according to the conventional linear cavity with a Brillouin pump (BP) pre-amplification technique. The FWM effect within the external cavity is achieved by an EDFA2 and a section of HNLF. The EDFA2 section is used to achieve a wide emission peak within the C+L bands so that the generated Brillouin comb of 120 laser lines can be tuned over a wide tuning range reaching 50 nm.

4.2 Experimental Setup

Figure 9 shows the experimental setup of the proposed multiwavelength fiber laser. Two cavities constitute the setup; an internal cavity generates a coherent Brillouin stokes comb and an external cavity that produces the FWM effect. The internal cavity (MBEFL cavity) consists of a linear cavity that incorporates BP pre-amplification technique. The TLS with a range of wavelengths of 150 nm (1480-1630 nm) achieves BP power. An optical isolator avoids any reflection back into TLS. The BP power is injected into both internal and external cavities through a 3-dB coupler. The injected BP within the internal cavity experiences a pre-amplification through EDFA1 before it is injected into the Brillouin gain medium (6 km DCF). Because the Brillouin gain achieved by DCF is five times that of a SMF, it is used as a Brillouin gain medium. The BP pre-amplification technique increases the Brillouin gain inside the DCF and achieves a wider tuning range of the obtained Brillouin stokes lines. The amplifier section EDFA1 consists of 3 m of EDF type M12, pumped by 10% of the total power of 1480 nm pump through WDM1 coupler. This length is used to achieve good flatness gain within C and L-bands to the generated Brillouin stokes lines. Two optical circulators Cir1 and Cir2, with a wide optical band of 1520-1620 nm, are used as Brillouin erbium cavity resonators. On the other hand, the external cavity consists of an EDFA2 section and 200 m of standard HNLF to achieve the FWM process. It is connected to the output port of the internal cavity so that the generated Brillouin comb can be injected into the cavity. EDFA2 section consists of 10 m of EDF type Er30/110, pumped by 90% of the 1480 nm pump power through the WDM2 coupler. Using such a type of EDF can result in a wide emission peak that covers both C and L-bands. A 200 m of standard HNLF is used to achieve the FWM effect. The power of the 1480 nm pump unit is 500 mW that is distributed to EDFA sections.

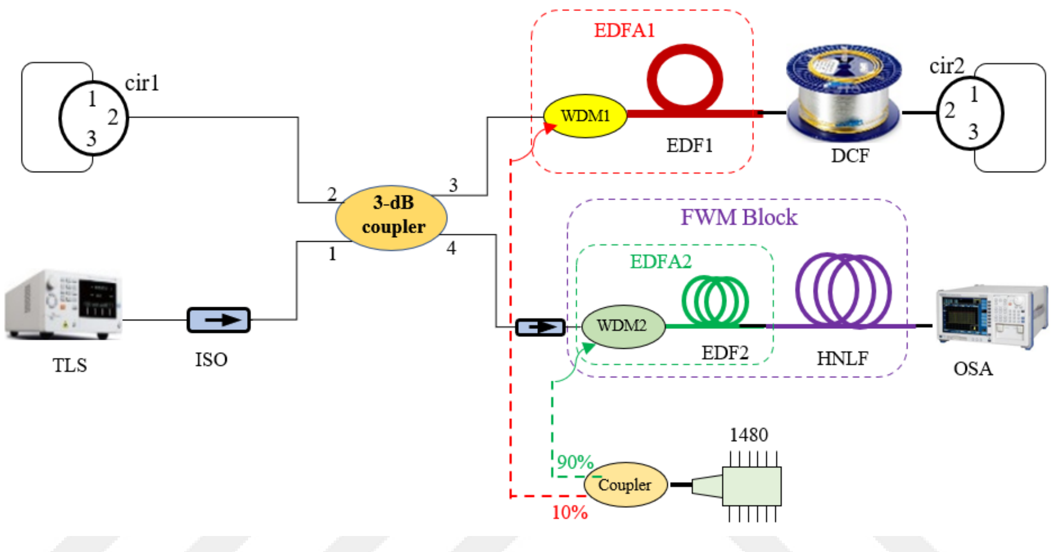


Figure 9. The proposed setup of combination BEFL cavity and FWM block.

At first, the BP is inserted to EDFA1 then into the DCF via a 3-dB coupler. When the amplified Brillouin pump (Bp) signal reaches the threshold value, the first order Brillouin stokes signal with Brillouin frequency shift of 0.075 nm is generated. The generated 1st stokes signal is experiencing gain within the EDFA1 section. Then, passing through ports 3 and 2 of the 3-dB coupler, the 1st stoke signal is reflected to port 2 of Cir1. After that, via port 2 of Cir1, the 1st stokes signal will be reflected into both EDFA1 and EDFA2 sections through port 3 and port 4 of the 3-dB coupler, respectively. The inserted 1st stokes power to EDFA2 section is to achieve FWM stokes and anti-stokes within HNLF. While the other part of the 1st stokes power that is inserted to EDFA1 is responsible for generating the higher-order stokes signal. The process can be continued until the total gain and the total loss is equal.

4.3 Results and Discussions

4.3.1 The Generated Stokes Lines Enhancement

Figure 10 shows the self-lasing cavity modes of the BEFL cavity in the absence of BP and FWM block (OSA is connected to port 4 of the 3-dB coupler). A 10% of the total pump power was used for the EDFA1 section. Two total pump powers values of 150 and 475 mW were used. Almost flat peak emission was achieved within 60 nm (1550-1610 nm). These modes were obtained after careful selection of EDF1 length and type in addition to the suitable pump power value. The self-lasing cavity mode was recorded to select the appropriate BP wavelength satisfying the maximum gain.

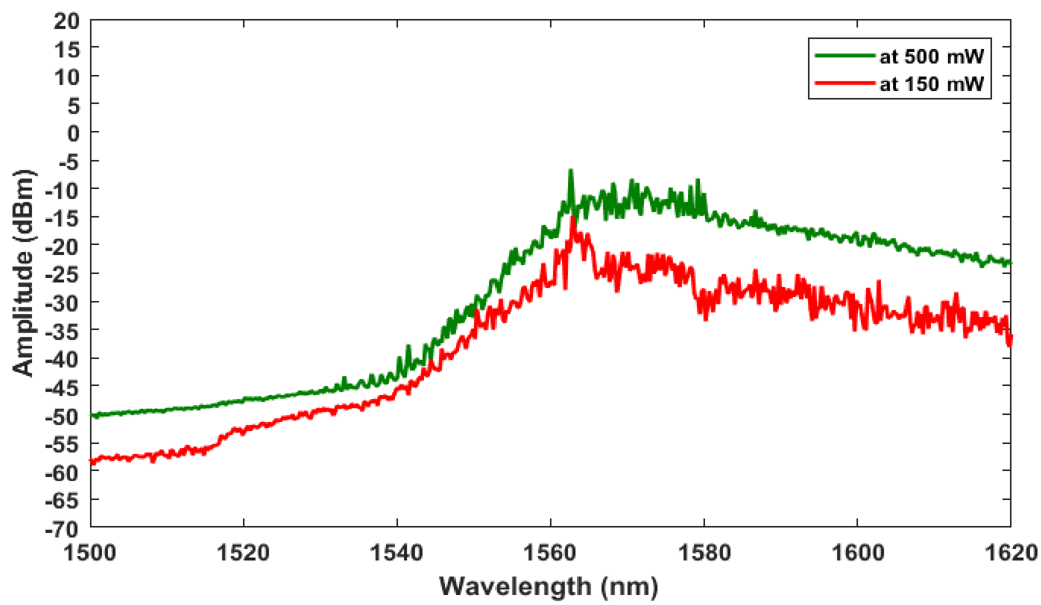
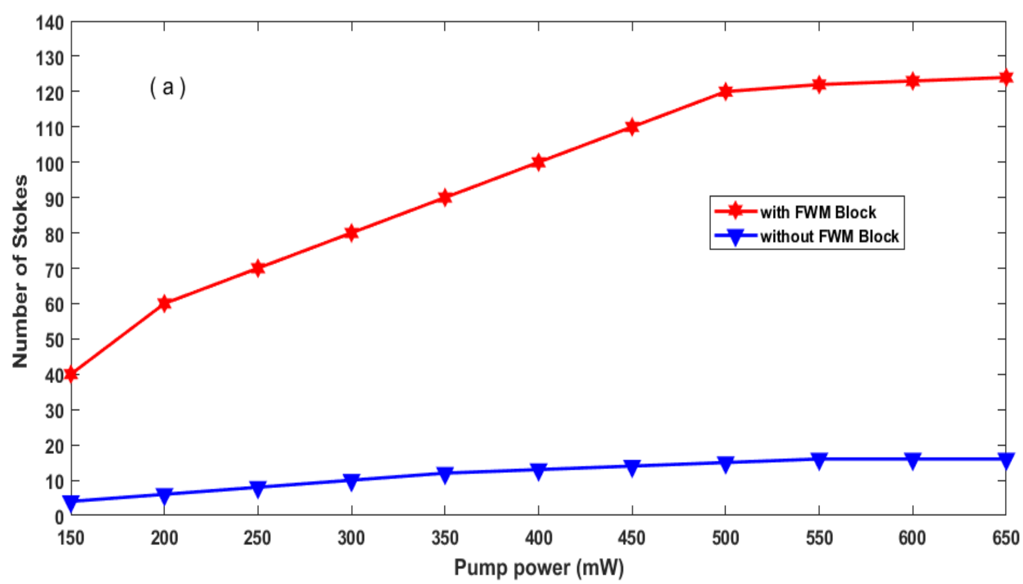


Figure 10. The free-running modes

Figure 11 illustrates the number of the created Brillouin laser lines at port 4 of the 3-dB coupler and after the FWM block as a function of 1480 nm pump power. To show the effect of the pump power on the number of generated stokes, a BP power value was fixed at 7 dBm. To achieve high gain, the BP wavelength of 1580 nm was utilized according to the emission peak of the EDFA1 (Figure 10) to experience high gain.

Figure 11 (a) shows the multiple stokes lines in the absence and presence of an FWM block at various pump powers of 1480 nm. While figure 11 (b) illustrates the output spectra of the multiple stokes lines in the presence of the FWM process. The two amplifier sections (EDFA1 and EDFA2) share the same 1480 nm pump power with 10 and 90% insertion ratios, respectively. The multiple Brillouin stokes lines are dependent on the induced gain within the EDFA1 section and changing the pump power of 1480 nm from 150 to 650 mW. So, the generated stokes lines increased by increasing the pump power until it tended to be saturated at a pump power value of 350 mW. The number of the generated stokes almost remained the same for pump power value more than 500 mW. The saturation was due to the large pump power inserted into the EDF1. The number of the fiber laser lines after the FWM block was also recorded. It can be clearly seen that the number of the stokes lines were increased with the increment of the 1480 nm pump power. Up to 40 fiber laser lines at 0.075 nm Brillouin frequency shift was obtained at 150 mW. By increasing the pump power from 200 to 450 mW, with 50 mW step, the recorded fiber laser lines were 60, 69, 78, 85, 97, and 108, respectively. At the optimum pump power of 500 mW, a total fiber laser line of 120 with a rigid frequency shift of 0.075 nm was achieved. The output spectra of the generated fiber laser lines were recorded after the FWM block, as depicted in figure 11 (b). The 1480 pump power was varied from 150 to the optimal pump power of 500 mW. It can be clearly seen that the output spectrum bandwidth was increased with the increment of the 1480 pump power.



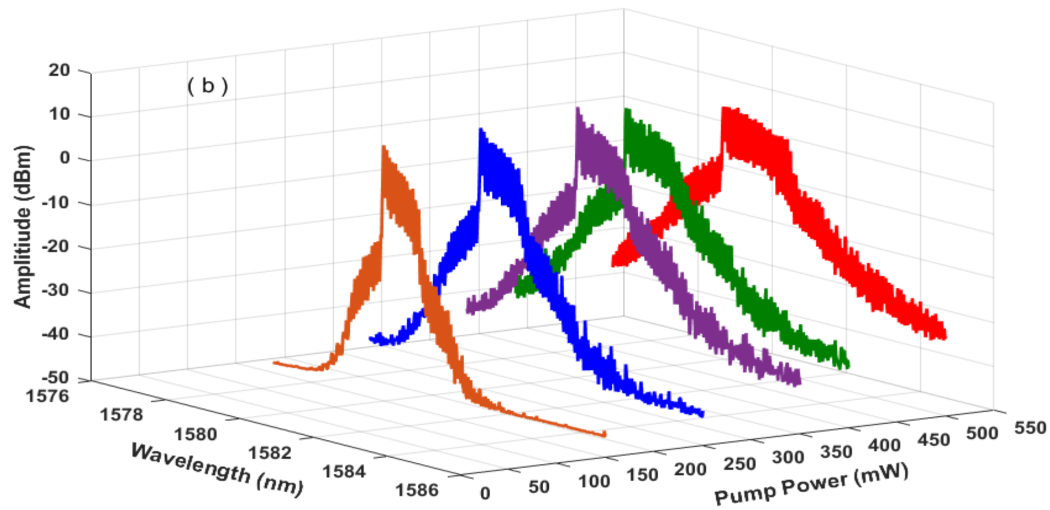
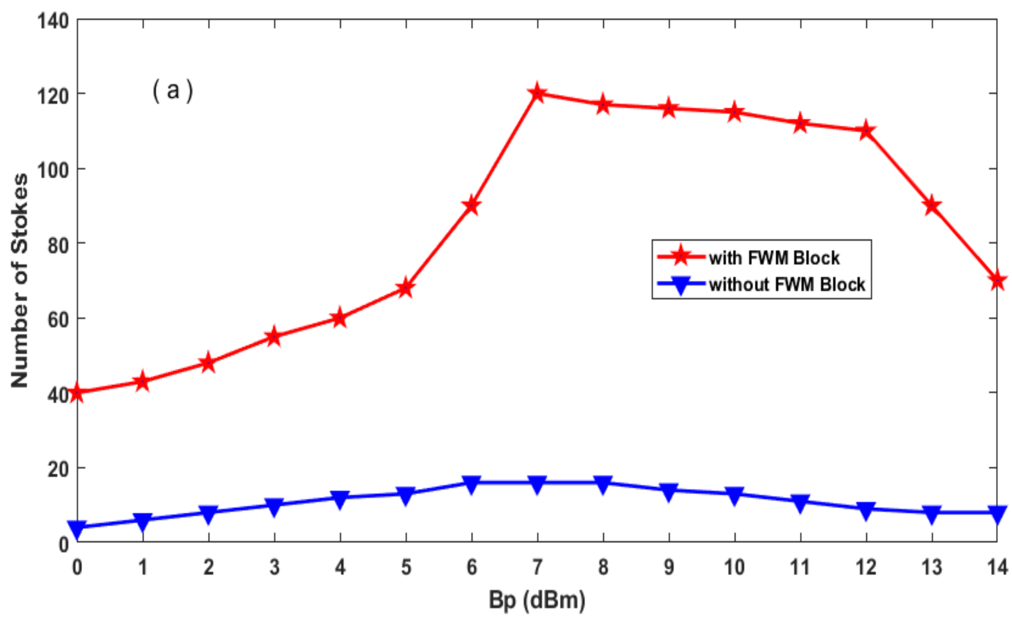


Figure 11. a) BEFL spectra for different 1480 nm pump powers and b) output spectra after FWM blook versus 1480 nm pump powers.

Figure 12 illustrates the effect of the BP power on the generated Brillouin stokes lines and the generated fiber laser lines after the FWM block at the optimal 1480 nm pump power of 500 mW. The BP power was varied from 0 to 14 dBm to show the optimal BP power to achieve higher Brillouin stokes lines to be inserted into the FWM block. Generating an increased number of stokes and anti-stokes lines within the FWM block is mainly dependent on the inserted coherence lines from the internal cavity. Therefore, the output spectrum after the FWM block can be improved by increasing the number of created Brillouin stokes lines. Figure 12 (a) shows the number of stokes lines generated before and after the FWM block. By varying the BP power from 0 to 14 dBm, with a 1dBm step, the recorded Brillouin stokes lines at port 4 of the 3-dB coupler (before FWM block) were 4, 7, 16, 16, 13, and 8 for the BP power of 0, 3, 7, 10, 12 and 14 dBm respectively. As shown in Figure 11 (a), EDF1 was saturated at 350 mW. Therefore, the EDFA1 section worked under deep saturation due to the large pump power of 500 mW, and the number of the generated stokes lines was highly dependent on the inserted BP. When the BP reached 7 dBm, the number of created stokes lines was raised from 4 to 16. At 10 dBm of the BP power, the same 16 stokes line numbers were created. Further increment in the BP power beyond 10 dBm, the number of the stokes lines was reduced to be 13 and 8 lines with BP power of 12 and 14 dBm, respectively. This is due to the deep saturation in the EDFA1 section caused by the large input signal power that makes the resulting Brillouin gain within the amplifier section insufficient to suppress the high self-lasing cavity modes inside the cavity. Figure 12 (a) also illustrates the number of the generated fiber laser lines after FWM blook at the BP power of (2, 6, 8, 10, 12, 14 dBm). It can be clearly seen that the number of stokes lines was increased almost linearly with increasing the BP power and reached the maximum of 120 lines at BP power of 7 dBm. After this value of BP power, the number of the generated stokes lines was almost saturated at the same lines, and the decay started at BP power more than 12 dB due to the same reason. The decline in the number of the stokes lines after the FWM block can be attributed to the decrease of the Brillouin stokes lines generated by the internal cavity. The output spectra of the generated stokes lines at the end of the FWM block as a function of BP power variation were recorded as shown in Figure 12 (b).



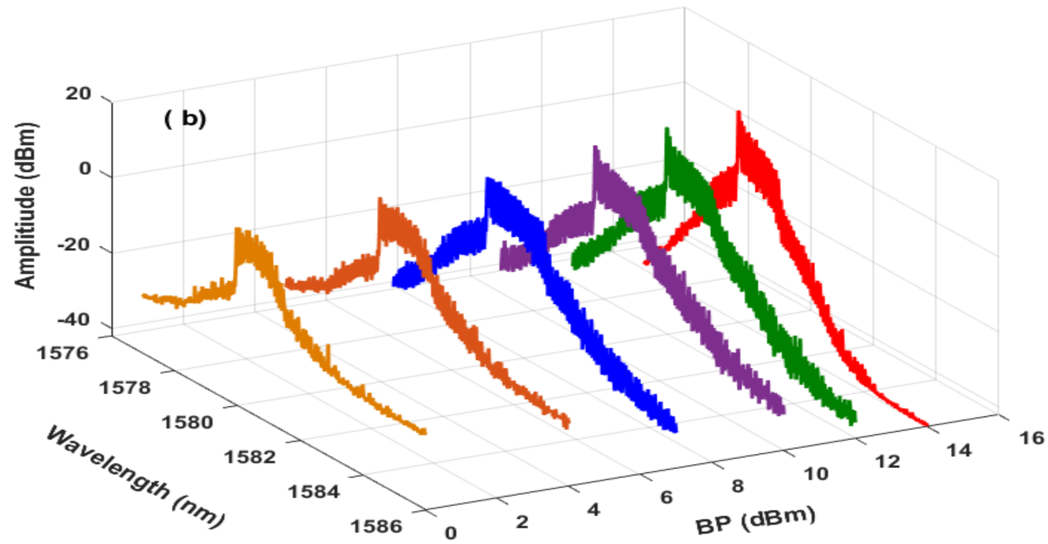


Figure 12 a) The output spectra at different BP power and optimal pump power of 500 mW b) output spectra after FWM block.

4.3.2 Improving Tunability

BP pre-amplification technique, high BP power, and wideband emission peak of EDFA2 were used to improve the multiwavelength fiber laser tunability. Both internal and external cavities had to be controlled to obtain a wide tuning range. For this context, high BP and pre-amplification techniques were implemented in the internal cavity to suppress the self-lasing cavity modes. Therefore, a wide tuning range of 1550 to 1600 nm was recorded for the Brillouin stokes lines. To keep the tunability at this wide range, EDFA2 was carefully chosen so that the inserted Brillouin lines to the FWM block can be tuned over a wide range or at least keep the tuning range of the generated Brillouin stokes lines. At the optimum values of BP and 1480 pump powers, the BP wavelength was tuned over a wide range of 50 nm (1550-1600 nm) with a step of 10 nm, and the output spectra at the end of the FWM block were recorded at a resolution of 0.1 nm as depicted in Figure 13. As it is easy to notice, the self-lasing cavity modes were completely suppressed and did not appear in the output spectra of the fiber laser. And that is because of suppressing the self-lasing cavity mode of the internal cavity using the high BP and pre-amplification technique. Subsequently, the high Brillouin gain of the induced Brillouin stokes lines was able to suppress the self-lasing cavity modes of EDFA2. In contrast, by tuning the BP wavelength beyond this range, the introduced Brillouin gain was insufficient to suppress the free-running modes of these two cavities.

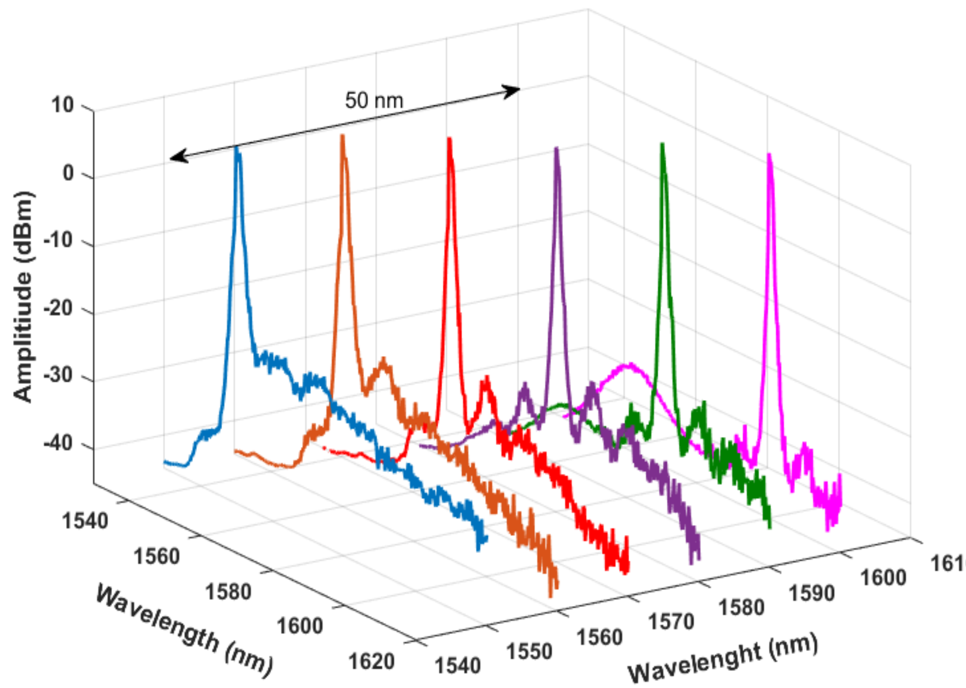


Figure 13. Fiber laser spectra at various BP wavelengths at the optimum values of BP and 1480 nm pump power.

To show the influence of the BP wavelength change on the generated fiber laser lines, after the FWM block, the output spectra of the fiber laser lines were recoded within the laser cavity tunability of 50 nm (1550-1600 nm) with a step of 10 nm as depicted in Figure 14 (a-f). Referring to Figure 10, the free-running mode has an almost flat peak gain from 1560 to 1590 nm. Therefore, within these BP wavelengths the internal and external cavities generated the same number of fiber laser lines. Experimentally, up to 120 lines were observed over the tuning range (Figure 14 (b-d)). The number of generated laser lines was reduced when moving away from the peak gain of the free-running mode at 1600 (Figure 14f). The worst-case was at 1550 nm due to the low peak gain of free-running modes at such wavelength. Thus, the number of laser lines was reduced due to the competition of the free-running modes with the low introduced Brillouin gain (Figure 14a).

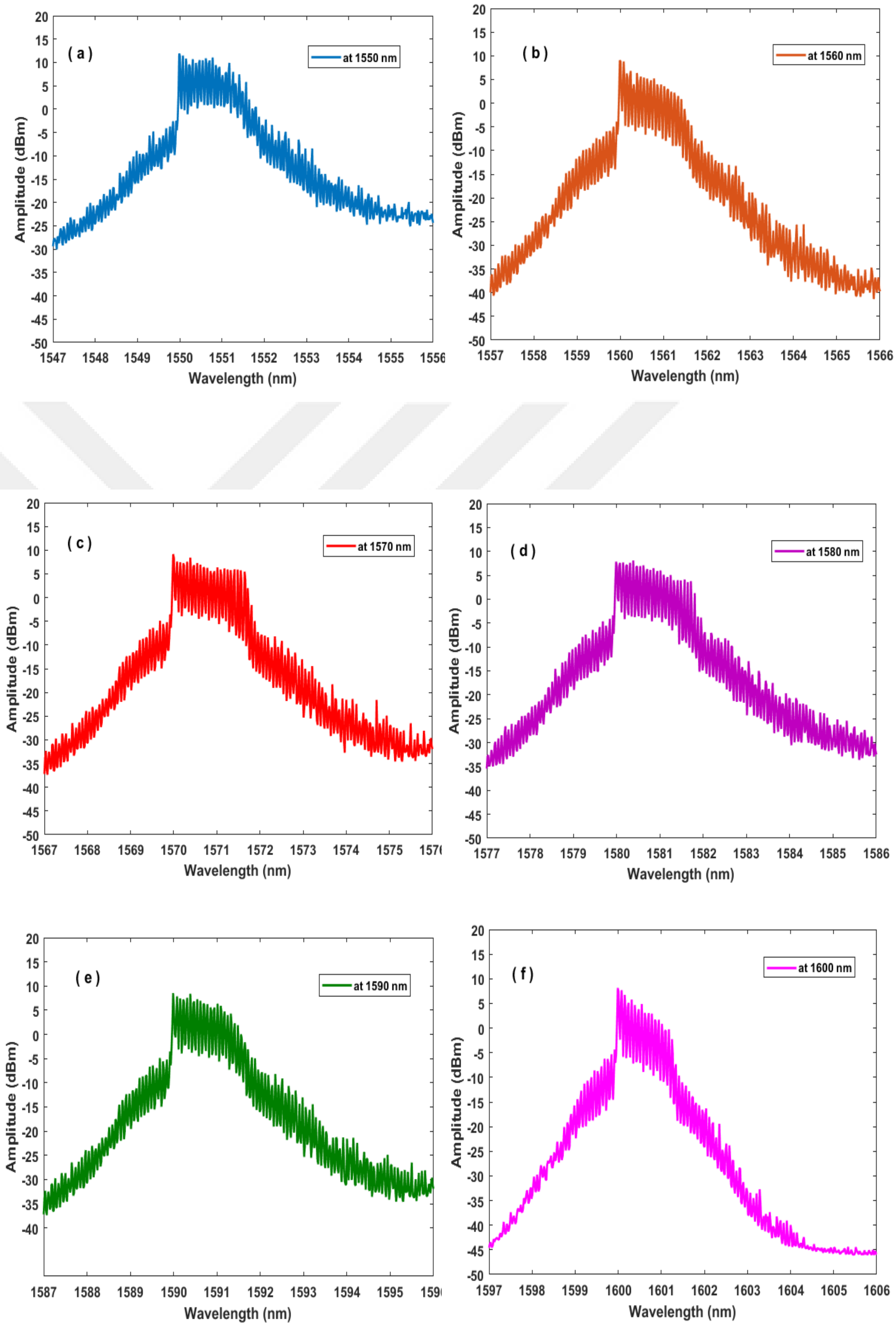


Figure 14 (a-f): Output fiber laser spectra at different BP wavelengths within tuning range band of 50 nm.

The output spectra of the lasers at the optimal BP power, BP wavelength, and optimal pump power showed in Figure 15 (a and b). In case of un usage of the FWM block, 9 Brillouin stokes lines with a 0.075 nm frequency shift were recorded within 3 dB bandwidth, 15 stokes lines were obtained within 10 dB bandwidth, and 16 stokes lines by expanding the bandwidth to 20 dB. When the FWM block was added to the cavity, 24 Brillouin stokes lines at the same frequency shift were recorded at 3 dB bandwidth; similarly, at a bandwidth of 10 and 20 dB, 29 and 52 stokes lines were generated, respectively.

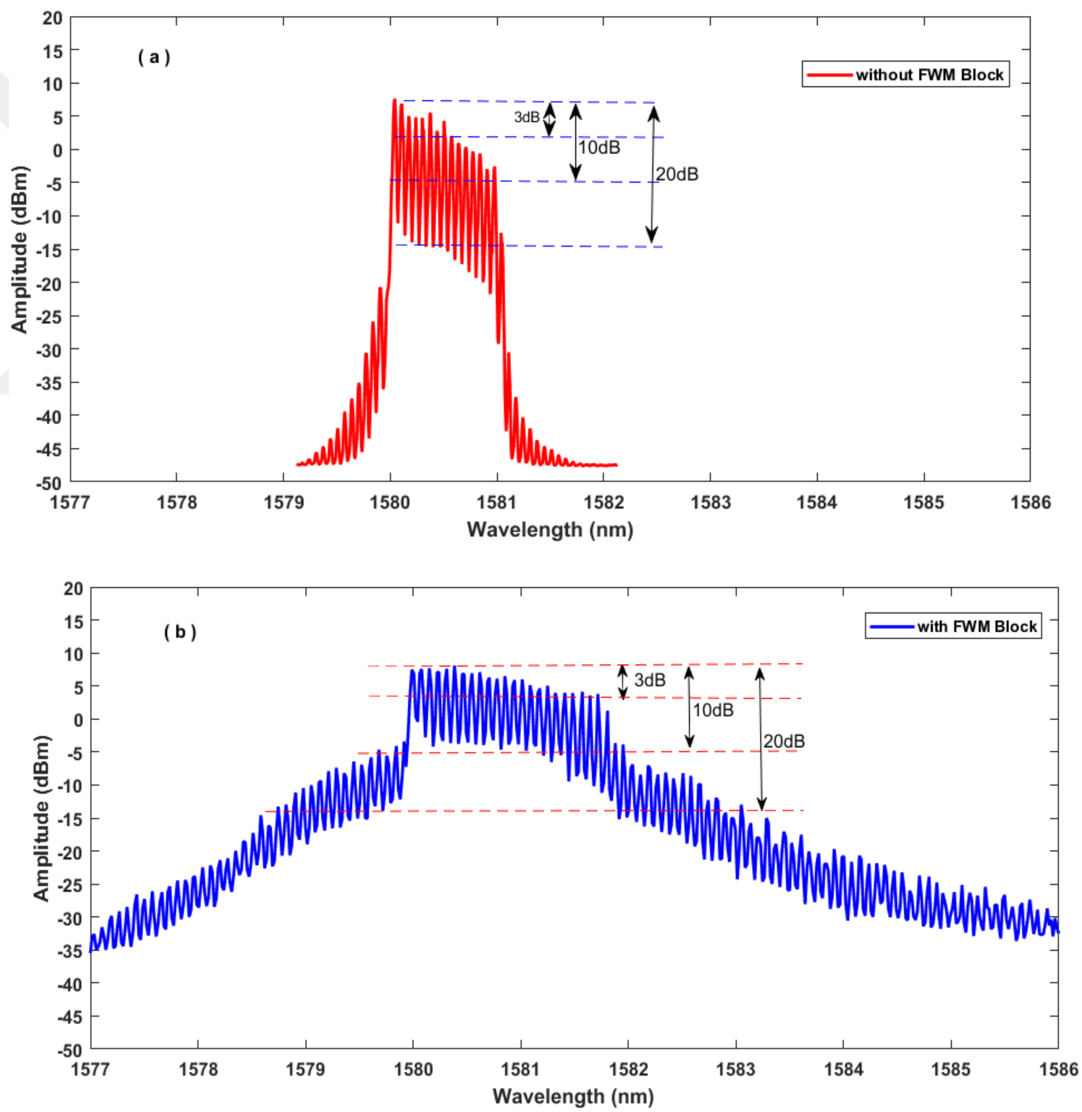


Figure 15. The output spectra at the optimal conditions: a) Brillouin Stokes lines without FWM block, b) fiber laser in the presence of FWM block.

4.4 Results Comparison

The performance comparison of the proposed design with (Zhou et al., 2019) and (P. Wang et al., 2019) in terms of generated laser lines number and the tuning range is shown in table 2.

Table 2. The comparison of setups performance

	No. of generated stokes	No. of stokes			Tuning range
		3 dB	10 dB	20 dB	
The proposed setup	120	24	29	52	50 nm
(Zhou et al., 2019)	NA	16	26	33	NA
(P. Wang et al., 2019)	110	NA	8	NA	30 nm

Due to the FWM's occurrence outside the linear cavity and the careful optimization of both EDFAs' sections, the results show that the proposed setup with 24, 29, and 52 generated laser lines within 3, 10, and 30 dB is effectively enhanced compared to the other setups.

Using the high BP power and pre-amplification technique in addition to the erbium-doped fiber with a wide emission peak, C+L, the laser lines tunability is improved to reach 50 nm, compared to only 30 nm limited to C band (1540-1570 nm) (P. Wang et al., 2019).

CHAPTER FIVE

CONCLUSIONS AND FUTURE WORK

5.1 Conclusion

In this thesis, a broadly Multiwavelength fiber laser created by Brillouin Stokes lines boosted four-wave mixing is experimentally presented. It combines two nonlinear phenomena of successive stimulated Brillouin scattering within the internal cavity, linear cavity, and the multiple four-wave mixing experiences out of the cavity. The fiber laser comb tunability is mainly dependent on the Brillouin Stokes lines' tunability and the FWM block's tuning range outside the cavity. So, using the high BP power and pre-amplification technique and the EDF2 with a wide emission peak, C+L, the laser lines tunability is improved. The characteristics of the achieved fiber laser lines in the case of with and without FWM process are investigated under the condition of different 1480 nm pump powers, different BP wavelength, and BP power variation.

Due to the FWM's occurrence outside the linear cavity and the careful optimization of both EDFAs' sections, the results show that at the optimal input parameters conditions: BP power (7dBm) with a wavelength of 1580 nm and pump power of 500 mW; 24 stokes lines within 3 dB bandwidth. Also, 29 and 52 stokes lines are achieved within 10 and 20 dB bandwidth, respectively. In total, over 120 stokes lines are obtained that tuned over 50 nm tuning range with a single Brillouin frequency shift of 0.075 nm.

Using the proposed setup, a multiwavelength fiber comb with a high stokes number and wide tuning range can be produced, and the used number of power units was reduced.

5.2 Recommendation for future work

The following suggestion can be taken in consider developing the work presented in this study.

1. Using a new type of optical amplifier in the internal cavity to improve the stokes flatness and broadening the tuning range of the FWM cavity.

2. The FWM process can be assisted by a wider Brillouin frequency shift (channel spacing) of 20, 30, 40 and 50 GHz to avoid any detection problem at the receiver side of the optical communication system.

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