DESIGN AND CHARACTERIZATION OF NARROW LINEWIDTH FIBER LASER FOR WIRELESS COMMUNICATION

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requirements for the award of the degree of
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Dedicated to:

My parents, siblings & my beloved husband…

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ABSTRACT

Ultra-high network capacity becomes more desirable mostly fueled by the widespread adoption of wireless communication and 3G cellular mobile radio system. Narrow linewidth fiber laser has become an essential criterion to realize high-speed data transmission technology. Optical filters are used widely as narrowing element in fiber laser system. A design of Erbium-Doped Fiber Laser (EDFL) configuration is constructed by incorporating different optical filters. The EDFL using Ultra-Narrow Bandwidth tunable filter (UNB-Tunable Filter) shows potential to become an ideal system with the ability to have high Optical-Signal-to-Noise-Ratio (OSNR), moderate output power and wide tunability. The Single Longitudinal Mode (SLM) and ultra-narrow linewidth was realized using Stimulated Brillouin Scattering (SBS) effect and 100 m highly nonlinear fiber. The proposed laser was operated in all-fiber ring configuration where the SBS effect takes place at the amplified output power of 26 dBm. Four Brillouin Stokes are produced spanning from 1550.17 nm to 1550.65 nm. Then, the amplified output was reduced to ~13 dBm intentionally to produce only the first Stokes. The Fabry-Perot filter (F-P filter) was applied to suppress the Brillouin Pump (BP) output signal to generate SLM laser. By utilizing delayed self-heterodyne measurement technique, the linewidth of 0.7 kHz was obtained which is the narrowest Brillouin linewidth reported so far. The application of narrow linewidth presented based on dual-wavelength fiber laser (DWFL). By implementing UNB-Tunable Filter and a Fiber Bragg Grating (FBG) within the EDFL ring configuration, the DWFL was successfully demonstrated. By varying the bandwidth of UNB-tunable filter from 50 pm to 650 pm, the DWFL spacing increased from 2 pm to 58 pm. The 2 pm DWFL found to be the narrowest spacing reported, which is really difficult to get due to mode competition faced by the cavity. The proposed design produced beat frequency spectrum of 0.25 GHz to 7.27 GHz corresponding to the DWFL output spacing of 2 pm to 58 pm. The obtained frequency will find applications and significantly potential in sensing and wireless communication.

ABSTRAK

Rangkaian berkapasiti tersangat tinggi menjadi lebih dikehendaki kebanyakannya didorong oleh penggunaan meluas komunikasi tanpa wayar dan sistem radio mudah alih selular 3 G. Laser gentian berkelebaran tirus telah menjadi satu kriteria yang penting untuk merealisasikan teknologi penghantaran data berkelajuan tinggi. Penuras optik digunakan secara meluas sebagai elemen penirusan dalam sistem laser gentian. Satu reka bentuk konfigurasi gentian laser terdop erbium (EDFL) dibina dengan menggabungkan penuras optik yang berbeza. EDFL dengan menggunakan penuras lebar jalur tersangat tirus boleh tala (UNB-penuras boleh tala) menunjukkan potensi untuk menjadi satu sistem yang ideal dengan keupayaan untuk mempunyai nisbah optik-isyarat-ke-hingar (OSNR) yang tinggi, kuasa output sederhana dan kebolehtalaan yang luas. Mod membujur tunggal (SLM) dan kelebaran tersangat tirus telah direalisasikan menggunakan kesan rangsangan penyerakan Brillouin (SBS) dan 100 m gentian ketaklinearan yang tinggi. Laser yang dicadangkan beroperasi dalam konfigurasi gelung berasaskan gentian di mana kesan SBS berlaku pada 26 dBm gandaan kuasa output. Empat Brillouin Stokes dihasilkan dari julat 1550.17 nm hingga 1550.65 nm. Kemudian, kuasa output yang digandakan telah dikurangkan kepada ~13 dBm bertujuan untuk menghasilkan hanya Stokes pertama. Penuras Fabry-Perot (penuras F-P) digunakan untuk mengurangkan isyarat output pam Brillouin (BP) bagi menjana laser SLM. Dengan menggunakan teknik pengukuran *heterodyne* kendiri tertunda, 0.7 kHz kelebaran telah diperolehi yang mana Brillouin berkelebaran paling tirus yang dilaporkan setakat ini. Aplikasi kelebaran tirus dikemukakan berdasarkan laser gentian dwi-panjang gelombang (DWFL). Dengan menggunakan penuras UNB-boleh tala dan gentian parutan Bragg (FBG) dalam konfigurasi gelung EDFL, DWFL telah berjaya ditunjukkan. Dengan mengubah UNB-penuras boleh tala dari 50 pm kepada 650 pm, jarak DWFL meningkat daripada 2 pm kepada 58 pm. 2 pm DWFL yang didapati adalah jarak tertirus pernah dilaporkan, yang mana sangat sukar untuk diperoleh akibat persaingan mod yang dihadapi oleh rongga. Reka bentuk yang dicadangkan menghasilkan 0.25 GHz hingga 7.27 GHz frekuensi rentak bersepadanan dengan jarak output DWFL dari 2 pm hingga 58 pm. Frekuensi yang diperolehi boleh digunakan dalam aplikasi dan mempunyai potensi yang penting dalam penderiaan dan komunikasi tanpa wayar.

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LIST OF SYMBOLS

Ʋ - Frequency

H - Planck’s Constant

E - Energy

R_{13} - Rate of Pumping From E_1 To E_3

R_{31} - Rate of Stimulated Emission from E_3 To E_1

W_{12} - Absorption Rates

W_{21} - Stimulated Emission Rates

A_{21}^{R} - Spontaneous Radiative Decay/Emission Rate from E_2 To E_1

A_{31}^{R} - Spontaneous Radiative Decay/Emission Rate from E_3 To E_1

A_{32}^{R} - Spontaneous Radiative Decay/Emission Rate from E_3 To E_2

A_{32}^{NR} - Spontaneous Nonradiative Decay/Emission Rate from E_3 To E_2

A_{21}^{NR} - Spontaneous Nonradiative Decay/Emission Rate from E_2 To E_1

ρ - Laser Ion Density

$\gamma(v)$ - Lorentzian Gain Coefficient

v_0 - Central Frequency

Δv - Emission Linewidth

$\gamma_\beta(v)$ - Gaussian Coefficient

Δv_s - Lorentzian Shape of Width

N_0 - Steady State Population Different

λ - Wavelength of the Signal

τ_{sp} - The Spontaneous Lifetime

λ_p - Pump Wavelength

k_s - Wave Number for Scatter Wavelength

k_p - Wave Number for Pump Wavelength

k_a - Wave Number for Acoustic Wavelength

T_b - Phonon Lifetime

Δv_B - Full-Width at Half-Maximum

p_0 - Material Density

L_{coh} - Pump Coherence Length

L_{int} - Interaction Length Of Pump

$I_s(0)$ - Intensity of Incident Pump At Z=0

A_s - The Amplitude

ω_o - Carrier Frequency

$\emptyset_s$ - The Phase

A_{LO} - Amplitude of the CWSignal

ω_{LO} - Frequency of the CW Signal

$\emptyset_{LO}$ - Phase of the CW Signal

$\Delta v_{s.hom}$ - The Bandwidth in the Self-Homodyne Technique

F - The Finesse of the Ring Cavity

α - The Loss Coefficient of the Fiber

S - Loss of the Electric Field Experienced at the Splices

τ_d - The Delayed Time

Δv_{res} - The Resolution of the Interferometric Method

L_d - Length of the Delay Fiber

L - Thickness of Etalon

d - Input Waveguide Separation

D - Output Waveguide Separation

v_p - Spacing between Two Adjacent Brillouin Stokes

v_A - Acoustic Velocity within the Glass

$\Delta \mathrm{Y}_{\mathrm{stokes}}$ - The Stokes Linewidth

$\Delta \mathrm{Y}_{\mathrm{pump}}$ - The Pump Linewidth

LIST OF ABBREVIATIONS

SMFs - Single Mode Fibers

EDFA - Erbium-Doped Fiber Amplifier

EDFL - Erbium-Doped Fiber Laser

SBS - Stimulated Brillouin Scattering

OSNR - Optical-Signal-to-Noise Ratio

BFLs - Brillouin Fiber Lasers

DCFs - Dispersion Compensating Fibers

TBF - Tunable-Bandpass Filter

AWG - Arrayed Waveguide Grating

UNB - Ultra-Narrow Bandwidth

FBG - Fiber Bragg Grating

HNLF - Highly Nonlinear Fiber

OSA - Optical Spectrum Analyzer

Nd - Neodymium

Yb - Ytterbium

BFA - Brillouin Fiber Amplifier

TDFs - Thulium Doped Fibers

SOAs - Semiconductor Optical Amplifiers

LD - Laser Diode

WDM - Wavelength Division Multiplexer

TLS	-	Tunable Laser Source
FWM	-	Four-Wave Mixing
CPM	-	Cross-Phase Modulation
SPM	-	Self-Phase Modulation
SA	-	Saturable Absorber
RFSA	-	Radio Frequency Spectrum Analyzer
FSR	-	Free Spectral Range
AOM	-	Acoustic Optical Modulator
OPM	-	Optical Power Meter
FPR	-	Free Propagation Region
OCS	-	Optical Channel Selector
BER	-	Bit Error Rate
PC	-	Polarization Controller
FWHM	-	Full-Width at Half-Maximum
BP	-	Brillouin Pump
SMSR	-	Side Mode Suppression Ratio
RF	-	Radio Frequency
EM	-	Electromagnetic
OFB	-	Optical Feedback
FLP	-	Fiber Loop Mirror

LIST OF APPENDICES

CHAPTER 1

INTRODUCTON

1.1 Background of Research

The invention of 'light amplification by spontaneous emission of radiation' or in short called laser in 1960 has triggered many development of fiber technology for communication system. Elias Snitzer issued theoretical description on single mode fibers (SMFs) whose core would be so small that it could carry light with only one mode of wave-guide. Later, he demonstrated an experiment of a laser passing through a thin glass of fiber, but the loss was too big for communication applications. The attenuation less than 20 dB/km [1] was achieved in 1970 through doping the fibers with low level of rare-earth elements and the attenuation is successfully reduced to less than 0.2 dB/km [2] owing to the rapid development in material fabrication. Late 1970s and early 1980s, fiber optics was used extensively for long distance of communication infrastructure. For long-distance applications, SMF at 800 nm is the first commercial operating wavelength available. The operating wavelength is then extended to O-band region (1300 nm) where it is offered lower loss of 1 dB/km and minimum dispersion. At C-band region (1550 nm), the fiber loss found to have minimum loss of 0.2 dB/km [3].

In 1986, David Payne and Emmanuel Desurvire invented erbium-doped fiber amplifier (EDFA), improving the long-distance fiber systems by reducing the cost since the used of optical-electrical-optical repeaters is eliminated due to EDFA naturally amplified at 1550 nm.

Today, various applications including military, medical, industrial and communication used fiber technology in their applications. Fiber laser nowadays becomes leading position in some application and starting to dominate the applications related to high power, pulsed oscillator and spectral manipulation. Even though fiber laser have been used for many applications, extensive effort on improving the quality of fiber laser signal are still progressing so that the wasted can be avoided. Common laser normally operates in multi-longitudinal modes due to large gain over 30 nm and small spacing between the longitudinal modes. Single longitudinal mode signal source which have narrow linewidth is highly preferable for many potential applications where coherence is necessary. The signal sources that possess narrow linewidth property is desirable for enabling ultra-high network capacity, corresponding to the narrower beam inside the waveguide. To meet the traffic demand of wireless communication system nowadays, the signal source that capable to support high capacity of data for one time is needed. However, to achieve narrow optical emission spectrum is a difficult task. Many methods have been introduced to achieve narrow linewidth operation of fiber lasers including fiber Fox-Smith resonators [4], intracavity wave-mixing in a saturable absorber [5], unidirectional ring resonator [6], and injection locking [7]. Nevertheless, no methods are free from operating difficulties from environmental problems such as nonlinear effect, mode competition and homogeneous line broadening. Therefore, improvement and modification in term of design and the use of suitable devices is proposed and demonstrated to yields narrow linewidth fiber laser. Also, the nonlinear phenomena are explored to opened new ways in the generation of narrow linewidth laser source. The potential of narrow linewidth fiber laser is well-known in communication. However, the idea to create carrier waves with narrow linewidth from each structure to obtain the wireless communication signal is still lack from many aspects.

1.2 Problem Statement

Fiber laser possess varsities of parameters and operating parameters that are attractive solution for certain application. Among the features possessed by fiber laser, the narrow linewidth sources have become strong interest in which single frequency laser become acceptance form of laser and commercially available in diverse application. In spite of that, there is minimal study on fiber laser system concerning optical filters implementation effect toward fiber laser signal source. Since the production of narrow linewidth laser source depends on optical filters that are use, hence a design of the cavity using different optical filters is form. The fiber laser sources performance that are produce is investigate. On the other hand, fiber laser is well known to produce multi-longitudinal mode with mode hopping due to the long cavity and narrow spacing of longitudinal mode. This problem may be overcome by construct a short cavity, however this design has the disadvantages in term of low efficiency and weak stability. Thus, a design using Stimulated Brillouin Scattering (SBS) effect are proposed and demonstrated with simple cavity structure that able to achieve ultra-narrow transmission band. Despite of generation of narrow linewidth fiber laser source, their usefulness and potential to work for wavelength conversion application to fulfill the communication demand is also determine. Thus, narrow linewidth dual-wavelength fiber lasers (DWFLs) becomes an alternative way to realize the wireless communication generation. However, a lot of efforts require to produce DWFLs that exhibit high spectral purity due to mode-competition and strong homogeneous line broadening.

1.3 Objectives of Research

The aim of the research presented in this thesis has been focused on improving the weakness faced by the current design in the optical communication systems. The objectives of the research are:

i. Designing and characterizing optical filters for erbium-doped fiber laser (EDFL) in improving and upgrading the fiber laser systems performance in term of compactness, output powers, tunability and primarily as an alternative to the narrowing element of the systems.
ii. Generating single longitudinal mode and narrow linewidth laser source. A novel approach of using stimulated Brillouin scattering effect (SBS) has been designed and reported.
iii. Determine dual-wavelength narrow linewidth fiber laser to realize the wireless communication band by beating the dual-wavelength signal. Different from other approaches, dual-wavelength laser generation has the advantage of simple setup configuration as well as low cost and power consumption.

1.4 Scope of Research

This research covered the experimental works on generating the narrow linewidth fiber laser. Firstly, the basic configuration of fiber laser is study and demonstrate. Then the comparative study on the systems performance is execute by insertion of narrowing wavelength elements within the cavity. The elements consists of tunable bandpass filter, arrayed waveguide grating and ultra-narrow bandwidth tunable filter. Erbium-doped fiber amplifier (EDFA) is used as predominant gain medium throughout these studies. Prior to that, the working principle of each wavelength selective mechanism is reviewed. The aspect of laser performance such as tunability, efficiency, optical-signal-to-noise ratio (OSNR) and the linewidth of lasing outputs were investigated. Subsequently, a technique is developed from the wavelength selective elements characterization in which a SLM narrow linewidth design of fiber laser demonstrated by incorporated UNB-tunable filter. Brillouin fiber lasers (BFLs) have been subjected of considerable research for many applications due to their extremely narrow linewidth. Thus, supported by availability of equipment in laboratory, focus was given to the generation of SBS in SMFs and also in dispersion compensating fibers (DCFs). The generation of multiwavelength Brillouin fiber laser is also studied. Comparative observation was made by using different optical spectrum analyzer (OSA) resolution. This is followed by the experimental technique to generate BFL. A novel configuration is proposed and demonstrated to generate ultra-narrow linewidth SLM based on BFL and using highly nonlinear fiber as gain medium. Finally, an approach is realized for radio frequency generation by operating experimental studies on narrow-linewidth dual-wavelength fiber laser.

1.5 Significance of Research

The fiber lasers has been widely and actively studied for its concept, designs, various physics phenomena operation. Thus, the results obtained from this study are important as a reference source for the later experiment implementation. Comprehensive study has been made to determine and suggest the best method for realizing the narrow linewidth fiber laser to meet not only today but also for future need. The technique that uses SBS effect to generate ultra-narrow linewidth signal that presented here also can be considered to be used towards communication industry and there are still room to be improvised for better and effective approach in particular applications. Moreover, new application of wireless communication can be provided by the design of narrow DWFLs that are proposed here.

1.6 Thesis Methodology

Prior to the experimental works start, literature reviews as well as the understanding of the operating principle of the fiber lasers and SBS effect are require to be sort out in the first place. Subsequently, reviews on narrow linewidth characteristic and operation is study and investigate. Upon completion of the review, the characterization of basic configuration of fiber laser is being done. The used of optical filter is most common method to producing narrow linewidth laser source. Thus, the experiment on fiber laser with vibration wavelength controlled by different optical filter is executed and the results are compared. The filter that offer promising output characteristic is determine and be applied for generation of narrow linewidth fiber laser. To extend the capability of fiber laser design, a design of narrow linewidth fiber laser assisted by the SBS effect is proposed and demonstrated. Finally, after desirable property of narrow linewidth has been produced, their potential to works in wireless communication applications is determined by beating narrow linewidth DWFLs output.

1.7 Thesis Arrangement

There are six chapters in this thesis. Chapter 1 covered the introductory description of this research which comprised of brief history and background of the fiber laser and its relation with the requirement of the related applications. The problem statement, objectives, scope and significance of this research are also included in this chapter.

Chapter 2 is a review on experimental works involving fiber lasers, including the atomic rate equation of erbium doped fiber (EDF) as the gain medium, different broadening effect inside the cavity and also principle of the fiber laser. This chapter also briefly covers literature review pertaining the methods and measurement of the narrow linewidth fiber lasers.

Chapter 3 demonstrate the basic configurations of fiber laser. In addition, the fiber laser setup by incorporating different wavelength selection elements also examined. These devices are efficient to be apply as narrowing elements of the signal. Prior to that, the working principle of wavelength selective mechanisms were reviewed and discussed in this chapter to determine the usefulness for practical applications. The aspects that we investigated include the tunability, the OSNR, efficiency and linewidth of lasing output produced.

Chapter 4 represents few designs of single and multiwavelength narrow linewidth fiber lasers. For single narrow linewidth fiber laser, two cavity designs are proposed. A design involved the use of UNB-tunable filter and fiber Bragg grating (FBG) within the ring cavity and EDF as the gain media, while the other design involved the use of high pump power and the highly nonlinear fiber (HNLF) as the nonlinear medium to generate the SBS effects. The architectures are considered to be a novelty by virtue the new element use and the impressive obtained result. On the other hand, the use of high resolution optical spectrum analyzer (OSAs) improved the recorded observations and analysis. Moreover, for the multiwavelength narrow linewidth fiber laser, a design was proposed and demonstrated by incorporating SBS effects together with UNB-optical filter. From the design, the single Stokes with high OSNR and narrow linewidth is extracted from the output.

In chapter 5, the research work on applications of narrow linewidth fiber laser are explained and presented. Tunable narrow linewidth DWFLs that are proposed considered to be novel due to new design and capabilities to be tune. Since there has been significant interest in wireless communication, DWFLs is present to be operated using the beating technique to serve its purpose.

The final chapter lists the conclusion of the research finding that answered the research's objectives. Recommendations for the future work in the field are also discussed as the extension of the works done in this research.

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