UNIVERSITI PUTRA MALAYSIA

OPTICAL SIGNAL ENHANCEMENT USING STIMULATED BRILLOUIN SCATTERING

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FK 2022 8

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By

SHAHAD KHUDHAIR ABBAS

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia in Fulfilment of the Requirements for the Degree of Master of Science

January 2021

DEDICATION

I dedicated this thesis to my beloved parents,
who continually provide their moral, spiritual,
emotional, and financial support

To my dearest sisters and brothers
for their love and support

And to all my friends

for their encouragement and guidance

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

OPTICAL SIGNAL ENHANCEMENT USING STIMULATED BRILLOUIN SCATTERING

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SHAHAD KHUDHAIR ABBAS

January 2021

Chairman : Zuraidah binti Zan, PhD
Faculty : Engineering

Stimulated Brillouin Scattering (SBS) is a third order non-linear effect that appears in the nonlinear medium which requires intense radiation to turn from a spontaneous state to a stimulated state. It is originated from the interaction between optical photons and acoustic phonons. The interaction produces a Stokes signal which is in the opposite direction to the transmitted signal. A typical Brillouin shift of the Stokes signal is approximately at 11 GHz in a standard optical fibre. In an optical transmission system, the Stokes signal is required to be suppressed because it will attenuate the laser power or the carrier signal power when an energy transfer or amplification takes place due to the Stokes and carrier signals beating. However, the SBS finds its application in optical sensors, optical filtering, amplification, optical delay and Brillouin fibre laser. In terms of an optical signal enhancement, the SBS can be used to amplify and perform signal filtering with a very narrow bandwidth (BW). These can improve an optical signal-to-noise ratio (OSNR) of an optical system. In this work, an SBS-based amplifier is developed using a pump-probe approach with a Mach-Zehnder modulator (MZM) as a frequency-locking or beating device to produce a seed signal at a Stokes frequency using an RF signal. The seed and Stokes signals will be beaten inside the optical fibre to produce an amplified signal with an OSNR enhancement. Three designs of seed generation blocks are developed based on modulation technique of a double-sideband suppress-carrier (DSB-SC) and single- sideband suppress carrier (SSB-SC). The SSB is generated using two techniques of an optical bandpass filter (SSB-SC/BPF) and in-phase quadrature Mach-Zehnder modulator (SSB-SC/IQ-MZM). Analysis and comparison of the OSNR enhancement between these three design is performed. The OSNR enhancement, Brillouin gain (BG), Brillouin gain BW (BGBW), amplified signal OSNR and the Stokes signal peak power are analyzed based on pump laser source linewidth (LW) pump power, MZM's extinction ratio, MZM biasing voltages to obtain carrier suppression level and the seed power. In this work, an OSNR enhancement of 40 dB, 36 dB and 37 dB was achieved using the DSB-SC, SSB-

SC/BPF and SSB-SC/IQ-MZM, respectively. The DSB-SC introduced double-energy transfer through the beating process of the lower-sideband (LSB) and the upper-sideband (USB) components compared to the single-energy transfer in the SSB-SCs seed signal. This suggests that the DSB-SC can provide a better OSNR enhancement than the SSB- SC. The level of carrier suppression obtained using the MZM's biasing voltages with respect to 30 dB extinction ratio shows an insignificant effect to the OSNR and BG improvement. Thus, a low-cost seed signal generation technique can be employed using a low-cost MZM with a typical small value of extinction ratio. A high level carrier suppression produces a high carrier signal power at the output of the seed generation block which results in a small seed signal power. With the obtained small seed signal power of-21 dBm provides the best amplified signal OSNR of 82.6 dB. This agreed with the reported works on the requirement of the seed signal power to be below than 10 μW. The pump laser LW shows a significant effect to the obtained BG, BGBW and the OSNR enhancement where a narrow LW within the range of 1 kHz to 10 MHz is required. This shows that a low-cost distributed feedback laser can also be used as the OSNR dropped of less that 1 dB is obtained when using the 10 MHz LW compared to 1 kHz. In this work, the design of the signal enhancement using SBS-based amplifier is developed based on the optimized seed signal generation techniques. Investigation and optimization focusing on the seed generation techniques are shown and the best parameter range to produce the best amplified signal OSNR has been identified. The parameters include the pump laser LW, MZM extinction ratio, carrier suppression and pump power including the performance of the SSB and DSB modulation as the seed generation technique.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PENINGKATAN ISYARAT OPTIK MENGGUNAKAN SERAKAN BRILLOUIN TERANGSANG

Oleh

SHAHAD KHUDHAIR ABBAS

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Serakan Brillouin terangsang (SBS) merupakan ketaklinearan peringkat ke tiga yang muncul di dalam medium tak linear di mana radiasi tinggi diperlukan untuk menukar keadaan spontan kepada terangsang. Ianya berasal daripada interaksi di antara foton optik dan fonon akustik. Interaksi ini menghasilkan isyarat Stokes yang mempunyai arah bertentangan dengan isyarat yang dihantar. Anjakan Brillouin biasa bagi isyarat Stokes adalah lebih kurang 11 GHz di dalam gentian optik biasa. Di dalam sistem penghantaran optikal, isyarat Stokes perlu ditekan kerana ianya akan mengurangkan kuasa laser atau isyarat pembawa bila pemindahan tenaga atau penguatan berlaku akibat daripada pukulan di antara isyarat Stokes dan pembawa. Walaubagaimanapun, SBS telah diterima di dalam aplikasi penderiaan optikal, penuras optikal, penguat, lambatan optikal dan laser gentian Brillouin. Dari segi peningkatan isyarat optikal , SBS boleh digunakan untuk menguatkan dan menuras isyarat dengan lebar jalur (BW) yang sangat sempit. Ini boleh menambahbaik nisbah isyarat-kepada-hingar optikal (OSNR) sistem optikal. Di sini, penguat berasaskan SBS telah dibangunkan dengan menggunakan kuar pam dengan pemodulat Mach-Zehnder (MZM) sebagai pengunci frekuensi atau peranti pukulan untuk menghasilkan isyarat benih pada frekuensi Stokes menggunakan isyarat RF. Isyarat benih dan Stokes akan dipukul di dalam gentian optik untuk menghasilkan isyarat penguat beserta peningkatan OSNR. Tiga rekabentuk blok penjaan isyarat benih telah dibangunkan berdasarkan teknik modulasi jalur dua sisi menekan pembawa (DSB-SC) dan jalur tunggal menekan pembawa (SSB-SC). SSB dijanakan dengan menggunakan dua teknik iaitu turas lintasan jalur (SSB-SC/BPF) dan MZM kuadratur sefasa (IQ-MZM). Analisa dan perbandingan peningkatan OSNR di antara ketiga-tiga rekabentuk ini telah dilakukan. Peningkatan OSNR, gandaan Brillouin (BG), lebar jalur BG, OSNR isyarat terkuat dan kuasa puncak isyarat Stokes. Di dalam kajian ini, peningkatan OSNR sebanyak 40 dB, 36 dB dan 37 dB telah dicapai dengan masing-masing menggunakan teknik DSB-SC, SSB-SC/BPF dan SSB-SC/IQ-MZM. DSB-SC berupaya memberikan pemindahan tenaga perduaan melalui proses pukulan di antara

komponen jalur sisi rendah (LSB) dan jalur sisi tinggi (USB) berbanding dengan pemindahan tenaga tunggal oleh isyarat benih dari SSB-SC. Ini mencadangkan bawaha DSB-SC boleh memberikan peningkatan OSNR yang lebih baik berbanding SSB-SC. Paras penekanan pembawa yang dicapai dengan voltan prasikap MZM berpandukan kepada nibah penghapusan 30 dB menunjukkan kesan tidak penting kepada pembaikan OSNR dan BG. Oleh itu, teknik penjanaan isyarat benih yang berkos rendah boleh digunakan menggunakan MZM berkos rendah dengan nilai nisbah penghapusan biasa yang kecil. Paras penekanan pembawa yang tinggi menghasilkan kuasa isyarat pembawa yang tinggi di keluaran blok penjana isyarat benih yang telah menghasilkan kuasa isyarat benih yang kecil. Kuasa isyarat benih sekecil -21 dBm telah menghasilkan OSNR isyarat terkuat yang terbaik sebanyak 82.6 dB. Ini bertepatan dengan laporan kajian yang mensarankan agar kuasa isyarat benih tidak melebihi 10 μW. LW pam laser menunjukkan kesan ketara ke atas BG, BGBW dan peningkatan OSNR di mana LW sempit di dalam julat 1 kHz ke 10 MHz diperlukan. Ini menunjukkan bahawa laser suap balik terbahagi (DFB) berkos rendah boleh digunakan di mana hanya kurang daripada 1 dB penurunan OSNR telah dicapai bila LW 10 MHz digunakan berbanding 1 kHz. Kajian ini meliputi rekabentuk teknik penambahbaikan isyarat penguat berasaskan SSB dengan menggunakan teknik penjanaan isyarat benih. Penyiasatan dan penambaikan dilakukan dengan memfokuskan kepada teknik penjaanaan isyarat benih di mana julat parameter untuk menghasilkan OSNR isyarat terkuat yang terbaik telah dikenalpasti. Parameter ini termasuk LW laser pam, nisbah kepupusan MZM, penekanan pembawa dan kuasa pam termasuk prestasi modulasi SSB dan DSB sebagai teknik penjanaan benih.

ACKNOWLEDGEMENTS

I would like to express my deep gratitude and appreciation to my supervisor, Dr. Zuraidah Zan for her patient guidance, immense knowledge, enthusiastic encouragement, and continuous and enormous support through the learning process of this master thesis without which, this work would not have been completed.

I would like to offer my special thanks to my co-supervisor, Prof. Mohd Adzir Bin Mahdi and Dr. Noran Azizan Bin Cholan for his assistance and suggestions that I received throughout this work.

I wish to acknowledge the moral support and valuable advice provided by my friends and colleagues during this journey to pursue my master's degree.

Finally, I must express my very profound gratitude to my parents and my brothers and sisters for providing me with unfailing support and continuous encouragement throughout my years of study and my life in general. This accomplishment and others would not have been possible without them and their sacrifices. My mighty God bless them all.

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

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Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) were adhered to.

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LIST OF ABBREVIATIONS

ASE	amplified spontaneous emission
BA	Brillouin amplifier
BBW	Brillouin Bandwidth
BER	bit-error-rate
BPF	band pass filter
BG	Brillouin gain
BGBW	Brillouin gain bandwidth
BOTDA	Brillouin optical time-domain analysis
BGS	Brillouin gain spectrum
BW	bandwidth
CNR	carrier-to-noise
DSB-SC	double sideband suppressed carrier
DFB	distributed feedback laser
EDFA	erbium-doped fiber amplifier
ER	extinction ratio
FWHM	full width at half maximum
FWM	four-wave mixing
LiNbO3	Lithium niobate
LSB	lower-sideband
LW	linewidth
MCM	multiple carrier modulation
MZM	Mach-Zehnder modulator
MZMER	Mach-Zehnder modulator extinction ratio
MPF	microwave photonic filter

MZMTF	Mach-Zehnder transfer function
MWP	microwave photonic
OFC	optical frequency comb
OSA	optical spectrum analyzer
OSNR	optical signal-to-noise ratio
PD	photodetector
RBW	resolution bandwidth
ROF	radio over fiber
SBS	stimulated Brillouin scattering
SCO-OFDM	self-coherent optical OFDM
SMF	single mode fiber
SNR	signal-to-noise ratio
SPM	self-phase modulation
SRS	stimulated Raman scattering
SSB-SC	single sideband suppressed carrier
SSB-SC/BPF	SSB-SC obtained by using an optical bandpass filter
SSB-SC/IQ-MZM	SSB-SC obtained by using an IQ Mach-Zehnder modulator
SBST	stimulated Brillouin scattering threshold
USP	upper-sideband
XPM	cross-phase modulation

CHAPTER 1

INTRODUCTION

1.1 Background

Fiber optic impairment factors can be categorized into linear and nonlinear effects. The nonlinear effects in an optical transmission system are self-phase modulation (SPM), cross-phase modulation (XPM), four-wave mixing (FWM), stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). The XPM and SPM are originated from the intensity-dependent refractive index that affects the transmitted data rate due to phase distortions. In contrast, SRS and SBS are classified as inelastic scattering can limit the laser's output power. Even though these are undesirable in the optical transmission system, the nonlinearity effects have found its' application in optical devices and fibre sensors [1]. The application include Raman and Brillouin filters [2]–[5], Raman and Brillouin amplifiers [2]–[5], tunable optical delay application [6], [7], strain and temperature applications [8]–[12], pressure and biochemical sensors for the fibre optics sensor [13]–[16]. In this work, the application of SBS is studied and investigated to improve and enhance the optical signal in terms of power and provide a noise suppression that enhances the signal's optical signal to noise ratio (OSNR).

Many studies have focused on the application of an SBS effect in optical fibre for sensor-based technologies and to develop optical devices to enhance the transmitted signal properties in terms of power and noise filtering [2], [17]–[19]. The interest in the SBS-based amplifier continues to increase due to its narrow bandwidth (BW) and its low required thresholds to turn to stimulated status. The use of the SBS amplifier has been demonstrated in a coherent transmission over a long-haul optical fibre [2], [20], [21].

1.2 Problem Statement

OSNR is one of the crucial parameters in both optical transmission and optical fibre sensor systems. The OSNR must be maintained to a certain level to satisfy the receiver's sensitivity to demodulate the received data correctly and perform accurate data analysis for the sensor outcomes. However, several factors degrades the OSNR. These factors are: laser phase noise, amplified spontaneous emission (ASE) induced by an erbium-doped fibre amplifier (EDFA), thermal noise, shot noise and dark current that is generated from a photodetector (PD) and beating noise due to multiple carrier modulation (MCM) transmission when the signal is detected upon the PD. These noises will be added up onto the total noise floor of the received signal. The OSNR reduction becomes critical with the fibre optic attenuation and the device insertion loss that will further bring down the received signal power. This will consequently reduce the electrical signal-to-noise ratio (SNR) after the PD, which in turn increases the bit- error-rate (BER) of the recovered original data.

A typical technique to reduce the background noise or the noise floor of the received signal is by using an optical filter. However, since the noise is within the transmitted BW, a good noise reduction and signal selection cannot be obtained due to a wide filter BW within the range of nm where 0.1 nm equal to 12.5 GHz. Therefore, a large amount of noise is still maintained within the bandpass optical signal. Also, applications that required a high data rate transmission, such as a self-coherent system, required a highly selective optical filter with a sharp response to precisely select the desired signal. In the self-coherent system, the transmitted optical carrier is required to be filtered from the signal to be a local oscillator for its receiver. The other approach is to amplify the signal using an EDFA. The EDFA has its drawback due to amplify the noise floor within the signal BW and adding its ASE noise to the signal as well. However, SBS introduces an effective way to enhance the OSNR owing to the narrow-gain BW. Thus, this work presents signal amplification and noise suppression capabilities that will enhance the OSNR of the optical signal. The obtained signal amplification does not induce an additional background noise compared to the EDFA that generated an ASE noise. Thus, the designed SBS-based signal enhancement technique can improve the received optical signal hence, improving the overall system performances.

1.3 Objectives

This thesis aims to analyze and investigate the SBS theory and the signal mixing effects between an RF-generated carrier and SBS Stokes to enhance the optical signal in terms of signal amplification, noise floor suppression. Furthermore, the analyses of the impact of the design parameters of the optical signal enhancement are performed. The outlined objectives involve in this study are as follow:

I. To investigate SBS-based amplifier theory and designs.
II. To design an SBS-based amplifier using DSB-SC and SSB-SC seed signal generation techniques.
III. To analyse the performance of the seed signal generation techniques for optical signal enhancement.

1.4 Scope of Work

The thesis focuses on an optical signal enhancement technique using an SBS nonlinearity effect to obtain signal amplification with a narrow gain BW and noise suppression. The work involves the generation of a single-Stokes SBS and a frequency-shifted optical signal obtained with an MZM. Comparison between a DSB- SC and SSB-SC modulation techniques as a seed signal generation block is performed. Optimization of the obtained OSNR, BG and BGBW of the DSB-SC seed signal generation in terms of carrier suppression level, seed signal peak power and pump laser LW is investigated and presented. The SBS-based signal enhancement technique is developed using VPItransmissionMaker^{TM} version 9.1, where the gain and BW of the technique are verified and the obtained OSNR improvement is analyzed.

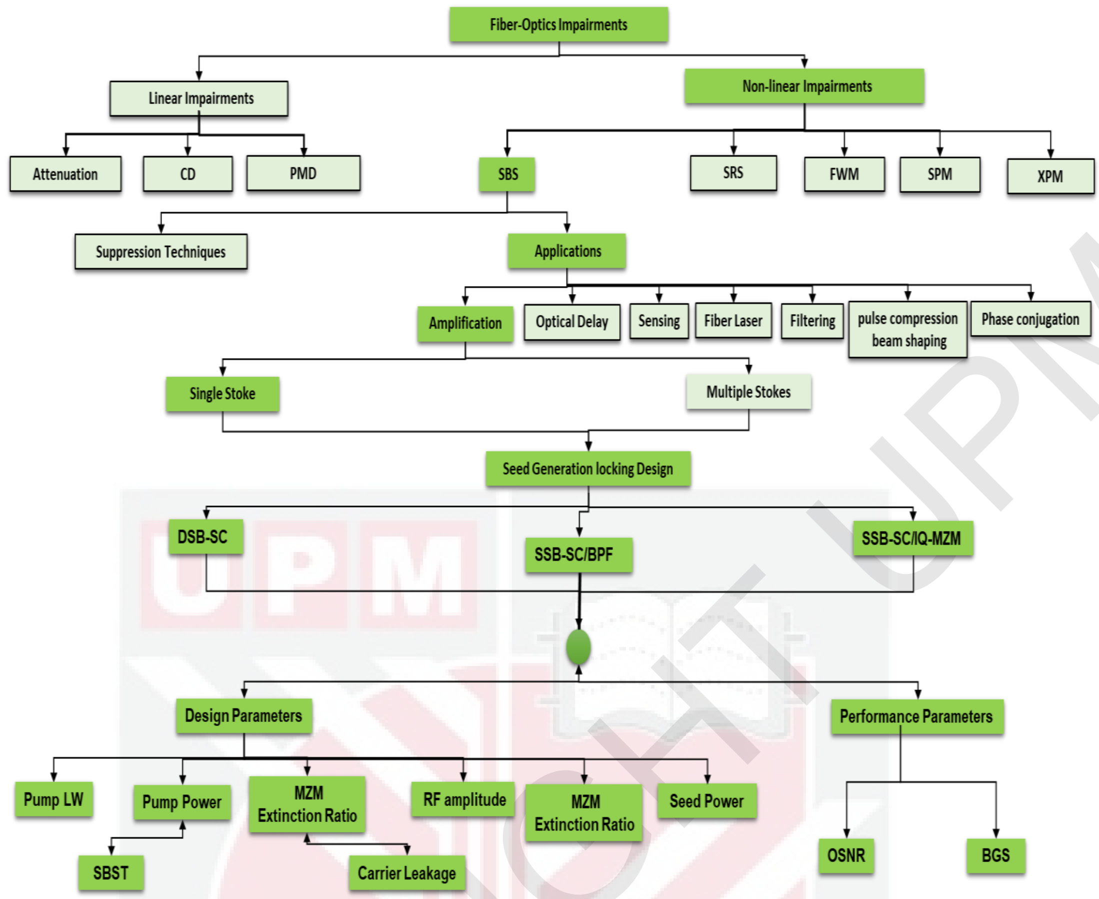

Figure 1.1 : Scope of work

Figure 1.1 shows the tree diagram to illustrate the scope of the work. In general, fibre optics impairment characteristics can be divided into linear and nonlinear effects. The chart shows that the thesis focuses on an SBS nonlinearity effect. The theory of SBS and its generation will be presented and explained. Furthermore, three designs based DSB-SC, SSB-SC obtained by using an optical bandpass filter (SSB-SC/BPF) and SSB-SC obtained by using an in-phase quadrature MZM (SSB-SC/IQ-MZM) for seed generation locking block will be discussed to show the performance of these three designs to achieve an optical signal enhancement using the SBS. In addition, the design parameters represented by pump laser source linewidth (LW), pump power, Mach- Zehnder modulator's extinction ratio, the amplitude of the RF function generator and seed's power will be analyzed. In addition to that, the performance parameters represented by Brillouin gain spectrum (BGS) in terms of Brillouin gain (BG) and Brillouin bandwidth (BBW)- and OSNR will be reviewed. The design and performance parameters will be explained in detail in the methodology chapter.

1.5 Thesis Organization

The thesis is organized as follows:

- **Chapter 1:** Chapter 1 begins with the introduction of the background study which includes the linear and nonlinear characteristics of an optical fibre. This is followed by an explanation of the problem statement and the scope of the study.

- **Chapter 2:** Chapter 2 presents the literature review starting with a nonlinear phenomenon in an optical fibre. Some history of the SBS and how it is originated are discussed. The implementation of the SBS in the signal enhancement technique is explained along with a basic understanding of the locking key device MZM.

- **Chapter 3:** Chapter 3 presents the methodology that is used to perform this study. This includes simulation setups, performance parameters, and design parameters.

- **Chapter 4:** Chapter 4 discusses the result achieved based on the design and performance parameters of the study. The effects of the design parameters on the signal's OSNR and BGS are analyzed.

- **Chapter 5:** Chapter 5 presents the conclusion of the result and findings of the study with some recommendations for future work.

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