



**UNIVERSITI PUTRA MALAYSIA**

***ANALYTICAL MODELING, EXPERIMENTAL INVESTIGATION  
AND APPLICATIONS OF STIMULATED BRILLOUIN SCATTERING  
IN OPTICAL FIBERS***

**HAMID ALI ABED AL-ASADI**

**FK 2011 59**

**ANALYTICAL MODELING, EXPERIMENTAL INVESTIGATION  
AND APPLICATIONS OF STIMULATED BRILLOUIN SCATTERING  
IN OPTICAL FIBERS**

**By**

**HAMID ALI ABED AL-ASADI**

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

**May 2011**

## DEDICATION

*This work is dedicated*

*To*

*The loving memory of my late father*

*May Allah (SWA) grant him Al-Jannat Firdaus, Amen.*

*The lovely and greatest person in my life*

*My mother.*

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

**ANALYTICAL MODELING, EXPERIMENTAL INVESTIGATION  
AND APPLICATIONS OF STIMULATED BRILLOUIN SCATTERING  
IN OPTICAL FIBERS**

By

**HAMID ALI ABED AL-ASADI**

**May 2011**

**Chair: Professor Mohd Adzir bin Mahdi, PhD**

**Faculty: Engineering**

In the work presented in this dissertation, the generation of stimulated Brillouin scattering (SBS) and its applications in optical fibres are theoretically and experimentally investigated. The initial work is concerned with the investigation of SBS threshold power reduction techniques. The method under study is namely a pump recycling technique in which the residual pump power is recycled back to act as the secondary pump. A new mathematical model was developed for the proposed technique. The results obtained from this model compare favorably with the experimental results. The pump recycling technique can reduce the SBS threshold by around 50% as compared to the one obtained from the conventional technique.

The threshold exponential gain of SBS is very critical in determining the performance of the Stokes signal. Particle swarm optimization (PSO) is utilized to optimize this parameter. The simulation results obtained from the PSO model are compared with two other established models: the localized, non-fluctuating source model and the distributed (non-localized) fluctuating source model. For the PSO model, the threshold exponential gain increases from 15.9 to 17.4 from 5 to 1 km respectively. The threshold exponential gain for long fibers ( $L > 5$  km) is gradually decreased and close to 14.6.

Theoretical models of the Brillouin fiber laser in a ring cavity were also developed. Even though the Stokes laser is designed to propagate unidirectionally along the optical fibre, the second-order Stokes signal can also be produced when the SBS threshold condition is satisfied. Even though this second-order Stokes signal cannot make a complete round trip because of the isolation provided by the circulator, it affects the amplification of the first-order Stokes signal. This influence has been considered in the development of the theoretical model. An optimum operating point is determined in order to obtain an acceptable output power with only 10% of the power transferred from the first-order Stokes signal to the second-order Stokes signal.

A theoretical model of a double-Brillouin-frequency shifter (DBFS) is demonstrated to achieve a double-spacing Stokes signal. Evidence of the higher-order Stokes signal generation becomes the foundation of the theoretical model development of DBFS. For the proposed structure, the 4-port circulator is used to isolate the propagation of odd- and

even-order Stokes signal in a ring cavity structure. Although the proposed double-Brillouin-frequency shifter is able to generate the second-order Stokes signal, it also suffers from producing higher-order Stokes waves. Therefore, the developed theoretical model includes the Stokes wave interaction up to its fourth order. The analysis of side-mode suppression ratio can be achieved because the proposed DBFS allows the propagation of the remaining Brillouin pump and higher even-order Stokes signal. There is an optimum Brillouin pump power to achieve a maximum side-mode suppression ratio.

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

**PEMODELAN ANALITIKAL, PENYELIDIKAN EKSPERIMENTAL DAN  
APLIKASINYA PENYERAKAN TERANGSANG BRILLOUIN DALAM  
GENTIAN OPTIK**

Oleh

**HAMID ALI ABED AL-ASADI**

**Mei 2011**

**Pengerusi: Professor Mohd Adzir bin Mahdi, PhD**

**Fakulti: Kejuruteraan**

Dalam hasil kerja yang dibentangkan dalam disertasi ini, penghasilan penyerakan terangsang Brillouin (SBS) dan aplikasinya dalam gentian optik telah disiasat secara teori dan eksperimen. Kerja-kerja awal ditumpukan kepada teknik-teknik merendahkan kuasa ambang SBS. Teknik yang dikaji adalah pengitaran semula kuasa pam, di mana kuasa pam yang berlebihan dikitar balik dan seterusnya digunakan sebagai pam kedua. Satu model matematik baru dibangunkan bagi teknik yang dicadangkan ini. Keputusan yang diperolehi dari model matematik ini adalah sejajar dengan keputusan dari eksperimen. Teknik pengitaran semula kuasa pam ini berjaya merendahkan kuasa ambang SBS kepada 50% berbanding dengan teknik biasa.

Penggandaan eksponen ambang SBS adalah kritikal dalam menentukan prestasi isyarat Stokes. Particle swarm optimization (PSO) telah digunakan untuk mengoptimumkan parameter tersebut. Keputusan simulasi yang diperolehi dari model PSO telah dibandingkan dengan dua model yang mapan; model nonfluctuating source dan model distributed (non-localized) fluctuating source. Bagi model PSO, penggandaan eksponen ambang meningkat dari 15.9 ke 17.4 untuk gentian optik berukuran dari 5 ke 1 km masing-masing. Untuk gentian yang panjang ( $L > 5\text{km}$ ), penggandaan eksponen ambang menurun sehingga 14.6 secara beransur-ansur.

Model teori laser gentian Brillouin dalam rongga cincin juga telah dibangunkan. Walaupun laser Stokes direka untuk bergerak sehala dalam gentian optik, laser Stokes tahap kedua boleh dijanakan apabila ambang SBS dicapai. Walaupun laser Stokes tahap kedua tidak dapat membuat lingkaran lengkap disebabkan pengasingan dari pengedar, ia mempengaruhi isyarat Stokes tahap pertama. Impak ini telah diambil kira dalam pengusahaan model teori ini. Satu titik operasi optimum telah ditentukan bagi memperoleh kuasa hasilan yang diterima dengan hanya 10% dari kuasa dipindahkan dari isyarat Stokes tahap pertama ke isyarat Stokes tahap kedua.

Model teori untuk double-Brillouin-frequency shifter (DBFS) didemonstrasikan untuk mencapai pemisahan isyarat Stokes berganda dua. Pengetahuan dalam isyarat Stokes tahap tinggi dijadikan asas dalam pembangunan model teori DBFS ini. Dalam struktur yang dicadangkan, pengedar 4-kaki digunakan untuk mengasingkan isyarat Stokes tahap



ganjil dan genap dalam struktur rongga cincin. Walaupun DBFS yang dicadangkan di atas berupaya menjanakan isyarat Stokes tahap kedua, tetapi ia juga menanggung penghasilan gelombang Stokes tahap atasan. Justeru itu, model teori yang dibangunkan ini merangkumi interaksi gelombang Stokes sehingga ke tahap keempat. Analisis terhadap nisbah peredaman mod sisi telah dijalankan memandangkan DBFS yang dicadangkan ini membenarkan pengaliran baki pam Brillouin dan isyarat Stokes tahap genap yang lebih tinggi. Terdapat satu kuasa optimum pam Brillouin untuk mencapai nisbah peredaman mod sisi yang maksima.

## ACKNOWLEDGEMENTS

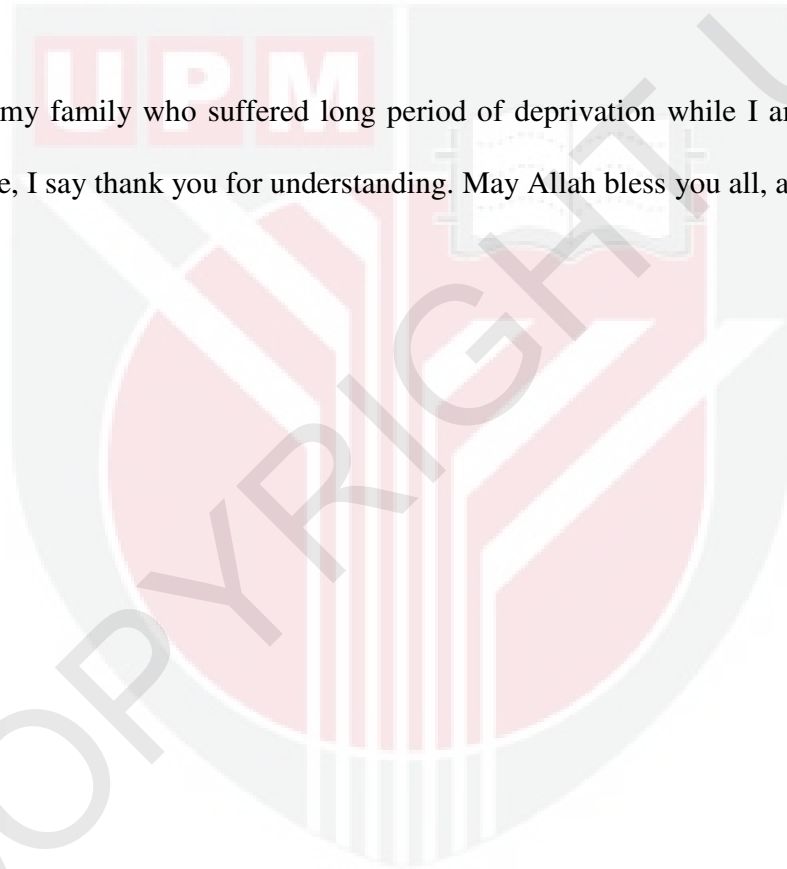
All praises are due to Allah (SWA), the almighty, Lord of the worlds, the most beneficent, the most merciful. I thank Him for help, support and allowing us to see to this stage of my quest for knowledge.

I would like to profoundly thank my supervisor, Prof. Dr. Mohd Adzir Bin Mahdi, without whose help and support, this dissertation may not be a reality. A distinguished gentleman, Prof. Adzir accorded us, the liberty to consult with him at any time, be it in his office, on the road or in the lab without prior appointment. He is always available to us despite his tight schedule as an administrator, a researcher, a lecturer and a wonderful head of a family. He always listens and offer prompt solutions to whatever problem we confronted him with. He continually supported us, in the lab, academically and morally. To Prof. Adzir, I say thank you. May Allah (SWA) guide, support and pour his blessings upon you and your family.

I also deeply appreciate the contributions, guidance and support of my other supervisory committee members, Assoc. Prof. Dr. Mohammed Hayder Al-Mansoori, Dr. Salasiah bt. Hitam and Dr. M. Iqbal bin Saripan. I benefitted tremendously from their wide and vast knowledge in the field of not only fiber laser but other aspects of general knowledge. May Allah help and reward him abundantly.

I appreciate the help and assistance of my colleagues in our research group. I cherish the brotherhood with which we stayed. I would also want to thank all staffs and other students of the photonic and fiber optic system laboratory, for their help and support. Equally, I would like to thank all the other staffs of the computer and communication systems engineering department.

Finally to my family who suffered long period of deprivation while I am pursuing the PhD degree, I say thank you for understanding. May Allah bless you all, amen.



I certify that an Examination Committee has met on 31 May 2011 to conduct the final examination of **Hamid Ali Abed AL-Asadi** on his degree thesis entitled “**Stimulated Brillouin Scattering in Optical Fibers: Analytical Modeling, Experimental Investigation and Applications**” in accordance with Universiti Putra Malaysia (Higher Degree) Act 1980 and Universiti Putra Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Examination Committee were as follows:

**Alyani binti Ismail, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Makhfudzah binti Mokhtar, PhD**

Faculty of Engineering  
Universiti Putra Malaysia  
(Internal Examiner)

**Hishamuddin bin Zainuddin, PhD**

Professor  
Faculty of Science  
Universiti Putra Malaysia  
(Internal Examiner)

**Lars Magnus Ingemar Karlsson, PhD**

Professor  
Faculty of Engineering  
Chalmers University of technology  
(External Examiner)

---

**BUJANG KIM HUAT, PhD**

Professor and Deputy Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:

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

**Mohd Adzir bin Mahdi, PhD**

Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Chairman)

**Salasiah bt. Hitam, PhD**

Senior Lecture  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**M. Iqbal bin Saripan, PhD**

Associate Professor  
Faculty of Engineering  
Universiti Putra Malaysia  
(Member)

**Mohammed H. Al-Mansoori, PhD**

Associate Professor  
Faculty of Engineering  
University Tenaga Nasional  
(External Member)

---

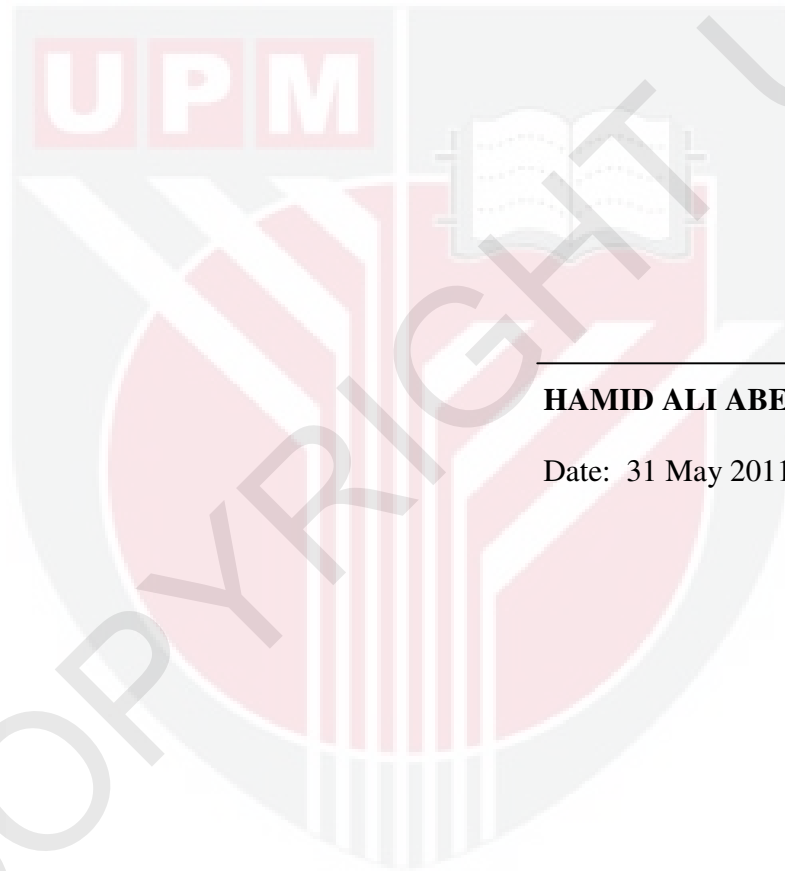
**HASANAH MOHD. GHAZALI, PhD**

Professor and Dean  
School of Graduate Studies  
Universiti Putra Malaysia

Date:

## DECLARATION

I declare that the thesis is my original work except for quotations and citations which have been duly acknowledged. I also declare that it has not been previously, and is not concurrently, submitted for any other degree at Universiti Putra Malaysia or at any other institution.



---

**HAMID ALI ABED AL-ASADI**

Date: 31 May 2011

## TABLE OF CONTENTS

	<b>Page</b>
<b>DEDICATION</b>	
<b>ABSTRACT</b>	iii
<b>ABSTRAK</b>	vi
<b>ACKNOWLEDGEMENTS</b>	ix
<b>APPROVAL</b>	xi
<b>DECLARATION</b>	xiii
<b>LIST OF TABLES</b>	xvii
<b>LIST OF FIGURES</b>	xviii
<b>LIST OF SYMBOLS/ABBREVIATIONS</b>	xxii
<b>CHAPTER</b>	
<b>1 INTRODUCTION</b>	<b>1</b>
1.1 Background	1
1.2 Motivation	4
1.3 Problem Statement	5
1.4 Research Objectives	7
1.5 Scope of Work	8
1.6 Thesis organization	9
<b>2 LITERATURE REVIEW</b>	<b>12</b>
2.1 Introduction	12
2.2 Linear and nonlinear optics	13
2.3 Optical fiber	16
2.3.1 Fiber loss	20
2.3.2 Advantage of optical fibers	24
2.3.3 Nonlinear refractive index effect	26
2.4 Light scattering	28
2.4.1 Spontaneous and stimulated scattering	28
2.4.2 Spectrum of the scattering light	30
2.5 Brillouin Scattering	32
2.5.1 Stimulated scattering processes in optical fiber	32
2.5.2 Stimulated Brillouin scattering in optical fiber	33
2.6 Applications of stimulated Brillouin scattering	38
2.7 Laser	39
2.7.1 Fiber laser	41
2.8 Frequency shift	51
2.8.1 Frequency shift classification	51
2.8.2 Frequency shift based on stimulated Brillouin Scattering	52
2.9 Summary	56

3	<b>STIMULTED BRILLOUIN SCATTERING MODELS FUNDAMENTALS</b>	57
3.1	Introduction	57
3.2	Wave propagation in nonlinear medium	58
3.3	Spontaneous Brillouin scattering in optical fibers	62
3.3.1	Stokes and anti-Stokes waves in optical fibers	67
3.4	Stimulated Brillouin scattering in optical fibers	74
3.4.1	Classical theory of stimulated Brillouin scattering	76
3.5	Basic models of initiation of stimulated Brillouin Scattering	81
3.5.1	Distributed (non-localized), fluctuating source Model	83
3.5.2	Localized, non-fluctuating source model	88
3.6	Steady state solutions	90
3.6.1	Intensity pump depletion included, absorption ignored	90
3.6.2	Intensity pump undepletion, absorption included	91
3.6.3	Intensity pump depletion, absorption included	92
3.7	Brillouin gain coefficient	93
3.8	Brillouin threshold	96
3.9	Summary	98
4	<b>EFFECTS OF PUMP RECYCLING TECHNIQUE ON STIMULATED BRILLOUIN SCATTERING THRESHOLD A THEORECTICAL MODEL</b>	99
4.1	Introduction	99
4.2	Theoretical model	99
4.3	Experimental validation	106
4.4	Summary	114
5	<b>PARTICLE SWARM OPTIMIZATION ON THRESHOLD EXPONENTIAL GAIN OF STIMULATED BRILLOUIN SCATTERING IN SINGLE MODE FIBERS</b>	115
5.1	Introduction	115
5.2	Particle swarm optimization	116
5.2.1	The origin of particle swarm optimization	116
5.2.2	Fundamental principle of particle swarm optimization	118
5.2.3	Implementation of particle swarm optimization	119
5.3	Initiation of stimulated Brillouin scattering source models and optimization	120
5.4	Experimental validation	128
5.5	Summary	139
6	<b>STIMULATED BRILLOUIN SCATTERING IN FIBER RING LASER AND ITS APPLICATIONS</b>	140
6.1	Introduction	140



6.2	Modeling of optical fiber ring laser	142
6.2.1	Condition for resonance	147
6.2.2	Cavity Finesse	151
6.2.3	Analysis of various parameters of optical fiber Laser	152
6.3	Brillouin fiber laser (BFL)	155
6.3.1	Modeling of ring cavity BFL	155
6.3.2	Ring cavity BFL simulation results	161
6.3.3	Generation the Second-order Stokes waves	165
6.4	Double Brillouin frequency shifter	172
6.4.1	Modeling of double Brillouin frequency shifter	172
6.4.2	Double Brillouin frequency shifter analytical model Validation	183
6.5	Summary	192
7	<b>CONCLUSION AND RECOMMENDATION FOR FUTURE WORK</b>	194
7.1	Conclusion	194
7.2	Recommendation for future work	197
	<b>REFERENCES/BIBLIOGRAPHY</b>	198
	<b>APPENDIX A</b>	218
	<b>BIODATA OF STUDENT'S</b>	225
	<b>LIST OF PUBLICATION AND PAPERS</b>	226