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 \((L > 5 \text{ km})\) 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

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>5km), penggandaan eksponen ambang menurun sehingga 14.6 secara beransur-ansur.


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
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

DEDICATION ................................................................. iii
ABSTRACT ........................................................................... vi
ABSTRAK ............................................................................. vi
ACKNOWLEDGEMENTS ...................................................... ix
APPROVAL ............................................................................ xi
DECLARATION ...................................................................... xiii
LIST OF TABLES ............................................................... xvii
LIST OF FIGURES ............................................................. xviii
LIST OF SYMBOLS/ABBREVIATIONS ................................. xxii

CHAPTER
1 INTRODUCTION .............................................................. 1
   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

2 LITERATURE REVIEW ..................................................... 12
   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 STIMULATED BRILLOUIN SCATTERING MODELS FUNDAMENTALS
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
  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 EFFECTS OF PUMP RECYCLING TECHNIQUE ON STIMULATED BRILLOUIN SCATTERING THRESHOLD
A THEORECTICAL MODEL
4.1 Introduction 99
4.2 Theoretical model 99
4.3 Experimental validation 106
4.4 Summary 114

5 PARTICLE SWARM OPTIMIZATION ON THRESHOLD EXPONENTIAL GAIN OF STIMULATED BRILLOUIN SCATTERING IN SINGLE MODE FIBERS
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 STIMULATED BRILLOUIN SCATTERING IN FIBER RING LASER AND ITS APPLICATIONS
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 183
    Validation
6.5 Summary 192
7 CONCLUSION AND RECOMMENDATION FOR FUTURE WORK 194
  7.1 Conclusion 194
  7.2 Recommendation for future work 197

REFERENCES/BIBLIOGRAPHY 198
APPENDIX A 218
B I O D A T A  O F  S T U D E N T ' S 2 2 5
L I S T  O F  P U B L I C A T I O N  A N D  P A P E R S  2 2 6