UNIVERSITI PUTRA MALAYSIA

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

HAMID ALI ABED AL-ASADI

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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

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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>5km), 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 peredeman mod sisi yang maksima.

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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

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