UNIVERSITI PUTRA MALAYSIA

DESIGN AND DEVELOPMENT OF RAMAN-ASSISTED MULTI-BRILLOUIN STOKES LASER USING DISPERSION COMPENSATING FIBRE

MUHAMMAD ZAMZURI ABDUL KADIR @ JAAFAR

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By

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

December 2008

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

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Chairman: **Professor Mohd. Adzir bin Mahdi, PhD**

Faculty: **Engineering**

Application of multiwavelength sources in Radio over Fibre (RoF) technology has been interesting research works since a last few decades. In order to achieve this source, many techniques have been proposed, whether using a single technology such as Brillouin fibre laser, Raman fibre laser, and erbium doped fibre laser (EDFL) or hybrid technology such as Brillouin-erbium fibre laser (BEFL) and Brillouin-Raman fibre laser (BRFL). Even though these proposed designs have their own advantages, they have not been thoroughly studied in terms of Stokes optical signal-to-noise ratio (S-OSNR), Stokes peak power (SPP), flattened SPP, Stokes linewidth (SLW), and Stokes line count (SLC).

In this research work, multiwavelength BRFL is proposed which consists of two different configurations, namely ring-cavity and linear cavity. These designs are configured so that the laser oscillation is assisted by internal reflection (e.g. Rayleigh scattering) and external reflection (e.g. Fresnel reflection, mirror or FBG). They are

pumped by the Raman pump source (RPS) having wavelength at 1455-nm or 1450-nm. The mediums used for Raman and Brillouin effects are a few lengths of dispersion compensating fibre (DCF) from different manufacturers. All the designed parameters are seriously taken care so that these two configurations are comparable.

It is observed that when the RPP is increased from 400-mW to 800-mW, the ring and linear cavity show the wavelength-shift of 2.12-nm and 3.72-nm respectively. The red-shift is larger for the latter since the forward and backward-Raman Stokes spectrum is amplified twice as well as the RPP is reflected into the DCF to be a second pump source.

When the RPP is above 1000-mW, Rayleigh scattering contributes to the peak-power discrepancy between the odd and even order Stokes line, and it is worse for the ring-cavity. This issue is nearly addressed by the linear-cavity design whereby all the Stokes lines are guided to make complete oscillation with the assistance of standing wave and Rayleigh scattering. The 3-dB SLW discrepancy between odd and even order is also observed from the ring-cavity. However, regardless of the BPP values, the 3-dB SLW becomes comparable to each other when the RPP is 1000-mW and above. For the linear-cavity, they become comparable when the RPP is 230-mW.

Relation between the S-OSNR and SLC is also studied. Both cavities show that as the SLC increases, the Stokes-OSNR decreases. However, multi-Stokes lines featured with flat amplitude and almost equal OSNR have been achieved with the linear-cavity just pumped by a single RPS. These spectra contain 360 Stokes lines with 18-dB OSNR.

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

REKAAN DAN PEMBANGUNAN LASER BRILLOUIN PELBAGAI JARAK GELOMBANG DIBANTU KESAN RAMAN MENGGUNAKAN MODUL GENTIAN OPTIK PEMAMPAS SERAKAN

Oleh

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Aplikasi teknologi fotonik di dalam teknologi radio-melalui-gentian memerlukan laser pelbagai frekuensi. Untuk menghasilkan laser ini pelbagai kaedah telah dicadangkan samada berdasarkan satu teknologi seperti laser berdasarkan erbium (EDFL), laser berdasarkan Brillouin (BFL) dan laser berdasarkan Raman (RFL) atau berdasarkan pelbagai teknologi seperti laser berdasarkan Brillouin dan erbium (BEFL) dan laser berdasarkan Brillouin dan Raman (BRFL). Novelti ini telah dicapai samada dari segi teknologi, konfigurasi, rekaan ataupun pengukuran. Walaupun berbagai-bagai rekaan telah dihasilkan dari teknologi tersebut, namun kajian mendalam tentang mutunya, seperti nisbah signal-optik ke kebisingan-optik (OSNR), puncak-kuasa Stokes (SPP), puncak kuasa Stokes setara (flattened SPP), jenis kebisingan (noise) seperti RIN dan kebisingan fasa (Phase-Noise) dan lebar-garisan gelombang Stokes (SLW) belum dilaksanakan lagi.

Di dalam kerja-kerja penyelidikan doktorat ini, konfigurasi yang telah dikaji adalah kaviti lurus dan kaviti gegelung. Bagi kaviti gegelung, komponen seperti pengasing arah aliran (isolator), pembahagi setara (3-dB splitter) dan lain-lain digunakan untuk menghasilkan ayunan sehala. Dan bagi kaviti lurus, dua cermin pembalik telah disambungkan di setiap hujung media-pengganda (gentian fibre) bagi memantulkan gelombang Stokes untuk melengkap ayunan. Kedua-dua kaviti ini dipam oleh punca kuasa pam Raman pada jarak-gelombang 1445-nm atau 1450-nm. Media pengganda yang digunakan di dalam rekaan ini adalah beberapa jenis gentian-optik pamampas serakan yang mempunyai sedikit perbezaan spesifikasi.

Di antara pemerhatian di dalam kajian ini ialah anjakan-merah yang berlaku bila kuasa pengepam Raman (RPP) dinaikkan dari 400-mW ke 800-mW. Anjakan merah berlaku sebanyak 3.72-nm dan 2.27-nm bagi setiap kaviti di atas. Kelebihan kaviti lurus adalah disebabkan oleh cirinya yang membenarkan aliran dua-hala RSS di dalam media pengganda. Hasilnya ialah, RPP mengalami dua-kali penggandaan.

Percanggahan di antara garisan Stokes genap dan ganjil pada kuasa pengepaman melebihi 1000-mW juga dikaji, iaitu bagi kuasa puncak (SPP) dan lebar garisan Stokes (SLW). Garisan Stokes genap dan ganjil mempunyai nilai SPP dan SLW yang berbeza dan bersilih ganti di antara satu sama lain dengan pertambahan bilangan garisan Stokes. Untuk kaviti lurus, percanggahan ini tidak terlalu ketara disebabkan oleh kesan dari serakan Rayleigh dan gelombang pegun yang dihasilkan oleh media pengganda yang sama. Percanggahan lebar-garisan setara (3-dB linewidth) di antara Stokes genap dan ganjil adalah sangat ketara bagi kaviti gegelung. Walaubagaimanapun, bila kuasa RPP mula mencecah nilai 1000-mW, percanggahan semakin berkurangan. Bagi kaviti lurus pula, kesan percanggahan ini hampir susut bila kuasa RPP mencecah 230-mW.

Hubungan di antara S-OSNR dan SLC juga dikaji bagi kedua kaviti tersebut. Kedua parameter tersebut didapati berkadaran secara sonsang di mana pertambahan SLC, akan mengakibatkan penurunan nilai S-OSNR. Walaubagaimanapun ratusan garisan Stokes setara (sekitar 360 garisan Stokes) bernilaikan OSNR sebanyak 18-dB telah diperolehi hanya dengan satu sumber pengepam Raman.

ACKNOWLEDGEMENTS

In the Name of Allah, the Most Gracious and the Most Merciful …

First of all, I would like to express my greatest gratitude to ALLAH the Almighty, for His help, guidance and mercy during the course of life and moment of truth.

I would also like to express my appreciation and sincerest gratitude to my supervisor, Associate Professor Dr. Mohd. Adzir Mahdi for his continual support, endless encouragement, patience, understanding and time spent towards completing this research work. Without his help, my entire endeavour would have been impossible.

My heartiest thanks are extended to other supervisory members, i.e. Prof Dr. Mohamad Khazani Abdullah and Prof Dr Kaharuddin Dimyati for their invaluable guidance and constructive critics. I also owe favours to all my colleagues and friends from Photonics Technology of TM Research and Development Sdn. Bhd. for their helps and encouragement. You all have been true friends in all aspects of my life.

My greatest appreciation is to very important persons in my life, first and foremost, is to my mother Maziah Ibrahim who without her I would have been impossible to learn the miracle of light, to my wife Suriani Ahmad Malik for her love, caring and understanding. My heartfelt thanks also go to my daughter Saidatul Najibah, my sons Ahmad Amir Akhtar and Ahmad Hakim Hannan who have been my inspiration throughout the research work. A special dedication also goes to a new family member, Saidatul A-Immah the fourth of my descendants and the second of my beautiful daughters. All of you are greatly welcomed into my life with open arms.

Last but not least is to you who read this dissertation and pick some priceless knowledge for the benefit of humankind, with a great honour, I express my sincere thanks and appreciation. Thank you

I certify that an Examination Committee has met on **5 December 2008** to conduct the final examination of **Muhammad Zamzuri Abdul Kadir @ Jaafar** on his degree of **Doctor of Philosophy** thesis entitled "**Raman-Assisted Multi-Brillouin Stokes Laser in Dispersion Compensating Fibre**" in accordance with Universiti Pertanian Malaysia (Higher Degree) Act 1980 and Universiti Pertanian Malaysia (Higher Degree) Regulations 1981. The Committee recommends that the student be awarded the relevant degree.

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Date: 9 April 2009

DECLARATION

I hereby declare that the thesis is based on my original work except for quotations and citations, which have been duly acknowledged. I also declare that it has not been previously or concurrently submitted for any other degree at UPM or other institutions.

MUHAMMAD ZAMZURI ABDUL KADIR @ JAAFAR

Date:

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LIST OF ABBREVIATIONS

ASRS	Amplified Spontaneous Rayleigh scattering
ASE	Amplified spontaneous emission
AWG	Array Waveguide Grating
BEFL	Brillouin Erbium Fibre Laser
BEFLL	Brillouin Erbium Fibre Linear Laser
BEFRL	Brillouin Erbium Fibre Ring laser
BFL	Brillouin Fibre Laser
BPP	Brillouin Pump Power
BPS	Brillouin Pump Source
BPW	Brillouin Pump Wavelength
BRFL	Brillouin Raman Fibre Laser
BRS	Backscattered Rayleigh Signal
BSL	Brillouin Stokes Line
BSLW	Brillouin Stokes Linewidth
BSS	Brillouin Stokes Spectrum
BSW	Brillouin Stokes Wave
BT	Backward Travelling
BTRSS	Backward Travelling Raman Stokes Spectrum
c-BEFL	Conventional Brillouin Erbium Fibre Laser
CCW	Counter Clock Wise
CD	Chromatic Dispersion
CW	Continuous Wave
DCF	Dispersion compensating fibre

DCM	Dispersion Compensating Module
DOP	Degree of Polarization
DBRS	Double back Rayleigh scattering
DWDM	Dense Wavelength Division Multiplexing
EDF	Erbium Doped Fibre
EDFL	Erbium doped fibre Laser
EDFA	Erbium Doped Fibre Amplifier
EYFL	Erbium-Ytterbium Fibre Laser
FBG	Fibre Bragg grating
FLM	Fibre Loop Mirror
FOBSS	First Order Brillouin Stokes Spectrum
FOBSL	First Order Brillouin Stokes Line
FOSL	First Order Stokes Line
FO-SPP	First Order Stokes Peak Power
FO-SNF	First Order Stokes Noise Floor
FOS-OSNR	First Order Stokes OSNR
FPF	Fabry-Perot Filter
FROG	Frequency Resolved Optical Gating
FRPG	First Raman Peak Gain
FT	Forward Travelling
FTRSS	Forward Travelling Raman Stokes Spectrum
FWHM	Full Width at Half Maximum
FWM	Four Wave Mixing
HR-OSA	High Resolution Optical Spectrum Analyzer
HWHM	Half Width at Half Maximum

LC-NOLM	Linear Cavity Nonlinear Optical Loop Mirror
LD	Laser diode
LIM	Linear Interpolation Method
MPS	Modulation Phase Shift
MMW	Millimetre-wave
NA	Numerical Aperture
NLC	Nonlinear Coefficient
NOLM	Nonlinear Optical Loop Mirror
OC	Optical Circulator
OPS	Optical Polarization Splitting
OSA	Optical spectrum analyzer
OSNR	Optical signal-to-Noise ratio
PBC	Polarization Beam Combiner
PC	Polarization Controller
PMF	Polarization maintaining Fibre
PS-WDM	Pump-Signal WDM
RA-BRFL	Raman Assisted Brillouin Raman Fibre Laser
RA-BSL	Raman Assisted Brillouin Stokes Line
RA-SCT	Rayleigh-Assisted Stokes Comb Threshold
RBW	Resolution Bandwidth
RC-NOLM	Ring Cavity Nonlinear Optical Loop Mirror
RFL	Raman Fibre Laser
RI	Refractive Index
RIN	Relative intensity noise
ROF	Radio over Fibre

RPG	Raman Peak Gain
RPP	Raman Pump Power
RPS	Raman Pump Source
RPU	Raman Pump Unit
RPW	Raman Pump Wavelength
RS	Rayleigh Scattering
RS-BSL	Rayleigh Scattered Brillouin Stokes Line
RS-BRFL	Rayleigh Scattered Brillouin Raman Fibre Laser
RSBW	Raman Stokes Bandwidth
RS-FOBSL	Rayleigh Scattered First Order Brillouin Stokes Line
RSPP	Raman Stokes Peak Power
RSPW	Raman Stokes Peak Wavelength
RSS	Raman Stokes Spectrum
RPU	Raman pump unit
SBS	Stimulated Brillouin scattering
SHB	Spectral Hole Burning
SiO_2	Silicon Dioxide
SLM	Single Longitudinal Mode
SLBW	Stokes Line Bandwidth
SLC	Stokes Line Count
SLPP	Stokes Lines Peak Power
SMF	Single mode Fibre
SMOF	Single Mode Optical Fibre
SOP	State of polarization
SOBSL	Second Order Brillouin Stokes Line