



The University of Adelaide
School of Chemistry and Physics

Experimental Study of Stimulated Brillouin Scattering
in Open Cells and Multimode Optical Fibres

By

Allan Chi-Lun Wong

B.Sc. (*Flinders*), B.Sc.(Hons.) (*Adelaide*)

Thesis submitted for the degree of
Master of Science

In

The Discipline of Physics
School of Chemistry and Physics
The University of Adelaide

June 2005

Statement of Originality

This work contains no material which has been accepted for the award for any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text.

I give consent to this copy of my thesis, when deposited in the university library, being available for loan and photocopying.

Signed:

Date:

Supervisor: Professor Jesper Munch

Acknowledgements

I sincerely give thanks to my Lord Jesus Christ.

I gratefully thank my supervisor Professor Jesper Munch. He is a very caring supervisor that cared a lot about my progress and how much I learned from the project. He is also an easy to approach teacher who is willing to listen to me and help me immediately when I got hindered from either experimental or conceptual problems.

I would also like to thank Blair Middlemiss for his technical assistance and ideas and Trevor Waterhouse for his help in the Physics Workshop.

Thanks to Dr. Murray Hamilton and Dr. Peter Veitch for their help and guidance while Professor Munch was unavailable or away.

Special thanks to Kwang-Ho Bae for his continuous help and support since my Honours year, Damien Mudge for provision of some equipments, Alex Hemming for the help of the laser.

I would like to thank my parents for their encouragements and endless supports.

Lastly, I would like to thank Professor Munch once again for his tremendous efforts in revising and proofreading my thesis in minute detail. His tireless energy is much admired and appreciated.

Abstract

An experimental study of the stimulated Brillouin scattering (SBS) were performed by performing optical phase conjugation in open cells and multimode optical fibres using a Q-switched, pulsed Nd:YAG laser ($\lambda = 1.064\mu\text{m}$). Experiments were done with test tubes that contained two SBS liquids – Fluorinert and Acetone, and multimode optical fibres with $62.5\mu\text{m}$ core diameter. The three fundamental parameters of SBS: the threshold energy, reflectivity and phase conjugate fidelity were characterised and analysed. In addition, the temporal behaviour of Stokes beam, phase correction, optical breakdown, and pulse compression were investigated.

Table of Contents

LIST OF FIGURES	3
LIST OF TABLES	7
1 INTRODUCTION.....	9
1.1 RESEARCH OBJECTIVES.....	9
1.2 OVERVIEW	11
1.3 ORGANISATION OF THE THESIS	13
2 THEORIES OF STIMULATED BRILLOUIN SCATTERING AND OPTICAL PHASE CONJUGATION	15
2.1 STIMULATED BRILLOUIN SCATTERING.....	15
2.1.1 General Descriptions.....	15
2.1.2 SBS in Ordinary Cell Geometry	19
2.1.3 SBS in Optical Fibres.....	21
2.2 OPTICAL PHASE CONJUGATION.....	23
2.2.1 General Descriptions.....	23
2.2.2 OPC by SBS.....	25
2.2.3 OPC by SBS in Optical Fibres.....	28
3 EXPERIMENTAL SETUP	33
3.1 EXPERIMENTAL PARAMETERS FOR MEASUREMENTS	33
3.2 MAIN SETUP	34
3.2.1 Pump Laser and its Performance Tests	34
3.2.2 Other Optical Components.....	37
3.3 DIAGNOSTICS SETUP.....	40
3.3.1 SBS Reflectivity Diagnostics Setup.....	41
3.3.2 Phase Conjugate Fidelity Diagnostics Setup	42
3.4 MEASUREMENT METHODS	46
4 SBS EXPERIMENTS IN OPEN CELLS.....	49
4.1 PROPERTIES OF SBS CELL	49
4.2 USING FLUORINERT	51
4.2.1 SBS Reflectivity of Fluorinert	52
4.2.2 Phase Conjugate Fidelity of Fluorinert	56
4.3 USING ACETONE	62
4.3.1 SBS Reflectivity of Acetone	63
4.3.2 Phase Conjugate Fidelity of Acetone.....	67
4.4 PHASE CORRECTION OF AN ABERRATED BEAM.....	71
4.5 OPTICAL BREAKDOWN.....	73
4.6 PULSE COMPRESSION	74
5 SBS EXPERIMENTS IN MULTIMODE OPTICAL FIBRES	79

5.1 PROPERTIES OF OPTICAL FIBRES	79
5.2 SBS REFLECTIVITY OF OPTICAL FIBRES	83
5.3 PULSE DYNAMICAL BEHAVIOUR IN OPTICAL FIBRES.....	87
5.3.1 General Descriptions.....	87
5.3.2 Unusual Stokes Pulse Temporal Behaviour.....	91
5.3.3 Fibre Transmitted Pulse Dynamical Behaviour.....	95
6 CONCLUSION	99
6.1 SUMMARY.....	99
6.2 FUTURE DIRECTION	101
BIBLIOGRAPHY	103

List of Figures

FIGURE 3.1 SCHEMATIC DIAGRAM OF THE MAIN EXPERIMENTAL SETUP. $\lambda/2$ = HALF WAVE PLATE, POL = BREWSTER POLARISER, W = WEDGE, $\lambda/4$ = QUARTER WAVE PLATE, L = 12CM POSITIVE LENS.	34
FIGURE 3.2 PULSE WIDTH OF PUMP VS ENERGY.....	35
FIGURE 3.3 COMPARISONS OF PUMP POWERS (UNCALIBRATED) VS. PUMP ENERGIES BETWEEN Q-SWITCHED AND NON-Q-SWITCHED OPERATIONS.	35
FIGURE 3.4 PUMP PULSE PROFILES IN VARIOUS OPERATING CONDITIONS UNDER THE SAME INPUT ENERGY TO THE LASER: (A) NON-Q-SWITCHED, (B) Q-SWITCHED BUT NOT INJECTION SEEDED, (C) Q-SWITCHED AND INJECTION SEEDED. NOTE (A) WAS IN DIFFERENT TIME (HORIZONTAL) AND AMPLITUDE (VERTICAL) SCALES.	36
FIGURE 3.5 SCHEMATIC DIAGRAM OF THE DIAGNOSTICS OF SBS REFLECTIVITY. ED = ENERGY DETECTOR, PD = PHOTODETECTORS, W = WEDGE.....	42
FIGURE 3.6 SCHEMATIC DIAGRAM OF THE DIAGNOSTICS OF PHASE CONJUGATE FIDELITY – THE “ENERGY-IN-THE-BUCKET” TECHNIQUE. FOR POWER MEASUREMENTS, REPLACE ENERGY DETECTORS WITH PHOTODETECTORS. ED = ENERGY DETECTOR, PD = PHOTODETECTOR, W = WEDGE, M = MIRROR, L = 1.15M POSITIVE LENS, PH = 0.40MM PINHOLE.	44
FIGURE 3.7 PINHOLE TRANSMISSION FACTORS FROM DIFFERENT COMBINATIONS OF FOCAL LENGTHS AND PINHOLE DIAMETERS AT DIFFERENT SEPARATIONS. DOTS ARE EXPERIMENTAL DATA; LINES ARE HIGH ORDER POLYNOMIAL CURVE FITS OF THE DATA POINTS.....	45
FIGURE 3.8 SYNCHRONISATION MEASUREMENT TO DETERMINE THE TIME DELAY BETWEEN TWO SIGNALS RECEIVED FROM THE PHOTODETECTORS TO THE OSCILLOSCOPE.....	48
FIGURE 4.1 REFLECTIVITY VS THRESHOLD ENERGY RATIO OF FLUORINERT WITHOUT ABERRATOR. EACH DOT REPRESENTS AN AVERAGE OF 6 PULSES.	53
FIGURE 4.2 REFLECTIVITY VS THRESHOLD ENERGY RATIO OF FLUORINERT WITH ABERRATOR. EACH DOT REPRESENTS AN AVERAGE OF 6 PULSES.	55
FIGURE 4.3 TEMPORAL PROFILES OF PUMP AND STOKES PULSES OF FLUORINERT WITHOUT (A) AND WITH (B) ABERRATOR INSERTED. CH1 = PUMP PULSE, CH2 = STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS.....	56
FIGURE 4.4 ENERGY FIDELITY VS THRESHOLD ENERGY RATIO OF FLUORINERT. E_{TH} (NO ABERRATOR) = 5.5MJ, E_{TH} (WITH ABERRATOR) = 8.7MJ. EACH DOT REPRESENTS AN AVERAGE OF 30 PULSES. ERROR BARS ARE MEASUREMENT UNCERTAINTIES.....	58
FIGURE 4.5 PEAK POWER FIDELITY VS THRESHOLD ENERGY RATIO OF FLUORINERT. E_{TH} (NO ABERRATOR) = 5.6MJ, E_{TH} (WITH ABERRATOR) = 6.8MJ. EACH DOT REPRESENTS AN AVERAGE OF 30 PULSES. ERROR BARS ARE MEASUREMENT UNCERTAINTIES.....	60
FIGURE 4.6 TEMPORAL PROFILES OF STOKES PULSES OF FLUORINERT WITHOUT (A) AND WITH (B) ABERRATOR INSERTED. HORIZONTAL SCALE SHOWS THE TIME, VERTICAL SCALE SHOWS THE AMPLITUDE. CH1 (UPPER TRACE) = NEAR-FIELD STOKES PULSE, CH2 (LOWER TRACE) = FAR-FIELD STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS.....	62
FIGURE 4.7 REFLECTIVITY VS THRESHOLD ENERGY RATIO OF ACETONE WITHOUT ABERRATOR. EACH DOT REPRESENTS AN AVERAGE OF 6 PULSES.	64
FIGURE 4.8 REFLECTIVITY VS THRESHOLD ENERGY RATIO OF ACETONE WITH ABERRATOR. EACH DOT REPRESENTS AN AVERAGE OF 6 PULSES.....	65

FIGURE 4.9 TEMPORAL PROFILES OF PUMP AND STOKES PULSES OF ACETONE WITHOUT (A) AND WITH (B) ABERRATOR INSERTED. CH1 = PUMP PULSE, CH2 = STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS.....	67
FIGURE 4.10 ENERGY FIDELITY VS THRESHOLD ENERGY RATIO OF ACETONE. E_{TH} (NO ABERRATOR) = 9.0MJ, E_{TH} (WITH ABERRATOR) = 10.2MJ. EACH DOT REPRESENTS AN AVERAGE OF 30 PULSES. ERROR BARS ARE MEASUREMENT UNCERTAINTIES.	68
FIGURE 4.11 POWER FIDELITY VS THRESHOLD ENERGY RATIO OF ACETONE. E_{TH} (NO ABERRATOR) = 6.1MJ, E_{TH} (WITH ABERRATOR) = 7.5MJ. EACH DOT REPRESENTS AN AVERAGE OF 30 PULSES. ERROR BARS ARE MEASUREMENT UNCERTAINTIES.	69
FIGURE 4.12 TEMPORAL PROFILES OF STOKES PULSES OF ACETONE WITHOUT (A) AND WITH (B) ABERRATOR INSERTED. HORIZONTAL SCALE SHOWS THE TIME, VERTICAL SCALE SHOWS THE AMPLITUDE. CH1 (UPPER TRACE) = NEAR-FIELD STOKES PULSE, CH2 (LOWER TRACE) = FAR-FIELD STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS. NOTE THE DIFFERENCE IN AMPLITUDE (VERTICAL) SCALE OF CH2.	70
FIGURE 4.13 NEAR-FIELD PATTERNS OF THE (A) PUMP PULSE, (B) ABERRATED PUMP PULSE, (C) RETURN PULSE FROM MIRROR, (D) STOKES PULSE.....	72
FIGURE 4.14 FAR-FIELD PATTERNS OF THE (A) PUMP PULSE, (B) ABERRATED PUMP PULSE, (C) RETURN PULSE FROM MIRROR, (D) STOKES PULSE.	73
FIGURE 4.15 EVOLUTION OF STOKES PULSE TEMPORAL PROFILE AS A FUNCTION OF THE DISTANCE FROM FRONT FACE OF SBS CELL TO EFFECTIVE FOCAL PLANE OF THE LENS: (A) 5CM, (B) 11CM, (C) 16CM, (D) 25CM, (E) 35CM, (F) 37CM, (G) 42CM, (H) 46CM, (I) 51CM, (J) 54CM, (K) 56CM, (L) 60CM. CH1: PUMP PULSE, CH2: STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS.....	77
FIGURE 5.1 FRESNEL REFLECTIONS FROM BOTH ENDS (A) AND FRONT END (B) OF THE 62.5 μ M CORE FIBRES. CH1 = PUMP PULSE, CH2 = REFLECTED PULSE.....	81
FIGURE 5.2 STOKES PULSES FROM A PARTIALLY DAMAGED FRONT FACE (A & C) AND FROM A NORMAL FLAT FRONT FACE (B & D) OF THE 62.5 μ M CORE FIBRES. CH1 = PUMP PULSE, CH2 = REFLECTED PULSE. CH1 LAGGED CH2 BY 2.31NS. NOTE THE DIFFERENCE IN AMPLITUDE (VERTICAL) SCALE OF CH2.	82
FIGURE 5.3 POWER REFLECTIVITY VS THRESHOLD ENERGY RATIO OF 62.5 μ M CORE FIBRE OF DIFFERENT LENGTHS WITHOUT ABERRATOR. EACH DOT REPRESENTS AN AVERAGE OF 5 PULSES. THE LINES ARE FOR EASIER VIEWING ONLY.	84
FIGURE 5.4 SBS THRESHOLD ENERGY OF 62.5 μ M CORE FIBRE WITHOUT ABERRATOR FOR DIFFERENT FIBRE LENGTHS. EACH DOT REPRESENTS AN AVERAGE OF 5 PULSES. THEORY LINE IS BASED ON EQ. (2.2.29).	85
FIGURE 5.5 POWER REFLECTIVITY VS PUMP ENERGY OF 62.5 μ M CORE FIBRE OF DIFFERENT LENGTHS WITH ABERRATOR. EACH DOT REPRESENTS AN AVERAGE OF 5 PULSES. THE LINES ARE FOR EASIER VIEWING ONLY.	86
FIGURE 5.6 SBS THRESHOLD ENERGY OF 62.5 μ M CORE FIBRE WITH ABERRATOR FOR DIFFERENT FIBRE LENGTHS. EACH DOT REPRESENTS AN AVERAGE OF 5 PULSES. THEORY LINE IS BASED ON EQ. (2.2.29).	87
FIGURE 5.7 POWER DISTRIBUTION OF THE PUMP AND STOKES WAVES INSIDE AN OPTICAL FIBRE. FROM REF. [46].	89
FIG. 5.8 SNAPSHOTS OF TYPICAL STOKES PULSES TAKEN DURING MEASUREMENTS OF DIFFERENT FIBRE LENGTHS WITHOUT ABERRATOR. CH1 = TRANSMITTED PULSE, CH2 = STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS. NOTE THE DIFFERENCE IN TIME (HORIZONTAL) AND AMPLITUDE (VERTICAL) SCALES.....	90
FIG. 5.9 SNAPSHOTS OF TYPICAL STOKES PULSES TAKEN DURING MEASUREMENTS OF DIFFERENT FIBRE LENGTHS WITH ABERRATOR. CH1 = TRANSMITTED PULSE, CH2 =	

	STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS. NOTE THE DIFFERENCE IN TIME (HORIZONTAL) AND AMPLITUDE (VERTICAL) SCALES.	91
FIG. 5.10	SNAPSHOTS OF UNUSUALLY HIGH POWER REFLECTIVITY, HIGHLY COMPRESSED STOKES PULSES TAKEN DURING MEASUREMENTS OF DIFFERENT FIBRE LENGTHS. CH1 = PUMP PULSE, CH2 = STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS. NOTE THE DIFFERENCE IN TIME (HORIZONTAL) AND AMPLITUDE (VERTICAL) SCALES.	93
FIG. 5.11	SNAPSHOTS OF UNUSUAL, SIMILARLY MODULATED PEAKS OF THE STOKES PULSES TAKEN DURING MEASUREMENTS OF DIFFERENT FIBRE LENGTHS. CH1 = PUMP PULSE, CH2 = STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS. NOTE THE DIFFERENCE IN TIME (HORIZONTAL) AND AMPLITUDE (VERTICAL) SCALES.	95
FIG. 5.12	SNAPSHOTS OF TRANSMITTED PULSES TAKEN DURING MEASUREMENTS OF DIFFERENT FIBRE LENGTHS. CH1 = TRANSMITTED PULSE, CH2 = STOKES PULSE. CH1 LAGGED CH2 BY 2.31NS. THE ADDITIONAL LAG OF THE TRANSMITTED PULSE (CH1) WAS THE TRANSIT TIME THAT THE PULSE TRAVELLED THROUGH THE WHOLE LENGTH OF THE FIBRE. NOTE THE DIFFERENCE IN TIME (HORIZONTAL) AND AMPLITUDE (VERTICAL) SCALES.	97

List of Tables

TABLE 4.1 EFFECTIVE INTERACTION LENGTHS FOR SBS PROCESS.....	50
TABLE 4.2 PHYSICAL PROPERTIES OF FLUORINERT FC-75 AT 25°C. FROM REF. [75].	51
TABLE 4.3 SBS RELATED PROPERTIES OF FLUORINERT FC-75 AT 25°C AND 1064NM. FROM REFS. [76, 77].	51
TABLE 4.4 PHYSICAL PROPERTIES OF ACETONE AT 20°C. FROM REF. [82].	62
TABLE 4.5 SBS RELATED PROPERTIES OF ACETONE AT 1064NM. FROM REFS. [44, 61, 62].	63
TABLE 5.1 SBS RELATED PROPERTIES OF SiO ₂ (FIBRE) AT 1.55μM. FROM REF. [46, 48, 61].	80