

Supercontinuum generation in higher order modes of microstructured optical fibre

Samuel Robert Legge

B.Sc (Hons)

A thesis submitted for the Degree of

Doctor of Philosophy

Discipline of Physics

School of Mathematical and Physical Sciences

The University of Newcastle

April 2016

Declaration

This thesis contains no material which has been accepted for the award of 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 made available for loan and photocopying subject to the provisions of the *Copyright Act 1968*.

(Signed)_____

Samuel Legge

Acknowledgments

I would like to thank my family for their love and understanding over the past years that I have worked on this project. I would like to give my mum and dad a special thank you for always being there for me and encouraging my curiosity in science.

I would like to thank my supervisors John Holdsworth and Bruce King for their help and guidance. John in particular has been an amazing mentor over the last nine years of my life and I thank him immensely for everything he has helped me achieve.

Thank you to all the undergraduate and honours students I have worked with on this project. Ben Zwan deserves a mention for both his experimental work and input into the scientific process.

Most importantly I would like to thank my wife Kim for all her support and encouragement over these last few years. Your love and kindness has kept me going through this and I look forward to our next big adventure together.

Abstract

The focus of this thesis is the observation and characterisation of supercontinuum generation within multimode microstructured optical fibre and the development of the techniques required to both create and measure the generated supercontinua. In addition, the nonlinear effects of light in silica are reviewed, and the experimental results from supercontinua generated with a low number of solitons add novel scientific weight to recent theories on dispersive wave and soliton interactions in microstructured optical fibre.

The supercontinua generated in various hexagonal core and elliptical core microstructured optical fibres when pumped with femtosecond pulses sourced from a Ti:Sapphire laser system are observed. The electromagnetic mode excited within the core is selected by an offset to the incident beam position on the fibre end face through a precise coupling system under computer control. A novel experimental measurement technique was developed to simultaneously characterise the electromagnetic mode output of these fibres in spectral and spatial domains.

This technique revealed previously unobserved complexity in the mode structure of the supercontinuum output from microstructured optical fibre. In the generated dispersive wave, it was found that the electromagnetic mode structure was orientated in a hexagonal higher order mode structure with each orientation producing a slightly varied wavelength of light.

From this work, and by selectively coupling into higher order modes, it was discovered that the creation of a “sparse supercontinuum” with a low number of solitons was possible while still maintaining strong nonlinear effects. This work allowed experimental soliton and dispersive wave pairs matched in higher order modes to be compared to the recent theories on dispersive wave trapping and the group index matching between these light pulses.

To aid in the understanding of this data the full vector solutions for the electromagnetic modes in all fibres used were simulated using finite element frequency domain analysis, providing both the mode field structure and the effective mode index and dispersion for all modes in each fibre.

A polarisation study was performed on the output of the higher order electromagnetic modes confirming the expected simulated vector modes and using the rotation direction of the field pattern with polarisation rotation to determine the specific mode generated.

This thesis comprises significant work that expands the scientific knowledge in the fields of supercontinuum generation, nonlinear optics and higher order electromagnetic modes in microstructured optical fibres through both simulation and experimental measurement and analysis.

Table of Contents

Declaration	i
Acknowledgments	iii
Abstract	v
Table of Contents	vii
1 Introduction.....	1
1.1 Optical Fibre	2
1.1.1 Numerical Aperture.....	2
1.1.2 Attenuation	3
1.1.3 Refractive Index of Optical Fibre	4
1.1.4 Electromagnetic Modes in Optical Fibre	6
1.2 Microstructured Optical Fibre	12
1.3 Nonlinear Optics.....	14
1.3.1 Kerr Effect.....	16
1.3.2 Self-Phase Modulation	17
1.3.3 Cross-Phase Modulation	19
1.3.4 Wave Mixing.....	22
1.3.5 Solitons.....	23
1.3.6 Stimulated Raman Scattering	26
1.4 Supercontinuum.....	28
1.4.1 Discovery and History.....	28
1.4.2 The Supercontinuum	29
1.4.3 Soliton Formation and Fission	30
1.4.4 Soliton Self-Raman Shift	30
1.4.5 Dispersive Wave	31
1.4.6 Gravity-like Trapping.....	33
1.4.7 Four Wave Mixing	36

1.4.8	Numerical Simulation	36
1.5	Supercontinuum in Higher Order EM Modes	37
1.5.1	Initial Research	38
1.5.2	Current Research.....	39
1.5.3	The Scope of this Thesis	44
2	Experimental.....	46
2.1	Ultrafast Lasers.....	46
2.1.1	Titanium-Sapphire Laser.....	46
2.1.2	Measurement and Characterisation of Ti:S Laser.....	47
2.2	Microstructured Optical Fibre	49
2.3	Optics.....	53
2.3.1	Faraday Isolator.....	53
2.3.2	Beam Steering and Stabilisation	54
2.3.3	Fibre Coupling System.....	58
2.3.4	Apparatus Configuration.....	59
2.3.5	Collimator and Mode Scanner	59
2.3.6	Polariser and Screen.....	61
2.4	Spectrometers	62
2.4.1	HR2000+.....	62
2.4.2	NIRQuest	62
2.5	Processing.....	64
2.5.1	Radiometric Calibration.....	64
2.5.2	Data Restructure and Visualisation.....	65
3	Modelling of Optical Modes in Microstructured Optical Fibres	67
3.1	Multipole Method.....	67
3.2	Finite Element Frequency Domain Method	68
3.3	Curve Fitting.....	68

3.4	Results	69
3.4.1	Thorlabs NL-2.8-850-02	69
3.4.2	Thorlabs NL-2.0-745-02	74
3.4.3	Thorlabs NL-3.0-850.....	77
3.4.4	OFTC Spun High Birefringence Fibre	79
4	Observation of Supercontinuum Generation in Higher Order Modes of Microstructured Optical Fibre.....	83
4.1	Overview	83
4.2	Results and Discussion	84
4.3	Conclusions	90
5	The Sparse Supercontinuum.	91
5.1	Overview	91
5.2	Method and Reasoning.....	92
5.3	Results and Discussion.....	93
5.4	Conclusions	97
6	Polarisation Study.....	98
6.1	Overview	98
6.2	Experimental and method.....	98
6.3	Results and discussion.....	102
6.4	Conclusions	106
7	Conclusions and Further Work.....	107
8	References.....	109
9	Papers.....	112
9.1	Supercontinuum Generation in Higher Order Modes of Photonic Crystal Fibre	113
9.2	Spatio-spectral Identification of Solitons Occupying Higher Order Electromagnetic Modes in Photonic Crystal Fibre.....	119

9.3	Spatio-spectral Analysis of Supercontinuum Generation in Higher Order Electromagnetic Modes of Photonic Crystal Fiber	123
9.4	Low Order Solitons in Higher Order Electromagnetic Modes of Photonic Crystal Fibre	129
9.5	Higher-Order Electromagnetic Mode Solitons Illuminate Theory.....	132
9.6	Sparse Supercontinuum with Low Order Solitons in Higher Order Electromagnetic Modes	135
10	Appendices	139
10.1	Taylor Series Expansion of Phase Constant.....	139
10.2	Radiometric Calibration	141
10.3	Source Code for Programs	142
10.3.1	List of other Programs Witten.....	142
10.3.2	Refraction of Fused Silica.....	143
10.3.3	Self-Phase Modulation Simulation	144
10.3.4	Quadrant Detection Simulation.....	145