http://researchspace.auckland.ac.nz

ResearchSpace@Auckland

Copyright Statement

The digital copy of this thesis is protected by the Copyright Act 1994 (New Zealand).

This thesis may be consulted by you, provided you comply with the provisions of the Act and the following conditions of use:

- Any use you make of these documents or images must be for research or private study purposes only, and you may not make them available to any other person.
- Authors control the copyright of their thesis. You will recognise the author’s right to be identified as the author of this thesis, and due acknowledgement will be made to the author where appropriate.
- You will obtain the author's permission before publishing any material from their thesis.

To request permissions please use the Feedback form on our webpage.
http://researchspace.auckland.ac.nz/feedback

General copyright and disclaimer

In addition to the above conditions, authors give their consent for the digital copy of their work to be used subject to the conditions specified on the Library Thesis Consent Form.
Picosecond Pulse Generation and Propagation in Erbium Doped Optical Fibres

by

Paul Bollond

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Physics at the University of Auckland

The University of Auckland 1997
Abstract

This thesis is concerned with the generation of picosecond pulses and their propagation through both resonant and non-resonant media. This was achieved by constructing a passively modelocked Erbium doped fibre laser (EDFL) which was used to study pulse propagation through sections of standard communications grade optical fibre, dispersion shifted optical fibre, and also through an Erbium doped fibre amplifier (EDFA) module.

The EDFL produced a train of ~2 psec pulses at 4 MHz, tunable over the erbium gain band (1520 - 1570 nm). The laser was constructed from commercially available components and had the property of stability combined with low pump power requirements to produce ~50 Watt peak power pulses. The laser cavity geometry included a nonlinear optical loop mirror, which has the property of efficiently switching high peak power pulses, and allowed pulsed operation without the aid of any high-speed electronics.

An EDFA module of identical geometry to that used in the laser was also constructed, and this was probed using the pulses from the EDFL. The traditional temporal and spectral measurements were found to be inadequate to allow a complete description of the pulse amplification process to be developed. To overcome this problem the technique of frequency resolved optical gating (FROG) was applied for the first time to optical fibre research, and allowed an indirect measurement of the electric field of the pulse. This complete description of the pulse was used in a numerical model to describe pulse propagation in an optical fibre. Fundamental propagation terms in the model were treated as free parameters in a minimisation scheme, which could be determined for a fibre under examination. This technique was shown to be accurate when used to examine pulse propagation through both standard and dispersion shifted optical fibre.

A comprehensive numerical model was developed for the EDFA, and it was apparent from this model that a pulse propagating through an optimised EDFA encounters an atomic inversion distribution which is a strong function of distance along the amplifying fibre. It was also shown from the experimental results that the EDFA exhibited resonant dispersion, which is characteristic for propagation through an atomic medium on resonance.
Acknowledgments

The work described in this thesis was conducted over a five year period, and was made possible by the contributions from many individuals and organisations. I would like to take this opportunity to thank them.

I would like to thank my supervisor Professor John Harvey for the assistance he has given me over this period, which has allowed the experimental laser physics research group at the University of Auckland to establish a research program in optical fibre technology for telecommunications. I would also like to thank Dr Graham Town of the University of Sydney for the opportunity to work in his lab during 1995. I also thank the research group at the Optical Fibre Technology Centre, The University of Sydney for manufacturing the Erbium doped fibre which was used in this thesis, and also for answering my many questions about it.

This work was initiated with financial support from Telecom New Zealand Ltd, who awarded me the 1992 Telecom New Zealand Fellowship in Telecommunications Engineering. I would like thank Telecom New Zealand Ltd for this award, and for their support of research conducted in New Zealand.

I also thank the Physics Department and the Applied Optics Centre at the University of Auckland for financial support over the latter part of this research. I also would like to thank the University of Auckland for allowing me to attend the Optical Fiber Communication (OFC) conference in Dallas Texas during February 1997 to present some results of the thesis, by awarding me a grant from the Graduate Research Fund. I also thank FibreNet New Zealand Ltd for sponsoring my trip to the Australian Conference on Optical Fibre Technology (ACOFT) in Surfers Paradise, Queensland, during December 1996, where I also presented some results. Thanks also to the Physico-Chemistry Department, the University of Auckland Medical School, for sponsoring me to travel to the OFC and ACOFT conferences. I thank the Applied Optics Centre at the University of Auckland for sponsoring my trip to the International Conference on Quantum Electronics (IQEC) in Sydney during July 1996, where I also gave a presentation and presented a poster, and also numerous other conferences. I also would like to thank Apple Computers for sponsoring me to give a presentation at the Apple University Consortium Conference in Perth during July 1995.
I would also like to thank Dr Rick Trebino for his useful discussions on the subject of Frequency Resolved Optical Gating (FROG), which was initiated from a meeting at the IQEC conference in July 1996. I would also like to thank Dr John Dudley and Dr Liam Barry for their assistance with the experiment and also with interpreting the electrical field measurements from the FROG results. Thanks also to Dr Rainer Leonhardt for his support and help with the many experiments conducted over the years. Finally, I thank my family for their support during my time at University.
Table of Contents

1) Introduction.................................................................................................................. 1
   1.1 Historical Perspective. .............................................................................................. 1
   1.2 Thesis Overview. ..................................................................................................... 4

2) The Propagation of Light in Optical Fibres................................................................. 6
   2.1 Introduction to Optical Fibres. ............................................................................... 6
   2.2 Fibre Characteristics. ............................................................................................. 7
      2.2.1 Intrinsic Losses. ............................................................................................. 7
      2.2.2 Chromatic Dispersion. ................................................................................. 9
      2.2.3 Birefringence and Polarisation Mode Dispersion. ..................................... 11
   2.3 Propagation Nonlinearities. .................................................................................... 14
      2.3.1 Self Phase Modulation ................................................................................ 15
      2.3.2 Self Steepening ............................................................................................ 17
      2.3.3 Stimulated Scattering Processes. ................................................................ 17
   2.4 The Propagation Equation. ..................................................................................... 18

3) Apparatus and Experimental Techniques.................................................................... 21
   3.1 Introduction of Excess Attenuation. ..................................................................... 21
   3.2 The Control of Polarisation. .................................................................................. 23
   3.3 Fibre based Isolators and Polarisers. ................................................................... 25
   3.4 Directional Couplers and Wavelength Division Multiplexing. ............................. 27
   3.5 Optical Fibre Loop Reflectors. ............................................................................... 28
      3.5.1 Linear Optical Loop Mirror. ....................................................................... 30
      3.5.2 Nonlinear Optical Loop Mirror (NOLM) .................................................. 31
      3.5.3 Nonlinear Amplifying Loop Mirror (NALM) ............................................. 32
   3.6 Data Acquisition and Analysis. .............................................................................. 34
   3.7 Time Domain Diagnostics. .................................................................................... 35
      3.7.1 Intensity Photodetection. ............................................................................. 35
      3.7.2 SHG Autocorrelation. ................................................................................ 36
   3.8 Frequency Domain Diagnostics. ............................................................................ 38
      3.8.1 An Infrared Spectrometer. .......................................................................... 38
   3.9 The Time-Frequency Domain. ................................................................................ 41
      3.9.1 SHG FROG. ............................................................................................... 41
      3.9.2 Chronocyclic Representations. .................................................................... 45
      3.9.3 Minimisation technique for determining Dispersion and Nonlinearity. .... 52
## 4) The Erbium Doped Fibre Amplifier

4.1 Rare Earth Elements and Ions ........................................... 53
4.2 Properties of Erbium in Glass ........................................ 54
4.3 Theory of Erbium Doped Optical Amplifiers ......................... 56
4.4 Numerical Solution of the Rate Equations .......................... 59
4.5 Refinement of the Numerical Model ................................ 61
4.6 Optical Amplifier Design ................................................ 64
   4.6.1 Amplifier length variation ....................................... 67
   4.6.2 Signal level variation ............................................. 69
   4.6.3 Signal wavelength variation ..................................... 70
   4.6.4 Pump power variation ............................................ 71
4.7 Conclusion ............................................................... 73

## 5) The Continuous Wave Erbium Doped Fibre Laser

5.1 The Physics of High Gain Lasers ...................................... 74
5.2 The Analytical Model for Erbium Doped Fibre Lasers ............ 77
5.3 The Numerical Model for Erbium Doped Fibre Lasers ............ 80
   5.3.1 Numerical Solution of Erbium Doped Fibre Laser Equations 81
   5.3.2 Results of the Numerical Simulations of Erbium Doped Fibre Laser 85
5.4 Experimental Results for CW Erbium Doped Fibre Lasers ....... 93
5.5 Conclusion ............................................................... 96

## 6) A Passively Modelocked Erbium Doped Fibre Laser

6.1 Introduction .............................................................. 97
6.2 The Average Soliton Model ............................................ 98
   6.2.1 Analytic solution of the Average Soliton Model .............. 99
   6.2.2 Numerical solutions of the Analytical Average Soliton Model 102
6.3 Sources of Self Amplitude Modulation ................................ 105
6.4 The Figure of Eight Laser Configuration ............................ 106
   6.4.1 Initial Design and General Performance ....................... 107
   6.4.2 Tunable Operation ............................................... 114
   6.3.3 Analysis of Modelocked Operation ............................ 117
6.5 Conclusion .............................................................. 134
List of Figures

Figure 2.1  Cross section and the refractive index profile of a step index fibre. .............................. 6
Figure 2.2  Typical loss profile of a single mode optical fibre [Corning SMF-28]. ............................ 8
Figure 2.3  Polarisation mode dispersion for a typical single mode optical fibre. .............................. 13
Figure 2.4  (a) Temporal intensity profile of a Sech pulse, and
(b) the corresponding frequency shift due to SPM. ................................................................. 16
Figure 2.5  N=2 soliton (2 psec; fig 2.4) over 2 soliton periods: (∂s = -23 ps²/km). ............................ 20
Figure 3.1  Curvature Loss for several values of the cut-off wavelength and index difference. ........... 22
Figure 3.2  Beat length due to bend induced birefringence. .......................................................... 24
Figure 3.3  Schematic diagram of a) Polarisisation Sensitive, and
b) Insensitive Fibre based Isolators. ............................................................................................... 26
Figure 3.4  Schematic of a fused fibre coupler. .................................................................................. 27
Figure 3.5  Schematic of a fibre loop reflector, with a gain element g. ................................................. 28
Figure 3.6  Fibre Loop Mirror Performance, Transmitted and Reflected Power. ............................... 30
Figure 3.7  Transmission of a NOLM, using coupling k = 0.1 and k = 0.4. ......................................... 31
Figure 3.8  Minimum switching power * length condition for a NOLM operating at 1.55 µm. .......... 32
Figure 3.9  Minimum switching power * length condition for a NALM operating at 1.55 µm. .......... 33
Figure 3.10 Minimum switching power * length condition for a k=0.5. ........................................... 33
Figure 3.11 4.2 MHz pulse train detected by the monitor photodiode. .............................................. 35
Figure 3.12 Schematic of a Background Free Autocorrelator. ........................................................... 37
Figure 3.13 Schematic of the Infrared Spectrometer. ......................................................................... 38
Figure 3.14 Diffraction Grating Efficiency, and Germanium Detector Efficiency. ............................. 39
Figure 3.15 Calculated Spectral Sensitivity of the Infrared Spectrometer. ......................................... 39
Figure 3.16 Spectral Linearity Curve comparison to
Frequency Doubled Fibre Laser Measurement. .............................................................................. 40
Figure 3.17 Spectral Linearity Correction Curve. .............................................................................. 40
Figure 3.18 Schematic of the Infrared Frequency Resolved Optical Gate. .......................................... 42
Figure 6.31 Measured Electrical field of the weak (top) and main output port (bottom) ........................................ 123
Figure 6.32 Numerical simulation of experimental field back into laser cavity .................................................... 124
Figure 6.33 Schematic diagram of the Figure of Eight Laser ............................................................................. 125
Figure 6.34 Calculated Intensity and Spectrum at the central 50:50 splitter using a minimisation algorithm .......... 126
Figure 6.35 Calculated Electrical fields propagating away from the 3 dB splitter in the NALM ......................... 127
Figure 6.36 Calculated Electrical fields propagating towards the 3 dB splitter in the NALM ............................ 128
Figure 6.37 Calculated Electrical field intensity after interference at the central 3 dB splitter propagating towards the isolator (top) and towards the filter (bottom) .............................. 129
Figure 6.38 Calculated Anti-clockwise (solid) and Clockwise (dashed) Peak Power propagating from the central 3 dB splitter around the NALM .................................................. 130
Figure 6.39 Calculated Anti-clockwise (solid) and Clockwise (dashed) Pulse Width propagating from the central 3 dB splitter around the NALM .................................................. 131
Figure 6.40 Calculated and Anti-clockwise (solid) and Clockwise (dashed) Soliton Order propagating around the NALM .............................................................................................................. 131
Figure 6.41 Theoretical Initial Chirp on a 2.5 W 2.2 psec Soliton ..................................................................... 132
Figure 6.42 Pulse Broadening as a function of distance for 3 Chirped 2.5 W 2.2 psec Solitons ....................... 133
Figure 6.43 Measured Autocorrelation before and after 60 metres of Standard SMF-28 Fibre ...................... 133
Figure 7.1 Theoretical EDF Resonant Dispersion .............................................................................................. 140
Figure 7.2 Experimental Configuration for the Erbium Fibre Amplifier .......................................................... 141
Figure 7.3 Amplification of the 1.9 psec pulses as a function of pump power .................................................. 142
Figure 7.4 Ratio of amplified pulse autocorrelation width to that of the laser pulses ......................................... 143
Figure 7.5 Intensity, phase, and spectrum of pulses after fibre propagation from experimentally measured FROG (solid lines), and from the numerical algorithm (circles) ........................................ 145
Figure 7.6 Values of $n_2$ (upper graph) and dispersion D (lower graph) over the range 1535–1560 nm for SMF28 ............................................................... 146
Figure 7.7 Measured Optical Spectrum of the Modelocked Fibre Laser Pulses at 1562 nm ............................ 148
Figure 7.8 Measured Autocorrelation function of the Fibre Laser Pulses at 1562 nm ..................................... 148
Figure 7.9 Measured FROG of the Modelocked Fibre Laser Pulses at 1562 nm .............................................. 149
Figure 7.10 Retrieved Intensity and Phase of the Modelocked Fibre Laser Pulses at 1562 nm ....................... 149
Figure 7.11 Chirp of the Modelocked Fibre Laser Pulses at 1562 nm ............................................................. 150
Figure 7.12  Computed Wigner Function of the Modelocked Fibre Laser Pulses at 1562 nm. ........ 150
Figure 7.13  Measured Optical Spectrum of the Amplified Pulses at 1562 nm, 4 mW Pump. .......... 151
Figure 7.14  Measured Autocorrelation of the Amplified Pulses at 1562 nm, 4 mW Pump. .......... 152
Figure 7.15  Measured FROG of the Amplified Pulses at 1562 nm, 4 mW 980 nm Pump. .......... 152
Figure 7.16  Retrieved Intensity and Phase of the Amplified Pulses at 1562 nm, 4 mW Pump. .......... 153
Figure 7.17  Chirp of the Amplified Pulses at 1562 nm, 4 mW 980 nm Pump. .................. 153
Figure 7.18  Computed Wigner Function of the Amplified Pulses at 1562 nm, 4 mW Pump. .......... 154
Figure 7.19  Measured Optical Spectrum of the Amplified Pulses at 1562 nm, 10 mW Pump. .......... 155
Figure 7.20  Measured Autocorrelation of the Amplified Pulses at 1562 nm, 10 mW Pump. .......... 155
Figure 7.21  Measured FROG of the Amplified Pulses at 1562 nm, 10 mW Pump. .................. 156
Figure 7.22  Retrieved Intensity and Phase of the Amplified Pulses at 1562 nm,
10 mW 980 nm Pump Power. ........................................ 156
Figure 7.23  Chirp of the Amplified Pulses at 1562 nm, 10 mW 980 nm Pump. .................. 157
Figure 7.24  Computed Wigner Function of the Amplified Pulses at 1562 nm, 10 mW Pump. .......... 157
Figure 7.25  Chirp of the Amplified Pulses at 1562 nm, 18 mW 980 nm Pump. .................. 158
Figure 7.26  Physical Configuration of the External Erbium Doped Amplifier Module. .......... 158
Figure 7.27  Simulation of the Amplified Pulses at 1562 nm, 10 mW 980 nm Pump. ............. 160
Figure 7.28  Comparison between the two measured fields, at the input to the EDF section. ......... 161
Figure 7.29  Comparison between the two measured fields, at the input to the EDF section. ......... 162
Figure 7.30  Dispersion and Nonlinearity for the Amplified Pulses at 1562 nm. .................. 163
Figure 7.31  Measured Optical Spectrum of the Modelocked Fibre Laser Pulses at 1543 nm. .......... 163
Figure 7.32  Measured Autocorrelation function of the Fibre Laser Pulses at 1543 nm. .......... 164
Figure 7.33  Retrieved Intensity and Phase of the Fibre Laser Pulses at 1543 nm. ............. 164
Figure 7.34  Chirp of the Modelocked Fibre Laser Pulses at 1543 nm. .................. 165
Figure 7.35  Measured Optical Spectrum of the Amplified Pulses at 1543 nm, 4 mW Pump. .......... 166
Figure 7.36  Measured Autocorrelation of the Amplified Pulses at 1543 nm, 4 mW Pump. .......... 166
Figure 7.37  Retrieved Intensity and Phase of the Amplified Pulses at 1543 nm, 4 mW Pump. .......... 167
Figure 7.38  Chirp of the Amplified Pulses at 1543 nm, 4 mW 980 nm Pump. .................. 167
Figure 7.39  Measured Optical Spectrum of the Amplified Pulses at 1543 nm, 18 mW Pump. .......... 168
Figure 7.40  Measured Autocorrelation of the Amplified Pulses at 1543 nm, 18 mW Pump. .......... 169
Figure 7.41  Retrieved Intensity and Phase of the Amplified Pulses at 1543 nm, 18 mW Pump. .......... 170
Figure 7.42  Chirp of the Amplified Pulses at 1543 nm, 18 mW 980 nm Pump. ........................................ 170
Figure 7.43  Comparison between the two measured fields, at the input to the EDF section. .................. 171
Figure 7.44  Comparison between the two measured fields, at the input to the EDF section. .................. 171
Figure 7.45  Beta 2 versus Wavelength for EDF, from FROG measurements and Simulations. ............. 172
Figure 7.46  Gamma versus Wavelength for EDF, from FROG measurements and Simulations. ............ 172
Figure 7.47  Beta 3 versus Wavelength for EDF, from FROG measurements and Simulations. ............. 173
Figure 7.48  Ratio of amplified pulse autocorrelation width to that of the laser pulses
for the Counter Propagating Amplified Pulses at 1532 & 1550 nm. ........................................... 174
Figure 7.49  Measured Optical Spectrum of the Modelocked Fibre Laser Pulses at 1562 nm. ............... 175
Figure 7.50  Measured Optical Spectrum of the Co-propagating Amplified Pulses at 1562 nm. ............. 175
Figure 7.51  Measured Optical Spectrum of the Counter propagating Amplified Pulses, 1562 nm. ....... 176
Figure 7.52  Retrieved Intensity and Phase of the Modelocked Fibre Laser Pulses at 1562 nm. ............ 177
Figure 7.53  Retrieved Intensity and Phase of the Co-propagating Amplified Pulses at 1562 nm. ......... 177
Figure 7.54  Retrieved Intensity and Phase of the Counter propagating Amplified Pulses, 1562 nm. ..... 178
Figure 7.55  Retrieved Intensity and Phase of the Modelocked Fibre Laser Pulses at 1543 nm. ............ 179
Figure 7.56  Retrieved Intensity and Phase of the Co-propagating Amplified Pulses at 1543 nm. ............ 179
Figure 7.57  Retrieved Intensity and Phase of the Counter propagating Amplified Pulses, 1543. ......... 180
Figure 7.58  Dispersion for the Co-propagating and Counter Propagating Amplified Pulses. ............... 180
Figure 8.1  Typical Refractive Index profile for SMF/DS fibre. .................................................. 183
Figure 8.2  Measured SMF/DS Dispersion, and fitted cubic polynomial. ........................................... 183
Figure 8.3  Calculated second and third order group velocity dispersion. ...................................... 184
Figure 8.4  Calculated fourth order group velocity dispersion. ..................................................... 184
Figure 8.5  Dispersion relation term with SMF/DF data. ............................................................... 186
Figure 8.6  Measured Optical Spectrum of the Fibre Laser Pulses at 1532.5 nm. .............................. 187
Figure 8.7  Measured Autocorrelation function of the Fibre Laser Pulses at 1532.5 nm. ...................... 187
Figure 8.8  Retrieved Intensity and Phase of the Fibre Laser Pulses at 1532.5 nm. ......................... 188
Figure 8.9  Measured Optical Spectrum after 700 metres SMF/DS propagation. ............................ 188
Figure 8.10 Measured Autocorrelation function after 700 metres SMF/DS propagation. ................... 189
Figure 8.11 Measured FROG after 700 metres SMF/DS propagation. ............................................ 190
Figure 8.12 Retrieved Intensity and Phase after 700 metres SMF/DS propagation. ......................... 190
Figure 8.13 Measured and Retrieved Autocorrelation function after 700 metres SMF/DS. ................ 191
Figure 8.14 Simulation of 22 W 1532.5 nm pulses through 700 metres SMF/DS (time domain) ...... 192
Figure 8.15 Calculated Intensity and Phase after 700 metres SMF/DS propagation. .................. 193
Figure 8.16 Simulation of 22 W 1532.5 nm pulses through 700 metres SMF/DS (freq. domain) .... 193
Figure 8.17 Calculated Optical Spectrum after 700 metres SMF/DS propagation. .................. 194
Figure 8.18 Calculated Autocorrelation function after 700 metres SMF/DS. .......................... 194
Figure 8.19 Calculated FROG after 700 metres SMF/DS propagation. ................................. 195
Figure 8.20 Measured Spectrum from F8L and after 700 metres SMF/DS. ......................... 196
Figure 8.21 Simulation of 10 W 1542 nm pulses through 700 metres SMF/DS (time domain) .... 197
Figure 8.22 Calculated Intensity and Phase after 700 metres SMF/DS. ............................. 198
Figure 8.23 Simulation of 10 W 1542 nm pulses through 700 metres SMF/DS (freq domain) .... 198
Figure 8.24 Comparison between Simulation and Experimental Spectrum. ......................... 199
Figure 8.25 Spectrum as a function 1533 nm Pulse Peak Power into 2 km SMF/DS. ............... 200
Figure 8.26 Typical Autocorrelation function after 2 km SMF/DS propagation. ................... 200
Figure 8.27 Modulation frequency as a function of Laser Wavelength and Peak Power. ........... 201
Figure 8.28 Comparison between Simulation and Experimental Spectrum for 27 W pulses. ....... 202
Figure 8.29 Simulation of 28 W 1560 nm pulses through 80 metres SMF/DS (time domain) ....... 203
Figure 8.30 Calculated Intensity and Phase after 80 metres SMF/DS. ............................... 203
Figure 8.31 Measured Autocorrelation function after 80 metres SMF/DS. .......................... 204
Figure 8.32 Measured Spectrum for 33 W pulses after 80 metres SMF/DS. ......................... 204
Figure 8.33 Measured Spectrum for 72 W pulses after 80 metres SMF/DS. ......................... 205
Figure 8.34 Measured Spectrum as a function of Peak Power. ........................................ 206
Figure 8.35 Measured Autocorrelation function as a function of Peak Power. ..................... 207
Figure A1.1 Inversion along an EDFA using 50 mW Pump, and 0.1 mW Signal at 1532 nm. ......... 212
Figure A1.2 Signal Gain versus Wavelength using 10 mW 980 nm Pump. ........................... 213
Figure A1.3 Signal Gain Difference versus Wavelength using 10 mW 980 nm Pump. ............... 213
Figure A1.4 Average Atomic Inversion versus Wavelength using 10 mW Pump. ................. 214
Figure A1.5 Signal Gain versus Wavelength using 50 mW 980 nm Pump. .......................... 215
Figure A1.6 Average Atomic Inversion versus Wavelength using 50 mW 980 nm Pump. .......... 215
Figure A1.7 Signal Gain versus Wavelength using 100 mW 980 nm Pump. ....................... 216
Figure A1.8 Average Atomic Inversion versus Wavelength using 100 mW 980 nm Pump. ....... 216
Figure A1.9 Signal Gain versus Wavelength using 2 mW 980 nm Pump. .......................... 217
Figure A1.10  Average Atomic Inversion versus Wavelength using 2 mW 980 nm Pump.....218
Figure A1.11  Average Atomic Inversion versus Wavelength using 2 mW 980 nm Pump.....218
Figure A1.12  Signal Gain versus Wavelength using 4 mW 980 nm Pump.................219
Figure A1.13  Average Atomic Inversion versus Wavelength using 4 mW 980 nm Pump.....219
Figure A1.14  Signal Gain versus Wavelength using 6 mW 980 nm Pump.................220
Figure A1.15  Average Atomic Inversion versus Wavelength using 6 mW 980 nm Pump.....220
Figure A1.16  Signal Gain versus Wavelength using 10 mW 980 nm Pump.................221
Figure A1.17  Average Atomic Inversion versus Wavelength using 10 mW 980 nm Pump.221
Figure A1.18  Signal Gain versus Wavelength using 18 mW 980 nm Pump.................222
Figure A1.19  Average Atomic Inversion versus Wavelength using 18 mW 980 nm Pump.222
List of Tables

Table 3.1  Second Order Autocorrelation Functions and Time-Bandwidth Products for several pulse shape models. .......................................................... 36
Table 4.1  EDF-2 Erbium co-doped optical Fibre parameters. .......................... 62
Table 4.2  Erbium doped, Alumo-germano-silicate core Optical Fibre parameters. 62
Table 4.3  Measured EDF-2 fibre in various amplifier configurations;
10 m length: 40 mW pump at 980 nm & signal at 1533 nm;
50 mW pump at 1480 nm & signal at 1550 nm. ........................................ 62
Table 4.4  Calculated EDF-2 fibre amplification in various amplifier configurations;
Fibre length variation. .......................................................... 63
Table 4.5  Calculated EDF-2 fibre amplification in various amplifier configurations;
Erbium doping concentration variation. ........................................ 63
Table 4.6  Calculated EDF-2 fibre amplification in various amplifier configurations;
Pump power level variation. ...................................................... 63
Table 5.1  Algorithm for Solving the Erbium Doped Fibre Laser Rate Equations. 83
Table 5.1  EDF-2 Erbium co-doped optical fibre parameters. .......................... 85
Table 6.1  Propagation Lengths and Losses of the Figure of Eight Laser. .......... 122
Table 7.1  Pulse Characteristics for Co-propagating Tunable Amplification Experiments. .... 142
Table 7.2  Summary of Dispersion and Nonlinear Refractive Index results for standard single mode fibre. .................................................. 146
Table 8.1  Corning SMF/DS fibre characteristics. ............................................. 182
Table 8.2  Empirical relations for dispersion of SMF/DS fibre. .......................... 185
# Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>APC</td>
<td>Angled Polished Connector</td>
</tr>
<tr>
<td>ASE</td>
<td>Amplified Spontaneous Emission</td>
</tr>
<tr>
<td>BBO</td>
<td>$\beta$-Barium Borate</td>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>DS</td>
<td>Dispersion Shifted</td>
</tr>
<tr>
<td>EDF</td>
<td>Erbium Doped Fibre</td>
</tr>
<tr>
<td>EDFA</td>
<td>Erbium Doped Fibre Amplifier</td>
</tr>
<tr>
<td>EDFL</td>
<td>Erbium Doped Fibre Laser</td>
</tr>
<tr>
<td>ESA</td>
<td>Excited State Absorption</td>
</tr>
<tr>
<td>F8L</td>
<td>Figure of Eight Laser</td>
</tr>
<tr>
<td>FROG</td>
<td>Frequency Resolved Optical Gate</td>
</tr>
<tr>
<td>FWHM</td>
<td>Full Width at Half Maximum intensity</td>
</tr>
<tr>
<td>GSA</td>
<td>Ground State Absorption</td>
</tr>
<tr>
<td>GVD</td>
<td>Group Velocity Dispersion</td>
</tr>
<tr>
<td>MFD</td>
<td>Mode Field Diameter</td>
</tr>
<tr>
<td>MI</td>
<td>Modulational Instability</td>
</tr>
<tr>
<td>NA</td>
<td>Numerical Aperture</td>
</tr>
<tr>
<td>NALM</td>
<td>Nonlinear Amplifying Loop Mirror</td>
</tr>
<tr>
<td>NLSE</td>
<td>Nonlinear Schrödinger Equation</td>
</tr>
<tr>
<td>NOLM</td>
<td>Nonlinear Optical Loop Mirror</td>
</tr>
<tr>
<td>OMA</td>
<td>Optical Multichannel Analyser</td>
</tr>
<tr>
<td>PC</td>
<td>Polarisation Controller</td>
</tr>
<tr>
<td>SAM</td>
<td>Self Amplitude Modulation</td>
</tr>
<tr>
<td>SHG</td>
<td>Second Harmonic Generation</td>
</tr>
<tr>
<td>SMF</td>
<td>Single Mode Fibre</td>
</tr>
<tr>
<td>SPM</td>
<td>Self Phase Modulation</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>----------------------------------</td>
</tr>
<tr>
<td>SS</td>
<td>Self Steepening</td>
</tr>
<tr>
<td>WDM</td>
<td>Wavelength Division Multiplexer</td>
</tr>
<tr>
<td>WPS</td>
<td>Weak Pulse Shaping</td>
</tr>
<tr>
<td>ZDW</td>
<td>Zero Dispersion Wavelength</td>
</tr>
</tbody>
</table>