

Novel optical fibre based laser sources for spectral and temporal versatility

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For Rachel

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Ben Chapman

Abstract

As laser amplifiers and oscillators continue to see widespread use in all branches of science and engineering, they continue to develop in terms of operating parameters to keep pace with their applications. Importantly, the temporal and spectral characteristics of laser systems must be carefully tailored to match application requirements. This thesis reports advances in the development of laser systems, based upon optical fibre technology, which demonstrate the flexibility of optical fibre and fibre integrated devices to cover a wide range of temporal and spectral characteristics.

First, the principle of spectrally masked phase modulation for short pulse generation is explored. Here, a phase modulator is used to generate a time dependent optical frequency shift, which can be turned into an effective amplitude modulation by the introduction of an optical band pass filter. This method is combined with nonlinear compression techniques based on solitonic propagation in optical fibre to generate optical pulses with duration of a few hundreds of femtoseconds and repetition rates of tens of gigahertz.

Increasing the range of wavelengths over which doped fibre amplifier systems will operate requires the development of laser/amplifier systems based on new active dopants. To this end amplifier systems based upon bismuth activated aluminosilicate fibre were evaluated. The amplifier stages were then incorporated into a master oscillator power fibre amplifier (MOPFA) scheme, demonstrating the applicability of bismuth doped silica fibre to advanced laser configurations.

Finally, the development of a novel laser source for use in fluorescent microscopy is detailed. The source was based on a gain switched diode which is amplified in a two stage Raman fibre amplifier system, subsequently frequency doubled in a periodically poled lithium tantalate crystal. Nonlinearity and optical filtering are exploited to re-shape the output pulse's temporal profile.

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Contents

Abstract	7
Acknowledgments	9
Contents	13
List of Figures	17
1 Introduction	19
1.1 Thesis Overview	20
1.2 Light propagation and nonlinear effects in optical fibre	21
1.2.1 Linear and nonlinear propagation	21
1.2.2 Self-phase modulation	27
1.2.3 Four-wave mixing	28
1.2.4 Stimulated Inelastic Scattering	29
1.3 Fibre structure and waveguide engineering	30
1.3.1 Total internal reflection	31
1.3.2 Guidance mechanism in fibre	32
1.3.3 Group velocity dispersion	34
1.3.4 Waveguide engineering and dispersion	35
1.4 The nonlinear Schrödinger equation	37
1.4.1 Modulation instability	38
1.5 Optical solitons	39
1.5.1 Soliton self-frequency shift and supercontinuum	40
1.5.2 High order solitons	41
1.6 Fibre amplifiers and lasers - a brief overview	44
2 Spectrally masked phase modulation for high repetition rate ultrashort laser pulses	47
2.1 Introduction	47
2.1.1 Optical modulation techniques	48

2.1.2	Spectrally masked phase modulation - a bias free electro-optic modulation technique	49
2.1.3	Pulse shaping in SMPM	52
2.1.4	Seed linewidth and pulse train quality	56
2.2	A SMPM system operating at $1.55 \mu\text{m}$	58
2.2.1	Adiabatic Raman soliton compression	59
2.2.2	Numerical simulation of the Raman soliton compressor-amplifier	60
2.2.3	Experimental Results	63
2.3	A SMPM system operating at $1.06 \mu\text{m}$	69
2.3.1	Fibre-Grating Compressor	73
2.3.2	Dispersion decreasing PCF for fundamental soliton compression	74
2.4	Outlook	79
3	Bismuth doped fibre for novel laser applications	81
3.1	Introduction	81
3.2	Amplification of telecommunications signals in bismuth doped optical fibre	84
3.2.1	Amplifier design	85
3.2.2	Amplification of picosecond pulses in Bi-doped aluminosilicate optical fibre	85
3.2.3	Amplification of gigabit signals in Bi-doped aluminosilicate optical fibre	89
3.3	Visible wavelength optical pulses based on a Bi-doped MOPFA and frequency doubling	92
3.3.1	Mode-locking - a brief introduction	93
3.3.2	Passively mode-locked Bi-doped fibre laser	95
3.3.3	Two stage MOPFA scheme based on Bi-doped fibre	98
3.3.4	Frequency doubling in a periodically poled crystal	99
3.4	Outlook	102
4	Visible laser sources based on Raman amplification and frequency doubling	105
4.1	Motivation - biophotonics and super resolution microscopy	105
4.1.1	STED Microscopy	107
4.1.2	Depletion source requirements for STED microscopy	108
4.2	Picosecond pulse generation from semiconductor diodes	111
4.2.1	Active mode-locking of an external cavity quantum dot diode laser . .	111
4.2.2	Gain switching of a quantum dot diode laser	115
4.3	Two-stage Raman MOPFA scheme	117
4.4	Outlook	127
5	Conclusions and outlook	131
	Bibliography	136

List of publications	147
List of acronyms	149

List of Figures

1.1	Second harmonic generation under different phase-matching conditions . .	25
1.2	Simulated Raman gain of fused silica (code courtesy J. C. Travers)	30
1.3	Total internal reflection in an optical fibre	31
1.4	Cartoon illustration of various fibre structure cross-sections	36
1.5	Simulated evolution of a third order soliton	42
1.6	Simulated evolution of a third order soliton with Raman scattering	43
2.1	Cartoon illustration of the spectrally masked phase modulation pulse generation technique.	51
2.2	Computed frequency and time domain envelope functions for spectrally masked phase modulated signals.	53
2.3	SMPM generated pulses using different spectral masks.	55
2.4	SMPM generated pulses using different spectral masks.	55
2.5	Time domain envelope functions of SMPM generated pulses with non-zero linewidth	57
2.6	Pulse shapes generated through SMPM seeded with noisy fields	57
2.7	System schematic for SMPM system operating at $1.55 \mu\text{m}$	58
2.8	Simulated pump field and signal powers along fibre length	62
2.9	Simulated pulse energy and implied soliton period along fibre length . . .	62
2.10	Simulated gain along fibre length for adiabatic soliton compression	62
2.11	Optical spectrum of the amplified phase modulated signal before and after band pass filtering	64
2.12	Output SHG autocorrelation of SMPM pulse train generator	64
2.13	Output power and output pulse duration with increasing pump power for SMPM signal amplified in Raman compressor-amplifier	65
2.14	Optical spectrum of Raman compressor-amplifier output for increasing pump powers.	66
2.15	Output power multiplied by pulse duration for increasing pump powers . .	67
2.16	Output autocorrelations for SMPM system operating across a range of wavelengths with 2 W of pump power supplied to Raman compressor-amplifier	68
2.17	System schematic for SMPM system operating at $1.06\mu\text{m}$	71

2.18	Optical spectrum of the phase modulated laser diode before and after spectral masking	72
2.19	Autocorrelation of the SMPM pulse train generator output	72
2.20	Evolution of the optical spectrum envelope of the output of the SMF with increasing amplification of the pulse train	74
2.21	Optical spectra and autocorrelations for pulses compressed in fibre-grating compressor	75
2.22	Dispersion curves and cross sectional SEM images for dispersion decreasing PCF	76
2.23	Autocorrelation of the output of the DDPCF. A sech^2 fit indicates a deconvolved FWHM duration of 190fs.	78
2.24	Optical spectrum of the output of the dispersion decreasing photonic crystal fibre	78
3.1	Absorption of fibres BDF1 and BDF2	84
3.2	Set-up schematic for Bi-doped fibre based amplifier.	85
3.3	Schematic of picosecond pulsed signal source	86
3.4	Spectrum of picosecond pulsed source	86
3.5	Output spectra of amplified picosecond signals	87
3.6	Gain with increasing optical pump power for ps pulsed input in Bi-doped fibre amplifiers using fibres BDF1	87
3.7	Gain with increasing optical pump power for ps pulsed input in Bi-doped fibre amplifiers using fibres BDF2	88
3.8	Autocorrelations of pulses amplified in Bismuth doped fibre amplifiers	89
3.9	Schematic of gigahertz repetition rate signal source	90
3.10	Pulse trains recorded for GHz pulse train	90
3.11	Optical spectra recorded for a gigahertz repetition rate signal	91
3.12	Gain with increasing optical pump power for a gigahertz repetition rate signal in Bi-doped aluminosilicate fibre samples BDF1 and BDF2	91
3.13	Numerical simulations illustrating the formation of a pulse train through mode-locking	94
3.14	Schematic of mode-locked Bi-doped fibre laser.	95
3.15	Autocorrelation of mode-locked bismuth laser output	97
3.16	Optical spectrum of mode-locked bismuth laser output	97
3.17	RF Power spectrum of mode-locked bismuth laser output	97
3.18	Schematic of Bi-doped fibre MOPFA	98
3.19	Optical spectrum of input and output to the two stage Bi-doped amplifier scheme.	100
3.20	Autocorrelation of Bi-doped MOPFA output	100
3.21	Conversion efficiency and spectrum of frequency doubled output.	101

4.1	Set-up of basic confocal scanning laser microscope	106
4.2	PSFs of excitation and depletion beam focal spots, resulting in fluorescence from a small central region	107
4.3	Jablonski diagram representing stimulated emission and fluorescence in a two-level fluorophore	108
4.4	Excitation and absorption spectra of YFP/pH 7.4	109
4.5	Cartoon depiction of active mode-locking	112
4.6	Set-up diagram for actively mode-locked external cavity quantum dot laser diode	113
4.7	Optical pulse generated through the active mode-locking of an external cavity quantum dot laser diode, measured with photodiode and digital sampling oscilloscope	113
4.8	Optical spectrum of actively mode-locked of an external cavity quantum dot laser diode	113
4.9	Cartoon representation of relaxation gain switching in semiconductor diodes	116
4.10	Electrical pulse provided to gain switched QD laser diode	118
4.11	Optical pulse generated by gain switched QD laser diode	118
4.12	Optical spectrum of gain switched QD laser diode	118
4.13	Experimental setup of mixed technology MOPFA system	119
4.14	Optical spectrum of gain switched QD laser diode before	120
4.15	Streak camera measurements of Raman amplified pulses	121
4.16	Evolution of pulse with increasing amplification	122
4.17	Peak powers of transient and secondary pulse components with increasing pump power	122
4.18	Evolution of fundamental pulse optical spectrum with increasing amplification	123
4.19	Time-averaged power of the infra-red (fundamental) laser output, and the time-averaged frequency doubled power with increasing pump power supplied to the second amplifier stage	125
4.20	Optical spectrum of frequency doubled laser output at maximum output power.	126
4.21	Evolution of frequency doubled (green) pulse with increasing amplification, labelled by time-averaged frequency doubled power.	128
4.22	Measured beam profile of frequency doubled laser output at maximum output power	129

Chapter 1

Introduction

The laser systems demonstrated in this thesis are motivated by a variety of applications, but all have in common their use of optical fibre technology and fibre-integrated devices. The development of low-loss silica optical fibre in the 1970s [Kap70] was one of the key technological developments of the second half of the twentieth century, and has enabled the global, high bandwidth optical telecommunication network to deliver an ever increasing volume of voice and internet traffic.

Whilst optical fibres can be fabricated from a variety of glasses, the most widely used material is fused silica, owing to its broad-band low-loss transmission capabilities, spanning 0.3-2 μm . Besides its use in telecommunications, optical fibre can be used for the development of a wide range of optical sources. The introduction of dopants to silica fibre has led to the development of highly efficient diode-pumped laser/amplifier systems operating at a range of wavelengths, most notably around 1.5 μm where the emission band of erbium overlaps with the minimum material attenuation of fused silica leading to its widespread application in telecommunications systems. Other popular active dopants include ytterbium which operates around 1 μm and, due to its low quantum defect when pumped with 980 nm diode lasers, can enable the development of efficient, high power lasers and thulium which provides broad band gain at the edge of the silica transmission window at 1.8-2 μm .

Additionally, the nonlinear properties of optical fibre can be used to access spectral regions which fall out of the emission bands of active dopants. Despite the relatively low

material nonlinearity of silica when compared to other popular nonlinear platforms, the low loss and high confinement means that nonlinearities can build up over long propagation distances.

Much of the work of this thesis has focused on exploiting optical nonlinear effects, both inherent to the fibre itself and in bulk nonlinear crystals, to widen the reach of fibre laser systems, both in the temporal domain (pulse duration and repetition rate) and in the spectral domain (operating wavelength).

After an overview of the content of this thesis as a whole, this chapter will introduce some of the key physical principles underlying the work undertaken in this thesis. First, light propagation in a dielectric will be discussed, including nonlinear effects of particular relevance to nonlinear fibre optics. Guidance mechanisms in optical fibre are then discussed, with a discussion of dispersion. The nonlinear Schrödinger equation will then be introduced, which combines these effects in a single mathematical model for the propagation of optical fields within fibre. Optical solitons, an important class of self-focusing optical pulses are introduced. The final section of this introductory chapter is a brief discussion of current fibre laser and amplifier technology.

1.1 Thesis Overview

This thesis is organised as follows: Chapter 2 details experimental work carried out in the generation of ultrashort optical pulses through spectrally masked phase modulation (SMPM) and subsequent nonlinear fibre optic based compression techniques. This comprises both theoretical work underpinning the modulation technique along with two experimental demonstrations of femtosecond duration, gigahertz repetition rate laser sources based on SMPM and adiabatic soliton compression.

This is followed by Chapter 3 which covers experimental work related to bismuth (Bi) doped silica fibre and its application as a novel gain medium for fibre-integrated devices. After initial investigations into the properties of Bi-doped fibre amplifiers, a master oscillator power fibre amplifier (MOPFA) scheme based entirely on Bi-doped fibre is presented.

Chapter 4 covers the development of a visible laser source exploiting Raman amplification and frequency doubling. A mixed technology MOPFA based on a gain switched laser diode oscillator and Raman fibre amplifier is demonstrated, and its application to biophotonics discussed.

Finally, Chapter 5 concludes the thesis and discusses future development of work presented therein. The remainder of this chapter is dedicated to the introduction of background information underpinning the physics of optical fibres.

1.2 Light propagation and nonlinear effects in optical fibre

This section studies the propagation of light in dielectric media and how the susceptibility of a material gives rise not only to refraction, but also to nonlinear effects. Specific nonlinearities which are routinely exploited in optical fibre based systems are then introduced.

1.2.1 Linear and nonlinear propagation

From Maxwell's equations, it can be shown that an electromagnetic wave with electric field, $\mathbf{E}$, propagating in a dielectric medium will be governed by the wave equation:

$$\nabla^2 \mathbf{E} - \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}}{\partial t^2} \quad (1.1)$$

where ε_0 and μ_0 are the permittivity and permeability of free space respectively, and $\mathbf{P}$ is the polarisation induced in the material by the incident electric field, which leads to re-radiation and propagation of the wave through the medium. The relationship between $\mathbf{E}$ and $\mathbf{P}$ can be expressed by the expansion

$$\mathbf{P} = \varepsilon_0 \left(\chi^{(1)} \mathbf{E} + \chi^{(2)} \mathbf{E}^2 + \chi^{(3)} \mathbf{E}^3 + \dots \right) \quad (1.2)$$

where $\chi^{(n)}$ is the material's n th order susceptibility. For low intensity electric fields, where the medium response is well approximated as harmonic, the first order term dominates and

the polarisation is linear with the electric field. This term is responsible for the linear optical properties of the medium (e.g. refractive index). With increasing magnitude of electric field, the higher order terms in the polarisation expansion become significant and the material response becomes nonlinear.

The refractive index

Considering an optical field propagating in a dielectric of sufficiently low intensity that it induces only a linear polarisation, Eq. 1.2 reduces to

$$\mathbf{P} = \varepsilon_0 \chi^{(1)} \mathbf{E}. \quad (1.3)$$

More generally, it can be said that the polarisation is a convolution of the electric field in time with the material susceptibility

$$\mathbf{P}(t) = \varepsilon_0 \int_{-\infty}^t \chi^{(1)}(t - \tau) \mathbf{E}(\tau) d\tau \quad (1.4)$$

which can be more conveniently expressed in the frequency domain, where a convolution integral becomes a product:

$$\mathbf{P}(\omega) = \varepsilon_0 \chi^{(1)}(\omega) \mathbf{E}(\omega). \quad (1.5)$$

In this case, Eq. 1.1 can be written as

$$\nabla^2 \mathbf{E} = \left[1 + \chi^{(1)}(\omega) \right] \mu_0 \varepsilon_0 \frac{\partial^2 \mathbf{E}(\omega)}{\partial t^2} \quad (1.6)$$

with a result that the phase velocity, v , of the propagating wave is given by

$$v = \frac{1}{\sqrt{[1 + \chi^{(1)}(\omega)] \mu_0 \varepsilon_0}} = \frac{c}{n_0(\omega)} \quad (1.7)$$

where $c = (\mu_0 \varepsilon_0)^{1/2}$ is the speed of light in vacuum and $n_0(\omega) = (1 + \chi^{(1)}(\omega))^{1/2}$ is the material refractive index, indicating that the phase velocity of a wave propagating in

a dielectric medium is, in general, dependent on the optical frequency. This gives rise to material chromatic dispersion, whereby optical waves of different frequencies are subject to different phase velocities and are therefore dispersed.

$\chi^{(2)}$ nonlinearity and second-harmonic generation

With higher intensity electric fields, the material's response will not be well approximated as harmonic and higher order polarisation terms will become important. The $\chi^{(2)}$ term in the polarisation expansion allows for the creation of new optical frequencies, not present in the applied optical field, and will give rise to nonlinear effects such as sum-frequency and difference-frequency generation, as well as second harmonic generation (which can be thought of as a degenerate case of sum-frequency generation). Quantum mechanically, second harmonic generation (SHG) can be thought of as the destruction of two photons at the fundamental frequency, ω and emission of a newly generated photon with twice the energy, i.e. double the optical frequency, 2ω . Energy and momentum conservation gives rise to the condition for efficient conversion:

$$\hbar k(\omega) + \hbar k(\omega) = \hbar k(2\omega) \quad (1.8)$$

where k is the wave-vector magnitude, given by

$$k(\omega) = \frac{n(\omega)\omega}{c}. \quad (1.9)$$

and $n(\omega)$ is the (linear) refractive index of the material evaluated at the frequency ω . Substituting Eq. 1.9 into Eq. 1.8 gives the phase-matching condition for second harmonic generation:

$$n(\omega) = n(2\omega). \quad (1.10)$$

Equation 1.10 can be satisfied by exploiting birefringence, whereby the refractive index experienced by light propagating through a material is dependent on the polarisation orientation of the field. In critical phase-matching schemes, the nonlinear medium is oriented

such that all three waves (the two fundamental waves and the generated second harmonic wave) are subject to the same refractive index and phase-matching is achieved.

If Eq. 1.10 is not satisfied, and there is a phase mis-match between the fundamental and the second harmonic fields, the relative phase between the two fields will periodically slip. As the direction of power flow is dependent on the relative phase, this results in power being periodically transferred between the two fields, with a result that the second harmonic field does not grow exponentially, but instead returns to zero (see dashed curve in Fig. 1.1) with a periodicity defined by the coherence length, L_c :

$$L_c = \frac{\pi}{k(2\omega) - 2k(\omega)} \quad (1.11)$$

$$= \frac{\lambda}{4(n(2\omega) - n(\omega))} \quad (1.12)$$

An alternative approach is that of quasi phase-matching (QPM), first proposed by Armstrong [Arm62] whereby a periodic structure is imposed on the nonlinear medium, with the sign of nonlinear susceptibility reversed every coherence length, such that the flow of energy is always from the fundamental beam to the second harmonic, as illustrated by the black curve in Fig. 1.1. While this decreases the overall efficiency of frequency doubling when compared to perfect phase-matching by a factor of $2/\pi$, the independence of phase-matching from birefringence means that the pump waves can be arbitrarily oriented within the crystal to access the largest components of the nonlinear susceptibility tensor. The result is that, practically, it is often possible to achieve greater conversion efficiencies employing QPM.

The first experimental demonstrations of QPM involved a stack of thin layers of binary semiconductors (GaAs, ZnSe), whose thickness matched the coherence length, each rotated 180° with respect to each other, with the layers separately grown and subsequently bonded [Gor93] or with the periodic crystal orientation switch patterned during growth [Ang94]. Currently, the most popular method for generating QPM crystals is the periodic poling of ferroelectric nonlinear crystals such as lithium niobate (LiNbO_3) and lithium tantalate (LiTaO_3) through ferroelectric domain engineering [Yam93]. Patterned electrodes on

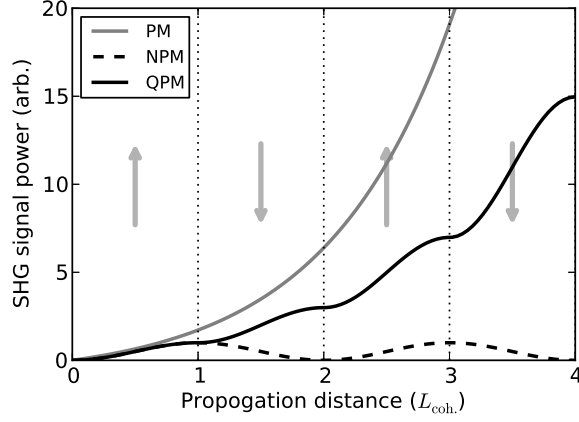


Figure 1.1: Second harmonic generation in the case of perfect phase-matching (PM), no phase-matching (NPM) and quasi-phase-matching (QPM). Light grey arrows indicate domain orientation.

a crystal surface are used to apply a strong, periodic electric field to a ferroelectric crystal, causing periodic domain reversal. The polling period, $\Lambda = 2L_c(\lambda)$ (typically on the order of a few μm), will determine the phase-matching condition for QPM second harmonic generation:

$$\Delta k = 4\pi \left(\frac{n(2\omega)}{\lambda} - \frac{n(\omega)}{\lambda} - \frac{1}{2\Lambda} \right) = 0 \quad (1.13)$$

A given poling period will precisely match one wavelength which will be subject to QPM. Control of the crystal temperature can be used to fine tune the phase matching condition and hence phase matched wavelength.

Practically, the incident fundamental radiation is of finite bandwidth, and so it is important to consider the acceptance bandwidth of the periodically poled crystal. As the poling period is fixed, wavelengths away from that which precisely satisfies Eq. 1.13 will not be phase-matched and see less efficient conversion. The FWHM bandwidth of the QPM process with regards to wavelength, $\Delta\lambda$, will be given by [Fej92]:

$$\Delta\lambda \approx \frac{4 \times 1.3916}{L} \left| \left(\frac{\partial \Delta k}{\partial \lambda} \right)^{-1} \right| \quad (1.14)$$

As the poling period, Λ is invariant with incident wavelength λ ,

$$\frac{\partial \Delta k}{\partial \lambda} = -4\pi \frac{n(2\omega) - n(\omega)}{\lambda^2} = \frac{-4\pi}{2\Lambda\lambda} \quad (1.15)$$

which gives an acceptance bandwidth of

$$\Delta\lambda = 0.4429 \frac{\lambda \cdot \Lambda}{L}. \quad (1.16)$$

This can be a consideration in the practical design of a frequency doubler in the case of, for example, a pulsed laser with significant spectral width. In selecting a crystal length there is usually a trade-off between the greater nonlinear interaction length with crystal length, and the deleterious effects of decreased phase-matching bandwidth.

$\chi^{(3)}$ nonlinearity in optical fibre

In fused silica, due to the inversion symmetry of amorphous glass, even order terms in the polarisation expansion will vanish, with a result that odd order terms dominate the nonlinear response of the material. As $\chi^{(3)} \gg \chi^{(\geq 5)}$, terms higher than the third order susceptibility can be ignored and the polarisation, $\mathbf{P}$, will be given by

$$\begin{aligned} \mathbf{P} &= \varepsilon_0 \left(\chi^{(1)} \mathbf{E} + \chi^{(3)} \mathbf{E} \mathbf{E} \mathbf{E} \right) \\ &= \varepsilon_0 \left(\chi^{(1)} + \frac{3}{4} \chi^{(3)} |E|^2 \right) \mathbf{E}. \end{aligned} \quad (1.17)$$

The dependence of the polarisation on $|E|^2$ leads to an intensity-dependent refractive index. Where the normal (linear) refractive index is defined as

$$n_0 = \sqrt{1 + \chi^{(1)}}, \quad (1.18)$$

the total refractive index will be given by

$$\begin{aligned} n &= \sqrt{1 + \chi^{(1)} + \frac{3}{4}\chi^{(3)}|E|^2} \\ &= n_0 \sqrt{1 + \frac{3}{4n_0^2}\chi^{(3)}|E|^2}. \end{aligned} \quad (1.19)$$

As $\chi^{(3)} \ll \chi^{(1)}$, Equation 1.19 can be written as

$$\begin{aligned} n &= n_0 + \frac{3\chi^{(3)}|E|^2}{8n_0} \\ &= n_0 + n_2 I, \end{aligned} \quad (1.20)$$

where I is the optical intensity, and n_2 is the nonlinear refractive index coefficient, given by

$$n_2 = \frac{3\chi^{(3)}}{4n_0^2 c \epsilon_0}. \quad (1.21)$$

The result is that an intense optical field in a dielectric medium will cause a local shift in the refractive index, proportional to the optical intensity. This is referred to as the optical Kerr effect and gives rise to parametric nonlinearities such as four wave mixing and self phase modulation in optical fibres.

In optical fibre, it is convenient to parametrise the effect of Kerr nonlinearity in the form of the nonlinear parameter γ , which factors out the mode size within the fibre (which is constant) and is given by

$$\gamma = \frac{n_2(\omega)\omega}{cA_{\text{eff}}} \quad (1.22)$$

where A_{eff} is the effective area of the optical field within the fibre.

1.2.2 Self-phase modulation

One of the key nonlinear effects apparent on pulses propagating in optical fibres is that of Kerr-mediated self-phase modulation (SPM), a parametric nonlinearity which can lead to the generation of new frequency components. Considering Eq. 1.20 in the presence of an

optical field with a time-varying optical intensity (i.e. $I = I(t)$), the nonlinear contribution to the local refractive index across an optical pulse will cause a time-dependent nonlinear phase delay, $\phi_{\text{NL}}(t)$. This will in turn lead to a shift in the instantaneous optical frequency across the pulse, due to the relationship

$$\Delta\omega = -\frac{\partial\phi_{\text{NL}}(t)}{\partial t}. \quad (1.23)$$

The result of this will be a frequency down-shift to the leading edge of the pulse, and a frequency up-shift to the trailing edge. This will lead to the generation of new optical frequency components.

Closely related to the effect of SPM is that of cross-phase modulation (XPM), by which the local nonlinear refractive index shift of an optical pulse at one carrier frequency, can induce a time-dependent frequency shift on a co-propagating optical field at a different carrier frequency.

1.2.3 Four-wave mixing

Four-wave mixing (FWM) can be understood through the coupling of four waves through $\chi^{(3)}$. Quantum mechanically it can be considered the destruction of two pump photons, at optical frequencies ω_1 and ω_2 and the generation of two new photons at ω_3 and ω_4 , mediated by a parametric interaction with the dielectric medium. Simple energy conservation considerations impose the following condition on the four frequencies:

$$\omega_1 + \omega_2 = \omega_3 + \omega_4 \quad (1.24)$$

Due to momentum conservation, the phase-mismatch between the four waves must be zero, which gives the condition:

$$\Delta k = -k(\omega_1) - k(\omega_2) + k(\omega_3) + k(\omega_4) + 2\gamma P_0 = 0 \quad (1.25)$$

where the last term, $2\gamma P_0$ is the nonlinear phase contribution due to the optically induced local refractive index shift, and is significant only for high powers.

Often, FWM is considered in the semi-degenerate case where $\omega_1 = \omega_2$. In this case, an intense pump beam at a single frequency can give rise to a Stokes and anti-Stokes wave, so long as the phase matching condition, Eq. 1.25, is satisfied either through chromatic dispersion or the nonlinear refractive index shift corresponding to the last term in Eq. 1.25.

1.2.4 Stimulated Inelastic Scattering

The previous sections detailed parametric nonlinearities, caused by the quasi-instantaneous electronic response of the dielectric medium through which a strong light wave travels. In addition to these, there are absorptive nonlinearities, owing to the imaginary part of the $\chi^{(3)}$ term in the polarisation expansion. These physically relate to the inelastic scattering of photons by phonons (quanta of material vibrational energy), and are referred to as Brillouin scattering, in the case of the interaction of photons with acoustic phonons, and Raman scattering, in the case of optical phonons. Due to the energy lost to phonons, these effects are considered to be inelastic with regard to the optical field.

Brillouin scattering is caused by the coupling of incident photons to acoustic phonons through the electrostriction effect. In stimulated Brillouin scattering (SBS) an optical wave propagating in a fibre will stimulate the formation of an acoustic wave, which will in turn lead to Bragg reflection of the incident wave. For silica fibre the Brillouin gain bandwidth is typically on the order of ~ 10 MHz, meaning that generally SBS is a significant effect only for narrow bandwidth optical fields.

Stimulated Raman scattering (SRS) originates from the molecular rotational and vibrational mode resonances of the medium and can be considered quantum dynamically in terms of the destruction of a photon and the generation of a new photon and an optical phonon. The energy lost to the generated phonon results in the generation of a frequency down-shifted photon. Figure 1.2 shows the gain profile of SRS in fused silica, in terms of frequency offset from the pump wave, with the peak of the Raman gain around 13 THz.

SRS can often be used in amplification schemes, whereby a weak signal field stimulates

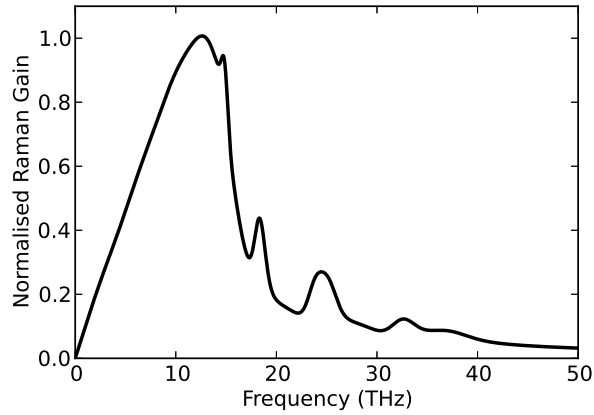


Figure 1.2: Simulated Raman gain of fused silica (code courtesy J. C. Travers)

the Raman scattering of a strong pump field, resulting in optical gain for the signal. Such a scheme is attractive as SRS is an intrinsic property of the silica fibre and so can provide gain at any wavelength across the transmission window of silica provided that a suitable pump source is available. This has obvious advantages over amplifiers based on doped optical fibre, where operation is restricted to the emission band of the dopant.

1.3 Fibre structure and waveguide engineering

Optical fibre is an excellent platform for the study and exploitation of nonlinear processes. Its waveguide nature means that the light field can be confined to a small cross-sectional area, increasing the intensity and enhancing nonlinear effects. Furthermore, due to the low-loss nature of silica, this confinement can be achieved over long lengths of optical fibre, increasing the distance over which nonlinear interactions can take place. Phase matching must also be achieved for parametric processes to efficiently take place, and the dispersive nature of optical fibre can be exploited to this end. This section briefly covers the basic principles underpinning the guidance of light in optical fibres, and how the waveguide structure can be tailored to enhance nonlinear interactions through engineering a fibre's dispersion.

1.3.1 Total internal reflection

Optical fibre is, in essence, an extended waveguide structure, whereby light is confined to a small core region of the fibre due to the cross-sectional refractive index profile of the fibre. For multi-mode optical fibres, the guidance of light within an optical fibre can be considered in terms of ray optics and total internal reflection. Figure 1.3 shows a cartoon illustration of the cross section of a step-index optical fibre and the guidance of a ray along its length by total internal reflection. The most simple fibre structure is the step-index, whereby the light is confined to a core region, with refractive index n_{co} surrounded by a cladding of refractive index n_{cl} , with $n_{co} > n_{cl}$. Practically this refractive index difference (typically on the order of a few per-cent or less) is achieved by the introduction of a low concentration of a dopant, normally germanium, to the fibre core, modifying its refractive index.

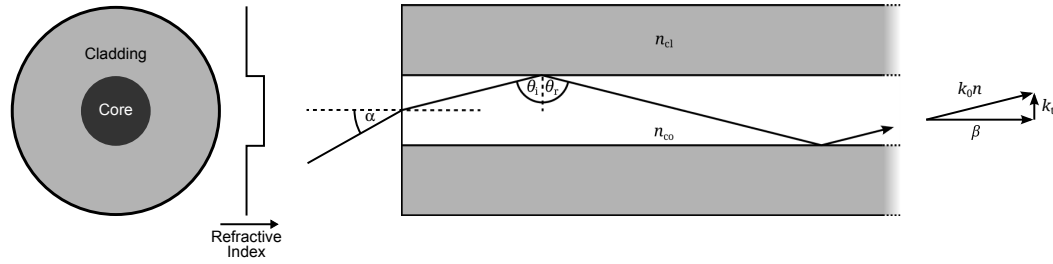


Figure 1.3: Cross sectional structure (left) of an optical fibre, resulting in internal reflection of a ray (centre). Also shown is the definition of the transverse and longitudinal propagation constants, k_t and β (right).

For a ray incident on a plane surface interface between materials of different refractive indices at an incident angle θ_i , the angle of the transmitted and reflected rays, θ_t and θ_r respectively, can be found from Snell's law:

$$\theta_r = \theta_i \quad (1.26)$$

$$\frac{\sin(\theta_i)}{\sin(\theta_t)} = \frac{n_t}{n_i} \quad (1.27)$$

where n_i is the refractive index of the material through which the incident and reflected rays propagate and n_t is the refractive index of the material in which the transmitted ray propagates. For a sufficiently great angle of incidence, the angle of the transmitted beam

will reach 90° (i.e. tangency with the interface), and at any greater angle of incidence all energy will be in the reflected beam and no light will be transmitted. This angle is referred to as the critical angle, θ_{crit} and is found from Eq. 1.27

$$\sin(\theta_{\text{crit}}) = \frac{n_t}{n_i}, \quad (1.28)$$

which in this case is

$$\sin(\theta_{\text{crit}}) = \frac{n_{\text{cl}}}{n_{\text{co}}}. \quad (1.29)$$

Rays within the core at an angle shallower than θ_{crit} , the light will be subject to total internal reflection along the axis of the fibre. The numerical aperture (NA) of the fibre will be given by the sine of its acceptance angle, α , which is the greatest angle at which a ray can enter the core and will result in total internal reflection along the fibre. Considering the ray entering the input end of the fibre from air (refractive index unity) at the greatest angle, α resulting in total internal reflection, the numerical aperture is given by

$$\text{NA} = \sin(\alpha) = \sqrt{n_{\text{co}}^2 - n_{\text{cl}}^2}. \quad (1.30)$$

1.3.2 Guidance mechanism in fibre

Whilst total internal reflection provides an intuitive picture of the confinement of light to the core of an optical fibre, a deeper understanding of the guidance mechanism can be understood by considering the full electric field distribution in the optical fibre. Assuming that the fibre is axially invariant (i.e. its cross-sectional refractive index profile is constant along its length), the electric field, $\mathbf{E}$ for a given optical frequency, ω can be expressed as

$$\mathbf{E}(\mathbf{r}, z, t) = \mathbf{E}_{\text{m}}(\mathbf{r}) \exp[i(\omega t - \beta z)] \quad (1.31)$$

where $\mathbf{r}$ is the transverse position across the fibre cross-section, z is the distance along the fibre length and $\mathbf{E}_{\text{m}}$ is the cross-sectional electric field distribution. As shown in Fig. 1.3, β is the propagation constant resolved parallel to the fibre axis (with k_t , the corresponding

transverse propagation constant, perpendicular to the fibre axis). The magnitude of the modified propagation vector in a material of refractive index n will be given by $k_0 n$ and will relate the transverse and axial propagation constants:

$$k_t = (k_0^2 n^2 - \beta^2)^{1/2}. \quad (1.32)$$

In the case of an optical fibre, with different refractive indices in the core and cladding region, the total magnitude of the propagation vector will be similarly modified - $k_0 n_{co}$ in the core and $k_0 n_{cl}$ in the cladding. Thus, a value of β , which is invariant across the fibre cross-section, can be chosen such that the magnitude of the transverse propagation constant is real in the core region and imaginary in the cladding region:

$$n_{cl} k_0 \leq \beta \leq n_{co} k_0. \quad (1.33)$$

This results in an electric field which decays monotonically away from the core in the cladding region, and whose propagation is confined to the core region of the fibre. The final condition that an electric field be guided along the fibre axis, is that the only phase difference accrued with propagation be given by the term proportional to distance, z , in Eq. 1.31, i.e. the phase difference between two arbitrary axial positions, z_1 and z_2 , say, be $\exp[-\beta(z_2 - z_1)]$.

A guided mode in an optical fibre, then, will be defined by its cross-sectional electric field distribution, $\mathbf{E}_m(\mathbf{r})$ and its (axial) propagation constant, β . As the size of the core region is reduced, close to that of a few wavelengths, the number of modes satisfying the conditions outlined above will be restricted. For a conventional step-index fibre with core radius a , the number of available guided modes is related to the normalised frequency parameter, V , defined as

$$V = a k_0 (n_{co}^2 - n_{cl}^2)^{1/2} \quad (1.34)$$

where for $V < 2.405$ (the first zero of the 0th order Bessel function), only one guided mode is available. In this case, the optical fibre is referred to as 'single mode'. Practically, it is often highly desirable to use single mode fibre, as this negates modal dispersion (which arises

from the differing propagation constants of different modes), but also as the fundamental mode of an optical fibre often has a modal field electric field distribution close to that of a Gaussian field, with obvious advantages in terms of free space coupling to and from the fibre.

1.3.3 Group velocity dispersion

As discussed in section 1.2.1, the material refractive index, and therefore propagation constant, of a dielectric material will be fundamentally dependent on the optical frequency. For a waveguide structure, there will also be a contribution to the propagation constant from the waveguide itself.

For an optical field propagating in a fibre which is not purely monochromatic, a pulse of finite bandwidth, say, this frequency dependence will lead to dispersion. The effect of the frequency dependence of the propagation constant on an optical pulse propagating within a fibre can be evaluated through its Taylor expansion about the pulse's central frequency, ω_0 :

$$\beta(\omega) = \beta(\omega_0) + (\omega - \omega_0)\beta_1 + \frac{1}{2}(\omega - \omega_0)^2\beta_2 + \dots \quad (1.35)$$

where

$$\beta_n = \left. \frac{d^n \beta}{d\omega^n} \right|_{\omega=\omega_0}. \quad (1.36)$$

The parameter β_1 is the inverse of the group velocity, v_g , while β_2 parametrises group velocity dispersion (GVD), i.e. the change in group velocity with optical frequency. GVD is responsible for pulse broadening within optical fibres.

GVD is often specified in engineering units of $\text{ps}\cdot\text{nm}^{-1}\text{km}^{-1}$ as the parameter D . This is given by the derivative of β_1 with respect to the wavelength, and is related to β_2 by

$$D = \frac{d\beta_1}{d\lambda} = -\frac{2\pi c}{\lambda^2}\beta_2 \quad (1.37)$$

GVD is said to be *normal* in the case of decreasing group velocity with increasing optical frequency (i.e. $\beta_2 > 0$) and *anomalous* for increasing group velocity with increasing optical

frequency ($\beta_2 < 0$). The wavelength for which $\beta_2 = 0$ is referred to as the zero dispersion wavelength (ZDW) and is the point at which a pulse is subject to minimum group velocity dispersion.

1.3.4 Waveguide engineering and dispersion

Fused silica naturally has a ZDW around $1.3 \mu\text{m}$, which led many early fibre optic telecommunications systems to operate in this spectral region, so as to minimise the effects of chromatic dispersion. The propagation constant, β , will be dependent not only on the variation in the material refractive index with optical frequency, but also will include a contribution dependent on the cross-sectional refractive index profile of the optical fibre. By engineering this profile, it is possible to alter the propagation constant and hence the dispersive properties of the optical fibre.

With the development of Erbium doped fibre amplifiers operating around the $1.5 \mu\text{m}$ region, it was desirable to shift the ZDW to longer wavelengths, which can be achieved by the introduction of increased germanium doping in the fibre core [Coh79]. Beyond the conventional step-index fibre design, engineering of the dispersion profile can be achieved through cross-sectional designs which gradually vary the refractive index across the core region of the fibre (known as graded-index fibres), or by decreasing the refractive index of the region immediately surrounding the fibre core (known as depressed cladding fibres) by the introduction of dopants such as fluorine, which will lower the refractive index. Examples of cross-sectional refractive index profiles are shown in Fig. 1.4.

From Eq. 1.34 it is clear that by increasing the difference in refractive index between the core and cladding regions, the core radius must be decreased to satisfy the condition for single-mode operation of the optical fibre. For this reason it is not possible to engineer step-index (or similar radially uniform designed) silica fibre with a ZDW less than the material ZDW of $1.27 \mu\text{m}$. This constraint can be overcome by employing a photonic crystal fibre (PCF) structure (also shown in Fig. 1.4). Since its development [Kni96], PCF has rapidly been adopted as a medium for nonlinear optics, owing to the unparalleled degree of flexibility in the engineering of its dispersive and nonlinear properties [Kni03, Rus06].

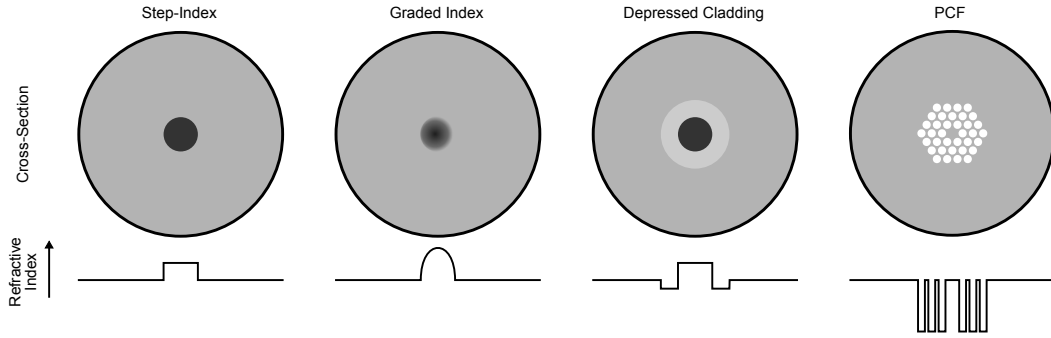


Figure 1.4: Cartoon illustration of various fibre structure cross-sections (coloured by the refractive index) and refractive index profiles

Photonic crystal structures are those whose optical properties are determined by periodic structure on the order of a wavelength. As shown in Fig. 1.4, PCF structures are most often fabricated from pure fused silica, with the periodic structure realised by the introduction of air holes running along the fibre length, with a central defect (i.e. a missing air hole) which forms the core region in which the propagating mode is confined. The refractive index in the cladding region surrounding this core will be modified by the photonic crystal structure, lowering its effective refractive index.

As in conventional fibre, in PCF the periodic air hole structure is used to achieve specific values of the propagation constant, β , that will forbid light propagation in the cladding region, confining the light to be guided in the core region. By modifying the separation and diameter of the air holes, it is possible to modify β , which enables the ability to engineer the dispersive properties of the fibre, with a result that fibres can be manufactured which exhibit single-mode, anomalous operation at near-arbitrarily short wavelengths, whilst confining the light to an incredibly small core region, thereby decreasing the effective mode area and enhancing nonlinear effects. Due to this, PCF has been one of the most influential changes in optical fibre technology of the last fifteen years, and has enabled the development of unique optical sources.

1.4 The nonlinear Schrödinger equation

The nonlinear and dispersive effects within an optical fibre are parametrised in the nonlinear Schrödinger equation (NLSE), which governs the propagation of the optical field amplitude envelope, A , and central frequency ω_0 within a single mode optical fibre. In its most simple form, taking into account only group velocity dispersion and self-phase modulation, the NLSE can be written as

$$i \frac{\partial A}{\partial z} - \frac{\beta_2(\omega_0)}{2} \frac{\partial^2 A}{\partial T^2} + \gamma |A|^2 A = 0 \quad (1.38)$$

where $T = t - z/v_g = t - \beta_1(\omega_0)z$ is the time in the retarded frame - the frame of reference travelling at v_g , the group velocity of the central wavelength of the optical field. β_n is the n^{th} order coefficient in the expansion of the wave number and γ is the nonlinear coefficient, as defined in Eq. 1.22.

The NLSE can be expanded to include terms related to other nonlinear and dispersive effects. This is referred to as the generalised NLSE, or GNLSE, which can take the form

$$\begin{aligned} \frac{\partial A}{\partial z} + \frac{\alpha}{2} A + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} - \frac{i\beta_3}{6} \frac{\partial^3 A}{\partial T^3} + \dots = \\ i\gamma \left(|A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial T} (|A|^2 A) - T_R A \frac{\partial |A|^2}{\partial T} \right) \end{aligned} \quad (1.39)$$

where α is the attenuation/gain coefficient (and can have frequency dependence), the β_3 term and following ellipsis represents further higher order terms in the expansion of the propagation constant, which become significant in magnitude close to $\beta_2 = 0$ (i.e. the ZDW) and for very short optical pulses. The terms on the right hand side of the equation relate to the nonlinear effects within the fibre. The first, as in the simplified NLSE, is proportional to $|A|^2$ and relates to SPM. The second, proportional to ω_0^{-1} , is the so-called ‘self-steepening’ term, arising from the fact that an optical pulse of sufficient spectral width, γ may vary significantly across the pulse. This variation in γ is corrected to the first order by the introduction of a term proportional to the inverse of the optical frequency. The final term on the right hand side relates to the non-instantaneous effects of stimulated Raman

scattering, where the constant T_R is the characteristic Raman response time. This has been experimentally deduced to be on the order of 3 fs [Kum91], under the assumption that the Raman gain increases linearly with frequency-detuning from the central frequency. This assumption is valid where the spectrum of the optical field is narrower than ~ 10 THz (See Fig. 1.2). For optical fields with greater spectral bandwidth, the Raman term may be replaced with a more general integral over the entire Raman response function in time.

1.4.1 Modulation instability

Under certain conditions, a high power optical wave propagating in an optical fibre will be fundamentally unstable against perturbation resulting in temporal break up of the field into a train of pulses.

This result can be derived by considering FWM in an optical fibre in the degenerate case. Considering a pump at optical frequency ω_p with power, P_0 , great enough that the nonlinear contribution is significant, Eq. 1.25 can be written as:

$$\Delta k = 2\beta(\omega_p) - \beta(\omega_p - \Omega) - \beta(\omega_p + \Omega) + \gamma P_0 \quad (1.40)$$

where $\omega \pm \Omega$ are the frequencies of the Stokes and anti-Stokes generated waves. Replacing the β terms in the above equation with those derived from the Taylor expansion about the pump wavelength to the second order, as given in Eq. 1.35, yields

$$\Delta k = -2\beta(\omega_p) + \left[\beta(\omega_p) - \Omega\beta_1 + \frac{1}{2}\Omega^2\beta_2 \right] + \left[\beta(\omega_p) + \Omega\beta_1 + \frac{1}{2}\Omega^2\beta_2 \right] + 2\gamma P_0 \quad (1.41)$$

$$= \Omega^2\beta_2 + 2\gamma P_0. \quad (1.42)$$

It is clear then that in the case of anomalous dispersion (i.e. $\beta < 0$), Eq. 1.42 will have real roots at

$$\Omega = \Omega_{MI} = \sqrt{\frac{2\gamma P_0}{|\beta_2|}} \quad (1.43)$$

where the phase-matching condition will be satisfied. In essence, then, this shows that in the case of a strong pump field in the case of low anomalous dispersion, the phase matching of degenerate FWM can be achieved through the nonlinear refractive index change induced by the pump field. This process is referred to as modulation instability (MI) as the newly generated frequency components will lead to the temporal modulation of the CW field, with periodicity defined by Ω .

It is also possible to derive this result solely from the NLSE through linear stability analysis, showing that the steady state (i.e. CW) solution to Eq. 1.38 is unstable against perturbation [Agr06]. This yields the result that in the case of a strong pump field in low anomalous GVD, weak perturbative waves (i.e. noise) with optical frequency $|\Omega| < \Omega_c$ will grow exponentially, where Ω_c is the cut-off frequency given by

$$\Omega_c = \left(\frac{4\gamma P_0}{|\beta_2|} \right)^{1/2} \quad (1.44)$$

and peak gain at Ω_{MI} . This is experimentally observed in the spectral domain as the generation of symmetric sidelobes about the central pump frequency and the temporal modulation of the field.

1.5 Optical solitons

Optical solitons are a class of pulses which are an exact solution of the NLSE (Eq. 1.38). Fundamental solitons are temporally self-focussing pulses, where the nonlinear effects of self-phase modulation are balanced by the effects of anomalous group velocity dispersion. The resulting pulse propagates as a transform limited (i.e. unchirped) sech^2 shaped pulse, whose temporal amplitude profile, $A_0(\tau)$ is given by

$$A_0(t) = \sqrt{P_0} \text{sech}(\tau/T_0) \quad (1.45)$$

where the soliton peak power, P_0 , and characteristic time¹, T_0 , are related by

$$P_0 = \frac{|\beta_2|}{\gamma T_0^2}. \quad (1.46)$$

This inverse relationship between a soliton's amplitude and its duration is one of the key features for its application in many lightwave systems.

1.5.1 Soliton self-frequency shift and supercontinuum

Owing to the high degree of stability of fundamental solitons against perturbation, solitonic propagation is observed even in the presence of effects such as attenuation, gain or Raman scattering. Indeed, for solitons of sufficient bandwidth, the high-frequency components can provide gain to the low-frequency components, resulting in a net transfer of energy to lower frequencies and overall red-shifting of the soliton. This effect is known as soliton self-frequency shift (SSFS) [Dia85, Mit86, Gor86] and for solitons of sufficient peak power, this can lead to continuous red-shifting of the pulse spectrum as it propagates along a length of fibre. The process is dependent on both the peak power of the soliton (to induce the nonlinearity) and its bandwidth (as for small frequency offsets, Raman gain increases quasi-linearly with frequency de-tuning). By considering the overlap of the soliton spectrum with the Raman gain spectrum it is possible to derive an equation for the expected shift in optical frequency, $\Delta\omega(z)$ with propagation distance, z [Gor86]:

$$\Delta\omega(z) = \frac{-8|\beta_2|T_R}{15T_0^4}z. \quad (1.47)$$

The result of the overall shift having an inverse quartic relationship with pulse duration is that the overall SSFS is highly dependent on the input soliton duration. This can be exploited to shift the optical frequency of a train of optical pulses, provided the pulse train is suitably uniform. SSFS forms the basis of Raman supercontinuum generation, whereby a population of solitons is generated after the break up of a high power pulse or continuous

¹The characteristic time, T_0 , is related to the full width at half maximum duration, T_{FWHM} , by $T_{\text{FWHM}} \approx 1.76T_0$

wave pump through modulation instability. Owing to the stochastic nature of the generation of the soliton population, there will be a broad spectrum of pulse durations, which will lead to a range of total frequency shifts and the net result of the generation of a smooth extended continuous spectrum, or supercontinuum [Dud10].

1.5.2 High order solitons

As alluded to above, fundamental solitons are the lowest order of a class of solutions to the NLSE. Each are characterised by an initial pulse shape given by

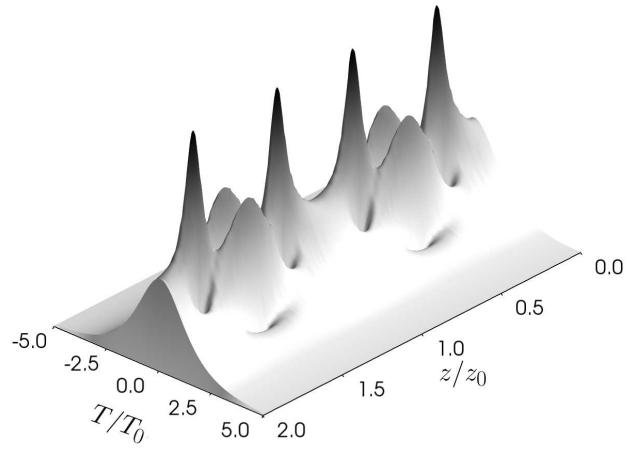
$$A_N(t) = N A_0(t) \quad (1.48)$$

$$= N \sqrt{P_0} \operatorname{sech}(\tau/T_0) \quad (1.49)$$

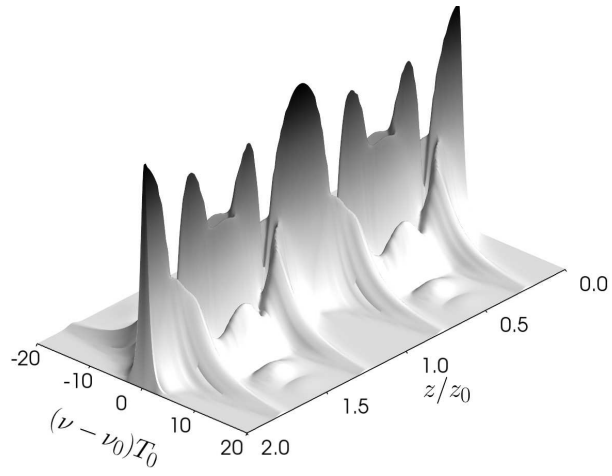
where N denotes the soliton order. High order solitons will propagate along the fibre length with a periodically evolving temporal and spectral profile. The periodicity of this evolution is given by the characteristic soliton period, z_0 :

$$z_0 = \frac{\pi}{2} \frac{T_0^2}{|\beta_2|}. \quad (1.50)$$

Figure 1.5 shows the simulated evolution of a third order ($N = 3$) soliton propagating over two soliton periods in an idealised optical fibre. This simulation includes only the terms in the idealised NLSE (Eq. 1.38), i.e. no high order dispersion, Raman or self-steepening terms. In both the temporal and spectral domain, at a propagation distance equal to integer multiples of the soliton period ($z/z_0 = 1, 2, \dots$), the soliton returns to its initial launched profile. As this third order soliton evolves, it periodically reaches a point of minimum duration (e.g. around $z/z_0 = 0.2$). The periodic temporal evolution of high order solitons can be exploited as a pulse compression technique, by carefully tailoring the length of the nonlinear fibre through which the soliton propagates to match the distance at which the soliton reaches its shortest duration [Mol83, GN87], and is sometimes referred to as soliton effect compression (SEC) or high order soliton compression.

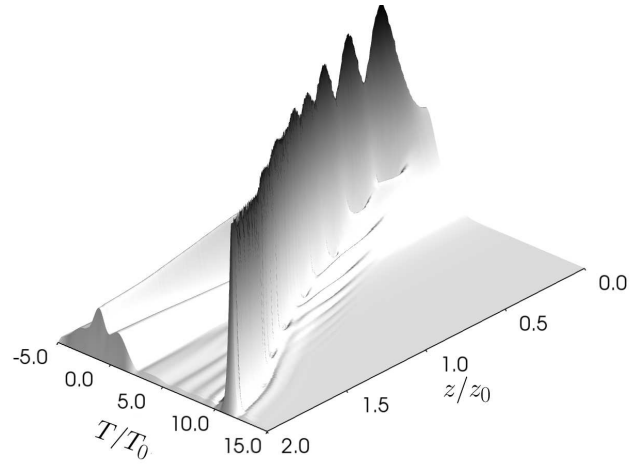


(a) Temporal evolution

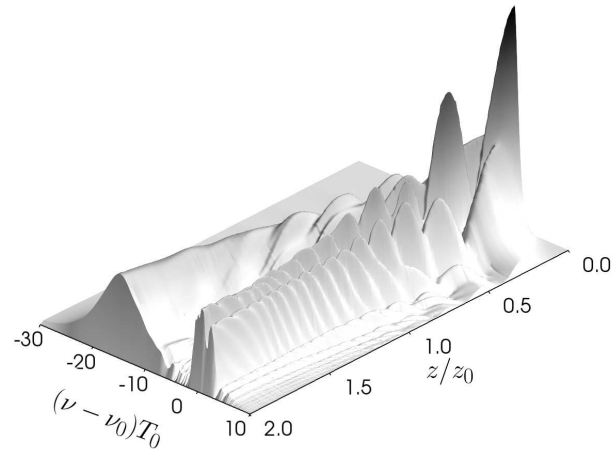


(b) Spectral evolution

Figure 1.5: Simulated evolution of a third order soliton (code courtesy J. C. Travers).



(a) Temporal evolution



(b) Spectral evolution

Figure 1.6: Simulated evolution of a third order soliton with Raman scattering (code courtesy J. C. Travers). Note change in axis scale compared to Fig. 1.5

Practically, however, the periodic high order soliton evolution and restoration of input pulse shape are often not observed. This is due to the perturbative effects of e.g. high order dispersion and Raman scattering, terms included in the generalised NLSE, Eq. 1.39. This is illustrated in Fig. 1.6, which shows the simulated propagation of a third order soliton, with the effects of Raman scattering included in the simulation. The soliton initially evolves in a manner similar to that shown in Fig. 1.5, compressing to a minimum duration around $z/z_0 = 0.2$. This also corresponds to the point of maximum spectral broadening. The presence of Raman scattering results in the self-frequency shift of the compressed part of the pulse, which ‘detaches’ from the remaining pulse pedestal, forming a fundamental soliton (which is more robust against perturbation). This is subject to continued self-frequency shift and is correspondingly delayed with respect to the remaining radiation associated with the temporal position of the launched pulse.

1.6 Fibre amplifiers and lasers - a brief overview

Soon after the invention of the laser, it was quickly realised that the optical fibre format presented an advantageous platform for the development of laser and amplifier systems. The first demonstration of a fibre laser system was in 1964 by Koester and Snitzer [Koe64], who demonstrated a neodymium (Nd) doped fibre amplifier operating around $1.06 \mu\text{m}$, pumped by a flash-lamp around which the fibre was wound. The next major innovation came in 1973 with the demonstration of an end-pumped fibre laser system by Stone and Burrus [Sto73], which took advantage of the fact that both the signal and pump light could be confined to the fibre core, increasing the efficiency. Neodymium was again used as the active dopant in a silica fibre host, initially pumped using visible wavelength pulsed dye laser systems, and later semiconductor diodes.

The next step-change in technology occurred in the 1980s with the development of low-loss rare-earth doped fibres using modified chemical vapour deposition technology [Poo85]. This enabled the development of lasers incorporating metres of fibre, rather than the few centimetres previously demonstrated. This also led to the incorporation of other rare earth

dopants such as erbium (Er), ytterbium (Yb) [Han88b] and thulium (Tm) [Han88a]. Erbium fibre amplifier systems have become the most ubiquitous of all fibre amplifier technologies owing to the coincidence of the gain band of Er-doped silica fibre with the attenuation minimum of silica glass around $1.5\ \mu\text{m}$. This has led to their widespread application in distributed optical fibre telecommunication systems.

Whilst the main drive of rare-earth doped fibre laser amplifier systems has been the use of Er-doping for telecommunication applications, their use in all branches of laser science has expanded over the past few decades owing to the high degree of configurability, excellent thermal management and mechanical properties of silica in an optical fibre format, exploiting other rare earth dopants. Owing to the overlap in fluorescence bands around $1.06\ \mu\text{m}$, Yb- and Nd- doped fibre lasers were effectively competing technologies early on in their development. Ytterbium eventually won out owing to its strong absorption around $0.98\ \mu\text{m}$, not found in Nd, which enabled pumping with commercially available $0.98\ \mu\text{m}$ diodes, with high efficiencies through the low quantum defect between the pump and laser lines. Furthermore, the solubility of Yb ions in silica allowed for a greater degree of homogeneity. The broad gain bandwidth (10s of nm) and long upper state lifetime (on the order of μs) means that Yb doped fibre has found wide application in the development of short pulsed laser systems.

The dispersive nature of optical fibre as a laser medium has led to a host of dispersion managed pulsed laser systems. The use of normally dispersive fibre in a laser cavity can lead to the generation of chirped optical pulses. Alternatively, either through the use of anomalously dispersive fibre, or other dispersive cavity elements, pulsed fibre lasers can operate in the net-anomalous dispersion regime. In this case solitonic propagation within the laser cavity can enable the generation of high quality, short duration transform limited pulses.

Chapter 2

Spectrally masked phase modulation for high repetition rate ultrashort laser pulses

2.1 Introduction

High repetition rate (tens of gigahertz) pulsed laser sources are of increasing importance due to their application in the field of optical frequency metrology [Jon00]. Such sources can be realised in using fibre-integrated technology through the active modelocking of laser cavities [Use04], control of intra-cavity modulation instability [Ken06] or through extra-cavity amplitude modulation of a continuous wave (CW) signal. Amplitude modulation using, for example, Mach-Zehnder amplitude modulators or electro-absorption modulators can achieve high repetition rate modulation, although the latter of these devices is restricted in terms of operating wavelength, and both suffer from the fact that they require a DC bias offset to their voltage supply to ensure correct pulse shaping, which can require active control to compensate for drift due to changing environmental conditions.

Spectrally masked phase modulation (SMPM) is a powerful electro-optic technique for the generation of high repetition rate (10s of GHz) optical pulses, which, as is discussed in Section 2.1.2, is highly versatile in terms of operating wavelength. Work in this chapter is

related to two experimental systems capable of producing femtosecond pulses at gigahertz repetition rates by combining SMPM with nonlinear compression techniques. In Section 2.2, adiabatic Raman soliton compression is employed in the $1.55\text{ }\mu\text{m}$ region, while Section 2.3 details a system operating at $1.06\text{ }\mu\text{m}$ where soliton compression in a dispersion-decreasing fibre is used. Results presented in this chapter have previously been published in part as peer-reviewed journal articles and conference proceedings [Cha12a, Cha12b, Cha13]. Details of the experimental work is preceded by an overview of current optical modulation techniques followed by the theoretical underpinnings of the SMPM technique.

2.1.1 Optical modulation techniques

This section gives a brief overview of two widely-used techniques (electro-absorption modulation and electro-optic amplitude modulation) which can be used to generate high repetition rate (tens of gigahertz) pulse trains.

Electro-Absorption Modulators

Electro-absorption modulators (EAMs) can apply amplitude modulation to optical signals to generate picosecond pulses at repetition rates of tens of gigahertz. These take advantage of the quantum confined Stark effect (QCSE) in quantum well structures [Mil84], whereby the absorption edge of a semiconductor is modified by the application of an electric field. These devices typically can provide up to ~ 30 dB of suppression for a bias voltage on the order of a few volts. In operation, the DC bias offset of the device must be set such that the absorption is maximised for the signal wavelength, so that as the oscillating voltage is applied, the absorption edge will shift across the signal wavelength, generating an optical pulse. Due to the inherent time dependence on the spectral characteristics of the EAM in operation, the pulses will be produced with a significant chirp, which can be subsequently compensated through use of a dispersive element such as dispersion-compensating fibre [Suz93, Moo94] to generate few-picosecond pulses.

Electro-Optic Modulators

Electro-optic modulators (EOMs) are devices based on Pockels effect whereby the refractive index of a material through which the light is guided is modified in linear proportion to an applied electric field (*cf.* the optical Kerr effect, where the refractive index change is quadratic with the applied field). The most simple EOM device is the electro-optic phase modulator, namely a single Pockels cell, across which is applied a time-varying electric field. This will in turn impose a time-varying phase delay to the light wave due to the change in refractive index. A device such as this can be used to impose an amplitude modulation to the signal by including the phase modulator on one arm of a Mach-Zehnder interferometer, such that there is a time varying relative phase difference between the two arms of the modulator, leading to periodic destructive interference, and thus modulation of the optical intensity. Such devices are referred to as Mach-Zehnder amplitude modulators (MZAMs). For the correct amplitude modulation to be achieved in such devices it is critical that the phase difference between the two arms of the interferometer be controlled through the application of a DC bias voltage across one of the arms.

The most widespread material used for EOMs is lithium niobate (LiNbO_3) [Woo00], which can be fabricated with a waveguide structure to enable compact integrated devices, suited for use with optical fibre based lasers and amplifiers. Fibre-integrated LiNbO_3 modulators are widely available at a range of operating wavelengths and electrical bandwidths of tens of gigahertz. One of the key specified parameters of an electro-optic device is V_π , the voltage required to induce a π phase shift (which in the case of an MZAM will result in maximum signal attenuation). For modern devices, this is typically on the order of a few volts.

2.1.2 Spectrally masked phase modulation - a bias free electro-optic modulation technique

Motivated by the clear practical advantages of employing an electro-optic modulation technique, but with a view to remove the requirement for a DC bias offset, and the problems this can introduce in terms of stability and repeatability, spectrally masked phase modula-

tion (SMPM) was employed. Figure 2.1 shows a cartoon illustration of the SMPM concept, which was first described and demonstrated by Mamyshev in 1994 [Mam94]. A sinusoidal phase shift, $\Delta\phi$, is applied to a CW signal. This will result in a signal whose frequency is subject to a cosinusoidal instantaneous frequency shift, $\Delta\omega$, due to the relationship

$$\Delta\omega(t) = -\frac{\partial\phi(t)}{\partial t}. \quad (2.1)$$

Importantly, whilst the amplitude of this signal is continuous with time, there is now a temporal mapping of optical frequency components. By applying a spectral mask (i.e. an optical band pass filter) to suppress all but the extreme optical frequency components, the resulting signal will consist of a train of pulses with a repetition rate equal to the frequency of the initial phase modulation. Furthermore, the pulse shaping takes place in the optical frequency domain, meaning that the resulting pulse shape is a function of the shape of spectral mask, and the amplitude of the time-varying phase modulation, and so has no relation to the absolute phase. Practically, this removes the requirement for any adjustment to the absolute DC voltage offset of the phase modulator, and so SMPM can be considered a bias-free method of electro-optic amplitude modulation. It is interesting to compare the principle of SMPM with that of EAM. In essence, SMPM imposes a fixed spectral filter to a signal with periodically swept optical frequency, while an EAM can be thought of as a periodically swept filter applied to a signal of fixed optical frequency.

The SMPM technique has parallels with other conceptually similar techniques, which impose a spectral mask on a signal with time-dependent optical frequency. This has been demonstrated in cases where self-phase modulation has caused a time dependent phase shift on a pulse, resulting in a chirp, meaning that an optical filter can be applied to generate a shortened pulse [Gom86]. Another comparable technique is the use of cross-phase modulation (XPM) to apply a time varying phase- (and corresponding frequency-) shift to a CW signal by a pulsed signal at another optical frequency. An optical filter can then be applied to remove the CW component, preserving only the newly generated frequency components, which will be temporally correlated with to the phase modulating pulse train [Ols00]. This is in turn closely related to other demonstrations of the use of XPM to phase modulate a

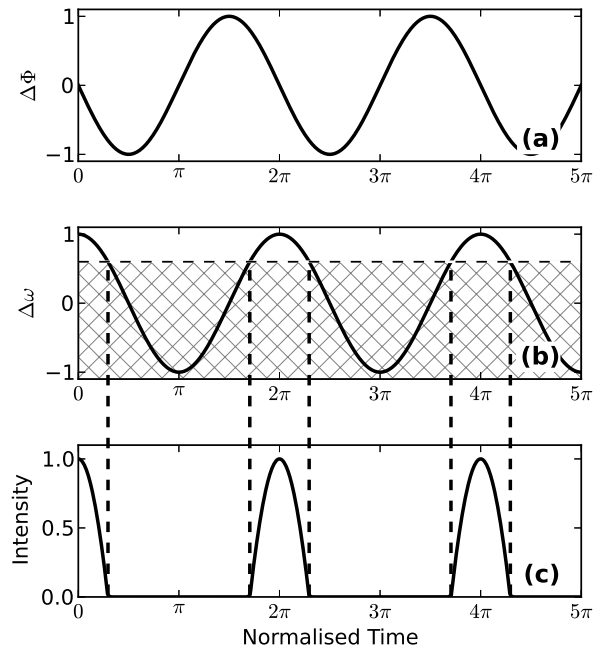


Figure 2.1: Cartoon illustration of the spectrally masked phase modulation pulse generation technique. A time-varying sinusoidal phase shift is applied to a CW signal (a), which results in a cosinusoidal shift to the instantaneous frequency (b). A band-pass filter (shown as the hatched area in (b)) is used to suppress all but the frequency extrema, resulting in pulse train generation (c).

co-propagating CW signal. Instead of filtering the optical spectrum, the phase modulation can be converted to an amplitude modulation by use of a polariser, which will discriminate the cross phase modulated parts of the CW signal due to the nonlinear polarisation rotation induced by XPM [Pat93]. Alternatively, use of anomalous dispersion at the signal wavelength can lead to pulse formation through the temporal compression of the new frequency components generated through the induced phase modulation [Sch87, Gre90].

2.1.3 Pulse shaping in SMPM

A numerical study of the SMPM method was undertaken to examine the effect of spectral mask shape on the generated pulse train.

An optical signal can be represented by its time and frequency domain envelope functions, $A(t)$ and $\hat{A}(\omega)$ respectively. These two domains are related by the Fourier transform. A monochromatic, continuous wave laser signal is given by an envelope function of constant amplitude and phase, i.e. for a monochromatic CW signal

$$A_{\text{cw}}(t) = A_0 e^{i\Phi_0}. \quad (2.2)$$

Applying a sinusoidal phase shift will give a field whose complex envelope function is given by

$$A_{\text{pm}}(t) = A_{\text{cw}} e^{ia \sin(\Omega t)} = A_0 e^{i\Phi_0 + ia \sin(\Omega t)}. \quad (2.3)$$

Figure 2.2a shows the frequency domain (Fourier transform) of the fields given by equations 2.2 and 2.3 for the case of $\Phi_0 = 0$, $a = 2\pi$ and $\Omega = 1$. The frequency domain envelope of the monochromatic CW field is given by a delta function at zero frequency offset. In the case of the phase modulated signal, a comb of new frequency components has been generated at a characteristic spacing of $\Omega/2\pi = 1/2\pi$.

Figures 2.2b-2.2e show the effect of introducing a mask to the frequency domain by multiplying the frequency domain envelope $\hat{A}(\omega)$ by a masking function $F(\omega)$. Figure 2.2b

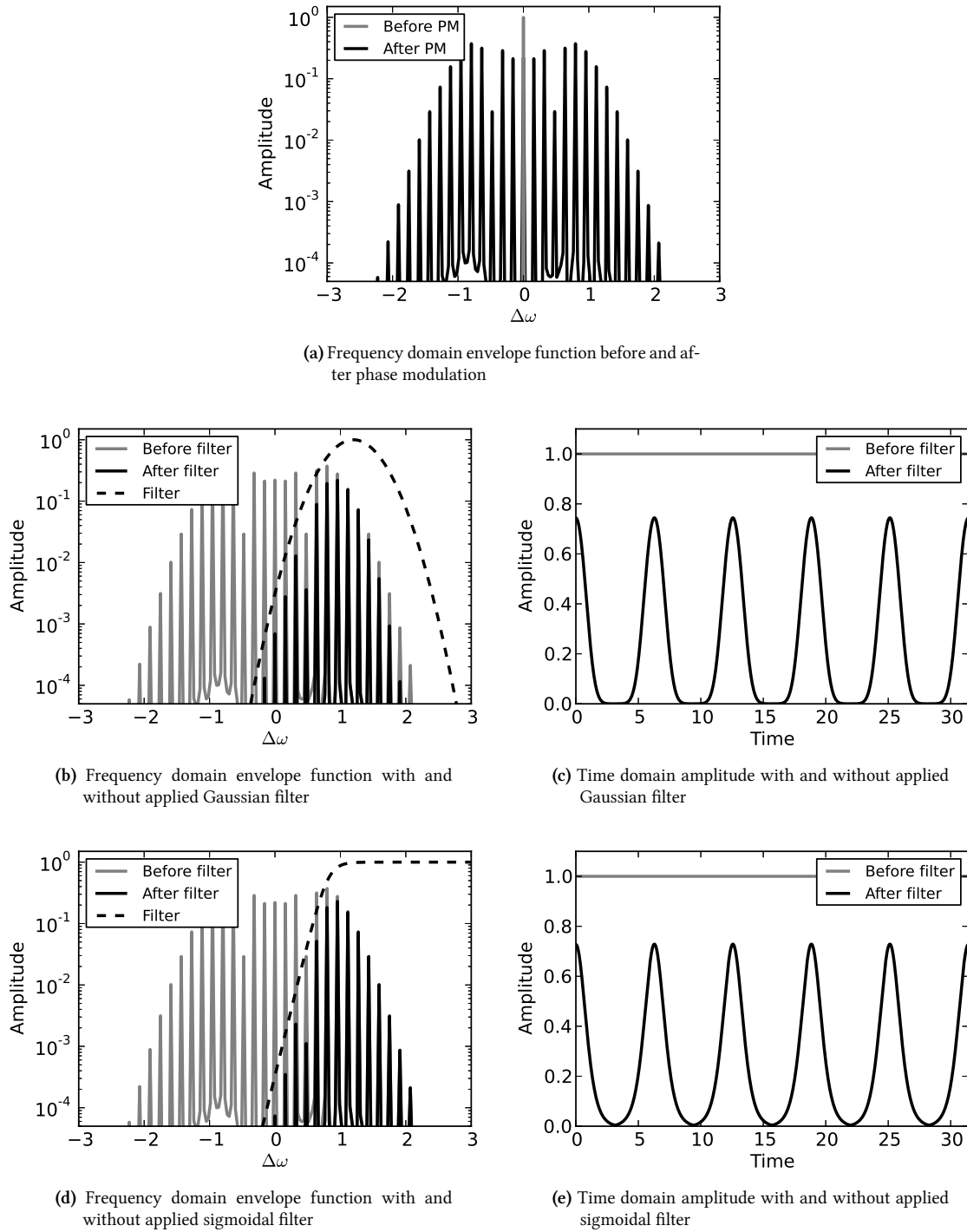


Figure 2.2: Computed frequency and time domain envelope functions for spectrally masked phase modulated signals.

shows the effect of a Gaussian filter function $F_G(\omega)$

$$F_G(\omega) = \exp\left(-\frac{(\omega - \Omega_0)^2}{2\Delta\Omega^2}\right) \quad (2.4)$$

with $\Omega_0 = 1.2$ and $\Delta\Omega = 0.35$. Performing the inverse Fourier transform of $\hat{A}_{\text{pm}}(\omega)F_G(\omega)$ will give the time domain envelope function, shown in Fig. 2.2c. Due to the time-to-frequency domain mapping arising from the phase modulation, the result of the spectral mask in the time domain is the generation of a train of optical pulses, at a repetition rate of $2\pi/\Omega = 2\pi$, governed by the frequency of the initial phase modulation.

It is important to note the effect of the shape of spectral mask on the shape of the generated pulses. Figure 2.2d shows the effect of a high-pass sigmoidal filter function $F_S(\omega)$

$$F_S(\omega) = \frac{1}{1 + \exp\left(\frac{-(\omega - \Omega_0)}{\Delta\Omega}\right)} \quad (2.5)$$

with $\Omega_0 = 0.8$ and $\Delta\Omega = 0.1$. In this case, the time domain envelope function still shows the generation of a pulse train at the characteristic repetition rate set by the initial phase modulation frequency, but comparing Fig. 2.2e to Fig 2.2c, it is evident that the pulses are differently shaped, differing primarily in the pulse wings.

To illustrate this, the pulses produced by Gaussian and sigmoidal masking are shown in Figs. 2.3a and 2.3b respectively. These have been plotted on a logarithmic scale to more clearly demonstrate the difference in the pulse shapes. Also shown are the curves of best fit for a Gaussian and a sech^2 function. From these plots, it is evident that a sigmoidal filter gives rise to pulses more closely fitting in shape to sech^2 , whilst Gaussian filtering results in pulses closer to Gaussian in shape.

The angular phase of the optical field, $A(t)$ is given by

$$\phi(t) = \arctan\left(\frac{\text{Im}[A(t)]}{\text{Re}[A(t)]}\right). \quad (2.6)$$

Figure 2.4 shows the amplitude and angular phase of pulses generated by the application of a Gaussian or a sigmoidal filter. In both cases, across the centre of the pulse, the angular

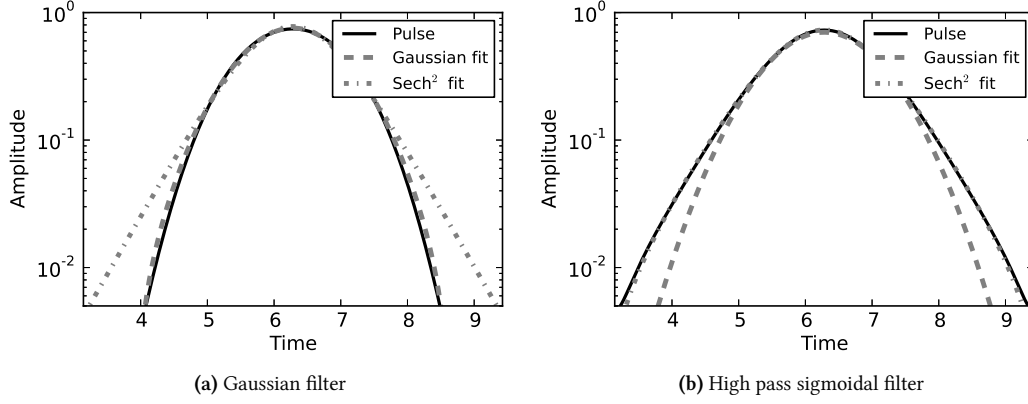


Figure 2.3: SMPM generated pulses using different spectral masks. Also shown are numerically fitted Gaussian and sech^2 shaped pulses.

phase is quasi-linear. As the instantaneous frequency of the optical field is given by the derivative of the angular phase (see Eq. 2.1), a linear phase (with respect to time) will yield a pulse with a constant optical frequency, i.e. an unchirped pulse. Also plotted on Fig. 2.4 is the derived instantaneous frequency shift, which is close to constant across both pulses. This figure also shows that the sigmoidal filter yields a pulse with a more linear phase profile and thus lower frequency deviation - the frequency deviation in the pulse generated using the Gaussian filter is 2.2 times higher than that generated using the sigmoidal filter.

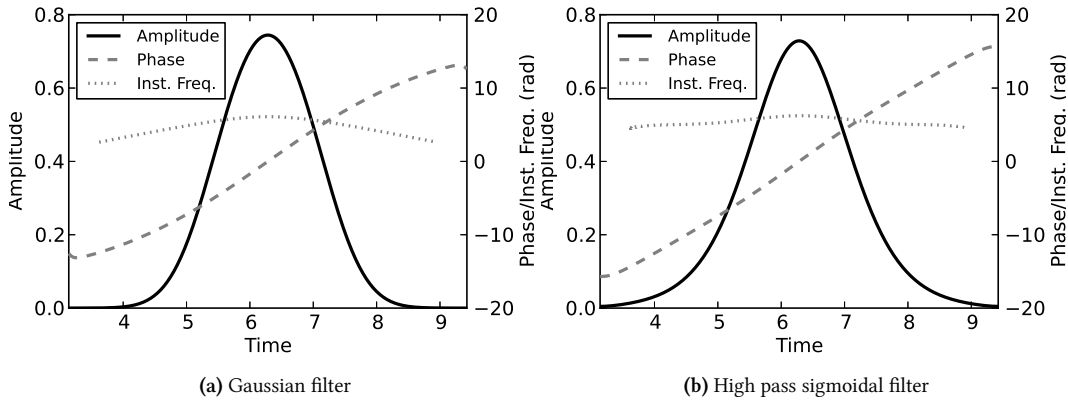


Figure 2.4: SMPM generated pulses using different spectral masks. Black curves show the pulse amplitude. Grey dashed curves show the angular phase across the pulse and dotted grey curves show the instantaneous frequency shift $\Delta\omega = \partial\phi/\partial t$.

2.1.4 Seed linewidth and pulse train quality

In the above simulations, the SMPM system is seeded by a pure continuous wave signal (i.e. with spectral phase constant with time), corresponding to a single frequency laser source. In reality SMPM sources may be seeded by lasers which do not operate in the single frequency regime, and so the effects of seed linewidth on the quality of the generated pulse train must be considered. The effects of non-zero linewidth were modelled using the phase diffusion model [Lax67], whereby normally distributed random phase noise is added to the initial seed laser field envelope function.

The bandwidth of the phase noise, $\Delta\omega_n$ (and hence the seed laser linewidth) was specified as a fraction of the phase modulation frequency, ω_{pm} . The pulse trains resulting from laser lines with noise bandwidths of $0.01\omega_{pm}$, $0.1\omega_{pm}$ and $0.25\omega_{pm}$ in the case of the Gaussian and the sigmoidal filter are shown in Figs. 2.5a and 2.5b respectively. These figures show the deleterious effects of seed phase noise on the resulting pulse trains, with an increasing degree of pulse-to-pulse variation with increasing noise bandwidth. There is a marked difference in the case of the two filters in terms of the pulse quality. This is further illustrated in Figs. 2.6a and 2.6b which show the generated pulse shapes using the Gaussian and sigmoidal filters respectively, plotted on a logarithmic scale. These are also shown with the ideal (noiseless) case where $\Delta\omega_n = 0$. Considering the case of $\Delta\omega_n = 0.25\omega_{pm}$, whilst both filters give rise to pulses with significant asymmetry, the Gaussian filter results in smoother pulses. This is due to the fact that the sigmoidal filter, acting as a high pass filter, allows for greater high frequency noise, corresponding to the short duration pulse features.

For phase noise bandwidths of $\omega_n \lesssim 0.1\omega_{pm}$, both filters produce pulse trains with little pulse-to-pulse variation, and the deviation from the pulse shapes generated in the ideal (noiseless) case is low. In all subsequent experimental work in this chapter, SMPM systems were seeded with lasers of linewidth on the order of 10s-100s of MHz, compared to modulation frequencies of 10s of GHz (i.e. $\omega_n < \omega_{pm}$), and so could be considered as pure continuous wave laser sources.

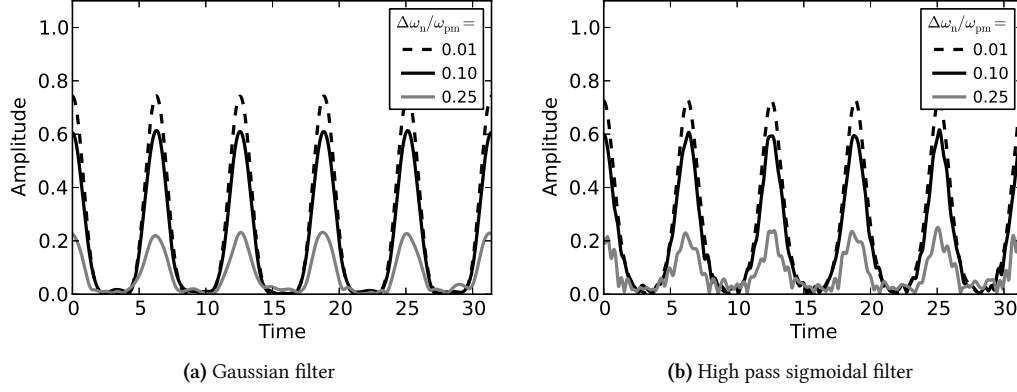


Figure 2.5: Time domain envelope functions of SMPM pulse trains seeded with noisy fields. Legend indicates phase noise bandwidth as a fraction of phase modulation frequency.

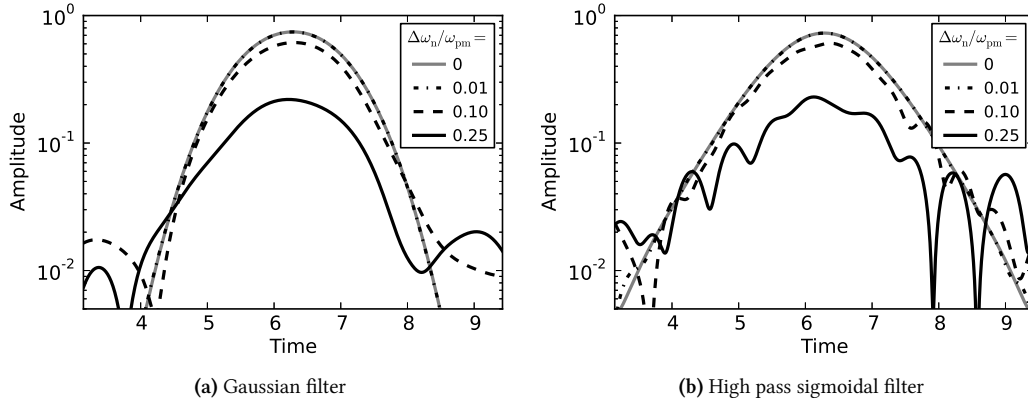


Figure 2.6: Pulse shapes generated through SMPM seeded with noisy fields, labelled by phase noise bandwidth as a fraction of phase modulation frequency. $\Delta\omega_n = 0$ corresponds to the noiseless case.

2.2 A SMPM system operating at 1.55 μm

From the simulations above, it is clear that spectrally masked phase modulation can yield pulse durations on the order of a quarter of the period of the initial phase modulation, meaning that for an applied modulation on the order of 10s of gigahertz, pulse durations on the order of tens of picoseconds can be expected. To access the femtosecond regime, subsequent compression of SMPM-generated pulses is necessary.

This section describes a pulsed laser source operating at 1.55 μm , capable of producing pulses as short as 265 fs. This was achieved by combining a SMPM pulse train generator with a Raman soliton compressor-amplifier stage. Figure 2.7 shows the experimental set-up.

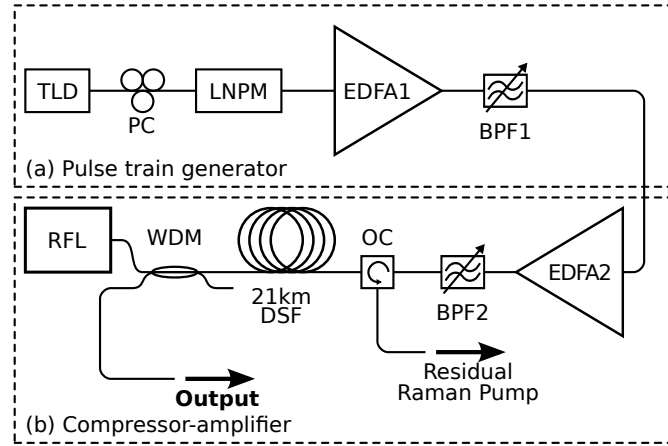


Figure 2.7: System schematic for SMPM system operating at 1.55 μm . Key to acronyms - TLD: Tunable laser diode; PC: Polarisation controller; LNPM: Lithium niobate phase modulator; EDFA: Erbium doped fibre amplifier; BPF: Band pass filter; OC: Optical circulator; DSF: Dispersion shifted fibre; WDM: 1450/1550 nm Wave-length division multiplexer; RFL: Raman fibre laser.

The pulse train generator (labelled (a) in Fig. 2.7) is based on a commercial external cavity tunable laser diode (TLD) (Santec TSL-210) and a fibre-connectorised lithium niobate phase modulator (LNPM) (Photline MPZ-LN10). The LNPM was driven with a 10 GHz sinusoid at 27 dBm RF power, equivalent to a peak voltage of $1.2V_{\pi}$. This signal was pre-amplified using a low-power erbium doped fibre amplifier (EDFA) (IPG Photonics EAU-10-C) before being spectrally masked. This was achieved through use of a fibre-connectorised band pass filter (BPF) (Alnair BVF-200) based on a diffraction grating and adjustable retro-reflector. The transmission function of the BPF closely matched a sigmoid. The output of

the pulse train generator was autocorrelated, showing pulsed output with a deconvolved FWHM duration of ~ 30 ps (assuming a sech^2 profile). These pulses were simultaneously compressed and amplified using a Raman soliton compressor-amplifier (labelled (b) in Fig. 2.7).

2.2.1 Adiabatic Raman soliton compression

Robustness to perturbation is a well-established and highly advantageous property of optical solitons. It enables continued solitonic propagation in the presence of loss, a property which can be exploited for long-length transmission systems [Has81], or in a changing dispersion profile, which enables a soliton to continue to propagate as it is subject to Raman self-frequency shift across a dispersion landscape [Dia85, Mit86].

The duration of a soliton, T_0 , can be expressed in terms of the pulse energy, E , and the dispersive and nonlinear parameters of the fibre through which it propagates, β_2 and γ respectively:

$$T_0 = \frac{2|\beta_2|}{\gamma E}. \quad (2.7)$$

Due to the self-focusing nature of the soliton solution, a slow change to any of these parameters will result in the pulse self-adjusting its duration to match the soliton condition, without the pulse breaking up or the loss of energy to co-propagating dispersive waves. The property of self-adjusting without energy loss is the root of the somewhat oxymoronic term ‘adiabatic amplification’.

In the context of soliton propagation, a change to any parameter in Eq. 2.7 is understood to be ‘slow’ if it is small ($< 10\%$) [Mam91] over the characteristic soliton period, z_0 , which is related to the pulse energy by

$$z_0 = \frac{2\pi|\beta_2|}{\gamma^2 E^2}. \quad (2.8)$$

A slow increase in the energy, then, will result in a decrease in the pulse duration, according to Eq. 2.7. It was first proposed by Hasegawa in 1983 [Has83, Has84] that a periodic distributed amplification scheme, such as Raman scattering, could be employed to provide low gain over a long length of fibre, enabling the propagation of solitons without average

temporal broadening due to energy loss. By subjecting solitons to slow amplification, it is possible to continually temporally compress the pulses [GN88, Iwa91, Hea93]. In particular, Raman amplification employed in a counter-pumped configuration is particularly advantageous, as due to the attenuation of the pump wave along the amplifier due to material loss and pump depletion, there will be a greater distribution of pump power, and therefore higher gain per unit length, at the output end of the amplifier. This will correspond to the highest pulse energy and therefore shortest soliton period, resulting in the gain per soliton period remaining low. The requirements for such an amplifier would be that the pump wave be spectrally located at a frequency around 13 THz greater than the signal (the peak frequency offset for Raman gain in silica - as shown in Fig. 1.2), that the signal wavelength be subject to anomalous dispersion (to enable soliton propagation) and the pump be subject to normal dispersion (to avoid the deleterious effects of modulation instability). For compression of pulses generated through SMPM (on the order of 10s of picoseconds) to femtosecond duration, it is also necessary that an optical fibre which meets these requirements be available in long (multi-km) lengths.

The compression of SMPM generated pulses at 1550 nm was achieved through a Raman amplifier scheme based on dispersion shifted fibre (DSF) with a zero-dispersion wavelength of 1464 nm. As a result, the SMPM signal was located in the anomalous dispersion region, allowing soliton propagation. The amplifier was pumped by a Raman fibre laser (IPG PYL-5-1455) with a maximum output power of 5 W operating at 1455 nm, in the normal dispersion region of the DSF.

2.2.2 Numerical simulation of the Raman soliton compressor-amplifier

The propagation of SMPM generated pulses through a long length counter-pumped Raman fibre amplifier was simulated.

For pump and signal powers at optical frequencies of ω_P and ω_S , the pump and signal

powers, P and S , are related by the pair of coupled first order differential equations:

$$\frac{\partial S}{\partial z} = g_R P S - \alpha_S S \quad (2.9)$$

$$-\frac{\partial P}{\partial z} = -\frac{\omega_P}{\omega_S} g_R P S - \alpha_P P \quad (2.10)$$

where g_R is the Raman gain coefficient at the pump-to-signal frequency separation and α_P and α_S is the attenuation at the pump and signal wavelengths respectively. The minus sign on the left hand side of Eq. 2.10 defines that the pump line is counter-propagating with regards to the signal line. The first term on the right hand side of Eq. 2.9 arises from the gain provided by the presence of the pump radiation. The corresponding term in Eq. 2.10 arises from the fact that any gain provided to the signal line is lost from the pump line, and that the total photon count must be conserved, so that the power lost by the pump line per unit length is the power gained in the signal line, multiplied by the ratio of the optical frequency of the two lines (proportional to the ratio of the photon energy). The second term in the right hand side of both equations arise from the (frequency dependent) material loss of the fibre through which the pump and signal propagate.

These equations were solved using an ordinary differential equation solver, iterated over the length of the amplifier in the forward signal direction. As the pump power is bound at the output end of the amplifier while the signal power is bound at the input end of the amplifier, the distribution of pump and signal powers along the amplifier length were found by integrating along the fibre length from the input end, and iterating over the residual pump power at the input end of the amplifier using a bisection goal seeking algorithm, to find a pump and signal distribution which satisfied the boundary conditions.

This model was used to simulate the propagation of a 10 GHz train of optical solitons through the counter-pumped Raman amplifier. The parameters for gain and attenuation matched those specified for the dispersion shifted fibre used in the amplifier, and the pump power was set to 2 W. The input signal (time averaged) power was set to 100 mW (i.e. a pulse energy of 10 pJ) and the amplifier length was 21 km, again, matching the experimental parameters.

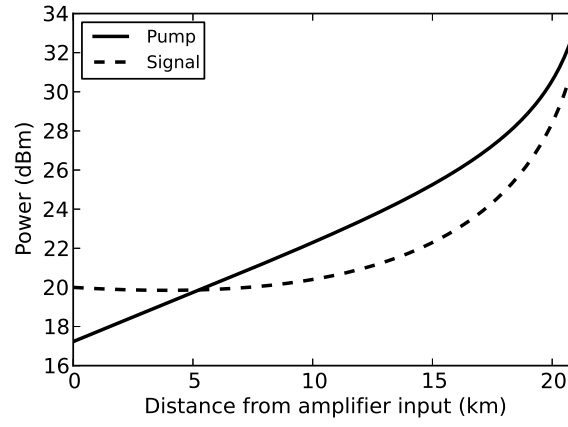


Figure 2.8: Simulated pump field and signal powers along fibre length

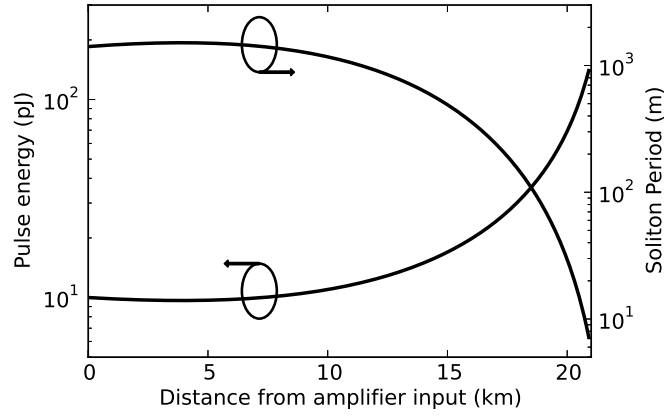


Figure 2.9: Simulated pulse energy and implied soliton period along fibre length

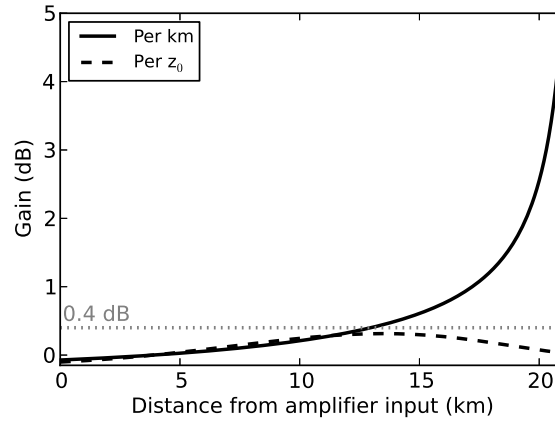


Figure 2.10: Simulated gain per km (solid black curve) and per soliton length, z_0 (black dashed curve). Grey dotted curve shows nominal threshold for adiabatic soliton propagation of 0.4 dB.

The distribution of pump and signal power along the length of the amplifier is shown in Fig. 2.8. This clearly shows the weighting of the distribution of pump power to the output end of the amplifier. The pulse energy can be inferred from the signal power by dividing by the fixed repetition rate of 10 GHz, which in turn will determine the length of the soliton period as the pulse propagates through the amplifier, according to Eq. 2.8. These two quantities are shown in Fig. 2.9. As is expected, the soliton period dramatically decreases (by a factor of over 100) along the length of the amplifier. The true advantage of this, and of the counter-pumped amplifier scheme in general, becomes apparent in Fig. 2.10. This shows both the gain per unit length along the length of the amplifier, but also the gain per soliton period. The gain per unit length increases along the length of the amplifier, following the distribution of the pump power, up to ~ 4.5 dB/km. The gain per soliton period, however, does not monotonically increase along the fibre length as the soliton period is decreasing along the length of the fibre, from 1 km at the input, to less than 10 m at the output. As such, the amount of gain per soliton period does not exceed 0.4 dB, the nominal threshold for adiabatic soliton propagation.

2.2.3 Experimental Results

This section details the experimental results of the compression of SMPM generated pulses at 10 GHz repetition rate, in an adiabatic Raman soliton compressor-amplifier. Figure 2.11 shows the optical spectrum of the SMPM pulse generator, before and after spectral masking using the band pass filter. In this case the short wavelength (high frequency) components have been selected. SHG autocorrelation of the output of the SMPM pulse generator, shown in Fig. 2.12, indicated that pulses with a deconvolved FWHM duration of 28 ps had been generated. These were launched into the compressor-amplifier stage, after pre-amplification in an EDFA (marked EDFA2 in Fig. 2.7, IPG Photonics EAD-500). This pre-amplifier was used to ensure that the pulse energy matched the soliton condition for the DSF in the Raman amplifier. This was achieved empirically by observing the output autocorrelation of the amplifier stage whilst adjusting the output power of EDFA2, maximising the peak-to-pedestal ratio, which corresponds with the lowest amount of co-propagating dispersive

radiation with the solitonic radiation, i.e. where the pulse is launched most closely matching the input soliton condition. A second tunable band pass filter (BPF2) is used to remove the excess ASE introduced by EDFA2 which otherwise would compete for gain in the Raman amplifier.

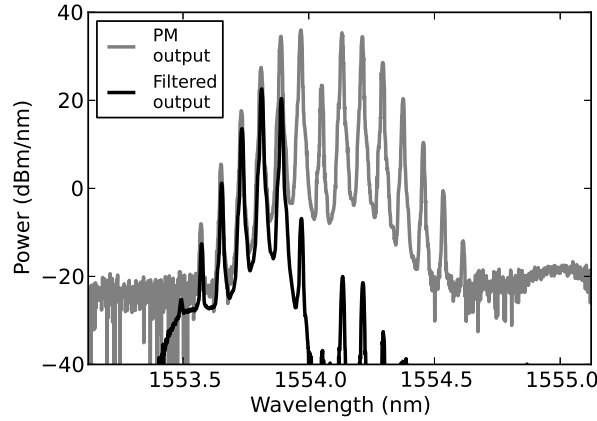


Figure 2.11: Optical spectrum of the amplified phase modulated signal before (grey curve) and after (black curve) band pass filtering. Only the high frequency (short wavelength) components have been selected

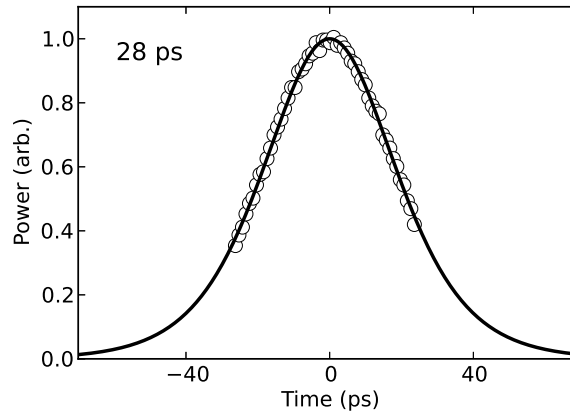


Figure 2.12: Output SHG autocorrelation of SMPM pulse train generator. Black curve shows sech^2 fit indicating a deconvolved FWHM duration of 28 ps.

The power and SHG autocorrelation of the amplifier output were recorded with increasing Raman pump power. The SHG autocorrelations were used to determine the output pulse duration (deconvolved FWHM) and these data are shown in Fig. 2.13. This figure shows that with increasing pump power, the output power increases, meaning that the pulse en-

ergy also continually increases. As expected, this results in a decrease in the output pulse duration, down to 290 fs. The decrease in pulse duration does not continue indefinitely with increasing pump power, but instead plateaus for pump powers above ~ 2 W. The cause of this is revealed by the evolution of the optical spectrum with increasing pump power, as shown in Fig. 2.14.

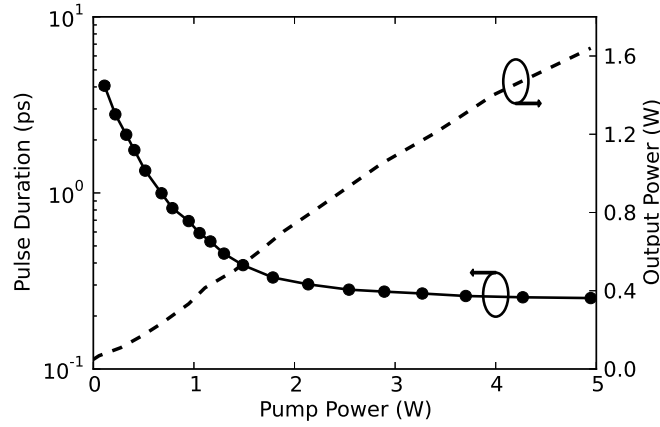


Figure 2.13: Output power and output pulse duration with increasing pump power for SMPM signal amplified in Raman compressor-amplifier

At powers above 2.52 W there is an extended flat component in the optical spectrum which can be attributed to supercontinuum generation. This indicates that the pulse has started to break up and the adiabatic condition has not been maintained throughout its amplification. This is also evidenced by Fig. 2.15, which shows the output power (in W) multiplied by the output pulse duration (in ps). From Eq. 2.7, it can be seen that the quantity ET_0 (the pulse energy multiplied by its duration) is equal to $2|\beta_2|/\gamma$, and so should remain constant as long as the soliton is subject to adiabatic amplification. As the output power is given by the pulse energy multiplied by the (constant) repetition rate, it is expected that the output power multiplied by the pulse duration should remain constant as long as the adiabatic soliton amplification condition is met. For low pump powers, this quantity is roughly constant at around 0.22 W·ps, but is seen to increase above a pump power of 2 W. This indicates non-adiabatic soliton amplification, and correlates with the onset of supercontinuum generation as observed in the optical spectrum. Because of this, the pump

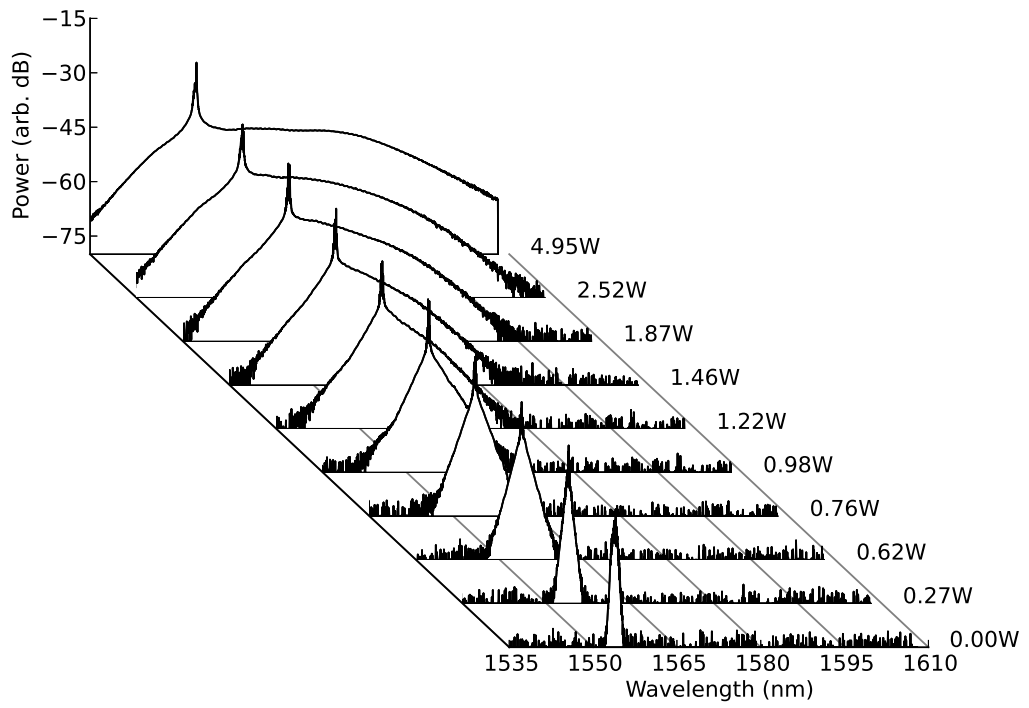


Figure 2.14: Optical spectrum of Raman compressor-amplifier output for increasing pump powers.

power was restricted to 2 W.

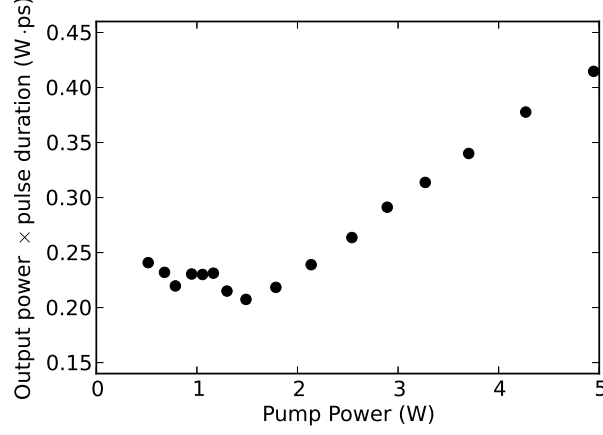


Figure 2.15: Output power multiplied by pulse duration for increasing pump powers

As the SMPM pulse train generator was based upon a tunable laser diode, and tunable band pass filters, the wavelength could be tuned across the gain of the amplifier. Practically, this was restricted by the gain bandwidth of EDFA1 and EDFA2 rather than the Raman compressor-amplifier. The central wavelength of the pulse was tuned over a ~ 20 nm range (1549 - 1567 nm). The resulting output autocorrelations for 2 W of pump power are shown in Fig. 2.16. Across this range, the output pulses were of similar durations (265 - 305 fs). As might be expected, the pulse duration increases for pulses centred at longer wavelengths, as they will be subject to slightly greater dispersion, β_2 . As is expected for solitonic propagation, the pulses fit well to a sech^2 profile, and all show a very low pedestal (<5%), indicating a low proportion of energy lost to co-propagating dispersive waves. The dispersive radiation that is present can be attributed to a combination of the input pulses not perfectly matching the required transform-limited sech^2 profile, and the subsequent shedding of excess dispersive radiation due to high order dispersion ($\beta_{\geq 3}$) in the Raman amplifier-compressor.

It should be noted that in addition to the wavelength being continuously tunable, the pulse duration is continuously tunable by simply adjusting the pump power supplied to the amplifier. Furthermore, the repetition rate could be tuned by altering the frequency of the drive voltage supplied to the LNPM in the SMPM pulse train generator. This system,

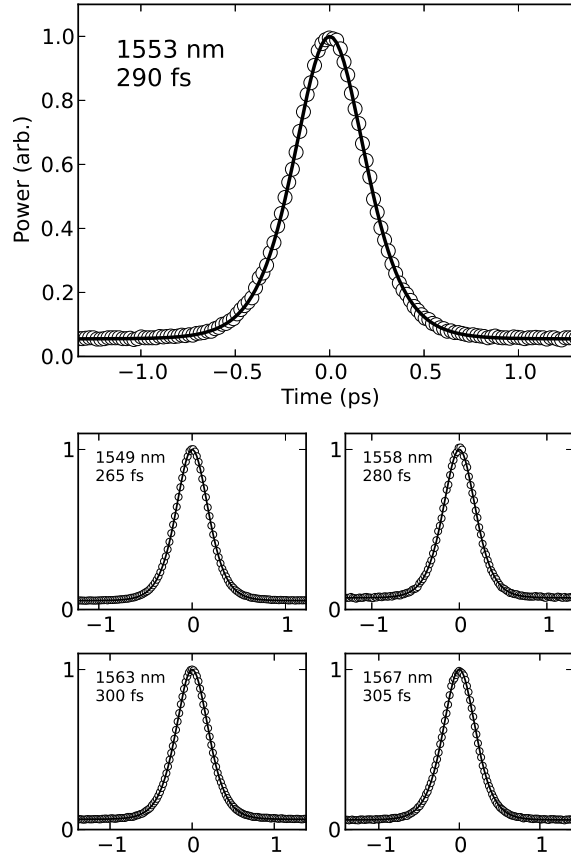


Figure 2.16: Output autocorrelations for SMPM system operating across a range of wavelengths with 2 W of pump power supplied to Raman compressor-amplifier. Labels show centre wavelength of pulse and the deconvolved FWHM duration.

then, displays desirable versatility as a source of pulses tunable in wavelength, duration and repetition rate, in a compact and convenient all-fibre format.

2.3 A SMPM system operating at 1.06 μm

As discussed above, the advantage of employing a lithium niobate based device compared to electro-absorption modulation is wavelength versatility. EAM devices are fundamentally restricted by the wavelength of the semiconductor absorption band edge, with a result that applying the technology to new wavelength regions would require significant investment to develop devices operating in different spectral regions. Lithium niobate, however, is broadly transmissive from 0.3 - 5 μm , meaning that it is an ideal platform for the development of an optical pulse shaping technology, as with minimal adaptation the same technique can be applied across a wide spectral range.

Nonlinear pulse compression through Raman amplification, however, does not have the same degree of universality. Whilst Raman gain is available across the transmission window of silica, dependent on pump source availability, its application for pulse compression is contingent on the requirement that the signal wavelength be in the anomalous dispersion region (for solitonic propagation) whilst the pump wavelength be in the normal dispersion region (to avoid the effects of modulation instability). As such, any amplifier-compressor must be based on an optical fibre with a zero dispersion wavelength (ZDW) just short of the signal wavelength. This presents a problem as for standard (non-microstructured) silica fibre, the minimum ZDW which can be achieved is the material ZDW of silica, located at 1.27 μm . For signal wavelengths shorter than this, photonic crystal fibre (PCF) must be used. Due to the greater engineerability of the waveguide contribution to the dispersion profile in PCF compared to non-microstructured fibre, PCF can be fabricated with ZDWs at virtually any wavelength. Raman soliton compression, however, required multi-kilometre lengths of such fibre for any practical compressor-amplifier scheme to achieve compression of pulses from picosecond to femtosecond duration. This would not be practical using photonic crystal fibre as the Raman gain medium, owing to greater loss in PCF compared to

standard fibre, difficulties in manufacturing such lengths with uniform dispersion profiles, and also the high cost associated with such a length.

Adiabatic Raman soliton compression, then, does not currently present a practical route to pulse compression for wavelengths shorter than $1.27 \mu\text{m}$. This does not mean, however, that adiabatic soliton compression is not available as a pulse compression technique at such wavelengths. Turning again to the soliton condition (Eq. 2.7):

$$T_0 = \frac{2|\beta_2|}{\gamma E},$$

if the pulse energy, E , remains constant, but the fibre parameters β_2 and γ slowly change along the fibre through which the soliton propagates, the soliton will adjust its duration, T_0 , to compensate. Assuming a constant energy, E , the change in T_0 will be proportional to $|\beta_2|/\gamma$, and as long as this change is slow compared to the soliton period (i.e. a change of less than 10% per soliton period), the compression should be achieved adiabatically. It was suggested as early as 1987 that nonuniform dispersion along the length of an optical fibre could be used to counteract the temporal broadening caused by loss [Taj87], and soon after it was suggested that such fibres could be used to affect pulse compression [Kue88]. Within a few years, the fabrication of such fibres [Bog91] and the experimental realisation of adiabatic soliton compression in dispersion decreasing fibre was demonstrated [Che91].

As microstructured fibre exhibits a greater degree of flexibility in dispersion profile engineering, due to the contribution of the microstructured cladding to the overall dispersion, PCF can be manufactured with low anomalous dispersion, suitable for soliton propagation, at virtually any wavelength in the silica transmission window. By varying the cladding structure along the fibre length, then, the dispersive and nonlinear properties of a PCF can be altered along its length, which can be exploited to achieve pulse compression [Tse06, Tra07].

The work in this section relates to a SMPM system operating at $1.06 \mu\text{m}$, which incorporates nonlinear compression through a dispersion decreasing PCF. The experimental set-up for the system is shown in Fig. 2.17.

The SMPM pulse train generator (labelled (a) in Fig. 2.17) is similar to that described in

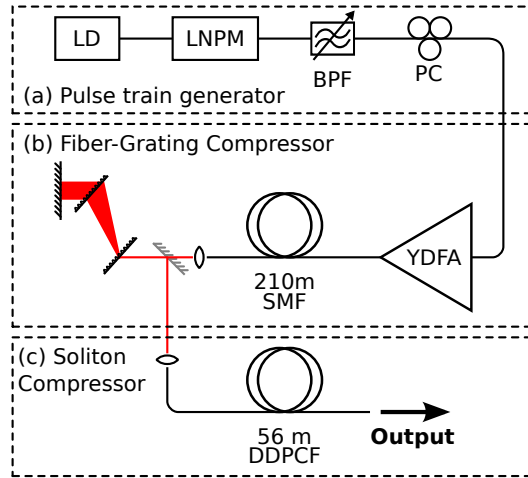


Figure 2.17: System schematic for SMPM system operating at $1.06\ \mu\text{m}$. Key to acronyms - LD: Laser diode; BPF: Band pass filter; PC - Polarisation controller; YDFA: Ytterbium doped fibre amplifier; SMF: Single mode fibre; DDPCF: Dispersion decreasing photonic crystal fibre.

Section 2.2.3, but in this case a temperature stabilised fixed frequency laser diode (IPG Photonics) was used. The output of this diode was phase modulated using a fibre connectorised LNPM (EOSpace), driven with a 20 GHz sinusoidal signal. The LNPM was supplied with 27 dBm of RF power, which corresponded to a peak voltage of 7 V or $3V_\pi$. Due to the higher output power of this diode compared to that used in Section 2.2.3, a booster amplifier was not required before spectral masking.

In this case, the spectral mask was a Gaussian shaped notch filter, based on a fibre connectorised interference filter with a spectral width of 0.6 nm. The angle of the interference filter relative to the optic axis could be manually adjusted to shift the transmission window of the mask. The filter was empirically optimised to minimise the duration of the generated pulses, and it was found that the optimum peak transmission wavelength was 1064.8 nm. The optical spectrum before and after spectral masking is shown in Fig. 2.18. A SHG autocorrelation of the output after spectral masking is shown in Fig. 2.19. As discussed in Section 2.1.3, as a Gaussian spectral filter has been used, a Gaussian shaped pulse is expected. This agrees with the observed optical pulse, which closely matches a Gaussian fit with a FWHM duration of 9 ps.

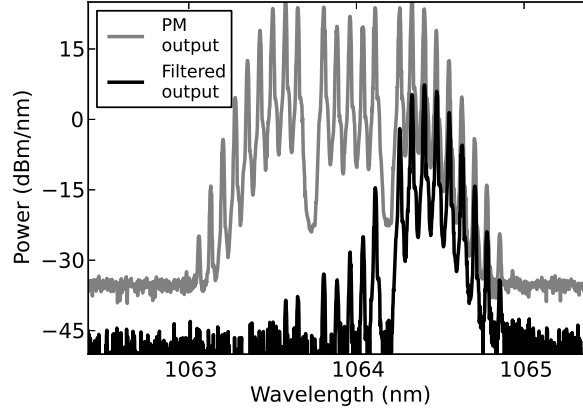


Figure 2.18: Optical spectrum of the phase modulated laser diode before (grey curve) and after (black curve) spectral masking using the band pass filter.

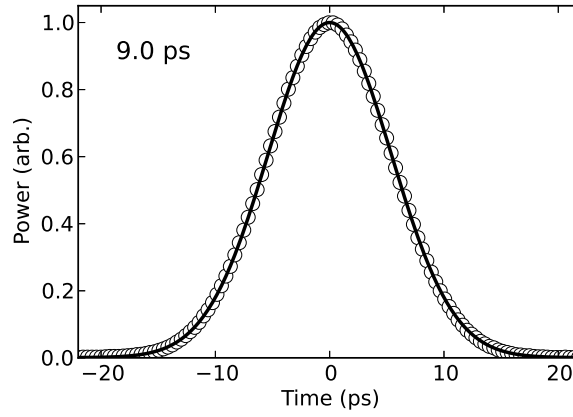


Figure 2.19: Autocorrelation of the SMPM pulse train generator output. A Gaussian fit indicates a deconvolved FWHM duration of 9 ps.

2.3.1 Fibre-Grating Compressor

As shown in Fig. 2.17, the pulses generated through SMPM were compressed using a two-stage nonlinear compression scheme. The first stage was a fibre-grating compressor, labelled (b) in Fig. 2.17. The fibre-grating compressor is a well established route to the compression of pulses and is based on the spectral broadening of an optical pulse in a fibre through self-phase modulation (SPM). Assuming the pulse was initially unchirped, and there is no significant higher order dispersion in the fibre, this new bandwidth will result in a linear chirp across the pulse, which can be compensated using a pair of gratings, resulting in a shorter pulse than that launched into the fibre.

The technique was first demonstrated by Shank *et. al.* in 1982 [Sha82], who produced 30 fs pulses, the shortest laser pulses ever produced at the time, using a 15 cm length of optical fibre to broaden the spectrum of a 90 fs pulse which was then compressed in a grating pair. It is interesting to compare this scheme to that of compression of pulses through the amplification of solitons, where simultaneous SPM and anomalous dispersion act in tandem to result in pulse compression, whilst in the case of fibre-grating compression, the nonlinear and dispersive effects act in a discrete manner to compress the pulse - spectral broadening through SPM occurs only in the SMF, and anomalous dispersion is subsequently provided by the grating pair.

As shown in Fig. 2.17, an ytterbium-doped fibre amplifier (YDFA) (IPG Photonics YAM-10) was used to boost the power of the pulses. The time-averaged power was increased from 0.17 mW at the output of the SMPM pulse train generator to 5.07 W. The peak power was correspondingly increased from 0.91 mW to 28.1 W. This was launched into a 200 m length of single mode fibre (SMF), which acted as the nonlinear fibre stage. This is a relatively long length compared to other fibre-grating compressor schemes in the literature, owing to the fact that in this case the peak power is relatively low. This is due to the low duty factor resulting from the ultrahigh pulse repetition rate. The evolution of the optical spectrum envelope with increasing amplification in the YDFA is shown in Fig. 2.20. The spectral broadening effects of SPM are evident. Figure 2.21a shows the optical spectrum at 5.07 W and the corresponding autocorrelation is shown in Fig. 2.21b. Due to the fact that the pulse

has been subject to normal dispersion in the SMF, the pulse has dispersed, increasing its duration to a deconvolved FWHM of 16.5 ps. A pair of holographic transmission gratings were used to compensate for this chirp and compress the pulse. The gratings were used in a double pass configuration, and each had an efficiency of 75%, meaning the total transmission double passed through the pair was 32%. The grating separation was adjusted to minimise the compressed pulse duration. A separation of 45 cm resulted in a pulse with a duration of 940 fs, shown as the black curve in Fig. 2.21b. These pulses were then further compressed in the second nonlinear compression stage which comprised a dispersion decreasing photonic crystal fibre.

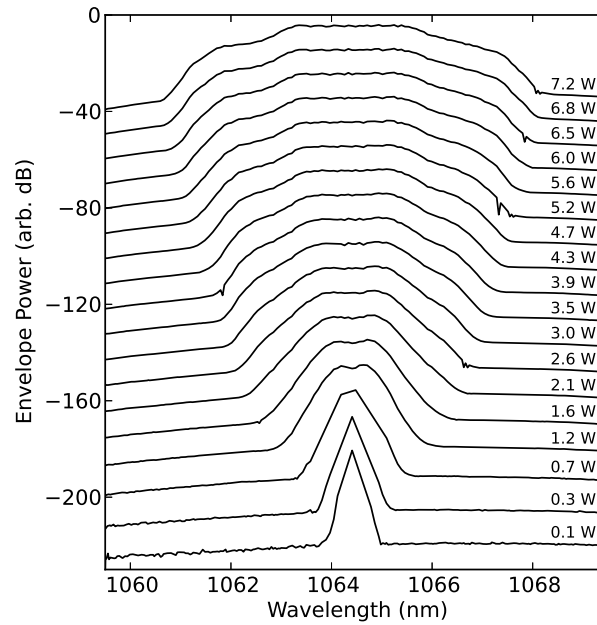


Figure 2.20: Evolution of the optical spectrum envelope of the output of the SMF with increasing amplification of the pulse train. Curves are labelled by the time-averaged power launched into the SMF.

2.3.2 Dispersion decreasing PCF for fundamental soliton compression

As discussed above, adiabatic soliton compression can be achieved for pulses whose energy is held constant by slow change to the nonlinear and dispersive parameters along the length of the fibre through which the soliton propagates. For PCF, the dispersion profile is engi-

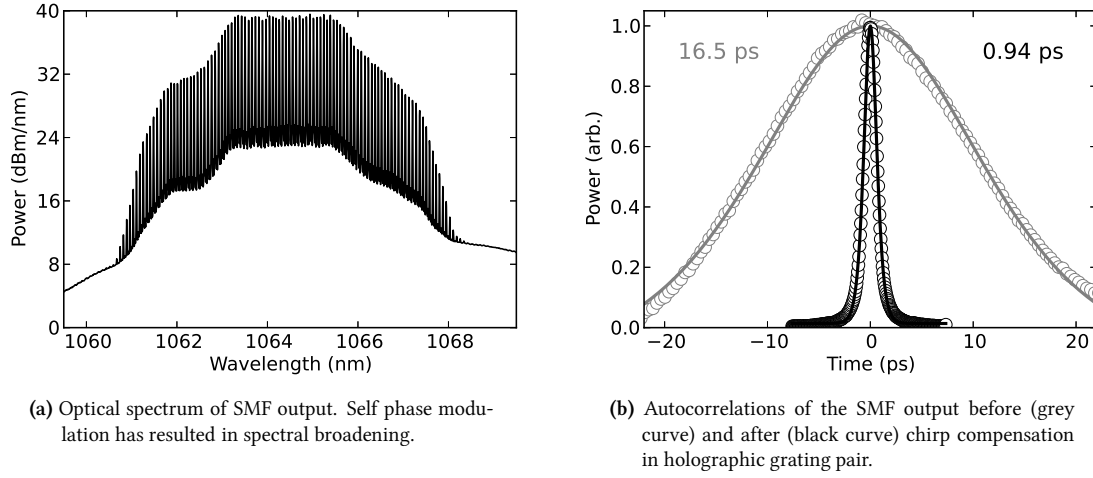
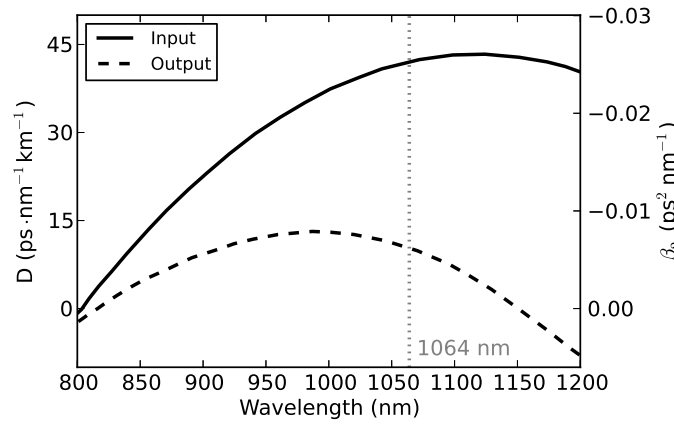


Figure 2.21

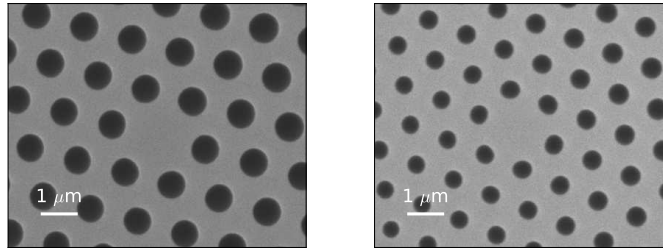
neered through the lattice structure of the photonic crystal cladding, parametrised by the air-hole diameter (d) and the air-hole diameter to pitch ratio (Λ). For pure silica PCF, the nonlinearity, γ is governed solely by the effective mode area in the fibre, as the material nonlinear index, n_2 , is constant. If, then, a monotonic reduction in T_0 is to be achieved, Eq. 2.7 suggests that the mode area should be reduced (increasing γ) whilst the surrounding surround structure remains constant (to hold β_2 constant), or alternatively that the mode area be held constant, and the dispersion reduced through a smooth change to the cladding structure.

The latter is more readily experimentally realised, as d and d/Λ can be altered by simultaneously changing the pressure at which the air-cores are held and the speed at which the fibre is pulled during fabrication on the drawing tower. In such a way the central defect region might be kept of roughly constant area, while the dispersion profile can be dramatically altered. A 56 m length of dispersion decreasing PCF (DDPCF) was manufactured in such a way at the University of Bath. The cross-sectional profiles at the input and output end are shown in Figs. 2.22b and 2.22c respectively. Note that the central region is relatively unchanged. The mode field effective area was ascertained numerically from the SEM images, and found to be $3.1 \mu\text{m}^2$ at the input and $3.6 \mu\text{m}^2$ at the output (γ of 52.8 and $45.4 \text{ W}^{-1}\text{km}^{-1}$ respectively), with a result that γ decreases by a factor of 0.86 over the

length of the fibre. 40 mm long samples taken from the input and output end were placed in an interferometer to find the group delay and hence the group velocity dispersion profiles. These are shown in Fig. 2.22a. At the operating wavelength of 1064 nm, the group velocity dispersion, D , reduces from 42 to 9.8 ps·nm⁻¹km⁻¹ (β_2 reduces from -0.027 to -0.006 ps²nm⁻¹), with a result that the dispersion decreases by a factor of 4.3. The quantity $|\beta_2|/\gamma$ decreases by a factor of 3.7 over the 56 m length of the DDPCF.



(a) Dispersion profiles



(b) Input

(c) Output

Figure 2.22: Dispersion curves (a) and cross sectional SEM images for the input (b) and output (c) end of the dispersion decreasing PCF.

The output of the fibre-grating compressor was launched into the input (high dispersion) end of the DDPCF using an objective lens, as shown in part (c) of Fig. 2.17. As the aim was the adiabatic compression of the optical soliton, it was important that pulse be launched into the DDPCF satisfying the fundamental soliton condition, i.e. $N = 1$, where N , the

soliton order of a pulse with energy E and duration T_0 , is given by

$$N = \sqrt{\frac{E}{E_s}} = \sqrt{\frac{E\gamma T_0}{2|\beta_2|}} \quad (2.11)$$

where E_s is the energy satisfying the fundamental soliton condition for a pulse of duration T_0 (see Eq. 2.7).

The launch of a fundamental soliton was achieved empirically by altering the coupling efficiency into the fibre, using the objective lens, and monitoring the autocorrelation of the output from the low dispersion end of the fibre. It was found that the optimal output pulse (in terms of shortest duration without evidence of high-order soliton propagation) was achieved for a launched pulse energy of 8.5 pJ. Considering only the pulse duration, Eq. 2.11 suggests that this pulse would be a soliton of order $N = 2.4$. The launched pulse, however, was not transform limited, as the chirp induced in the SMF of the fibre-grating compressor had not been fully compensated by the grating pair, 940 fs corresponding to a pulse 2.2 times the transform limit for the optical bandwidth. Instead, if the pulse is considered in terms of its optical bandwidth of 2.9 nm, the pulse corresponds to a soliton of order $N = 1.5$ and as such can be expected to propagate as a fundamental soliton. From Eq. 2.8, the soliton period for these pulses at the input end of the DDPCF was $z_0 = 0.7$ m, which compares favourably to the total length of the DDPCF of 56 m. As such, the change in the fibre parameters can be considered slow compared to the soliton period, and so adiabatic soliton compression is expected.

The output pulse autocorrelation is shown in Fig. 2.23, indicating that the pulse has been compressed to a duration of 190 fs. The output also exhibits high pulse quality, with near-perfect sech^2 shape and very low (<1%) pedestal. This is characteristic of adiabatic compression of a fundamental soliton. The fact that the pulse was launched with an energy slightly in excess of that of a fundamental soliton (i.e. with $N = 1.5$), can be accounted for by the fact that the pulse will be subject to some loss while propagating through the DDPCF, and the slight uncertainty in ascertaining the precise values of β_2 and γ .

Figure 2.24 shows the optical spectrum of the output, which has broadened as the pulse

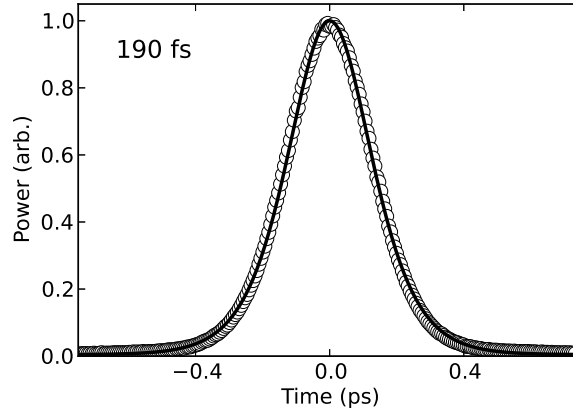


Figure 2.23: Autocorrelation of the output of the DDPCF. A sech^2 fit indicates a deconvolved FWHM duration of 190fs.

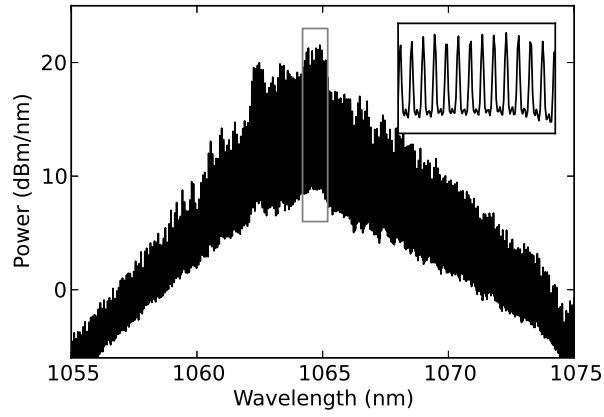


Figure 2.24: Optical spectrum of the output of the dispersion decreasing photonic crystal fibre. Inset shows zoomed-in section of the spectrum (denoted by the grey box) revealing the 20 GHz comb line spacing.

has been temporally compressed. Also shown is a zoomed-in view of the central region, showing that the spectrum still exhibits comb lines separated at the 20 GHz spacing characteristic of the initial phase modulation frequency.

2.4 Outlook

Work in this section has demonstrated the versatility of the SMPM concept, especially when combined with nonlinear pulse compression techniques, in the generation of high repetition rate trains of femtosecond pulses. As an SMPM system fundamentally requires only three optical components - a laser source, a phase modulator and an optical filter, experimental realisations have the potential to be incredibly compact, durable and cost-effective devices.

Combined with this, work in this chapter has shown that nonlinear pulse compression based on adiabatic soliton compression can result in high quality femtosecond pulses. As shown in Section 2.2, if Raman adiabatic soliton compression is used as a nonlinear compression technique, the devices can exhibit a highly desirable degree of tunability, in terms of repetition rate, operating wavelength and pulse duration.

The alternative route to adiabatic soliton compression in dispersion decreasing photonic crystal fibre, as detailed in Section 2.3, has some significant benefits in that it would be possible to engineer such a system operating at any wavelength over the entire silica transmission window, owing to the high degree of engineerability in the dispersion profiles of PCF. The trade-off for this universality is that any system based on dispersion decreasing PCF will only operate at a limited range of wavelengths and output pulse duration. However, as methods of fabrication for DDPCF improve, with greater on-tower control over the draw speed and air-core pressure, it is conceivable that the two-stage compression scheme used in Section 2.3 could be replaced by a single stage comprised of a longer DDPCF, resulting in a high repetition rate source of ultrashort pulses with a small footprint and high degree of environmental and mechanical stability.

Chapter 3

Bismuth doped fibre for novel laser applications

3.1 Introduction

Work in this section is motivated by the widespread citation of bismuth doped silica optical fibre as a potential platform for increasing the wavelength diversity of fibre amplifier systems for telecommunication applications. As the global internet continues to increase in size year on year, predicted to exceed 1 zettabyte per annum by 2016 [Cis12], greater capacity across the optical fibre backbone of the internet will be sought. To this end, there is continuing interest in the diversification of the range of wavelengths over which optical fibre links operate, so as to increase the wavelength division multiplexing efficiency. Raman amplifiers can effectively span any spectral region within the silica transmission window, dependent on the selection of a suitable pump source, and/or the use of cascaded Stokes-shifted Raman orders. Dopant-activated silica fibres, however, present a potentially more desirable platform as optical amplifiers, as they may enable direct pumping with multi-mode diodes, with potential gains in terms of operating efficiency and fabrication complexity, compared to fibre-laser pumped Raman amplifier schemes.

The only active fibre dopant which has seen widespread commercial deployment is er-

bium (Er). Er-doped silica amplifiers cover the ‘conventional’- or C-band of the silica transmission window, typically operating at $1.53\ \mu\text{m}$ - $1.57\ \mu\text{m}$. This region coincides with the region of minimal material loss in silica fibre, an obvious advantage for long-distance communication links. Another spectral region of particular interest is the ‘original’ or O-band (covering the $1.26\ \mu\text{m}$ - $1.36\ \mu\text{m}$ range), corresponding to the region of minimum material chromatic dispersion ($1.27\ \mu\text{m}$ for pure silica). Currently, no commercially available doped fibre amplifiers exist for the O-band, which is serviced instead by semiconductor technology and Raman amplifiers.

Since the discovery of near-infrared luminescence of bismuth in a glass host [Fuj01], Bi-doped optical fibre has gained traction as a potential candidate for increasing the operational spectrum of next generation telecommunications infrastructure, due to its surprisingly broad band emission, covering not only the O-band, but also the E-band and wavelengths below the O-band. Potentially, then, bismuth doping of silica optical fibre may bridge the gap between the ytterbium and erbium gain windows. This has driven a significant and continuing interest in the development of Bi-doped silica fibre devices. Soon after the demonstration of luminescence in Bi-doped glass, optical amplification was demonstrated both in bulk glass [Fuj03] and fibre [Dia05, Dvo06] formats. There has been ongoing work to ascertain the precise underlying gain mechanisms in Bi-doped optical fibres, particularly in ascertaining the bismuth ionisation state responsible for the gain - Bi^+ , Bi^{2+} and Bi^{5+} or clustered combinations of Bi ions [Sun09]. Indeed recent work suggests that the broad band fluorescence observed may not be homogeneous, but in fact the result of a continuum of emission spectra associated with different Bi ionisation states and structures [Raz11]. Other work has investigated the effects of co-dopants such as aluminium or germanium, and how this might effect active centre clustering and the properties of optical gain in Bi-doped silica [Pen04, Men05, Buf08]. This work has, however, still not resulted in an accepted consensus on the specific mechanism by which bismuth doped silica gives optical gain.

Bismuth-activated glasses also show a high degree of temperature dependance, with a result that in many experimental systems, the Bismuth glass must be cryogenically cooled

to achieve appreciable gain. It has been suggested that at room temperature, Bi-doped silica is a three-level laser system, with a broad lower laser level due to thermalisation. Cryogenic cooling dethermalises the lower level, effectively splitting it and depopulating the lower laser transition, resulting in quasi-four level laser action and greater efficiency [Gum11]. Other recent work has suggested that Bi-doped silica may have multiple active centres, responsible for fluorescence in different bands [Raz11, Fir11a, Buf11].

Even at this early stage of technological development, there have been demonstrations of Bi-doped fibre amplifier and laser systems operating in the O- [Seo07, Dia09] and L-bands [Buf09, Fir11b], as well as at sub-O-band wavelengths [Raz07, Dia07, Rul07]. This wavelength region is of interest, not only for potential wavelength diversification in optical telecommunications, but also as frequency doubling provides access to a visible wavelength region which has been of increasing interest due to the availability of mutagen variants of green fluorescent protein (GFP) for biomedical imaging applications [Mat02] and is currently served by dye laser systems, parametric nonlinear optical systems and supercontinuum sources [Dud10].

Work in this chapter was undertaken to ascertain the viability of bismuth doped optical fibre for applications in optical telecommunications and also as a platform for advanced configuration frequency doubled laser systems. Section 3.2 details the first demonstration of single pass amplification of picosecond pulses and gigahertz repetition rate signals in a bismuth doped fibre amplifier, fundamental requirements for any telecommunications amplifier system. Section 3.3 covers work undertaken to demonstrate that, whilst still at an early stage of development, bismuth doped optical fibre shows promise in advanced laser configurations. Specifically, a master-oscillator, power amplifier system was developed, and subsequently frequency doubled to provide picosecond pulses in the orange part of the visible spectrum. Work undertaken in this chapter has also been published as peer-reviewed journal articles [Cha11a, Cha11b].

3.2 Amplification of telecommunications signals in bismuth doped optical fibre

Two gain fibres were examined, both fabricated using a surface-plasma chemical vapour deposition process. Both are Bi-doped aluminosilicate fibres, whose core glass is composed of 97 mol% SiO_2 and 3 mol% Al_2O_3 , with a core diameter of 8 μm and a core/cladding refractive index contrast of 5×10^{-3} . The fibres differ in their core Bi centre content. The first (hereafter referred to as BDF1) has a core Bi centre content of 0.002 mol%, and the second (hereafter referred to as BDF2) has a content of 0.004 mol%. Fibre 2 also has a significantly reduced OH content. The attenuation spectra for both fibres are shown in Fig. 3.1, and specifics of the fabrication technology, absorption spectra, and near-IR luminescence of BDF1 and BDF2 can be found in [Buf08] and [Gol10], respectively. The lower OH content in BDF2 is evident in the greatly suppressed loss feature around 1.4 μm .

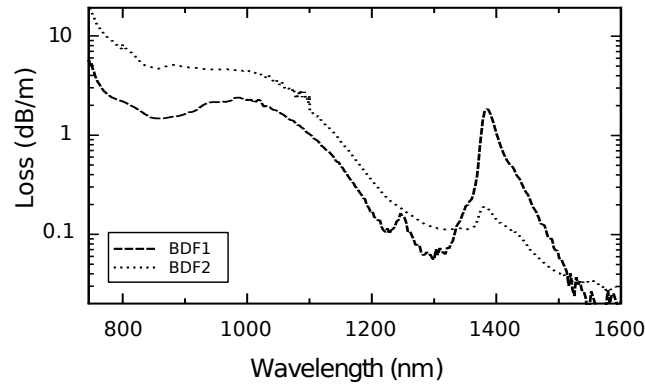


Figure 3.1: Absorption of fibres BDF1 and BDF2 measured through cut-back method

The potential of these two different fibre samples for the amplification of picosecond pulses and high bit-rate signals was investigated by integrating the samples into Yb fibre laser pumped amplifiers. The properties of these amplifiers would then be examined and the two samples compared.

3.2.1 Amplifier design

Figure 3.2 shows the schematic of the amplifier used to test the bismuth doped optical fibre. The fibre was counter-pumped using an ytterbium (Yb) fibre laser. The pump radiation was coupled in to and out of the amplifier using fused fibre coupler WDMs. In both cases, 30 m sample lengths were used and the amplifier was pumped with up to 6 W.

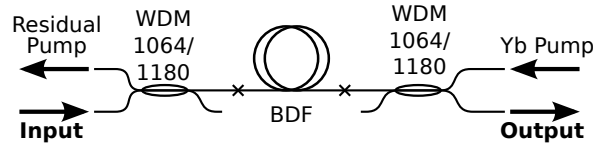


Figure 3.2: Set-up schematic for Bi-doped fibre based amplifier. Key to acronyms - WDM: wavelength division multiplier; BDF: bismuth doped fibre.

3.2.2 Amplification of picosecond pulses in Bi-doped aluminosilicate optical fibre

A source of picosecond pulses operating in the amplification band of the bismuth doped fibre amplifiers was required. To this end a spectrally filtered picosecond pulsed supercontinuum source was used. A schematic of the source is shown in Fig. 3.3. It comprised a commercial mode-locked laser (Fianium, Ltd.) with a 50 MHz repetition rate, generating 6 ps pulses at 1064 nm. These pulses were amplified in an Yb-doped fibre amplifier (YDFA) before being launched into a photonic crystal fibre (Crystal Fibre A/S) with a zero dispersion wavelength (ZDW) of 1038 nm. The output from the PCF was filtered using a fibre-connectorised band pass filter (BPF), at either 1160 or 1180 nm. The spectrum was recorded directly from the PCF and after band pass filtering. These spectra are shown in Fig. 3.4.

The filtered sources at 1160 and 1180 nm provided signal levels of -4 dBm and -7 dBm, respectively. The filtered output from the SC source was autocorrelated, and the measured pulses are shown as the black curves in Fig. 3.8. These indicate pulse durations of 2.5 ps for the 1160 nm band source and 1.6 ps for the 1180 nm band. It should be noted that these pulses are not expected to be transform limited (indeed, comparing their duration with their spectral width confirms this) as they have been subject to normal dispersion in the

single-mode fibre pigtails of the BPF.

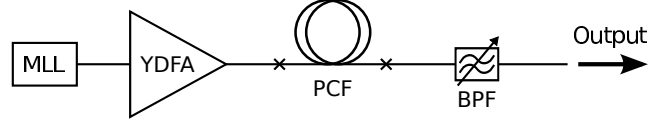


Figure 3.3: Schematic of picosecond pulsed signal source. Key to acronyms - MLL: Mode locked laser; YDFA: Ytterbium doped fibre amplifier; PCF: Photonic crystal fibre; BPF: Band pass filter

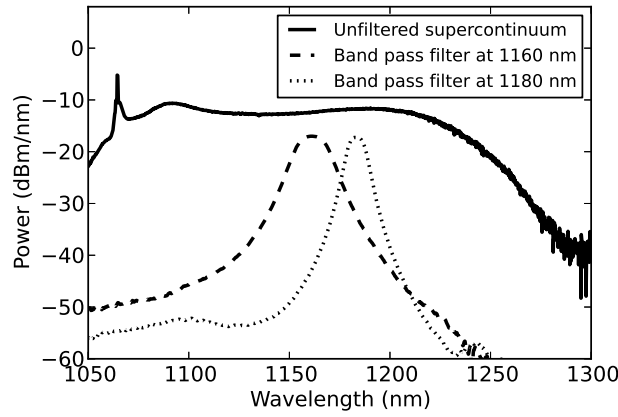


Figure 3.4: Spectrum of picosecond pulsed source. Black curve shows supercontinuum output from PCF, dashed and dotted curves show output spectra after band pass filtering at 1160 nm and 1180 nm, respectively.

These pulses were launched into the amplifier, and the gain was measured for increasing pump power to find the gain saturation curves. This was carried out for both wavelength band sources in both optical fibres, up to the maximum pump power of 6 W. The measurements were taken with the BDF in the amplifier kept at room temperature (300K) and then repeated with the BDF subject to cryogenic cooling through immersion in a liquid nitrogen bath (77 K), so that the effect of cooling on the amplifier performance could be examined.

The output spectra from the amplifier for both sources in both fibre samples at maximum pump power are shown in Fig. 3.5. As can be seen, there is a significant contribution from amplified spontaneous emission (ASE) generated in the amplifier. To mitigate the effects of this on measurements of the output power (and hence amplifier gain), both the output power from the amplifier and the output optical spectrum was recorded with increasing pump power. As such, the output power falling within the spectral width of the signal could be measured, and the gain calculated from this.

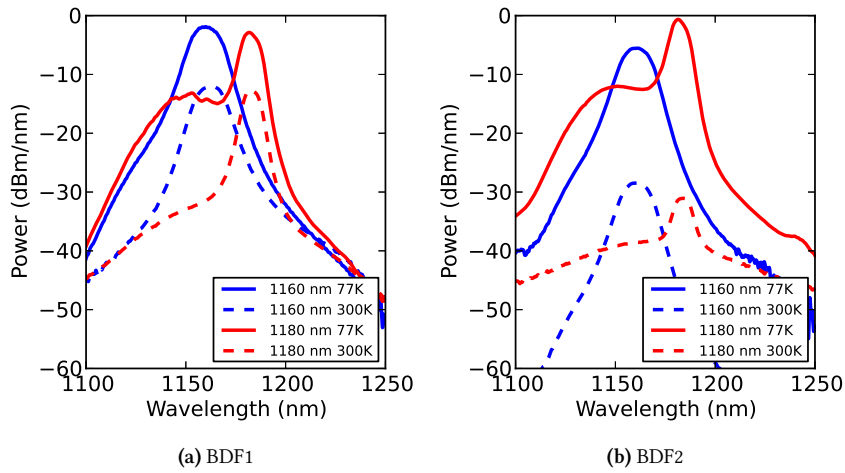


Figure 3.5: Output spectra of amplified picosecond signals at 1160 nm (blue) and 1180 nm (red) at 77K (solid curves) and 300K (dashed curves) (a) BDF1 and (b) BDF2

The resulting small signal gain saturation curves from these measurements using fibre sample BDF1 are shown in Fig. 3.6. There is evidently a marked difference in amplifier performance with temperature. With cryogenic cooling, the amplifier saturates above ~ 2.5 W for both signal wavelengths, giving a maximum gain of 21.2 dB for the 1160 nm signal and 15.7 dB for 1180 nm. Without cryogenic cooling, the amplifier exhibits significantly lower gain, saturating at 6.3 dB for 1160 nm and 5.5 dB for 1180 nm.

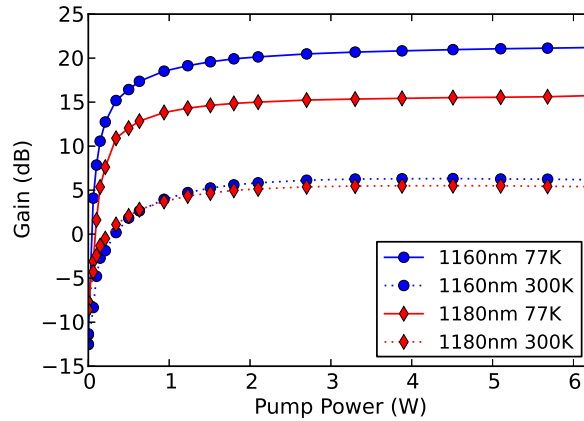


Figure 3.6: Gain with increasing optical pump power for ps pulsed input in Bi-doped fibre amplifiers using fibres BDF1

Fibre BDF2 presented slightly different results. In the cryogenically cooled case, even

at maximum pump power, the small signal gain did not saturate, reaching a maximum of 21.8 dB for the 1160 nm band and 16.1 dB for 1180 nm - slightly higher than for BDF1. The effect of temperature on performance is even more noticeable in BDF2 compared to BDF1 - the gain in BDF2 was found to saturate before the amplifier reached transparency. This is consistent with the higher core concentration of Bi in BDF2 as compared to BDF1, resulting in higher non-saturable loss.

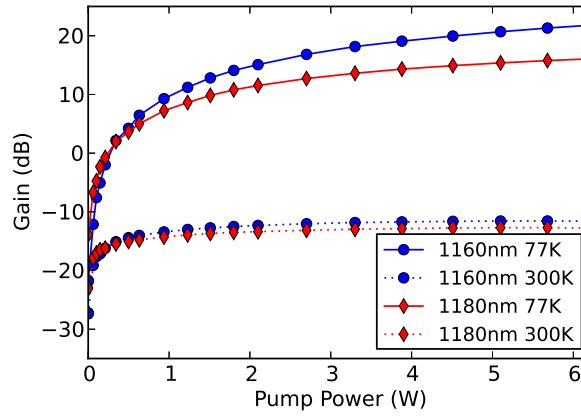


Figure 3.7: Gain with increasing optical pump power for ps pulsed input in Bi-doped fibre amplifiers using fibres BDF2

At the maximum amplification (i.e. maximum pump power with the fibre sample subject to cryogenic cooling), the output pulse autocorrelations for the 1160 nm and 1180 nm signal source were recorded, and are shown in Figs. 3.8a and 3.8b respectively. In both fibres, the pulses were subject to normal dispersion and were broadened to over 10 ps. Again, as the launched pulses were not transform-limited, this degree of pulse broadening was not unexpected. The deconvolved output pulse durations at 1160 nm were measured to be 10.7 ps for BDF1 and 13.3 ps for BDF2. For the 1180 nm band source the output durations were measured as 17.0 ps for BDF1 and 20.0 ps for BDF2. As the output pulse durations from BDF2 were $\sim 20\%$ greater than those from BDF1, it is possible to infer that there is a slightly greater degree of dispersion in the amplifier incorporating sample BDF2 as compared to BDF1, though due to experimental uncertainty the difference in dispersion cannot be quantified with a great degree of confidence.

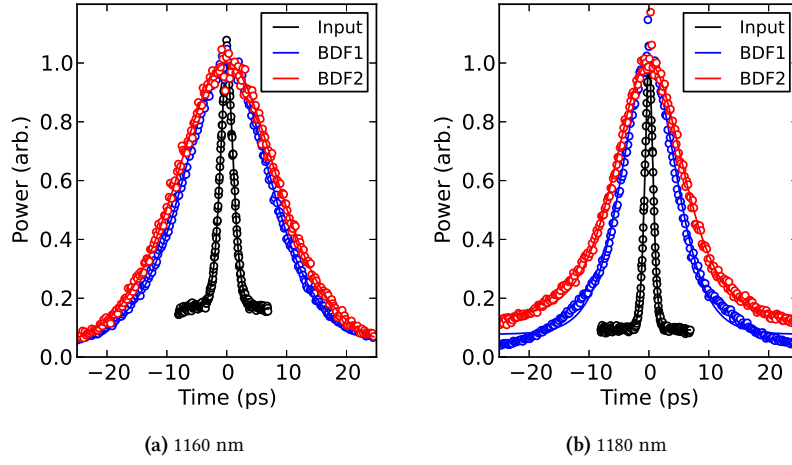


Figure 3.8: Autocorrelations of input (black) pulses and amplified output from Bismuth doped fibre amplifiers using BDF1 (blue) and BDF2 (red) at (a) 1160 nm and (b) 1180 nm

3.2.3 Amplification of gigabit signals in Bi-doped aluminosilicate optical fibre

As mentioned above, work in this section was undertaken to demonstrate the suitability of Bi-doped fibre for telecommunications applications, in the wavelength diversification of doped fibre amplifiers. For any technology to be applicable to modern telecommunications networks, signals with repetition rates of tens of gigahertz must be accommodated. To this end, a gigahertz repetition rate laser source operating at 1178 nm was constructed to act as a signal source for such a demonstration. This was based on a continuous wave (CW) cascaded Raman fibre laser which was subsequently amplitude modulated using a lithium niobate (LiNbO_3) Mach-Zehnder amplitude modulator (MZAM) (Photline MX-LN15-945). A schematic of the signal source is shown in Fig. 3.9.

A cascade of fibre Bragg gratings were used to generate two Raman lasing lines at 1120 nm and 1178 nm, pumped with an ytterbium fibre laser at 1064 nm. A 50% fibre Bragg grating at 1178 nm on the output side of the cavity acted as the output coupler. Residual pump light was extracted using a fused fibre coupler WDM, and a band pass filter was used to suppress any residual radiation at 1064 and 1120 nm. The CW output of this laser was then subject to amplitude modulation in a LiNbO_3 MZAM. The MZAM was driven by a

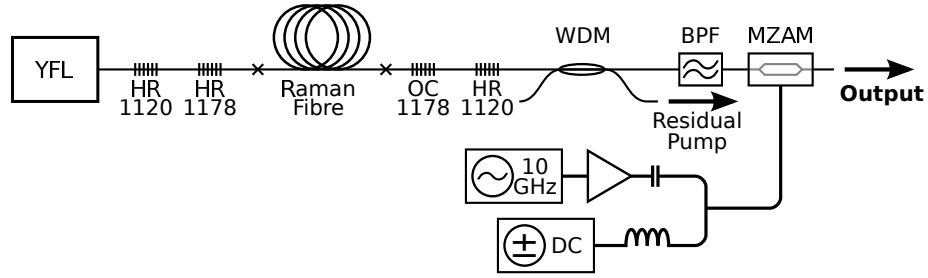


Figure 3.9: Schematic of gigahertz repetition rate signal source. Key to acronyms - YFL: Ytterbium fibre laser; HR: High reflector grating; OC: Output coupler (50%) grating; WDM: Wavelength division multiplexer; BPF: Band pass filter; MZAM: Mach-Zehnder amplitude modulator.

10 GHz sinusoid amplified to 27 dBm RF power ($4.5 \text{ V} \simeq V_{\pi}$), combined with a DC bias offset via a bias-tee. The DC bias was adjust to ensure the generation of a return-to-zero (RZ) signal, shown as the black curve in Fig. 3.10. The spectrum of the launched input is shown in Fig. 3.11. This signal was amplified in amplifiers incorporating sample BDF1 or BDF2 under cryogenic cooling, with gain recorded, as described above, for increasing pump power (i.e. numerically integrated within the input spectral width).

The resulting small signal gain saturation curves for both fibre samples are shown in Fig. 3.12. The gain curves agree with those measured for the amplification of picosecond pulses, insofar as the gain in BDF1 is seen to saturate at around $\sim 2 \text{ W}$, whilst the gain in BDF2 does not reach saturation at the maximum available pump power. The maximum gain measured for BDF1 was 14.4 dB, and the maximum gain recorded for BDF2 was 17.7 dB.

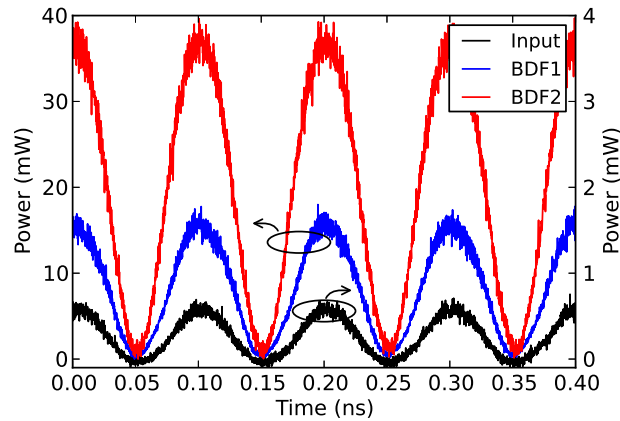


Figure 3.10: Pulse trains recorded for GHz pulse train recorded at the input (black) and output from Bi-doped fibre amplifiers with maximum pump power using fibre BDF1 (blue) and BDF2 (red)

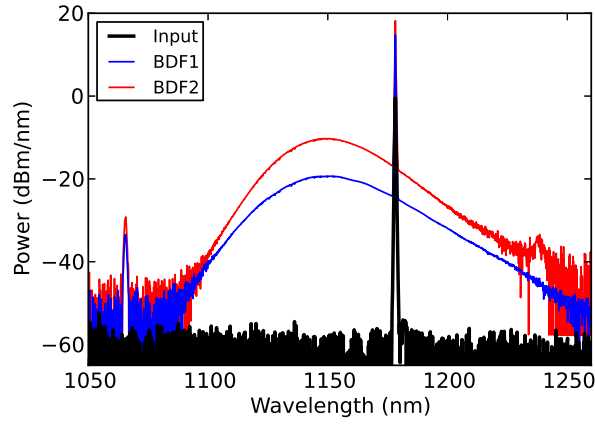


Figure 3.11: Optical spectra recorded for a gigahertz repetition rate signal recorded at the input (black curve) and output from Bi-doped fibre amplifiers with maximum pump power using BDF1 (blue) and BDF2 (red).

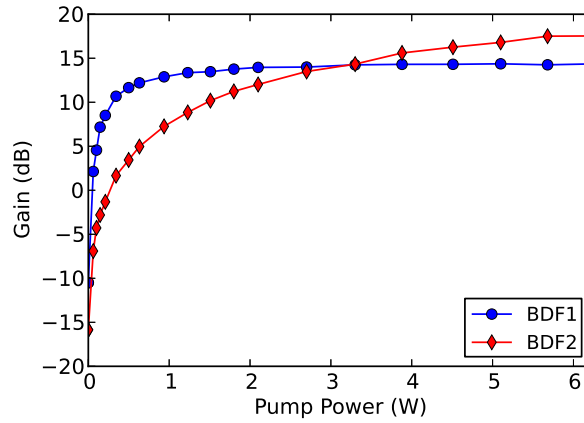


Figure 3.12: Gain with increasing optical pump power for a gigahertz repetition rate signal in Bi-doped alumino-silicate fibre samples BDF1 and BDF2

Also shown in Figs. 3.10 and 3.11 are the output pulse train and optical spectra. The optical spectra imply a signal peak to ASE peak isolation of 25 dB and 28 dB for BDF1 and BDF2 respectively. In the temporal domain, Fig. 3.10 shows that the gigahertz rate signal has been amplified without noticeable distortion.

3.3 Visible wavelength optical pulses based on a Bi-doped MOPFA and frequency doubling

As discussed above, the promise of wavelength versatility brought by Bi-doped silica fibre technology to doped fibre amplifiers has applications in telecommunications, but also in the generation of visible radiation at wavelengths of interest to the wider scientific community through second harmonic generation. As with the previous section here, Bi-doped aluminosilicate fibre is considered. Its broad band emission in the 1100-1200 nm region, when frequency doubled, corresponds to the 550-600 nm region, covering the yellow-orange-red part of the visible spectrum. Development of narrow line sources in this region has been of ongoing interest due to its application in so-called 'laser guide-star' adaptive optic systems [Fug91, Max97], which rely on the excitation of sodium atoms in the upper atmosphere with radiation at 589 nm. This has led to the development of narrow linewidth, continuous wave Bi-doped fibre laser sources operating at 1178 nm, and subsequently frequency doubled to 589 nm [Rul07].

There is also an increased interest in the development of pulsed sources in this region of the visible spectrum, owing to the increased use of green fluorescent protein (GFP) mutagens in biomedical imaging systems, with fluorescence in the orange-red part of the spectrum [Mat02]. The use of single-mode optical fibre based sources in frequency doubled systems for microscopy applications is desirable owing to the high beam quality of the output, which will result in a high quality frequency doubled mode. To this end, the development of a pulsed laser source operating at 589 nm was undertaken. This took the form of a master oscillator, power fibre amplifier (MOPFA) system, and was based solely on Bi-doped silica fibre as the gain medium, so as to demonstrate the potential of Bi-doped fibre in advanced laser configurations, even as the Bi-doped silica technology continues to mature.

MOPFA schemes are a proven route to high-power optical pulses, where the output pulse power of an oscillator cannot be indefinitely scaled, but instead is amplified in an external cavity amplifier or amplifier chain. In the case of this system, the output pulse power of the mode-locked laser (described in Section 3.3.2) was limited as it operated in the average soliton regime. The pulses were amplified in a two stage amplifier scheme (as detailed in

Section 3.3.3), and then frequency doubled in a periodically poled crystal.

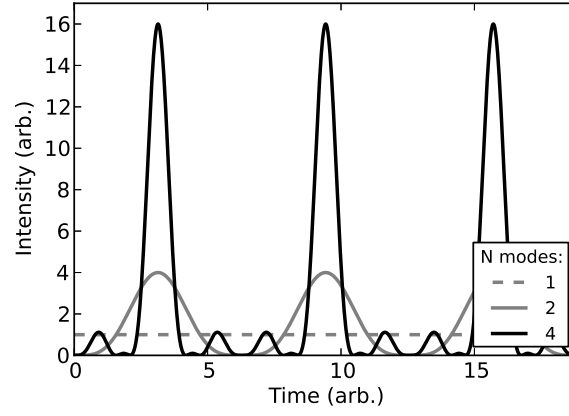
3.3.1 Mode-locking - a brief introduction

Figure 3.13 shows numerical simulations illustrating the principle of pulse train formation by the process of mode-locking. Figure 3.13a shows the field intensity with time of a single longitudinal mode, and also with 2 and 4 superposed longitudinal modes, all with no phase offset with respect to the fundamental mode. With an increasing number of modes, pulses of shorter duration are generated, equally spaced by 2π , which corresponds to the fundamental harmonic. This is further illustrated in Fig. 3.13b which shows the superposition of 100 modes. Also shown is the same number of modes but with a random phase offset between each mode. In this case, each of the longitudinal modes are essentially independent, leading to a quasi-continuous-wave signal with significant intensity noise.

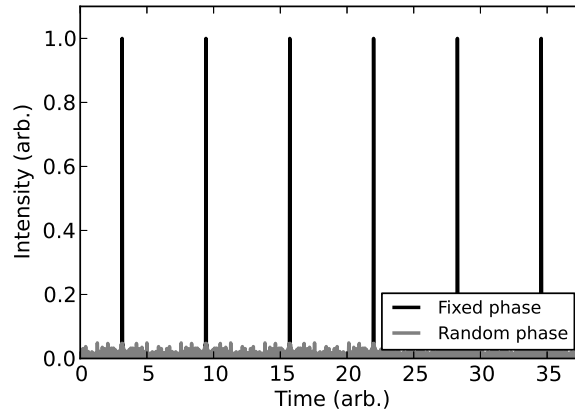
Experimentally the required phase-locking of laser cavity modes can be achieved by modulation of either the net gain or phase within the laser cavity with a frequency corresponding to a harmonic of the fundamental longitudinal mode of the laser. Broadly speaking there are two schemes of mode-locking: active and passive.

Active mode-locking involves introducing a periodic modulation to the net gain or phase of the cavity. This can be achieved by introducing periodicity to the cavity gain, for example by driving a semiconductor diode laser with a sinusoidal voltage drive. Alternatively, an optical amplitude modulator can be included in the cavity, which will similarly modulate the net cavity gain, or in the case of a phase modulator, the net cavity phase delay.

Passive mode-locking presents some significant practical advantages over active mode-locking, as the methods rely on the introduction of a cavity element which will have an intensity dependent loss, modifying the net gain, promoting the formation of intensity localisations, and by extension, the phase-locking of the cavity longitudinal modes. These cavity elements can take the form of pseudo saturable absorbers, whereby intrinsic nonlinearities within the laser cavity are combined with linear optical components to introduce intensity-dependent loss. Examples of this include Kerr-lens mode-locking, one of the most popular mode-locking techniques in bulk laser systems, where Kerr-induced self-focusing



(a) 4 modes



(b) 100 modes

Figure 3.13: Numerical simulations illustrating the formation of a pulse train through mode-locking. (a) shows the effects of adding increasing longitudinal modes to a linear cavity up to 4 modes. (b) shows 100 modes with fixed phase relationship (black line) and the same number of modes with a random phase offset between each mode (grey line).

of the laser beam within the gain crystal, combined with an aperture creates self-amplitude modulation. Another pseudo saturable absorber method is that of nonlinear polarisation evolution mode-locking, widely used in fibre laser systems, whereby intensity dependent nonlinear polarisation rotation is combined with a polarising element within the cavity to similarly create a self-modulating effect.

Real saturable absorbers, by contrast, are physical cavity elements introduced into a laser which exhibit intensity dependent absorption, one such example of which is the semiconductor saturable absorber mirror (SESAM). These are typically made up of a semiconductor Bragg mirror and a quantum well absorber layer. The saturable absorbance of the quantum well layer is based on the excitation of electrons from the valence to conduction band of the absorber by incident radiation. At high optical intensities, electrons will accumulate in the conduction band which will deplete the available states to which electrons can be excited and block the absorption of incident photons, increasing the overall reflectivity of the SESAM device. In this work, a mode locked laser was developed employing Yb-pumped Bi-doped optical fibre as the gain medium, with mode-locking effected by use of a SESAM.

3.3.2 Passively mode-locked Bi-doped fibre laser

A schematic of the mode-locked Bi-doped fibre laser upon which the MOPFA scheme is based is shown in Fig. 3.14.

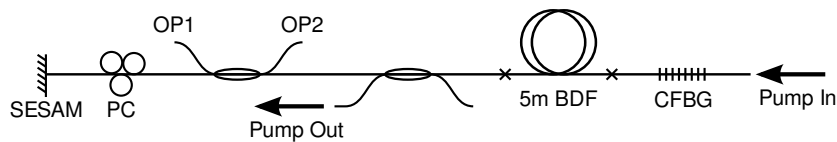


Figure 3.14: Schematic of mode-locked Bi-doped fibre laser. Key to acronyms - CFBG: Chirped fibre Bragg grating; BDF: Bismuth doped fibre; OP1, OP2: Output Port 1, 2; PC: Polarisation controller; SESAM: Semiconductor saturable absorber mirror.

The laser was based on a linear cavity design. Mode-locking was achieved through use of a SESAM with modulation depth of 10%, fabricated at Tampere University of Technology [Kiv10]. the laser incorporated 5 m of active Bi-doped aluminosilicate fibre as the gain medium, which was pumped through a highly reflective chirped fibre Bragg grating

(CFBG) using an Yb-doped fibre laser (YFL). The fibre was cryogenically cooled through submersion in liquid nitrogen. Excess pump power was removed from the cavity by use of a 1064/1180 nm fused fibre coupler WDM. A fused fibre coupler was also used as an output coupler, meaning that the laser had two output ports, labelled OP1 and OP2. As such, the oscillator output could be monitored at OP2, while the output from OP1 was amplified. The CFBG meant that the net cavity dispersion was anomalous, resulting in intra-cavity solitonic pulse shaping. A fibre-strainer type polarisation controller (PC) was also included in the cavity to control intra-cavity polarisation evolution.

Mode-locking was achieved with a pump power of 1.6 W. This gave a time-averaged output power from OP1 of -4 dBm. The laser operated at a repetition rate of 9.3 MHz, corresponding to the fundamental frequency of the total cavity length. An autocorrelation of the laser output is shown in Fig. 3.15. A sech^2 fit implies a deconvolved FWHM duration of 3.9 ps. The autocorrelation displays minimal pedestal with a pulse shape well fitted by a sech^2 function, as expected for a mode-locked laser operating in the average soliton regime. The measured optical spectrum of the laser is shown in Fig. 3.16. This displays side-bands characteristic of slight deviation from average soliton operation, the asymmetry of which implies the presence of third order dispersion in the CFBG [Hau93].

The radio frequency (RF) power spectrum of the laser was measured using a photodiode and electrical spectrum analyser and are shown in Fig. 3.17. This shows a 60 dB isolation between the fundamental harmonic and the noise pedestal, caused by low frequency power fluctuations in the laser output. The RF spectrum of the fundamental frequency component can be used to find the average pulse to pulse energy fluctuations, $\Delta E/E$, as given by [Lin86]:

$$\Delta E/E = \sqrt{\frac{\Delta P \Delta f}{\Delta f_{\text{res}}}} \quad (3.1)$$

where ΔP is the isolation of the fundamental RF component to the noise component, Δf is the width of the noise component (FWHM) and Δf_{res} is the resolution of the measurement, in this case 100 Hz. From Eq. 3.1, $\Delta E/E$ is calculated to be 8.8×10^{-3} .

3.3 Visible wavelength optical pulses based on a Bi-doped MOPFA and frequency doubling

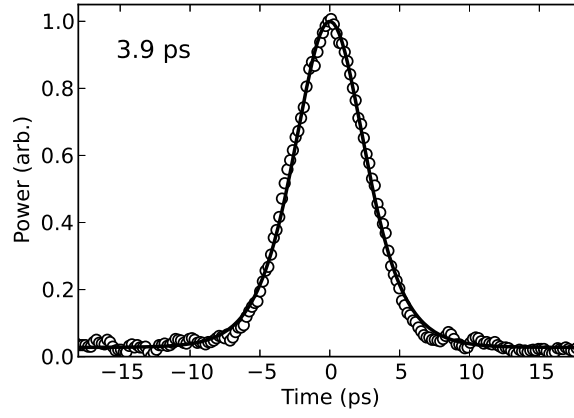


Figure 3.15: Autocorrelation of mode-locked bismuth laser output

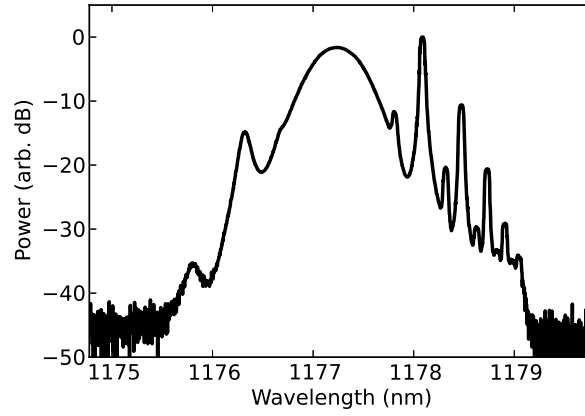


Figure 3.16: Optical spectrum of mode-locked bismuth laser output

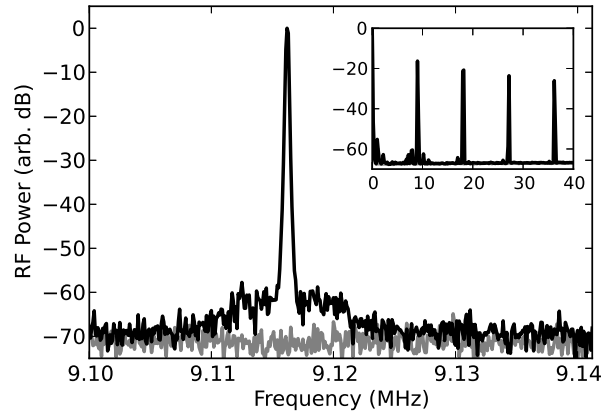


Figure 3.17: RF Power spectrum of mode-locked bismuth laser output. Gray curves indicate background level. Inset shows broad band scan.

3.3.3 Two stage MOPFA scheme based on Bi-doped fibre

The Bi-doped MLL was incorporated into a MOPFA system. The overall schematic of the MOPFA is shown in Fig. 3.18. The output of the MLL is amplified in a two stage amplifier scheme, incorporating two Bi-doped fibre amplifiers (BiDFA). Each of these amplifiers were identical in design to those developed in Section 3.2.1 (see Fig. 3.2). The first BiDFA (hereafter referred to as the pre-amplifier stage) used Bi-doped fibre sample BDF1, while the second BiDFA (hereafter referred to as the power-amplifier stage) used sample BDF2. Both, as in Section 3.2.1, used 30 m lengths of active fibre and were subject to cryogenic cooling through submersion in liquid nitrogen. Each amplifier was pumped with an Yb fibre laser operating at 1064 nm. The pre-amplifier was supplied with pump power of 2 W, and the power-amplifier with 5 W.

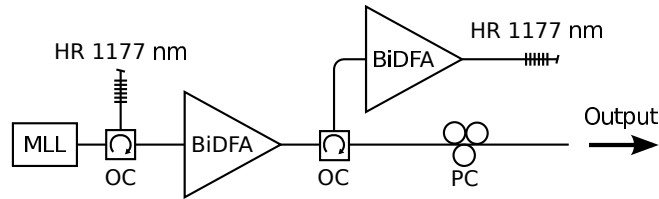


Figure 3.18: Schematic of Bi-doped fibre MOPFA. Key to acronyms - PC: Polarisation controller; BiDFA: Bismuth-doped fibre amplifier; HR 1177 nm: High reflecting FBG centred at 1177 nm; OC: Optical circulator; MLL: Mode-locked laser.

As the frequency doubling was to be achieved in a periodically poled crystal, it was important that after amplification spectral fidelity be preserved, as a large degree of spectral broadening would have a potentially significant deleterious effect on the phase matching efficiency in the poled crystal. This consideration is reflected in the design of the MOPFA. Due to the short duration of the pulses generated by the MLL, initially an unacceptably large degree of self-phase modulation (SPM) was observed in the amplifier chain. As the pulses generated by the MLL were near transform limited (owing to the solitonic nature of the MLL operation), a spectral filter could be applied to select a small part of the bandwidth and increase the pulse duration. This resulted in a lower peak power and so lower SPM in the amplifiers. The spectral filter was experimentally realised by the inclusion of an optical circulator (OC) and fibre Bragg grating (FBG), which acted as a band-pass filter. The optical

spectrum directly after the output port of the circulator is shown as the grey curve in Fig. 3.19a.

To maximise the amplification in the amplifier chain, the power-amplifier stage was double passed by use of an OC and a highly reflective FBG at the pulse centre wavelength. This had the secondary beneficial effect of removing out-of band optical radiation arising from SPM and also ASE generated in the pre-amplifier and the first pass of the power-amplifier.

With the maximum pump power supplied to the power-amplifier, the signal output power from the MOPFA was 150 mW. The output of the MOPFA system is shown as the black curve in Fig. 3.19a. The optical spectrum shows that while the pulse has been subject to some spectral broadening, the two FBGs have effectively confined the spectral power to a ~ 1 nm bandwidth. On a wider span measurement of the optical spectrum, as shown in Fig. 3.19b, the suppression of the ASE from the amplifier chain is evident, with 45 dB isolation of the peak ASE from the signal.

The autocorrelation of the output, shown in Fig. 3.20, reveals the effect of the two filtering elements in the MOPFA. The output pulse is evidently significantly broadened compared to that directly from the MLL, with a FWHM duration of 28 ps. The pulse also displays a winged structure. This is attributed to a combination of the spectral broadening in the amplifier stages resulting in the pulse acquiring a chirp, combined with the spectral filtering effect of the FBGs giving rise to temporal structure apparent as wings in the autocorrelation.

3.3.4 Frequency doubling in a periodically poled crystal

The output of the MOPFA was frequency doubled in a 20 mm long periodically poled lithium niobate crystal (PPLN). The output was collimated using a 3.3 mm focal length lens, and then focused into the crystal using an 88 mm focal length lens, giving a focal beam waist of $44 \mu\text{m}$ and confocal length of 10 mm. It was found that a confocal length shorter than the physical length of the crystal resulted in greater conversion efficiency. This is owing to the fact that the output spectrum exceeded the nominal phase matching bandwidth of the crystal at its full length, and so over-focusing, which results in an effective broadening of the phase matching bandwidth of the crystal (though with the detrimental

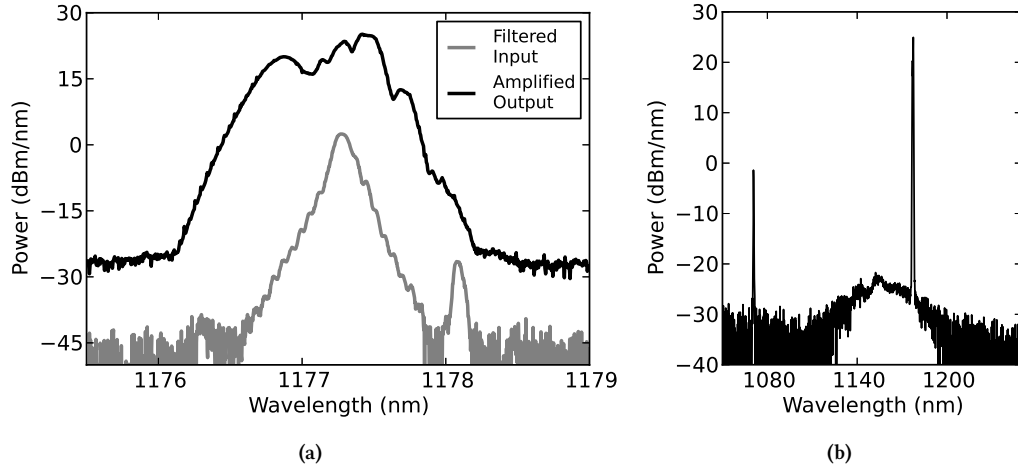


Figure 3.19: Optical spectrum of input and output to the two stage Bi-doped amplifier scheme. (a) Spectrum of filtered mode-locked laser output input to amplifier chain (grey) and spectrum of the amplified output (black). (b) Spectrum of the amplifier output on broader wavelength span, showing residual pump radiation at 1064 nm and a slight ASE pedestal.

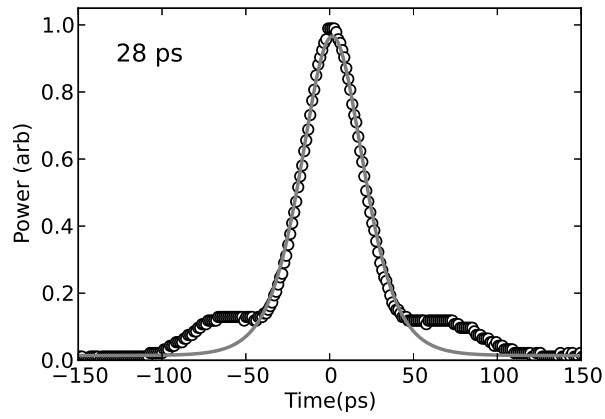


Figure 3.20: Autocorrelation of Bi-doped MOPFA output

3.3 Visible wavelength optical pulses based on a Bi-doped MOPFA and frequency doubling

effect of increasing the average mode-field diameter, hence decreasing the average intensity, along the crystal length). The collimating and focusing optics were anti-reflection (AR) coated at the fundamental wavelength, as was the input face of the PPLN crystal. The output face of the PPLN was uncoated. The PPLN had a poling period of $9.27 \mu\text{m}$, and phase matching was achieved through temperature tuning by mounting the crystal in a temperature controlled oven held to a phase-matched temperature of 106.6°C . A fibre strainer PC was used to adjust the output polarisation of the MOPFA to ensure correct polarisation alignment in the PPLN crystal. A dichroic beamsplitter after the PPLN was used to remove the residual fundamental (infra-red) radiation.

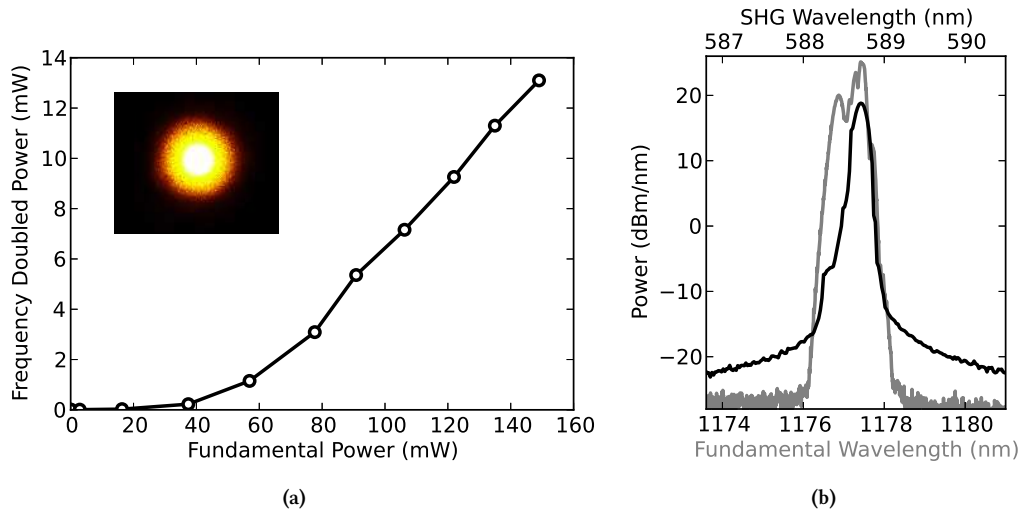


Figure 3.21: (a) Conversion efficiency and (b) spectrum of frequency doubled output from Bi-doped MOPFA system. Inset to (a) shows the far field beam pattern.

The MOPFA output power was tuned up to its maximum of 150 mW by varying the pump power supplied to the power-amplifier stage and the frequency doubled output power recorded, as shown in Fig. 3.21a. A maximum visible output power of 13.7 mW was recorded, corresponding to a conversion efficiency of 9%. The relationship is initially quadratic with the fundamental power, though quickly becomes linear. This is due to the spectral broadening of the MOPFA output reducing the phase-matching efficiency. Figure 3.21b shows the optical spectrum of the frequency doubled output overlaid on the corre-

sponding spectrum of the MOPFA output. This illustrates that only a limited fraction of the total optical bandwidth of the MOPFA output was phase matched and hence frequency doubled. The conversion efficiency with respect to the fundamental power within the phase matching bandwidth of the crystal was 20%. Inset to Fig. 3.21a is an image showing the far-field beam profile, indicating a high quality circular mode, as is expected from the frequency doubling of a fundamental source based on single mode optical fibre.

3.4 Outlook

This chapter has demonstrated the application of Bi-doped aluminosilicate fibre in the development of novel amplifier and laser systems. As discussed in Section 3.1, Bi-doped silica fibre holds promise in the field of telecommunications and, combined with second harmonic generation in bulk nonlinear crystals, as a front-end for visible laser systems operating in the orange-red region.

First, in Section 3.2, Bi-doped fibre was integrated into an ytterbium-pumped amplifier scheme, and the amplification of telecommunication-like signals with gain in excess of 15 dB was demonstrated in two different Bi-doped fibre samples. Section 3.3 demonstrated the application of Bi-doped fibre amplifier technology in advanced laser configurations. A Bi-doped mode-locked laser, combined with a two stage Bi-doped amplifier scheme, provided 28 ps pulses at a 9.3 MHz repetition rate with a time averaged power of 150 mW. These pulses were frequency doubled in a PPLN crystal, generating 13.7 mW of power at 589 nm.

As discussed in Section 3.1, there are still some significant questions over the specific gain mechanisms in Bi-doped silica, along with problems in manufacture of homogeneously distributed Bi doped silica. Without these being addressed, it is difficult to envisage a solution to the problems of temperature dependent performance and high non-saturable losses present in current generation Bi-doped silica fibres.

Despite all of this, the laser/amplifier systems demonstrated in this chapter go some way to demonstrate the potential of Bi-doped silica as a laser gain medium. While bismuth

activated silica fibre is still at an early stage of development, and work on the underlying physical mechanisms behind lasing action is needed, the technology can still be applied to novel and practicable advanced laser systems.

Chapter 4

Visible laser sources based on Raman amplification and frequency doubling

This chapter details the development of a novel laser system operating at 560 nm, designed for biophotonic fluorescence microscopy applications. The system is based upon a mixed technology master oscillator power amplifier (MOPFA). The oscillator comprised a gain-switched pulsed quantum dot laser whilst amplification was provided by a two stage Raman fibre amplifier scheme. The output of the MOPFA was frequency doubled in a periodically poled crystal. The MOPFA system exploited nonlinear effects in the amplifier stages, coupled with spectral filtering, to effect pulse re-shaping to achieve a final output pulse of 130 ps duration and 11 W peak power.

4.1 Motivation - biophotonics and super resolution microscopy

Fluorescence microscopy [Lic05] has seen increasing interest in recent decades and is now an invaluable tool in understanding structural and functional aspects of biochemistry, allowing the visualisation of structures in living organisms in real time. Confocal laser scan-

ning fluorescent microscopy (CLSM) techniques make use of fluorescent proteins which can be used to label specific molecules within an organism. Figure 4.1 illustrates the concept. A focussed laser beam with a wavelength resonant with the excitation energy of the fluorophore can be used to excite the fluorophore, resulting in spontaneous emission of Stokes-shifted radiation. The intensity of the emitted fluorescent radiation is measured, after removing scattered excitation radiation by use of a dichroic beam splitter. Optical sectioning is improved by use of a pinhole aperture. This aperture is positioned conjugate to the focus of the excitation beam and restricts the detected fluorescence signal to the focal plane of the excitation beam. As such, the aperture removes background signal arising from the out-field excitation of the sample

The focal spot of the excitation beam can then be raster scanned throughout the volume of the specimen providing a background-free volumetric image of the fluorophore distribution.

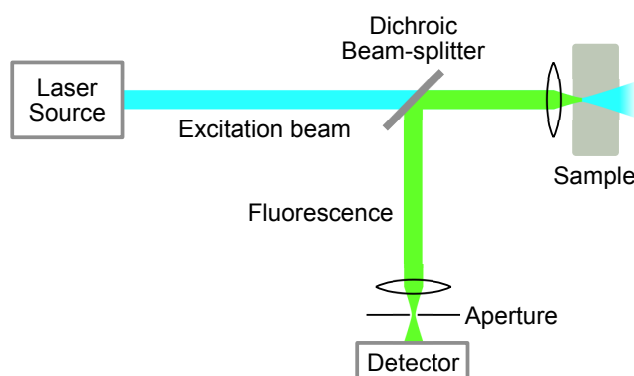


Figure 4.1: Set-up of basic confocal scanning laser microscope

The fundamental resolution of the scheme described above would be limited by the diffraction limit. As the excitation beam is focused not to an infinitesimal point, but a finite spot, points in the object will be correspondingly blurred out in the image. The three dimensional intensity distribution in the image from a point-like object is called the point spread function (PSF), and details smaller than this will be irresolvable. Practically this PSF is on the order of ~ 200 nm in the lateral plane and ~ 500 nm axially. Whilst this resolution is adequate for imaging of biological systems at the tissue level, features of interest within a

cell can be very much smaller than this, requiring techniques which can achieve resolutions beyond the diffraction limit, or ‘super-resolution’ techniques.

4.1.1 STED Microscopy

One method to achieve imaging beyond the diffraction limit is that of stimulated emission depletion (STED) microscopy, a scanning microscopy technique first proposed in 1994 [Hel94], by which an excitation spot is scanned across a specimen in tandem with an overlapping ring-shaped de-excitation beam which acts to reduce the fluorescent area.

The technique relies on the use of two overlapping laser sources, the first of which excites the sample, and the second of which selectively depletes a region of excited fluorophore by use of an overlapping structured beam, as depicted in Figure 4.2. The depletion beam is structured as a ring such that off-centre fluorescence is suppressed and the PSF is effectively sharpened. This suppression is achieved through stimulated emission (See Fig. 4.3) - by illuminating off-centre fluorophores with radiation of a wavelength falling within their emission spectrum, the emission of a resonant photon is stimulated and the fluorophore can be brought back to its ground state before spontaneous emission occurs. This effectively depletes the off-centre excited state fluorophores, such that spontaneous emission only occurs from centre of the excited region. This requires a beam profile which is of zero intensity at the centre, and non-zero at its periphery. This is generally achieved by applying a phase mask to a Gaussian laser beam.

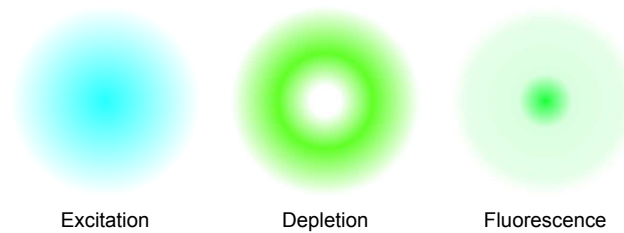


Figure 4.2: PSFs of excitation (left) and depletion (centre) beam focal spots, resulting in fluorescence from a small central region (right)

As the rate of stimulated emission is dependent on the intensity of the incident radiation, an increase in power of the STED beam will increase the area which is subject to sufficient

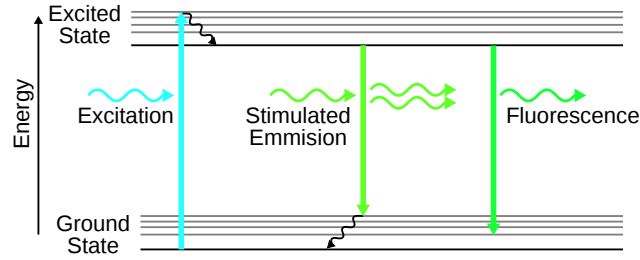


Figure 4.3: Jablonski diagram representing stimulated emission and fluorescence in a two-level fluorophore

illumination that stimulated emission is saturated and fluorescence is effectively fully depleted. The fluorescence from the central region will not be affected as this is where the intensity of the depletion beam is zero. An increase in power in the depletion beam, then, will result in a reduction in the effective PSF (with the trade-off being a net reduction in the fluorescence signal). The size of the effective PSF, Δ_{eff} , will be given by [Hua09]

$$\Delta_{\text{eff}} \approx \frac{\Delta_{\text{psf}}}{\sqrt{1 + I_{\text{STED}}/I_s}} \quad (4.1)$$

where Δ_{PSF} is the diffraction limited PSF, I_{STED} is the intensity of the depletion beam and I_s is the saturation intensity - that is, the intensity at which the rates of stimulated and spontaneous emission are equal.

By scanning this reduced PSF across the specimen, a super-resolution image can be built up. The technique has seen widespread application since its first demonstration [Kla99], providing lateral resolutions less than ~ 20 nm using biological fluorophores [Don06], and as low as 8 nm when examining crystal colour centres in diamond [Rit09].

4.1.2 Depletion source requirements for STED microscopy

The work in this chapter was motivated by the development of a laser source suitable for use in a STED microscopy system currently in development. One of the most significant specifications for a laser source in a fluorescent microscopy set-up is that its wavelength be appropriate for the fluorophore to be used. In this case yellow fluorescent protein (YFP) will be used, the excitation/emission spectrum of which is shown in Fig. 4.4. A wavelength of

560 nm was selected for the STED beam, as it is spectrally located far enough away from the excitation peak so as to not result in re-excitation of the fluorophore, and is also long enough a wavelength that a large portion of the auto-fluorescent emission spectrum can be recovered. These wavelengths are commonly accessed by means of optical parametric oscillators, which have been used in STED microscopy schemes exploiting GFP [Ran11] and YFP [Hei08].

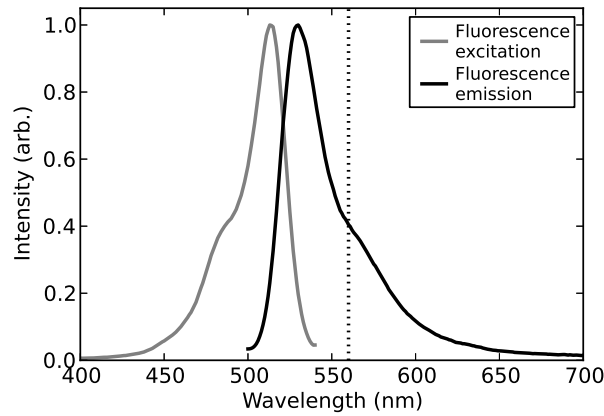


Figure 4.4: Excitation and absorption spectra of YFP/pH 7.4 (Life Sciences). Dotted line shows STED wavelength of 560 nm

Another requirement for a STED system is a precise synchronisation of the excitation and depletion pulses. In this case the excitation pulse will be provided by a supercontinuum source. An 80 MHz Ti:Sapphire laser will pump a highly nonlinear photonic crystal fibre to provide a supercontinuum spanning from 500 nm to above 1 μm . The excitation light will be selected by use of a band pass filter centred on the absorption peak of YFP at 510 nm. The depletion pulse must be exactly synchronised to the excitation pulse. One option would be to spectrally select the depletion radiation from the supercontinuum source, as this would be synchronous with the excitation pulse. This has been successfully demonstrated using low repetition rate supercontinuum sources (1 MHz) [Wil08], achieving lateral resolutions as low as 19 ± 3 nm [Wil09]. Supercontinuum sources provide a further advantage in that multiple wavelengths can be selected from the same source enabling the use of multiple co-located fluorophores which can be discriminated in separate colour channels

[Büc11]. Due to the broadband nature of supercontinuum sources, however, achieving sufficient spectral power density at a given wavelength for higher repetition rates necessarily requires increasing the power across the spectrum, which can make scaling of supercontinuum excitation/depletion sources challenging, and increase the overall complexity of the supercontinuum pump sources.

For fluorophores used in STED, the non-radiative transition which brings the fluorophore to the base level of the excited state generally takes place on the order of a few picoseconds, with the upper state lifetime being on the order of a nanosecond. To ensure that spontaneous fluorescence is sufficiently suppressed, the STED pulse must be of a duration much shorter than that of the upper state lifetime (the characteristic time for spontaneous emission). The lower limit on the STED pulse duration will be dictated by the non-radiative transition that depopulates the lower level of the stimulated emission transition. Theoretical considerations of these two factors for typical fluorophores suggest an idealised STED pulse duration on the order of 20 ps, but practically it is generally found that the optimum pulse duration for a STED source is 100-150 ps [Leu10]. There are several reasons cited for this including the minimisation of photo-bleaching effects [Dyb03], and also that a slightly longer pulse will allow time for fluorophores to rotate, reducing the effect of polarisation [Wes05].

According to Eq. 4.1, the effective PSF achieved in a STED microscopy system scales with $(1 + I_{\text{STED}}/I_s)^{1/2}$, where I_s is the saturation intensity of the fluorophore. This implies that for a factor of ~ 10 improvement to the PSF compared to a diffraction limited system, an intensity ~ 100 times greater than the saturation intensity is required. For stimulated emission in GFP mutagens such as YFP, I_s is typically on the order of $\sim 10^7 \text{ W/cm}^2$ [Hua09], which means that the STED beam should be in excess of 10^9 W/cm^2 . Assuming an effective mode area of 10^{-8} cm^2 for the STED beam at the focus, this corresponds to a peak power of 10 W. For 100 ps pulses at 80 MHz repetition rate, this corresponds to 80 mW of time-averaged power. This, then, reveals why supercontinuum sources may not be well suited as sources for STED, owing to the fact that the spectral power density in the visible part of the spectrum for a supercontinuum source operating at 10s of MHz is rarely in excess

of a few mW/nm.

4.2 Picosecond pulse generation from semiconductor diodes

This chapter details the development of a 560 nm source based upon the frequency doubling of a master oscillator power fibre amplifier (MOPFA) system operating around 1120 nm. This wavelength coincides with the first Raman Stokes shift from the typical Yb fibre laser operating wavelength of 1064 nm. This enables the realisation of a fibre integrated scheme for the amplifier stages of the MOPFA system. Whilst pulsed Raman fibre laser oscillators operating in this wavelength band have been demonstrated with mode-locking achieved using carbon nanotubes [Cas13] and in other wavelength regions using SESAMs [Cha10] or graphene [Cas12], the seed oscillator for this system was based upon a quantum dot semiconductor laser diode.

Quantum dot (QD) semiconductor devices are based on nanoscale three-dimensional structures which confine carriers to a small volume. As the density of states is highly dependent on the carrier confinement which in turn is determined by the quantum dot dimensions and material, this enables a high degree of engineerability of the energy levels, and hence operating wavelength, for the device. QD lasers also generally offer lower temperature sensitivity and lower threshold current compared to bulk semiconductor devices [Ara82].

Two pulse generation techniques were investigated in quantum dot semiconductor diode lasers: active mode-locking and gain switching.

4.2.1 Active mode-locking of an external cavity quantum dot diode laser

Active mode-locking is a well established route to the generation of short pulses, with a history nearly as long as that of the laser itself [Har64]. The technique has been demonstrated in a variety of laser devices, including semiconductor laser diodes [Ho79]. The active mode-locking principle is depicted in Fig. 4.5. As discussed in Section 3.3.1, mode-locking requires

that a fixed phase relationship between longitudinal laser modes be effected. Active mode-locking of a laser cavity relies on periodic modulation of the net cavity gain at a repetition rate matched to the cavity round trip time, or an integer multiple thereof, resulting in a higher average gain for the phase-locked state, promoting the formation of a pulse train. The centre of the pulse effectively sees greater gain than the wings, sharpening the peak of the pulse, promoting the generation of short pulses.

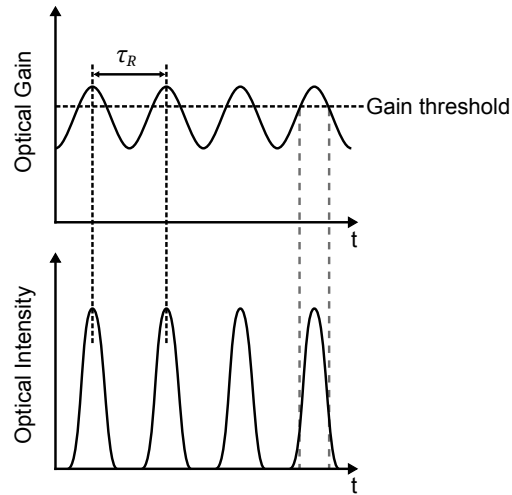


Figure 4.5: Cartoon depiction of active mode-locking. Gain is modulated about threshold at the cavity repetition rate, τ_R . The centre of each pulse will receive more gain than the pulse wings (as illustrated by the grey dashed lines) promoting the formation of short pulses.

In general, active mode-locking requires the net gain of the laser cavity be modulated, whether this be through the introduction of a modulated lossy element (such as an amplitude modulator), or by modulating the pump. For electrically pumped semiconductor lasers, this can be achieved by supplying the device with modulated injection current. A sinusoidally modulated signal can be combined with a DC bias offset such that the drive current oscillates about the threshold current for the laser diode. Matching the modulation frequency to the cavity round trip time (or a harmonic thereof) can give rise to mode-locking. Due to the small size of the diode itself, semiconductor lasers tend to have a compact geometry, where the total cavity length is on the order of, at most, a few centimetres, meaning that the repetition rate of such devices is typically on the order of many hundreds of megahertz, or gigahertz.

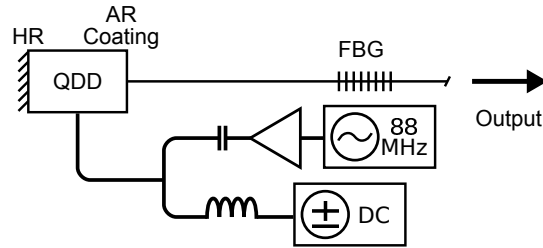


Figure 4.6: Set-up diagram for actively mode-locked external cavity quantum dot laser diode. Key to acronyms - QDD: quantum dot laser diode; HR: high reflector; FBG: fibre Bragg grating.

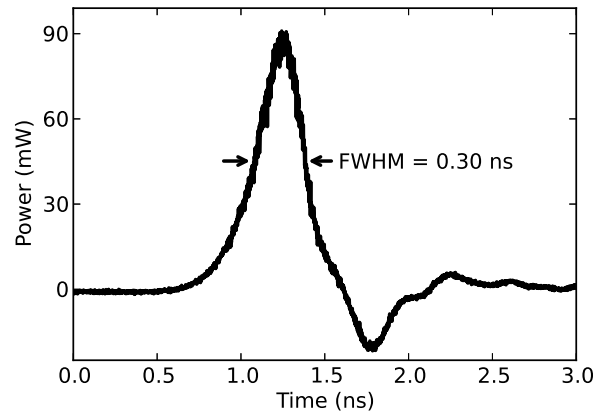


Figure 4.7: Optical pulse generated through the active mode-locking of an external cavity quantum dot laser diode, measured with photodiode and digital sampling oscilloscope

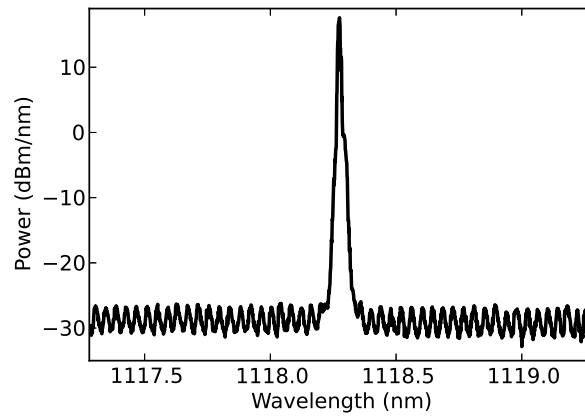


Figure 4.8: Optical spectrum of actively mode-locked of an external cavity quantum dot laser diode

In this case, where a repetition rate around 80 MHz is desired, an extended cavity scheme must be employed. Figure 4.6 shows the experimental set-up, where a semiconductor QD laser diode (Innolume LD-1118-FBG-100) forms part of an external cavity fibre integrated laser. The back facet of the diode is coated with a highly reflective dielectric, the output facet is anti-reflection coated, with the output coupled into a polarisation maintaining (PM) optical fibre. This fibre contains a partially reflective fibre Bragg grating (FBG) which acts as the output coupler for the cavity. The diode was driven with a modulated pump current, with minimum pulse duration found for a modulation frequency of 88.4 MHz (with a DC offset voltage combined with the sinusoidal signal using a bias-tee). This corresponds to a cavity length of 1.1 m, which agrees with the total fibre length between the diode and FBG.

The output optical pulse was recorded using a high speed photodiode (15 ps rise time) on a digital sampling oscilloscope and is shown in Fig. 4.7. Note that electrical ringing of the photodetector causes the presence of negative power data. This ringing, however, does not affect the measurement of the leading edge and central part of the pulse, and as such the FWHM duration of the resultant pulses can be measured as 300 ps. Figure 4.8 shows the optical spectrum of the source, which is centred around 1118.3 nm. Whilst the output pulse quality is high, and the narrow optical spectrum well suited to frequency conversion in a periodically poled nonlinear crystal, the actively mode-locked external cavity diode suffers from the fact that the repetition rate is fundamentally related to the cavity length, potentially problematic as the STED depletion pulses will, in this case, need to be synchronised to an external laser source of fixed repetition rate. In this case, mode-locking was achieved for drive frequencies over a range of ~ 1 MHz about that which minimised the pulse duration, corresponding to around 1.5 cm of cavity length - close to the length of the FBG which formed the output coupler. Potentially then, by adjusting the fibre length to give a cavity with a fundamental frequency close to repetition rate required, the laser could be synchronised to an external clock. However, the pulse duration in this case is significantly longer than the nominal optimum duration of 100-150 ps. For this reason, combined with the issue of closely matching the cavity fundamental frequency to the desired repetition rate, an alternative route to the generation of picosecond pulses from a QD laser diode was

taken.

4.2.2 Gain switching of a quantum dot diode laser

The generation of short duration pulses from semiconductor laser diodes can also be achieved through gain switching, whereby a modulation of the electrical current supplied to the diode is used to generate optical pulses through relaxation oscillations. This method has an obvious advantage over mode-locking in that the repetition rate of the modulation need not necessarily match the cavity length of the laser, but instead can be synchronised to an external clock - ideal for a STED source where the STED pulse must be synchronised with the excitation pulse. Using this method it is possible to generate pulses which are much shorter than the driving electrical pulse.

Figure 4.9 shows how short optical pulse generation can be achieved through relaxation oscillation gain switching. The diode is biased such that it is held below gain threshold (and hence laser action). A pulse of current brings the diode above threshold. With the laser cavity now above threshold, light builds up in the cavity, which in turn saturates the available gain, pulling the net gain below threshold and quenching laser action - the result of which is the generation of a short 'transient' pulse. Subsequent, longer, pulses are generated by similar oscillation of the gain about threshold.

In this case, a commercial, fibre integrated distributed feedback (DFB) quantum dot laser diode (QDLaser QLD1161) was gain switched. A DFB laser diode differs from a normal, Fabry-Perot type laser, as the diode includes an axial periodicity in the structure which provides feedback at a single wavelength along the length of the active region. Not only does this restrict the laser to operate at a small wavelength range, it also enables the operating wavelength to be tuned by use of temperature control. In this case, temperature tuning was used to ensure that the laser operated at a wavelength of 1120 nm.

A pulsed current source was used to drive the diode, in conjunction with a DC bias voltage offset, combined using a bias-tee. This provided electrical pulses of 680 ps duration, an oscilloscope trace of which is shown in Fig. 4.10. In this prototype system, the repetition rate was selected as 50 MHz. The pulse driver can, however, be synchronised with an

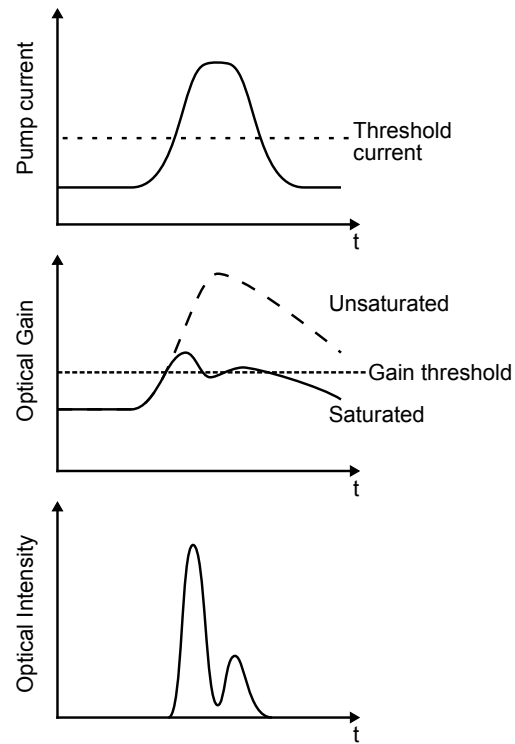


Figure 4.9: Cartoon representation of relaxation gain switching in semiconductor diodes. An electrical pulse (top) induces optical gain (centre). Saturation of the gain (black line) results in net gain for a duration very much shorter than the pump pulse or in the case of unsaturated pulse (dashed line), resulting in a short duration optical pulse (bottom).

external clock source, up to 100 MHz.

The resulting optical pulses produced by the diode are shown in Fig. 4.11. Here the effect of relaxation oscillations in the gain switching mechanism are evident, with the generated optical pulse being significantly shorter than the driving electrical pulse. The pulse displays significant structure, with a sharp transient pulse whose FWHM duration is 70 ps, with subsequent ringing resulting in a structured secondary pulse with significantly longer duration. The optical spectrum of the gain switched laser is shown in Fig. 4.12, with a 3 dB bandwidth of 0.03 nm.

As the sharp transient pulse duration is significantly shorter than the nominal optimum pulse duration of 150 ps, an amplification scheme was devised whereby fibre nonlinearity was exploited to suppress the frequency conversion of this part of the pulse, and conversion of the longer duration secondary pulse favoured.

4.3 Two-stage Raman MOPFA scheme

The output of the gain-switched QD laser diode was amplified using a two-stage amplifier scheme, before frequency doubling in a periodically poled stoichiometric lithium tantalate (PPSLT) crystal. A block diagram of the overall MOPFA scheme is shown in Fig. 4.13a. 1120 nm is coincident with the first Raman Stokes shift from the typical ytterbium lasing wavelength of 1064 nm, which enables the use of Raman gain.

One relevant advantage of Raman amplification in comparison to the use of rare earth doped amplifiers is the comparative resilience to self Q-switching. Owing to the relatively long lifetime of rare-earth dopants in silica (typically on the order of μs), high power fibre amplifiers can suffer from self-Q-switching. If there is a disruption to the input, say, resulting in a significant drop in input power whilst a rare earth doped fibre amplifier is strongly pumped, gain can quickly be stored to a high level throughout the amplifier which is then released as a high energy pulse which can cause catastrophic damage to components. With its relatively short response time (~ 3 fs), Raman scattering is not as susceptible to self-Q-switching. This is a desirable feature in a system designed to be synchronised with an

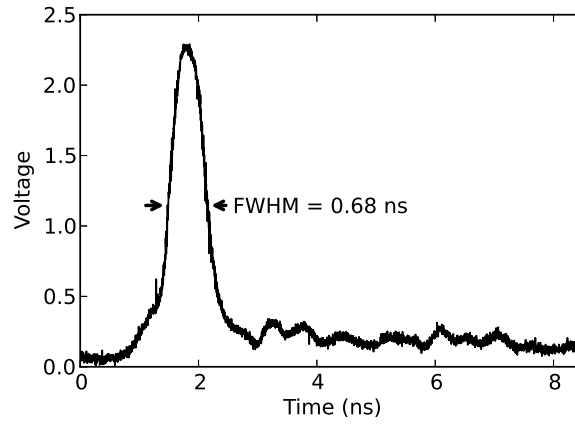


Figure 4.10: Electrical pulse provided to gain switched QD laser diode

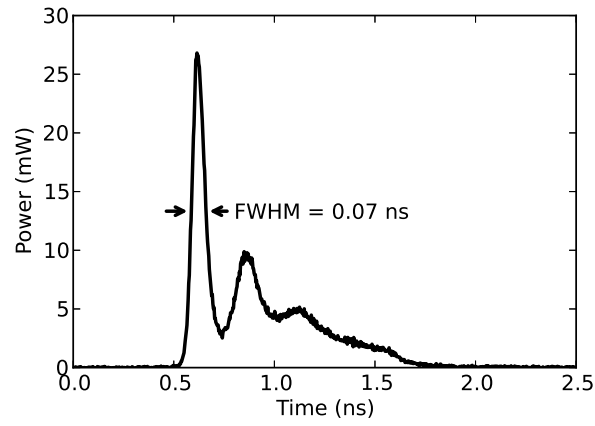


Figure 4.11: Optical pulse generated by gain switched QD laser diode

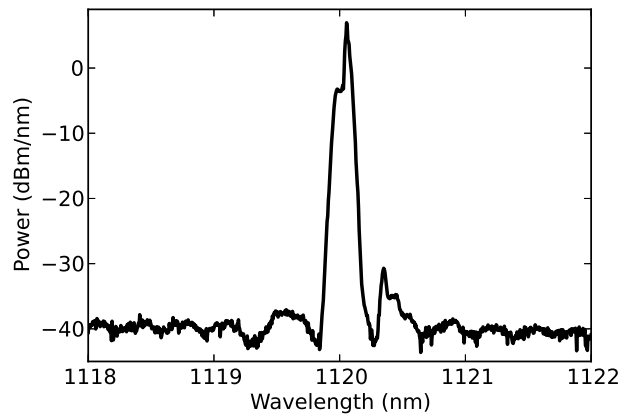


Figure 4.12: Optical spectrum of gain switched QD laser diode

external pump laser, where a failure in upstream components could potentially lead to a halt in seed laser operation.

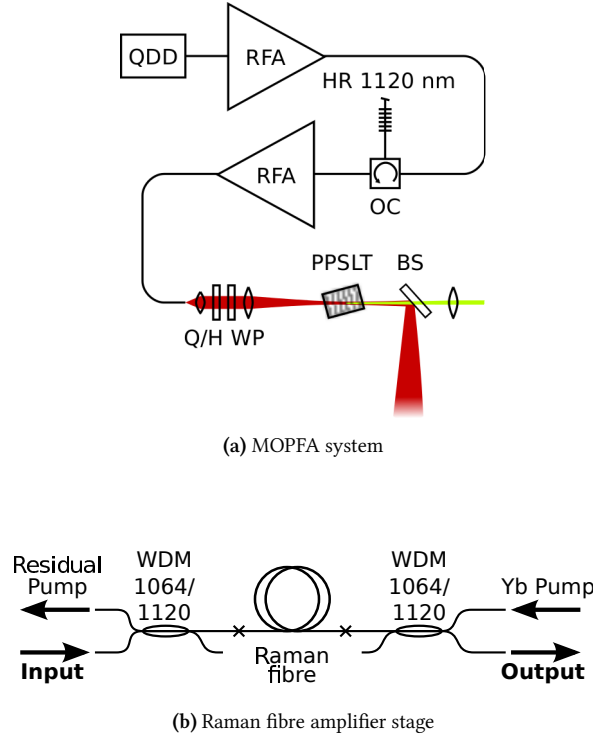


Figure 4.13: Experimental setup of mixed technology MOPFA system. Key to acronyms - QDD: Quantum dot laser diode; RFA: Raman fibre amplifier; OC: Optical circulator; Q/H WP: Quarter/half waveplate pair; PPSLT: Periodically polled stoichiometric lithium tantalate crystal; BS: Beam-splitter.

Both amplifier stages were based upon specially designed Raman active fibre. This fibre had an increased core concentration of germanium, with a specified Raman gain ¹ of $g_R = 2.51 \text{ W}^{-1}\text{km}^{-1}$. Both amplifiers were similar in design (shown in Fig. 4.13b), comprising a length of Raman fibre counter-pumped using ytterbium doped fibre lasers, coupled in and out of the Raman active fibre by use of 1064/1120 nm fused fibre WDMs. The two amplifier stages differed in fibre length and the pump power provided. The first stage amplifier comprised a 390 m length of Raman fibre and was pumped up to 3.8 W. The length of fibre in the second stage was 60 m and was pumped up to 20 W.

Inter-stage filtering was achieved using a 3 port optical circulator (OC) and a highly

¹Note here that the Raman gain, g_R is in units of $\text{W}^{-1}\text{km}^{-1}$ as the effective area of the mode-field within the fibre has been factored in.

reflective narrow band fibre Bragg grating centred at 1120 nm. This removed newly generated frequency components which arose due to nonlinear spectral broadening in the first amplifier stage. It has the added effect of suppressing the transient pulse in favour of the secondary pulse. Figure 4.14 shows the optical spectrum of the seed oscillator compared to the output of the first stage amplifier. The effects of SPM are evident, with significant broadening of the spectrum. The OC and FBG effectively function as a 0.2 nm filter about the peak of the spectrum, removing the majority of the newly generated frequency components. The effect of this on the pulse shape is shown in Fig. 4.15, which shows the pulse before and after passing through the OC-FBG filter, with the filtered pulse displaying a reduced initial transient pulse compared to the secondary pulse - before optical filtering the ratio of the transient pulse power to secondary pulse power is 2.8, and after filtering the ratio is 2.2. This is due to the fact that the transient pulse, having a greater peak power, is subject to more self-phase modulation than the secondary pulse, with a result that the spectral broadening is largely associated with the transient pulse which will in turn be subject to greater loss compared to the secondary pulse in the OC-FBG filter.

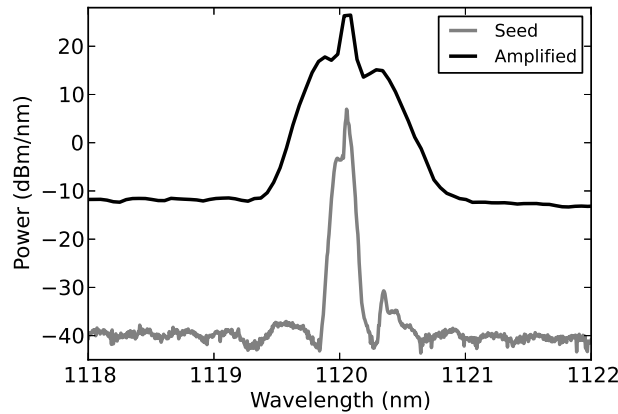


Figure 4.14: Optical spectrum of gain switched QD laser diode before (grey) and after (black) amplification in first stage Raman amplifier

The second amplifier stage, incorporating a 60 m length of Raman active fibre, was pumped by an Yb fibre laser up to 19.5 W. The output pulses were measured using a streak camera for increasing pump power, the results of which are shown in Fig. 4.16. With in-

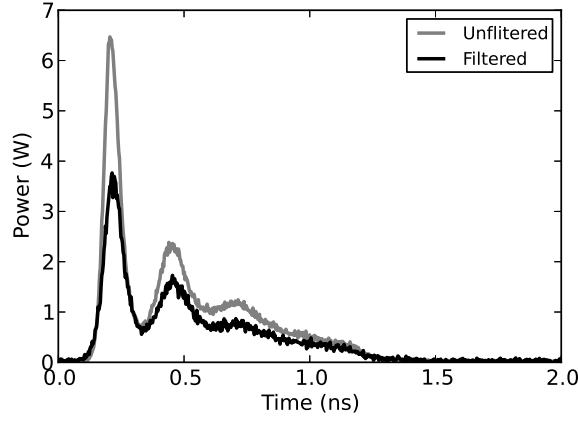


Figure 4.15: Streak camera measurements of Raman amplified pulses before (grey) and after (black) optical filtering

creasing pump power, a relative decrease in the peak power of the initial transient pulse compared to the secondary pulse is observed. The cause of this is revealed in the optical spectrum, also recorded with increasing pump power and shown in Fig. 4.18.

This shows that with increasing pump power, a broad spectral component develops centred around 1180 nm. This wavelength corresponds with the Raman Stokes shift from the 1120 nm line. As the amount of Raman scattering is proportional to the local optical intensity, the higher power transient part of the pulse will more strongly pump the newly generated Raman component, resulting in a greater proportion of the transient pulse being Raman shifted compared to the secondary pulse. The Raman threshold power [Smi72], P_{th} , is defined as the power at which half of the pump power will be transferred to the first Raman Stokes shift and is given by

$$P_{\text{th}} = \frac{16}{g_R L_{\text{eff}}} \quad (4.2)$$

where g_R is the Raman gain coefficient and L_{eff} is the (loss adjusted) effective length of propagation at the pump wavelength. In this case, due to the relatively low loss at the pump wavelength and relatively short length of the second amplifier stage, $L_{\text{eff}} \approx 60$ m, giving a threshold power of ~ 105 W. Figure 4.17 shows the recorded peak powers of the transient and secondary parts of the pulse. There is a pronounced levelling off of the peak

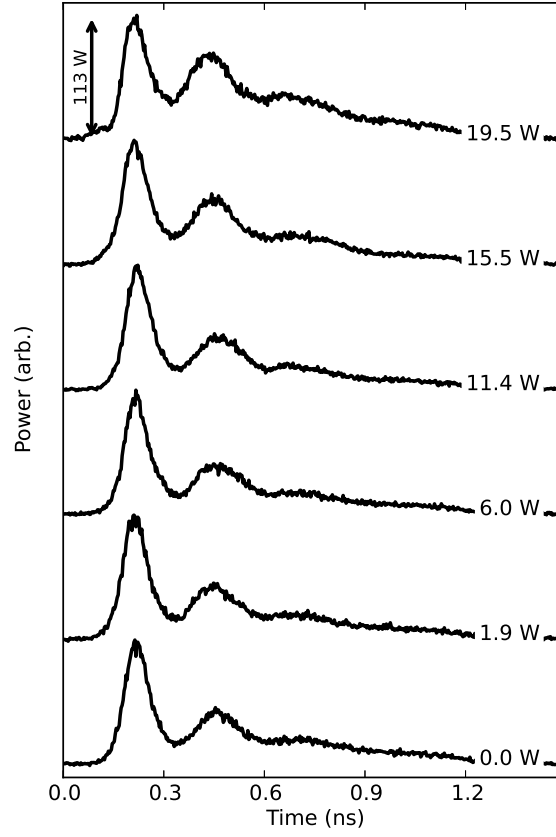


Figure 4.16: Evolution of pulse with increasing amplification, labelled by pump power provided to second amplifier stage (N.B. axis scale not common between curves)

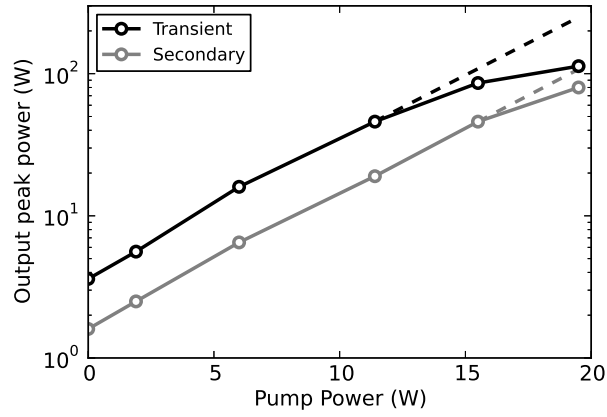


Figure 4.17: Peak powers of transient and secondary pulse components with increasing pump power. Dashed lines show extrapolated powers without saturation and losses to Raman scattering.

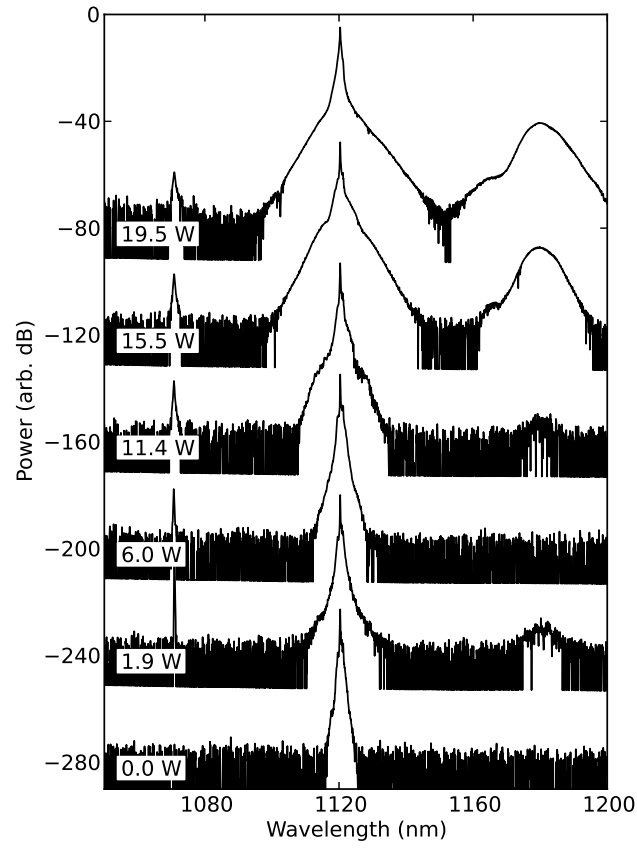


Figure 4.18: Evolution of fundamental pulse optical spectrum with increasing amplification, labelled by pump power provided to second amplifier stage.

power of the transient part of the pulse, which illustrates that the transient part of the pulse more readily pumps the 1180 nm component. Also shown in the figure are the peak powers extrapolated from the small signal gain of each component (i.e. before gain saturation or nonlinear losses become significant). This shows that, for both pulse components, the deviation from the small signal gain through nonlinear loss only becomes significant as the output pulse power approaches the Raman threshold power.

As the streak camera used to record the pulses is ~ 50 times more sensitive to radiation at 1120 nm compared to the 1180 nm component, the measurements can be considered as only measurements of the 1120 nm component. The spectral conversion of the transient pulse results in a drop in power relative to the secondary pulse: At the input the ratio of the relative powers of the two pulses was 2.2:1 and at the maximum pump power this has reduced to 1.4:1.

As in the first amplifier stage, there is also significant spectral broadening of the 1120 nm line through SPM. Due to the phase matching condition of the nonlinear conversion in the frequency doubling crystal, this will lead to the transient pulse being almost entirely suppressed, and the secondary pulse favoured.

Frequency doubling and pulse re-shaping

The output of the Raman MOPFA system was collimated using a 12 mm focal length lens. It was important to eliminate back reflections from the output end of the fibre, so as to avoid laser action in the second amplifier stage. To this end, an anti-reflection (AR) coated fibre connector was spliced onto the second stage output. The output was collimated using an 8 mm focal length lens and a quarter/half waveplate pair used to compensate for the polarisation rotation to which the signal was subject in the amplifier chain and ensure the polarisation was oriented to maximise frequency conversion.

The MOPFA output was frequency doubled using a periodically poled stoichiometric lithium tantalate (PPSLT) crystal, with a poling period of $9.11 \mu\text{m}$ and a crystal length of 20 mm. The crystal was held at a temperature of 126°C by use of an oven. The beam was focused into the crystal using a 100 mm focal length lens, giving a confocal parameter of

~ 10 mm. For a narrow line laser, it is nominally optimal to focus into the crystal such that the confocal parameter matches the crystal length. In this case, however, it was empirically found that over-focusing optimised the second harmonic generation, due to the effect of the confocal length on the effective phase matching bandwidth of the crystal. As discussed in Section 1.2.1, a periodically poled crystal will have an acceptance bandwidth (see Eq. 1.14) which is inversely proportional to the interaction length in the crystal. As the pulse spectrum is subject to SPM-induced spectral broadening, it was found that a shorter confocal parameter (and hence shorter interaction length) yielded a greater conversion efficiency due to the increase in phase matching bandwidth. The infra-red radiation was removed using a dichroic beam splitter, and the second harmonic beam re-collimated using an AR coated singlet lens.

The output power of the second stage with increasing output power is shown in Fig. 4.19, along with the power in the frequency doubled beam. At maximum pump power, the total output power of the second amplifier stage was in excess of 2 W. Of this, 130 mW was converted to visible radiation.

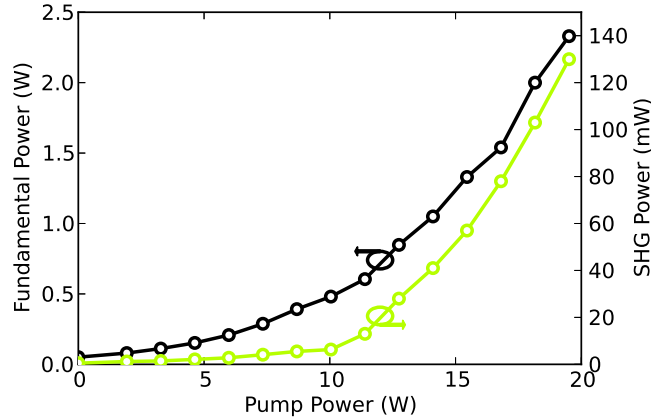


Figure 4.19: Time-averaged power of the infra-red (fundamental) laser output, and the time-averaged frequency doubled power with increasing pump power supplied to the second amplifier stage

Figure 4.20 shows the optical spectrum of the frequency doubled beam at the maximum output power. From Eq. 1.14 the nominal input acceptance bandwidth in the crystal for an interaction length for $L = 10$ mm (the confocal parameter of the focused beam within the

crystal) is

$$\Delta\lambda \approx 0.4429 \frac{\lambda \cdot \Lambda}{L} = 0.45 \text{ nm.} \quad (4.3)$$

The optical bandwidth of the frequency doubled beam will be half of this and so an output bandwidth of 0.23 nm is expected. The recorded spectrum has a 3 dB bandwidth of 0.2 nm, which compares favourably to the predicted bandwidth.

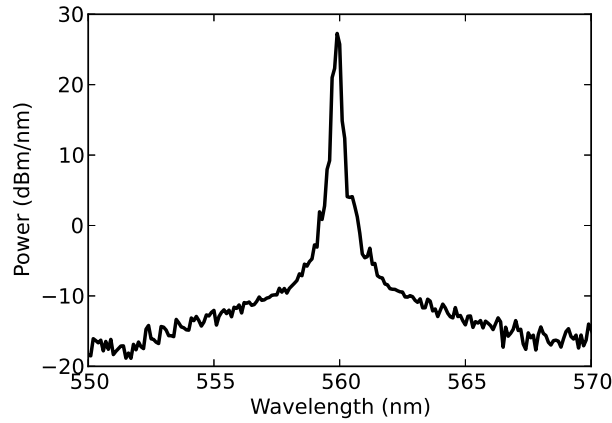


Figure 4.20: Optical spectrum of frequency doubled laser output at maximum output power.

The bandwidth restriction has a deleterious effect on the overall conversion efficiency, as input bandwidth increases through self-phase modulation as second stage pump power is increased. In this case, however, it acts to re-shape the visible pulse, as the conversion of the secondary pulse is enhanced in relation to the transient pulse. This is illustrated in Fig. 4.21 which shows the evolution of the pulse shape with increasing power. At low powers, the transient pulse dominates, as is expected due to the intensity squared relationship between the generated second harmonic radiation to the fundamental. With increasing power, however, the conversion efficiency of the transient pulse rapidly decreases until at high powers it is all but suppressed. This can readily be understood in terms of the filtering effect of the acceptance bandwidth of the frequency doubling crystal. With increasing power, the transient pulse, being of greater peak intensity, will undergo a greater degree of spectral broadening through SPM, with a result that more power will fall outside of the acceptance bandwidth of the crystal and therefore not undergo frequency conversion. The result is a

pulse of 11 W peak power whose FWHM duration is 130 ps, well matched to the nominal ideal pulse duration of 100-150 ps.

For any microscopy application, the beam quality is of great importance. As the frequency doubling process is dependent on the square of the intensity, inhomogeneities in the infrared beam profile will be accentuated in the second harmonic beam. Fibre based laser sources are well suited to frequency doubling applications, then, as single mode operation can be achieved, with high output beam quality. In a MOPFA system such as this, back-reflection into the amplifier must be avoided. This is often achieved by used of an angle cleaved output facet, however this tends to introduce ellipticity to the collimated beam, and so in this system the output of the MOPFA was coupled out through an anti-reflection coated fibre connector. This ensured a high quality, symmetric output beam, which subsequently resulted in a high quality second harmonic beam. Figure 4.22 shows the beam profile measured for the 560 nm beam. A Gaussian fit indicates a beam width of 0.96 mm. The M^2 of the beam was also measured to be below 1.07 in both axes.

4.4 Outlook

Work in this chapter has detailed the development of a new fibre laser source based on newly available quantum dot semiconductor laser diodes used in conjunction with multi-stage Raman fibre amplifiers in a mixed technology MOPFA configuration. This is combined with second harmonic generation in a periodically poled PPSLT crystal to generate pulses of 130 ps duration and 11 W peak power at a wavelength of 560 nm and a repetition rate of 50 MHz. Owing to the gain switched nature of the seed laser, the system can be synchronised to an external clock source. The convenience of gain switching comes at a cost of the generation of structured pulses. Here, however, pulse re-shaping has been effected through fibre nonlinearities and spectral filtering, both within the MOPFA and the effective filter are brought about by the finite phase matching bandwidth of the crystal.

As described, this system meets the key nominal specifications outlined in Section 4.1.2, in that it can produce pulses of the correct wavelength with a duration of 130 ps and peak

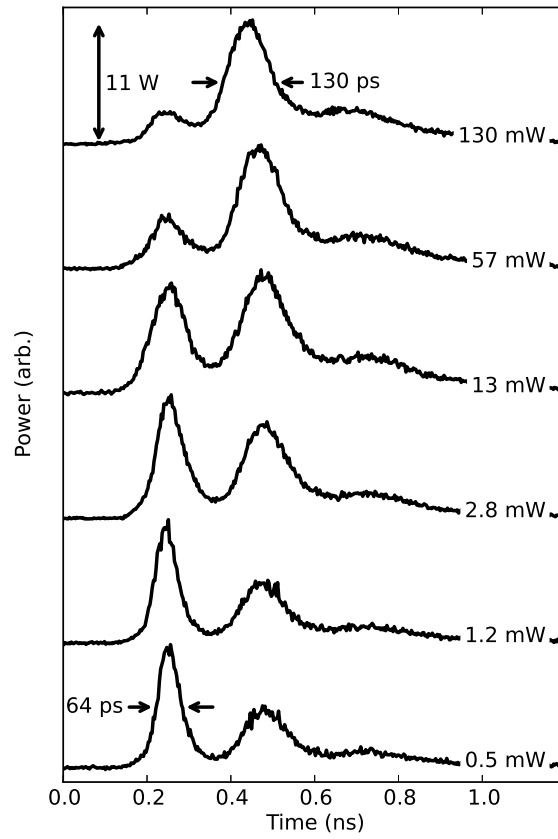


Figure 4.21: Evolution of frequency doubled (green) pulse with increasing amplification, labelled by time-averaged frequency doubled power.

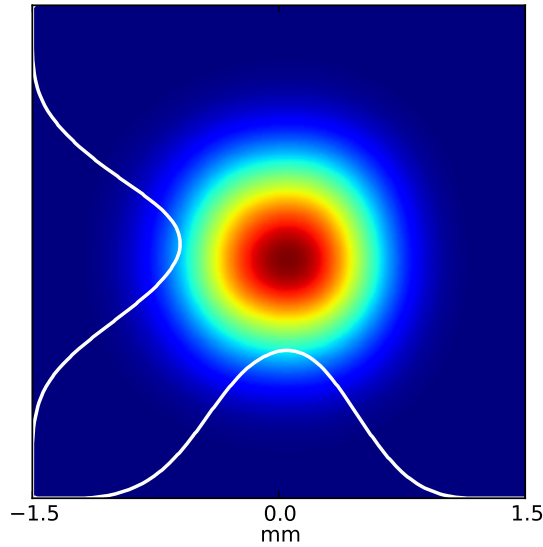


Figure 4.22: Measured beam profile of frequency doubled laser output at maximum output power. A Gaussian fit indicates a beam width of 0.96 mm and the M^2 was measured to be below 1.07 in both axes.

power in excess of 10 W. It does, however, suffer from a number of practical limitations. Due to the long length of the amplifier stages, coupled with the fact that the Raman active fibre is not polarisation maintaining, there is a long term drift on the output polarisation state of the pulses from the MOPFA system, due to the nonlinear polarisation shift induced in the amplifiers. Currently, this must be compensated for using a quarter-/half- waveplate pair before coupling into the periodically poled crystal. This is not ideal for a system intended to be an entirely ‘turn-key’ laser source. One obvious improvement to the system, then, would be replacing the gain fibre in the amplifier stages with commercially available polarisation maintaining (PM) Raman active fibre. When combined with PM fused fibre couplers, the Raman fibre amplifier stages could preserve the single polarisation of the gain switched laser output, suppressing nonlinear polarisation shift. This would improve the stability the source. Additionally, while the current peak power achieved in the visible pulses is in excess of 10 W, there are losses associated with the application of a phase mask to the beam to create the required donut-shaped beam profile, so the power delivered to the sample in a STED scheme may be significantly less than this. To this end, an increase in the peak power

would be advantageous.

Further refinement, then, is required for the architecture described above to be entirely practicable for use in STED microscopy. Work detailed in this chapter, though, demonstrates this mixed-technology MOPFA scheme, based on fibre-integrated components and Raman amplification provides a viable route to the development of laser sources with biophotonic applications.

Chapter 5

Conclusions and outlook

The laser systems which form this thesis were developed with a view to demonstrate the versatility of optical fibre and fibre-integrated photonic devices for the development of laser sources, configurable both in the temporal and spectral domain, to meet application needs. Three broad laser schemes were explored, each presented in its own chapter. This chapter revisits each topic with a brief summary, highlights of significant results and a discussion of future developments which may be prompted by work presented in this thesis.

Spectrally masked phase modulation

Chapter 2 introduced the concept of spectrally masked phase modulation (SMPM) - a bias-free optical modulation technique. Here, a phase modulator is used to impose a time-varying shift to the optical frequency of a CW laser signal, such that a spectral mask (optical filter) can be used to map this time-frequency dependence to an effective amplitude modulation. The effect of spectral mask shape on the pulse shape was examined. Two experimental systems then demonstrated that SMPM, combined with nonlinear fibre optic techniques based on soliton propagation, can lead to the generation of femtosecond pulses at repetition rates of tens of gigahertz. The best performance was obtained from the SMPM system operating at $1.06\text{ }\mu\text{m}$, capable of producing pulses of 190 fs duration at a repetition rate of 20 GHz. This system, however, suffered from the fact that it relied on a fibre-grating

compressor to pre-compress the pulses before adiabatic soliton compression (ASC) could take place in a dispersion decreasing photonic crystal fibre (DDPCF). What, then, is the feasibility of realising a SMPM system, with subsequent compression based on ASC in a DDPCF capable of producing femtosecond pulses in a fully fibre integrated configuration? This would require both a reduction in the pulse duration generated from the SMPM system, and also an increase in compression factor achieved from the DDPCF.

The first would be readily achieved through an increase in the operating repetition rate, which in turn decreases the pulse duration. This has the added advantage of increasing the spacing of the comb lines in the optical spectrum, allowing for a broader band-pass filter to be used. Low V_π phase LiNbO₃ phase modulators, such as the one used in Section 2.3, are available commercially with bandwidths in excess of 40 GHz - double the repetition rate of the SMPM system demonstrated. Using these, pulse durations as short as ~ 5 ps would readily be achievable from the SMPM system itself.

An increase in the compression factor of the DDPCF would require fibres of greater length exhibiting a greater change in dispersion between the input and output ends. The fibre used in this work was fabricated at the University of Bath by dropping the air-core pressure whilst simultaneously slowing the drawing rate of the fibre at the point of fabrication. This, in comparison to post-production tapering techniques, enables far longer fibres with axially non-uniform dispersion profiles. Recent investment in the pressure and draw speed control at the University of Bath should enable even longer length DDPCF to be fabricated with greater accuracy. Longer length fibres will mean that a greater shift in the group velocity dispersion from fibre input to output will be achievable whilst maintaining the low change in dispersion per soliton length required for adiabatic compression. This, combined with a shorter input pulse duration, means that a fully fibre integrated, ASC-compressed SMPM system is fast becoming a technical possibility, which may enable the development of stable, ultra-short, high repetition rate laser sources with an incredibly small footprint.

Bismuth doped silica fibre

Bi-doped silica is a promising medium for the diversification of the operational wavelength of doped fibre amplifiers. Novel laser/amplifier systems based upon this new technology were presented in Chapter 3. First, the amplification of ultra-short pulses and gigahertz repetition rate signals was demonstrated in a Bi-doped fibre amplifier for the first time, with gain in excess of 20 dB achieved around 1180 nm. A master oscillator/power fibre amplifier (MOPFA) system was then demonstrated exclusively using Bi-doped fibre as a gain medium. The output of a semiconductor saturable absorber mirror (SESAM) based mode-locked laser was amplified in a two stage amplifier scheme, producing pulses with peak powers of 0.5 kW. Frequency doubling was then performed in a periodically poled lithium niobate (PPLN) crystal, resulting in a picosecond pulsed laser source operating at 589 nm.

This work demonstrated that it is indeed possible to use Bi-doped silica as a platform for the development of novel laser systems. Many problems would need to be addressed, however, before these systems could be developed to a standard of efficiency and ease of use required by most laser end-users. The requirement that cryogenic cooling be applied before appreciable gain can be extracted from the fibre would be particularly challenging, and precludes its use from most applications. The relatively low efficiency achieved in long length amplifiers, particularly when not subject to cooling, and high pump requirements also erode the attractiveness of Bi-doped fibre. Before any of these problems may be tackled, however, fundamental questions of the optical gain mechanisms in Bi-doped silica must be addressed. A greater understanding of the interaction between different ionic states of bismuth, and interactions with glass co-dopants may lead the way to greater control of gain centres and perhaps help solve the persistent problems of non-saturable losses which lie at the heart of performance issues in Bi-doped silica.

Quantum dot diodes, Raman amplification and STED microscopy

The final experimental chapter of this thesis detailed the development of a picosecond pulsed visible laser source, based on a mixed technology MOPFA and a periodically poled stoichiometric lithium tantalate (PPSLT) crystal. This was motivated by the need for new pulsed laser sources which are required to address requirements for confocal fluorescence microscopy based upon the ever widening range of biological fluorophores. Gain switching of laser diodes presents an attractive technology for the seed oscillator of any such system, owing to its compact nature, stability and reliability. Due to recent advancements in quantum dot semiconductor technology, fibre connectorised, compact laser diodes are available at the half-harmonic of wavelengths of interest in biophotonic applications. For schemes such as stimulated emission depletion (STED), the most useful property of a gain switched diode is the fact that it can be synchronised to an external laser source, separating the excitation and depletion sources in such a scheme. Whilst broadband sources based on supercontinua provide auto-synchronous excitation/depletion pulses, separately developing a depletion source should lead to greater spectral power density at the target wavelength, which due to the relationship between the effective point spread function and depletion radiation intensity in such a scheme, may in turn lead to greater imaging resolution. In this case, where a visible source was required which matched the emission spectrum of yellow fluorescent protein (YFP), the use of a gain switched quantum dot diode enabled the development of a Raman amplified MOPFA system which operated at 1120 nm - the half-harmonic of the target wavelength. Gain switched diodes, such as the one used in Chapter 4 can suffer from a high degree of temporal structure to the output pulses. This work, however, demonstrated that this can be overcome to some extent by exploiting the inherent nonlinearity of an optical fibre amplification scheme in a mixed technology MOPFA to effect pulse re-shaping. Some changes, however, could improve the system, in terms of the reliability of its performance, its efficiency and the overall foot-print of the MOPFA. By employing a polarisation maintaining Raman active fibre, the long term polarisation drift which currently affects the output of the amplifier chain could be mitigated, which in turn would stabilise the frequency doubled output. The design choices for the laser system were

motivated, in part, by the increasing commercial availability of quantum dot semiconductor laser devices at appropriate wavelengths. This suggests another potential improvement to the system - replacing the first of the two Raman fibre amplifier stages with a quantum dot semiconductor optical amplifier. This would decrease the overall footprint of the laser system, and potentially significantly increase its overall efficiency (removing the need for one of the ytterbium fibre pump lasers). However, due to the relatively short upper-state lifetime of semiconductor laser devices compared to the megahertz repetition rate of the seed laser, the amplifier would have to be driven by a pulsed current source, synchronised to the seed laser, to avoid inter-pulse spontaneous emission dominating the output of the amplifier. Even without these improvements, the laser system described in Chapter 4 has demonstrated that the combination of a gain switched quantum dot diode with Raman amplification and frequency doubling is a practicable route to the development of optical sources for biophotonic applications. This is encouraging, as the demand for sources to be used in STED microscopy will continue to increase as the range of available fluorophores continues to increase.

Closing remarks

Optical fibre provides an excellent platform for the development of laser systems with a wide range of spectral and temporal properties. The work in this thesis has demonstrated laser systems operating over a range of parameters, from femtosecond to picoseconds, and at wavelengths from 1.5 μm to the visible. This work has exploited optical fibre in amplifiers, using active dopants or Raman scattering, and also made use of the intrinsic nonlinearity of the medium itself. This has been supported by a range of complementary technologies - electro-optic devices, semiconductor lasers and bulk nonlinear crystals.

Undoubtedly, as technologies continue to develop, fibre laser devices will find use in an even greater range of applications. It is hoped that the work presented in this thesis may play some small part in demonstrating the variety of sources which can be developed based on optical fibre, and fibre-integrated photonic devices.

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List of publications

The following publications form the basis of the present thesis:

Journal papers

1. B. H. Chapman, A. V. Doronkin, J. M. Stone, J. C. Knight, S. V. Popov, and J. R. Taylor “Femtosecond pulses at 20 GHz repetition rate through spectral masking of a phase modulated signal and nonlinear pulse compression” *Optics Express*, Vol. 21, Issue 5, pp. 5671-5677 (2013)
2. B. H. Chapman, A. V. Doronkin, S. V. Popov, and J. R. Taylor “All-fiber integrated 10 GHz repetition rate femtosecond laser source based on Raman compression of pulses generated through spectral masking of a phase-modulated diode” *Optics Letters*, Vol. 37, Issue 15, pp. 3099-3101 (2012)
3. B. H. Chapman, E. J. R. Kelleher, S. V. Popov, K. M. Golant, J. Puustinen, O. Okhotnikov, and J. R. Taylor “Picosecond bismuth-doped fiber MOPFA for frequency conversion” *Optics Letters*, Vol. 36, Issue 19, pp. 3792-3794 (2011)
4. B. H. Chapman, E. J. R. Kelleher, K. M. Golant, S. V. Popov, and J. R. Taylor “Amplification of picosecond pulses and gigahertz signals in bismuth-doped fiber amplifiers” *Optics Letters*, Vol. 36, Issue 8, pp. 1446-1448 (2011)

Conference contributions

1. B. H. Chapman, A. V. Doronkin, S. V. Popov, and J. R. Taylor “Gigahertz Repetition Rate Ultrashort Pulses Through Phase Modulation, Spectral Masking and Fibre Non-linearity” *Frontiers in Optics 2012*, Rochester NY, USA (Oct 2012)

List of acronyms

Below is a list of acronyms used in this thesis:

AR - Anti-reflection
ASC - Adiabatic soliton compression
ASE - Amplified stimulated emission
BDF - Bismuth doped fibre
BPF - Band pass filter
BiDFA - Bismuth doped fibre amplifier
Bi - Bismuth
CFBG - Chirped fibre Bragg grating
CLSFM - Confocal laser scanning fluorescent microscopy
CW - Continuous wave
DC - Direct Current
DDPCF - Dispersion decreasing photonic crystal fibre
DFB - Distributed feedback
DSF - Dispersion shifted fibre
EAM - Electro-absorption modulator
EDFA - Erbium doped fibre amplifier
EOM - Electro-optic modulator
Er - Erbium
FBG - Fibre Bragg grating
FWHM - Full width at half maximum
FWM - Four wave mixing
GFP - Green fluorescent protein
GNLSE - Generalised nonlinear Schrödinger equation
GVD - Group velocity dispersion
LNPM - Lithium niobate phase modulator
LiNbO₃ - Lithium Niobate
LiTaO₃ - Lithium Tantalite

List of acronyms

MI - Modulation instability
MLL - Mode locked laser
MOPFA - Master oscillator power fibre amplifier
MZAM - Mach-Zehnder amplitude modulator
NA - Numerical aperture
NLSE - Nonlinear Schrödinger equation
Nd - Neodymium
OC - Optical circulator
PCF - Photonic crystal fibre
PC - Polarisation controller
PM - Polarisation maintaining
PPLN - Periodically poled lithium niobate
PPSLT - Periodically poled stoichiometric lithium tantalite
PSF - Point spread function
QCSE - Quantum confined Stark effect
QD - Quantum dot
QPM - Quasi phase matching
RF - Radio frequency
RZ - Return-to-zero
SBS - Stimulated Brillouin scattering
SESAM - Semiconductor semiconductor amplifier
SHG - Second harmonic generation
SMPM - Spectrally masked phase modulation
SPM - Self phase modulation
SRS - Stimulated Raman scattering
SSFS - Soliton self frequency shift
STED - Stimulated emission depletion
Tm - Thulium
XPM - Cross phase modulation
YDFA - Ytterbium doped fibre amplifier
YFL - Ytterbium fibre laser
YFP - Yellow fluorescent protein
Yb - Ytterbium
ZDW - Zero dispersion wavelength