

UNIVERSITY OF GHANA
COLLEGE OF BASIC AND APPLIED SCIENCES

**MODE-LOCKED ERBIUM DOPED FIBER LASER,
SUPERCONTINUUM GENERATION IN SOLID NORMAL
DISPERSION PHOTONIC CRYSTAL FIBERS AND
SUPERCONTINUUM AMPLIFICATION**



JOANNA ABA MODUPEH HODASI

DEPARTMENT OF PHYSICS

DECEMBER 2017

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**THIS THESIS IS SUBMITTED TO THE UNIVERSITY OF GHANA,
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THE AWARD OF THE DEGREE OF DOCTOR OF PHILOSOPHY IN
PHYSICS.**

DEPARTMENT OF PHYSICS

DECEMBER 2017

DECLARATION

I hereby declare that this thesis is my own work produced from research conducted under supervision.

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ABSTRACT

A mode-locked erbium doped fiber laser has been constructed and coherent octave spanning supercontinua have been generated and amplified. Mode-locking in the erbium-doped fiber laser, which produced parabolic pulses, was achieved by nonlinear polarization evolution. A 355 cm all-fiber ring cavity produced 73 fs pulses at a wavelength of 1572 nm with an average output power of 24 mW and a pulse energy of 0.46 nJ. A second all-fiber ring cavity of length 510 cm produced 63 fs pulses at a wavelength of 1604 nm and an average output power of 3.3 mW. The supercontinua were generated in all-solid, all-normal dispersion photonic crystal fibers (PCFs) specially designed to maintain normal dispersion over a wide bandwidth up to 3000 nm. The spectral broadening that leads to the supercontinuum arises from self-phase modulation and optical wave-breaking because of the normal dispersion character of the solid core photonic crystal fibers, giving a highly coherent supercontinuum pulse with a spectrum that spanned an octave, from 1100 nm to an upper wavelength limit of 2200 nm. The spectral envelope was generally smooth with a flat-top profile except for the central portion which contained cladding modes. The supercontinuum was used to seed an erbium-doped fiber amplifier (EDFA), a thulium-doped fiber amplifier (TDFA), and a thulium-holmium co-doped fiber amplifier (THDFA). The EDFA was pumped at 974 nm at a power of 650 mW and gave a net gain of 5.6 dB at a slope efficiency of 11.3%. The TDFA, which was pumped at 793 nm, amplified the supercontinuum over a bandwidth of 54 nm in forward pumping configuration whereas backward pumping gave a bandwidth of 40 nm. The amplified supercontinuum was centred at 1991 nm in forward pumping and at 1979 nm in backward pumping configuration. The widest bandwidth of amplified supercontinuum was obtained with the THDFA, which produced a 120 nm bandwidth pulse centred at 1.94 μm and which is compressible to a pulse width below 40 fs in an all-fiber system with 1 W maximum output power.

DEDICATION

To Sammy, you are the reason for this PhD.

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LIST OF ABBREVIATIONS

ANDi	All-Normal Dispersion
ASANDi	All-Solid All-Normal Dispersion
ASE	Amplified Spontaneous Emission
FWDM	Fused Wavelength Division Multiplexer
FWHM	Full Width Half Maximum
FWM	Four Wave Mixing
GNLSE	Generalised Nonlinear Schrodinger Equation
GVD	Group Velocity Dispersion
IWDM	Isolating Wavelength Division Multiplexer
MI	Modulation Instability
NLPR	Nonlinear Polarization Rotation
NLSE	Nonlinear Schrodinger Equation
PBS	Polarizing Beam Splitter
PCF	Photonic Crystal Fiber
PSC	Pump Signal Combiner
PM	Polarization Maintaining Fiber
SC	Supercontinuum
SPM	Self-Phase Modulation
SRS	Stimulated Raman Scattering
UHNA	Ultra-High Numerical Aperture
WDM	Wavelength Division Multiplexing
ZDW	Zero Dispersion Wavelength

CHAPTER 1

GENERAL INTRODUCTION

Since its discovery in 1960, lasers have revolutionised science and technology, with applications in industry, medicine, defence, telecommunications and much more, that have had great impact on modern society. From the demonstration of the first ruby laser [1], solid state lasers have dominated the laser industry as they produce the highest peak powers and pulse energies, and have the shortest pulses, with the most popular being the Nd:YAG and Ti:sapphire lasers. Most of these lasers, however, are not user friendly, with large bulky systems containing free-space optics which makes them susceptible to environmental conditions. This environmental susceptibility results in the need for constant monitoring and maintenance by trained personnel. They are also expensive, limiting their use for research in ultrafast science to well-endowed research facilities.

The use of doped optical fibers as laser gain media has led to a class of solid state laser in the form of the fiber laser [2]. A fiber laser is made up of a length of doped optical fiber serving as the gain medium which is placed in a resonant cavity, either between two mirrors as in the case of a linear resonator, or in a ring fiber laser cavity design which excludes mirrors. Optical pumping occurs either in the core or, in the case of double clad fibers, in the inner cladding of the fiber laser. The generated stimulated radiation propagates in the core of the fiber and this gives rise to high beam quality of the laser. Rare earth ions such as Er^{3+} , Yb^{3+} , Nd^{3+} , Tm^{3+} , Ho^{3+} , are mainly used as dopants in the gain optical fiber as they have a broad spectral gain bandwidth and high single pass gain which is ideal for short pulse operation. Fiber lasers operate in both the continuous mode and the pulsed mode.

1.1 Mode-locked optical fiber sources

Ultrashort pulses are obtained by the process of mode-locking, which is simply the locking together of the longitudinal modes of the laser cavity. This can be done using active or passive elements within the laser cavity to periodically modulate cavity losses to produce a pulsed output. For ultrashort pulse widths in the femtosecond range, passive mode-locking is the preferred method. The first observation of mode-locking in fiber lasers was made with the passive mode-locking technique of additive pulse mode-locking [3]. A summary of mode-locking in fiber lasers, with emphasis on passive mode-locking using the technique of nonlinear polarization rotation, which is based on the nonlinear interference of two polarizing modes of the electromagnetic radiation, is given in chapter 2 of this thesis. This method is one of the popular mode-locking techniques for fiber lasers [4, 5] and is used later in this thesis for the construction of an erbium-doped fiber laser. Though the various techniques for passive mode-locking of fiber lasers have been available for some time now, the generation of stable pulses is still a delicate interplay of gain, nonlinearity and dispersion. For stable mode-locking, it is essential that the propagating pulse amplitude recover its initial profile at the end of each cavity round trip, making it a nonlinear attractor of the system.

The most famous type of mode-locked pulse in fiber lasers is the soliton pulse [6, 7]. Solitons are obtained when the group velocity dispersion of the fiber laser is anomalous and the resulting temporal broadening of the propagating pulse is balanced by the induced spectral broadening from self-phase modulation. Soliton pulsed lasers dominated the mode-locked pulse regime but are limited to pulse energies around 100 pJ. This is because excessive nonlinearity resulting from small fiber core size leads to large nonlinear phase shifts and eventual pulse break-up. The pulse energy of a soliton fiber laser can be improved by a dispersion map that allows the soliton pulse to be stretched in a normal dispersion segment of the laser, reducing its peak power and hence the nonlinearity. Higher energy pulses can then

be produced. This is known as the stretched pulsed soliton laser [8] or the dispersion managed soliton laser.

The emergence of dissipative soliton pulsed fiber lasers brought the highest pulse energy obtained in a single-mode fiber laser to 31 nJ with a pulse width of 80 fs [9]. In the last decade however, new pulse regimes have opened-up the possibilities for higher pulse energies and shorter pulses.

The possibility of high energy pulse propagation in optical fiber without the pulse break-up associated with soliton pulse formation was theoretically investigated [10] to reveal self-similar or similariton pulses. These are asymptotic solutions to the non-linear Schrödinger wave equation. The pulse shape has a parabolic intensity profile both in the time and spectral domain, and in the presence of normal group velocity dispersion, the high nonlinearity produces a linear chirp in the pulse, leading to increased spectral broadening resulting in a pulse with a large spectral bandwidth. Self-similar pulses were simulated [11] and experimentally proven to propagate in nonlinear optical amplifiers [12], where the asymptotic pulse characteristics are determined by the incident pulse energy and parameters of the amplifier. Propagation of self-similar pulses in a laser takes on a different approach as self-similar pulses are not stable solutions in an optical feedback system and hence there is the need for a mechanism to restore and stabilize the solution after propagation through the cavity. The first fiber laser with self-similar pulse evolution was experimentally realised in 2004 [13]. The fiber laser operated with self-similar pulse propagation in the passive normal dispersion section of the cavity. The design of the laser cavity was such that a long length of normal dispersion single-mode fiber was followed by a short portion of gain fiber which had negligible group velocity dispersion (GVD) and nonlinearity. The gain fiber filters the generated bandwidth resulting from the nonlinear phase shifts in the single-mode fiber, restoring the system such that consistent stable solutions were obtained. After the gain fiber, polarizers serving as a

saturable absorber were used to initiate mode-locking by nonlinear polarization evolution. The chirp accumulated in the self-similar pulse is compensated for by a dispersive delay line in the form of gratings with anomalous GVD. The gratings join the gain fiber to the single-mode fiber to form a ring cavity fiber laser with the output taken from the nonlinear polarization evolution port. A self-similar pulse of energy 10 nJ, with close to transform-limited pulse duration of 130 fs after external compression, was achieved in this setup.

The generation of similaritons in the gain section of a laser is not easy to achieve as spectral broadening of the pulse must be compensated for. The prediction of amplifier similaritons [14] was given almost ten years before its actual realization. The first generation of these amplifier similaritons was in the form of a soliton–similariton fiber laser [15] giving two different types of pulses each propagating within different sections of the same fiber cavity. Similaritons propagate in the gain fiber (amplifier similaritons) with normal dispersion. The spectral broadening in the gain medium, is however exponential and so there is a need to compensate for this effect. The bandpass filter is the key component to initiate the compensation of spectral broadening of the similariton within the gain segment. On being spectrally filtered in both the time and frequency domains, as there is also a large linear frequency chirp produced in the similaritons, they gradually evolve into solitons as they propagate through the anomalous dispersion segment of the cavity. The unchirped soliton pulse serves as a seed pulse for the similariton formation in the gain fiber. Amplifier similaritons have further been generated in all-normal dispersion fiber lasers [16], this time eliminating the need for soliton pulse formation. The spectral filter and saturable absorber in the cavity are sufficient to converge the similariton pulse evolution after the gain section. As long as there is sufficient normal dispersion gain fiber, any input pulse will reach the asymptotic solutions for similariton pulse formation. Amplifier similaritons have also been generated in a dispersion mapped fiber laser [17] showing that similariton pulse formation is independent of the net

group velocity dispersion, whether anomalous, normal, or zero net dispersion. It is rather the strong nonlinear attraction to the asymptotic solution that determines the pulse characteristics. Sub 100 fs, nanojoule pulses are expected from any type of dispersion mapped amplifier similariton fiber laser.

The advancement in research on pulsed fiber lasers have proven their potential for high pulse energies and peak powers, as well as ultrashort pulsed operation [18-20]. With the added advantage of thermal management because of their large surface to volume ratio, compact design, especially in the case of all-fiber laser setups, and relative low cost as compared to solid state lasers, fiber lasers are becoming the preferred choice for many applications [21, 22]. Broadband sources are required for some applications such as nonlinear microscopy [23] , optical coherence tomography [24], metrology [25, 26], and ultra-short pulse generation [27]. Optical fiber based broadband sources can be obtained by supercontinuum generation.

1.2 Supercontinuum generation

Supercontinua are generated when short pulses of high energy laser light are converted to continuous broadband spectra of high intensity radiation, when propagated in a nonlinear medium. The first observation of supercontinuum (SC) was in normal dispersion bulk material [28], where the nonlinear effects of self-phase modulation and four wave mixing led to spectral broadening in the range of 400 nm. The first supercontinuum generated in optical fiber [29] was also obtained by ~ 1 kW coupled peak power pumping of a 10 nanosecond dye laser within the normal dispersion regime to obtain spectral bandwidths ranging between 110 nm to 140 nm in the visible, depending on the pump source. Additional research showed similar spectral broadening pumping in the normal dispersion region [30-32]. It was observed that long nanosecond pump pulses produced incoherent supercontinuum because of noise seeded Raman

scattering and self-phase modulation. Sub-picosecond pump pulses in the normal dispersion regime generate highly coherent supercontinuum but with limited spectral broadening because of the steepness of the dispersion curve (in the normal dispersion region) leading to faster temporal broadening associated with normal dispersion propagation [33]. The limited spectral broadening shifted interest to pumping in the anomalous dispersion regime where wider bandwidths could be achieved [34, 35]. The spectral broadening in this region is attributed to modulation instability and effects of soliton self-frequency shift.

With ongoing developments in optical fiber technology, the advent of photonic crystal fibers [36] enhanced supercontinuum generation in optical fibers [37-39]. Photonic crystal fibers with a solid core surrounded by an array of air-holes along the length of the fiber were designed such that they have greater degrees of freedom for the wave guiding properties to be changed due to the microstructured nature of its refractive index profile. The effective index contrast between the core and the cladding is determined by the size and distribution of the air-holes and determines the waveguide group velocity dispersion, altering the net group velocity dispersion of the photonic crystal fiber. This then can significantly shift the zero-dispersion wavelength of the fiber more than what is possible in standard single-mode fiber [40]. Again, a reduction in the effective area of the propagating mode due to the geometry of the photonic crystal fiber or due to its air-hole spacing being less than the propagating wavelength significantly enhances the non-linearity of the photonic crystal fiber [41]. The combined effects of the enhanced nonlinearity and modified dispersion are what make it possible for the dramatic supercontinuum effects obtained in photonic crystal fibers to occur. This has been demonstrated with a 100 fs, 8 kW peak power Ti:Sapphire laser with pulses centred at 790 nm which produced a continuum spanning the wavelength range from 390 nm to 1600 nm [37]. The broad spectral range of the supercontinuum was made possible by the closeness of the zero-dispersion wavelength of the PCF, which was 767 nm, to the centre wavelength of the

pump pulses. Research conducted on supercontinuum generation in photonic crystal fibers [42, 43] shows that the nature of the continuum is mainly determined by the dispersive nature of the medium in which the continuum is generated and the pump characteristics, namely, the pulse duration, peak power, and propagating wavelength. In an anomalous dispersion medium, if the pump laser being used has long pulse widths, then modulation instability and four wave mixing are the nonlinear processes that produce the supercontinuum. Femtosecond pulses produce supercontinuum in the anomalous dispersion region due to solitons which eventually break up in the time domain, giving a spectrum with good spatial coherence but poor temporal coherence and fine structure over the spectral bandwidth [44, 45]. The temporal profile and phase stability of the generated supercontinuum pulse is important as the sensitivity to noise is a limiting factor for applications where resolution is of importance. These applications require sources that have highly coherent broadband spectrum, uniform and smooth spectral power density, and a single pulse that is conserved in the time domain having stable and recompressible phase distribution [46].

Several approaches have been suggested for overcoming the coherence limitations of pumping in the anomalous dispersive regime [47-49]. The elimination of modulation instability by pumping in the normal dispersion region of photonic crystal fiber led to the development of photonic crystal fibers that have two zero dispersion wavelengths (ZDW) [50-52] near the pump wavelength. The dispersion profile is flattened and convex, giving a coherent spectrum with two peaks on the normal dispersion side of each zero-dispersion wavelength. The revolution in coherent supercontinuum generation coupled with large spectral bandwidths, however, came about with the introduction of all-normal dispersion (ANDi) photonic crystal fibers. Initial research had shown coherent wideband spectral broadening generated from highly nonlinear fibers which have normal dispersion characteristics over the entire wavelength range of the supercontinuum [53, 54]. This was translated to the photonic crystal fiber where

fiber characteristics were changed to have a normal convex dispersion profile, flattened near the pump wavelength. This enables the temporal broadening of the pump pulse to be at a minimum, aiding in the generation of supercontinuum with more than octave spanning bandwidths [55-57]. This comes with the added advantage of low noise sensitivity, as well as preservation of the initial pump pulse.

An alternative to the solid-core photonic crystal fibers used for supercontinuum generation are the all-solid photonic crystal fibers [58, 59]. These fibers have the air-holes of the conventional solid-core photonic crystal fibers replaced with soft glass rods which are thermally matched to give an all-solid wave guide structure. The use of soft glass instead of air gives additional degrees of freedom in the design of photonic crystal fibers. The glass rods have a lower refractive index than the host glass lattice, giving an effective cladding refractive index that is lower than that of the core. In addition to the geometric structure of the fiber, the chromatic dispersion of the glasses and the glass combination selected for the rods and the surrounding lattice structure which gives the refractive index difference determines the dispersive nature of the fiber. The dispersive characteristics of soft glass are similar and so an all-solid photonic crystal fiber would have a flatter dispersion profile than air-glass photonic crystal fibers. Low refractive index contrast of the two glass types gives rise to flat normal dispersion properties, whereas high contrast all-solid photonic fibers give flat anomalous dispersion. For example, an all-solid photonic crystal fiber fabricated using Schott F6 glass and a specially fabricated silicate glass designated NC21 gave flat all-normal dispersion from 1.55 μm to 2.5 μm [60]. Another all-solid photonic crystal fiber fabricated with a soft glass pair, N-F2 lead glass and the in-house fabricated silicate glass NC21, giving a normal dispersion profile ranging up to 3000 nm, was used for supercontinuum generation. The supercontinuum was generated by pumping the photonic crystal fiber with 120 fs, 9 nJ coupled pulses obtained from a Ti:sapphire-pumped optical parametric amplifier at a wavelength of

1360 nm. The bandwidth of the supercontinuum ranged from 900 nm to 1900 nm, and was flat within a 7 dB dynamic range [61]. By modifying the geometrical parameters of the lattice of the all-solid photonic crystal fiber used in [61], the normal dispersion characteristics were affected such that decreasing the dimensions of the photonic structure caused a lowering of the dispersion profile, and shifted its maximum dispersion point to shorter wavelengths [62]. Supercontinua were generated with these fibers from pumping at a wavelength of 1550 nm with 75 fs pulsed laser. Estimated coupled pulse energy of 30 nJ yielded octave spanning bandwidth with the shorter wavelength edge of the spectra around 900 nm. The longer wavelength end of the spectrum ranged between 2100 nm and 2300 nm. The wavelength at the red-shifted edge decreased with decreasing fiber geometry. The broadest and flattest spectrum was generated from the fiber that had the lowest absolute value of normal dispersion, with its dispersion maximum occurring at $-20 \text{ ps nm}^{-1} \text{ km}^{-1}$ at the pump wavelength. The bandwidth of the supercontinuum was limited by the coupled pump power.

In this thesis, almost perfectly flat octave spanning supercontinuum is generated using one of the all-solid all-normal dispersion photonic crystal fibers from [62]. The fiber, pumped by an erbium doped fiber laser at a wavelength of 1560 nm, results in a broadband span of 1200 nm, with the red-shifted end of the spectrum at 2200 nm. The highly coherent spectrum is used for broadband amplification in Er-doped, Tm-doped and Tm-Ho co-doped fiber amplifiers to generate ultrashort pulses.

1.3 Applications of supercontinuum

The broad bandwidth of supercontinua generated in photonic crystal fibers make them ideal for ultrashort pulse generation. The shortest pulses generated in optical fibers have been achieved by the recompression of supercontinua. An argon gas filled hollow fiber was used to

generate supercontinuum spanning a bandwidth of 500 nm. A liquid crystal spatial light modulator was then used for the recompression of 1.3 mJ, 30 fs Ti:sapphire laser seed pulses, generating 2.6 fs pulses at a central wavelength of 600 nm [63]. Pulse compression of supercontinua from solid core photonic crystal fibers where lower input pulse energies are needed was demonstrated also using a spatial light modulator [64]. Spectral broadening generated in the normal dispersion side of a solid core photonic crystal fiber with one zero dispersion wavelength covered a bandwidth of 430 nm and produced compressed pulses of 5.5 fs. Spectra generated by pumping in the anomalous dispersion region, though spanning a larger bandwidth, was not compressible. The limitation of the compression is spectral coherence which is caused by soliton dynamics. The generated supercontinuum varies greatly in spectral structure and phase for each pulse, making it impossible for effective pulse compression. The limits of coherence are overcome by supercontinuum generated from all-normal dispersion photonic crystal fibers, which do not depend on input pulse characteristics and fiber length. Single cycle pulse compression [65, 66] has been successfully achieved by the compression of octave spanning supercontinuum generated from all-normal photonic crystal fibers. 5 fs pulses were achieved by linear chirp mirror compression, and a pulse width of 3.64 fs at a central wavelength of 810 nm was achieved by a spatial light modulator and chirped mirror external temporal compression system.

The generation of ultrashort pulses can also be achieved through the broadband seeding of amplification systems [19, 67, 68]. This approach makes it possible for the generation of ultrashort pulses at wavelengths other than the pump source wavelength. Notable in this is the generation of ultrashort pulses in the 2 μm region. A Tm: fiber amplifier was seeded by the solitonic part of a supercontinuum generated from a highly nonlinear fiber which was pumped by 8 nJ pulses of a 1.55 μm fiber laser [69]. The broadband seed pulse centred at 1.94 μm had a FWHM bandwidth of 350 nm which covered the entire amplification bandwidth of the Tm-

amplifier. Amplification produced pulses with FWHM of 50 nm at 1.95 μm , with transform limited pulse width of 110 fs. In another development, broadband self-frequency shifted Raman soliton pulses generated from a highly nonlinear fiber were amplified in a Tm-Ho co-doped fiber amplifier to give 80 fs pulses centred at 1925 nm with average power of 3 W after compression in a silicon prism [70].

The use of coherent supercontinuum generated from an all-solid all-normal photonic crystal fiber for broadband fiber amplification promises to be another interesting system for the generation of ultrashort pulses in the near infrared spectrum. The lack of modulation instability and soliton dynamics in this dispersion regime ensures that stable coherent pulses are generated, and so no additional pieces are needed for controlling the pulse coherence [69]. A simple all-fiber system can be implemented.

1.4 Thesis overview

The significance of high energy ultrashort pulse fiber lasers to industry, medicine and research cannot be over emphasised. The particular use of coherent ultrashort pulsed supercontinuum sources for time-resolved applications such as optical coherence tomography and nonlinear pulse compression would greatly impact the field and advance its applications.

1.4.1 Objectives of study

The main purpose of this thesis is in two parts: the construction of an ultrashort pulsed erbium-doped fiber laser and the generation of supercontinuum and its amplification in selected rare earth doped optical fibers. The specific objectives are as follows:

- Construction of a femtosecond, amplifier similariton erbium-doped fiber laser, which can ultimately serve as a pump source for supercontinuum generation in an all-fiber configuration.
- Generation of octave spanning coherent supercontinuum from an all-solid all-normal photonic crystal fiber.
- Broadband amplification of coherent supercontinuum in:
 - o Erbium-doped fiber amplifier;
 - o Thulium-doped fiber amplifier;
 - o Thulium-holmium co-doped fiber amplifier.

1.4.2 Thesis outline

The thesis has been structured such that chapter 2 gives a theoretical background to the characteristics of optical fibers and the nonlinear effects that come into play as a consequence of high intensity pulse propagation. The nonlinear Schrödinger equation used in describing the propagation of electromagnetic radiation in optical fibers and its application to numerical simulations is employed to obtain solutions representing the principal behaviour of the sources and amplifiers presented in subsequent chapters.

In chapter 3, the generation of ultrashort amplifier similariton mode-locked pulses from an erbium-doped fiber laser is demonstrated numerically and experimentally. It is shown that the normal dispersion of the gain fiber results in the generation of a broad spectrum within the laser cavity and studies on the effects of varying cavity length are presented.

Supercontinuum generation from all-solid all-normal photonic crystal fibers with bandwidth spanning an octave is demonstrated in chapter 4. Such wide band supercontinua can be recompressed to transform-limited pulse widths of a few femtoseconds.

The use of the supercontinuum pulse for broadband amplification in Er-doped, Tm-doped, and Tm-Ho co-doped fibers is presented in chapter 5. Pulses with FWHM spectral widths averaging 100 nm are generated in the Tm-Ho amplifier. Standard single-mode fiber is used for pulse compression to obtain femtosecond pulses.

The thesis concludes in chapter 6 with a summary of the work and an outlook of the possibilities from the work done.

CHAPTER 2

NONLINEAR INTERACTIONS IN OPTICAL FIBERS

The interaction of electromagnetic radiation with a material can generate a nonlinear response of the material. This is due to bound electrons of the material medium oscillating anharmonically because of the presence of the strong electromagnetic field. Several fundamental phenomena occur as a consequence of this interaction: optical Kerr effect, self-phase modulation, and stimulated Raman scattering, to name a few. These phenomena give rise to several effects when a sufficiently intense light field propagates through the medium, with the consequence that, a nearly monochromatic light field can generate signals at frequencies far removed from its frequency. This chapter presents the theoretical description of these nonlinear effects and discusses the processes that lead to supercontinuum generation, a phenomenon which results from a combination of some of these nonlinear effects.

The chapter begins with a discussion of dispersion, a fundamental occurrence in optical fibers that profoundly affects the nature of the electromagnetic field as it propagates within the optical fiber. This is principally a linear phenomenon but is of tremendous importance for a discussion of the nonlinear phenomena. Next, the principal nonlinear effects of interest in optical fibers, namely self-phase modulation, four-wave mixing, modulation instability and stimulated Raman scattering are discussed. These form the foundation for an exposition on supercontinuum generation, which is discussed both for the normal and anomalous dispersion regimes.

2.1 Dispersion

Dispersion is an important parameter in optical fibers as it affects the nature of propagating optical fields along a fiber. The interaction of electromagnetic radiation with the bound electrons of the optical fiber produces a response which is dependent on the frequency ω of the propagating electromagnetic wave with the consequence that, the refractive index of an optical fiber depends on optical frequency. This frequency dependence of the optical response of the medium in which a light wave propagates leads to chromatic dispersion.

A simple classical model for the optical response of a material can be derived from the Lorentz model of the atom [71-73]. The optical response of the medium results in an induced polarization which is summed over all resonance frequencies ω_j and is defined as the total dipole moment per unit volume,

$$\mathbf{P} = \mathbf{E}_{\text{loc}} \sum_j \frac{e^2 N_j / m_e}{\omega_j^2 - \omega^2} \quad (1)$$

where N_j is the number density of atoms that contribute to the resonance of frequency ω_j . The Maxwell displacement field $\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$ is related to the electric field $\mathbf{E}$ by the constitutive relation $\mathbf{D} = \epsilon_0 \epsilon_r \mathbf{E}$, where ϵ_0 is the permittivity of free space and ϵ_r is the dielectric constant or relative permittivity of the medium. For non-magnetic materials, the relative permittivity is related to the refractive index n of the medium by $\epsilon_r = n^2$. Evidently, the polarization of such a medium can be written as $\mathbf{P} = \epsilon_0 (n^2 - 1) \mathbf{E}$; however, the electric field $\mathbf{E}$ is a macroscopic quantity distinct from the local field $\mathbf{E}_{\text{loc}}$ in equation (1). The relationship between the local and macroscopic electric fields is given by

$$\mathbf{E}_{\text{loc}} = \mathbf{E} + \frac{\mathbf{P}}{3\epsilon_0}. \quad (2)$$

This field property and a detailed discussion of the averaging procedure that leads from the microscopic field to the macroscopic field can be found in [74]. Substitution of equation (2) in equation (1) and a suitable Taylor expansion then lead to the Sellmeier equation [75]

$$n^2(\omega) = 1 + \sum_{j=1}^m \frac{B_j \omega_j^2}{\omega_j^2 - \omega^2} \quad (3)$$

where

$$B_j = \frac{e^2 N_j}{m_e \epsilon_0 \omega_j^2} \quad (4)$$

is the strength of the j th resonance. In terms of wavelength,

$$n^2(\lambda) = 1 + \sum_{j=1}^m \frac{B_j \lambda^2}{\lambda^2 - \lambda_j^2}. \quad (5)$$

For bulk fused silica, $B_1 = 0.6961663$, $B_2 = 0.4079426$, $B_3 = 0.8974794$, $\lambda_1 = 0.0684043 \mu\text{m}$, $\lambda_2 = 0.1162414 \mu\text{m}$, and $\lambda_3 = 9.896161 \mu\text{m}$ over the wavelength range spanning $0.21 \mu\text{m}$ and $3.71 \mu\text{m}$ [76].

Any light wave characterized by a non-zero spectral bandwidth that is propagating in a dielectric medium undergoes dispersion whereby spectral components of the light wave propagate at different velocities within the dielectric due to the frequency dependence of the refractive index. The phase velocity of a spectral component of frequency ω is

$$v = \frac{c}{n(\omega)}. \quad (6)$$

A pulsed light wave propagating in such a dispersive medium experiences pulse broadening since each wavelength component arrives at a slightly different time, resulting in stretching of the pulse in the time domain.

The electric field of a monochromatic electromagnetic wave propagating in the z direction can be represented by

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0 \exp(i\omega t - i\beta z) \quad (7)$$

in which β is the wave propagation constant (or wave number) and $\mathbf{E}_0$ is the wave amplitude. In vacuum, the wave number is related to wavelength λ by $\beta = 2\pi/\lambda = \omega/c$ whereas in a dielectric, $\beta = \omega n/c$. The electric field $\mathbf{E}(\mathbf{r}, t)$ of a pulse travelling in a dielectric medium can be represented by a superposition of harmonic waves as

$$\mathbf{E}(\mathbf{r}, t) = \int_{-\infty}^{\infty} \mathbf{E}(\mathbf{r}, \omega) \exp(i\omega t - i\beta z) d\omega. \quad (8)$$

If the frequency spectrum $\mathbf{E}(\mathbf{r}, \omega)$ of the pulse is centred around ω_0 and the field of the pulse is negligible outside a frequency interval of width $\Delta\omega'$, equation (8) can be written as

$$\mathbf{E}(\mathbf{r}, t) = \int_{\Delta\omega'} \mathbf{E}(\mathbf{r}, \omega) \exp(i\omega t - i\beta z) d\omega. \quad (9)$$

The wave propagation constant $\beta(\omega) = \omega n(\omega)/c$ can be used to derive the dispersion coefficient by expanding it in a Taylor series around the central frequency ω_0 of the pulse spectrum. We assume $\beta(\omega)$ is smoothly varying. Then,

$$\begin{aligned} \beta(\omega) &= \sum_{j=0} \frac{1}{j!} (\omega - \omega_0)^j \left(\frac{d^j \beta}{d\omega^j} \right)_{\omega=\omega_0} \\ &= \beta(\omega_0) + (\omega - \omega_0) \left(\frac{d\beta}{d\omega} \right)_{\omega=\omega_0} + \frac{1}{2} (\omega - \omega_0)^2 \left(\frac{d^2 \beta}{d\omega^2} \right)_{\omega=\omega_0} + \dots \end{aligned} \quad (10)$$

In a nondispersive medium, terms proportional to $(\omega - \omega_0)^2$ and higher powers of the detuning $\Delta\omega = \omega - \omega_0$ are negligible. In the case of a dispersive medium, the quadratic and higher order terms play a significant role in light wave propagation, causing the spreading out of a pulse.

Substituting equation (10) into equation (9) and truncating the series at second order yields

$$\begin{aligned}
\mathbf{E}(\mathbf{r}, t) &= \int_{\Delta\omega'} \mathbf{E}(\mathbf{r}, \omega) \exp \left[i(\Delta\omega + \omega_0)t - i \left(\beta_0 + \frac{d\beta}{d\omega} \Delta\omega + \frac{1}{2} \left(\frac{d^2\beta}{d\omega^2} \right) \Delta\omega^2 \right) z \right] d\omega \\
&= \exp(i\omega_0 t - i\beta_0 z) \int_{\Delta\omega'} \mathbf{E}(\mathbf{r}, \omega) \exp \left[i\Delta\omega \left(t - \frac{d\beta}{d\omega} z \right) \right] \exp \left[-i \left(\frac{d^2\beta}{d\omega^2} \right) \Delta\omega^2 z \right] d\omega.
\end{aligned} \tag{11}$$

Equation (11) describes the evolution of the electric field of the pulse as it propagates through the dielectric medium. The factor outside the integral can be interpreted as representing a carrier light wave with phase $(\omega_0 t - \beta_0 z)$. A consideration of the constant phase loci of this carrier wave yields a phase velocity

$$v_p = \frac{dz}{dt} = \frac{\omega_0}{\beta_0} \tag{12}$$

of the carrier wave. The integral in equation (11) represents the pulse envelope. The two exponential factors of the integrand represent distinct propagation phenomena. The term with a phase that is linear in the detuning $\Delta\omega$ describes the motion of the pulse envelope. By a consideration of constant phase loci of this term, we obtain the group velocity v_g , the velocity of the propagating pulse envelope, as

$$v_g = \frac{d\omega}{d\beta}. \tag{13}$$

The exponential term that is quadratic in the detuning describes the spreading out or dispersion of the group velocity, which causes broadening of the pulse. Group velocity dispersion (GVD) is quantified by

$$\frac{d^2\beta}{d\omega^2} = \frac{d}{d\omega} \left(\frac{1}{v_g} \right). \tag{14}$$

Alternatively, for propagation of a light wave in optical fiber, the group velocity dispersion can be expressed as

$$\Delta\tau = D_m \Delta\lambda_0 L. \tag{15}$$

Here, D_m is the material dispersion and is related to the group velocity dispersion, $\Delta\lambda_0$ is the spectral width of the optical wave and L is the fiber propagation length.

To quantify the pulse broadening, we evaluate the time taken for a pulse to propagate along a length of fiber, which is given by

$$\tau = \tau(\lambda_0) = \frac{L}{v_g}. \quad (16)$$

The group delay is expressed as

$$\frac{1}{v_g} = \frac{d\beta}{d\omega} = \frac{d}{d\omega} \left(n(\omega) \frac{\omega}{c} \right) \quad (17)$$

from which we obtain

$$\frac{1}{v_g} = \frac{1}{c} \left[n(\lambda_0) - \frac{2\pi c}{\omega} \frac{dn}{d\lambda_0} \right] \quad (18)$$

where $\lambda_0 = 2\pi/\omega_0$ is the central wavelength of the pulse. Thus, the transit time τ of the pulse through an optical fiber of length L is given by

$$\tau(\lambda_0) = \frac{L}{v_g} = \frac{L}{c} \left[n(\lambda_0) - \lambda_0 \frac{dn}{d\lambda_0} \right]. \quad (19)$$

A pulse propagating along the fiber is made up of several frequency components and has spectral width $\Delta\lambda_0$ in the wavelength domain. Each component arrives at the end of the fiber at a different time; this gives rise to temporal pulse broadening $\Delta\tau$ given by

$$\Delta\tau = \frac{d\tau}{d\lambda_0} \Delta\lambda_0 = -\frac{L}{c} \lambda_0 \frac{d^2n}{d\lambda_0^2} \Delta\lambda_0. \quad (20)$$

The ratio of temporal broadening of the pulse to the product of fiber length and spectral width of the light wave is the material dispersion

$$D = \frac{\Delta\tau}{L\Delta\lambda_0} = -\frac{\lambda}{c} \frac{d^2n}{d\lambda_0^2}. \quad (21)$$

The material dispersion is related to the group velocity dispersion by the relation

$$D = -\frac{2\pi c}{\lambda^2} \left(\frac{d^2\beta}{d\omega^2} \right). \quad (22)$$

This shows that dispersion is wavelength dependant. For fused silica, the dominant material used for optical fibers, there is a large variation in dispersion, ranging from $-40 \text{ ps km}^{-1} \text{ nm}^{-1}$ to $25 \text{ ps km}^{-1} \text{ nm}^{-1}$ for the wavelength range from $1 \text{ }\mu\text{m}$ to $1.6 \text{ }\mu\text{m}$. For both the GVD and the material dispersion, there is a wavelength at which the dispersion is zero, and where they change sign. The zero-dispersion wavelength for fused silica is around $1.27 \text{ }\mu\text{m}$, but the zero of GVD shifts to $1.31 \text{ }\mu\text{m}$ in standard fibers because of the presence of dopants and the contribution of waveguide dispersion to the total GVD. Waveguide dispersion arises from the frequency dependence of the group velocity due to the waveguide structure. The composition of the core and cladding gives the refractive index profile of the wave guide. This together with other optical fiber wave guiding design parameters such as the core radius and the propagating mode leads to pulse broadening. The contribution of the wave guide to dispersion is given by

$$D_w = -\frac{n_2\Delta}{c\lambda} V \left(\frac{d^2bV}{dV^2} \right) \quad (23)$$

Δ is the core-cladding index difference, b is a normalised propagation constant which depends on V , a waveguide parameter that depends on the index profile of the optical fiber. The contribution of waveguide dispersion to the total GVD is relatively small. Figure 2-1 shows the variation of dispersion with wavelength for fused silica calculated using the Sellmeier parameters for the bulk material.

For wavelengths shorter than the zero-dispersion wavelength, the optical fiber is said to have normal dispersion as $\frac{d^2\beta}{d\omega^2} > 0$, giving the GVD a positive value. In this regime, the longer wavelength (red-shifted) components of the optical pulse travel faster than shorter

wavelength (blue-shifted) components and the pulse spreads out. For wavelengths greater than the zero-dispersion wavelength of the fiber, the opposite occurs where shorter wavelength components arrive at a point in the waveguide before longer co-propagating wavelength components. This regime of the fiber is known as the anomalous dispersion regime. Both regimes are illustrated in Figure 2-2 [73].

The extent of pulse broadening depends also on the pulse width T_0 and the distance the pulse propagates along the fiber. This is summarised in what is known as the dispersion length L_D which is given by

$$L_D = \frac{T_0^2}{|\beta_2|}. \quad (24)$$

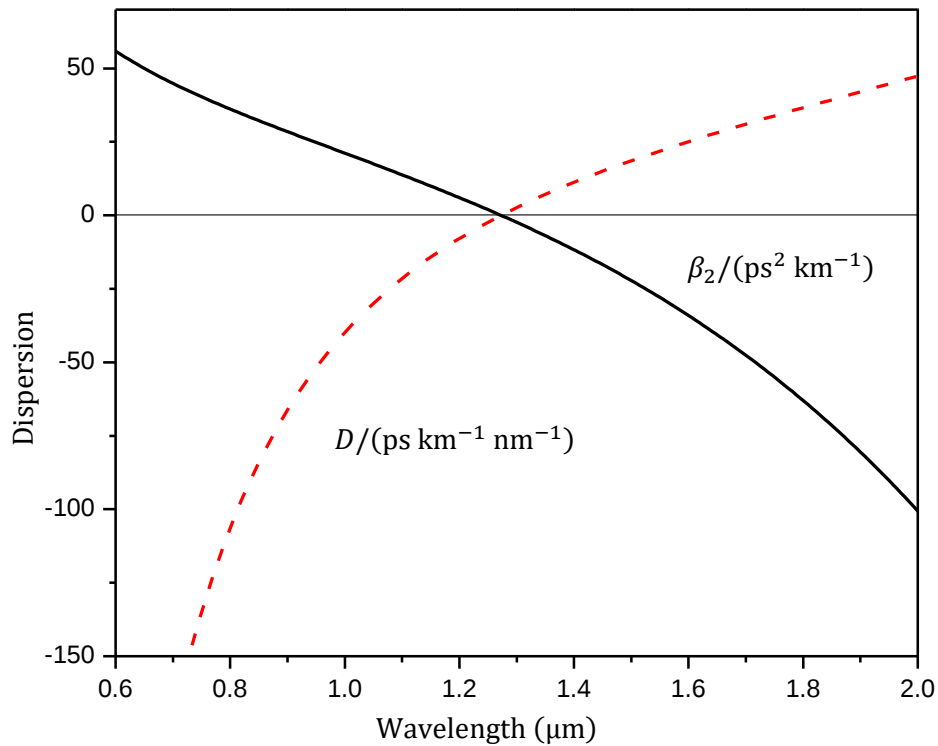


Figure 2-1 Variation of material dispersion D and group velocity dispersion β_2 for bulk silica.

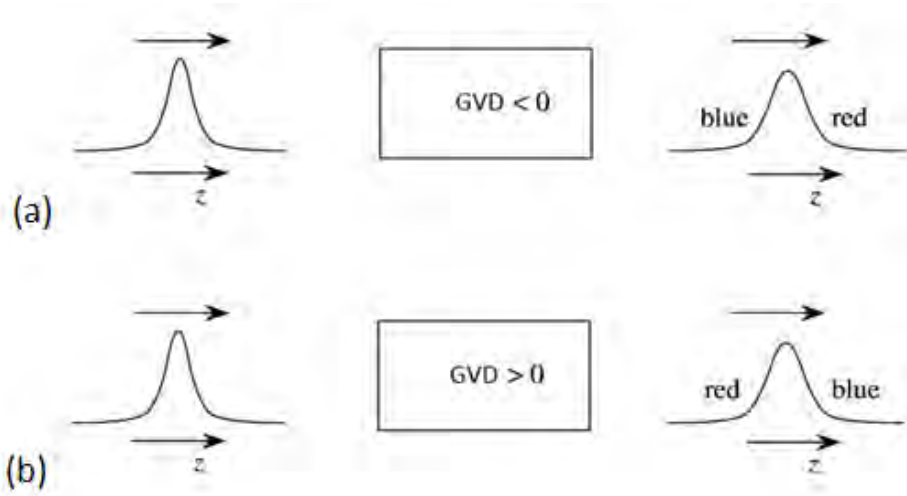


Figure 2-2. Pulse spreading resulting from (a) normal group velocity dispersion and (b) anomalous group velocity dispersion. Adapted from [73].

When the length L of fiber is such that $L \ll L_D$, dispersion does not have any significant effect on the propagating pulse. In the absence of nonlinearity, the pulse shape is maintained during propagation.

Group velocity dispersion has an important effect on the nonlinear phenomena in optical fibers. The sign of the GVD determines to a large extent the variety of nonlinear effects observed. For example, in the presence of anomalous dispersion, nonlinear effects lead to the generation of soliton pulses as a result of the inter-play between dispersion and self-phase modulation. This will be discussed in section 2.3.

2.2 Nonlinearity

As discussed in section 2.1, an applied electromagnetic field induces a net dipole moment in a dielectric: for a dielectric made up of nonpolar molecules, the polarization is

induced by charge separation; in the case of materials with permanent dipoles, a torque is also exerted on the permanent dipoles which tends to line up the moments in the direction of the field. Thus, for both polar and non-polar molecules, the effect of the applied field is to induce a polarization. For weak fields, the induced polarization responds linearly to the electric field and gives rise to the familiar phenomena of linear optics that are described by a linear constitutive relation. For sufficiently high electric fields, the material response is sensibly nonlinear.

The model for optical response presented in section 2.1 only examines the induced electric dipole moment for a harmonically bound atomic electron (Lorentz atomic model). Higher vibrational excitation of the electrons, driven by the applied optical field, leads to anharmonicity. The induced electric dipole moment per unit volume, or the induced polarization, is then no longer linear in the exciting field and can be usefully expressed as a power series in the electric field [73, 77] as

$$\mathbf{P}(\mathbf{r}, \omega) = \varepsilon_0 [\chi^{(1)} \cdot \mathbf{E} + \chi^{(2)} : \mathbf{E}\mathbf{E} + \chi^{(3)} : \mathbf{E}\mathbf{E}\mathbf{E} + \dots] \quad (25)$$

where ε_0 is the vacuum permittivity and $\chi^{(1)}$, $\chi^{(2)}$, $\chi^{(3)}$ are the first, second, and third order susceptibility tensors respectively. The susceptibility is a property of the material and it depends on the frequency of the applied field. The first order susceptibility is linear and is the major contributor to the polarization. The second order susceptibility is responsible for second order nonlinear optical interactions such as second-harmonic generation, sum-frequency generation, and optical rectification. Second order phenomena, however, only occur in materials that are noncentrosymmetric. Silica displays inversion symmetry and so does not normally produce second order nonlinear optical effects. The third order nonlinear susceptibility allows for interactions in both centrosymmetric and noncentrosymmetric materials. Some of the effects these interactions produce are third-harmonic generation, four-wave mixing, stimulated Raman scattering (SRS), and an intensity-dependent refractive index

which leads to self-phase modulation (SPM). These effects can be generated in silica-based optical fibers and are discussed in the following sections. Since the present discussions apply to optical fibers, consideration of nonlinearity omits the second order susceptibility and focuses mainly on the third order susceptibility.

We begin with the simple case of an electromagnetic field with a single carrier frequency and a slowly varying envelope propagating along an optical fiber. We define an electric field with slowly varying envelope as

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{E}_0(\mathbf{r}, t) \cos(\omega t). \quad (26)$$

On substituting equation (26) into equation (25) and ignoring the second order susceptibility, the induced polarization expression becomes

$$\mathbf{P} = \epsilon_0 [\chi^{(1)} \mathbf{E}_0(\mathbf{r}, t) \cos(\omega t) + \chi^{(3)} \mathbf{E}_0^3(\mathbf{r}, t) \cos^3(\omega t)]. \quad (27)$$

Expanding the last term using trigonometric identities results in

$$\mathbf{P} = \epsilon_0 \left\{ \chi^{(1)} \mathbf{E}_0(\mathbf{r}, t) \cos(\omega t) + \frac{\chi^{(3)}}{4} \mathbf{E}_0^3(\mathbf{r}, t) [3 \cos(\omega t) + \cos(3\omega t)] \right\}. \quad (28)$$

The first and second terms of equation (28) oscillate at the frequency of the incident wave. The first term is a response due to the linear susceptibility, whereas the response associated with the second and third terms arises from the nonlinear susceptibility. The third term describes a response of the dielectric at frequency 3ω to the applied frequency ω . This is a specific case of sum frequency generation which is responsible for third harmonic generation. This is however considered to be negligible in optical fibers unless certain phase matching conditions are met. The case of sum and difference frequency generation is discussed later, but for the present, we assume the 3ω frequency term to be negligible and omit it so that equation (28) is reduced to

$$\begin{aligned}\mathbf{P} &= \varepsilon_0 \left(\chi^{(1)} + \frac{3\chi^{(3)}}{4} \mathbf{E}_0^2(\mathbf{r}, t) \right) \mathbf{E}_0(\mathbf{r}, t) \cos(\omega t) \\ &= \varepsilon_0 \chi \mathbf{E}_0(\mathbf{r}, t) \cos(\omega t).\end{aligned}\quad (29)$$

where the effective susceptibility χ is given by

$$\chi = \chi^{(1)} + \frac{3\chi^{(3)}}{4} \mathbf{E}_0^2(\mathbf{r}, t). \quad (30)$$

The general relation for the refractive index of a material of susceptibility χ is

$$n^2 = 1 + \chi. \quad (31)$$

Substituting equation (31) into equation (30) yields

$$n^2 = 1 + \chi^{(1)} + \frac{3\chi^{(3)}}{4} \mathbf{E}_0^2(\mathbf{r}, t). \quad (32)$$

For an electromagnetic wave of amplitude E_0 , intensity I is given by

$$I = \frac{1}{2} c \varepsilon_0 n_0 E_0^2. \quad (33)$$

Thus,

$$n^2 = 1 + \chi^{(1)} + \frac{3\chi^{(3)}}{2c\varepsilon_0 n_0} I(t). \quad (34)$$

The intensity-dependent term in equation (34) is usually a small quantity. Therefore, a Taylor series expansion can be performed to obtain, to first order in the intensity,

$$n \cong n_0 + \frac{3\chi^{(3)}}{4c\varepsilon_0 n_0^2} I(t) \quad (35)$$

where

$$n_0 = \left(1 + \chi^{(1)} \right)^{1/2} \quad (36)$$

is the weak field refractive index and the intensity dependant refractive index becomes

$$n = n_0 + n_2 I(t) \quad (37)$$

with

$$n_2 = \frac{3\chi^{(3)}}{4c\epsilon_0 n_0^2}. \quad (38)$$

The intensity dependence of the refractive index leads to the optical Kerr effect where refractive index increases with intensity. The rise and fall of intensity at any point in the medium as the radiation propagates causes a time dependant refractive index of the medium. The nonlinear effects that result from the intensity dependent refractive index is summed up in the nonlinear parameter γ which is given by [78]

$$\gamma(\omega_0) = \frac{n_2(\omega_0)\omega_0}{cA_{\text{eff}}}. \quad (39)$$

The parameter A_{eff} is the effective mode area of the optical fiber.

2.2.1 Self-Phase Modulation

The dependence of refractive index on light intensity leads to a number of nonlinear optical effects, one of which is self-phase modulation (SPM). In this effect, a propagating pulse induces a phase shift on itself that may vary across the pulse envelope and result in the appearance of additional frequencies in the pulse spectrum.

The electric field of an electromagnetic pulse propagating through an optical fiber is represented by

$$E(z, t) = E_0(z, t) \exp(i\omega t - i\beta z) \quad (40)$$

the phase of which is given by

$$\phi = \omega_0 t - \frac{n\omega_0}{c} z \quad (41)$$

where the propagation constant $\beta = n\omega_0/c$ with ω_0 being the carrier frequency. Substituting the nonlinear refractive index (37) into equation (41) yields

$$\phi = \omega_0 t - \beta_0 z - \frac{\omega_0 n_2}{c} z I(t). \quad (42)$$

The field of the electromagnetic radiation after propagation through a distance z becomes

$$\mathbf{E}(z, t) = E_0 \exp \left[i \left(\omega_0 t - \beta_0 z - n_2 \frac{\omega_0}{c} z I(t) \right) \right]. \quad (43)$$

The amplitude of the electromagnetic radiation does not change during the propagation indicating that the pulse shape is preserved. There is, however, an additional frequency term to the phase of the propagating field which is induced by the nonlinear properties of the fiber. This is known as the nonlinear phase shift and it varies with time. This phenomenon is called self-phase modulation since the electromagnetic field modulates its own phase. The instantaneous frequency as found by differentiating the phase with respect to time is

$$\omega = \frac{d\phi}{dt} = \omega_0 - \frac{\omega_0 n_2}{c} z \frac{dI(t)}{dt}. \quad (44)$$

The intensity can be written as $I(t) = P_0 U(t)/A_{\text{eff}}$ where the peak power P_0 , effective mode field area A_{eff} , and the normalized intensity $U(t)$ are terms defined and used later in the thesis. The instantaneous frequency thus depends on position and time and is of form

$$\omega(z, t) = \omega_0 - \gamma P_0 \frac{\partial U(t)}{\partial t} z. \quad (45)$$

As the optical pulse propagates along a fiber, changes in its spectrum increase with nonlinearity γ , peak power, and the slope of the pulse.

Figure 2-3 shows the frequency variation across the envelope of a typical Gaussian pulse as it experiences self-phase modulation in a nonlinear medium. The top (blue) curve in Figure 2-3(a) shows the intensity of the Gaussian pulse as it propagates through a nonlinear medium and experiences self-frequency shift (red curve), as the intensity varies. The front

portion of the pulse is shifted to frequencies below the center frequency ω_0 (red-shifted) and the trailing end has frequency above ω_0 (blue-shifted). The central portion of the spectrum has a linear frequency shift or chirp given by

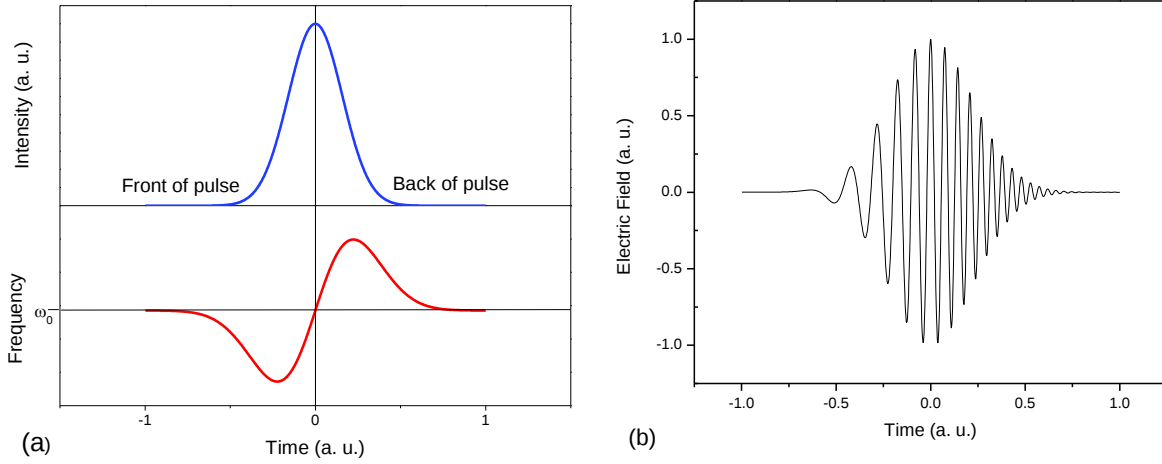


Figure 2-3 Self-phase modulation of Gaussian pulse in nonlinear medium where (a) the pulse (top curve) self-frequency shifts (bottom curve); (b) Linear frequency chirp.

$$\omega(z, t) = \omega_0 + \alpha t \quad (46)$$

where α is the slope of the frequency shift. Figure 2-3(b) shows the nature of positive linear frequency chirp for which frequency increases linearly across the pulse envelope. The additional frequencies generated by SPM broaden the pulse, and the extent of the broadening is determined by the GVD of the medium of propagation. As stated in section 2.1, a positive GVD causes temporal pulse spreading such that longer wavelengths arrive earlier than shorter wavelengths. If a pulse experiences SPM in such a medium, then the spreading of the pulse due to SPM is further increased temporally because of the positive GVD. The leading edge of the self-frequency shifted pulse which has longer wavelengths (red shifted components) travel faster and arrive earlier than the blue shifted components, increasing the pulse spreading. In the situation where the medium of propagation for a pulse experiencing nonlinear effects of SPM has anomalous dispersion, there is pulse compression. The SPM broadened pulse

experiences the effect of negative GVD whereby the trailing short wavelength or blue shifted end travels at a faster rate than the leading long wavelength portion, compressing the pulse.

The extent of self-phase modulation depends on the peak power P_0 of the propagating pulse, which determines the intensity and hence the nonlinearity. A measure of this in terms of fiber length is the nonlinear length L_{NL} which is given by

$$L_{NL} = \frac{1}{\gamma P_0}. \quad (47)$$

In the absence of dispersion, a pulse propagating in a fiber with $L \ll L_{NL}$ will not experience the effects of SPM or any other nonlinear effect for that matter to any significant extent. A fiber length comparable to or greater than the nonlinear length will induce changes in the pulse spectrum.

2.2.2 Four Wave Mixing (FWM)

Another nonlinear process that occurs in dielectrics due to the nonlinear refractive index is four-wave mixing. The effect is a consequence of the third-order nonlinear susceptibility of the dielectric which causes either two or three propagating waves in a dielectric to interact and generate new frequencies based upon the sum or difference of the incident wave frequencies. In the situation where an incident propagating wave is composed of three different frequencies, their interaction causes scattering of the incident photons giving rise to a fourth photon at a different frequency. This is known as degenerate four-wave mixing. Nondegenerate four-wave mixing occurs when two of the incident waves have the same frequency and hence there is coupling between a total of three frequencies.

2.2.3 Modulation instability (MI)

Modulation instability is a nonlinear effect which occurs in the presence of anomalous dispersion due to instability of the nonlinear system resulting from the effects of dispersive and nonlinear interactions. The periodic waveform of an electromagnetic radiation is disturbed in such a way that sidebands are generated in the spectral domain of the waveform, and the wave eventually breaks-up into a train of pulses. The nonlinear effect is a special case of four-wave interaction where two photons at the same frequency create two additional photons.

2.2.4 Stimulated Raman Scattering (SRS)

In the presence of electromagnetic radiation, molecular vibrations within a dielectric can result in stimulated inelastic scattering process in which electromagnetic radiation couples to vibrational modes of the dielectric such that Stokes and anti-Stokes photons may be emitted. This is known as stimulated Raman scattering, and the change in energy results in the emission, or absorption of an optical phonon to conserve energy and momentum. The re-emitted or scattered photons are at a frequency lower or higher than the incident photon, giving a spectrum with corresponding Stokes ($\omega_p - \omega_s$) and anti-Stokes ($\omega_p + \omega_s$) peaks which form a symmetric pattern around the frequency of the incident photon ω_p . The difference in frequency between the incident and scattered photons, $\Delta\omega \equiv (\omega_p - \omega_s)$, is associated with a Raman gain coefficient $gR(\Delta\omega)$ which is related to the imaginary part of the third-order nonlinear susceptibility.

2.3 Mode-locking

There are various ways the different axial modes within a laser cavity can be forced to coincide and be locked in phase with each other. An external signal can be used to modulate the intracavity laser signal, leading to active mode-locking. An electro-optic modulator which induces amplitude modulation, or an acousto-optic modulator inducing frequency modulation are the most popular devices used. Passive mode-locking results from an element placed within the resonant cavity to cause the laser light to self-modulate. The element behaves as an intensity dependant saturable absorber, transmitting high intensity light and blocking low intensity light. The effect of intensity dependant light absorption can also be produced using nonlinear effects of the laser cavity components, eliminating the need for a saturable absorbing material. Kerr-lens mode-locking, additive-pulse mode-locking and nonlinear polarization rotation are methods that use nonlinear phase shifts of the intracavity light. Nonlinear polarization rotation is the method that is used in the work reported in this thesis for the generation of amplifier similariton mode-locked pulses.

2.3.1 Nonlinear Polarization rotation (NLPR)

Nonlinear polarization rotation is a popular method for achieving passive mode locking in fiber lasers. It works on the principle that optical intensities in an optical fiber can change the direction of polarization of a pulse propagating in the fiber.

A pulse propagating through an optical fiber can induce birefringence in the fiber. This birefringence depends on the intensities of the two orthogonal polarization components of the pulse. The x- and y- components of an elliptically polarized pulse propagating within the fiber will therefore experience different phase shifts due to the intensity dependent self-phase modulation, and this will rotate the ellipse. The rotation of the polarization depends on the local

intensity of the pulse, and so at a high intensity portion of the pulse, the orientation of the ellipse will be different from that at a lower intensity portion. The pulse is then propagated through a linear polarizer such that another linear polarizer or an analyser can be used to select linear polarizations that correspond to the high intensity part of the pulse. This process leads to the cutting of the lower intensity wings of the pulse, and eventually, shortening the pulse. Usually, quarter and half wave-plates along with a polarizing beam splitter are used as the polarizing controllers. By rotating them, mode-locked short pulses in the range of pico- and femto-seconds are obtained.

2.4 Soliton

In section 2.1, soliton pulses were stated as one of the consequences of the nonlinear effects that occur in an optical fiber when there is a balance between the effects of nonlinearity and anomalous group velocity dispersion. In that case the fiber length for the propagating pulse is longer or comparable to the dispersive and nonlinear fiber lengths, a situation where

$$N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_0 T_0^2}{|\beta_2|} = 1. \quad (48)$$

The pulse propagates in such a manner that the broadening of the pulse due to lower wavelength components of the pulse spectrum moving faster, is counter balanced by the nonlinear spectral broadening of self-phase modulation. When $N = 1$, this is the fundamental or first-order soliton pulse. Higher intensity light causes a change in the SPM-GVD balance in such a way that SPM initially dominates during pulse propagation. The pulse splits up into multiple peaks but recovers as GVD effects increase along the fiber, eventually recovering the soliton pulse. The original shape and spectrum of the propagating pulse is restored at what is known as the soliton period. This occurs for integral numbers of N , giving higher order solitons. Pulse input

conditions that do not match an integer or the soliton order eventually evolve into fundamental solitons with part of the pulse energy dissipated.

2.5 Supercontinuum generation in photonic crystal fibers

The processes responsible for the generation of supercontinua are nonlinear, a combination of some of the processes discussed in the previous sections. The main factors that determine the nature of the continuum are the dispersive nature of the medium in which the continuum is generated, and the characteristics of the pump, namely, the pulse duration, peak power, and propagating wavelength. This section summarizes supercontinuum generation using femtosecond pulsed sources and photonic crystal fiber as the medium of generation [79, 80].

High power femtosecond pulses with wavelength close to the zero-dispersion wavelength (ZDW) of a photonic crystal fiber are normally pumped at the anomalous dispersion side of the ZDW. The pulse initially experiences spectral broadening due to SPM and temporal compression of the pump pulse, giving rise to the formation of high-order soliton pulses. As the pulse propagates through the PCF, higher order effects, namely third order dispersion and intra-pulse Raman scattering causes soliton fission (the break-up of the soliton pulse into its fundamental short pulse width solitons). In the temporal domain, the pulse is seen to be broken up into individual fundamental solitons and a dispersive wave. The soliton pulse self-frequency shifts to longer wavelengths continuously, adding new spectral components and converting the spectrum into a highly fine structured spectrum, with part of the pulse energy transferred to the dispersive waves on the normal dispersion side of the ZDW. The dispersive waves result from non-solitonic radiations emitted from the soliton fission process. Individual Raman solitons give rise to multiple spectral peaks and the pulse broadening extends into the

normal dispersion domain of the fiber. There can be coupling of the dispersive waves and the Raman solitons in the time domain through cross-phase modulation and four wave mixing to produce additional wavelengths and to give rise to a broadband supercontinuum.

The spectral broadening process is sensitive to the input pulse conditions, with fluctuations and random noise from the pump source (unless at a pulse duration less than 50 fs) causing incoherence in the generated supercontinuum pulse profile.

2.6 Pulse propagation in optical fiber

The propagation of electromagnetic radiation in an optical fiber can be described by equations based on the wave equation. These equations incorporate the nonlinear and dispersive phenomena that occur during propagation in the optical fiber. This is discussed in this section along with numerical schemes for the solution of the equations obtained.

2.6.1 Nonlinear Schrödinger equation

In the following, a summary based on [78] is given of how the NLSE is obtained from the wave equation. The wave equation is given as

$$\nabla^2 \mathbf{E} = \mu_0 \frac{\partial^2}{\partial t^2} (\epsilon_0 \mathbf{E} + \mathbf{P}) \quad (49)$$

where the polarization $\mathbf{P}$ is made up of a linear part $\mathbf{P}_L$ and a nonlinear part $\mathbf{P}_{NL}$.

The wave equation can thus be written in the form

$$\nabla^2 \mathbf{E} - \frac{1}{c^2} \frac{\partial^2 \mathbf{E}}{\partial t^2} = \mu_0 \frac{\partial^2 \mathbf{P}_L}{\partial t^2} + \mu_0 \frac{\partial^2 \mathbf{P}_{NL}}{\partial t^2}. \quad (50)$$

In deriving the nonlinear Schrödinger equation, the following assumptions are made.

1. A scalar approach is used in the derivations on the assumption that the state of polarization of a propagating field is maintained along the optical fiber.
2. The propagating field is quasi-monochromatic whose spectrum has a spectral width $\Delta\omega \ll \omega_0$, (ω_0 is a central frequency). This is true for picosecond or longer pulses.
3. The nonlinear polarization part of the induced polarization is treated as a perturbation to the linear polarization. This is reasonable as nonlinear effects under normal conditions are very small in silica fibers.
4. A slowly varying envelope approximation is also assumed.

In the slowly varying envelope approximation, the rapidly varying part of the electric field is separated such that

$$\mathbf{E}(\mathbf{r}, t) = \frac{1}{2} \hat{\mathbf{x}} [E(\mathbf{r}, t) \exp(-i\omega_0 t) + \text{c. c.}] \quad (51)$$

with $\hat{\mathbf{x}}$ representing the polarization unit vector and $E(\mathbf{r}, t)$ the slowly varying amplitude of the electric field compared to one optical cycle. The polarization components are also expressed in a similar manner with

$$\mathbf{P}_L(\mathbf{r}, t) = \frac{1}{2} \hat{\mathbf{x}} [P_L(\mathbf{r}, t) \exp(-i\omega_0 t) + \text{c. c.}] \quad (52)$$

and

$$\mathbf{P}_{NL}(\mathbf{r}, t) = \frac{1}{2} \hat{\mathbf{x}} [P_{NL}(\mathbf{r}, t) \exp(-i\omega_0 t) + \text{c. c.}]. \quad (53)$$

In obtaining the wave equation for the slowly varying envelope $E(\mathbf{r}, t)$, the frequency domain is used for convenience, with the nonlinear polarization treated as a perturbation.

Substituting equations (51), (52) and (53) into equation (50) and taking its Fourier transform give

$$\tilde{E}(\mathbf{r}, \omega - \omega_0) = \int_{-\infty}^{\infty} E(\mathbf{r}, t) \exp[i(\omega - \omega_0)t] dt. \quad (54)$$

The Fourier amplitude in equation (54) satisfies the Helmholtz equation

$$\nabla^2 \tilde{E} + \varepsilon(\omega) k_0^2 \tilde{E} = 0 \quad (55)$$

with $k_0 = \omega/c$ and the dielectric constant $\varepsilon(\omega) = 1 + \tilde{\chi}_{xx}^{(1)}(\omega) + \frac{3}{4} \chi_{xxxx}^{(3)} |E(\mathbf{r}, t)|^2$ [81].

The method of separation of variables is used to solve equation (55), assuming a solution of form

$$\tilde{E}(\mathbf{r}, \omega - \omega_0) = F(x, y) \tilde{A}(z, \omega - \omega_0) \exp(i\beta_0 z) \quad (56)$$

where $\tilde{A}(z, \omega - \omega_0)$ is a slowly varying function, $F(x, y)$ is the transverse distribution of the fundamental fiber mode and β_0 is the wave number. Equation (56) gives the following equations for $F(x, y)$ and $\tilde{A}(z,)$, respectively, in the slowly-varying amplitude approximation:

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) F + [\varepsilon(\omega) k_0^2 - \tilde{\beta}^2] F = 0 \quad (57)$$

$$2i\beta_0 \frac{\partial \tilde{A}}{\partial z} + (\tilde{\beta}^2 - \beta_0^2) \tilde{A} = 0. \quad (58)$$

The eigenvalue $\tilde{\beta}$ is given as

$$\tilde{\beta}(\omega) = \beta(\omega) + \Delta\beta(\omega). \quad (59)$$

Using the eigenvalue of equation (59) and approximating $\tilde{\beta}^2 - \beta_0^2$ to $2\beta_0(\tilde{\beta} - \beta_0)$, equation (58) can be written as

$$\frac{\partial \tilde{A}}{\partial z} = i[\beta(\omega) + \Delta\beta(\omega) - \beta_0] \tilde{A}. \quad (60)$$

Its inverse Fourier transform, taken using

$$A(z, t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} \tilde{A}(z, \omega - \omega_0) \exp[-i(\omega - \omega_0)t] d\omega \quad (61)$$

where $\omega - \omega_0$ is replaced by the differential operator $i\left(\frac{\partial}{\partial t}\right)$, yields

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} = i\Delta\beta_0 A. \quad (62)$$

The term $\Delta\beta_0$ in equation (62) accounts for fiber loss and nonlinearity and is evaluated from equation (57) such that

$$\Delta\beta_0 = -\frac{\alpha}{2} + i\gamma(\omega_0)|A|^2. \quad (63)$$

The evaluation of $\Delta\beta_0$ can be found in [78]. The nonlinear parameter γ given in equation (39) and defined as

$$\gamma(\omega_0) = \frac{n_2(\omega_0)\omega_0}{cA_{\text{eff}}}$$

has the effective mode area of the fiber given as

$$A_{\text{eff}} = \frac{\left(\iint_{-\infty}^{\infty} |F(x, y)|^2 dx dy\right)^2}{\iint_{-\infty}^{\infty} |F(x, y)|^4 dx dy}; \quad (64)$$

n_2 is the nonlinear Kerr parameter with units $\text{m}^2 \text{W}^{-1}$. The resulting pulse propagation equation takes the form

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial t^2} + \frac{\alpha}{2} A = i\gamma(\omega_0)|A|^2 A \quad (65)$$

The equation describes the change in pulse envelope as picosecond (or longer) pulses propagate in the z -direction in single-mode optical fiber. The pulse amplitude A has units V m^{-1} , and its squared modulus is usually used to represent optical power. The second and third terms represent the effects of chromatic dispersion, with their significance explained in section 2.1.

The fourth term represents the effect of loss within the fiber and the fifth term gives the nonlinear effects.

To obtain the nonlinear Schrödinger equation, a transformation of equation (65) is made whereby, the retardation time T for a frame of reference co-propagating with the pulse envelope is used:

$$T = t - \frac{z}{v_g} \equiv t - \beta_1 z. \quad (66)$$

The attenuation is also approximated to zero as in silica fibers the loss is negligible for short propagation lengths. The NLSE is obtained as

$$\frac{\partial A}{\partial z} + \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} = i\gamma(\omega_0)|A|^2 A. \quad (67)$$

2.6.2 Generalised nonlinear Schrödinger equation

The nonlinear Schrödinger equation is extremely accurate in explaining linear and nonlinear effects in optical fibers, but to a limit. In the situation where high peak power pulses propagate, the NLSE must be modified to account for related nonlinear effects such as those resulting from stimulated inelastic scattering. Ultrashort pulses close to or less than a picosecond [82-86] have to be accounted for as their large spectral widths make some of the assumptions given above inaccurate. An important consequence of this is the Raman effect discussed in section 2.2.2. If the bandwidth of the propagating pulse is large enough to accommodate the bandwidth of the Stokes frequency, then energy can be transferred from the higher frequency components to the lower frequency components through the Raman gain. This is known as intrapulse Raman scattering. The amplified lower frequency components result in a shift of the pulse spectrum towards the lower frequencies (Raman-induced frequency

shift) as the pulse propagates along the fiber. This is the effect responsible for the soliton self-frequency shift [82, 84, 87, 88].

The generalised nonlinear Schrödinger equation (GNLSE) accounts for the effects of third order nonlinearity through the nonlinear polarization. The third order susceptibility is therefore given to be [89]

$$\chi^3(t_1, t_2, t_3) = \chi^3[R(t_1)\delta(t_2)\delta(t_3 - t_1) + \delta(t_1 - t_2)R(t_2)\delta(t_3) + \delta(t_1)\delta(t_2 - t_3)]. \quad (68)$$

The nonlinear response function $R(t)$ is normalised so that $\int_{-\infty}^{\infty} R(t)dt = 1$. The scalar form of the nonlinear polarization then becomes:

$$P_{NL}(\mathbf{r}, t) = \frac{3\epsilon_0}{4}\chi_{xxx}^{(3)}E(\mathbf{r}, t) \int_{-\infty}^t R(t - t_1)E^*(\mathbf{r}, t_1)E(\mathbf{r}, t)dt_1. \quad (69)$$

Using a similar derivation process for the NLSE (details in [78]), the pulse propagation equation is obtained as [86]

$$\begin{aligned} \frac{\partial A}{\partial z} + \frac{1}{2}\left(\alpha(\omega_0) + i\alpha_1 \frac{\partial}{\partial t}\right)A - i \sum_{n=1}^{\infty} \frac{i^n \beta_n}{n!} \frac{\partial^n A}{\partial t^n} \\ = i\gamma \left[\gamma(\omega_0) + i\gamma_1 \frac{\partial}{\partial t} \right] \left[A(z, t) \int_0^{\infty} R(t') |A(z, t - t')|^2 dt' \right] \end{aligned} \quad (70)$$

The integral in the last term of equation (70) is responsible for intrapulse Raman scattering. The nonlinear response function $R(t)$ is made up of the instantaneous electronic response and the delayed vibrational response and is given by [90]

$$R(t) = (1 - f_R)\delta(t - t_e) + f_R h_R(t) \quad (71)$$

where f_R is the fractional contribution of the delayed Raman response to nonlinear polarization and h_R is the Raman response function. t_e accounts for a delay in electronic response, but it is, however, negligible (< 1 fs).

For pulse widths greater than 100 fs, equation (70) can be simplified further by using a Taylor series expansion on a slowly varying pulse envelope:

$$|A(z, t - t')|^2 \approx |A(z, t)|^2 - t' \frac{\partial}{\partial t} |A(z, t)|^2. \quad (72)$$

The response function is also redefined as

$$T_R \equiv \int_0^\infty t R(t) dt \approx f_R \int_0^\infty t h_R(t) dt \quad (73)$$

to give the GNLSE for a pulse propagating in the retarded reference frame

$$\begin{aligned} \frac{\partial A}{\partial z} + \frac{(g - \alpha)}{2} A - \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} - \frac{i\beta_3}{6} \frac{\partial^3 A}{\partial T^3} \\ = i\gamma \left[|A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial T} (|A|^2 A) - T_R A \frac{\partial |A|^2}{\partial T} \right]. \end{aligned} \quad (74)$$

The effects of net gain $(g - \alpha)$ are accounted for by the second term in the GNLSE. The expansion of the propagation constant results in the third term being responsible for group velocity dispersion while the fourth term deals with the effects of third order dispersion (significant for ultrashort pulses). The nonlinear terms in the bracket represent the effects of self-phase modulation, self-steeping and stimulated Raman scattering respectively.

2.6.2.1 Parabolic pulse solution of the GNLSE

Denoting the net gain as g and omitting higher order nonlinear terms, the GNLSE (74) is simplified to

$$\frac{\partial A}{\partial z} = \frac{g}{2} A - \frac{i\beta_2}{2} \frac{\partial^2 A}{\partial T^2} + i\gamma |A|^2 A. \quad (75)$$

In the situation where ($\beta_2 > 0$), that is for a pulse propagating in a medium with normal dispersion and gain, asymptotic self-similar solutions of equation (75) are found in the limit as $z \rightarrow \infty$ [91]. The amplifier similariton pulse, as it is known, is therefore a nonlinear attractor to the GNLSE with a parabolic pulse profile given as

$$A(z, T) = A_0(z) \sqrt{1 - \left(\frac{T}{T_0}\right)^2} \exp i\varphi(z, T) \quad (76)$$

and a quadratic phase given as

$$\varphi(z, T) = \varphi_0 + \frac{3\gamma}{2g} A_0^2 - \frac{gT^2}{6\beta_2} \quad (77)$$

for $|T| \leq T_0(z)$ and φ_0 a constant. The SPM induced quadratic phase results in an acquired linear chirp given as

$$\partial\omega(T) = \frac{-\partial\varphi(z, T)}{\partial T} = \frac{gT}{3\beta_2}. \quad (78)$$

The pulse propagates self-similarly such that its amplitude and effective pulse width increase exponentially while maintaining a parabolic profile given by

$$A_0(z) = \frac{1}{2} (gE_{in})^{1/3} \left(\frac{\gamma\beta_2}{2}\right)^{1/6} \exp \frac{gz}{3} \quad (79)$$

$$T_0(z) = 3g^{2/3} \left(\frac{\gamma\beta_2}{2} \right)^{1/3} E_{in}^{1/3} \exp \frac{gz}{3}. \quad (80)$$

The energy that is input into the amplifier E_{in} is what determines the amplitude and width of the resulting parabolic pulse. This implies that any pulse shape input into a normal dispersion gain fiber will eventually evolve asymptotically to a similariton pulse profile.

2.6.3 The split-step Fourier method

The nonlinear and generalised nonlinear Schrödinger equations are partial differential equations which are difficult to solve using analytical means. Solutions are only attainable under special conditions and reduced forms of the NLSE and the GNLSE, where the inverse scattering method has been used [92]. Numerical methods are therefore used to solve the equations, with the most popular being the split-step Fourier (SSF) method. The finite Fourier transform algorithm used in conjunction with the split-step Fourier method makes the computation of the numerical process faster and more efficient. The SSF method works by separating the NLSE and the GNLSE into a dispersive and a nonlinear part. Although the effect of dispersion and nonlinearity on a pulse as it propagates through an optical fiber occur simultaneously, the split-step method obtains its solution by assuming that for a short propagation distance h , the dispersion and nonlinear effects act separately and consecutively on the pulse. This means that initially, dispersion acts alone over the short distance h , after which nonlinearity acts on the radiation for the same short distance. The resulting radiation is then acted upon again by the dispersive element for another short distance, then the nonlinear element, and the sequence is performed over the entire length of the fiber to get the total effect of dispersion and nonlinearity.

The NLSE is rewritten in the form:

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N})A \quad (81)$$

where $\hat{D}$ accounts for dispersion and losses and $\hat{N}$ represents the nonlinearities within the fiber.

Using the GNLSE (98), the dispersive and nonlinear operators are

$$\hat{D} = \frac{\alpha}{2}A - \frac{i\beta_2}{2}\frac{\partial^2 A}{\partial T^2} - \frac{i\beta_3}{6}\frac{\partial^3 A}{\partial T^3} \quad (82)$$

$$\hat{N} = i\gamma \left(|A|^2 A + \frac{i}{\omega_0} \frac{\partial}{\partial T} (|A|^2 A) - T_R A \frac{\partial |A|^2}{\partial T} \right). \quad (83)$$

Integrating equation (81) in the z -direction over a small distance from z to $z + h$ gives

$$A(z + h, T) = \exp[h(\hat{D} + \hat{N})] A(z, T). \quad (84)$$

The SSF method however operates such that

$$A(z + h, T) \approx \exp(h\hat{D}) \exp(h\hat{N}) A(z, T). \quad (85)$$

The dispersive term is easily solved in the spectral domain using the Fourier transform operation to get

$$\exp(h\hat{D}) B(z, T) = F_T^{-1} \exp[h\hat{D}(-i\omega)] F_T B(z, T) \quad (86)$$

F_T is the Fourier transformation operator and $\hat{D}(-i\omega)$ is obtained by replacing $\frac{\partial}{\partial T}$ with $-i\omega$ in equation (82).

Equations (84) and (85) show that there is some amount of error in the SSF. The SSF assumes the dispersion and nonlinearity operator commute whereas in reality the exponential operator with argument $\hat{D} + \hat{N}$ cannot be factored as in equation (85). This deficiency is remedied by invoking the Baker-Hausdorff formula for noncommuting operators $\hat{a}$ and $\hat{b}$ as

$$\exp(\hat{a}) \exp(\hat{b}) = \exp\left(\hat{a} + \hat{b} + \frac{1}{2}[\hat{a}, \hat{b}] + \frac{1}{12}[\hat{a} - \hat{b}, [\hat{a}, \hat{b}]] + \dots\right). \quad (87)$$

If $\hat{a} = h\hat{D}$ and $\hat{b} = h\hat{N}$, the main error comes from the $\frac{1}{2} h^2 [\hat{D}, \hat{N}]$ commutator term, giving the split-step Fourier method an accuracy that is second order in the step size h .

An approach to improve the accuracy of the split-step Fourier method is to apply the nonlinear effect on the middle portion of the short segment h as the pulse propagates. This is known as the symmetrized split-step Fourier method and yields

$$A(z + h, T) \approx \exp\left(\frac{h}{2}\hat{D}\right) \exp\left(\int_z^{z+h} \hat{N}(z') dz'\right) \exp\left(\frac{h}{2}\hat{D}\right) A(z, T). \quad (88)$$

The application of equation (88) over M successive steps along the propagation length of an optical fiber results in

$$A(L, T) \approx e^{-\frac{1}{2}h\hat{D}} \left(\prod_{m=1}^M e^{h\hat{D}} e^{h\hat{N}} \right) e^{\frac{1}{2}h\hat{D}} A(0, T) \quad (89)$$

The integral of equation (88) is approximated to $h\hat{N}$, and the total fiber length $L = Mh$.

2.6.4 The Runge-Kutta in the interaction picture method

A method which has proven to be more accurate than the split-step Fourier method in solving the generalised nonlinear Schrodinger equation is the fourth order Runge-Kutta in the interaction picture (RK4IP) numerical method. This method is similar to the symmetric split-step method in that the NLSE is separated into linear and nonlinear components. Originally designed for studies on the Bose-Einstein condensate by solving the Gross-Pitaevskii equation [93], the RK4IP has been adapted for use in nonlinear optics by applying it to the GNLSE [94]. The GNLSE is transformed into an interaction picture where it is separated into dispersive and nonlinear terms. The RK4IP algorithm can then be used to obtain the solution of the equation in the normal picture. Results using this method give fourth-order global accuracy, greater accuracy than that of the symmetrized SSF method, and its implementation is easy with faster iterations. The RK4IP has been successfully used in simulations of a number of nonlinear optical interactions [95, 96].

The pulse envelope $A(z, T)$ is transformed into the interaction picture representation through the relation [94]

$$A_I = \exp(-(z - z')\hat{D}) A \quad (90)$$

where z' represents the coordinate of the boundary point from which propagation proceeds to the point with coordinate z . The propagation of the pulse envelope in the interaction picture is obtained by differentiating equation (90) to obtain

$$\frac{\partial A_I}{\partial z} = \hat{N}_I A_I \quad (91)$$

where $\hat{N}_I$ is the nonlinear operator in the interaction picture and is given by

$$\hat{N}_I = \exp(-(z - z')\hat{D}) \hat{N} \exp((z - z')\hat{D}) \quad (92)$$

The fourth order Runge-Kutta interaction picture algorithm is used to solve equation (91) by taking $z' = z + \frac{h}{2}$. Then, the RK4IP algorithm for propagating the pulse envelope from $A(z, T)$ to $A(z + h, T)$ in step size h in the normal picture is [94]

$$A(z + h, T) = \exp\left(\frac{h}{2}\hat{D}\right) \left[A_I + \frac{k_1}{6} + \frac{k_2}{3} + \frac{k_3}{3} \right] + \frac{k_4}{6} \quad (93)$$

$$A_I = \exp\left(\frac{h}{2}\hat{D}\right) A(z, \omega) \quad (94)$$

$$k_1 = \exp\left(\frac{h}{2}\hat{D}\right) [h\hat{N}A(z, \omega)] A(z, \omega) \quad (95)$$

$$k_2 = h\hat{N} \left(A_I + \frac{k_1}{2} \right) \left[A_I + \frac{k_1}{2} \right] \quad (96)$$

$$k_3 = h\hat{N} \left(A_I + \frac{k_2}{2} \right) \left[A_I + \frac{k_2}{2} \right] \quad (97)$$

$$k_4 = h\hat{N} \left(\exp\left(\frac{h}{2}\hat{D}\right) (A_I + k_3) \right) \exp\left(\frac{h}{2}\hat{D}\right) [A_I + k_3]. \quad (98)$$

CHAPTER 3

SIMULATION AND DEVELOPMENT OF ULTRASHORT PULSED MODE-LOCKED ERBIUM-DOPED FIBER LASER

Advances in technology, coupled with the growth of the optical fiber telecommunications industry, have resulted in erbium doped fibers and other optical fiber pigtailed components operating at 1550 nm and their associated devices becoming readily available at low cost. This makes it possible to construct an inexpensive all-fiber erbium-doped fiber laser. The mode-locked pulse regime of popular interest for fiber lasers is the amplifier similariton pulse. This is expected to be the most probable pulse shape that will lead to the production of fiber lasers with the highest pulse energies and shortest pulse widths. The amplifier similariton pulse characteristics are determined mainly by the normal-dispersion, nonlinear gain medium. The nature of the other cavity parameters is not of importance. This allows for a dispersion map fiber laser configuration with net anomalous, normal or zero group velocity dispersion [17]. Though much research has been done in this pulse regime, there is still the need for better understanding of the dynamics of the amplifier similariton and its applications [97].

In this chapter, an erbium-doped fiber laser operating in the net normal amplifier similariton pulse regime that generates femtosecond pulses at high repetition rate is developed. The general configuration and the characterisation of the laser is presented. The presented configuration for the fiber laser is an adaptation of an all-normal dispersion ytterbium-doped fiber laser from the Optical Fibers and Fiber Laser Group of the Institute of Applied Physics (IAP), University of Bern. Before this, we present a simulation study of an erbium-doped fiber laser which operates with net normal dispersion such that self-similar pulses are generated. The

purpose of the simulation is to have a general guide for the design and construction of the erbium-doped fiber laser.

3.1 Simulation of Er-doped fiber laser

A simulation code [98] based on the RK4IP approach presented in chapter 2 has been incorporated into a simulator for studying mode-locked fiber lasers and nonlinear phenomena in optical fibers. A schematic of the simulated erbium fiber laser is given in Figure 3-1. The cavity comprises two segments of standard single-mode fiber (SMF) of unequal length that sandwich a length of erbium-doped fiber (EDF). Coupling to the EDF is achieved through a pair of fiber pigtails (HI1060). The laser ring is closed through a saturable absorber which incorporates a spectral filter. The saturable absorber is implemented as the transmission function $1 - \delta / \left(1 + \frac{E^2}{P_{sat}} \right)$, where the saturation power P_{sat} is chosen to be 1 kW and the modulation depth δ is selected as 90%. A filter bandwidth of 10 nm is adopted and the gain of the EDF is set at 30 dB.

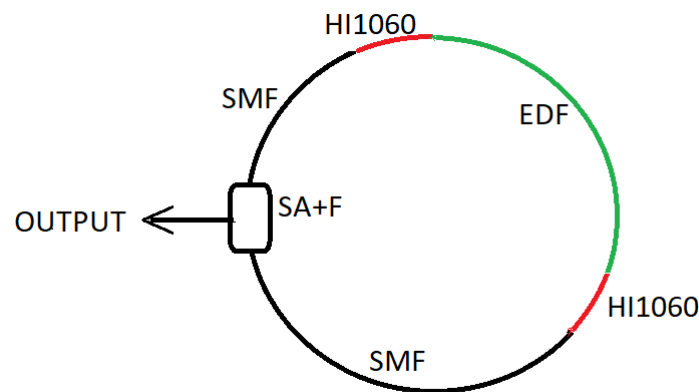


Figure 3-1 Schematic of an erbium-doped fiber ring laser. SMF: standard single-mode fiber; EDF: erbium-doped fiber; HI1060: fiber pigtails; SA+F: Saturable absorber and spectral filter.

Figure 3-2 shows the evolution of the spectral and temporal widths of the field in the fiber ring at steady state. The initial state is white noise which evolves to a pulse after several iterations in which the output of one iteration is injected into the input for the next iteration until steady state is achieved. At steady state, the spectral width increases as the pulse propagates through the EDF amplifier section of the cavity and again through the adjoining

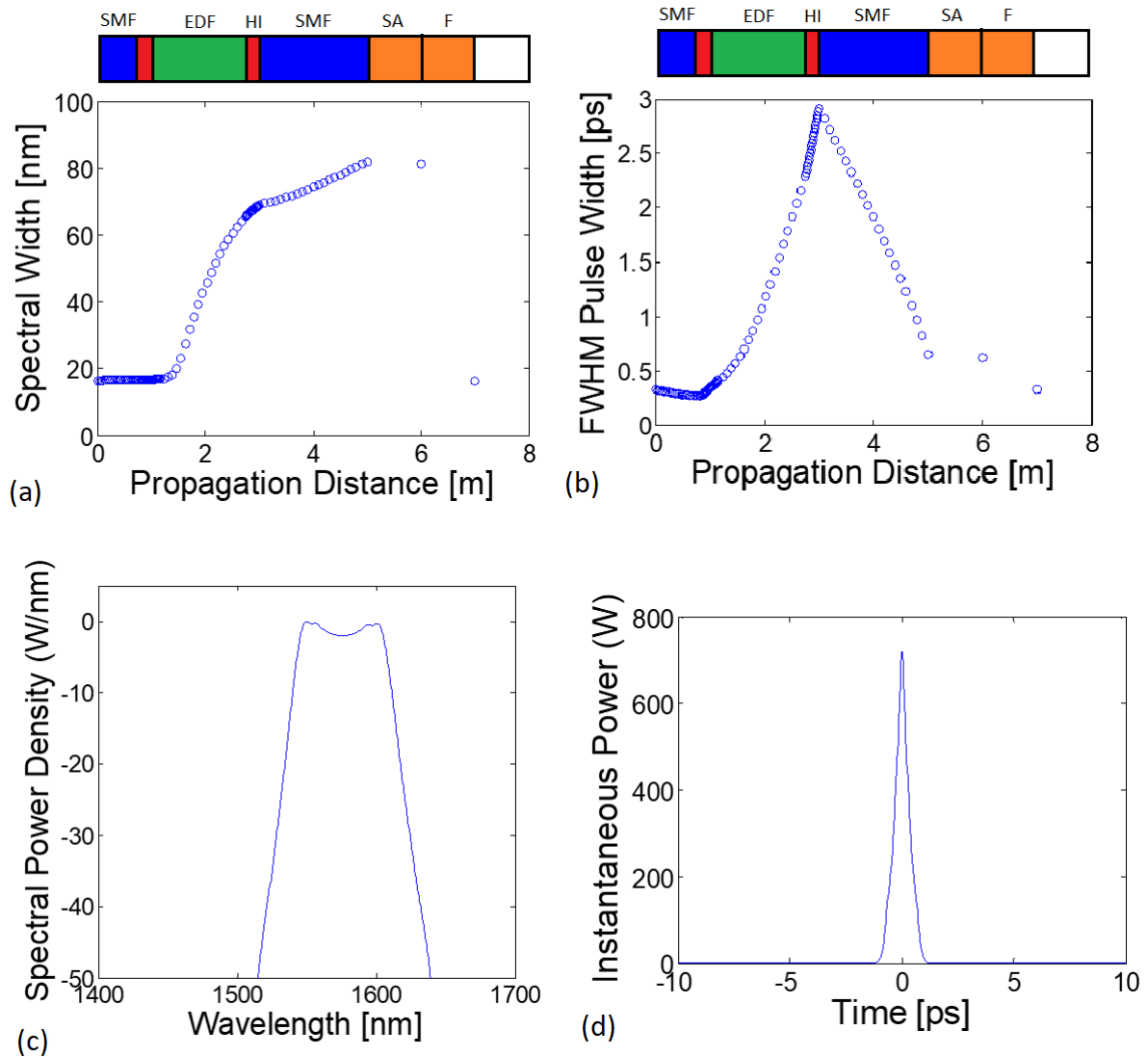


Figure 3-2 Steady state spectral width (a), pulse width (b), spectral power density (c), and temporal profile (d) of a simulated erbium-doped fiber laser.

standard single-mode fiber, in which pulse compression simultaneously occurs with increasing propagation distance towards the saturable absorber and spectral filter. This behaviour is consistent with the dispersion map of the cavity.

The output spectrum, shown in Figure 3-2(c), has a characteristic dip that depends on the filter bandwidth and saturation energy and is suggestive of a similar spectral dip in the output of the actual laser presented in the following section. Simulations indicate that the spectral dip arises from self-phase modulation. Whereas the simulation is intended to model the principal components of the physical mode-locked fiber laser, it only does so in a gross manner and omits details such as the mechanism by which the saturable absorber function is realized and the gain spectrum of the EDF amplifier. At any rate, the simulation results are indicative of the values of such parameters as fiber lengths at which mode-locking is to be expected.

3.2 Development of amplifier similariton erbium-doped fiber laser

Two separate Er-doped fiber laser cavities with lengths of 355 cm and 510 cm were constructed. Nonlinear polarization evolution was used to achieve the saturable absorber function. Details of each implementation are presented in turn.

3.2.1 355 cm cavity

3.2.1.1 Experimental setup

The schematic diagram for the 355 cm laser cavity is given in Figure 3-3. The cavity has two segments made-up of normal group velocity dispersion and anomalous group velocity dispersion. The anomalous group velocity dispersion arises from a combination of 151 cm of

single-mode fiber, 21 cm of polarization maintaining fiber and 63 cm of HI1060 fiber ($\beta_2 = -5.8 \text{ ps}^2 \text{ km}^{-1}$, $\gamma = 4.0 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$) which comes as the pigtail of the wavelength division multiplexer (WDM) used to couple pump light into the cavity. The single-mode fiber has a group velocity dispersion of $-22 \text{ ps}^2 \text{ km}^{-1}$ and a nonlinearity of $1.4 \times 10^{-3} \text{ W}^{-3} \text{ m}^{-1}$. The gain fiber, which is an OFS erbium doped fiber (EDF-150), provides normal group velocity dispersion of $59 \text{ ps}^2 \text{ km}^{-1}$ and has a nonlinear parameter value of $6.2 \times 10^{-3} \text{ W}^{-1} \text{ m}^{-1}$. The gain fiber has a high erbium concentration of $223.351024 \text{ m}^{-3}$, with an absorption of 103.56 dB m^{-1} near 980 nm. The core radius is $1.24 \text{ }\mu\text{m}$ with a numerical aperture of 0.268. The length of EDF-150 used in this laser cavity is 120 cm, giving a total net cavity dispersion of 0.029 ps^2 . The laser cavity therefore operates in the normal dispersion regime.

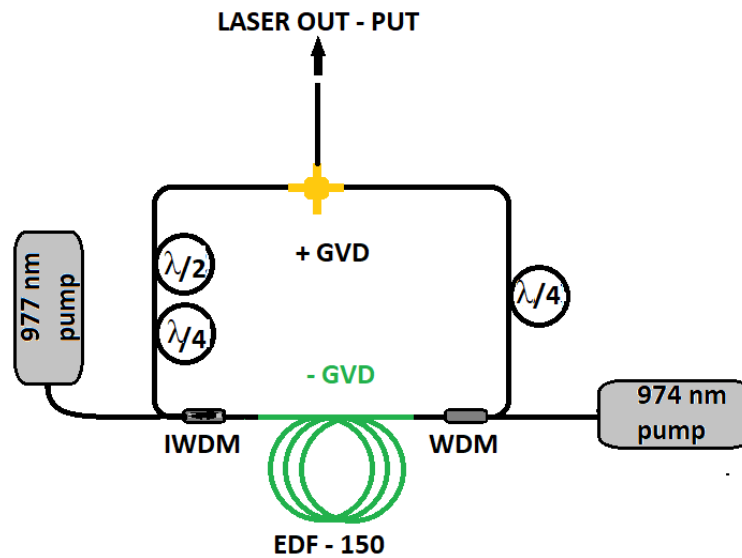


Figure 3-3 Experimental setup for 355 cm erbium-doped fiber laser cavity.

The EDF-150 erbium doped fiber is pumped bi-directionally by two separate diode lasers: a QPhotonics diode laser which operates at a wavelength of 974 nm and at a maximum power of 450 mW, and a second diode laser operating at a wavelength of 977 nm with

maximum power of 600 mW. Pumping at both ends of the erbium doped fiber ensures that population inversion occurs along as much of the doped fiber length as possible. The 974 nm diode pump laser is coupled to the EDF-150 fiber through a high-power fused wavelength division multiplexer (FWDM), and the 977 nm pump laser is coupled to the Er-doped gain fiber through 26 cm of the HI1060 fiber pigtail port of a hybrid isolating wavelength division multiplexer (IWDM). The IWDM forces propagation of the generated radiation in one direction by the presence of an integrated isolator in its construction. The single-mode fiber pigtailed pass port of the IWDM is used to form a quarter and half wave-plate by wrapping it round a Thorlabs FPC020 fiber paddle polarization controller. The length of the pigtailed SMF fiber is 75 cm and the diameter of the individual paddles is 18 mm, with one loop of single-mode fiber around a paddle corresponding to a quarter-wave plate, and two loops of fiber corresponding to a half-wave plate. The fiber pigtail of the WDM pass port is made with HI1060 fiber and so it is spliced to 46 cm of SMF which forms a quarter wave-plate. A 2×2 polarizing beam splitter (PBS) with 21 cm of pigtailed polarization maintaining (PM) fiber as input port is spliced to the quarter wave-plate. The other input port is not used in the cavity. One of the output ports of the PBS is made with SMF and the other with PM fiber. A length of 30 cm of the SMF output port is spliced to the halfwave-plate, closing the ring cavity. The PM fiber port of the PBS is the output for the laser cavity. Because of the sensitivity to high power of most monitoring equipment, a 1:99 fused PM fiber splitter is spliced to this output port and laser signal from the 1 percent port of this splitter is again divided by a 50:50 single-mode coupler. One arm of the 50:50 coupler goes to an InGaAs photodetector from Thorlabs (DETO1CFC) which has a specified maximum input peak power of 70 mW. The photodetector converts the optical signals and gives corresponding electrical signals which are monitored with a Picoscope6 oscilloscope together with Signal Hound spectrum analyser software. The other arm of the 50:50 coupler is connected to a Yokogawa AQ6370 optical spectrum analyser.

3.2.1.2 Results and discussion

Initial mode locking was obtained at a combined pump power of 990 mW, with 400 mW from forward pumping at 974 nm and 590 mW from the backward pumping 977 nm diode. Pulsed laser mode operation was obtained by passive mode-locking based on nonlinear polarization evolution as explained in section 2.3.1. This was achieved by the combined action of the polarizing beam splitter and the rotation of the quarter and half waveplates. Nonlinear polarization evolution was chosen for realizing the saturable absorber function because it is easy to implement in this all-fiber setup and it is inexpensive compared to other methods that rely on separate components with bulk optics [99]. Within the laser cavity, linearly polarized radiation from the PBS is converted to elliptical polarization by the “fiber quarter wave-plate”. On reaching the next fiber quarter wave-plate after propagating through the remaining single-mode and erbium doped fiber, the state of polarization of the beam, which is elliptically polarized but with different polarization orientations on the beam depending on the local intensity, is changed to an almost circular polarization with portions of low intensity being more elliptical in nature [100]. The half wave-plate changes the handedness of the circular and elliptical polarization. The half wave-plate is aligned such that the elliptically polarized lower intensity portions of the radiation are cut off by the polarizing beam splitter which serves as a linear polarizer. The central, high intensity circular polarization of the propagating radiation is transmitted through the polarizing beam splitter, shortening the beam and giving rise to mode-locked pulses. The generated mode locked spectrum (Figure 3-4) has a 3 dB span of 17 nm with a central wavelength at 1575 nm. The average power of the pulse is 27 mW.

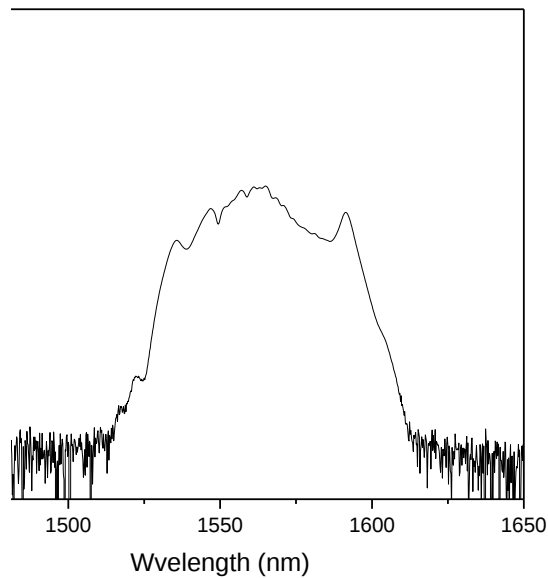


Figure 3-4 Experimental results showing mode-locked spectrum for 355 cm cavity with average power of 27 mW.

In studies of the behaviour of the laser, the pump lasers were shut off for several hours and the laser was re-started. It was observed that mode-locked pulses were not obtained immediately the pump lasers were switched back on. Mode-locking was initiated again at the same pump power by re-orientation of the polarization controller paddles. A slightly lower average laser power of 25 mW was obtained at this new setting of the rotation paddles. This confirms the observation that different combinations of the orientations of the polarization controllers give different saturation levels of mode-locking, which results in different mode-locked regimes with different pulse energies [8].

It is known that bending, twisting and other environmental factors affect the birefringence of optical fiber and hence the state of polarization of the propagating radiation. To see the effect on mode-locking due to changes in fiber birefringence, the fiber laser cavity components were re-secured in the set-up, altering its birefringence and hence the polarization of the propagating radiation. On rotation of the wave-plates, the newly oriented cavity had a

maximum average laser power of 92 mW in CW mode. Mode-locked pulses were obtained at a total power of 740 mW, with the 974 nm pump diode giving 450 mW and the 977 nm pump diode giving 290 mW. The mode-locked pulses had a repetition rate of 52.13 MHz calculated from the 19.18 ns period of the pulse train shown in figure 3-5c. This is confirmed by the RF analyser measurement shown in Figure 3-5d. The pulses are stable and self-starting with an average power of 24 mW giving a pulse energy of 0.46 nJ. The pulse spectrum of figure 3-5 has a central peak at 1572 nm with a broader FWHM of 50 nm as compared with earlier

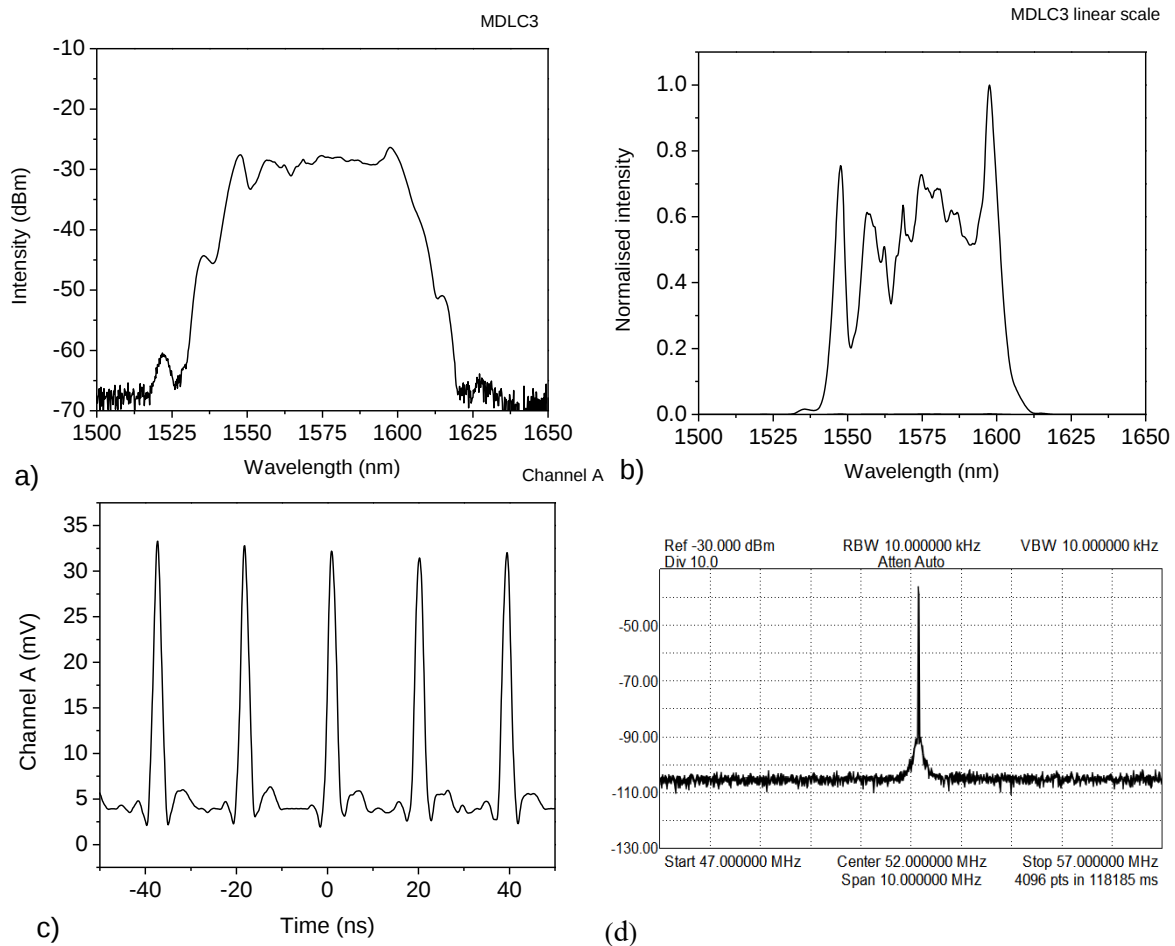


Figure 3-5 Characteristics of 1572 nm mode-locked fiber laser cavity showing the pulse spectrum in the logarithmic (a) and linear (b) scale. The oscilloscope display of the pulse train (c), and the RF spectrum (d).

measurements taken from the cavity. Such a spectral width indicates a pulse width of 72.7 fs for a transform limited pulse. However, as the spectrum of the pulse is structured, the lower limit of the time-bandwidth product does not give a good estimate of the pulse duration. A more realistic estimate of the pulse duration is given by the FWHM of the Fourier transform of the pulse spectrum. This gives the pulse a calculated pulse duration of 105.42 fs.

The spectral shape of the mode-locked pulses obtained in all three situations of this cavity are approximately parabolic, which is indicative of similariton pulse evolution. Observation of spectral bandwidth increase was made as pump power increased to its maximum stable mode-locked state. This spectral increase is as a result of SPM confirming that the propagating pulse is an amplifier similariton and not a stretched pulse, or dispersion managed soliton as has been reported elsewhere [8]. The reported stretched pulse laser cavity is similar to the setup of this thesis and yielded similar pulse spectral bandwidth of 56 nm, but was not able to meet the requirements for amplifier similariton generation. The spectrum of the generated pulse from the 355 cm laser cavity was also structured indicating the occurrence of chirping. Even without the physical presence of a spectral filter in the cavity as has been indicated in an earlier paper [16], amplifier similaritons have been achieved similarly to [101]. The polarizing beam splitter acts as a filter since polarization is wavelength dependant, filtering out and allowing specific wavelengths for mode locking. The isolating WDM may also play a role in this as it is also wavelength dependant with the same passband of width 20 nm.

3.2.2 510 cm cavity

A second erbium-doped fiber laser cavity is built for the generation of amplifier similariton pulses. A new set of polarization rotation paddles are constructed with loop diameter of 50 mm. These paddles are designed such that they can be attached to motorised

controllers with the aim of automating the mode-locking system for further studies. Three loops of single-mode fiber wrapped around the 50 mm diameter rotation paddles are needed to generate quarter wave retardation at an operating wavelength of 1550 nm. Six loops around the rotation paddles are needed for half wave retardation. The increase in the number of loops results in an increase in the length of single-mode fiber needed in the cavity. 287 cm of single-mode fiber was used and maintaining 63 cm of HI1060 fiber, a total anomalous dispersion of -0.06679 ps was obtained in the new cavity. The length of the erbium doped fiber EDF-150 was increased to 160 cm to maintain a net normal cavity dispersion. The total cavity length thus increased to 510 cm, with a calculated net cavity dispersion of 0.02761 ps. The setup of the erbium fiber laser is similar to that of the 355 cm cavity described earlier; however, in addition to the change in fiber lengths, a change in position of the pump laser diodes was also implemented. The QPhotonics diode laser operating at 974 nm wavelength was moved from forward pumping position to backward pumping by splicing it to the FWDM. The 977 nm diode laser was moved to forward pumping position.

Stable mode-locking was achieved in this new cavity with 600 mW pump power from forward pumping at 977 nm and 50 mW from the 974 mW pump diode. This is much lower than the 740 mW pump power of the 355 cm cavity. The recorded mode-locked spectrum is shown in Figure 3-6. The spectrum is structured with an approximately parabolic envelope centred at 1604 nm with a FWHM bandwidth of 60 nm,. The pulse gives an average power of 3.30 mW. On restarting the erbium-doped fiber laser after switching it off for two days, mode-locking was easily achieved by a slight adjustment in total pump power to 643 mW. The slight decrease in pump power (forward pump power of 591 mW, and slightly increased backward pump power of 52 mW), resulted in pulses with an average power of 3.95 mW, centred at 1603 nm. Figure 3-7a shows the output pulse spectrum with a spectral bandwidth of 59 nm. The profile of the spectrum is similar to the profile of the mode-locked spectrum of

this cavity at the slightly higher pump power (Figure 3-6). The RF spectrum shows single stable pulsing at a repetition rate of 37.65 MHz which is confirmed by the pulse train with a period of 26.5 ns (Figure 3-7c).

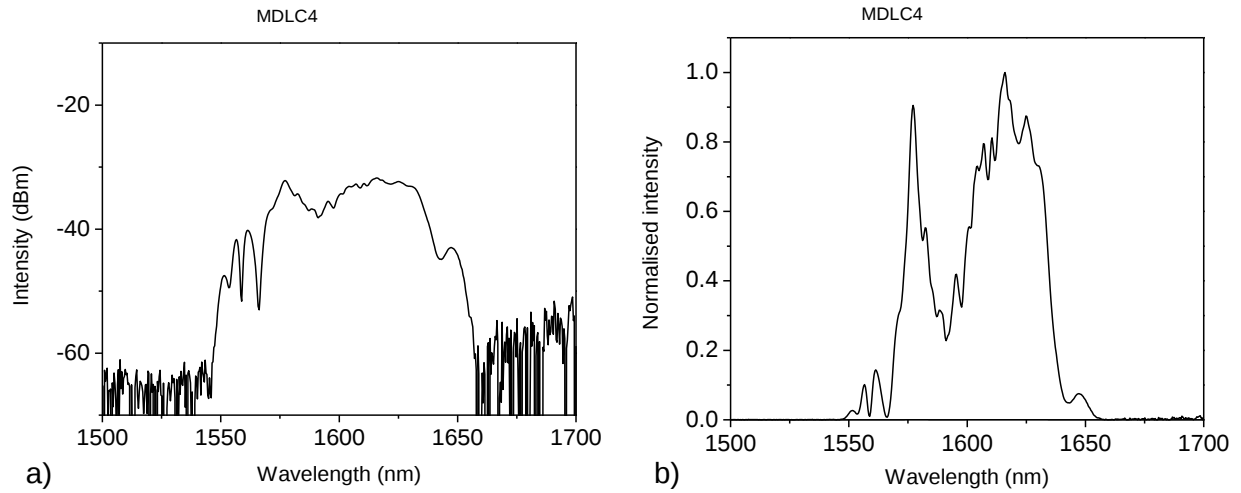


Figure 3-6 Logarithmic (a) and linear (b) pulse spectrum of 510 cm cavity at pump power of 650 mW.

Power adjustments were made to the 510 cm laser cavity such that the 974 nm pump was turned off and only pump power from the 977 nm diode laser pumped the laser cavity in the forward pumping direction. At a pump power of 600 mW, mode-locking was achieved with the pulses giving an average power of 6.7 mW at the same repetition rate of 37.65 MHz. The profile of the pulse spectrum is different from what has been previously observed. The spectrum remains structured but with a more defined parabolic profile, broken by the dip at 1625 nm seen in Figure 3-8a. The central wavelength of the pulse is at 1588 nm, giving a

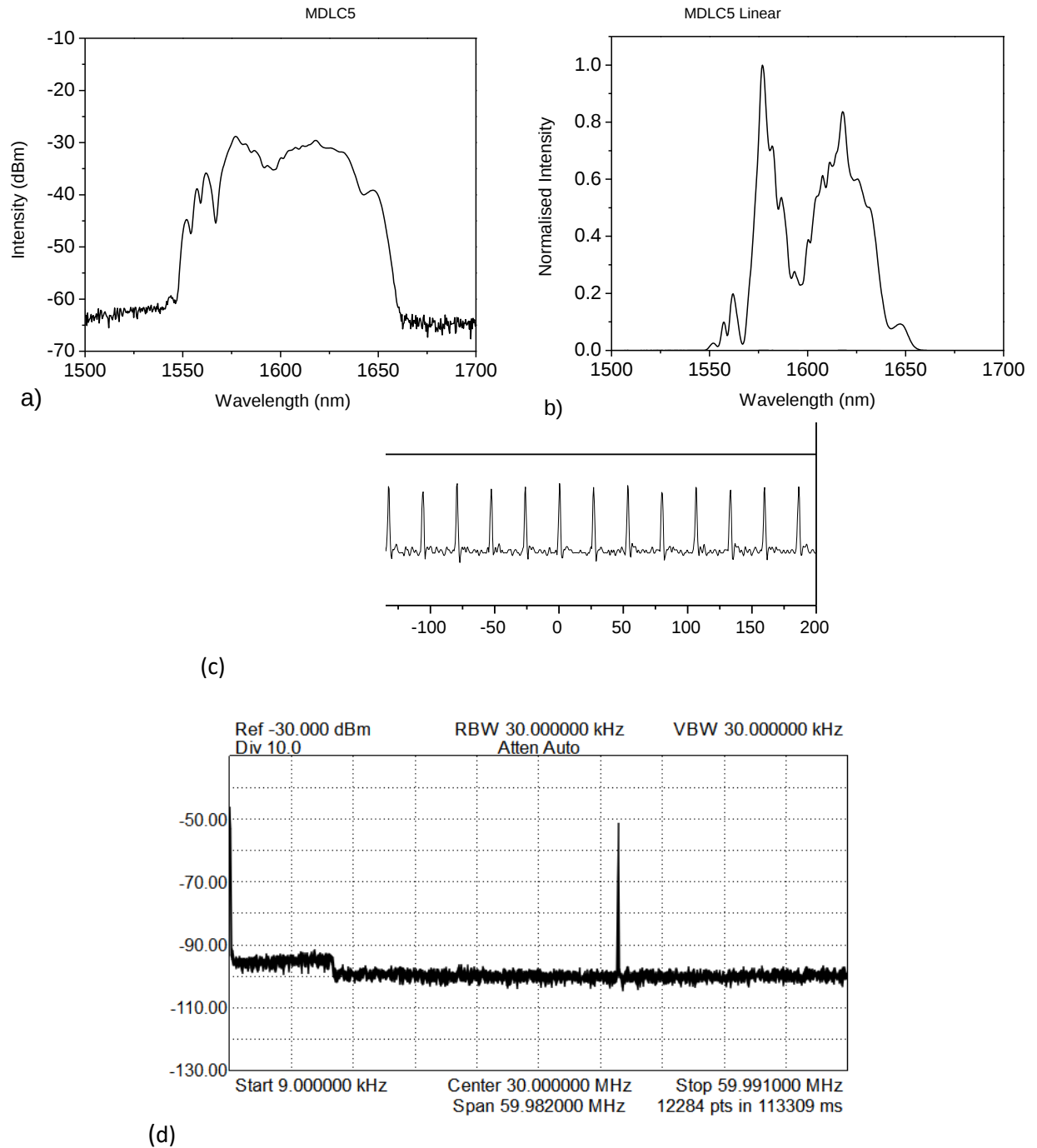


Figure 3-7 Characteristics of 510 cm cavity at a pump power of 643 mW, showing the pulse spectrum in the logarithmic (a) and linear (b) scale. The oscilloscope display of the pulse train (c), and the RF spectrum (d).

spectral bandwidth of 53 nm. A further decrease in pump power to 515 mW, maintaining forward pumping with no pumping from the second pump gives a mode-locked pulse with average power of 6.35 mW. The pulse spectrum is shown in Figure 3-8c. At this pump

power, the structures on the spectrum are reduced, giving an almost smooth parabolic shape with a bandwidth of 40 nm and a central wavelength at 1600 nm. A summary of the characteristics of the mode-locked pulses from the 510 cm cavity is given in Table 3-1 together with the calculated pulse duration.

Comparing the mode-locked pulses from the different configurations of the 510 cm cavity shows that, lower pump powers result in mode-lock pulses with reduced spectral

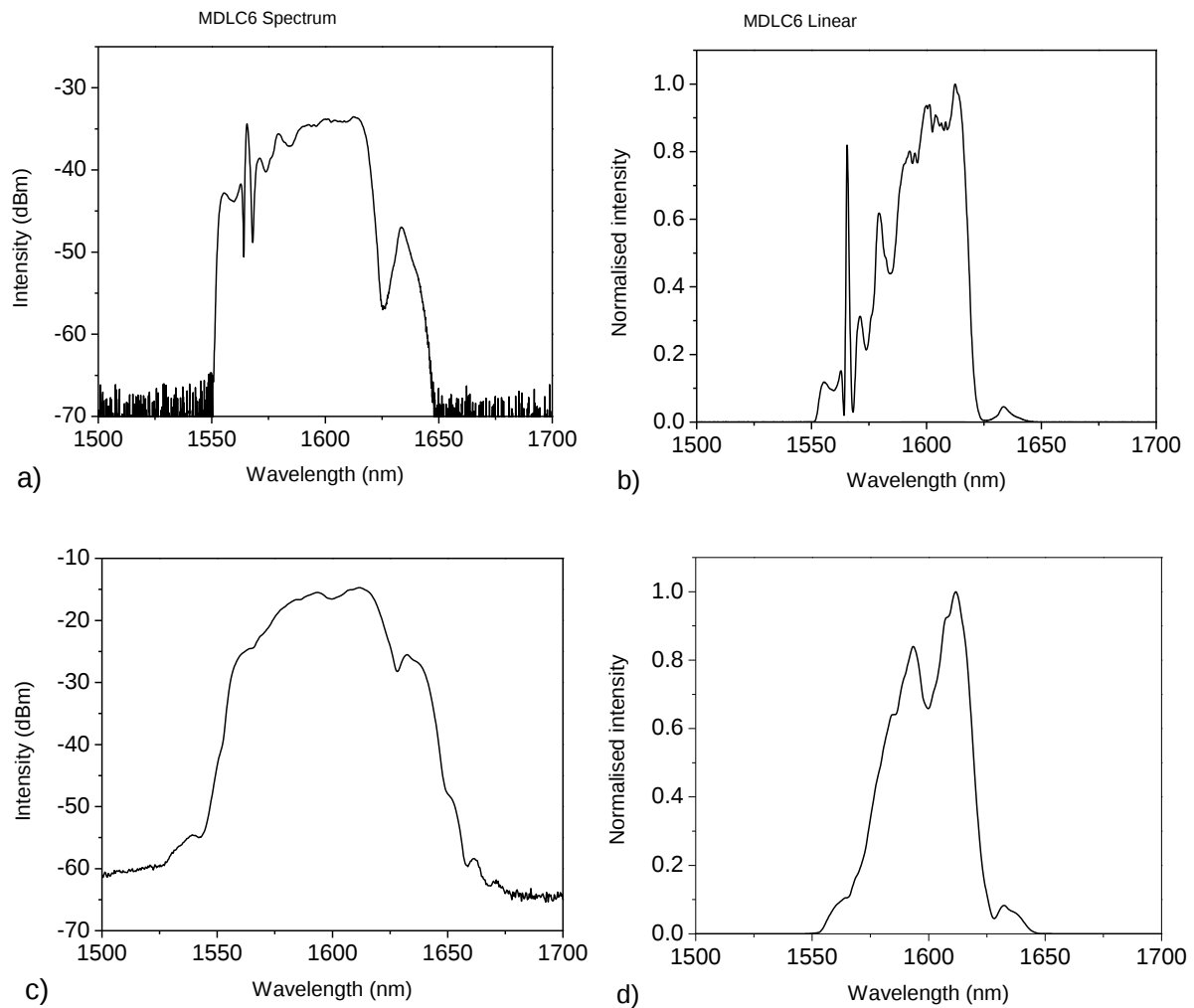


Figure 3-8 Pulse spectrum of 510 cm laser cavity. Logarithmic scale (a) and (c), and linear scale (b) and (d) of 600 mW and 515 mW pumping.

Table 3-1: Characteristics of mode-locked pulses from the 510 cm cavity.

Pump power (mW)		Total Pump power (mW)	Pulse Average power (mW)	Central wavelength (nm)	Pulse spectral bandwidth (nm)	Calculated pulse width (fs)
977 nm diode	974 nm diode					
600	50	650	3.30	1604	60.0	78.58
591	52	643	3.95	1602	58.5	76.84
600	-	600	6.70	1588	53.0	105.05
515	-	515	6.35	1600	40.0	104.43

bandwidth. This is attributed to reduced nonlinearity in the cavity which results in reduced spectral broadening in the erbium doped fiber, giving a pulse with longer pulse width as compared to one pumped at higher power.

A comparison of the 355 nm cavity and the 510 cm cavity shows that the shortest pulse is obtained from the 510 cm cavity. The longer cavity has a longer length of gain fiber which in effect enhances the SPM broadening (limited by the gain bandwidth of the erbium fiber) giving it a broader spectral bandwidth and hence a shorter pulse. It is observed that the central wavelengths of pulses from the 510 cm cavity are at a longer wavelength range, around 1600 nm, than the 355 cm cavity. This shift in wavelength may be due to reabsorption of stimulated radiation within the laser cavity by the erbium doped fiber, and its re-emission at longer wavelengths. Increasing the pump power shifts the central wavelength of the pulse to longer wavelengths. The shortest pulse is obtained at the highest pump power, and its emission is centred at the longest wavelength.

An autocorrelation measurement was made on the output of the 510 cm cavity operated at a pump power of 600 mW. Polarization maintaining fiber (PM1550 nm) was spliced to the output of the laser cavity (the PM fiber pigtail from the PBS), and this was used for pulse compression by its anomalous dispersion. The pulse spectrum with a parabolic shape is shown

in Figure 3-9b. The Fourier transform of this spectrum gives a pulse width of 83.5 fs. The experimentally measured autocorrelation of the pulse gives a pulse width of 85 fs, comparable to the calculated pulse duration. To aid in pulse compression, 40 cm of UHNA fiber was spliced to the output of the laser cavity to stretch the pulse, after which the PM1550 fiber was used to compress the pulse. An autocorrelation of the stretched pulse shown in Figure 3-9c gave a pulse width of 68 fs which is close to the transform limited pulse width of 60 fs.

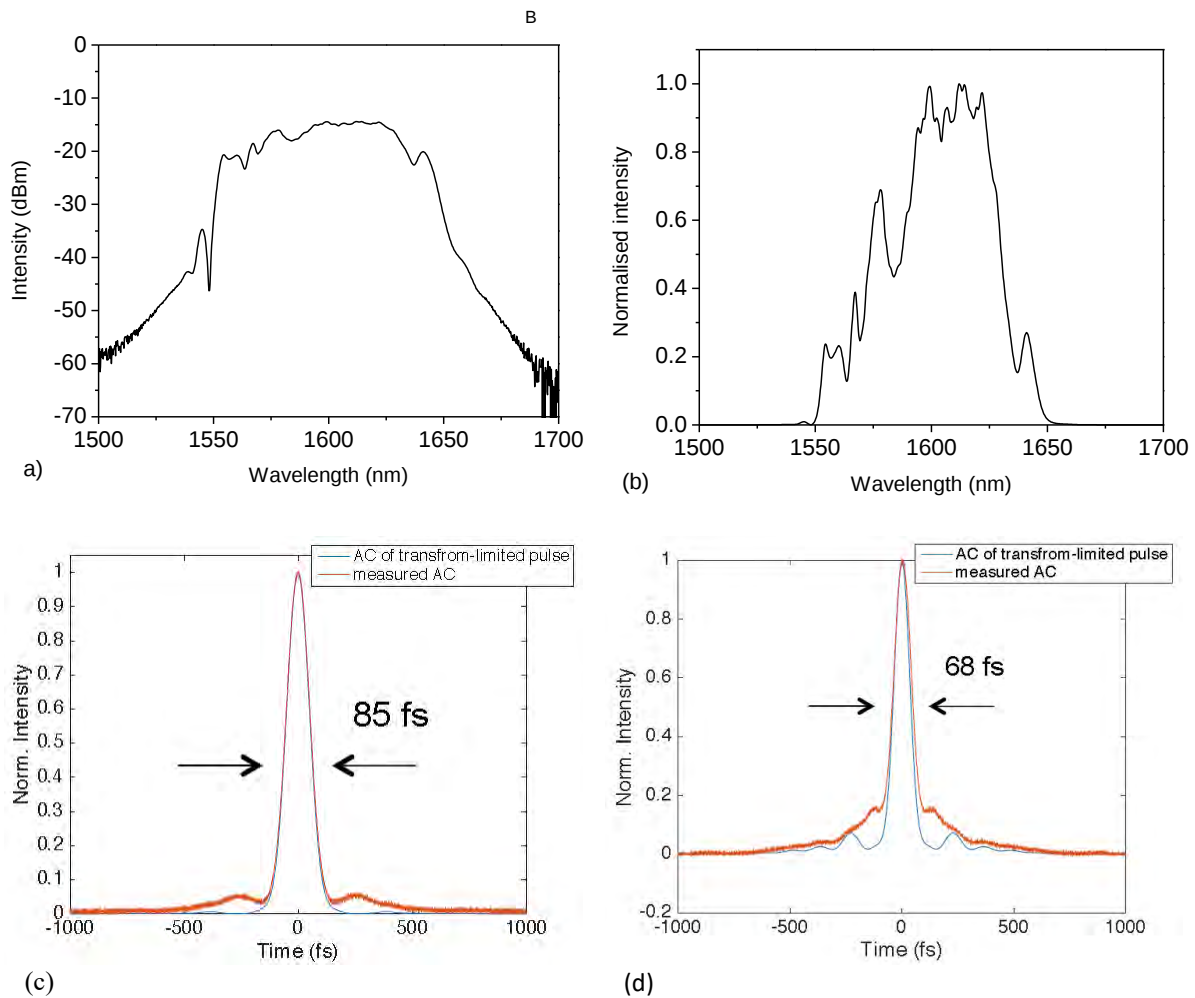


Figure 3-9 Pulse measurements for 510 cm cavity. Spectrum on logarithmic (a) and linear (b) scale of measured pulse. Autocorrelation of transform limited (blue curve) and actual measured pulse width (red curve) for the laser when (c) compressed by single-mode fiber after the cavity and (d) stretched by UHNA fiber and then compressed by the single-mode fiber.

At pump powers higher than what has been reported here in the 510 cm cavity case, the laser system starts to show signs of rich nonlinear dynamics. When both pump diodes are operational with forward pumping at its maximum of 600 mW and backward pumping at powers ranging from 90 mW to an upper limit of 430 mW, several behaviours were observed, including satellite pulses leading and trailing the main pulse with temporal displacement from the main pulse that increase as pump power was increased. This behaviour, first observed on the PicoScope, was confirmed by autocorrelation measurements, an example of which is presented in Figure 3-10. Figure 3-10 (a) shows the spectrum and Figure 3-10 (b) shows the autocorrelation trace when the second pump diode at 974 nm pumps an additional 136 mW of power into the cavity. The autocorrelation trace indicates the presence of two temporally separated pulses of unequal intensity separated by 4.33 ps. The spectrum is modulated into closely-spaced channels separated in wavelength by about 1 nm and with an on-off contrast exceeding 11 dB. At a total pump power of 802 mW with 202 mW from the backward pumping direction, the number of pulses generated per cavity round trip is increased as can be seen in the autocorrelation trace presented in Figure 3-10 (d), which indicates three closely spaced pulses in the time domain. The separation between the pulses is not uniform, with that between one pair of adjacent pulses being 4.76 ps. The separation between the second pair of adjacent pulses is larger at 8.90 ps. The spectrum is again modulated into channels on a wavelength grid. However, the on-off contrast is lower compared to the two-pulse case. High pump power increases the pulse energy and that affects the balance of gain, dispersion and nonlinearity, leading to unstable mode-locking of the pulses.

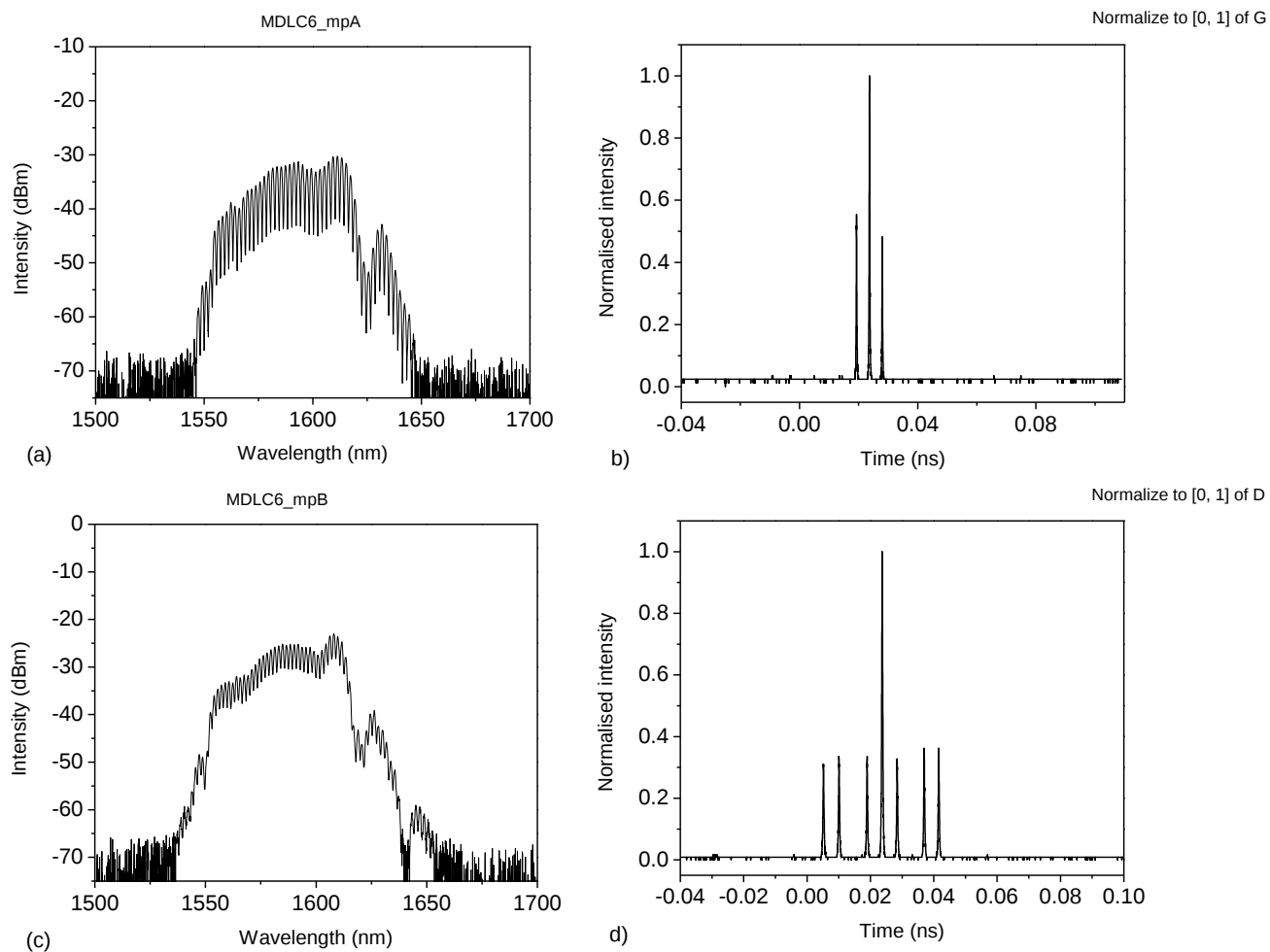


Figure 3-10 Spectrum of unstable laser cavity at (a) pump power of 736 mW and (c) 802 mW. The respective autocorrelation traces of multiple pulses are shown in b) and (d).

CHAPTER 4

SUPERCONTINUUM GENERATION IN ALL-SOLID ALL-NORMAL DISPERSION PHOTONIC CRYSTAL FIBERS

Material dispersion design limitations due to the glass and air hole structure of silica PCF and hence ANDi photonic crystal fibers can be overcome by eliminating the air, and having two types of glass, giving rise to both a solid core and a solid cladding structure [102]. Based on this idea, an all-solid all-normal photonic crystal fiber was produced [59] having broadband normal dispersion which is flattened from 1200 nm to 3000 nm. In 2014, octave spanning supercontinuum generation using this type of normal dispersion, all-solid nonlinear photonic crystal fiber was demonstrated for the first time [61]. This chapter presents the generation of broadband supercontinuum spanning an octave with its upper limits in the 2 μm range. This is done with the use of all-solid all-normal dispersion photonic crystal fibers. The nature of the spectral broadening is such that it is possible to recompress the supercontinuum to give single cycle pulses.

4.1 Generation of coherent octave spanning supercontinuum in all-solid all-normal photonic crystal fiber

In this experiment, all-solid normal dispersion photonic crystal fibers (PCF1 and PCF2) were used to generate supercontinuum. Both PCFs were obtained from the Institute of Electronic Materials Technology (ITME), Wólczyńska, Warsaw. The general structure is that of a central rod surrounded by capillaries made of the same glass type. This structure is inserted into a glass tube made of a second glass type, which is also used to fill the capillaries. The

standard stack and draw technique is used to draw the PCFs into a solid structure with a hexagonally shaped photonic crystal lattice. The normal dispersion profile is flattened from $-30 \text{ ps nm}^{-1} \text{ km}^{-1}$ to $-50 \text{ ps nm}^{-1} \text{ km}^{-1}$ within the range 1200 nm to 2600 nm, and has its zero-dispersion wavelength at 3000 nm, avoiding the possibility of supercontinuum within the anomalous dispersion region. The dispersion profile and geometrical cross section of the PCFs are shown in Figure 4-1.

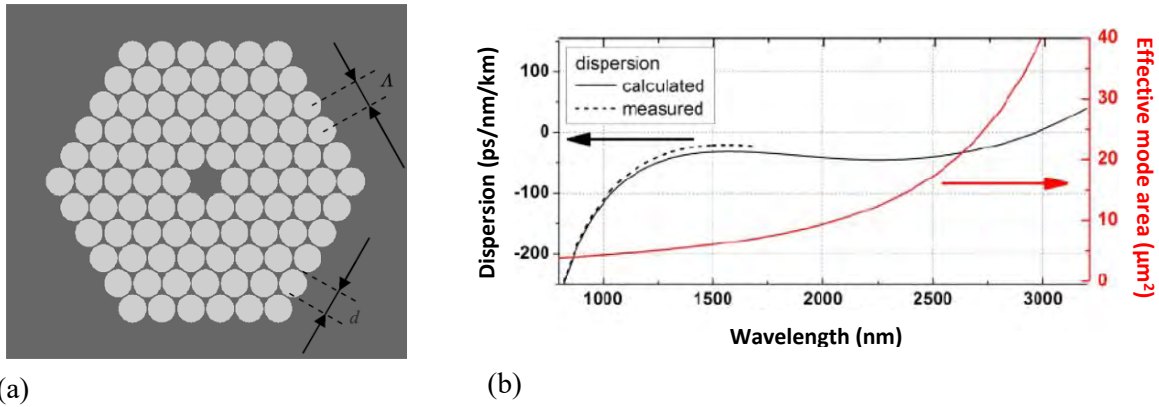


Figure 4-1 (a) Geometry of all-solid all-normal PCF [58]. (b) Calculated dispersion profile of all-solid all-normal PCF [103].

The all-solid all-normal dispersion photonic crystal fiber used for the generation of the supercontinuum in the first set-up, PCF1, is similar to the one used in [61]. It is made from commercial silicate glass (N-F2) which forms the central rod and the capillaries, and borosilicate glass (NC21) which is used to fill the capillaries and the glass tube that surrounds the photonic structure. The uncoated PCF has diameter $136.6 \mu\text{m}$, with the photonic cladding measured to be $34.65 \mu\text{m}$ diagonally, and the solid core having a diameter of $2.37 \mu\text{m}$. The capillary diagonal has diameter $d = 2.11 \mu\text{m}$ with pitch $\Lambda = 2.3 \mu\text{m}$.

4.1.1 Pump source for supercontinuum generation

The pump source requirements for the generation of supercontinuum extending into the 2 μm wavelength range in this experiment are such that the operating wavelength should be around 1550 nm, a maximum pulse width of 100 fs, with a pump power of at least 100 mW. Although the erbium-doped fiber laser developed in chapter 3 has characteristics that place it within the required wavelength and pulse width range, it does not meet the threshold pump power requirements and requires further optimization for use in supercontinuum generation. Therefore, a commercial laser was used in the supercontinuum generation setup.

A commercial femtosecond Er-doped fiber laser FemtoFiber pro NIR, from Toptica photonics, was used as the pump source for the PCFs, and hence serves as the source for all the supercontinua experimentally generated in this thesis. The operation of this Er-doped fiber laser has some similarities to that which is described and developed in chapter 3, the major difference being the method of mode locking, which is by a saturable absorber mirror instead of nonlinear polarization rotation. The Er-doped fiber laser comprises a three-stage system having a ring cavity oscillator, an amplifier and a pulse compression unit as shown in Figure 4-2. A fiber pigtailed laser diode pumps the oscillator comprising a core pumped Er-doped fiber which serves as the gain medium. The saturable absorber mirror provides mode locking of the generated radiation by only selecting and amplifying pulses beyond a certain amplitude threshold. The optical power extracted from the oscillator is used to pump an all-fiber, core pumped high gain Er-doped fiber for pulse amplification. The amplified pulse is compressed through dispersion control by using a pair of motorised prisms. The pump laser operates at a central wavelength of 1565 nm and generates 100 fs pulses with a repetition rate of 80 MHz at a power of 350 mW, giving rise to a pulse energy of 4.375×10^{-9} J and a peak power of 43.75 kW. Figure 4-3 shows the autocorrelation function and the spectrum of pulses generated by the laser.

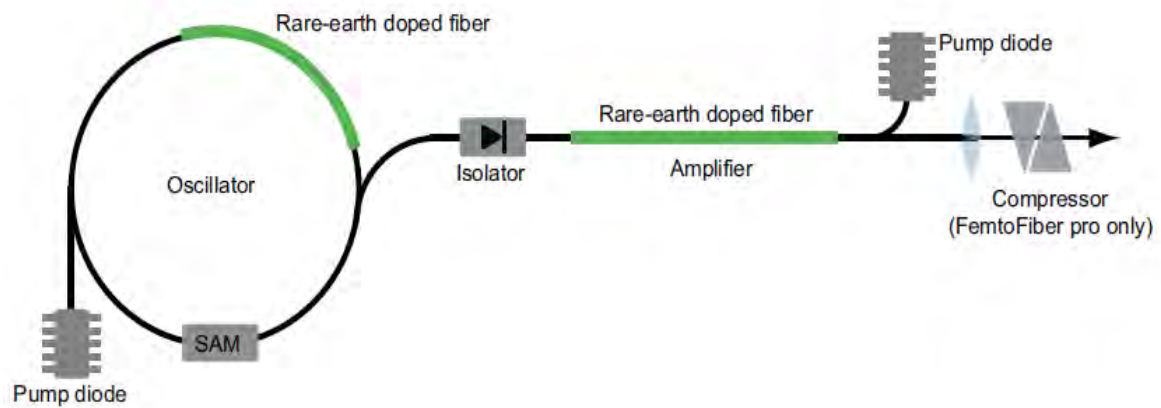


Figure 4-2 Schematic of Toptica FemtoPro NIR laser system. SAM: Saturable absorber mirror.

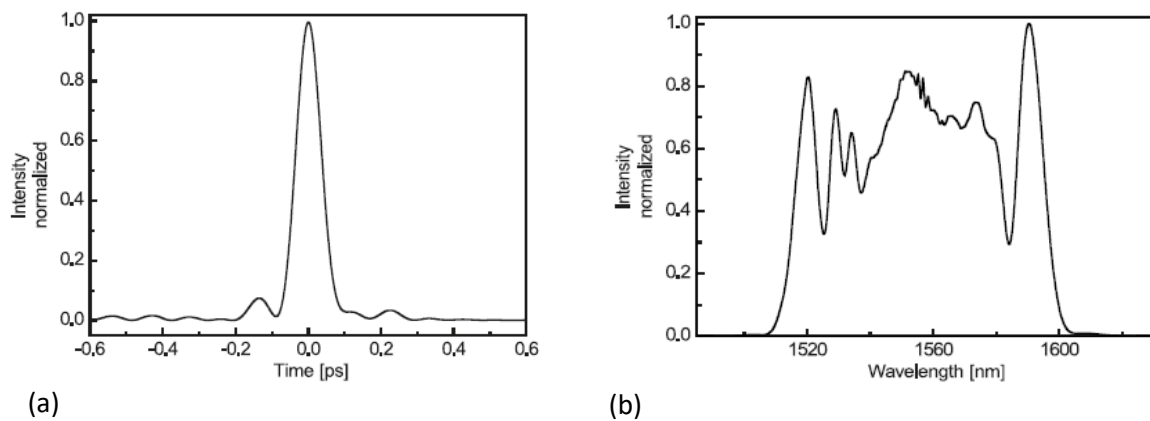


Figure 4-3 (a) Autocorrelation and (b) spectrum of pump laser.

4.1.2 Supercontinuum generation with PCF1

4.1.2.1 Experimental setup

The schematic setup for supercontinuum generation in PCF1 is shown in Figure 4-4. A lens with focal length 50 cm is used to converge the pump beam from the FemtoPro laser source, which is 2 m away, to the optical bench of the main experimental setup. Although the FemtoPro laser has an isolator within its oscillator, after the amplification stage, there is no isolation and so an isolator (IO-4-1550-VLP) from Thorlabs is placed in front of the FemtoPro laser output aperture to prevent back reflections from entering the laser and disturbing its operation. The beam is then directed by two mirrors to a fiber coupling stage. The beam from the lens is coupled into 30 cm and then 15 cm of PCF1. Alternate aspheric lenses with focal lengths 15 mm, 11 mm, 6.24 mm, 4.15 mm and 3.10 mm were used for coupling the source light into the PCF. Aspheric lenses were chosen because of their small focal spot size. The spectral broadening process was monitored on an optical spectrum analyser (Yokogawa AQ6375) through a multimode fluoride fiber which served as a bridge fiber. A lens with focal length 4.51 mm and numerical aperture 0.55 (Thorlabs C230 TM-C) was selected for best coupling and maximum supercontinuum generation. The resulting spectra for the two fiber lengths are shown in Figure 4-5.

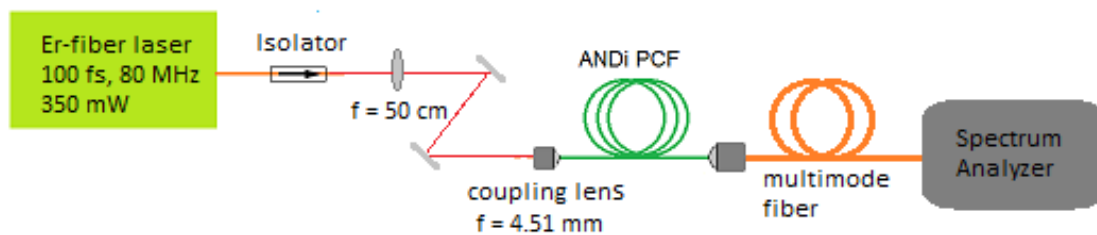


Figure 4-4 Schematic of experimental setup for supercontinuum generation with PCF1.

4.1.2.2 Results and discussion

Supercontinuum was measured after 30 cm of PCF1 (Figure 4-5 (a)) and 15 cm of PCF1 (Figure 4-5 (b)). The lengths of the PCF were chosen based on the observation that broadening is completed by 10 cm of PCF1 length [61] and also for a convenient fiber handling length.

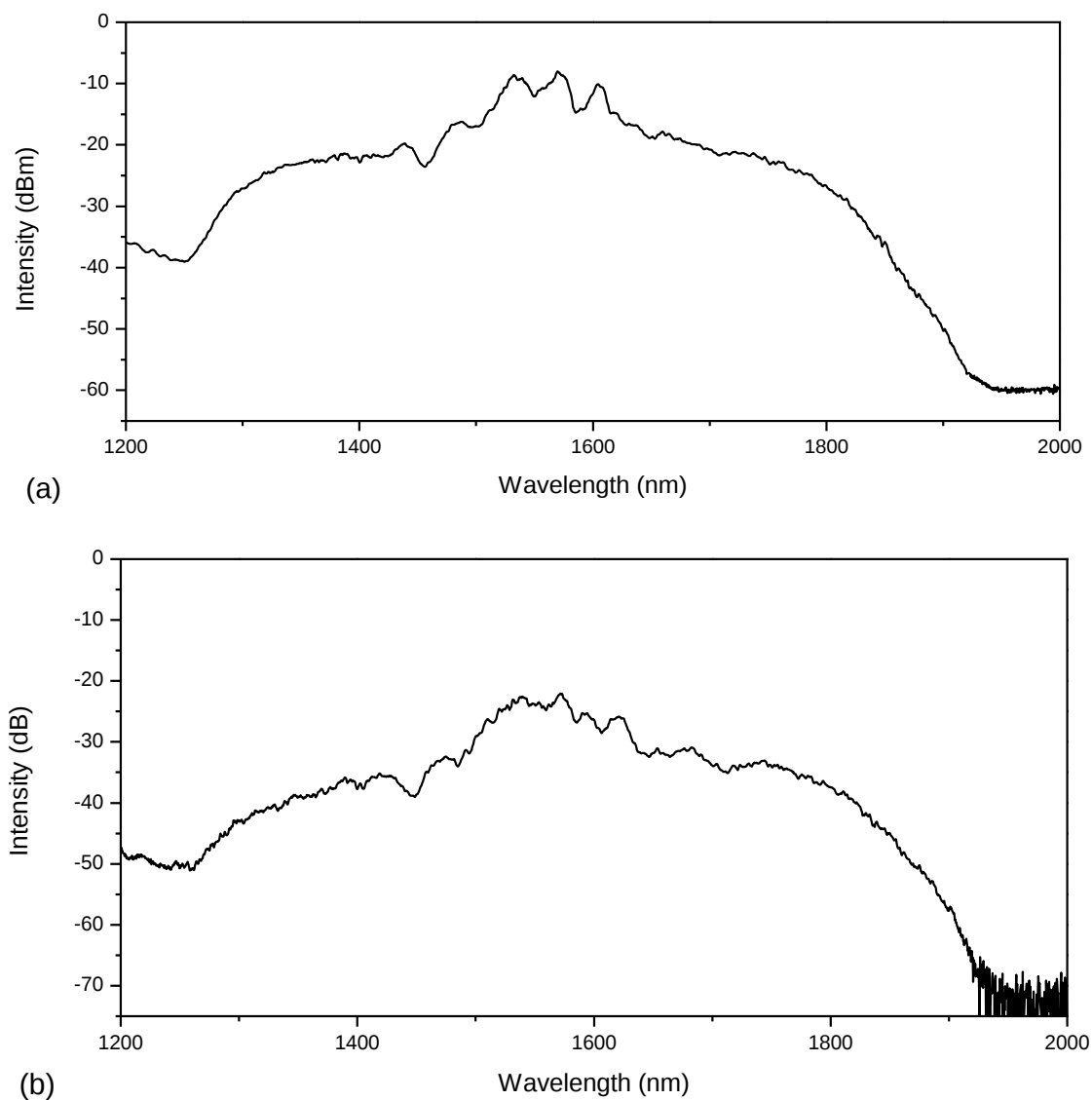


Figure 4-5 Experimentally generated supercontinuum spectra for (a) 30 cm of PCF1 and (b) 15 cm of PCF1.

Hardly any difference was observed between the generated bandwidth obtained with the 30 cm and the shorter 15 cm length of PCF1. This confirms earlier findings that the length of PCF does not influence the spectral width of the supercontinuum [104]. The generated spectra extend up to about 1950 nm on the long wavelength side. Its lower wavelength limit was not captured due to the lower wavelength limit of the optical spectrum analyser. Figure 4-5 also shows remains of the pump power which did not couple into the core but propagated in the cladding of the fiber. This is seen around the central pump wavelength of 1565 nm, spanning a bandwidth of about 160 nm, with the curve peaking to an intensity difference of 10 dB. This has been attributed to the PCF not being coated [104], affecting the light guidance.

It is evident from the generated supercontinuum that spectral broadening results from a normal dispersion material as the profile of the supercontinuum envelope is smooth and almost flat-top, except for the central peaking portion. This is unlike the uneven nature of supercontinuum generation from an anomalous dispersion medium as discussed in chapter 2. The spectral broadening in this case is initiated by self-phase modulation of the incident pump pulse, creating new intermediate frequencies within the pulse spectral bandwidth. Due to the overlap of spectral components in the leading and trailing edges of the pulse with the intermediate frequencies as it broadens in the normal dispersion medium, optical wave breaking (OWB) takes over. Additional frequencies are generated through this four-wave-mixing process, extending the spectral bandwidth beyond the original spectrum of the pulse on both sides of the central wavelength. Energy is distributed from the central frequency components to the wings smoothening out the pulse (except for the central portion) until a uniform spectral structure is obtained. The spectra in the two cases were very stable with fluctuations only occurring when there were pump power fluctuations. It was observed that the stability of the supercontinuum was affected by pump beam walking, which shifted the coupling, reducing output power and even at times resulting in the loss of the supercontinuum.

An objective of obtaining a continuum with upper wavelength greater than 2000 nm was not realised with this fiber. This limitation is attributed to inadequate pump power coupled into the fiber core.

4.1.3 Supercontinuum generation with PCF2

The experiment described in section 4.1.2 was repeated with PCF1 replaced with a second photonic crystal fiber (PCF2) for greater spectral broadening. PCF2 has a double cladding structure in which the solid core is surrounded by the hexagonal photonic crystal structure which is in turn surrounded by a glass tubing. The layering is arranged in decreasing refractive index profile. The core, made of SF6 lead-silicate glass, has a linear refractive index of 1.8049 and the outer tube made from F2 glass has a refractive index of 1.6199. The F2 glass capillaries of the photonic crystal lattice are filled with SF6 glass and the value of its refractive index lies between the refractive index of the core and that of the outer cladding [103]. Glass combinations of SF6/F2 generate greater supercontinuum broadening than combinations of F2/NC21 glass (which was used in PCF1) because of the higher Kerr nonlinearity of SF6 glass.

4.2.2.1 Experimental setup

The experimental set-up for supercontinuum generation using PCF2 differs slightly from the setup used with PCF1 as shown in Figure 4-6. The same laser used for the SC generation in PCF1 is used here. The converging lens is brought closer to the mirrors to reduce the beam diameter to 3 mm for better coupling efficiency, and a free space isolator (Thorlabs IO-4-1550-VLP) is placed after the pump laser to prevent back reflections from the end of the

PCF from disturbing the mode-locking in the Er-fiber laser. The beam is focused into 30 cm of PCF2 using the same aspheric lens with focal length of 4.51 mm as was used with PCF1. An IR camera was used to aid monitoring of power coupling into the core.

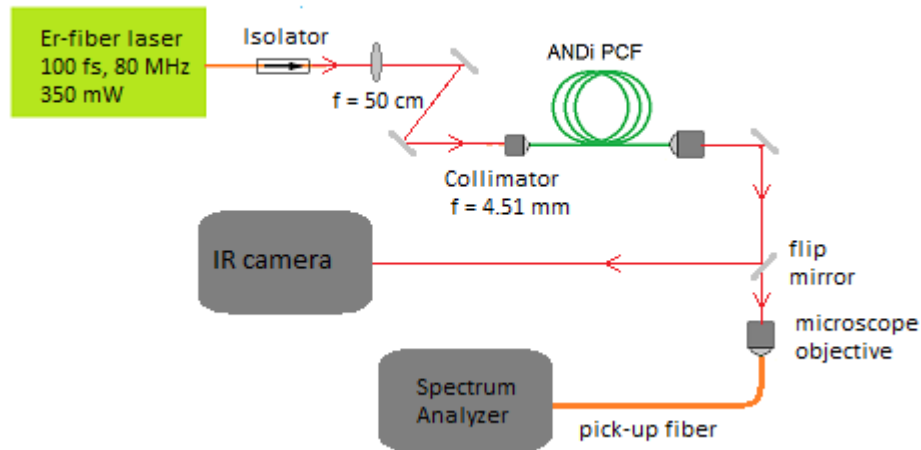


Figure 4-6 Experimental set-up for supercontinuum generation in PCF2.

4.2.2.2 Results and discussion

Results of the spectral broadening experiments conducted with PCF2 are shown in Figure 4-7 and Figure 4-8. Comparison of the coupled power versus the SC spectra generated (Figure 4-7) shows that, broadening occurs asymmetrically around the pump wavelength with the energy distribution being greater on the shorter wavelength side. Full broadening occurs at 2200 nm after which increased energy coupling causes the spectrum to get smoother through the degenerate FWM process, evenly distributing energy from the central pulse to the sides. The fully generated supercontinuum with a broad and close to flat top spectrum, spanning a bandwidth of 1100 nm and reaching a wavelength of 2200 nm is shown in Figure 4-8. A second Yokogawa optical spectrum analyser with operating wavelength range from 700 nm to

1700 nm was used to obtain readings below the lower wavelength limit of the Yokogawa AQ6373 optical spectrum analyser. Cladding mode signals are observed around the pump wavelength, from about 1400 nm to 1700 nm, more visibly seen on the linear scale (inset of Figure 4-8). The continuum is stable and repeatable with signature dips representing OH ion [105] and other mineral absorption peaks. The spectrum also shows multimode behaviour of the PCF2 below 1400 nm. By placing a half wave plate before the coupling lens to the PCF, polarization state of the seed laser affected the long wavelength end of the continuum, extending or shortening it by at most 40 nm. The measured average power of continuum generated is 18 mW.

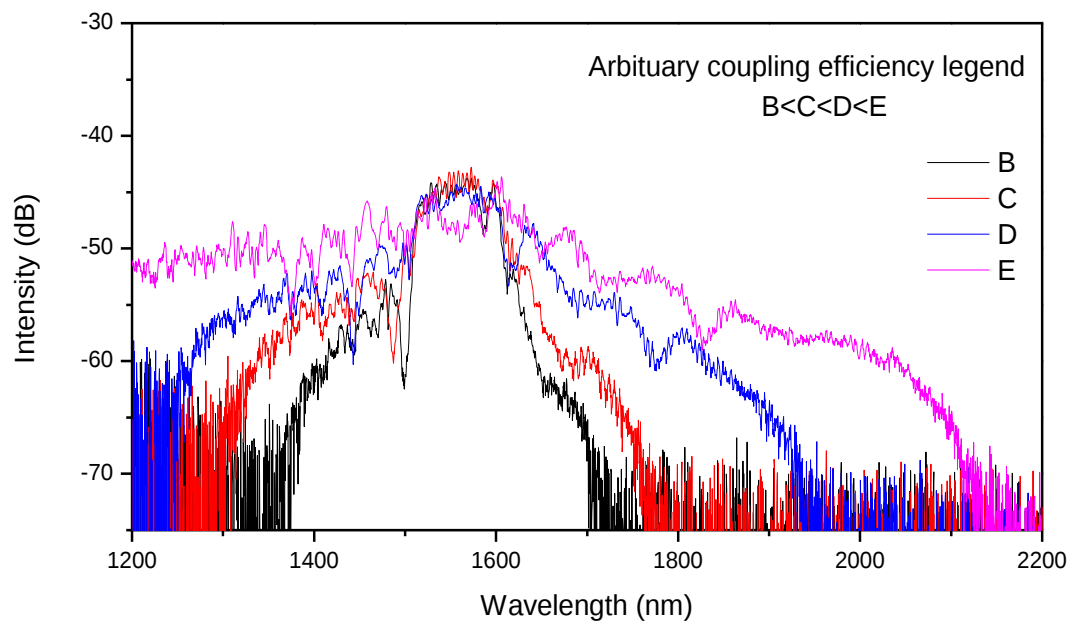


Figure 4-7 Supercontinuum generation from PCF2 pumped at 1565 nm. Spectral broadening increases from the black curve (B) to the purple curve (E) as coupling efficiency increases.

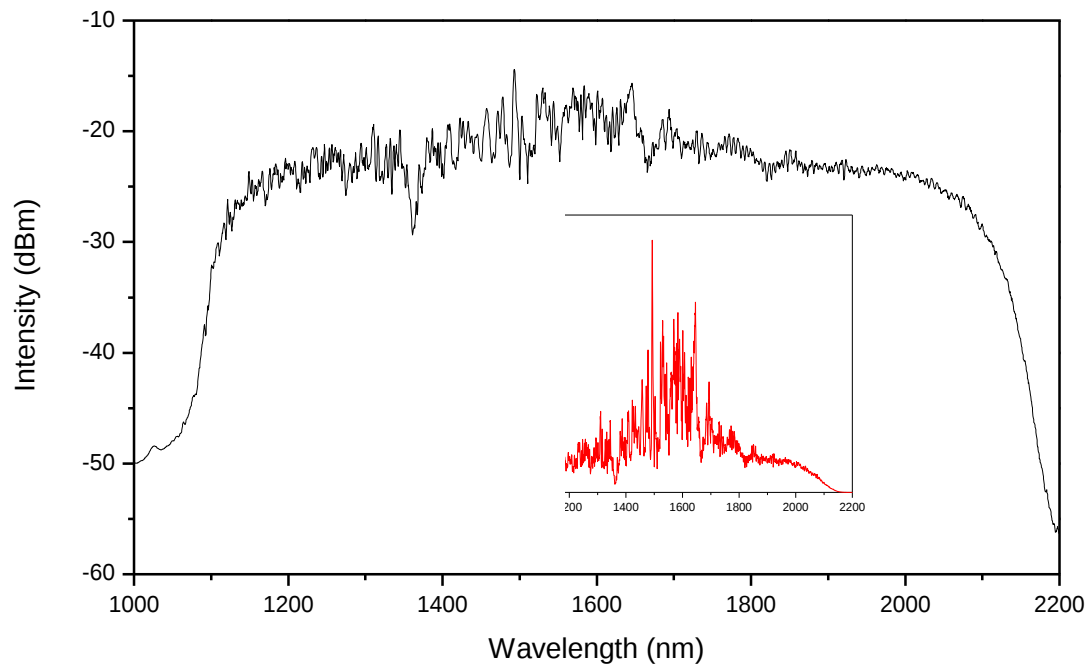


Figure 4-8 Spectrum of completed supercontinuum in PCF2. Inset is spectrum on the linear scale.

CHAPTER 5

AMPLIFICATION OF SUPERCONTINUUM

The spectral power density of the supercontinua generated in the normal dispersion regime can be enhanced by amplification. Broadband amplification in rare earth doped fiber amplifiers using the supercontinuum as a seed source is possible. This is particularly useful for WDM applications in telecommunications. Of particular interest would be the wavelength division multiplexing of all the possible amplified sources generated from the spectral slicing of the supercontinuum source.

In this chapter, the supercontinuum source presented in chapter 4 is used for broadband amplification in rare earth doped fibers. The spectrum of the supercontinuum is generally flat top except for a dynamic range of 10 dB from 1400 nm to 1600 nm, attributed to pump power in the cladding. The almost flat top spectrum obtained in the 1800 nm to 2000 nm wavelength range makes the supercontinuum ideal for broadband amplification in the 2 μ m wavelength range. In this chapter, amplification of the supercontinuum within the spectral gain bands of Er^{3+} , Tm^{3+} , and Tm-Ho^{3+} are studied.

5.1 Coherent broadband seeding of Er-doped fiber amplifier

Erbium-doped fiber amplifiers have become widely popular due to the telecommunications industry. With components easily available and at relatively low cost, erbium is chosen as the first amplifier to test the amplification of the broadband supercontinuum radiation.

5.1.1 Experimental set-up

Figure 5-2 shows the experimental setup for broadband amplification in erbium-doped fiber amplifier. The setup is made up of two main sections, the seed source and the amplifier. The seed source used for the amplifier is the coherent broadband supercontinuum source developed in chapter 4. It is produced by femtosecond pulses from an erbium-doped fiber laser pumping an all-solid all-normal dispersion photonic crystal fiber (ASANDi PCF). The ASANDi PCF in this setup is butt-coupled in air to 20 m of an ultrahigh numerical aperture fiber (UHNA3) obtained from Thorlabs. The UHNA3 has a SiO₂/GeO₂ core of radius 1.8 μm and a numerical aperture of 0.35 and stretches the supercontinuum pulses in the time domain to 600 ns. The output end of the UHNA3 is spliced to a 2 μm isolator to prevent any reflections back into the supercontinuum source. A 7 m length of polarization maintaining erbium-doped fiber is used as the gain medium. The erbium-doped fiber, PM-ESF-7 from Nufern, is optimized for operation in the wavelength range of 1530 nm to 1610 nm. It has a numerical aperture of 0.15 and a core diameter of 7 μm , with mode field diameter of 8.8 μm at a wavelength of 1550 nm. It has a core absorption of (55.0 ± 5) dB/m near 1550 nm.

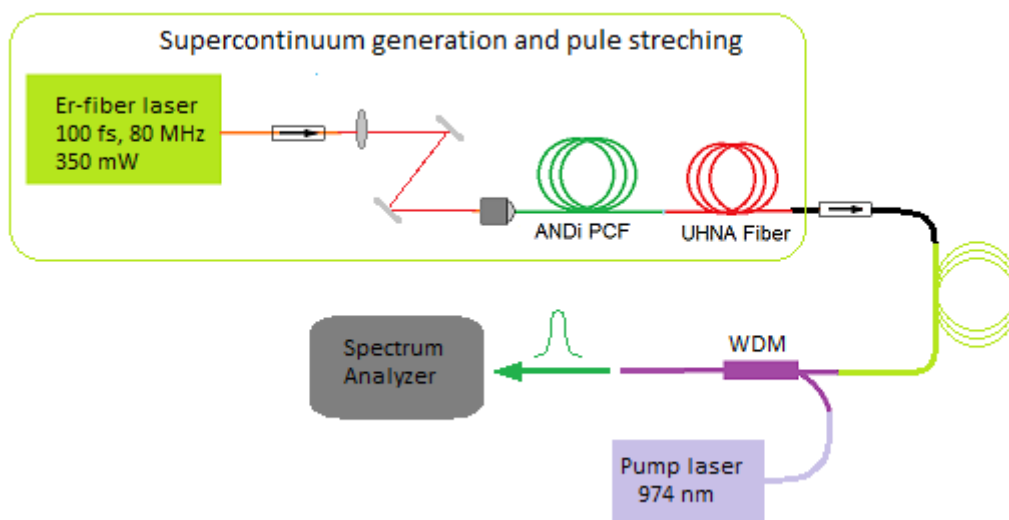


Figure 5-1 Schematic of erbium doped fiber amplifier.

The erbium doped fiber is pumped in the backward direction by a 974 nm pump diode through a 1.5 μm optimized wavelength division multiplexer. The pass port of the wavelength division multiplexer delivers the output radiation.

5.1.2 Results and discussions

The supercontinuum seed, which ranges from about 1100 nm to about 2200 nm with an average power of 18 mW, is made to propagate through the amplifier setup without the pump power turned on. The resulting spectrum from the erbium doped fiber is shown in Figure 5-2 (a) as the red curve with clear evidence of supercontinuum signal absorption. Figure 5-2 (b) shows the absorption spectrum of the system with two major absorption bands ranging from 1200 nm to 1360 nm and from 1460 nm to 1600 nm. Within the 1460 nm to 1600 nm range, the two well-known absorption peaks for erbium at long wavelengths are present at 1480 nm and 1530 nm, with a possible additional absorption peak at 1493 nm.

The 974 nm pump diode pumps the erbium doped fiber at a power of 650 mW, and the resulting amplified signal emission spectrum curve (Figure 5-3 (a)) is that of a typical erbium doped fiber amplifier with two closely spaced peaks. The inset curve presents the spectrum on a linear scale. The peaks occur at wavelengths of 1533 nm and 1553 nm with the peak at 1533 nm having a higher intensity (0.286 dBm) than the peak at 1553 nm. The spectral bandwidth of the output is 25 nm with central wavelength at 1540 nm. At the maximum pump power of 650 mW, the amplified output power is 65.7 mW giving an amplification of 5.6 dB. Measurements of the amplifier output power were made for pump powers ranging from 50 mW to 650 mW and the results are plotted in Figure 5-3 (b). The slope efficiency from the curve is 11.3 %, with no signs of saturation.

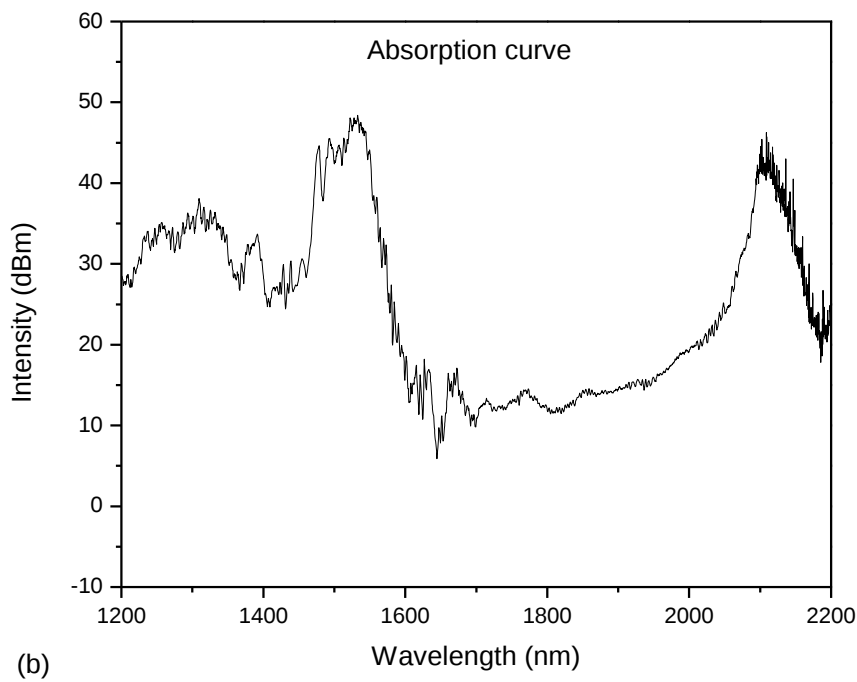
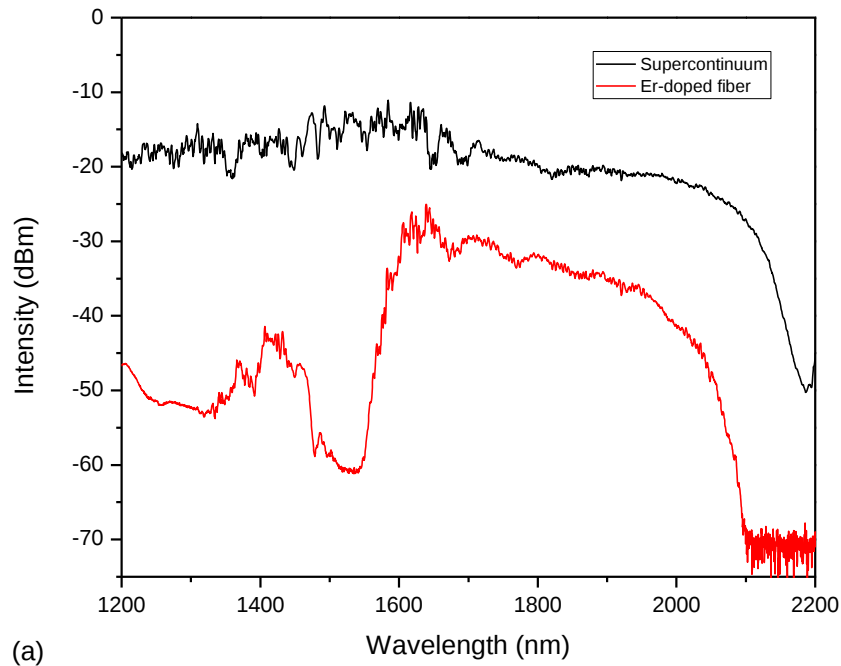


Figure 5-2 Erbium doped fiber amplifier output characteristics: (a) Spectrum of seeded amplifier with no pump power; (b) is the absorption spectrum.

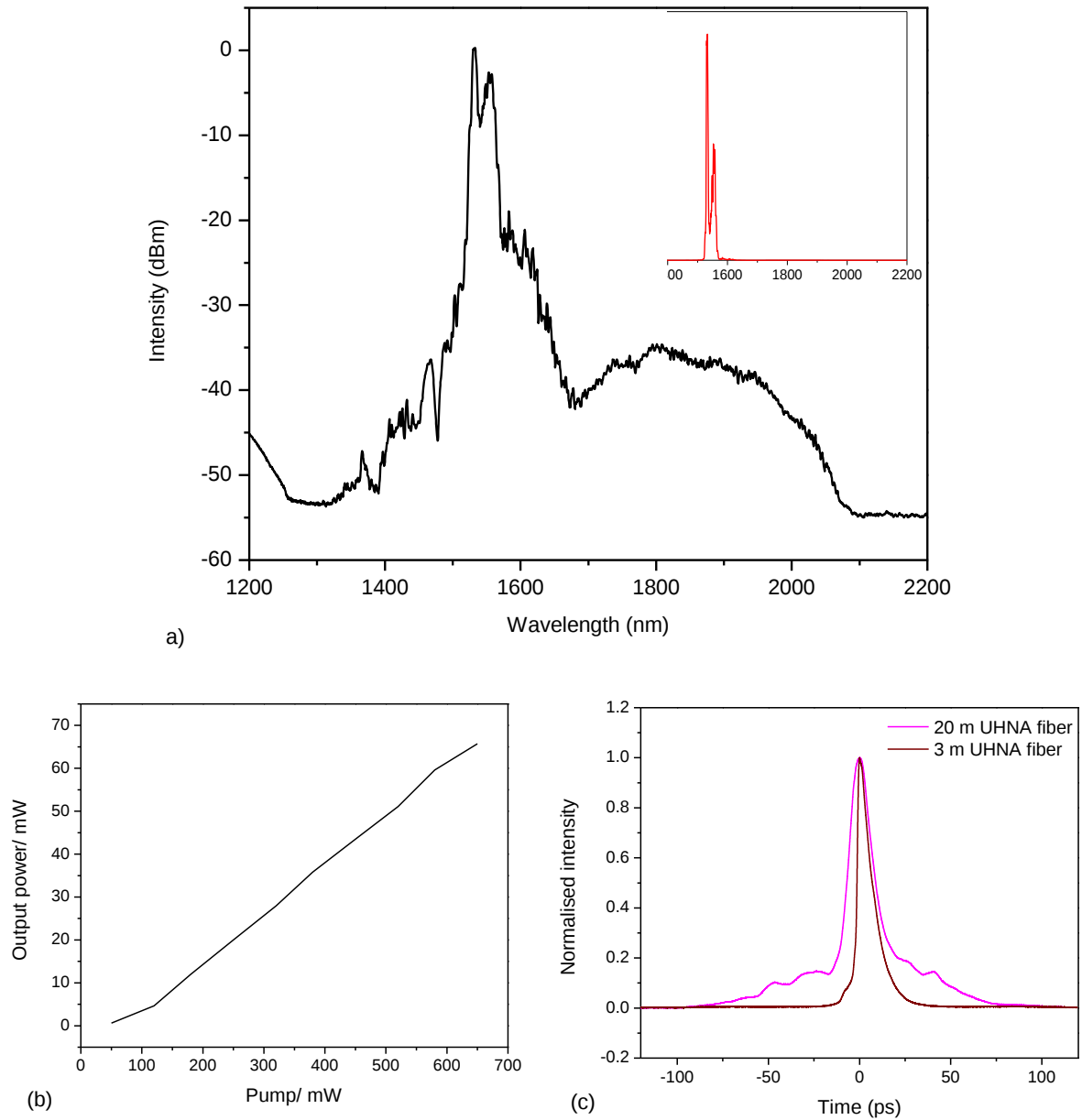


Figure 5-3 Erbium doped fiber amplifier output characteristics. (a) Emission spectrum; (b) Variation of output power with pump power; (c) Autocorrelation of pulse for seed stretched by 20 m UHNA3 fiber (red curve) and for seed stretched by 3 m UHNA fiber (black curve).

An interferometric autocorrelator with model number FR-103XL from Femtochrom was used to make measurements of the amplified pulse width. An initial autocorrelation measurement taken directly from the output end of the wavelength division multiplier was made on the amplified signal from the erbium-doped fiber pumped at a power of 500 mW. A

measured pulse width of 11.6 ps assuming a Gaussian pulse shape was obtained. A 3 m standard singlemode fiber patch cord was inserted between the wavelength division multiplexer and the autocorrelator to determine if there are any observable pulse broadening effects. The pulse width obtained using the 3 m patch cord was 11.1 ps, a reduction by 0.5 ps. The pulse shortening indicates that the net dispersion of the amplifier system is normal, since dispersion of standard single-mode fiber at 1550 nm is anomalous.

The group velocity dispersion of the photonic crystal fiber and the UHNA3 fiber are both normal, whereas the dispersion of the erbium-doped fiber is unknown, though assumed to be anomalous at 1550 nm. It seems possible therefore to use standard singlemode fiber for compression of amplified pulses from this system. The repetition rate of the pulses was measured with an oscilloscope, and the initial 80 MHz from the Toptica erbium doped pump fiber laser is maintained. The average power of the erbium amplifier is 49 mW, with pulse energy of 0.61 nJ. A 20 m length of UHNA3 was used to stretch the supercontinuum pulse to reduce peak power and hence limit nonlinearities in the amplifier. The generated peak power of 52.8 W directly from the amplifier is however not too high, and it is assumed that the seed pulse is overly stretched. The UHNA was shortened to 3 m and autocorrelation measurements were made. A pulse width of 6.2 ps was measured directly from the end of the wavelength division multiplexer. When a 3 m singlemode fiber patchcord was used to couple the amplifier to the autocorrelator, the pulse width decreased to 5.9 ps. All pulse width measurements assumed a Gaussian pulse profile. Figure 5-3 (c) shows the autocorrelation trace for the amplifier when 20 m and 3 m of the UHNA3 were used for pulse stretching along with 3 m of singlemode fiber as patchcord to the autocorrelator.

5.2 Coherent broadband seeding of Tm-doped fiber amplifier

The WDM serves well as a band pass filter of the broadband seed source selecting appropriate range of wavelengths for amplification in the erbium-doped fiber amplifier. The same method is applied for slicing the supercontinuum for amplification in a Tm-doped amplifier.

5.2.1 Experimental set-up

The schematic setup for the Tm-fiber amplifier is shown in Figure 5-4. It is made up of a coherent broadband supercontinuum source, a fiber for pulse stretching, a pump laser and Tm-doped fiber for amplification. The supercontinuum source setup is identical to the supercontinuum source employed in the erbium doped fiber amplifier experiment of section 5.1. The fiber for pulse stretching is a 20 m length of UHNA3 fiber, which is butt-coupled to the end of the supercontinuum generating PCF. The output end of the UHNA3 fiber was initially spliced to the signal input end of a fiber based pump signal combiner (PSC). The PSC is a 2000 nm and 793 nm $(2 + 1) \times 1$ multimode pump and signal combiner from Advance Fiber Resources. It has a 10/125 double clad fiber for the signal input and the common output ends. The pump input end is a 105/125 multimode fiber. The second signal input was not used. The coupling was such that the supercontinuum seed travelled in the core of the double clad fiber of the PSC. The pump laser, spliced to the PSC pump input end, has its radiation propagating at a wavelength of 974 nm, and travels in the cladding of the PSC. The three splice sections of the PSC were covered with copper tape to shield any uncoupled stray light and to help with heat dissipation. An initial 6 m of double clad Tm-doped fiber spliced to the output of the PSC provides the amplification. The PM-TDF-10P/130 HE double clad Tm-doped

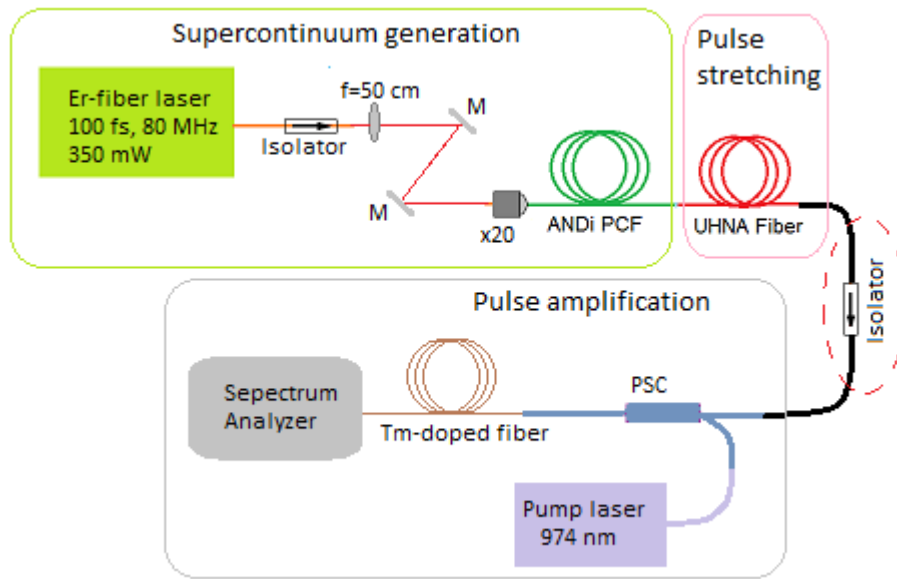


Figure 5-4 Schematic set-up for Tm-doped fiber amplifier seeded by a coherent supercontinuum source.

fiber from Nufern is maximised for operation between 1900 nm to 2100 nm. It has a core diameter of 10 μm with numerical aperture of 0.150, cladding diameter of 130 μm with first cladding numerical aperture ≥ 0.46 . The cladding absorption is 4.70 dB/m at a wavelength of 793 nm. The end of the Tm-doped fiber is directly connected to a Yokogawa AQ6375 optical spectrum analyser which monitors the system.

5.2.2 Results and discussion

The femtosecond supercontinuum pulsed seed source which spans a bandwidth of 1000 nm starting from 1200 nm to 2200 nm, operates at a repetition rate of 80 MHz, with average output power of 18 mW. When seeded through the Tm-amplifier system without pump source turned on, the supercontinuum gives the spectrum shown in Figure 5-5. Absorption occurs within the Tm-amplifier, and the resulting calculated profile of the system is shown in Figure 5-6 (b). Though not very smooth, it takes the form of the absorption spectrum for Tm^{3+}

in silica (Figure 5-6 (a)), which has its absorption peak around 1645 nm, within a bandwidth range from 1500 nm to 2100 nm. The peaks around 1500 nm in the measured profile (Figure 5-6 (b)) are a result of OH ion absorption in the all-solid ANDi PCF during the supercontinuum generation process, and imprinted in the seed pulse. Figure 5-5 shows that the seeded broadband source extends beyond the entire absorption bandwidth range for Tm:silica, allowing for its full amplification bandwidth to be explored. Pump power of 10 W was used to excite the Tm^{3+} ions to obtain the amplified spontaneous emission (ASE) of the thulium amplifier. When the seed signal was allowed to propagate through the amplifier, at the same pump power, an amplified average power of 230 mW was obtained. The output spectra of the amplifier are shown in Figure 5-7. The red curve shows the ASE of the Tm-doped fiber, and the black curve represents the amplified signal. The ASE is centred at 2 μm with a FWHM bandwidth of 20 nm, and the amplified signal spans a bandwidth of 39 nm with its central wavelength at 2011 nm, giving it a transform limited pulse duration of 152.5 fs assuming Gaussian pulse profile.

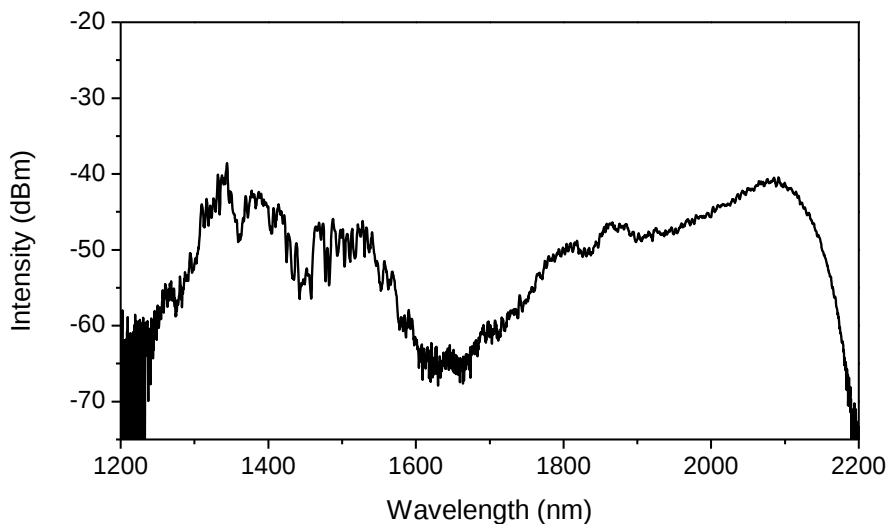


Figure 5-5 Spectrum of transmitted signal from Tm-doped fiber amplifier with seeding from coherent octave spanning supercontinuum source.

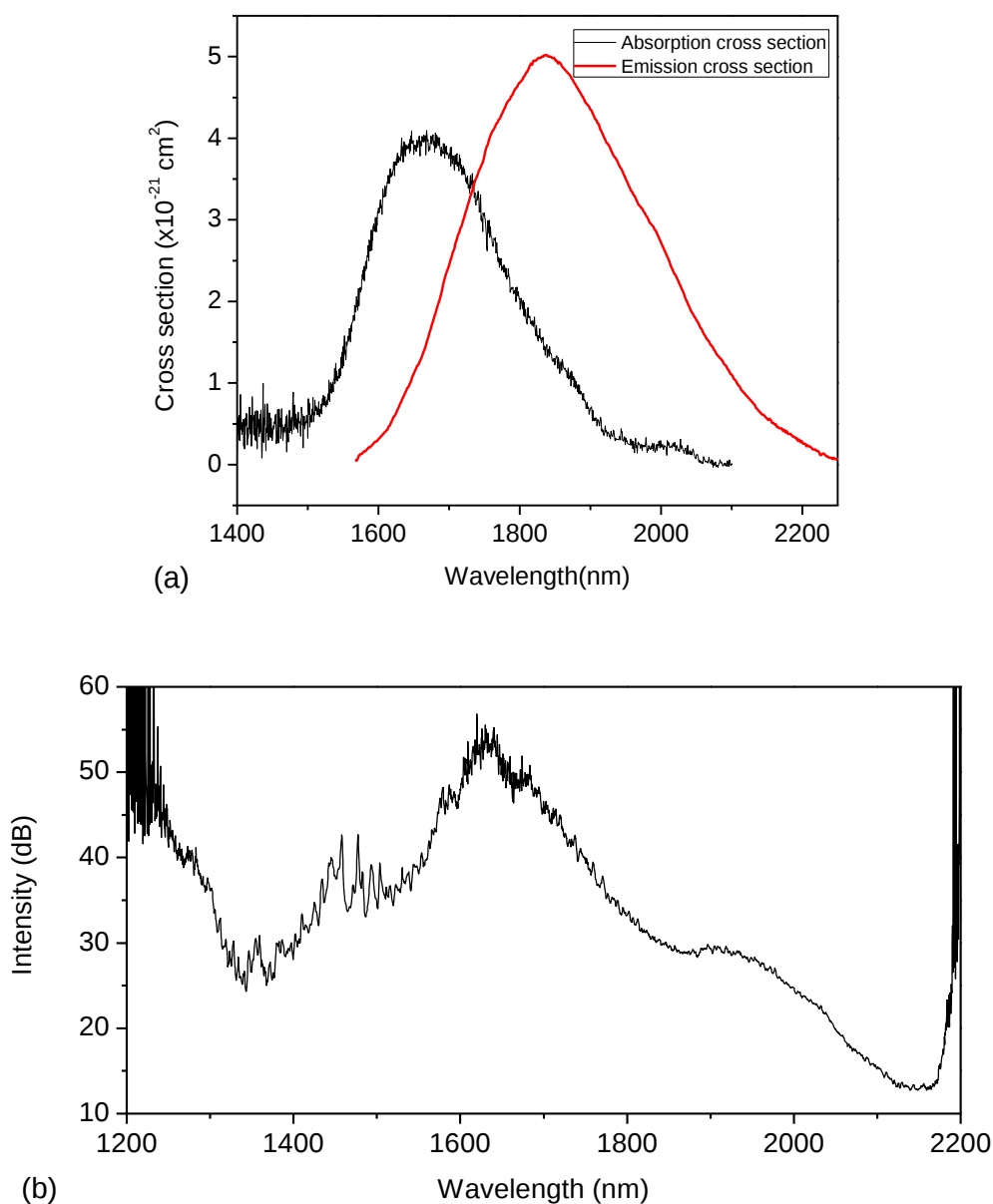


Figure 5-6 (a) Absorption and emission spectra for Nufern Tm-doped fiber as given on the company's website (http://www.nufern.com/marketing/fiber_data/Tm_Cross_Section.xlsx); (b) measured absorption spectrum of Tm amplifier.

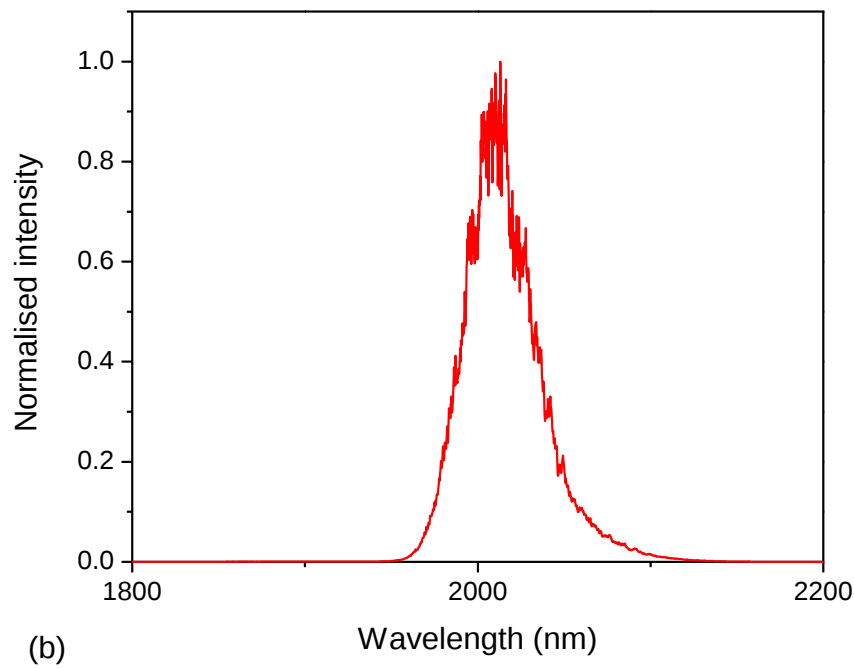
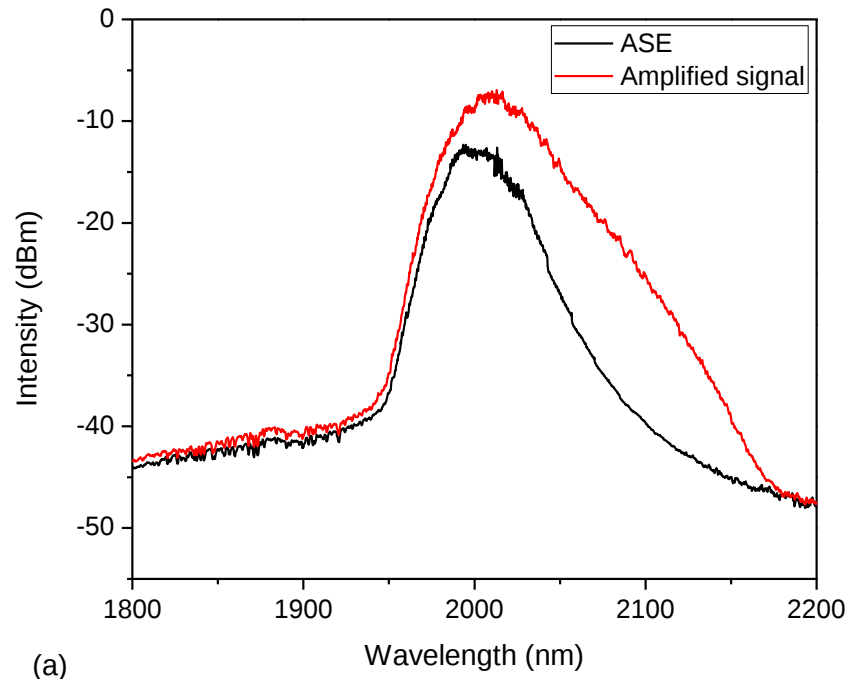


Figure 5-7 Output spectrum of the double clad Tm-doped fiber amplifier. (a) the red curve shows the ASE and the black curve the amplified signal. (b) Spectrum of the amplified signal on a linear scale.

The Tm-doped fiber is shortened to 3.3 m as the 6 m fiber initially used is seen to be too long. In addition to that, a 2 μm isolator is placed before the Tm-doped fiber amplifier, that is between the UHNA fiber and the WDM, to prevent back reflection to the seed source. The

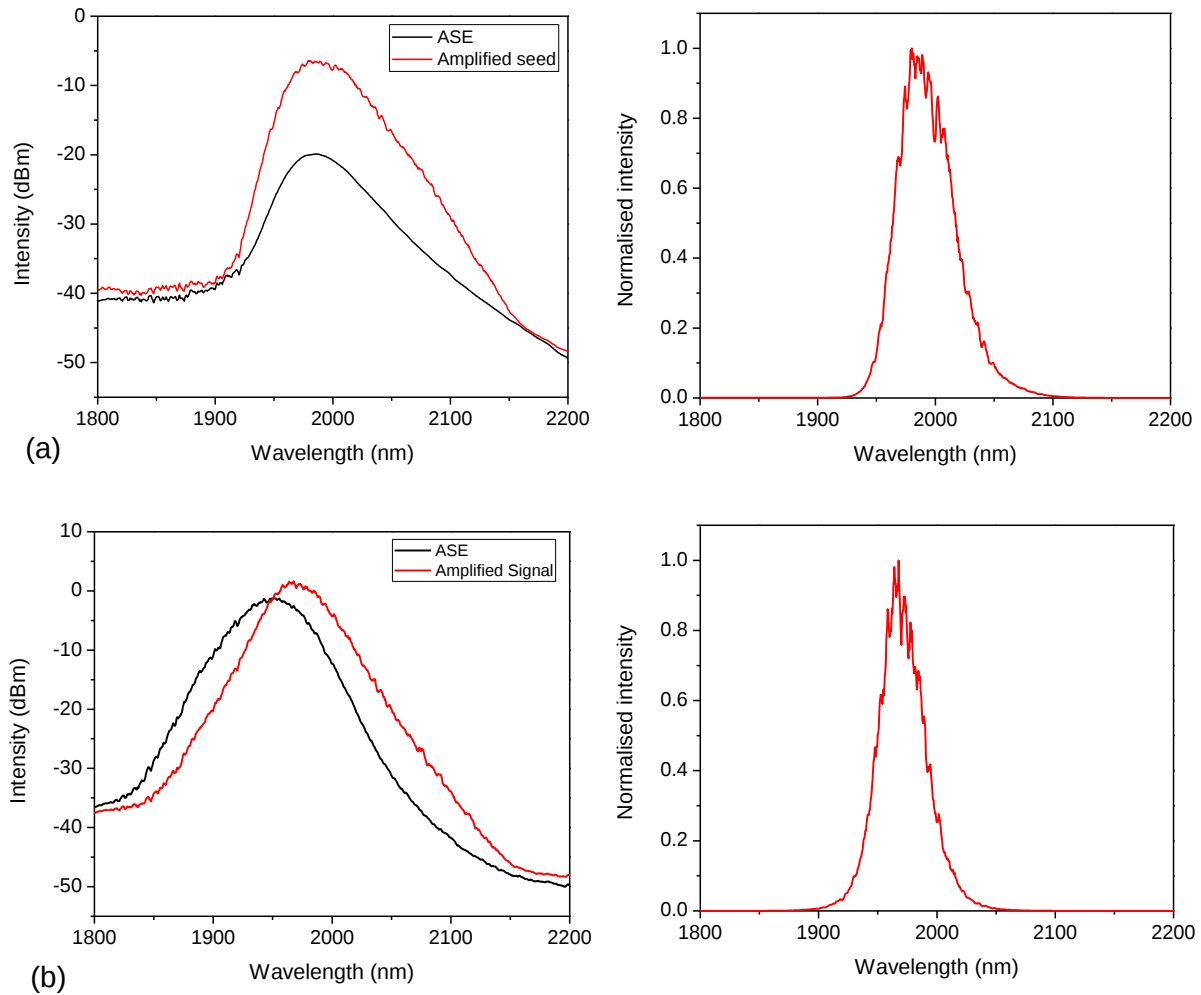


Figure 5-8 Output spectra of Tm-doped amplifier on logarithmic (left) and linear (right) scales at a thulium-doped fiber length of 3.3 m, with (a) forward pumping and (b) backward pumping scheme.

generated spectra under the same pumping conditions are given in Figure 5-8. The amplifier, when pumped in the forward direction as depicted in Figure 5-4, gives pulses with FWHM spectral bandwidth of 54 nm at a central wavelength of 1991 nm. It is observed that the pulse envelope is smoother than that for the 6 m amplifier without the isolator. When the amplifier is reconfigured for pumping in the backward direction, the generated spectrum shifts towards

shorter wavelengths as compared to the forward pumping orientation, giving a central wavelength of 1970 nm within a FWHM bandwidth of 40 nm. It is more symmetric, indicating a better distribution of radiated energy. The spectrum of the forward pump amplifier is broader giving transform limited pulse duration of 108 fs assuming a Gaussian pulse profile. The generated results from the Tm-amplifier are comparable to those obtained from a system where the Tm-amplifier is seeded by the solitonic part of a supercontinuum generated from a highly nonlinear fiber [69]. 110 fs was generated from that system.

5.3 Coherent broadband seeding of Tm-Ho fiber amplifier

Attention is now turned to amplification of the supercontinuum source with Tm-Ho co-doped fiber amplifier. Tm³⁺ fibers co-doped with Ho³⁺ ions have enhanced fluorescence, with emission wavelength extending beyond 2 μm . Figure 5-9 [106] shows the attenuation spectrum of the Tm-Ho co-doped fiber. From the graph, the possible pumping schemes for 2 μm lasing can easily be selected with pumping at 0.78 μm , 1.2 μm and around 1.65 μm being the most appropriate. The energy level diagram for Tm-Ho co-doped fiber is shown in Figure 5-10. The desired emission at 2 μm takes place by atomic transitions from the ⁵I₇ energy level to the ⁵I₈ energy level of Ho³⁺. The excitation of the ⁵I₇ energy level of Ho³⁺ is by energy transfer from the ³H₄ energy level of Tm³⁺. Pumping at ~ 1.7 μm leads to the ³H₄ energy level of Tm³⁺ being excited. Pumping at ~ 1.2 μm and ~ 0.8 μm causes excitation of the ³H₅ and ³F₄ energy levels respectively, and they in turn decay to the ³H₄ energy level for energy transfer to the Ho³⁺ energy level. For this work, pumping at the longer wavelength using erbium

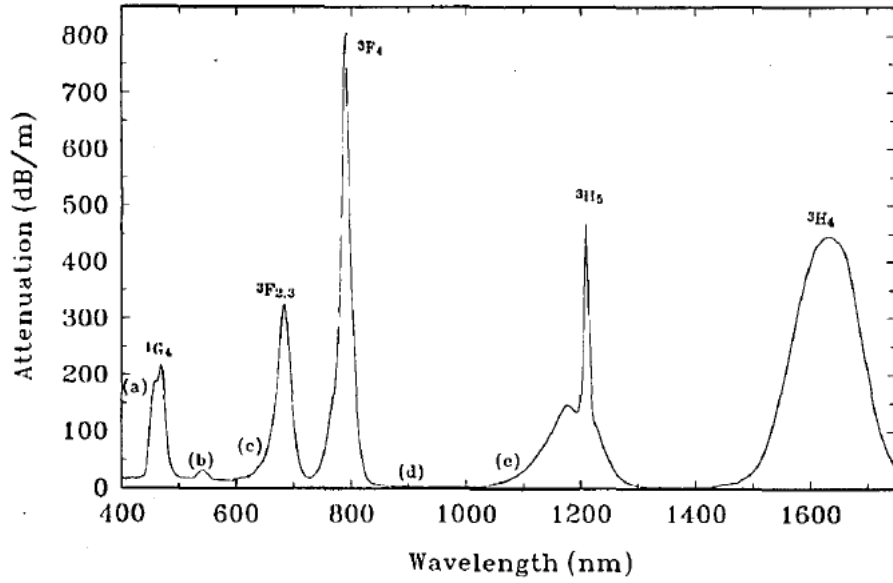


Figure 5-9 Attenuation curve of TmHo co-doped fiber. Spectroscopic symbols represent Tm^{3+} absorption bands, and alphabetical labels represent Ho^{3+} bands: (a) $^5\text{I}_8 \rightarrow ^5\text{F}_1, ^5\text{G}_6$, (b) $^5\text{I}_8 \rightarrow ^5\text{F}_4, ^5\text{S}_2$, (c) $^5\text{I}_8 \rightarrow ^5\text{F}_5$, (d) $^5\text{I}_8 \rightarrow ^5\text{I}_5$, (e) $^5\text{I}_8 \rightarrow ^5\text{I}_6$ [106].

doped fiber laser is chosen since high powered erbium doped fiber lasers are easily available, and it falls within the absorption band of Tm^{3+} . Studies show that though not as efficient as pumping at 800 nm, pumping of Tm-Ho at 1557 nm leads to sufficient fluorescence [107].

The upper limit of the generated supercontinuum source is around 2.2 μm . This makes it possible for a study of the behaviour of Tm-Ho fiber amplifier seeded across its entire fluorescence bandwidth, with the aim of generating ultrashort, high peak power pulses.

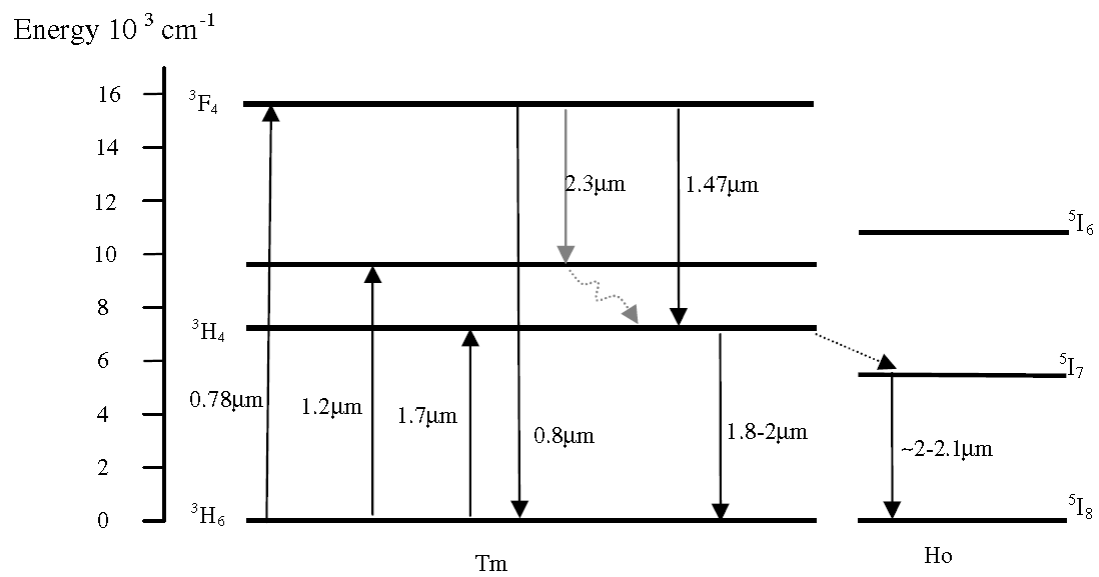


Figure 5-10 Energy level diagram for Tm-Ho co-doped fiber. Energy transfer is shown by the arrows. [107].

5.3.1 Experimental set-up

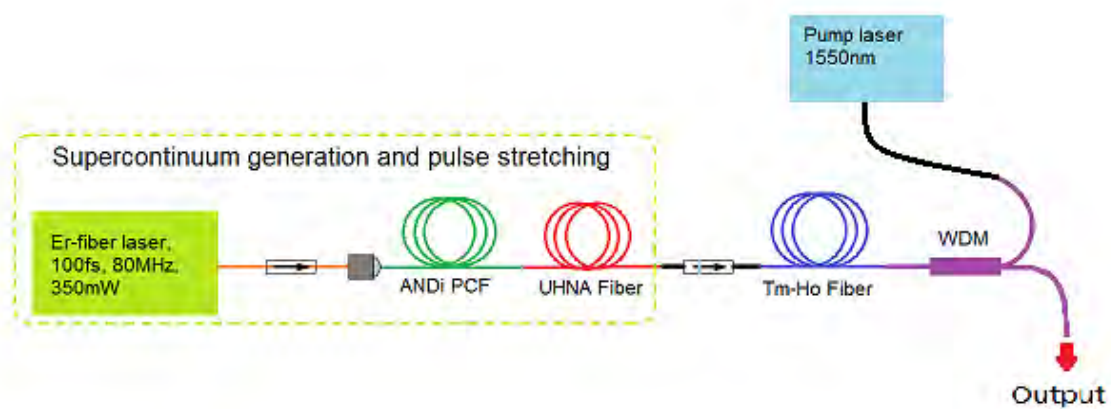


Figure 5-11 Schematic for Tm-Ho doped fiber amplification.

The setup for broadband amplification using a Tm-Ho co-doped fiber amplifier is shown in Figure 5-11. The generated supercontinuum from chapter 4 is again used as the seed source for the Tm-Ho amplifier, maintaining the same characteristics that were used for the Er-doped and Tm-doped amplifiers. The supercontinuum is initially stretched through 20 m of UHNA3 to a pulse width of 400 ps to reduce its peak power and limit excess nonlinearities. An isolator optimised for 2 μm operation connects the UHNA3 to the amplification stage, preventing any back scattered or reflected light from disturbing the supercontinuum. Initial pumping of the amplifier is by backward pumping and so the isolator is spliced to 90 cm of a single clad, single-mode Tm-Ho doped fiber (TH530) from CorActive, which serves as the gain medium. The Tm-Ho co-doped fiber has a core diameter of 6 μm , with cladding diameter of 125 μm . The absorption of the Tm-Ho co-doped fiber near 1212 nm is 144 dB/m. A 1560 nm Er-Yb doped fiber laser with maximum power of 5 W, locally designed and built at the Institute of Applied Physics, University of Bern, serves as the pump laser for the amplifier. A high power 2 μm wavelength division multiplexer from Opneti is used to couple pump signals to the Tm-Ho doped fiber. The wavelength division multiplexer filters the supercontinuum such that the seed signal is shaped with spectrum spanning from 1750 nm to 2200 nm Figure 5-12 (a). This is within the limits of Tm-Ho emission bandwidth, as shown by the amplified spontaneous emission (ASE) of the TH530 Tm-Ho doped fiber in Figure 5-12 (b). The amplified signal is monitored with a Yokogawa AQ6375 optical spectrum analyser which has a measurement range of 1200 nm to 2400 nm. The Tm-Ho co-doped amplifier is pumped from a threshold of 0.1 W to 4.8 W and corresponding spectral and average power measurements were made. Spectral results for the 90 cm length of Tm-Ho amplifier are presented in Figure 5-13.

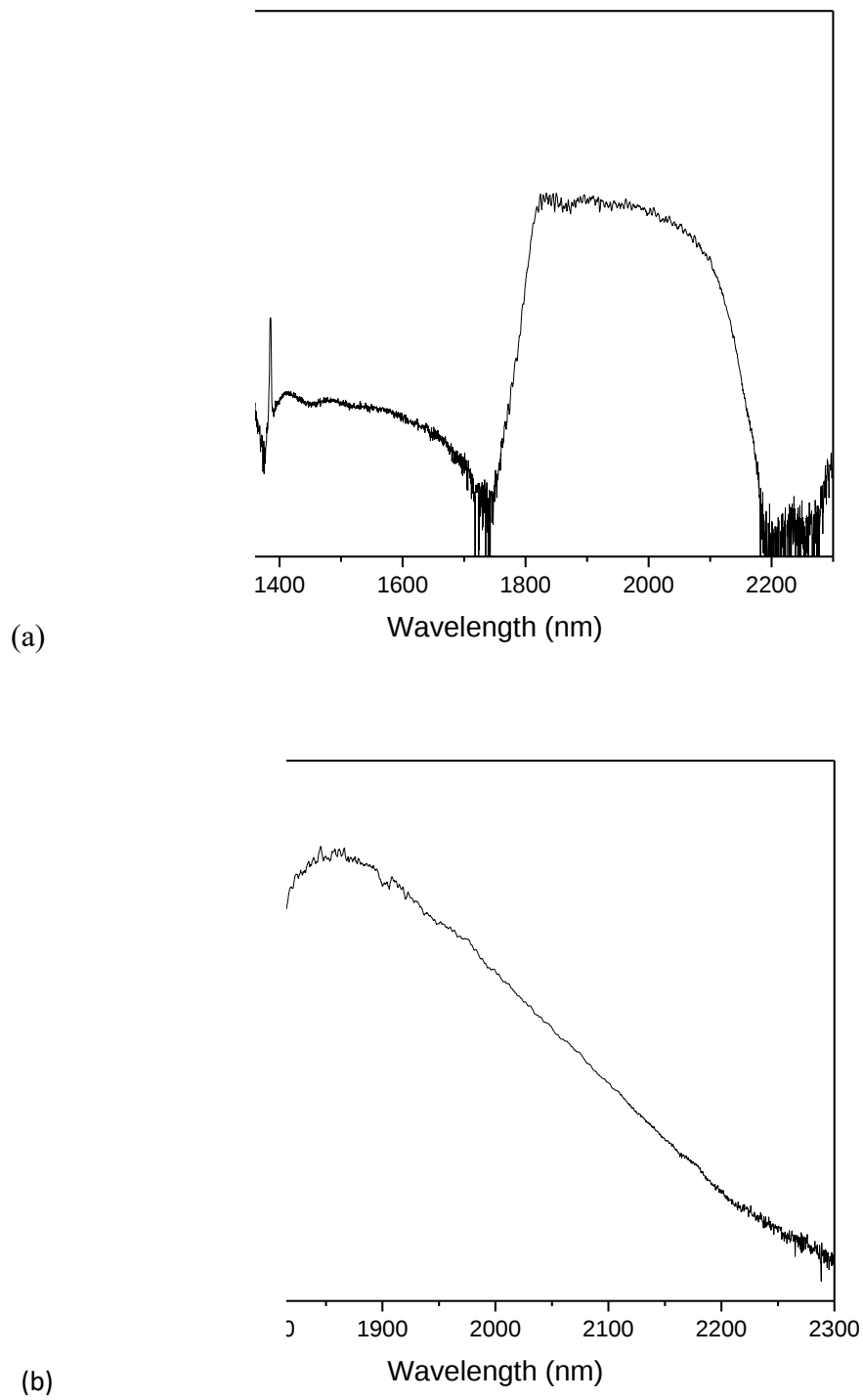


Figure 5-12 Spectrum of (a) filtered supercontinuum after the wavelength division multiplexer, and (b) ASE of 120 cm of Tm-Ho amplifier pump at 1550 nm.

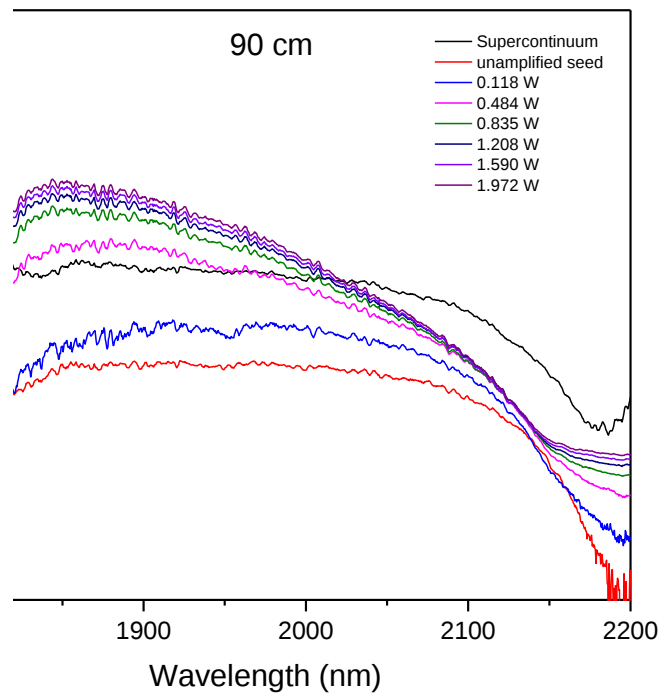


Figure 5-13 Spectrum of Tm-Ho amplifier of length 90 cm. The curves indicate the spectra of the amplified seed at the indicated pump levels.

The supercontinuum seed source indicated by the black curve, when propagated through the amplifier, is filtered by the wavelength division multiplexer and has a spectrum given by the red curve in Figure 5-13. The span of the filtered seed spectrum is from about 1750 nm to 2200 nm, with a flat top having a 3 dB bandwidth of 226 nm and central wavelength at 1950 nm. This gives the amplifier a broadband seed signal with an average power of 0.18 mW. The amplifier is pumped at an initial power of 0.118 W and gives an output signal of average power 0.37 mW, with central wavelength at 1947 nm, and 3 dB spectral bandwidth of 178 nm shown by the blue curve. The amplifier is again pumped at powers of 0.484 W, 0.835 W, 1.208 W, 1.590 W and 1.972 W, with their respective output spectra shown in Figure 5-13. The average output power of the amplifier as a function of pump power is shown in Figure 5-14 (a), with a fitted slope efficiency of 28%. Observation from the

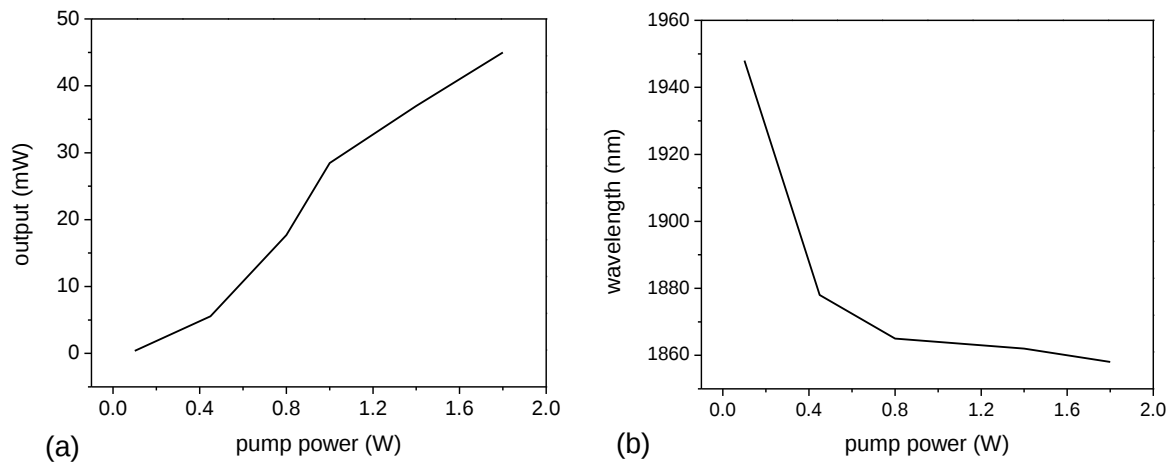


Figure 5-14 90 cm Tm-Ho amplifier (a) output and (b) central wavelength as a function of pump power.

generated spectra indicate that as the pump power increases, the central wavelength shifts to shorter wavelengths (plotted in Figure 5-14 (b)). The spectral bandwidth also decreases, with the spectral shape approaching that of the amplifiers ASE Figure 5-12 (b) as the pump power increases. At a pump power of 1.97 W, the 70 cm Tm-Ho fiber amplifier produces a signal with wavelength centre at 1862 nm and a 3 dB bandwidth of 70 nm. The average power is 46 mW.

The length of the Tm-Ho amplifier was increased to 120 cm with pumping maintained in the backward direction, from 0.1 W to 4.8 W at an interval of 0.35 W. The corresponding output spectra are shown in Figure 5-15. The longer amplifier length of 120 cm shifts the general central wavelengths of the output laser spectra to longer wavelength as compared to the 90 cm length amplifier. The central wavelength of the seed signal (red curve in Figure 5-15) is at 2025 nm, with a 3 dB spectral bandwidth of 125 nm. There is a significant shift of 75 nm in wavelength when compared to the wavelength of the seed signal in the 90 cm Tm-Ho doped amplifier. There is also a noticeable dip in its spectrum at 1950 nm. This is a

characteristic absorption wavelength band of Ho^{3+} in silica (Figure 5-16). The dip is prominent at lower amplified signal levels but flattens out from pump powers of 0.835 W. The central wavelength of the spectrum shifts to shorter wavelengths as the pump power is increased from 0.118 W to 1.97 W just as in the 90 cm Tm-Ho doped amplifier. 3 dB spectral bandwidth also decreases as the pump is increased to 1.97 W. With an average supercontinuum input power of 1 mW, the average amplified signal power is 58.5 mW at a pump power of 1.97 W. Pumping the Tm-Ho amplifier beyond 1.97 W seems to stabilise the shifting of the central wavelength, and the amplified signal maintains the same wavelength of 1875 nm and spectral bandwidth of 54 nm whilst output power increases. The maximum output power obtained at a pump power of 5 W is 130 mW. Higher amplification was limited by the pump laser.

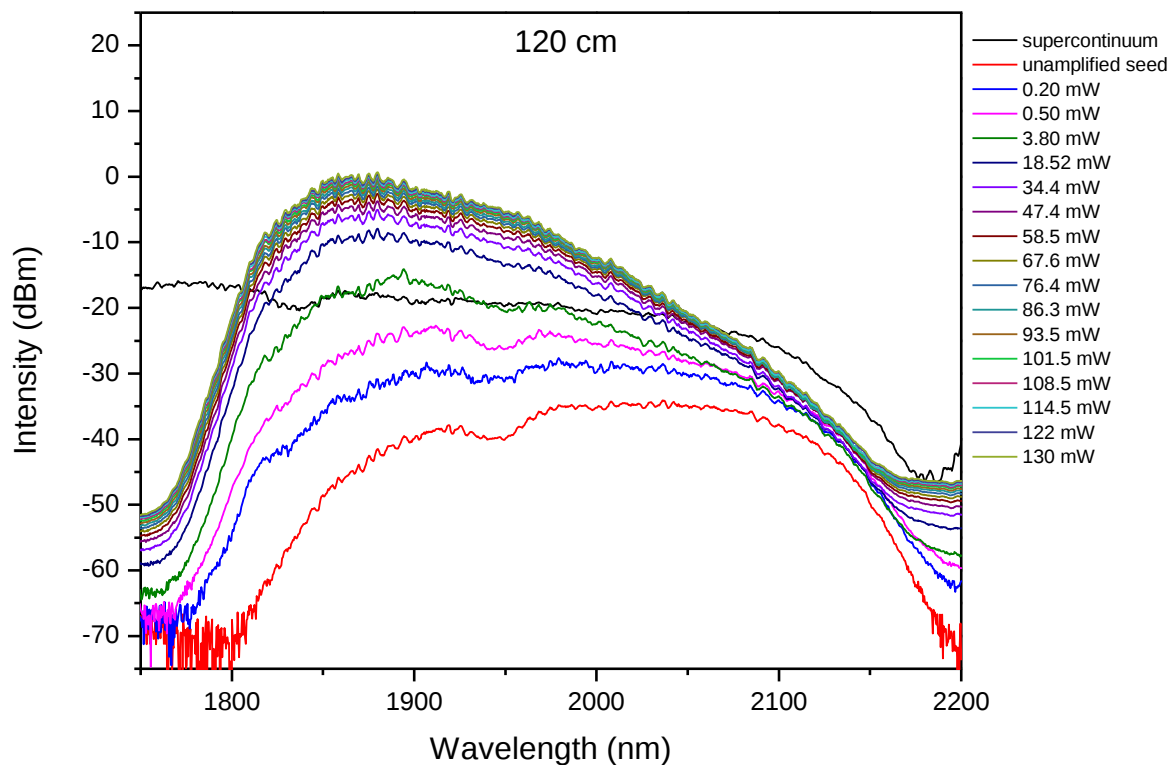


Figure 5-15 Spectra of 120 cm Tm-Ho amplifier at indicated output power levels

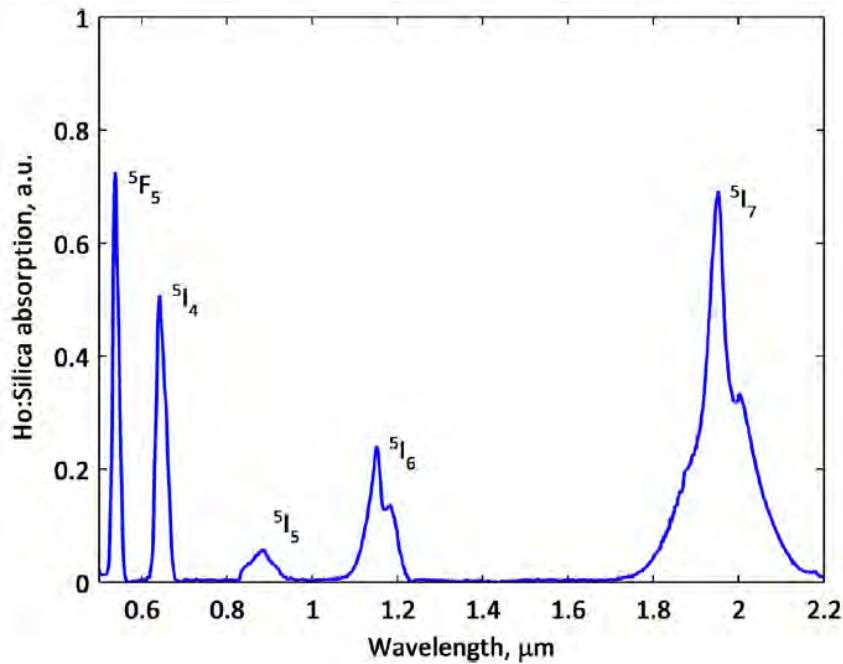


Figure 5-16 Absorption spectrum of holmium doped silica [108].

As has been shown by the two sets of spectral measurements made on the Tm-Ho amplifier, longer lengths of Tm-Ho doped fiber should shift the emission wavelength of the amplifier into the 2 μm region. In view of that, Tm-Ho amplifier lengths of 210 cm, and 350 cm were investigated to determine the best length of the amplifier that would give the broadest spectrum at the longest wavelength. The corresponding spectral results generated at the same pump powers for the 120 cm Tm-Ho amplifier are presented in Figure 5-17. The central wavelength of the seed source through the 210 cm amplifier when not pumped is 2032 nm with a 3 dB spectral bandwidth of 111.16 nm. Its spectrum spans from about 1850 nm to 2150 nm whilst that of the 350 cm amplifier spans from 1900 nm to 2150 nm. The 350 cm Tm-Ho amplifier has an initial seed bandwidth of 99 nm, centred at 2063 nm, confirming the shift to longer wavelengths. The characteristic absorption dip at 1950 nm is present in both amplifiers and flattens out after a pump power of 1.590 mW. Shifting of the central wavelengths of the spectra to short wavelengths for each amplifier with increasing

pump power occurs as in the 90 cm and 120 cm amplifiers. This stabilizes after a pump power of 1.972 mW maintaining an almost constant wavelength (Figure 5-18 (b)).

The dependence of the central wavelength on the fiber amplifier length, as well as on the pump power are summarised in the graphs of Figure 5-18. At a pump power of 2 W, the 90 cm Tm-Ho amplifier has a central wavelength of 1858 nm. The 120 cm Tm-Ho amplifier has a wavelength of 1875 nm, the 210 cm amplifier has a wavelength of 1907 nm and the longer amplifier length of 350 cm has wavelength of 1930 nm. From the curves (Figure 5-18 (a)), it is seen that the entire 120 cm amplifier spectrum is shifted to the right of the 90 cm amplifier spectrum, and the spectrum of the 210 cm amplifier shifts to the right of the 120 cm amplifier spectrum. A report [107] on a Tm-Ho fiber laser pumped at 1600 nm shows that with increasing fiber length, the central peaks and the shorter wavelength end of the fluorescence spectra shift to longer wavelengths, consistent with the results obtained here. At the longest Tm-Ho fiber length of 350 cm, the short wavelength end of the spectrum does not shift to longer wavelength as expected, but is rather shifted towards shorter wavelengths, lying between the 120 cm and 210 cm shorter wavelength end.

The pumping scheme of the Tm-Ho amplifier was changed to find the effects, if any, on the output of the amplifier when pumped in the forward direction, and when pumping is bi-directional, that is, pumping simultaneously from both ends of the Tm-Ho doped fiber. In the forward pumping scheme, the isolator is spliced directly to the ‘pass’ port of the wavelength division multiplexer, injecting the seed signal to the amplifier. The ‘common’ port delivers both the seed signal and the pump signal to the Tm-Ho doped fiber which is spliced to one end of it. The other end of the Tm-Ho fiber delivers the amplified signal. The output spectrum for 190 cm, and 345 cm of Tm-Ho doped fiber lengths in the amplifier are shown in Figure 5-19.

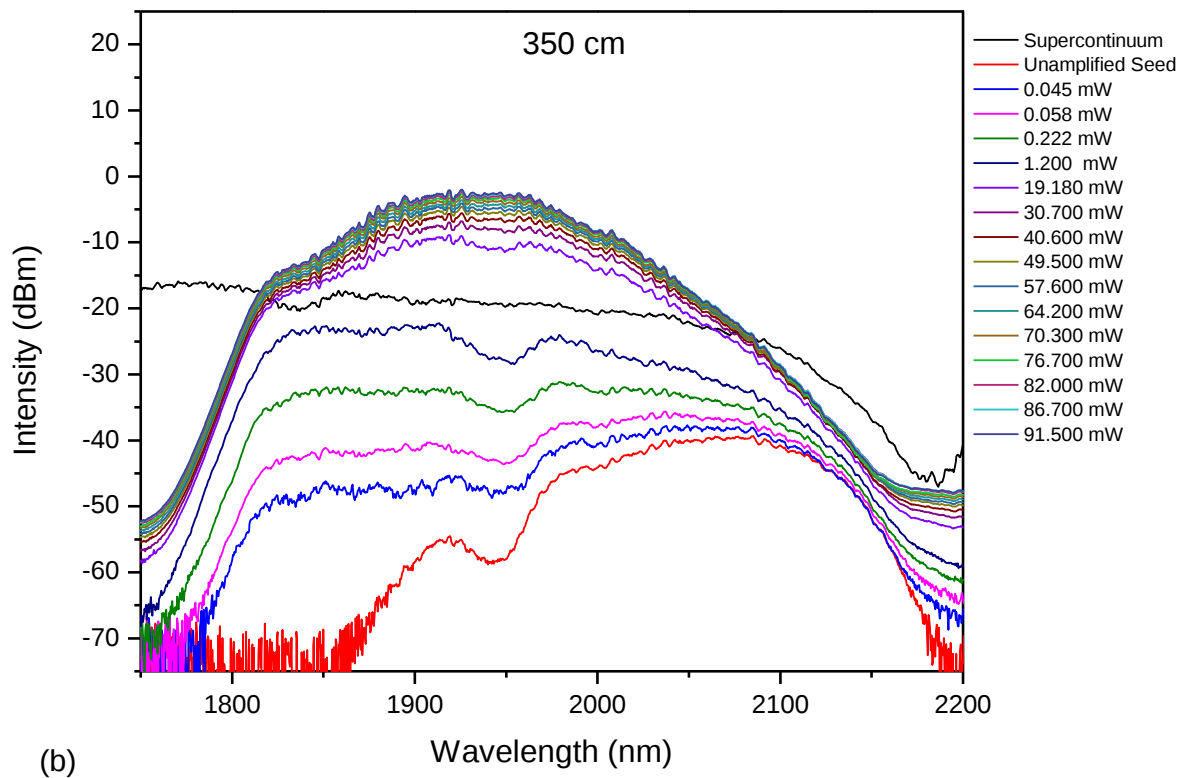
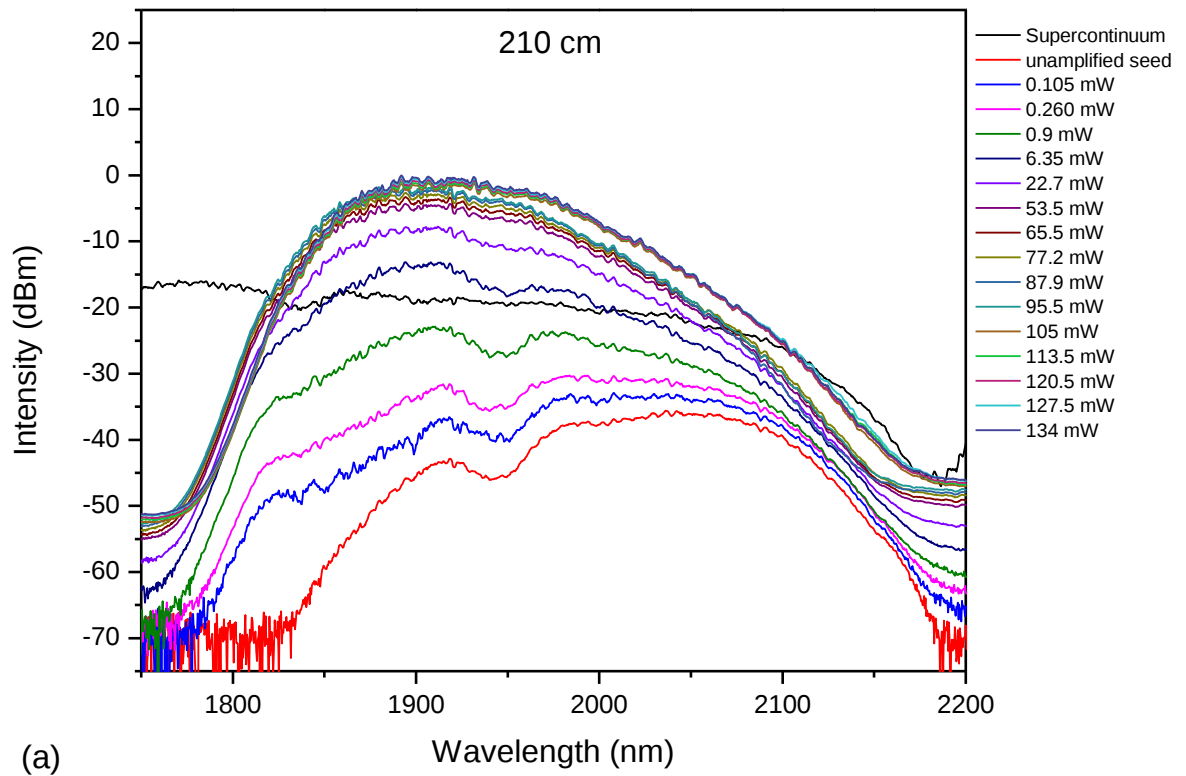


Figure 5-17 Spectra of (a) 210 cm, (b) 350 cm Tm-Ho amplifier with increasing pump power. Legend indicates corresponding output power.

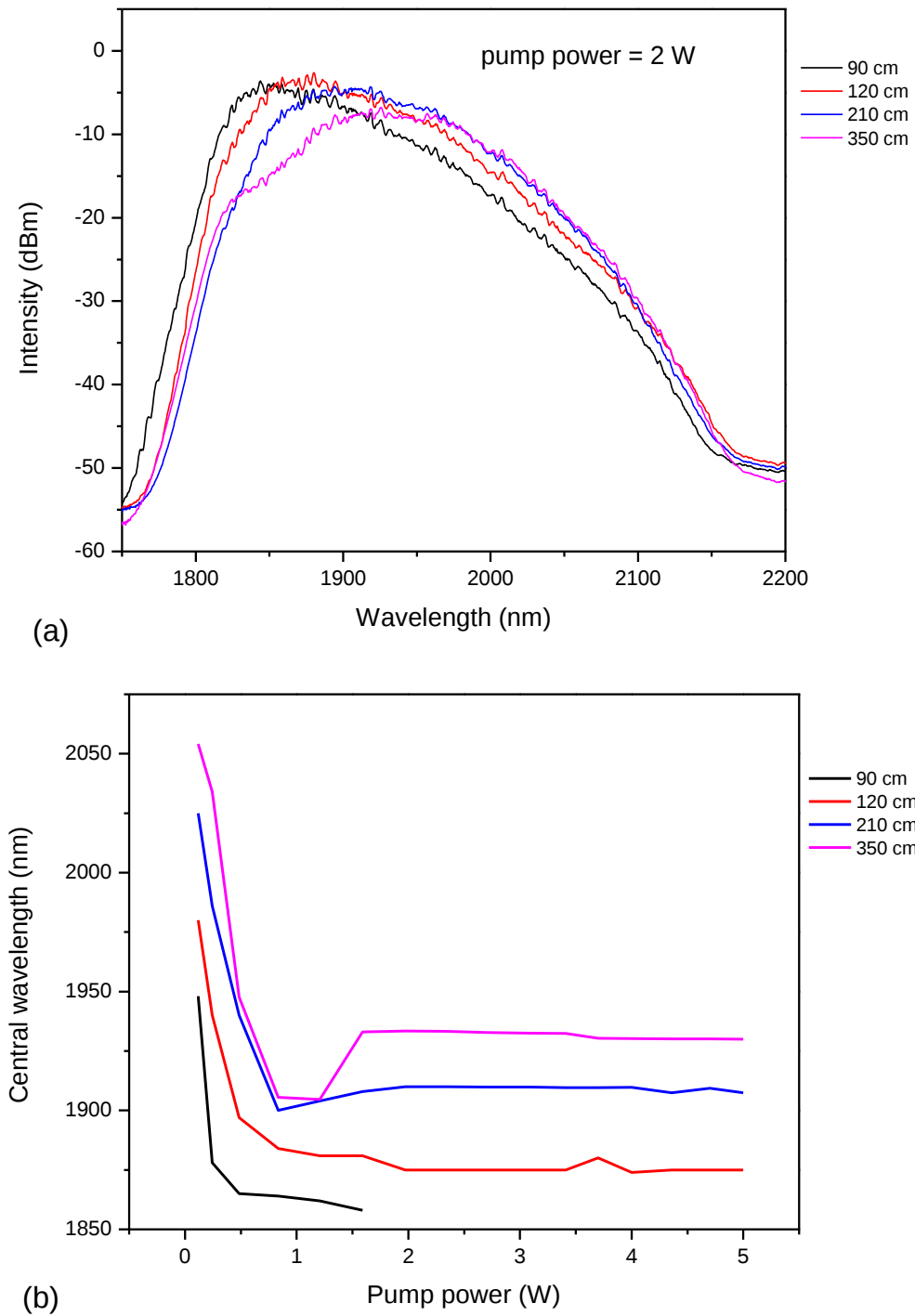


Figure 5-18 Dependence of the Tm-Ho amplifier wavelength on (a) Tm-Ho fiber length at pump power of 2 W and (b) varying pump power.

The spectrum follows the general pattern observed in the backward pumping scheme where the central wavelength of the seed spectrum is shifted to longer wavelengths with a reduction in its span as amplifier length is increased. With a Tm-Ho doped fiber length of 190 cm, the central wavelength of the seed is 1905 nm, and for a length of 345 cm, it is 1926 nm. Increasing the pump power shifts the central wavelength of the spectrum towards shorter wavelengths for each amplifier. From the spectra of the forward pumping case, as pump power is increased, the short wavelength end of the individual spectra gradually shifts towards shorter wavelengths till a pump power of 1.2 W, where it reaches its limit on the short wavelength side. This is however not the case in the backward pumping scheme where the spectra shift to their lower wavelength limit as soon as the pump is turned on, maintaining a constant span as amplification occurs.

A maximum length of 410 cm Tm-Ho co-doped fiber was used in the amplifier in a bi-directional pumping scheme. A 70:30 fiber coupler was used to split the pump power from the 1560 nm pump source and distribute 30 percent of the power to the wavelength division multiplexer for forward pumping. A second wavelength division multiplexer with similar characteristics to the wavelength division multiplexer originally in the amplifier was used for the backward pumping, delivering 70 percent of the pump power to the Tm-Ho doped fiber. The 'pass' port of the second wavelength division multiplexer outputs the amplified pulses and its spectra is shown in Figure 5-20. The spectra generated are similar to the backward pumped 350 cm amplifier. The general spectral shape at lower pump levels take on a rectangular shape with the 1950 nm Ho^{3+} absorption dip in the middle giving it two peaks, one centred at 1910 nm and the other around 1980 nm. Increase in pump power evens out the spectra eventually removing the absorption dip and giving the spectra a more central wavelength. At a maximum pump power of 5 W, the central wavelength of the 410 cm amplifier is 1940 nm with a 3 dB bandwidth of 99 nm.

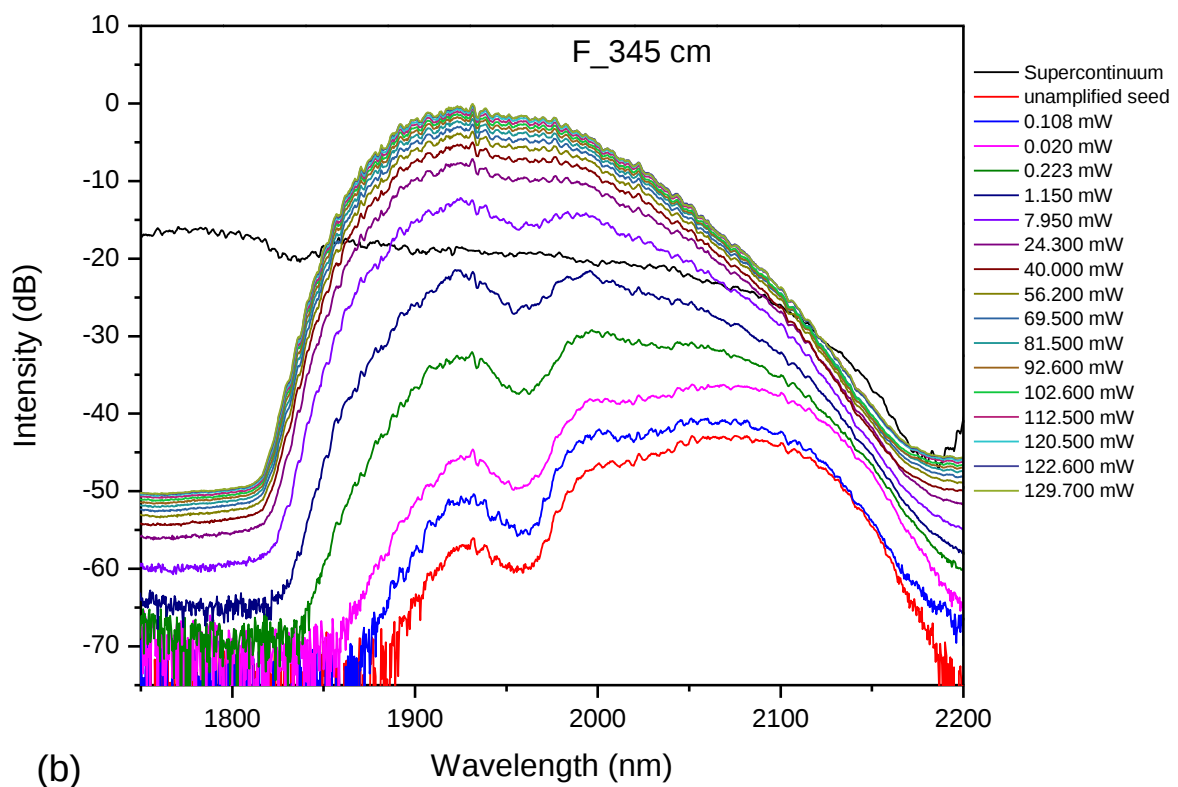
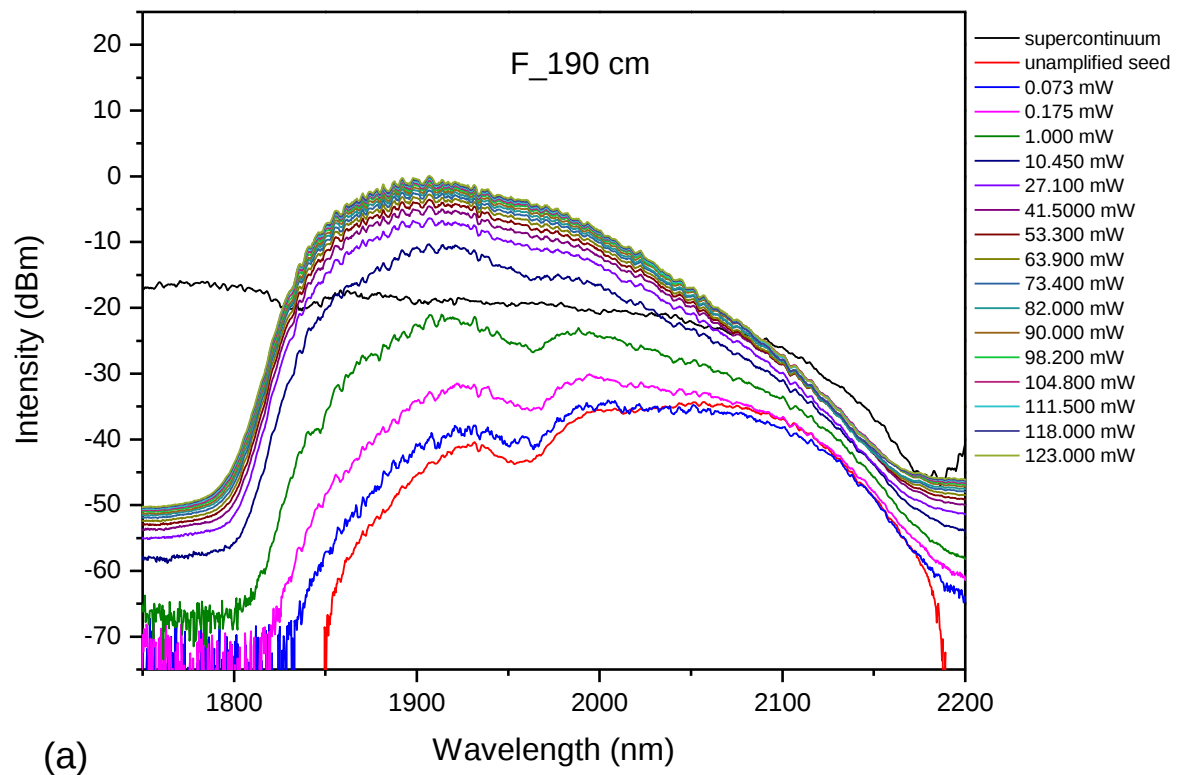


Figure 5-19 Spectrum of forward pumped Tm-Ho amplifier of length (a) 190 cm, and (b) 345 cm.

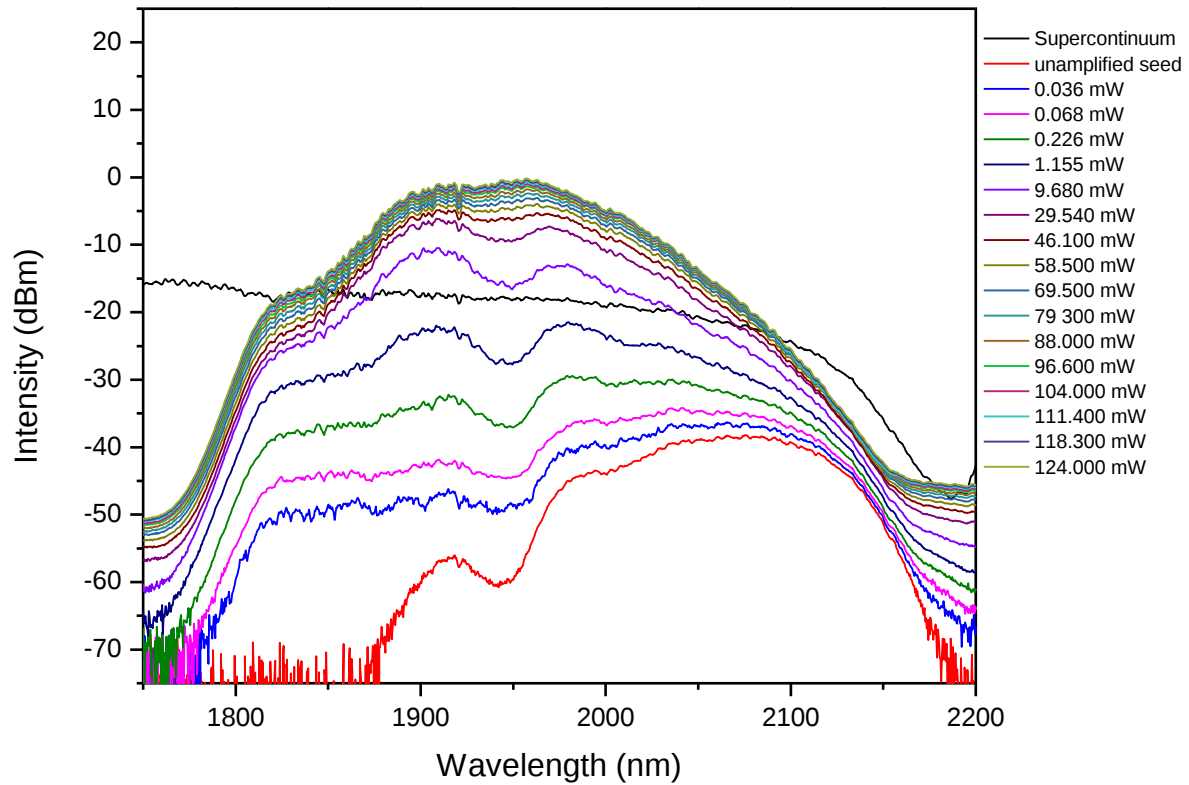


Figure 5-20 Spectrum of bi-directionally pumped 410 cm Tm-Ho amplifier.

5.4 Femtosecond source at 2 μm

Based on the results obtained from the amplification of the supercontinuum source through various lengths of Tm-Ho co-doped fiber (section 5.3), the length of 410 cm is selected to form an amplifier for the generation of ultrashort pulses at 2 μm as its spectrum is shifted the most towards longer wavelengths. Its spectral bandwidth is in the range of 100 nm giving the generated radiation at 1940 nm sufficient spectral bandwidth for it to have sub 100 fs transform limited pulse duration. The 410 cm Tm-Ho-doped fiber amplifier is known to have a negative GVD whereas the dispersion of the supercontinuum seed is positive. The generated pulse from the amplifier system is linearly chirped with a net normal GVD. Standard single-mode fiber can be used to compress such a pulse, and simulated results of the pulse compressed

with SMF28 gives a transform limited pulse of 38 fs pulse duration assuming a Gaussian pulse profile [109]. The experimentally measured spectrum of the generated pulse and the calculated pulse profile are given in Figure 5-21. The side modulations seen at the base of the pulse are indications of the presence of third order dispersion in the pulse. The third order dispersion of UHNA3 is positive, whereas the third order dispersion of UHNA4, another type of ultra-high numerical aperture fiber, is negative. Thus, UHNA4 can be used instead of UHNA3 to balance the positive third order dispersion of the SMF28, removing the perturbations and giving a clean pulse.

Generation of 80 fs pulses from a Tm-Ho amplifier seeded by the self-frequency shifted Raman soliton pulse generated from a highly nonlinear fiber has been reported [70]. The setup of this amplifier involves bulk optics making it complex and more expensive. With the simpler Tm-Ho amplifier system developed in this thesis, shorter pulse widths are expected.

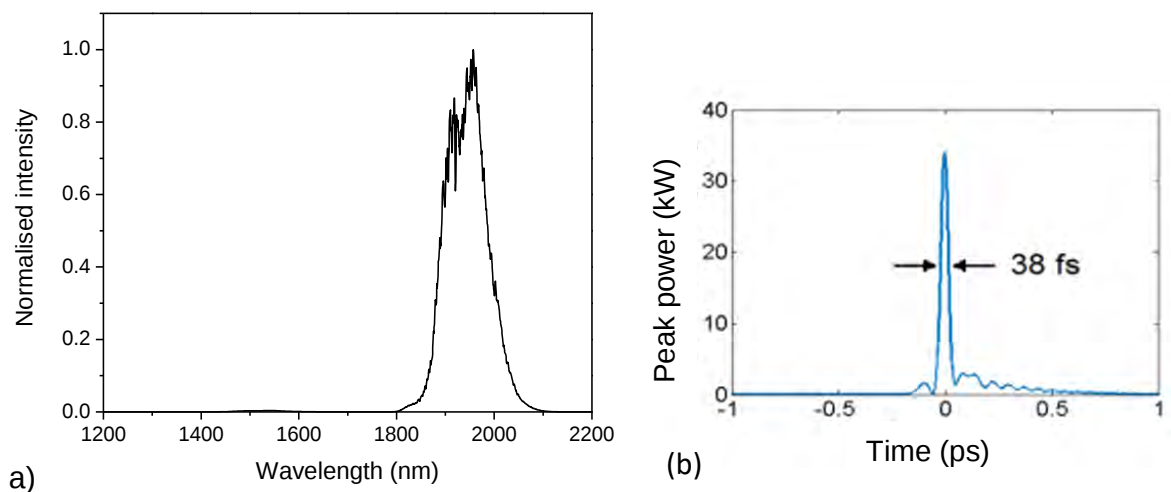


Figure 5-21 410 cm Tm-Ho fiber amplifier with (a) spectrum in linear scale (b) pulse profile calculated from Fourier transform of output spectrum.

To optimise the presented Tm-Ho fiber amplifier system, shorter lengths of fiber are used based on simulated calculations. The 20 m UNHA3 fiber for stretching the supercontinuum source is shortened to 3 m, and the Tm-Ho doped fiber is also shortened to 2 m. Pumping of the Tm-Ho doped fiber amplifier is in the backward direction. At a maximum pump power of 4.8 W, the average power of the amplified stretched pulse is 640 mW, measured from the WDM output. 6 m of single-mode fiber (PM2000 from Thorlabs) was spliced to the end of the 25 cm pigtail of the WDM for pulse compression. The cut-back method was used to find the point of maximum compression in the single-mode fiber. At a fiber length of about 390 cm after the WDM, a point was reached where the autocorrelation trace showed increased pulse width at fiber lengths longer or shorter than the 390 cm. This indicates the point of shortest pulse width. Autocorrelation measurements taken at the 390 cm single-mode fiber length gave a pulse duration of 88 fs at a pump power of 2.5 W. The autocorrelation trace in Figure 5-22 (a), however, shows signs of the onset of multi-pulsing. At higher pump powers the autocorrelation trace shows an increased effect of nonlinearity leading to pulse break-up (Figure 5-22 (b)) confirmed by previous work [110]. A major drawback to the measurements of the generated pulses was the phase matching angle of the autocorrelator crystal which was not optimised for measurements at 2 μm , limiting the measured pulse duration to 88 fs.

At a shorter Tm-Ho doped fiber length of 140 cm, the effects of third order dispersion are eliminated. Spectral and autocorrelation measurements are taken of the resulting compressed pulse, and these are shown in Figure 5-23. The measured pulse duration is 90 fs, again limited by the autocorrelator.

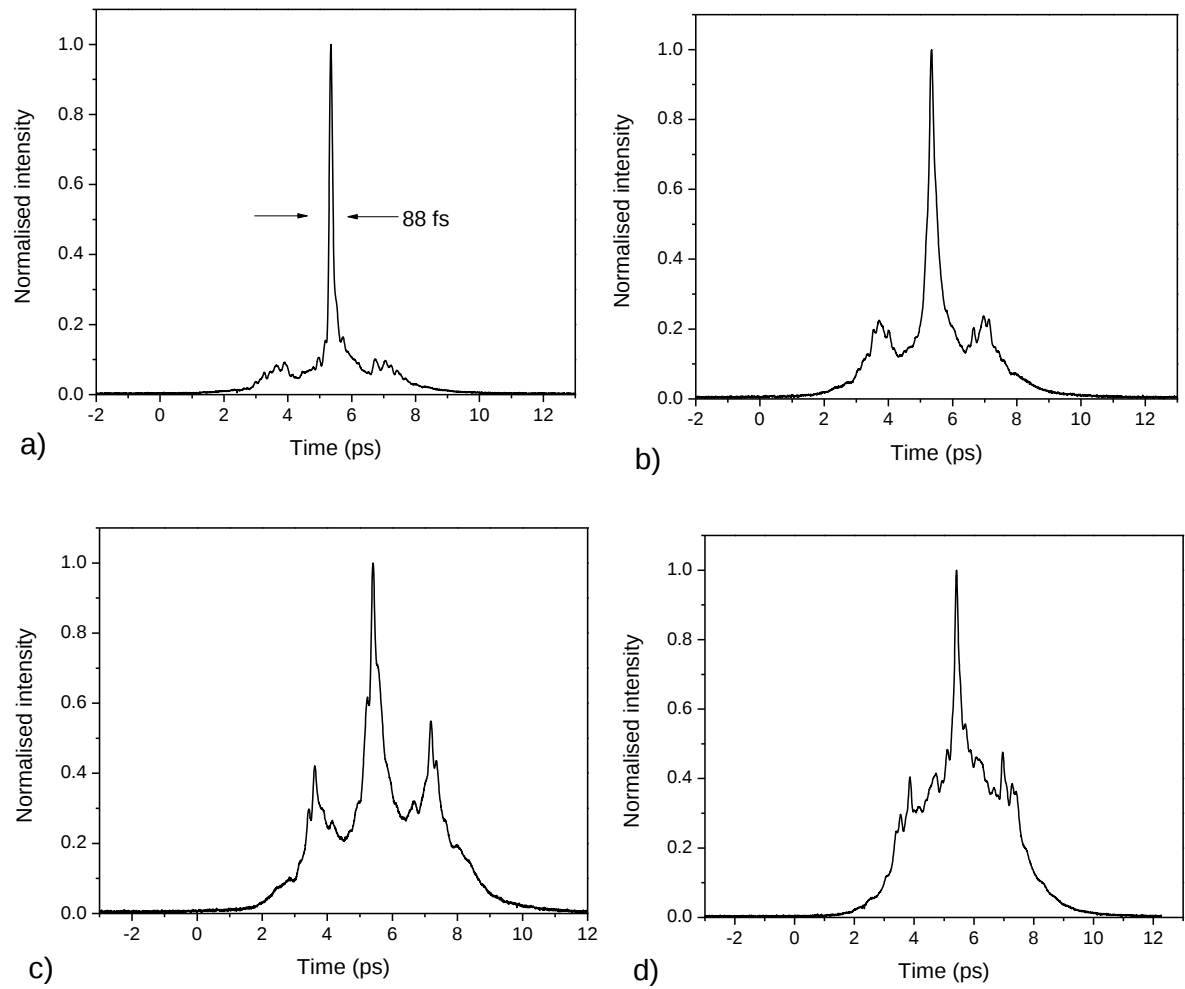


Figure 5-22 Measured autocorrelation of (a) shortest pulse and (b) – (d) pulse break-up with increasing pump power.

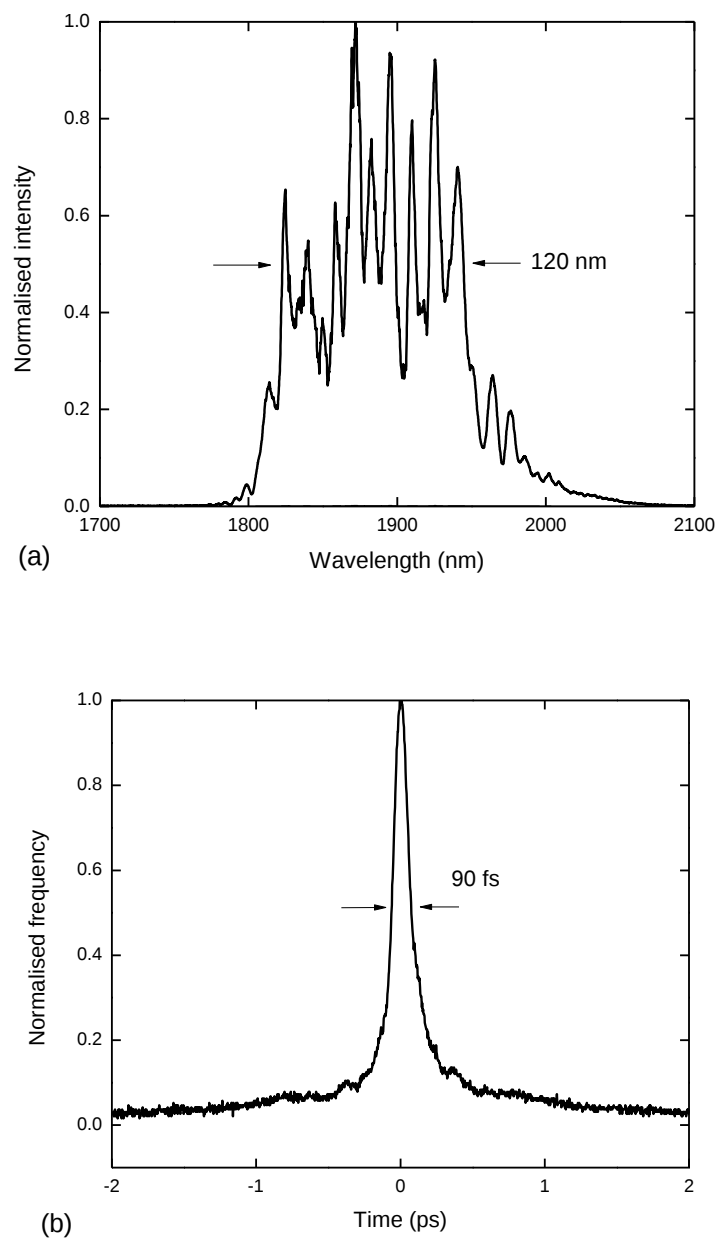


Figure 5-23 Compressed pulse characteristics for Tm-Ho doped fiber length of 140 cm. (a) Pulse spectrum and (b) autocorrelator measured pulse duration of 90 fs assuming sech^2 pulse shape.

CHAPTER 6

CONCLUSION AND FUTURE PROSPECTS

The main objectives of this thesis were the generation of femtosecond pulses from an erbium-doped fiber laser in the amplifier similariton mode-locked regime, the generation of coherent broadband supercontinuum, and the amplification of the supercontinuum using rare earth doped fiber gain media. This chapter gives a summary of the work done and presents results which are indicative of the achievement of the outlined objectives.

6.1 Summary of work

6.1.1 Erbium-doped fiber

Two erbium doped fiber laser cavities have been constructed to serve as a pump laser source for supercontinuum generation. Using a normal dispersion erbium doped-fiber in a ring cavity design made up of sections with anomalous group velocity dispersion, a net normal group velocity dispersion of the laser was obtained. Standard single-mode fibers wrapped around rotation paddles served as polarization controllers for mode-locking, maintaining an all-fiber laser cavity. Femtosecond amplifier similaritons were generated from the two laser cavities. A pulse energy of 0.46 nJ with a pulse spectral bandwidth of 50 nm at a repetition rate of 52 MHz was generated in the 355 cm long ring cavity. A second cavity with a greater length of SMF in the rotation paddles necessitated an increase in length of the erbium doped fiber to maintain the net normal dispersion of the cavity.

The longer cavity of length 510 cm produced pulses with spectral bandwidth up to 60 nm at a wavelength of 1603 nm. The longer gain medium generated broader spectrum

pulses with centre wavelength shifted to longer wavelengths. The 510 cm cavity gave a pulse width of 85 fs at a repetition rate of 37 MHz. Additional compression of the pulse yields a pulse duration of 68 fs which is among the shortest pulse widths generated from an erbium doped similariton fiber laser.

Low power obtained from the erbium doped fiber laser constructed would require that the output be amplified in a suitable amplifier configuration for use as a pump source for supercontinuum generation.

6.1.2 Generation of supercontinuum

A commercial erbium-doped fiber laser producing 100 fs pulses, operating with an average power of 350 mW was used as the pump source for supercontinuum generation. Specially designed all-solid all-normal dispersion photonic crystal fibers were used as the medium for the supercontinuum generation. Octave spanning supercontinuum stretching into the NIR wavelength region was generated. The initial spectrum obtained with PCF1 gave a bandwidth of 600 nm with the upper limit at 1920 nm. A second photonic crystal fiber, PCF2, gave a greater spectral span of 1100 nm extending from 1100 nm to 2200 nm. The generated supercontinuum did not have the characteristics of spectral broadening due to soliton fission as in the case of anomalous dispersion pumping. The spectral broadening was due to self-phase modulation and optical wave breaking, giving a relatively smooth spectrum (except for the central portion attributed to remains of pump power) and temporal profile. The single pulse preserved in the time domain during the spectral broadening process is recompressible to 10 fs.

6.1.3 Broadband amplification in rare earth doped amplifiers

Broadband amplification using erbium-doped, thulium-doped and thulium-holmium co-doped fibers have been successfully achieved for the first time using the supercontinuum source generated from the all-solid all-normal dispersion fiber. The entire bandwidth of the selected rare earth amplifiers was seeded by the supercontinuum.

The erbium doped amplifier produced a source with central wavelength at 1540 nm with a FWHM bandwidth of 25 nm. The generated pulse has a calculated transform limited pulse duration of 139.5 fs. The slope efficiency of the amplifier is 11.3% with a 5.6 dB gain and an average output power of 49 mW at a maximum pump power of 650 mW.

The thulium amplifier with a doped fiber length of 6 m produced pulses centred at 2011 nm with a FWHM spectral bandwidth of 39 nm. At a length of 3 m, pulses were produced at a wavelength of 1991 nm with a FWHM spectral bandwidth of 54 nm in a forward pumping configuration. In the situation of backward pumping at the same thulium amplifier length, the output was centred at 1979 nm with a reduced FWHM bandwidth of 40 nm. The shortest pulse duration of 108 fs assuming transform limited Gaussian pulse profile was obtained when the amplifier was in the forward pumping configuration.

The thulium-holmium amplifier gave the broadest spectral bandwidth out of the three amplifiers used. The amplified pulse spectral bandwidth ranged from 54 nm from a Tm-Ho amplifier of doped fiber length 120 cm pumped in the backward direction at 5 W to 239 nm for an amplifier of doped fiber length 350 cm also pumped in the backward configuration at 0.5 W. The average amplified spectral bandwidth is 100 nm. The broadest spectrum at the longest wavelength was generated from forward pumping of the 345 cm and the 410 cm Tm-Ho co-doped fiber pumped bi-directionally at 5 W to give 110 nm and 100 nm spectral widths respectively.

Compression of the 1940 nm centred pulse, generated from the thulium-holmium amplifier with gain fiber of length 410 cm, using single-mode fiber resulted in ultrashort pulse generation. Accurate measurement of the pulse duration was not possible due to limitation of the autocorrelator. The shortest pulse duration that could be measured by the autocorrelator at 2 μm was 88 fs. The Fourier transform of the spectrum however gave a calculated pulse duration of 38 fs. Experimental compression of pulses from a shorter amplifier cavity with 2 m Tm-Ho doped fiber resulted in pulse break-up of the generated pulse at pump powers above 2 W.

6.2 Conclusion

The objectives set forth in chapter 1, namely, construction of a mode-locked erbium-doped fiber laser, generation of broadband coherent supercontinua, and broadband coherent supercontinuum amplification have been achieved. It has been demonstrated that nonlinear polarization evolution in an erbium-doped fiber laser incorporating single-mode optical fiber polarization control elements leads to generation of mode-locked similariton pulses with the characteristic parabolic spectral and temporal profiles. This laser achieves the shortest known pulse width reported to date for an erbium-doped all-fiber mode-locked similariton fiber laser. Octave-spanning coherent supercontinua are generated in all-solid, all-normal dispersion photonic crystal fibers, with prospects for applications in few-cycle pulse generation, optical coherence tomography, and metrology. This constitutes the first known report of supercontinuum extending up to wavelengths in excess of 2.0 μm in an all-solid, all-normal dispersion photonic crystal fiber pumped at 1.5 μm . Power scaling of the supercontinua is possible with various rare earth doped fiber amplifiers, opening up additional application avenues. Ultrashort pulses were obtained from the amplification of the generated supercontinuum in thulium-holmium-

doped fiber amplifier, and its subsequent compression in standard single-mode fiber. This is the first time a normal dispersion broadband supercontinuum source has been used to generate sub-100 fs pulses.

6.3 Future prospects

The erbium-doped fiber laser constructed produced femtosecond pulses with average power in the few milliwatt range for the larger 510 cm laser cavity, and an average of 25 mW for the 355 cm cavity. In some applications and in particular, for use as a pump for supercontinuum generation, there is the need for amplification of the emitted laser radiation from the constructed laser. With the laser emission around 1600 nm, amplification is not easy as appropriate erbium-doped fibers with suitable gain bandwidth must be used. Preliminary studies using EDF-150 erbium doped fiber give an amplification of 11 dB. Studies also show that amplification of 15 dB is attainable for fiber laser sources in the 1600 nm wavelength range using bismuth based erbium-doped fiber for the amplifier gain medium [111]. Appropriate amplifier configurations should give the required output power.

In chapter 3, during the process of mode-locking, it was realised that the mode-locked state of the erbium laser cavity depended on the orientation of the polarization rotation paddles. A number of mode-locked states are therefore possible within the same laser cavity. The automation of the polarization controllers will allow for monitoring of all the possible model-locked states of the laser cavity. It is expected that a maximum pulsed spectral bandwidth of 100 nm is achievable in the 510 cm erbium-doped fiber laser cavity.

An all-fiber system for broadband amplification is aimed for. With the development of an amplification system for the erbium-doped fiber laser, the fiber output of the amplifier can be spliced to the all-solid all-normal photonic crystal fiber, making the system completely all-

fiber and robust. There will be challenges in the splicing of the solid core photonic crystal fiber to single-mode fiber because of material and structural differences of the two fiber types. This would have to be considered for maximum coupling efficiency.

The extensive spectral bandwidth of the supercontinuum implies that the generated pulse can have a very short pulse duration. By employing the method of nonlinear pulse compression [66], the supercontinuum can be recompressed to generate ultrashort pulses on the order of few cycle pulses.

The system is well suited for further power scaling using multiple amplification stages. The supercontinuum seed is able to simultaneously and coherently seed fiber amplifiers whose gain bandwidth overlaps any part of the SC bandwidth, for example ytterbium, erbium, and thulium-holmium, paving the way for fiber-based wavelength-division multiplexed few-cycle pulse amplification. Other applications envisaged include synchronised amplified frequency combs and ultrashort pulse amplification.

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