



UNIVERSITY
OF WARSAW

DOCTORAL THESIS

Nonlinearity shaping in specialty tellurite glass optical fibers

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"Sometimes, science is more art than science. A lot of people don't get that."

Rick Sanchez, *Rick and Morty*

UNIVERSITY OF WARSAW

Abstract

Doctor of Philosophy

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by Tanvi KARPATE

This dissertation presents specialized cases of microstructured and nanostructured optical fibers made of tellurite glass for the advancement of nonlinear optical femtosecond pulse propagation field. Under the scope of this dissertation, specialty optical fibers were designed, developed, and characterized for shaping their nonlinearity to obtaining a wide soliton detuning in the short-wave infrared wavelength range, low noise supercontinuum generation and analysis, and temporal pulse reshaping. The shaping of pulse propagation in optical fibers has been carried out in three ways; by dispersion engineering of fiber, by nonlinear propagation dynamics within the fiber, and by choosing and optimizing the material. Since this dissertation is focused mainly on short-wave (SWIR) wavelengths, tellurite soft-glass was chosen for fiber fabrication due to its high transmission in this wavelength range and high nonlinear response which enables attaining nonlinear dynamics with commercial standard femtosecond laser pumps.

The first research outcome of this dissertation is that a wide soliton detuning of 68.5 THz was attained using a suspended core fiber structure. The fiber was dispersion engineered for a flat anomalous dispersion in tellurite soft-glass to obtain Raman scattering-assisted self-frequency which facilitated the broad range of detuning in soliton from the pump center wavelength over short fiber lengths. This reduces the dependence on dispersion management for an end-to-end fiberized ultrafast system. The prominent soliton showed an input power-based tunability through the spectral range of 1560 nm (pump wavelength) upto 2400 nm when pumped with a 90 fs laser pulses from a robust mode-locked fiber laser. Such a soliton self-frequency shift-based light source, has the potential of being used as a source itself and also as a seed in amplifier systems for SWIR wavelengths that cannot be easily attained by commercial lasers.

The second research outcome of this dissertation demonstrates a low noise supercontinuum generation by designing an optical fiber for non-solitonic femtosecond pulse propagation with polarization maintaining properties. The fiber was shaped for all-normal chromatic dispersion with optimized hexagonal lattice parameters. A polarization maintaining (PM) variant of the fiber was also developed by structurally introducing birefringence in the fiber. Both the fibers successfully showed broad supercontinuum generation, which were then studied for their noise properties using real-time shot-to-shot dispersive Fourier transformation technique. The real-time noise measurements showed that the supercontinuum generated in PM fiber has less shot-to-shot noise as compared to the non-PM variant fiber. Thus the feasibility of PM fiber for low-noise octave-spanning coherent supercontinuum generation was successfully demonstrated.

As for the third research outcome of this dissertation, new dynamics leading to quasi-periodic temporal reshaping of a femtosecond pumped pulse were observed for a range of average power of the incident input pulses. The demonstrated temporal reshaping was attained in a tellurite glass-based graded-index multimode fiber, which was explored for spatiotemporal-spectral dynamics of pump femtosecond pulses. This study shows that the new observed dynamics, do not occur due to mode self-cleaning effects as earlier reported for long pump pulses. These dynamics are rather attributed to the alternating influence of negative group velocity dispersion and self-phase modulation with positive group velocity dispersion which makes the GRIN fiber act like a classic grating pair compressor as a function of input power. The tellurite graded-index fiber developed also showed an octave-spanning supercontinuum under different pumping conditions. Thus the fabricated tellurite GRIN fiber shows a high degree of manipulation capabilities in terms of spectral, spatial as well as temporal propagation, making it a great potential for high power applications which require broadband light sources or spatially stable beam or all-fiber pulse compressors, under appropriate pumping conditions.

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Streszczenie

Doctor of Philosophy

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Niniejsza rozprawa zawiera omówienie wyników badań nad mikro- i nanos- trukturalnymi światłowodami wykonanymi ze szkła tellurowych. Włókna te zostały zaprojektowane w celu badania nieliniowej propagacji impulsów femtosekundowych. Wszystkie opisane światłowody specjalne zostały zaprojektowane, opracowane i scharakteryzowane pod kątem kształtowania ich nielin- iowości w celu uzyskania szerokiego odstrojenia solitonu w zakresie podczer- wonych fal krótkofalowych (short-wave infrared - SWIR), generowania i anal- izy superkontinuum o niskim poziomie szumów oraz przekształcania ultra- krótkich impulsów laserowych w dziedzinie czasu. Możliwości kształtowania warunków propagacji impulsów laserowych we włóknach światłowodowych były badane na trzy sposoby; poprzez modyfikację dyspersji chromatycznej włókna, poprzez pomiary nieliniowej dynamiki propagacji światła we włóknie oraz przez wybór i optymalizację materiałów włókna. Rozprawa jest skon- centrowana na długofalowym zakresie bliskiej podczerwieni (SWIR) i dlatego wybrana platforma materiałowa do realizacji wszystkich projektów światłow- odów w pracy to miękkie szkła tellurowe. Charakteryzują się one wysoką transmisją w tym zakresie długości fali i silną odpowiedzią nieliniową, która umożliwia osiągnięcie nieliniowej dynamiki za pomocą komercyjnych stan- dardowych laserów femtosekundowych.

Pierwszym wynikiem badań zaprezentowanym w tej rozprawie jest szerokopas- mowe (68,5 THz) odstrojenie solitonu które zostało osiągnięte przy użyciu włókna z zawieszonym rdzeniem. Włókno ze szkła tellurowego zostało za- projektowane z kryterium osiągnięcia możliwie płaskiej anomalnej dyspersji chromatycznej, aby uzyskać przestrojenie częstotliwości solitonu z wykorzysta- niem zjawiska rozpraszania Ramana. Ułatwiło to osiągnięcie szerokiego za- kresu odstrojenia solitonu od centralnej długości fali lasera pompującego z za- stosowaniem relatywnie krótkich odcinków światłowodu. Rozwiązanie takie jest ważne, ponieważ ułatwia zarządzanie bilansem dyspersji chromatycznej

w praktycznych układach laserowych. Wyodrębniony soliton wykazał przes-
trajalność bazującą na zmianie mocy wejściowej poprzez zakres widmowy
od 1560 nm (długość fali pompy) do 2400 nm przy pompowaniu impulsami
laserowymi 90 fs z lasera femtosekundowego. Takie solitonowe źródło światła
oparte na przesunięciu częstotliwości środkowej impulsu może być wykorzysta-
ne np. jako źródło sygnału w systemach wzmacniaczy dla długości fal SWIR
których nie można łatwo osiągnąć za pomocą komercyjnych laserów ultraszy-
bkich.

Drugim wynikiem tej rozprawy jest demonstracja generacji superkontinuum o
niskim poziomie szumu kwantowego poprzez zaprojektowanie światłowodu
zachowującego polaryzację w celu bezsolitonowej propagacji impulsów fem-
tosekundowych. Włókno zostało zaprojektowane z całkowicie normalną dys-
persją chromatyczną poprzez zoptymalizowanie fotonicznej sieci heksagonal-
nej. Został również opracowany wariant włókna utrzymujący polaryzację (po-
larisation maintaining - PM) poprzez strukturalne wprowadzenie dwójłomności.
Oba włókna umożliwiły generację szerokiego widma superkontinuum, które
następnie badano pod kątem szumu impuls-do-impulsu przy użyciu techniki
dyspersyjnej transformacji Fouriera (DFT) w czasie rzeczywistym. Pomiar
szumu w czasie rzeczywistym wykazały, że superkontinuum generowane we
włóknie PM ma mniej szumu impuls-do-impulsu w porównaniu superkontin-
uum wygenerowanego w wariancie światłowodu bez intencjonalnej dwójłom-
ności. W ten sposób z powodzeniem zademonstrowano możliwość wykorzysta-
nia włókna PM do generowania koherentnego superkontinuum o szerokości
oktawy z niskim poziomem szumów.

Trzecim wynikiem badań zaprezentowanym w tej rozprawie, jest zaprojek-
towanie włókna z nieliniową dynamiką propagacji światła prowadzącą do
quasi-okresowego czasowego przekształcania wejściowych impulsów femtos-
ekundowych. Zjawisko to zostało zaobserwowane w światłowodzie w sze-
rokim zakresie mocy średniej impulsów wejściowych. Zademonstrowane prz-
eksztalcenie czasowe osiągnięto w wielomodowym światłowodzie z gradien-
tową zmianą współczynnika załamania (Graded index - GRIN) opartym na
szklach tellurowych. Włókno to badano pod kątem dynamiki czasoprzestrzenno-
spektralnej impulsów femtosekundowych lasera wejściowego. Zarejestrowane
wyniki pokazały, że zaobserwowana dynamika nie jest spowodowana efek-
tami samooczyszczania modów, jak wcześniej opisywano dla długich impul-
sów laserowych (nanosekundowych). Dynamika ta może być raczej przyp-
isana naprzemiennemu wpływowi ujemnej dyspersji prędkości grupowej i sa-

modulacji fazy z dodatnią dyspersją prędkości grupowej. Sprawia to, że włókno GRIN, w funkcji mocy wejściowej, działa jak klasyczny kompresor siatkowy impulsu. Opracowane włókno tellurowe GRIN pozwoliło również na generację impulsów o widmie superkontinuum i szerokości pełnej oktawy w różnych warunkach pompowania laserowego. Wytworzony ten sposób światłowód tellurowy pozwala na szeroką swobodę manipulacji spektralnej, przestrzennej i czasowej ultrakrótkich impulsów laserowych, co pokazuje duży potencjał dla zastosowań laserowych o dużej mocy, wymagających szerokopasmowych źródeł światła, stabilnej przestrzennie wiązki lub światłowodowych kompresorów siatkowych.

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To my parents...

Chapter 1

Introduction

This dissertation aims at expanding the current state-of-the-art in non-oxide fibers for nonlinear optics applications such as coherent supercontinuum generation, broadband soliton tuning, and multimode nonlinear frequency conversion. The research undertaken in this dissertation comprises of different approaches to shape nonlinearity in micro- and nano-structured fibers for dispersion-engineered propagation and evolution of femtosecond laser pulses. I use a highly nonlinear tellurite soft glass in order to take advantage of its unique mixture of properties. These include strong nonlinear response (ten times higher than silica), reasonable transmission across the visible up to the short-wave infrared (also referred to as SWIR) wavelength range and material dispersion, which can be compensated by waveguide dispersion in photonic crystal fiber designs making them compatible with table-top femtosecond lasers operating in the near-infrared. This dissertation explores different structural designs of tellurite glass-based fibers, each for a specific nonlinear optics application, in single-mode as well as multimode propagation regimes.

1.1 Objectives

Detailed objectives of the research within scope of this dissertation include:

- shaping of nonlinear response of tellurite fibers with structure, i.e. mode confinement and anomalous chromatic dispersion for isolated soliton propagation; this is to be carried out through the development of highly nonlinear fibers designed for broadband detuning of solitons and subsequently through the verification of nonlinear performance of the proposed fiber structures in conditions when the input soliton is delivered

from robust, moderate power femtosecond lasers; identification of optimal fibers for soliton detuning in context of structure and center wavelength of the input signals;

- assessment of the feasibility for shaping nonlinear response of fiber designed for efficient spectral broadening of femtosecond pulses exploiting non-soliton dynamics, specifically through the development of nonlinear fibers with designed chromatic dispersion profiles in the normal range of values with particular attention to the determination of polarization state of light coupled into the fiber and its role in the observed dynamics, evaluation of signal-to-noise ratio for selected polarization orientations of the input pulse;
- exploring the spatial and temporal complexity of femtosecond pulse propagation in conditions of strong nonlinear response and support of multiple guided modes of the fiber; during the study, the dynamics of nonlinear propagation in these conditions will be of particular interest and this will be realized by through time-domain characterization of light pulses at the fiber output using cross-correlation frequency resolved optical gating.

The theses of the dissertation which are to be confronted with the research results are:

1. **Shaping of nonlinearity in specialty optical fibers developed using highly nonlinear tellurite glasses enables achieving significantly improved tuning bandwidth of Raman solitons, covering the entire SWIR wavelength range, without applying complex and high peak power laser systems, compared to existing state-of-the-art fibers exploiting the silica glass technology.**

To prove this thesis, I carry out research and development of a suspended-core tellurite fiber designed for a unique balance between dispersion and nonlinearity to achieve a widely tunable soliton across 68.5 THz (outperforming previous results from silica as well as soft glasses) as a promising candidate to overcome the current lack of robust, versatile laser light sources based on nonlinear optics in the SWIR wavelength compatible with femtosecond erbium fiber-based lasers and thulium fiber-based ultrafast amplifiers.

2. **Shaping of nonlinearity in specialty optical fibers developed using highly nonlinear tellurite glasses enables achieving practical fibers for**

octave-spanning coherent supercontinuum generation without the noise-susceptible soliton dynamics and under conditions of determined state of polarization favorable to preserve low-noise dynamics.

To verify this thesis, I provide evidence of the detrimental role played by polarization modulational instability in non-solitonic supercontinuum generation by experimentally comparing real-time noise in supercontinuum generated in non-polarization maintaining and polarization maintaining variants of a regular air-hole lattice fibers. This result experimentally confirms the feasibility of state-of-the-art ultra-low-noise supercontinuum generation by femtosecond pumping the polarization maintaining all-normal dispersion fiber.

3. **Multimode nonlinear propagation can be exploited for the shaping of femtosecond laser pulses in terms of their temporal, spectral as well as spatial properties with specific input parameters under graded-index designs of fibers.**

The third research outcome extends into studying the multimode propagation of femtosecond pulses in a highly nonlinear graded-index fiber made from two types of in-house developed tellurite glasses. The study demonstrates a quasi-periodic temporal pulse reshaping which holds potential in advancing all-fiber based pulse compression techniques.

1.2 Dissertation outline

Chapter 1: This chapter introduces the motivation of pursuing research in the area of supercontinuum generation and characterization in the short-wave infrared wavelength range. I list the objectives followed by the thesis achieved in the scope of the dissertation. Further, I present an outline of the thesis highlighting the contents of each chapter. Lastly, I list the contributions and acknowledgements for each chapter.

Chapter 2: I begin with listing and describing linear propagation of light in fibers along with their characterization techniques used in this dissertation. These experimental techniques include measurements of chromatic dispersion, numerical aperture, fiber attenuation and birefringence. I discuss the technological advancements of photonic crystal fibers (PCFs) and state the role of dispersion engineering of PCFs which is crucial to realize and tailor nonlinear phenomena such as soliton self-frequency shift, optical wave-breaking or self-phase modulation - which although does

not depend on dispersion, can still interact with dispersion impacting how solitonic and non-solitonic nonlinear frequency conversion evolves along propagation of ultrashort laser pulses. I then summarize nonlinear pulse propagation in micro- and nanostructured optical fibers. I present an overview of the existing model for nonlinear pulse propagation and explain the nonlinear dynamics and processes involved. Further I also describe various techniques for characterization of different pulse parameters such as the dispersive Fourier transform and second harmonics generation-based frequency resolved optical gating (or its sum frequency-based cross-correlation variant) and the general optical setups that were used in this dissertation. In this chapter I bring forth research gaps that were identified from a detailed literature review and summarize the objectives of this dissertation.

Chapter 3: This chapter focuses on the development of the two tellurite soft glasses and fiber fabrication process used in this dissertation. The chemical composition of glasses play a crucial role in determining the physical and optical properties of the glass. The glasses are characterized for their recrystallization resistance, thermal properties, optical properties to be best suited for the targeted fiber fabrication. Further, this chapter outlines the fiber fabrication carried out by the stack-and-draw method. This chapter then extends to highlight the fabrication anomalies for each of the four fibers used in this dissertation.

Chapters 4, 5 and 6 contain results of my original research obtained in scope of this dissertation

Chapter 4: I demonstrate an isolated phenomenon of soliton self-frequency shift over a bandwidth of 68.5 THz in the short-wave infrared spectral range. I designed, fabricated, and characterized a suspended core microstructured fiber made of highly nonlinear tellurite glass. The fiber is designed for a flat anomalous dispersion to leverage on Raman scattering-assisted frequency shift of a fundamental-order soliton. I demonstrate a prominent soliton with an input-power-based tunability in the spectral range from the 1560 nm central pump wavelength up to around 2400 nm central wavelength of the frequency-shifted soliton, when the fiber is pumped with 90 fs pulses from a commercial, fiber-based, mode-locked laser.

- Chapter 5:** In this chapter, I demonstrate a direct comparison of noise in the supercontinuum generated in polarization maintaining (PM)-ANDi and non-PM ANDi fibers made from highly nonlinear tellurite glass using real-time dispersive Fourier transformation technique. The fibers were designed and fabricated with a tellurite glass with a hexagonal lattice structure consisting of seven rings of air-holes surrounding the core. The noise measurements revealed that the noise in SC in the non-PM fiber was drastically higher than that in PM fiber, indicating a detrimental role of polarization modulational instability in the nonlinear evolution of the injected femtosecond laser pulses. This provides experimental evidence that for similar pump parameters and fiber lengths, the PM fibers enable coherent supercontinuum generation with lower intensity noise, than their non-PM variants, which can be beneficial for various applications such as optical coherence tomography and confocal microscopy or compression of coherent, broadband pulses to few optical cycle durations.
- Chapter 6:** This chapter explores nonlinear propagation in graded-index multimode fiber made from tellurite glasses. It aims at filling the research gap on temporal measurements of multimode nonlinear propagation in optical fibers in conditions combining femtosecond duration of the injected laser pulses and high nonlinearity of the waveguide. I demonstrate a quasi-periodic temporal pulse reshaping as a function of input power in graded-index multimode fiber. The observed pulse reshaping is attributed to the interplay of self-phase modulation and dispersion (both intermodal and intramodal) in the fiber, leading to compression and expansion of the pulse in time.
- Chapter 7:** In this chapter I outline the general conclusions achieved in this work and state their relevance to the target thesis achieved. I also talk about future prospects of expanding the knowledge and technology of supercontinuum generation and related nonlinear process in the short-wave infrared wavelength range for non-silica glasses. Further, I give a brief review of potential applications for light sources in the short-wave range that could be catered by the outcomes of this dissertation.

1.3 Contributions and acknowledgements

The author of this dissertation is responsible for all the work presented here within. Fabrication of all the fibers developed in the scope of this dissertation was carried out by and under the supervision and expertise of Mr. Dariusz Pysz MSc. All the work presented here was carried out under the guidance and supervision of Dr. hab. Mariusz Klimczak.

In Chapter 4, I performed numerical simulations leading to the design of the fiber investigated in Chapter 4. I also measured chromatic dispersion characteristics of that fiber, with the help from Dr. Grzegorz Stepniewski, who carried out SEM imaging of the fiber structure. I carried out the numerical simulations of nonlinear propagation for this fiber to demonstrate isolated soliton tuning. In the experimental part of this work, I was assisted by Grzegorz Stepniewski and the experiments took place in Dr. hab. Yuriy Stepanenko laboratory at Institute of Physical Chemistry, Polish Academy of Sciences. I also acknowledge Dr. Anupamaa Rampur for making available her fiber amplifier setup for pumping my experiment at the central wavelength of 1900 nm.

In Chapter 5, I carried out the DFT measurements with the help from Dr. Thibaut Sylvestre from FEMTO-ST in France, along with the DFT measurements for non-PM and PM fibers and I carried out the analysis of the results. I did not design the non-PM fiber, which was performed by Mgr. Damian Michalik, while I designed the PM variant of the fiber. I carried out the characterization of both fibers for their chromatic dispersion and birefringence profiles, with help from Dr. Grzegorz Stepniewski, and I measured supercontinuum generation spectra in the two fibers. The DFT measurements for the two fiber were carried out by me during my secondment at Dr. Thibaut Sylvestre's laboratory at the FEMTO-ST Institut in France. I acknowledge Dr. Amar Nath Ghosh, Dr. Shreesha D. Rao and Dr. Thibaut Sylvestre for their assistance during both the DFT measurements and subsequent discussion of obtained results. I also received help from Dr. Cyril Billet with the algorithm for post processing the measurements from the DFT. I would also like to acknowledge the expertise of Prof. Ole Bang and Prof. John Dudley, whose vision lead this work to fruition.

In the Chapter 6, I contributed to the fabrication of the fiber by cleaning the preform elements, stacking the fiber preform and drawing the fiber with the help of Mgr. Dariusz Pysz. I did not design that fiber, the designing of the fiber presented in Chapter 6 was carried out by dr hab. Rafał Kasztelan from

University of Warsaw. The dispersion measurement of this fiber was carried out by me and the SEM imaging was carried out by Dr. Adam Filipkowski. Supercontinuum generation in this fiber when pumped at central wavelength of 1030 nm was carried out by me. I extended the existing FROG setup to XFROG by introducing a delay line to measure the spectro-temporal characterization of the fiber performance and I carried out the measurements in collaboration with Dr. Grzegorz Stepniewski. I was also supported by Dr. Katarzyna Krupa and Dr. hab. Yuriy Stepanenko with fruitful discussion on understanding the science that was brought forth in these results. Octave-spanning supercontinuum generation measurements under a high peak power of 2.2 MW with a tunable pump center wavelength of 1700 nm, 1800 nm and 1900 nm in the normal dispersion regime were carried out by Ekaterina Krutova, MSc. at Tampere University in Finland.

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Chapter 2

Linear and nonlinear propagation in optical fibers

2.1 Optical fibers

Nonlinear optical processes require high intensity of optical beams to interact with the material [1]. A light beam incident in a bulk medium experiences diffraction which limits its high-intensity propagation. Optical fibers are the most widely used waveguides as light can be confined in them, without significant diffraction, to attain high-intensity beam propagation [2]. Light guidance mechanism in a standard step-index fiber (SIF – fig.2.1a) is essentially that of transverse confinement of light in the core due to total internal reflection arising from the refractive index difference in the core and cladding. The light is thus guided longitudinally in the core. For a core of refractive index n_{core} and a cladding of refractive index n_{clad} , the numerical aperture (NA) is defined by the maximum input angle θ_{max} of incident beam to be guided in the core as [3]

$$\sin(\theta_{max}) = \sqrt{n_{core}^2 - n_{clad}^2} = NA \quad (2.1)$$

Each optical path that light can take in a fiber is defined as a mode. The number of modes that can propagate in a fiber depends on the refractive indices of the core and the cladding, the radius of the core, a , and the wavelength of input light, λ . An important parameter to assess the mode propagation in the fiber is called normalized frequency or the V-parameter and is defined as [4]

$$V_{SIF} = \frac{2\pi a}{\lambda} \sqrt{n_{core}^2 - n_{clad}^2} \quad (2.2)$$

In step-index fibers, when the value of the V-parameter is lower than 2.405, the fiber supports only fundamental mode propagation and is called single

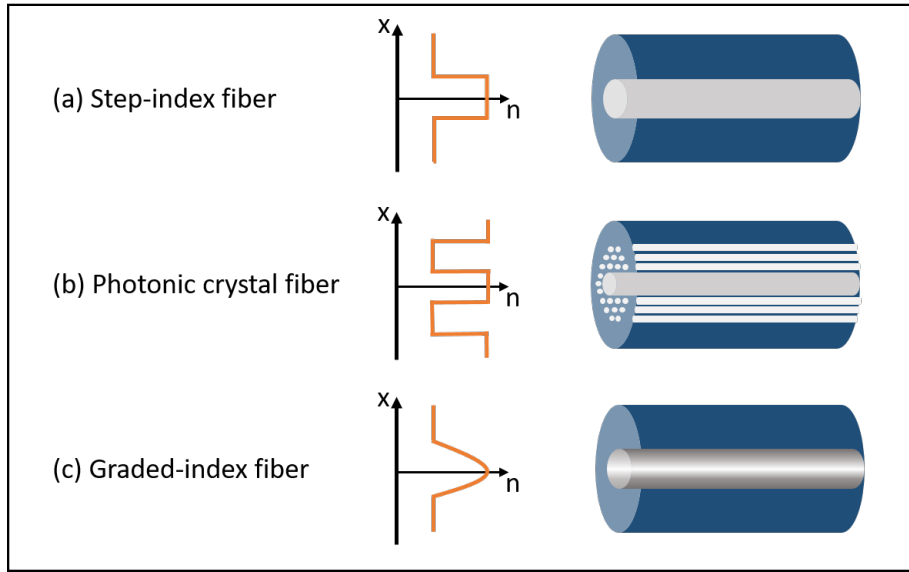


FIGURE 2.1: Types of optical fibers and their index profiles

mode fiber (SMF). When $V > 2.405$, the fiber supports multiple modes and is called multimode fiber (MMF). The wavelength at which $V = 2.405$ corresponds to the cut-off wavelength, λ_c . λ_c physically corresponds to the lowest wavelength at which a certain optical fiber supports single mode propagation. For wavelengths lower than the cut-off wavelength, the fiber supports multimode propagation [4].

Photonic crystal fibers (PCFs), also known as microstructured fibers, consist of arrangement of air-holes around the core to provide specialized light confinement. The effective index experienced by light propagating in this “holey” fiber is a cumulative effect of the photonic crystal arrangement of the air-holes as shown in Fig. 2.1. (b). The interesting aspect of PCFs is that the arrangement and the size of air-holes determine the characteristics of the fiber. Large difference in air-glass refractive index, without the need for doping, aids in tighter light confinement in PCFs than SIFs. PCFs with very small effective area can be fabricated, thus providing a high intensity beam propagation that is required for nonlinear optics applications. PCFs are commonly designed for single mode as well as multimode propagation. The V-parameter of the PCF can be obtained by substituting n_{clad} with the effective refractive index contributed by the fiber structure as n_{eff} [5]

$$V_{PCF} = \frac{2\pi a}{\lambda} \sqrt{(n_{core}^2 - n_{eff}^2)} \quad (2.3)$$

The most prominent feature of PCFs, and the one that I exploit here, is the ability to engineer the occurrence of nonlinear mechanisms in the fiber by designing the dispersion properties of the fiber. Dispersion engineering of PCFs, has vastly revolutionized the nonlinear optics field in last 20 years. In graded-index (GRIN – fig.2.1c) fibers, the refractive index $n(r)$ of the core is a function of the radial distance, r , such that the refractive index at the centre $n(r = 0) = n_1$ with a gradual decrease to $n(r = a) = n_2$ at the boundary between the core and the cladding, where a is the core radius and $n_1 > n_2$ [6, 7]. Modes in GRIN fibers propagate such that only the modes that phase match with the fundamental mode are guided in the fiber due to the difference in effective refractive index experienced by different modes. The fractional refractive index difference of a GRIN fiber is given as [8]

$$\Delta = \frac{(n_1^2 - n_2^2)}{(2n_1^2)} \approx \frac{(n_1 - n_2)}{n_1} \quad (2.4)$$

While GRIN fibers are largely used for multimode propagation, single-mode propagation of GRIN fibers can be defined by the normalized frequency V_{GRIN} [8]

$$V_{GRIN} = \frac{2\pi}{\lambda} a n_1 \sqrt{2\Delta} \quad (2.5)$$

However, the V-parameter is sensitive to the index profile of the fiber, α , such that [8]

$$V_{GRIN} < 2.405 \sqrt{\left(1 + \frac{2}{\alpha}\right)} \dots Eq.2.6 \quad (2.6)$$

For a quadratic index profile, $\alpha = 2$ and the fiber is single mode for $V < 3.53$. The maximum number of modes that a GRIN fiber can support in multimode propagation regime can be approximated to $M = \frac{V^2}{4}$ [8].

2.2 Linear propagation in optical fibers

2.2.1 Dispersion: theory

When an optical pulse propagates through a medium, different frequencies of the pulse experience different phase and group velocity. Such a frequency dependence of the propagation constant $\beta(\omega)$ is known as dispersion and induces temporal broadening of the pulses. Dispersion occurs due to intrinsic properties of the material, called material dispersion, as well as due to structurally bound propagation conditions provided by waveguides or optical

fibers, called waveguide dispersion. Material dispersion can be mathematically approximated using Sellmeier's equation as [9]

$$n^2(\lambda) = 1 + \sum_{j=1}^k (B_j \lambda^2) / (\lambda^2 - C_j^2) \quad (2.7)$$

Where n is the refractive index at wavelength λ , B_j is the strength of the j^{th} resonance at the material resonance wavelength C_j . The Sellmeier's coefficient of the tellurite glasses used in this dissertation are listed in section 3.4.3. Waveguide dispersion can further be of two types: chromatic dispersion and intermodal dispersion. Intermodal dispersion comes to existence when multiple modes propagate and interact together in MMF. Intermodal dispersion pose a strong limitation on the achievable data transmission rate in MMFs, thus limiting their efficiency [10]. Intermodal dispersion can be limited by using SMFs where the pulse propagates in the fundamental mode and experiences only chromatic and material dispersion. Thus I use SMFs in in Chapter 4 and 5 of this thesis to be able to not account for intermodal dispersion. Intermodal dispersion can also be minimized by using parabolic-index MMFs as done for the MMF used in Chapter 6. Chromatic dispersion can be analytically obtained by Taylor series expansion of the propagation constant $\beta(\omega)$ around the central frequency ω_0 as [1]:

$$\beta(\omega) = \frac{\omega}{c} n_{eff}(\omega) = \beta_0 + \beta_1(\omega - \omega_0) + \frac{1}{2}\beta_2(\omega - \omega_0)^2 + \dots \quad (2.8)$$

Such that the dispersion coefficient is given by $\beta_k = \frac{\partial^k \beta}{\partial \omega^k} |_{\omega=\omega_0}$

In the physical sense, β_0 is the propagation constant at the central frequency ω_0 . β_1 corresponds to the inverse of group velocity experienced by the envelope of the pulse. β_2 is the group velocity dispersion (GVD) that accounts for the frequency dependence of propagation speed and is responsible for temporal pulse broadening. An important feature in dispersion management is the wavelength at which β_2 attains a value of zero. Such wavelength is called zero-dispersion wavelength (ZDW). Higher orders of dispersion become crucial for ultrashort pumping close to the ZDW [9]. Waveguide dispersion can be tailored by either doping the glass or by introducing a change in effective refractive index by changing the geometry of the PCFs. Material dispersion provides an intrinsic ZDW to the fiber, which can be then shifted to longer wavelengths by the contribution of waveguide dispersion. This is crucial in the realm of

nonlinear optics as the occurrence of nonlinear optical phenomenon depend on the ZDW and the dispersion at which the fiber is pumped. Often, GVD is expressed in terms of the dispersion parameter D , such that [1]

$$D = \frac{-2\pi c}{\lambda^2} \beta_2 = \frac{\lambda}{c} \frac{d^2 n_e f}{d\lambda^2} \quad (2.9)$$

Waveguide dispersion D (or β_2) depends on the core radius and the core-cladding refractive index, which make it a crucial feature that enables **shaping of nonlinear dynamics**. Waveguide dispersion can be tailored by either doping the glass or by introducing a change in effective refractive index by changing the geometry of the PCFs. Material dispersion provides an intrinsic ZDW to the fiber, which can be then shifted to longer wavelengths by the contribution of waveguide dispersion. This is crucial in the realm of nonlinear optics as the occurrence of nonlinear optical phenomenon depend on the relation of the ZDW and the dispersion at which the fiber is pumped. The length of fiber at which dispersion causes an initial Gaussian pulse of duration t_0 to broaden by a factor of $\sqrt{2}$ is called dispersion length and is given as $L_D = (T_0^2)/(|\beta_2|)$ [1]. The nonlinear mechanisms in an optical fiber manifest differently based on the sign of the dispersion parameter. For wavelengths shorter than the ZDW, D is negative ($\beta_2 > 0$) and the fiber is said to exhibit normal dispersion. In the normal dispersion, red-shifted frequency components of an optical pulse travel faster than the blue-shifted components. When wavelength is longer than ZDW, D is positive ($\beta_2 < 0$) and the fiber exhibits anomalous dispersion. Blue-shifted frequency components travel faster than the red-shifted components of the pulse in the anomalous dispersion.

2.2.2 Mach-Zehnder interferometer for chromatic dispersion measurements

Experimental measurement of chromatic dispersion of the photonic crystal fibers in this work is carried out using an unbalanced Mach-Zehnder interferometer. The Mach-Zehnder interferometer measures phase delay experienced by a dispersive component such as an optical fiber. Dispersion of the fiber can be then numerically obtained from the measured phase. The set-up used for this spectral interferometric measurements was identical to the one described by Ciacka et al. [11] and earlier proposed by Hlubina et al [12]. A beam from a compact supercontinuum source from Leukos, with spectral coverage across the visible and near-infrared, was collimated using a lens (L_1) and input into

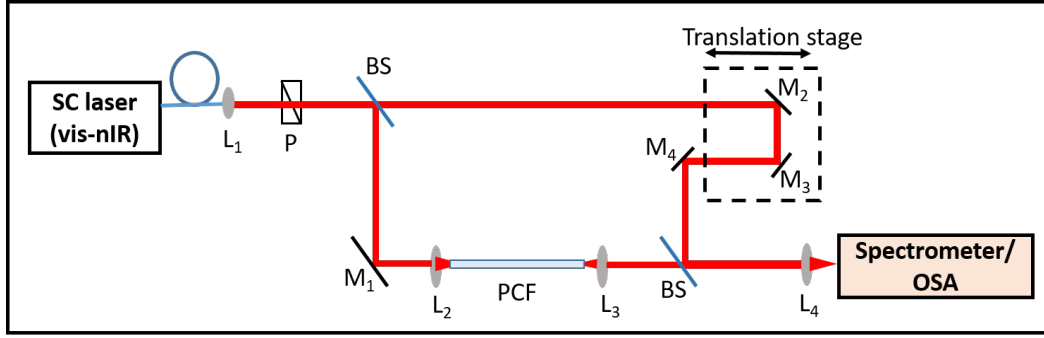


FIGURE 2.2: Mach-Zehnder interferometer setup to measure chromatic dispersion. L_1 :collimating lens; L_2 :input coupling lens; L_3 :output coupling lens; L_4 :lens to couple signal into spectrometer; BS:beam splitter; P:polarizer; M_1, M_2, M_3, M_4 :mirrors

the interferometer as shown in Fig. 2.2. The beam passed through a polarizer (P) to ensure linear polarization of the pulses, and then was then split using a beam splitter (BS) into the reference arm (with mirrors mounted on the translation stage to provide path difference compensation) and into sample arm. The light was coupled into the fiber sample placed in the sample arm using aspheric lenses L_2 and L_3 . The beams from the two arms of the interferometer were then coupled into an Avantes spectrometer with 900-1750 nm sensitivity range or an optical spectrum analyser (OSA) with a sensitivity range of 1200-2600 nm to observe the interference fringes.

Clear interference pattern in the tellurite fibers studied in this work were observable only over a limited wavelength range. For this reason, instead of using the approach proposed by Hlubina et al. [12], I employed the method described by Koch et al. [13], where I traced the prominent central fringe across a wavelength range. Interference fringes were observed and recorded with the spectrometer by balancing the interferometer for the zero-order fringe at individual wavelengths, by changing the length of the reference arm. This method of observation of equalization path length for each wavelength shift provides us with the phase information. A plot of path lengths across the wavelength range is further processed with Taylor-expansion and polynomial fitting to return the dispersion values. Wavelength position is measured for a central bright interference fringe that satisfies the relation $L - l - n(\lambda)z = m\lambda$ [12] where L is the path length in the reference arm, l is the path length in sample arm in air, $n_{eff}(\lambda)$ is the effective refractive index of the fiber glass and z is the fiber length. By including the optical path difference (OPD) contributed by the lenses used in the sample arm, the effective refractive index that the light

propagating in the fiber experiences is given by [12]

$$n_{eff}(\lambda) = \frac{(-OPD_{ref} - OPD_{lens})}{(z + 1)} \quad (2.10)$$

A consecutively measured $n_{eff}(\lambda)$ tracing the zero-order fringe at individual wavelength is plotted. Using the Cauchy dispersion formula, the relation between wavelength and the effective refractive index is determined as [14]

$$n_{eff}(\lambda) = A_1\lambda^6 + A_2\lambda^4 + A_3\lambda^2 + A_4 + A_5\lambda^{(-2)} + A_6\lambda^{(-4)} + A_7\lambda^{(-6)} \quad (2.11)$$

where A_i are the coefficients of expansion. The group effective index $N(\lambda)$ is then obtained by the relation

$$N(\lambda) = n_{eff}(\lambda) - \lambda \frac{dn_{eff}(\lambda)}{d\lambda} \quad (2.12)$$

From which the dispersion parameter can be then deduced as [12]

$$D(\lambda) = 1/c \frac{dN(\lambda)}{d\lambda} \quad (2.13)$$

I developed a MATLAB algorithm to simplify the process of deriving the dispersion values from the measured dispersion data, especially in case of soft glass fibers where fringe order counting method used by Ciacka et al. [11] cannot be used. This code follows the above mathematical description and is listed in appendix A.

2.2.3 Cut-back method for fiber attenuation measurement

Attenuation relates to loss of optical power due to absorption, scattering, bending and other defects in the fiber. Attenuation due to light absorption in the material stems from imaginary part of the complex refractive index [15]. The total attenuation experienced by the fiber is a function of wavelength denoted by $\alpha_{dB}(\lambda)$ and is expressed in dB/km or in dB/m, depending on fiber type. Attenuation plays a crucial role in wave propagation in fibers, significantly affecting the nonlinear dynamics. Most common practice to measure attenuation in fibers is by cut-back method. In this method, transmitted optical power (P_1) or intensity (I_1) is measured at the end of a long fiber of length L_1 . Then the fiber is cut into a shorter piece of length L_2 and the optical power (P_2) or intensity (I_2) is measured for this length. The attenuation can be then calculated

as][1]

$$\alpha_{dB}(\lambda) = 10/(L_1 - L_2) \log_{10} \frac{I_2(\lambda)}{I_1(\lambda)} \quad (2.14)$$

Consecutive cutting of the fiber can provide a more statistically relevant value of attenuation of the fiber. Since the fibers I use in this dissertation are designed for short-wave IR transmission, a supercontinuum source (Leukos) with an optical bandwidth from visible to near IR is used to measure attenuation across the short-wave IR transmission window. It is crucial to ensure that the input coupling conditions remain the same while carrying out these measurements. The transmitted optical intensity is measured using a spectrometer to account for the spectral bandwidth of the laser.

2.2.4 Birefringence: theory

When light travelling through an optical medium experiences different refractive index along the two orthogonal polarization modes, this property of the optical medium is called birefringence. It is present in most optical fibers as the fundamental mode propagation in any single-mode fiber shows some degree of birefringence in the two degenerate polarization modes. This happens because it is very hard to fabricate a perfectly circular fiber core which is required to ensure that the polarization of the modes do not change as the pulse propagates in the fiber. The ability to maintain the polarization mode in a fiber plays a very important role in linear as well as nonlinear propagation dynamics. This occurs because the two orthogonal polarization modes have different propagation constants. Fabricating a fiber that can be used in a single polarization mode requires development of specialty high birefringence fibers, such as the polarization maintaining (PM) fiber designed and developed in chapter 5. In highly birefringent fiber, the relative phase of the two modes rapidly drift away due to significantly different propagation constants of the two polarization modes. The phase birefringence of a fiber for the two polarization modes β_x and β_y experiencing refractive index n_x and n_y respectively is given by [16]

$$B_m(\lambda) = \Delta n = |n_x - n_y| \quad (2.15)$$

Which corresponds to $\Delta\beta = \beta_x - \beta_y = 2\pi\Delta n/\lambda$ The polarization direction of mode of the light propagating with a larger propagation constant is called the fast axis. The polarization direction with lower propagation constant is called the slow axis. Fast and slow axes are the principal axes of the PM fiber. When a linearly polarized beam is launched at 45° angle to the two axes, the

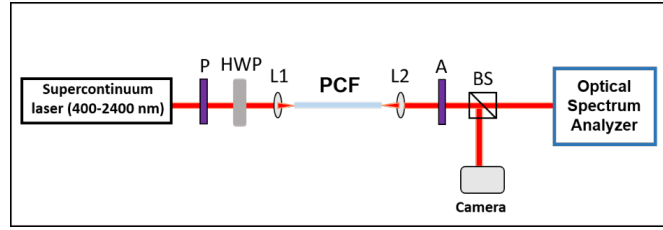


FIGURE 2.3: Experimental set-up for measurement of birefringence of the PM fiber

polarization state of the beam changes periodically between linear, elliptical and circular state with a beat length of $L_B(\lambda) = 2\pi/\Delta\beta$ [16]. The group birefringence $G(\lambda)$ of the fiber is derived from the phase birefringence as [17]

$$G(\lambda) = B_m(\lambda) - \lambda \frac{dB_m(\lambda)}{d\lambda} \quad (2.16)$$

Group birefringence is responsible for polarization mode dispersion and consequently leads to pulse spreading. This dependence arises from the differential group delay which is experienced by the two orthogonal modes as a function of optical frequencies. A high degree of birefringence can be introduced in a fiber by making the core elliptical in shape as shown in this dissertation in chapter 5. Other commonly used method is to stress-induce birefringence due to introduction of stress components such as in PANDA [18] and bow-tie fibers [19]. PM fibers are widely used thanks for their high birefringence in various for sensing applications of temperature [20], pressure [21], magnetic field [22], electric current [23] etc.

2.2.5 Birefringence measurements

Experimental measurement of birefringence derive phase birefringence from the measured group birefringence. Fig 2.3. illustrates a schematic of setup used for birefringence measurement. A collimated beam from a supercontinuum source (Leukos) was coupled into the PM fiber using an aspheric lens (L_1) after passing through a broadband linear polarizer (P) and a broadband half-wave plate (HWP). The polarizer (P) was used to ensure that the light from the source remains at a fixed linear polarization throughout the measurement. The broadband HWP was used to determine the axis of the fiber and to excite both the polarization modes for measurement of the birefringence. The output beam, collimated using another aspheric lens (L_2) and passes through

an analyzer (A) and the signal was observed on a camera to obtain maximum extinction between the two modes.

2.3 Nonlinear Pulse Propagation

Nonlinear optics is a study of interaction of intense light with the medium in such a way the properties of the medium are altered. The optical response of a material, often gauged by its properties such as absorption and refractive index, scales linearly with incident light. However, when the intensity of this incident light is high, the change of the optical response of the medium alters as a function of the intensity of the incident beam. Such a nonlinear interaction, in return leads to changing the properties of the light giving rise to phenomenon such a second harmonic generation, Kerr self-focusing, supercontinuum generation, four-wave mixing, etc. In the following sections, I will summarize the phenomena that occur when a high intensity pulse propagates in a nonlinear medium, especially for the case of optical fiber which provides high confinement of light and geometry-based dispersion management and at the end I'll describe the techniques used in this dissertation to measure and study nonlinearly generated pulses for their properties such as phase, intensity, noise, etc.

2.3.1 Self-phase modulation and Cross-phase modulation

In the absence of dispersion and attenuation in the fiber, the temporal intensity $I(t)$ of an optical pulse brings forth a time-dependent modulation in the refractive index of the medium as $n = n_0 + n_2 I(t)$ where n_0 and n_2 corresponds to the linear and nonlinear refractive index respectively [1]. This in-turn introduces a time-dependent phase with the pulse itself (self-phase modulation, SPM) or with a co-propagating pulse (cross-phase modulation, XPM). SPM-induced phase shift in a fiber of length L and peak power of P_0 is given as $\phi_{NL} = \gamma P_0 L$ [1]. Thus the length at which a maximum phase shift is observed is called the nonlinear length, given by $L_{NL} = 1/\gamma P_0$ [1]. The physically observed effect of this phase-shift is the broadening of the spectrum of the pulse as it propagates through the fiber [24]. The SPM-induced phase shift leads to a time-dependent frequency shift as $\delta\omega(t) = d\phi_{NL}(t)/dt$ [24]. This frequency shift is instantaneous and adds a chirp to the pulse as shown in Fig. 2.4.(a). A chirp is the dependence of instantaneous frequency dependence of an optical pulse on time [25]. As the pulse broadens, the leading edge of the

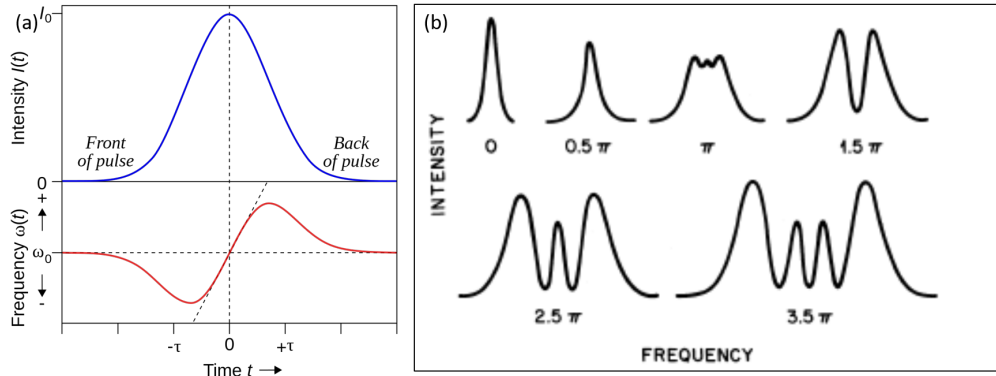


FIGURE 2.4: (a) Time-dependent frequency shift introduced by SPM in the leading and trailing edges of the pulse. (b) SPM-induced spectral broadening as first observed and taken after Stolen et. al. [24]

pulse experiences a red shift while the trailing edge experiences a blue shift due to SPM as demonstrated in Fig.2.4 [24]. For an unchirped input pulse, SPM and XPM, leads to generation of new frequency components of the pulse, leading to spectral broadening. The spectral pulse shape due to SPM has a characteristic oscillatory structure with symmetrical broadening around the pump frequency as shown in Fig.2.4.(b). This oscillatory structure occurs due to the generated identical spectral components existing simultaneously that interfere with each other. In a spectrogram, SPM is identified by a characteristic 'S' shape relating to the oscillatory structure. In the time domain, the temporal pulse shape is unaffected by SPM. SPM, in presence of dispersion, behaves differently and brings forth further interesting nonlinear effects, such as soliton generation and fission, dispersive wave generation, self-steepening etc. SPM in normal dispersion pumping leads to a simultaneous spectral and temporal broadening of the pulse. SPM in the anomalous dispersion regime can balance each other out to form a self-sustaining soliton.

2.3.2 Four-Wave Mixing and Modulation Instability

Four-wave mixing (FWM) is a third-order nonlinear process, where two co-propagating waves of similar or different frequencies, interact with each other parametrically to create two waves of different frequencies [26, 27]. However, for significant FWM to occur, it is essential that the pump waves are perfectly phase matched with each other. Two pump waves of frequencies ω_1 and ω_2 , create a Stokes/signal wave of frequency ω_s , and an anti-stokes/idler wave of

frequency ω_i such that they satisfy the phase matching condition [1]

$$\Delta\beta = \beta_{\omega_s} + \beta_{\omega_i} + \beta_{\omega_1} - \beta_{\omega_2} = 0 \quad (2.17)$$

In case the initial pump waves are of the same frequency, $\omega_p = \omega_1 = \omega_2$, then the FWM signal and idler waves are generated at a frequency shift $\Omega_s = \omega_p - \omega_s = \omega_p - \omega_i$. This case is called degenerate FWM and follows the phase matching condition

$$\Delta\beta = \beta_{\omega_s} + \beta_{\omega_i} - 2\beta_{\omega_p} = 0 \quad (2.18)$$

Due to dispersion walk-off, it is easier to satisfy the phase matching condition for degenerate FWM than for non-degenerate FWM [1]. Degenerate FWM gain bands, when pumped in anomalous dispersion regime are wide and continuous with the pump while in normal dispersion regime the gain bands are narrow and discrete from the pump [28]. Another manifestation of degenerate FWM is in the form of a break-up of a continuous-wave (CW) field or long pulses into a train of ultra-short pulses (fs). This process is called modulation instability (MI) and it occurs in the anomalous dispersion regime where a CW signal is unstable as $\beta_2 < 0$. The CW signal breaks up due to a perturbation caused by among others pump noise and quantum noise and the perturbation sees an exponential growth to the waveform. The ultrashort pulses arise from MI with an oscillation period [29]

$$T_{MI} = \sqrt{\frac{2\gamma^2|\beta_2|}{\gamma P_0}} \quad (2.19)$$

MI leads to amplification of noise on the side-bands that correspond to the frequency of modulation in time domain on both sides of the pump. The maximum MI-gain occurs at a frequency shift of Ω_{MI} on both sides of the pump frequency such that [30]

$$\Omega_{MI} = \pm \sqrt{\frac{2\gamma P_0}{|\beta_2|}} \quad (2.20)$$

Despite the seemingly undesired nature of MI which causes noise enhancement, MI can be managed to obtain wide spectral broadening and be used to produce ultrashort pulses with high repetition rates.

2.3.3 Raman scattering

The second term in the response function $R(t) = (1 - f_R)\delta(t) + f_R h_R(t)$ of the GNLSE accounts for Raman scattering that an optical pulse experiences. The Raman response is given by $h_R(t)$ and the fractional Raman contribution is f_R . Raman scattering is an inelastic scattering of photon-phonon interaction and is an intrinsic property of the optical medium. The Raman response $h_R(t)$ can be derived from the Raman gain response $g_R(\Omega)$ of the fiber material as [1]

$$g_R(\Omega) = 2\gamma f_R \text{Im}[\mathcal{F}(h_R(t))] \quad (2.21)$$

The degree of Raman scattering that a pulse experiences from its central frequency is defined by Raman gain bands. Raman gain band at downshifted frequencies from the central pump frequency is called Stokes band and at upshifted frequencies is called the anti-Stokes band. The spectral intensity at Stokes band is usually higher than that at the anti-Stokes band. Raman scattering plays a very important role by scattering solitons and broadening in the spectra, as explained in the section 2.3.5 below.

2.3.4 Soliton generation

In anomalous dispersion, when negative GVD ($\beta_2 < 0$) and the SPM balance each other out, a soliton is generated [31]. Soliton is wave that has its temporal and spectral profile constant (for fundamental soliton) or periodically evolving (higher order solitons) as it propagates through the fiber. Mathematically, solitons are solutions to the generalized nonlinear Schrodinger equation (GNLSE) [28, 32]:

$$\begin{aligned} \frac{\partial A(z, T)}{\partial z} + \frac{\alpha}{2} A - \sum_{k \geq 2} \frac{i^{k+1}}{k!} \beta_k \frac{\partial^k A(z, T)}{\partial T^k} = i\gamma(1 + i\tau_{shock} \frac{\partial}{\partial T}) \\ (A(z, T) \int_{-\infty}^{\infty} R(T') |A(z, T - T')|^2 dT') \end{aligned} \quad (2.22)$$

such that peak power $P_0 = |\beta_2|/(\gamma T_0^2)$. An important parameter to understand soliton dynamics is soliton number $N = \sqrt{(\gamma P_0 T_0^2)/|\beta_2|} = \sqrt{L_D/L_{NL}}$ which is governed by fiber and pulse parameters. In general, during pulse propagation in an optical fiber, when $L_D \gg L_{NL}$, nonlinear effects dominate while when $L_D \ll L_{NL}$, linear dispersive effects dominate. For the fundamental soliton, i.e. $N=1$, $L_D = L_{NL}$, and irrespective of the initial pulse shape,

fundamental soliton takes up a secant-hyperbolic shape. For $N \geq 2$, higher order solitons evolve periodically as a function of the peak power. However, this periodic evolution of higher order solitons is only sustained if there are no perturbations as higher order solitons are highly unstable. In the presence of perturbation, such as due to Raman scattering or higher order dispersion, the higher order soliton pulse breaks up into a train of fundamental solitons, which identical soliton number N [33]. This process is called soliton fission and occurs after the fundamental soliton reaches its maximum bandwidth at a distance of $L_{fiss} \approx L_D / N$ [32]. Soliton fission causes some energy to be shed in the form of dispersive waves as discussed in section 2.3.6.

2.3.5 Soliton self-frequency shift (SSFS)

When a soliton is sub-picosecond, it experiences Raman amplification along the longer wavelength edge, with a simultaneous loss of power at the shorter wavelength edge of the soliton pulse spectrum. This introduces a spectral shift of the soliton towards longer wavelengths and is called the soliton self-frequency shift (SSFS) [34]. SSFS provides a way to obtain pulses in the spectral range, which cannot be obtained by traditional lasers, due to power-dependent tunability of solitons. By changing the input energy or the fiber length, the central wavelength of such solitons can be tuned. The frequency shift ν_R caused due to SSFS depends on the input pulse duration t_0 and dispersion β_2 as $\frac{d\nu_R}{dz} \propto \frac{|\beta_2|}{t_0^4}$ [35]. This implies that the first soliton experiences a stronger frequency shift as compared to the higher order solitons, consequently increasing the separation between individual solitons as they propagate in the fiber. Since its first demonstration in 1999, SSFS has been of prime interest as a potential tunable laser source [36]. Table 2.1 contains an overview of theoretical and experimental work in the past 20 years on soliton shift dynamics in the near- and mid-infrared wavelength ranges. SSFS depends strongly on the pulse duration of the pump, length of the fiber as well as its nonlinearity and chromatic dispersion characteristics of the fiber. It is an important nonlinear process widely exploited in seeding of ultrafast amplifiers [37]. From the literature review summarized in table 2.1, it can be inferred that experimental work on SSFS in soft glass fiber majorly involved pumping with laser pulses centred at 1560 nm, or around 1900-2000 nm for some cases. The pertinent condition is to provide suitable chromatic dispersion characteristic of the fiber to facilitate efficient soliton shift. In this work I will show wide detuning of fundamental

soliton in tellurite suspended core fiber, effectively extending the state of the art for SSFS-based tunable sources in the near-IR wavelength range.

TABLE 2.1: Literature review of soliton shifting in the near- and mid-IR range

No.	Pump parameters	Fiber type and length (if given)	Range of tunability	Type of results	Results reported	Year, Ref
1	1550 nm; 180 fs; 48 MHz	PM; 75m	1560-1780 nm	Experimental	First demonstration of linear shifting of a soliton in an optical fiber by changing input power	1999[36]
2	1556nm, 250 fs, 48 MHz	PM; 220m	1560-1876 nm	Theoretical+ Experimental	Dependence of soliton on input pulse width, power, mode field diameter	2000[38]
3	1550 nm	PM	1560-2030 nm	Experimental	Characterized soliton pulse by FROG measurements: almost transform-limited 340-fs soliton pulse generated at 2 μ m	2001[39]
4	1060 nm	Silica HOM fiber	1060-1300 nm	Experimental	SSFS from 1.06 nm to 1.3 μ m in an HOM fiber	2008[40]

5	1557 nm; 400 fs; 16.75 MHz	Tellurite SCF; 6.5 cm	1582-1851 nm	Theoretical+ Experimen- tal	Comparison of Raman response be- tween various samples of tellurite and silica	2010[41]
6	1550 nm, 37 MHz, 1.5 μ W	Chalcoge- nide SIF	9.7-14.9 μ m	Experimental	Soliton tuning in mid-IR with sub- picosecond pulses	2010[42]
7	1550 nm, 150 fs	Tellurite; 10 cm	1660-1732 nm	Theoretical	Comparison between dif- ferent tellurite compositions for the Raman response and SSFS	2011[43]
8	2 μ m	Chalcogenide nanowire	2100-650 nm	Theoretical	Mid-IR tuning of soliton by changing the diameter of the fiber	2012[44]
9	1560 nm	Tellurite SCF	1591-1935 nm	Theoretical+ Experimen- tal	Blue-shift of soliton by a CW laser	2013[45]
10	1600 nm, 150 fs, 49 MHz and 2000 nm amplifier	Tellurite SCF; 63 cm	1600- 2250 nm 2000-2650 nm	Theoretical+ Experimen- tal	Demonstration of wide tun- ability of solitons by pumping at two different wavelengths	2015[46]

11	OPO 200 fs, 80 MHz, Pumped at 1750, 1810 and 1900 nm	ZDW at 1.6 μm	1855-2090 nm	Experimental	SSFS at different pump wavelengths; wavelength shift of soliton becomes smaller as pump wavelength shifts farther from ZDW	2015[47]
12	Pumping at 1560, 1958, 2300 nm; 40 fs	Tellurite SCF; ZDW at 1500 nm; 41 cm	1999-2264 nm	Theoretical+ Experimental	Red shifted solitons up to 2264 nm	2016[48]
13	1900 nm, 120 nJ, 40 fs	Fluoride fiber; 2 m	2000-4300 nm	Theoretical + Experimental	100 fs soliton generation	2016[49]
14	1560 nm; 48MHz	PM	1560-1900 nm	Experimental	Tunability from 6-9 μm via DFG in OP-GaP crystal	2018[50]
15	1560 nm; 45 MHz; 27 fs	GeO ₂ -doped PM fiber; 2.6 m,	1800-2000 nm	Experimental	Ultrashort coherent soliton pulses	2018[37]
16	3.5 μm ; 1560 nm, CW	Tellurite SIF; 22 cm	3.5-6 μm	Theoretical	SSFS in tellurite step index	2019[51]
17	01550 nm, 90 fs, 100 MHz	Tellurite SCF; 5.6 cm	1560-2400 nm	Theoretical + Experimental	Soliton shift from 1560-2400 nm	2020 this work[52]

PM: Polarization maintaining; HOM: Higher-order mode; SCF: Suspended core fiber; SIF: Step-index fiber; ZDW: Zero dispersion wavelength

2.3.6 Dispersive wave

Solitons preserve their fundamental sech nature by dissipating energy in the form of dispersive wave (DW) in the normal GVD regime. DW occurs such that the soliton and the dispersive wave have a phase-matching overlap and DW co-propagates along with the soliton in a fiber [31]. DW also arises for each of the fundamental-like solitons that result from a higher order soliton fission. DW generation leads to spectral broadening at wavelengths shorter than the pump [58]. For a peak power of P_0 and group velocity $v_{g,s}$, the soliton-dispersive wave pair co-propagate at the frequency Ω_s and ω_{DW} such that [32]

$$\beta(\omega_s) - \frac{\omega_s}{v_{g,s}} + (1 - f_R)\gamma P_0 = \beta(\omega_{DW}) - \frac{\omega_{DW}}{v_{g,s}} \quad (2.23)$$

The frequency shift between the soliton and DW can be approximated by neglecting fourth-order dispersion and f_R as [32]

$$\Omega = \omega_s - \omega_{DW} \approx -\frac{3\beta_2}{\beta_3} + \frac{\gamma P_0 \beta_3}{3\beta_2^2} \quad (2.24)$$

Fig.2.5. shows nonlinear effects arising from soliton dynamics such as soliton fission, Raman shift, dispersive wave along the length of the fiber in their spectral and temporal forms.

2.3.7 Optical wave breaking

In normal dispersion, blue-shifted frequency components created by SPM at the trailing edge of the pulse travel faster than the centre of the pulse. This leads to steepening of the trailing edge and consequently to optical wave breaking (OWB) [30]. The two components of the pulse then overlap in time domain to generate new frequency components by FWM process [53]. For SPM-generated frequency component considered as the pump and the pulse tail considered as the seed, the newly generated frequency component is obtained as [28]

$$\omega_{OWB} = 2\omega_{Pump} - \omega_{Seed} \quad (2.25)$$

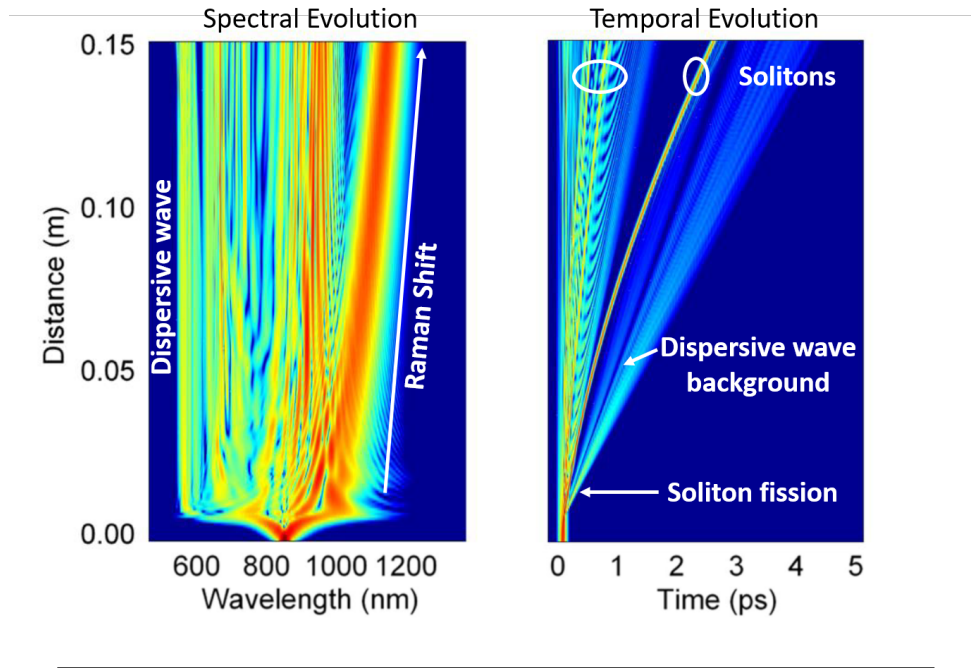


FIGURE 2.5: Deconstruction of soliton dynamics undergone by a 50 fs pulse centered at 835 nm, with energy 0.5 nJ in a 15 cm PCF taken after [38]

As the pulse propagates further in the fiber, OWB also occurs at the leading edge of the pulse along with redistribution of energy from the central frequency to the spectral wings of the pulse. OWB generates new frequency components in non-interfering dynamics leading to a smooth temporal and spectral profile along with a well-defined phase distribution [54]. SPM+OWB based broadening underlines the physics behind generation of coherent SC in all-normal dispersion (ANDi) fibers [55].

2.3.8 Supercontinuum generation

Supercontinuum (SC) generation is an extreme nonlinear process that is characterized by wide spectral broadening of a laser pulse in an optical medium. SC occurs as a consequence of collection of nonlinear processes depending on the input pulse duration, peak power of the pump, pump wavelength and the chromatic dispersion and length of the fiber. The first report of efficient SC generated in a PCF was demonstrated by Ranka et al. in a silica microstructured fiber in the year 2000 [56].

Over the last two decades, fiber-based supercontinuum (SC) sources have gained popularity due to their strong waveguide confinement, enhanced nonlinearity, and dispersion management [32, 56]. Being able to regulate the properties of

TABLE 2.2: Overview of SC dynamics based on pulse duration and dispersion characteristics

Pulse duration	Anomalous Dispersion	Normal Dispersion
Long Pulse (>10 s to ps)	Modulation instability Raman scattering Four-wave mixing Soliton fission Soliton self-frequency shift Dispersive wave generation	Raman Scattering Four-wave mixing
Short Pulse (fs to sub-ps)	Self-phase modulation Soliton fission Soliton self-frequency shift Raman scattering Four-wave mixing Modulation instability Dispersive wave	Self-Phase Modulation Four-wave mixing Raman Scattering Optical wave breaking

SC by engineering fiber parameters has led to major advancements in understanding the mechanisms behind SC generation. This in turn has facilitated advancement of applications requiring SC sources such as LIDAR [57], Biophotonics [58], spectroscopy [59], laser and amplifier systems [60]. etc.

Table 2.2 outlines the different nonlinear phenomena that take place leading to SC generation in optical fibers based on the pump pulse duration and chromatic dispersion characteristics. In case of pumping the fiber with long pulses of pulse durations measured in seconds to picoseconds, the early dynamics are noise seeded. In those, anomalous pumping leads to MI-based amplification of noise. Soliton generation and fission, dispersive waves generation as well as Raman scattering of solitons further broaden the spectra leading to SC generation. This means that SC generated in anomalous dispersion regime, with long pulses, show the highest degree of noise and is highly incoherent. Long pulse pumping in the normal dispersion regime broadens the pulse by FWM and Raman scattering. However, normal dispersion SC does not attain wide spectral bandwidth as power required for OWB to occur is not achieved with

long pump pulses.

When the fiber is pumped with a short pulse within the range of femtoseconds to sub-picoseconds pulse duration, the SC generation dynamics stem from SPM which is a self-seeded process. In the anomalous dispersion regime, although the nonlinear processes that take place are similar to that in the long pulse anomalous pumping case, the processes can be tailored to be coherent depending on the soliton number and the input peak power. In normal dispersion short pulse pumping, SPM and GVD have the same sign and thus spectrally broadens the spectrum coherently. OWB which occurs in this case aids in a wide broadband light generation in a coherent manner. In this dissertation, I focus on femtosecond pumping, thus limiting the nonlinear dynamics to low noise-seeded processes.

SC generation is sensitive to pump noise and fluctuations introduced by Raman scattering and MI. This leads to a significant shot-to-shot noises in the output SC. The bandwidth and the apparent uniformity of SC generated is not sufficient to obtain good quality SC source for applications such as frequency metrology [61], OCT [62], coherent anti-stokes Raman scattering spectroscopy [63]. For such applications, a crucial parameter is the coherence of supercontinuum pulses. Coherence is the property of the electric fields of a light pulse to interfere with each other. When the phase between different electric field values of a pulse is fixed, the light pulse is said to be coherent. The coherence of SC light in the spectral domain was first described by Dudley and Coen as an ensemble average across the spectral range as [64–66]

$$|g_{12}(\omega)| = \left| \frac{\langle E_1^*(\omega) E_2(\omega) \rangle}{\langle |E(\omega)|^2 \rangle} \right| \quad (2.26)$$

From research point of view, it is a challenge to preserve the coherence of SC. One way to achieve coherence is by pumping the fiber with short pulses. In short pulse range, the dynamics behind SC generation are self-seeded and enhance coherence. A great example of using this approach is that of frequency combs which lead Theodor W. Hänsch. to a Nobel Prize in 2005 [67]. Another approach to obtain coherent SC is by using ANDi fibers where the SPM and GVD have the same sign, leading to coherent broadening of the pulse.

While single mode fibers (SMFs) have been widely explored for coherent octave spanning supercontinuum, lately research interests have seen a shift from one-dimensional nonlinear dynamics in SMFs to three-dimensional (3-D) propagations in multimode fibers (MMF) with high power density. Thanks to that

shift interesting intermodal nonlinear phenomenon such as spatial beam cleaning [68, 69], multimode solitons [70, 71], classical wave condensation [72] have recently come forth. These phenomena have demonstrated a nonlinear phase and/or power transfer between selected combinations of modes [73]. The nonlinear mode self-cleaning in graded-index (GRIN) fibers underpins spatiotemporal dynamics in many schemes of 3-D propagation of laser pulses in waveguides. It has been established both numerically [73, 74] and experimentally [71, 75] that modes in a GRIN fiber propagate mainly in guided modes that are phase matched with the fundamental mode. Much of these studies have been in the picosecond/nanosecond pumping regime where the peak power of the input pulse was well below the critical power of self-focusing. When working in the ps/ns regime, which corresponds to a few kW of peak power, the effect of dispersion on the pulse can also be neglected. In the ps/ns regime, mechanisms due to possible and observed nonlinear interactions between multiple modes have been now well identified and characterized numerically using MMGNLSE [76]. However, limited studies have been conducted in the femtosecond regime.

Femtosecond pulse propagation is distinct from the ps/ns cases, because it brings forth a significant contribution of dispersion into the pulse propagation dynamics. In bulk media with anomalous dispersion, self-focusing has been identified as the cause of binding together solitons into multimode “light bullets” [70]. In the spectral domain, the multimode soliton forms the bases of supercontinuum generation, analogous to that observed in single mode propagation [71]. In normal dispersion, spatiotemporal analysis at femtosecond pumping in GRIN fiber has been earlier reported by Liu et al. showing Kerr self-cleaning of the beam and the corresponding autocorrelation plots in temporal domain demonstrating pulse compression [77]. In terms of temporal studies, they carried out autocorrelation measurements to show that as the pulse evolves with power, it compresses in time due to nonlinear phase accumulation. Results of a recent study involving time-domain measurements in GRIN fiber by Wu et al. revealed weak self-cleaning of beam when pumped with femtosecond pulses, accompanied by pulse compression in the anomalous dispersion regime [78]. They highlighted that strong temporal evolution of the pulse hindered spatial beam cleaning dynamics. In this dissertation, I aim at expanding the state of the art by studying the temporal and spectral dynamics in a soft-glass GRIN fiber under femtosecond regime.

2.3.9 FROG and XFROG

With the increase in research on nonlinear optics and advancement in the field of ultrafast pulses, there rose a need to accurately characterize these pulses. To overcome problems with measuring pulses of femtosecond durations, Rick Trebino et al. developed a pioneering technique called frequency-resolved optical gating (FROG) [79, 80]. FROG provides a complete characterization of ultrafast pulses for not just the measurement of pulse duration or pulse energy but also a full time-dependent electric field analysis along with the study of optical spectrum. The basic principle of FROG is that of gating a pulse with another pulse, which is a delayed replica of itself. The gating occurs in a nonlinear optical medium and the gated pulse is then spectrally resolved. When a second-harmonic generation crystal is used as a nonlinear optical medium and the two pulses are resolved by a subsequent second harmonic generation based on their interaction, the technique is called second-harmonic generation frequency-resolved optical gating (SHG-FROG). SHG-FROG is just one of the types of FROG techniques. The other types involve polarization gated (PG) FROG, self-diffraction (SD) FROG, transient grating (TG) FROG, interferometric FROG, and cross-correlation FROG (XFROG). The major difference in each of these is the type of nonlinear mixing that occurs between the two pulses to give the frequency-resolved pulse. The intensity of the signal generated from the nonlinear mixing of two pulses at a delay τ is given as [79]

$$I_{FROG}(\omega, \tau) = \left| \int E_{sig}(t, \tau) e^{-i\omega t} dt \right|^2 \quad (2.27)$$

Where $E_{sig}(t, \tau) \propto E(t)E(t - \tau)$ is the measured signal. SHG-FROG, that I used in this thesis to measure the laser signal, is the most used FROG technique as it has no contribution of the material dispersion that could possibly elongate the pulse thus making it ideal for measuring short pulses. As crucial as it is to be able to physically measure the signal, it is also pertinent to retrieve the characteristic of the pulse from the measured signal. This complex retrieval of the pulse and its characteristics from the measured signal is carried out using sophisticated iterative strategies forming the FROG algorithm.

A variation of FROG as mentioned earlier is XFROG in which an additional reference pulse is used to gate a broadband pulse such as a supercontinuum [81]. In this case, the reference pulse needs to be known and not necessarily shorter or spectrally matching. The nonlinear mixing of the two signals in this case occurs via sum or difference frequency generation. From a known

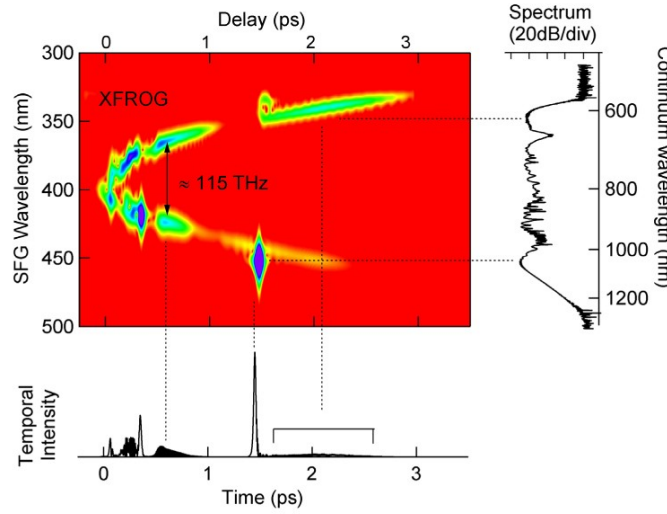


FIGURE 2.6: Calculated XFROG trace with its structure correlated with the intensity and spectrum showing evolution with propagation distance taken after [90].

reference pulse, and a measured sum or difference frequency signal, the characteristics of the unknown pulse can be determined. This method is widely used to characterize spectrally broadened pulses against a known laser pulse. XFROG signal is retrieved in a similar manner as the FROG signal from the FROG software (Femtsoft Technologies). XFROG trace is obtained as [81]

$$I_{XFROG}(\omega, \tau) = \left| \int_{-\infty}^{\infty} E(t) E_g(t, \tau) e^{-i\omega t} dt \right|^2 \quad (2.28)$$

Where $E_{SF}(t, \tau) \propto E(t) E_g(t - \tau)$ with a dependence on the reference signal $E(t)$ as well as the unknown signal E_g . Unlike in SHG-FROG measurements, a weak unknown signal can still be traced if the reference is strong enough in XFROG. XFROG is a highly sensitive method allowing detection of weak pulses. The first report on applying XFROG measurement technique to SC generation revealed a complete intensity and phase characterization of SC generated in PCFs [82]. Dudley et al. reported a complex XFROG-based numerical analysis of SC generation in a PCF. These simulations identify several important processes underlying SC generation and provide an intuitive interpretation of correlated temporal and spectral features of SC as shown in Fig.2.6. A preliminary qualitative agreement of measured XFROG were also reported [83].

In this dissertation, I carry out XFROG measurement to characterize the temporal features of a spectral broadened pulse from a GRIN MMF. I measure the XFROG pulses from the fiber using a spectrometer and retrieve these pulses using the FROG software (Femtosoft Technologies). As a reference for the XFROG pulses, I separately measure the FROG pulse of the laser without the fiber sample and use it as a reference for the XFROG measurements. Before the step of pulse retrieval, for both the cases of FROG and XFROG, the signal from the spectrometer needs to be cleaned as much as possible in its raw form. This process is called noise subtraction. This is an important step as a noisy signal and/or background will lead to noisy wings of the retrieved pulse increasing the error in the retrieval process. The FROG software provides various options of noise reduction techniques such as:

- full spectrum (the average of the spectra at the two smallest and two largest delays is determined and subtracted from the data at every time delay)
- lowest pixel (the pixel with the lowest value is identified and subtracted from every pixel)
- edge (an average value of every data within 2 pixels of the edge is taken and then subtracted from every pixel)
- Fourier low pass (a low-pass Fourier filter is used)
- cleanup pixels (removes stray pixels)

A combination of these techniques can be used multiple times to obtain a clean raw data for retrieval. The noise subtracted FROG/XFROG data is then retrieved using iterative algorithm to invert the FROG/XFROG traces to determine the electric field that created them. The most used strategy for retrieval, and the one I have used here, is by the method of generalized projections (GP) [84] proposed and formulated by DeLong et al [85]. A projection of a guess of the electric field of the waveform is mapped as close as possible within the constraints. After this initial guess, each subsequent iteration of the algorithm reveals a new copy of the retrieved electric field. From the electric field, a FROG/XFROG trace is generated. When the retrieved FROG/XFROG traces matches the one from original raw data to a high degree, the algorithm is stopped. The generated FROG/XFROG traces will always be limited by noise and systematic error. The algorithm converges to give the best matching retrieved FROG/XFROG trace with the lowest possible error. Thus, the

algorithm should be run until a clear minimum error has been reached. This retrieved FROG/XFROG trace contains all crucial spectro-temporal characteristic such as phase and intensity best projected and matched with the raw data of the signal. I then reconstructed retrieved FROG/XFROG pulse in Matlab, for which the code I developed is presented in Appendix B.

2.3.10 Dispersive Fourier transformation technique

Dispersive Fourier transformation (DFT) technique holds a pivotal advantage of enabling measurement of real-time shot-to-shot noise [86, 87]. Single-shot measurement techniques such as frequency-resolved optical gating (FROG) and spectral phase interferometry for direct electric-field reconstruction (SPIDER) [88], despite being powerful tools are unable to perform pulse-resolved measurements in real-time. While DFT has been used in ultrafast spectroscopy [86] and imaging [87] since the late 1990s, it was first used to measure real-time fluctuation in SC in optical fibers in 2012 [89]. A detailed methodology of spectral analysis using DFT was presented by Goda and Jalali in 2013. DFT not only statistically characterizes the SC but also provides insights in the SC dynamics.

DFT technique works on the principal of dispersion-compensated time stretching of a pulse whose intensity essentially mimics that of the frequency spectrum due to large linear stretching of the temporal pulse. Fig.2.7 illustrates the time stretching that a pulse undergoes when propagating through a highly dispersive element. To understand the physics and mechanisms behind the DFT technique, I outline the Fourier transform theory acting on an ultrashort wave in a dispersive element as defined in [90]

Consider an initial temporal field $A(t)$ with Fourier transform $\tilde{A}(\omega)$, propagating over a distance z in a dispersive fiber with quadratic dispersion β_{2s} . On neglecting the loss and nonlinear terms in GNLSE, we obtain a dispersion dependent GNLSE with a Fourier transformed solution as [91]

$$\tilde{A}(z, \omega) = \tilde{A}(0, \omega) \exp\left(\frac{i\beta_2}{2} \omega^2 z\right) \quad (2.29)$$

After sufficient propagation with a stationary phase approximation, the field gain a temporally stretched form defined as [91]

$$A_z(t) \approx \tilde{A}\left(\frac{t}{\beta_{2s}z}\right) \exp\left(\frac{-it^2}{2\beta_{2s}z}\right) \quad (2.30)$$

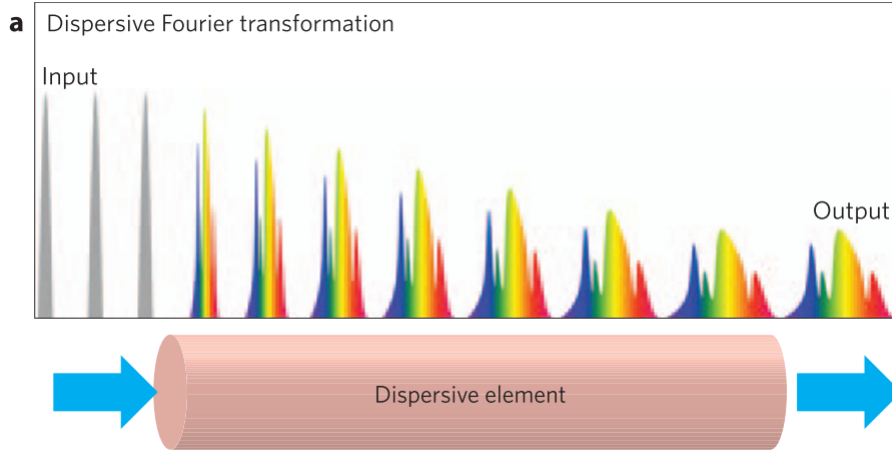


FIGURE 2.7: When a train of optical pulses enters a dispersive element with a large GVD, the spectrum of each pulse is mapped to a temporal waveform by the dispersive element and then captured by a single-pixel photodetector, taken after Ref. [87]

Thus the obtained time-stretched intensity profile is similar to the initial spectrum given as [91]

$$|A_z(t)|^2 \approx |\tilde{A} \frac{t}{\beta_{2s} z}|^2 \quad (2.31)$$

Thus the temporal pulse can be mapped into the frequency domain with the conversion of time coordinate to frequency. SC generated in a nonlinear fiber can thus be coupled into a dispersive element (like a stretching fiber) and the stretched temporal pulses can be detected using a fast photodiode and oscilloscope. A large number of pulses can be thus mapped to obtain statistical fluctuations in SC generated. A key feature in this method is the resolution of the system in wavelength scale after Fourier transformation of the time-measured pulses. The resolution of such a system is given by

$$\delta\lambda = 1/(B|D|z) \quad (2.32)$$

Where B is the bandwidth of the photodiode used and D is the dispersion of the fiber of length z.

Chapter 3

Material and Fiber fabrication

Development of optical fibers, since their inception in 1966 [92], have been majorly focused on data transmission through light pulses over long distances mainly for telecommunication applications. To achieve this, optical fibers evolved to have single mode propagation with loss minimized to only that of the material [93]. The limits of fiber technology were then pushed for not just increased transmission but also for controlling the properties of light pulses in an optical fiber by the means of nonlinear optics. This led to a growth in development of fiber laser and amplifiers as well as all-fiber systems in continuous wave propagation [94] as well as pulsed regime [95]. Single mode propagations in optical fibers have been deeply studied theoretically using generalized nonlinear Schrodinger equation and well correlated with the experimental observations of soliton dynamics, intrapulse Raman scattering, modulation instabilities, phase modulations and parametric processes [96]. In the late 1990s, fiber technology revolutionized by the invention of photonic crystal fibers (PCFs) [97]. Use of PCFs increase the number of degrees of freedom, thanks to increased possibilities in designing geometrical structure of the fiber. PCFs provide a wide-ranging flexibility in structural fiber modeling to tailor their optical properties such as chromatic dispersion, nonlinearity and birefringence, to the extent which are unachievable with conventional optical fibers. PCFs have thus become a medium of choice for studying nonlinear optical phenomena such as supercontinuum light generation, soliton generation and fission, modulation instability and four-wave mixing. While single-mode fiber (SMF) based systems have paved way for several non-telecommunication applications in fiber lasers and amplifiers, supercontinuum generation and nonlinear interactions [5,7], etc., the next step in fiber technology is that of fibers [1, 96] with large mode areas and able to withstand high power thresholds. In the recent years multimode fibers (MMFs) have made a promising comeback in high

power transmissions through spatiotemporal propagation. In particular, the renewed interest in multimode propagation has been due to the advancement of graded-index fibers (GRIN). Graded index fibers were initially developed in the 1970s in optical communication systems to reduce modal dispersion for long-haul propagation [98, 99]. Over last ten years, GRIN fibers have shown proofs of concepts for high power nonlinear propagation such as spatiotemporal beam cleaning [68], multimode solitons [100], supercontinuum generation [101] and classical wave condensation [72]. In this dissertation, I design and use PCFs and GRIN fibers for nonlinear light propagation studies by shaping the fibers for their dispersion, nonlinearity and material composition as explained below.

3.1 Fiber designing: Dispersion control

The beam propagation in a 3-D optical waveguide such as a photonic crystal fiber can be understood by analyzing the transverse electric ($\vec{E}$) and magnetic ($\vec{H}$) fields of a monochromatic wave of frequency ω , propagation in the z direction with a propagation constant β given as [1]

$$\vec{E}(x, y, z, t) = \vec{E}(x, y)e^{-i(\omega t - \beta z)} \quad (3.1)$$

$$\vec{H}(x, y, z, t) = \vec{H}(x, y)e^{-i(\omega t - \beta z)} \quad (3.2)$$

Where phase of the wave is given as $\phi = \omega t - \beta z$. The corresponding wave equation for a medium with constant dielectric constant in terms of cylindrical coordinates (r, ϕ, z) is [1]

$$\frac{\partial^2 E}{\partial r^2} + \frac{1}{r} \frac{\partial E}{\partial r} + \frac{1}{r^2} \frac{\partial^2 E}{\partial \phi^2} + \frac{\partial^2 E}{\partial z^2} = \mu \epsilon \frac{\partial^2 E}{\partial t^2} \quad (3.3)$$

In this work, I modelled the beam propagation in optical fibers using the software Lumerical Mode Solutions. Mode solutions is a Finite-Difference Eigenmode (FDE) solver that calculates mode profiles and their frequency dependence by solving Maxwell's equation [102]. The solver derives the spatial profiles of the modes, the effective index and the confinement loss by running the Eigenmode equations through a cross sectional mesh of the waveguide. The structural dimensions, such as the air-hole diameter d , the lattice constant Λ , number of air-hole rings in the PCF or refractive index profile in the GRIN fiber, along with the refractive index of the materials involved set the base for

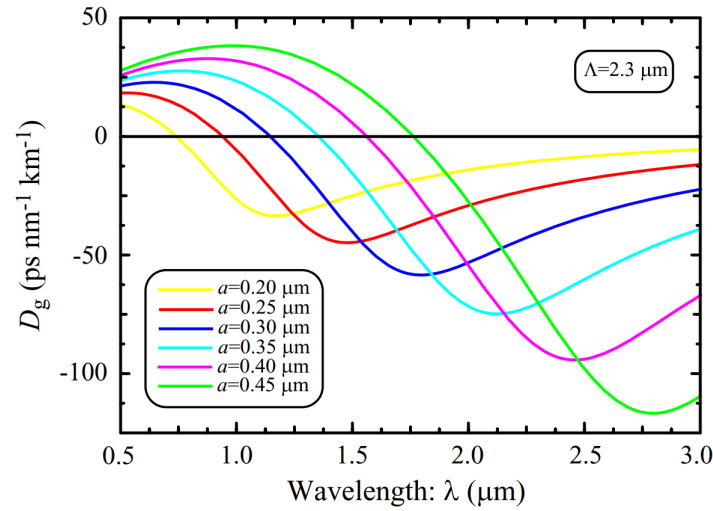


FIGURE 3.1: Waveguide dispersion engineering of PCF with filling fraction d/Λ ; taken from [5]

the beam propagation model. Fig 3.1 shows how the dispersion of a fiber can be changed by changing the filling fraction d/Λ . The constructed waveguide geometry is meshed in order to accommodate arbitrary waveguide structures. The finite-difference algorithm then formulates Maxwell's equations into a matrix eigenvalue problem and is solved by sparse matrix technique. This method, incorporated in the Mode Solutions software is based on the method proposed by Zhu and Brown [103]. Meshing plays a role of optimization and accuracy of the eigenmode values. The denser the mesh, the higher the accuracy for obtaining correct eigen values. However, this often comes at the cost of simulation time and memory requirements of the computer used. The mesh is defined over a specific boundary in the fiber structure to demarcate the area to implement the finite-difference algorithm. The implementation of the boundary provides the boundary conditions for the eigenvalue equations, it is important to assure that the boundary does not provide any instabilities. A perfectly matched layer (PML) is taken as the boundary condition as it is designed to absorb incident light with minimal reflections. PML helps in getting rid of numerical instabilities without increasing the simulation time [104]. The eigenmode solver computes the beam dynamics within the mesh to provide a frequency dependent profile of physical properties of the fiber as output as listed below. The propagation constant β relates to the effective refractive index as per Eq. 2.8. The imaginary part of the effective refractive index obtained

from FDE analysis derives the confinement loss as [105]

$$\alpha_{confinement} = \frac{40\pi l_m(n_{eff})}{\lambda \ln(10)} \quad (3.4)$$

The effective area $A_{eff}(\omega)$ of the modes in the core of area A surrounded by air holes is approximated as [1]

$$A_{eff} = \frac{[\int |E|^2 dA]^2}{\int |E|^4 dA} \quad (3.5)$$

Further, the group delay and dispersion can be obtained via integrated frequency sweep and n_{eff} value using Eq. 2.9. Ultimately, FDE returns frequency/wavelength plots for properties such as effective area, group delay, dispersion, confinement loss for the constructed geometry of the fiber for a selected spatial mode profile. In this work, I use this method to model and design the geometry of the fiber for desired properties such as all-normal dispersion, low loss, birefringence etc.

3.2 Fiber designing: nonlinear propagation

Nonlinear pulse propagation in an optical fiber is a combined result of linear and nonlinear effects on an optical field, $E(z, T) = A(z, T)\exp(-i\omega_0 T)$, where $A(z, T)$ represents the envelope of the field. A model describing the dynamics in nonlinear pulse propagation has been established by Dudley et al. It employs GNLSE as follows [32, 96]:

$$\begin{aligned} \frac{\partial A(z, T)}{\partial z} + \frac{\alpha}{2}A - \sum_{k \geq 2} \frac{i^{k+1}}{k!} \beta_k \frac{\partial^k A(z, T)}{\partial T^k} &= i\gamma(1 + i\tau_{shock} \frac{\partial}{\partial T}) \\ &\quad (A(z, T) \int_{-\infty}^{\infty} R(T') |A(z, T - T')|^2 dT') \end{aligned} \quad (3.6)$$

The left side of the equation accounts for linear phenomena such as dispersion (β_k) and linear power attenuation (α). In the nonlinear regime, the sign of group velocity dispersion (β_2) significantly influences the dynamics of pulse propagation. The right-side of the equation constitutes of nonlinear parameters such γ , the nonlinear coefficient at ω_0 , self-steepening and optical shock formation $\tau_{shock} = 1/\omega_0$, and the Kerr and Raman response, $R(T)$. The nonlinear coefficient is defined as $\gamma = \frac{\omega_0 n_2(\omega_0)}{c A_{eff}(\omega_0)}$, where $n_2(\omega_0)$ is the nonlinear refractive index and $A_{eff}(\omega_0)$ is the effective mode area. The response function

$R(t) = (1 - f_R)(t) + f_R h_R(t)$ accounts for instantaneous electronics response as well as the Raman contribution f_R .

From Kerr nonlinearity originates self-phase modulation (SPM) which, in the normal dispersion regime, leads to symmetric spectral broadening of the pulse. However, in the anomalous dispersion regime, an interplay between SPM and GVD stemmed from modulational instability (MI) leads to the generation of solitons. These solitons further undergo higher order dispersion and Raman scattering causing soliton fission and self-frequency shifts, and consequent spectral broadening. The GNLSE however is modelled on three principal assumptions:

1. The pulse propagation is considered to be strictly unidirectional
2. The pulse is assumed to propagate in fundamental mode. A separate multimode GNLSE has been modelled with high degree of complexities by Poletti and Horak [106].
3. The model is purely scalar. Vectorial properties of the pulse are neglected, which restricts the model to account for polarization modes.

Modelling of pulse propagation using GNLSE has been popularly implemented using split-step Fourier transform method. The split-step Fourier method solves an approximate solution of an optical field over a small distance h , by assuming that the dispersive and nonlinear processes act independently. Thus, the propagation from z to $z+h$ is carried out in two separate steps; one accounting for dispersion and the other for nonlinearity. The propagation along the entire length of the fiber occurs over an adaptive step size method alternating between dispersive and nonlinear steps.

3.3 Fiber designing: materials

The ability of PCFs to tailor the properties of light has opened wide application-specific customization of fibers and light sources. The degrees of freedom in PCFs in terms of geometry, effective index, dispersion, attenuation, effective mode areas has led to successful optimization of light sources in silica wavelength ranges, i.e. visible and near IR [107–110]. On the other hand, for multimode propagation, GRIN fibers provide an additional degree of freedom by using two types of materials/glasses arranged in a particular mosaic to obtain a desired effective refractive index. The main advantage of such a graded-index profile is that the modes tend to propagate together as a cluster as the

propagation constants of such modes are equally spaced [111]. However, with advancement in technologies, there is an increase in the need of near and mid-IR light sources. 2-5 μm is a crucial spectral window where the atmosphere is transparent, thus being ideal for applications such as remote sensing and detection [112, 113], security and communication systems [114]. In the field of fiber laser systems, there is an ever-increasing demand for seed lasers in 2-5 μm wavelength range for amplifiers systems such as Tm:Ho, Tm:ZBLAN, Ho : SiO_2 amplifiers [115, 116]. Furthermore, in microscopy and spectroscopic applications, many biological as well as chemical processes have absorption/emission in the mid-IR wavelengths [117, 118]. Most importantly, the mid-IR range is fairly nascent in terms of nonlinear optics-based applications such as supercontinuum generation [56, 96], nonlinear parametric generation [119], fiber OPO [120] and frequency combs [121, 122]. This is because, while PCF engineering enables achieving these nonlinear phenomena for the above-listed applications, most of the work is still limited to the spectral window of widely used silica glass.

Generally, glasses tend to lose transparency at the IR edge due to multiphoton absorption [123]. Silica shows low transparency beyond 2 μm because of strong hydroxyl vibration-based absorption at 2.7 μm followed by high loss (>50 dB) starting from 3 μm due to multi-phonon absorption of Si-O network [124]. To overcome the transmission limitations of silica glass, soft glasses such as tellurite, fluoride and chalcogenide are promising candidates for mid-IR applications. Fig. 3.2. illustrates a statistical overview of different glasses in terms of linear and nonlinear refractive index [123]. In order to maximize efficiency of nonlinear frequency conversion in the mid-IR range, the fiber needs to have ZDW at 1.5 μm or 2 μm [56]. Fluoride and tellurite glasses provide higher spectral transmission in the IR range (up to 7 μm and 5 μm respectively) than silica glass and have a ZDW around 2 μm which makes them a good candidate for mid-IR applications. However, in comparison with tellurite glass, fluoride glass has lower linear and nonlinear refractive index, comparable to that of silica as can be seen in Fig. 3.2. This gives an edge to tellurite glasses over fluoride glasses as tellurite glasses have high nonlinearity which can enable nonlinear applications over short propagation lengths. Another candidate for mid-IR applications are chalcogenide glasses, which have wider transmission in the IR wavelengths (upto 20 μm [125, 126]) and a nonlinearity of 100-1000 times higher than that of tellurite glasses. However, chalcogenide glasses are very difficult to make, and have high recrystallization susceptibility [127]. Additionally the ZDW of bulk chalcogenide glass is around 5 μm , which

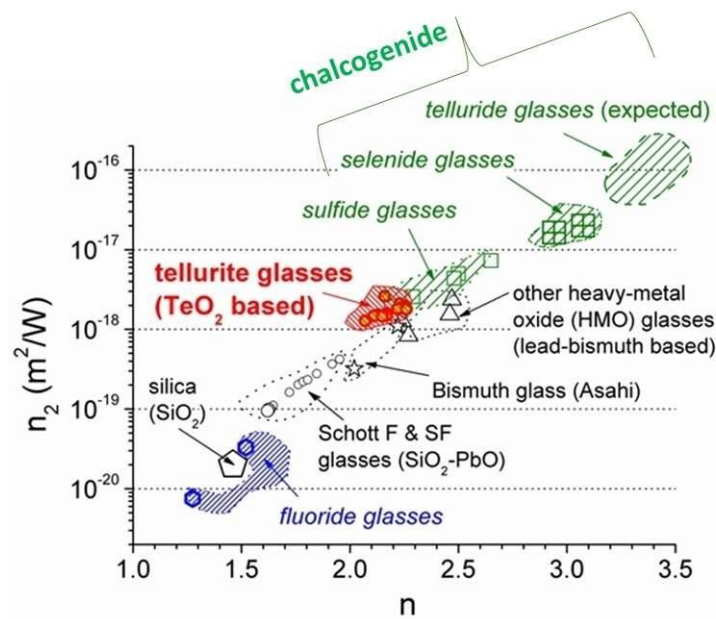


FIGURE 3.2: Relation between linear and nonlinear refractive indices in various optical glasses used in fiber fabrication; taken from [123]

would require technologically challenging fabrication of very small core fibers in order to be moved to 2 μm . They are also highly toxic, thus limiting the scope of possible applications [128]. Thus, tellurite glass is the best candidate for near and mid-IR light sources as well as applications.

3.4 Tellurite glasses

3.4.1 Composition

Owing to its electronegativity ($\chi = 2.1$), tellurium forms a good substrate for making glass [129]. Tellurium dioxide (TeO_2), a heavy metal oxide, along with a combination of other oxide systems such as WO_2 and Na_2O_5 allows us to design a thermally stable tellurite glass [129]. Since the energy of Te-O bonds is lower than that of Si-O bonds, tellurite glass has a lower softening temperatures than silica glass. The in-house developed tellurite glasses contain a multicomponent oxides system of $\text{TeO}_2 - \text{WO}_3 - \text{Na}_2\text{O} - \text{Nb}_2\text{O}_5$. TeO_2 and WO_3 together form the glass while Na_2O and Nb_2O_5 are used as glass lattice modifiers [130]. In this work, two types of in-house developed tellurite glasses have been used, namely: TWPNI/6 and TWZN-22. The mole percentage of the oxides for the two tellurite glasses is outlined in table 3.1. The

TABLE 3.1: Chemical composition (in mol %) of tellurite glasses
TWPNI/6 and TWZN-22

Glass Composition	TWPNI/6 (Mol %)	TWZN-22 (Mol %)
TeO_2	65	60
WO_3	28	22
ZnO	0	9.5
Na_2O	5	6.5
Nb_2O_5	2	2

major difference between the two glasses is the presence of ZnO in TWZN-22. $ZnO - TeO_2$ bonds contribute to a shorter wavelength edge in the UV [131]. An overall change in the composition provides for a slightly different refractive index of the two glasses, which is desired for fabrication of GRIN fibers. The two tellurite glasses have been optimized for their composition for high nonlinear refractive index and broad transmission range with low concentration of -OH group and low susceptibility to recrystallization [130].

3.4.2 Physical properties

The linear thermal expansion coefficient of the two tellurite glasses were measured using a dilatometer 801 (Baehr Thermoanalyse GmbH) [132]. The thermal expansion coefficient values are listed in table 2.4. for 200 °C and 300 °C respectively. For two glasses to be matched together into a fiber, the thermal expansion coefficient difference of the two glasses should be less than 10 % which is fulfilled in the case of TWPNI/6 and TWZN-22 as seen in the table 3.2. The dynamic viscosity of the glass can be obtained from the measured thermal expansion curve. Tellurite glass shows a steep viscosity curve around the fiber drawing temperatures, which means that the working temperature range is limited to 50 °C as opposed to other soft glasses which has a range above 100 °C [132]. Dilatometric measurements also indicate the softening points of the glasses, which in case of TWPNI/6 and TWZN-22 are almost the same as shown in table 3.2. This thermal matching is crucial for successful fabrication of fibers with multiple glasses, eg. GRIN fiber.

The transition temperatures for the glasses were measured using differential scanning calorimetry (DSC) method [132]. The transformation temperature T_g and the temperature at which crystallization starts to occur T_x were obtained from the DSC measurements as listed in table 3.2. The thermal stability of glass

TABLE 3.2: Physical properties and characteristic temperatures of tellurite glasses [48]

Physical properties	TWPN/I/6	TWZN-22
Linear thermal expansion coefficient		
200°C [$10^{-6}K^{-1}$]	13.98	14.4
300°C [$10^{-6}K^{-1}$]	14.39	14.72
Dilatometric softening point (SP) [°C]	385.3	385.6
Transformation temperature T_g [°C]	374.5	366.1
Crystallization beginning temperature T_x [°C]	506	-
$\Delta T = T_x - T_g$ [°C]	131.5	-
Density [g/cm^3]	5.881	-

is indicated as $\Delta T = T_x - T_g$ such that when $\Delta T > 100^\circ\text{C}$ the glass is considered thermally stable without any crystallization observed at the softening temperatures. For tellurite glass TWPN/I/6, $\Delta T = 131.5^\circ\text{C}$ thus making this glass a good candidate for PCF fabrication. For the TWZN-22 glass crystallization was not observed in the whole measured temperature range, meaning that this glass is also safe for use in the drawing tower. Lastly, the density of tellurite glass was determined to be 5.881 g/cm^3 by hydrostatic weighing technique [130].

3.4.3 Optical properties

Transmittance of tellurite glass TWPN/I/6 was measured in ref. [132] using a spectrophotometer (VARIAN Cary 500) with sensitivity range of 200-3300 nm as can be seen in Fig. 3.3 (blue). Tellurite glass of the above mentioned composition shows high transmittance throughout the visible and near IR wavelength range. As shown in ref. [130], the long wavelength edge of transmittance goes beyond $5 \mu\text{m}$. However, due to strong absorption by -OH group present in the glass, the transmittance is reduced to about $3.1\text{-}3.3 \mu\text{m}$. The amount of the -OH groups in the glass bulk can be reduced by melting glass in anhydrous atmosphere or by increasing melting time during the glass making process. Owing to high transmittance in visible as well as IR wavelengths (upto $5 \mu\text{m}$), tellurite glass is attractive as fiber material for near and mid-IR applications. Refractive indices of the two glasses were measured by a goniometer and a prism using different light sources in visible (H, Hs, He, Ne,

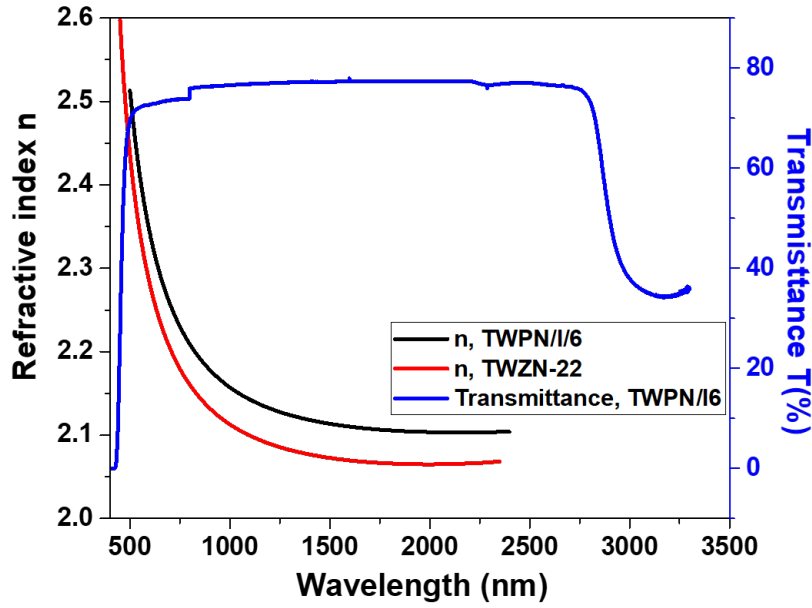


FIGURE 3.3: Transmittance and refractive index of the tellurite glasses

Na spectral lamps) as well as in near IR using lasers [132]. Fig. 3.3. shows refractive index profiles for tellurite glasses TWPNI/6 and TWZN-22 as a function of wavelength. The refractive index for tellurite glass is above 2 as can be seen in the above Fig. 3.3, which is higher than silica which has refractive index around 1.5 [133]. TWZN-22 has slightly lower refractive index due to difference in glass composition. This is advantageous to construct a gradient index profile in fiber. The material dispersion relation of the tellurite glasses calculated from the measured refractive index values are as follows.

Material dispersion of TWPNI/6 is given by Sellmeier's equation:

$$n^2(\lambda) = 1 + \frac{2.49628\lambda^2}{\lambda^2 - (0.01699)^2} + \frac{0.79831\lambda^2}{\lambda^2 - (0.07728)^2} + \frac{1.8848\lambda^2}{\lambda^2 - (162.9949)^2} \quad (3.7)$$

Material dispersion of TWZN-22 is given by Sellmeier's equation:

$$n^2(\lambda) = 1 + \frac{2.876397801\lambda^2}{\lambda^2 - (0.025339328)^2} + \frac{0.259498399\lambda^2}{\lambda^2 - (0.094741208)^2} + \frac{0.237774448\lambda^2}{\lambda^2 - (28.23657539)^2} \quad (3.8)$$

The ZDW of bulk tellurite glass is around $\sim 2\mu\text{m}$, which is longer wavelength than that of silica at $\sim 1.3\mu\text{m}$, making tellurite glass highly suitable for applications in the IR wavelengths. The nonlinear refractive index n_2 , of tellurite

glass TWPNI/6 was measured using a Z-scan set-up as shown in ref. [134]. The TWPNI/6 glass has n_2 of $(5.110.23) \times 10^{-19} \text{m}^2/\text{W}$ at 1064 nm, which is significantly higher than that of silica glass at $(0.430.03) \times 10^{-19} \text{m}^2/\text{W}$ at the same wavelength [134]. Another glass known to possess high nonlinearity is chalcogenide with n_2 of $100\text{-}1000 \times 10^{-20} \text{m}^2/\text{W}$ [135]. Chalcogenide glass also shows excellent IR transmission up to 20 μm . However, the glass is highly toxic and has a high recrystallization susceptibility. Thus, owing to the 2 μm ZDW, high refractive index and high nonlinear refractive index, tellurite glass is an excellent candidate for nonlinear applications in the IR wavelength range.

3.5 Fiber fabrication process

Owing to the widespread of optical fiber-based telecommunication networks, the fiber fabrication technology has advanced significantly in the last couple of decades to keep up with the high demand of developing highly efficient optical fibers. The challenge in the fiber fabrication technology is to cater to developing different application-specific fibers, which in turn depend on various parameters such as thermal and optical parameters of glass, core-cladding geometry of the structures etc. Fiber can be drawn by direct melting of glass from the crucible or be made into a preform to get the desired fiber structure and then drawn from this preform into the fiber [131]. Preform based fiber fabrication technology can be divided into two: vapor deposition techniques such as outside vapor deposition (OVD) [136], modified chemical vapor deposition (MCVD) [137], plasma activated chemical vapor deposition (PCVD) [138], vapor axial deposition (VAD) [139] and non-vapor technique such as rod-in-tube stack and draw method [140, 141]. In this dissertation, I employ the stack-and-draw method for fiber fabrication as it is best suited for microstructured and nanostructured fiber with complex geometries such as suspended core fiber, PCFs and GRIN fibers used in this work.

3.5.1 Stack-and-draw fabrication method

Stack-and-draw fiber fabrication is a multistep process in which a mosaic of glass rods and tubes are arranged in microscopic structure and then drawn into the fiber [140, 141]. Fig 3.4. and the steps below outline the process of the stack-and-draw fabrication technique which was used to develop all the fibers used in this dissertation.

1. *Glass casting*: Stack-and-draw fabrication method is highly efficient for glasses with high recrystallization resistance. First the glass is molten and casted into either thick-wall tubes or rectangular blocks. Then glass blocks are cut and ground into glass rods. In the last steps both rods and tubes are polished to obtain optical quality surfaces.
2. *Drawing of preform elements*: This step occurs in the drawing tower where the rods and tubes are fed into a furnace, heated above the softening temperature and then drawn into capillaries and canes of specific desired preform diameters. In this process the temperature of the furnace, the feed rate and the pulling speed together control the diameter of the elements drawn. The diameter of the drawn elements is measured by a laser-based diameter monitor system placed below the furnace.
3. *Preform stacking*: The preform elements are cleaned and assembled into a macroscopic mosaic structure. At this stage, type of lattice, hole/spacing ratio, distribution of capillaries and canes is decided. The elements used in a single structure are often made of different materials, hence ensuring thermal matching of the glasses involved is essential for a defect-free fiber fabrication. In this case thermal matching means that thermal expansion coefficients of the glasses are within 10 % of each other and drawing temperatures of both glasses are within 50 °C. Stacking can be done in periodic lattice structure such as PCFs, GRIN or suspended core fiber.
 - (a) For the PCF fibre each air hole is typically a single capillary stacked into a hexagonal structure. Hexagonal structure is to ensure that each element doesn't move during later drawing. Fibre is made from one type of glass
 - (b) For the suspended core the structure, stacking occurs in a similar method as for PCFs, but the number of elements is smaller as compared to PCFs and consist of only single ring. Suspended core fiber is also made from a single type of glass.
 - (c) GRIN fibre is made by stacking thousands of canes in an arrangement such that the overall effect is achieved such that light sees an effective refractive index. GRIN structure is made from two types of glass, representing minimum and maximum refractive index. Canes used in such fibers have to be subwavelength as the distribution of

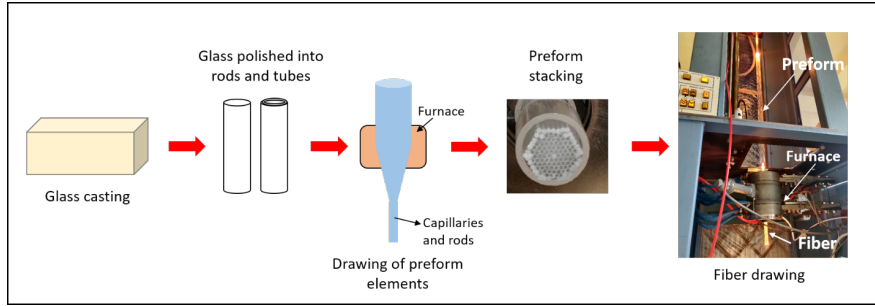


FIGURE 3.4: Schematic representation of the stack-and-draw fiber fabrication process

canes determines the effective refractive index distribution in the fibre cross section.

Such assembled structure is then placed into a large diameter glass tube to achieve the desired photonic structure/ fiber diameter ratio and structural rigidity of the preform.

4. *Fiber drawing from the preform:* The stacked preform is then drawn at correct temperature in the fiber drawing tower to obtain the fiber. At this stage, the size of the air-holes and lattice is controlled by tuning drawing parameters such as temperature, preform feeding rate, drawing speed as well as the pressure inside the preform. This process can take place multiple times until desired structure and dimensions are achieved. In case of PCFs, often an intermediate step of subpreform is drawn which is larger in size than the fiber but has the same dimension ratios. In the last drawing the fiber is often coated with a protective jacket made from a high index polymer such as PVC, in order to provide mechanical stability to the fiber and to absorb cladding modes.

3.6 Fiber geometries

In this dissertation, we develop and explore 4 different types of fibers fabricated with tellurite glass as shown in Fig.3.5. Each such fiber shown here has been fabricated for a specific nonlinear application. The tellurite glasses used for fabrication of these fibers have been developed in-house and optimized for spectral transmission, attenuation, photonic crystal structure, index properties etc. [132, 142]. All the fibers listed below were fabricated using the stack-and-

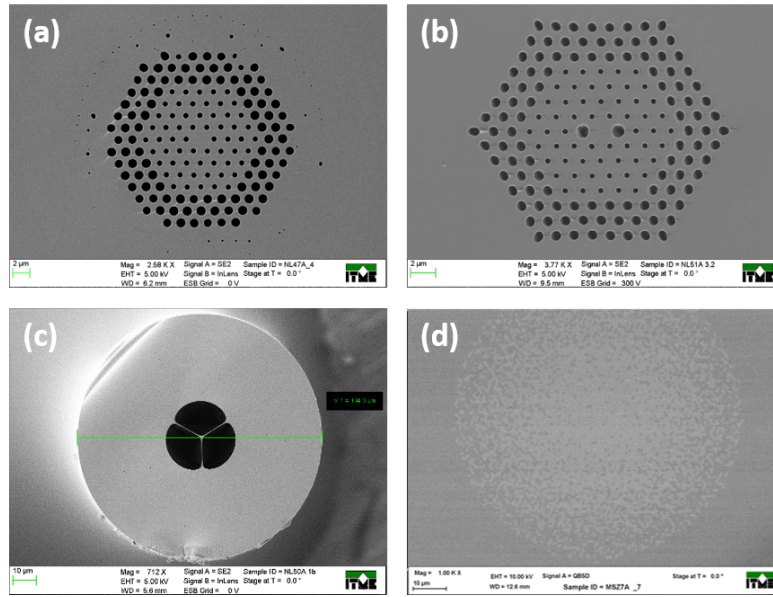


FIGURE 3.5: Scanning electron microscope (SEM) images of fabricated specialty fibers (a) Hexagonal lattice air-hole PCF- NL47A (b) Highly birefringent PCF-NL51-A (c) Suspended core fiber-NL50A (d) GRIN fiber MS27A

draw method. The parameter control while fiber and preform drawing for each of fibers used in this dissertation is summarized in table 3.3.

3.6.1 Air-hole PCF- NL47A

This fibre is a modified hexagonal lattice PCF made with TWPNI/6 glass. This fiber was engineered to reduce attenuation of modes by using two lattice constants in the fiber geometry. The fiber had 7 rings of air-holes, out of which, the outer three rings had larger air-holes as compared to the inner four rings, and thus different lattice constants as shown in Fig. 3.5 (a). This fiber series was labelled NL47A and was used in research described in chapter 5.

3.6.2 Highly birefringent PCF- NL51A

Photonic crystal structure allows to achieve a PCF with a birefringence of the order $10^2 - 10^3$. Such birefringence requires a crystal lattice asymmetry with an elliptical core where the light is strongly guided in one of the polarization modes Birefringence in fiber series NL51A was introduced by using large size capillaries for two opposite air-holes around the core as shown in Fig. 3.5 (b). The rest of the structure remained similar to that of NL47A and was also used in the research described in chapter 5. Fiber was also made from the same

TABLE 3.3: Drawing parameters for tellurite fibers and subpre-forms fabricated

Fiber label	Preform outer di- ameter [mm]	Temperature [°C]	Feeding speed [mm/min]	Pulling speed [m/min]	Diameter
NL47A subpre- forms	19.0	485 - 490	0.37	0.31	0.72 – 0.8 mm
NL47A fiber	3.0	560	0.93	0.43 – 0.51	125 – 140 µm
NL50A subpre- forms	18.5	490 - 500	1.86	0.06	1.7 – 2.3 mm
NL50A fiber	1.75 pres- surized at 370 mb	582 - 585	1.67	0.23 – 0.32	110 – 130 µm
NL51A subpre- forms	18.4	492 - 500	0.47	0.31 -0.34	0.75 – 0.8 mm
NL51A fiber	3.0	568	1.1	0.51 – 0.7	110 – 140 µm
MS27A subpre- forms	41.2	495 - 500	0.3 – 0.5	0.25 – 0.76	0.7 – 1.3 mm
MS27A fiber	2.3	582 - 590	0.17 – 3.7	0.57 – 0.91	100 – 185 µm

tellurite glass TWPN/I/6. The drawing process of this fiber had an additional complexity, as compared to the previous fiber series, as pressure had to be maintained such that the birefringence inducing air-holes as well as the core remained of the desired dimensions.

3.6.3 Suspended core fiber- NL50A

A three air-holed suspended core fiber made from tellurite glass was used to observe soliton detuning. Preform of this fiber consisted of three large capillaries, surrounding a solid cane rod. In order to obtain large air-holes and thin struts to hold the core, this fiber was drawn under high pressure of 370 mb. A successful fiber series labelled NL50A was drawn with core diameters ranging from 0.75-1.5 μm and strut widths of 57-100 nm as shown in Fig. 3.5 (c). Drawing fiber with such thin struts was a challenging task quite on the edge of fiber fabrication technology. This fiber was developed for the research results presented in chapter 4

3.6.4 GRIN fiber- MS27A

GRIN fiber labelled MS27A as shown in Fig. 3.5. (d) was fabricated by nanostructurization of preform. This fiber was made from two types of tellurite glass described in section 3.3, TWPN/I/6 and TWZN-22. The preform of this fiber consisted of 10267 canes of tellurite glasses forming a pre-determined arrangement to obtain a parabolic index profile. This fiber was designed and studied for the research results presented in chapter 6.

Chapter 4

Soliton detuning in tellurite suspended core fiber

The demand from the growing range of applications exploiting optical frequency metrology [143], LIDAR [57], molecular fingerprinting [144] and spectroscopy [59], as well as active hyperspectral imaging [145] motivate ongoing interest in light sources combining efficiency, ease of operation and high quality of generated light pulses. Solutions based on nonlinear fiber optics have a proven track record of combining these requirements. Existing fiber based light sources mostly exploit the silica glass as the primary materials platform. Silica has the major limitation as it is lossy beyond a wavelength of $2\text{ }\mu\text{m}$. Soft-glass based fibers not only have very good transmission [59] into the mid-infrared wavelengths but also have 10-100 times larger intrinsic nonlinearities than in silica glass (with the exception of fluoride glasses). Dispersion engineered PCFs made from such soft glasses are promising to overcome the current lack of robust versatile nonlinear optics-based laser light sources. In this work, I have used highly nonlinear tellurite glass-based PCF to overcome the limitations of silica and to obtain a light source in the short wave IR region (SWIR). A popular nonlinear method for obtaining laser light sources in near and mid-IR wavelength range is through soliton self-frequency shift (SSFS). SSFS, explained in chapter 2, has been widely explored as a potential tunable laser. SSFS also is one of the primary process that takes place in anomalous supercontinuum generation. Table 2.1 outlines the state of the art for SSFS-based tunable sources in silica as well as soft glass fibers. As can be seen from table 2.1, SSFS-based tunability in silica and soft glass PCFs obtained so far has been limited to less than 300 nm from the pump wavelength (with the exception of chalcogenide PCFs that transmit in mid-IR). A recent review [115] showed that the short wavelength IR range not only holds a promising role in ultrafast

lasers and amplifiers but also has numerous applications to cater to such as telecommunication, biomedical imaging and diagnostics, atmospheric sensing etc. Silica based seed successfully covers upto 2 μm beyond which silica possess high attenuation. Amplifiers such as $\text{Ho} : \text{SiO}_2$ and $\text{Tm}:\text{ZBLAN}$ efficiently cover the range between 2-2.5 μm . But there is a challenge in obtaining a seed signal for such amplifiers. The soft glass fiber used in this work not only integrates well with soft glass amplifiers such as $\text{Tm}:\text{ZBLAN}$ but also provides a tunable seed for such amplifier systems. In this chapter, I demonstrate the isolation of SSFS phenomenon in a suspended core microstructured fiber made from highly nonlinear tellurite glass. The fiber was dispersion engineered for a flat anomalous dispersion to obtain Raman scattering-assisted self-frequency shift of soliton over a bandwidth of 68.5 THz in the SWIR range. The prominent soliton shows an input power-based tunability through the spectral range of 1560 nm (pump wavelength) upto 2400 nm when pumped with a 90 fs laser pulses from a robust mode-locked fiber laser.

4.1 Fiber development

Isolation of the phenomenon of SSFS in a fiber, while suppressing other nonlinear processes (such as four-wave mixing, supercontinuum generation), essentially comes from an interplay of three parameters; high Kerr nonlinearity of the material, chromatic dispersion characteristics, and position of pump wavelength with respect to the ZDW. In my work, the criterion of high positive Kerr nonlinearity was satisfied by using tellurite glass as the fiber material. The material dispersion of tellurite glass (in-house developed TWPNI/6)[132] used in this work is given by Sellmeier's equation:

$$n^2(\lambda) = 1 + \frac{2.49628\lambda^2}{\lambda^2 - (0.01699)^2} + \frac{0.79831\lambda^2}{\lambda^2 - (0.07728)^2} + \frac{1.8848\lambda^2}{\lambda^2 - (162.9949)^2} \quad (4.1)$$

The measured nonlinear refractive index n_2 of this glass at a wavelength of 1064 nm is $(5.11 \pm 0.23) \times 10^{-19} \text{m}^2/\text{W}$ [134]. The position of ZDW and consequently the chromatic dispersion profile depends on the design of the fiber. In literature, Hartung et al.[146] showed that the flatness of the dispersion profile of a suspended core structure depends on the size of the core while the shape of the core determines the ZDW. In this work, I numerically modelled a suspended core structure surrounded by three air-holes using finite difference

Eigenmode solver (Mode solutions, Lumerical). The fiber design was aimed at blueshifting the ZDW across near-IR wavelength i.e. from the glass ZDW of 2050 nm [132] to around 1200 nm and achieving flat anomalous dispersion for wavelengths redshifted from the ZDW. In order to achieve the desired ZDW at 1200 nm, and flat anomalous dispersion profile for wavelengths above 1200 nm, I changed the size of core as shown in the linear modelling below. Another factor which supports the choice of a suspended core microstructure is that tellurite glass is highly susceptible to recrystallization as compared to silica glass. Thus, the number of drawing steps can be reduced for a suspended core structure as compared to a regular lattice PCF. The parameter that can be modified for designing such a suspended core structure is the size of core. The size of the core is expressed as the diameter of the largest possible circle that can be inscribed between the three air holes. In the modelling of this fiber, the diameter of the core was changed so as to blueshift the ZDW to 1200 nm and to obtain flat anomalous dispersion with low values near the desired pump wavelength (1560 nm). Fig. 4.1. shows dispersion plots obtained numerically for a range of core diameters. For a core diameter of 1 μm , the fiber had an all normal dispersion profile. When the core diameter was considered to be 1.2 μm , the dispersion profile showed a second ZDW around 1900 nm. A dispersion profile with two ZDW limits the wavelength range where soliton propagation is supported to in-between the ZDWs, and in the case of a soliton-self frequency shift process, in practice to a wavelength range between the pump center wavelength and the second ZDW. Hence, such a dispersion profile is not desirable to obtain wide detuning of a soliton. When the core diameter was taken to be 1.4 μm , the dispersion profile was flat for the working transmission range of the glass (500-2800 nm) and did not show a second ZDW in this wavelength range. Furthermore, with a 1.4 μm core, we obtain the most blue shifted ZDW at 1267 nm. While a suspended core size of 1.4 μm supports multiple guided modes, it is ensured experimentally that the fiber propagates a single fundamental mode at our intended central pump wavelength of 1560 nm. This is achieved by the coupling conditions adjusted so as to assure that only the fundamental mode is excited in the fiber. Thin struts of the microstructure contribute high confinement of the fundamental mode by providing negligible scope for the mode to leak into the cladding. For these reasons, a 1.4 μm core structure has been considered for fabrication of fibers for this work.

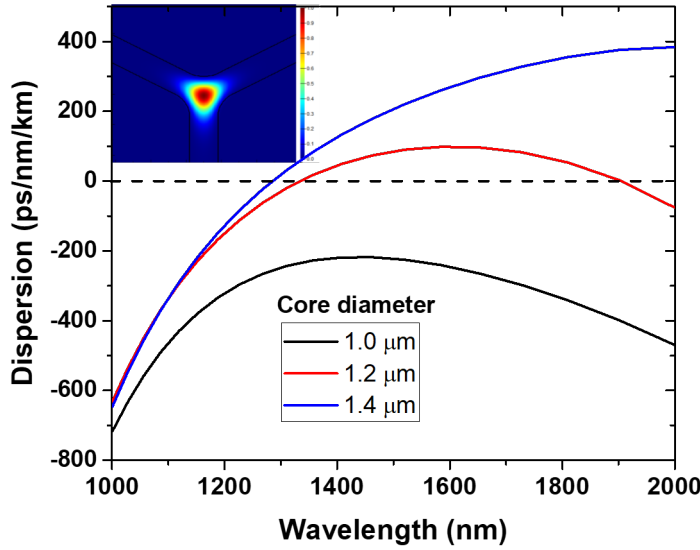


FIGURE 4.1: Dispersion profile modelling for different core diameters. (Inset) Electric field distribution of fundamental mode LP01 in the designed fiber

4.2 Fabrication of tellurite suspended core PCF

Based on the geometric parameters of the suspended core fiber obtained in the above section, two series of fibers were fabricated: labelled NL50A and NL50C. These fibers were fabricated using the stack-and-draw technique where three tellurite glass capillaries were stacked into a 15 mm-diameter jacket tube and drawn to obtain the desired structure. Neutral gas was introduced into the three tubes simultaneously and gas pressure was changed to control the size of the core, air-holes, and core struts. By stabilization of conditions such as neutral gas pressure while preform drawing and through laser diameter control, longitudinal homogeneity of the fibers drawn for this work was ensured during the drawing process. Fiber samples used in the experiments were only those that were obtained in stabilized drawing conditions. Longitudinal homogeneity of the fibers drawn for this work was assured over several meters-scale length by stabilization of drawing conditions at the tower, i.e. through laser diameter control and pressure stabilization of the neutral gas pumped into the preform during the drawing process. Only fiber samples obtained in stabilized drawing conditions have been used in experiments. Used fiber sample lengths (both in dispersion measurements and in subsequent soliton

TABLE 4.1: Structural parameters of the fabricated PCF series.

Fiber Label	Outer diameter of fiber (μm)	Diameter of core (μm)	Strut width (nm)
NL50A 1a	109.0	1.55	77.3
NL50A 1b	104.0	1.22	119.4
NL50A 2	106.9	1.20	107.4
NL50A 3	93.0	1.06	67.6
NL50A 4	95.8	1.07	61.1
NL50A 5	119.1	1.44	61.7
NL50C 1	81.4	0.94	61.1
NL50C 2	89.7	0.85	56.9
NL50C 3	85.9	0.88	57.3
NL50C 4	84.3	0.82	64.5
NL50C 5	76.2	0.75	47.2

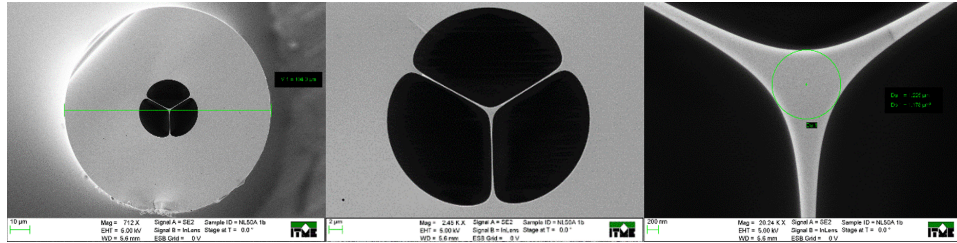


FIGURE 4.2: Scanning electron microscope image of the fabricated fiber.

shift measurements) did not exceed 5-6 cm, which additionally supports longitudinal homogeneity of the structures in the actual experiments. A scanning electron microscope (SEM) images of one of the fabricated fibers, NL50A 1b, is shown in Fig. 4.2. The diameter of the fiber core is obtained by inscribing largest possible circle in the core also shown in Fig. 4.2. Table 4.1 outlines the structural dimensions of the two series of fibers fabricated. From the SEM images and numerical calculations, the ZDWs of the fabricated series of fibers is anticipated to be between 1200-1300 nm, making them ideal to be pumped in the anomalous chromatic dispersion regime. In this work, I experimentally pumped these fibers at 1560 nm and 1900 nm to obtain and study the consequent soliton shifts.

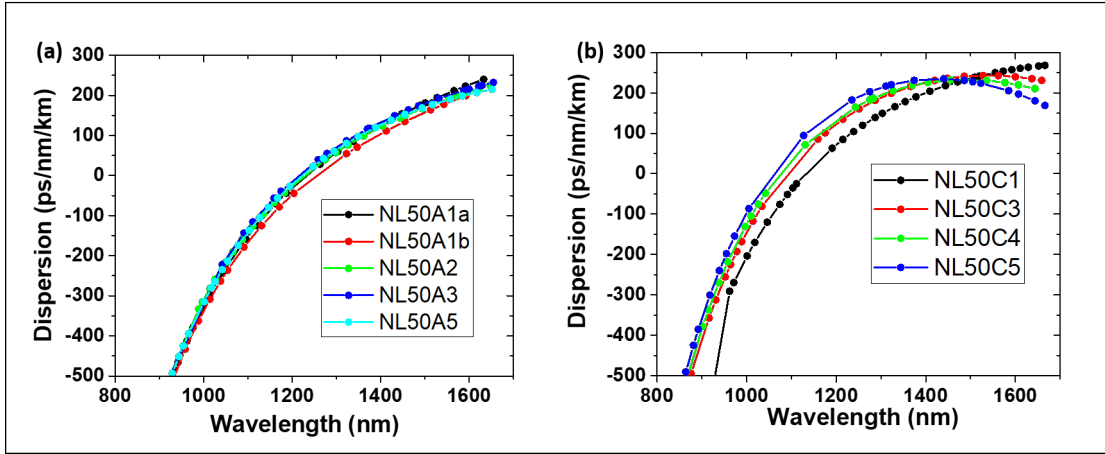


FIGURE 4.3: Measured chromatic dispersion profiles of (a) NL50A and (b) NL50C series fibers. Dots represent measurement points and solid lines are guides for the eye.

4.3 Measurement of chromatic dispersion of the fabricated fiber series

The chromatic dispersion properties of the fabricated fibers were measured using a balanced Mach-Zehnder interferometer. A beam from a compact supercontinuum source from Leukos, with spectral coverage from 450-2400 nm, was split by a beam splitter into reference arm and sample arm in the Mach-Zehnder interferometer setup. At the output of the interferometer was a spectrometer (Avantes) with sensitivity range of 900-1750 nm. In this work, fiber samples of length 5-6 cm have been used so as to further ensure longitudinal homogeneity of the fibers. For tellurite fibers, clear interference pattern was seen only over a limited wavelength range. Thus, I employed the method described by Koch et al. [13], where the dispersion measurement was carried out by tracing the prominent central fringe across the wavelength range (as described in section 2.2.2). The dispersion plots of the two fabricated fiber series NL50A and NL50C are shown in Fig. 4.3. The fabricated fiber series had ZDWs between 1200-1300 nm as was desired from numerical simulations. Beyond the ZDWs, the fibers show flat dispersion profiles in the anomalous dispersion region, with dispersion values lying mainly between 100-250 ps/nm/km, making the fibers ideal for observation of SSFS.

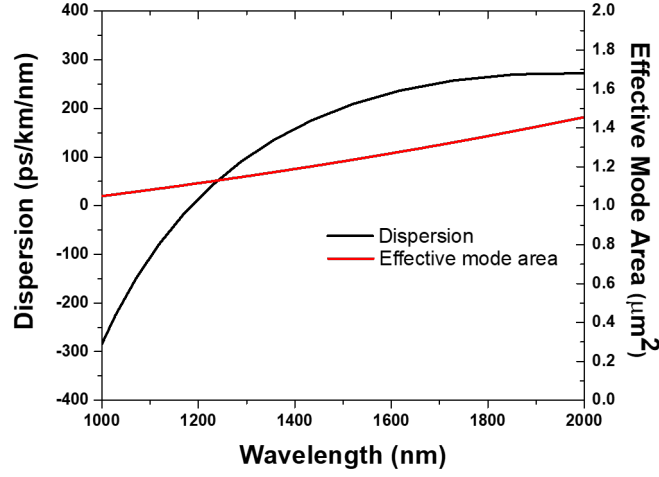


FIGURE 4.4: Chromatic dispersion and effective mode area of the fiber selected for Raman soliton detuning simulations.

4.4 Numerical modelling of Raman soliton detuning in the fabricated fibers

To study the generation and fission of soliton and the effect of Raman scattering on the soliton in the fiber, nonlinear pulse propagation based on generalized nonlinear Schrodinger equation (GNLSE)[96] was numerically solved using split-step Fourier method. I modelled the soliton dynamics based on the pump pulse characteristic, similar to be used in the experimental setup. I considered a Gaussian pulse catered at 1560 nm wavelength having a pulse energy of 1 nJ and pulse width of 90 fs. The chirp of the pulse was neglected in the simulations. The fiber parameters were taken from the fabricated fiber NL50A1a. This fiber sample was chosen as it showed the flattest dispersion profile in the anomalous dispersion wavelength range. The dispersion profile and the effective mode area plots for the fiber that were considered in the simulations are shown in fig. 4. 4. The effective mode area at the pump wavelength of 1560 nm is $1.25271 \mu m^2$. The simulations account for the Kerr nonlinearity γ , obtained from the nonlinear refractive index of tellurite glass ($n_2 = 5.11 \times 10^{-19} m^2/W$) and effective mode area as:

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (4.2)$$

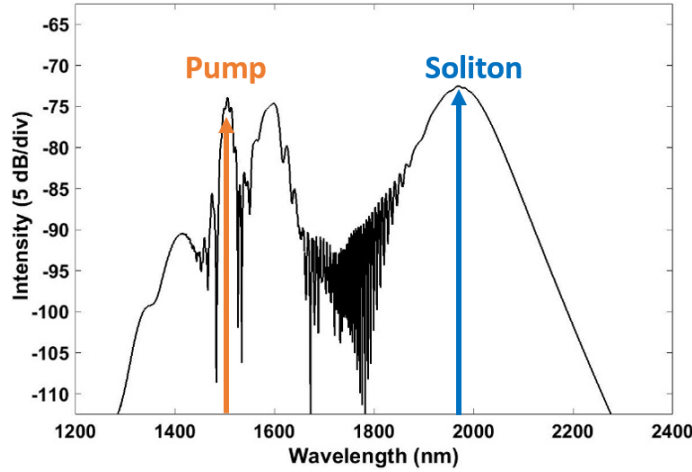


FIGURE 4.5: Numerically simulated spectra of the pump with a broad soliton.

The Kerr nonlinearity of the fiber at 1560 nm was $\gamma = 1.6421/W/m$. For tellurite glass TWPNI/6, the Raman gain peak lies at $\Omega_R=20.4$ THz, corresponding to Raman fraction $f_R=0.2$, which was considered in the simulations [134, 147]. Fiber length taken into account in the simulations was 5 cm. The simulations were run for a time window of 30 ps to accommodate not only the pump pulse (90 fs) and generated soliton, but also the delay of the detuned soliton within the time window.

Fig. 4.5 shows that when the fiber is pumped with a pulse centered at 1560 nm, a prominent fundamental soliton peak centred at 1900 nm is observed spectrally. Fig. 4.6 (a) and (b) show the numerical propagation and evolution of the pulse along the length of the fiber in spectral and time domain respectively. It can be seen in time domain that the soliton is generated instantaneous as the pulse begins propagating in the fiber. This is attributed to high nonlinearity of the fiber. The soliton splits from the pump signal just after 0.5 mm of propagation and experiences a group delay of about 4.5 ps along 5 cm of propagation in the fiber. Spectrally, it can be seen in Fig. 4.6. (a) that the generation of broad fundamental soliton is an energy efficient process. Energy efficiency of SSFS has been described in details in below section 4.5.1.

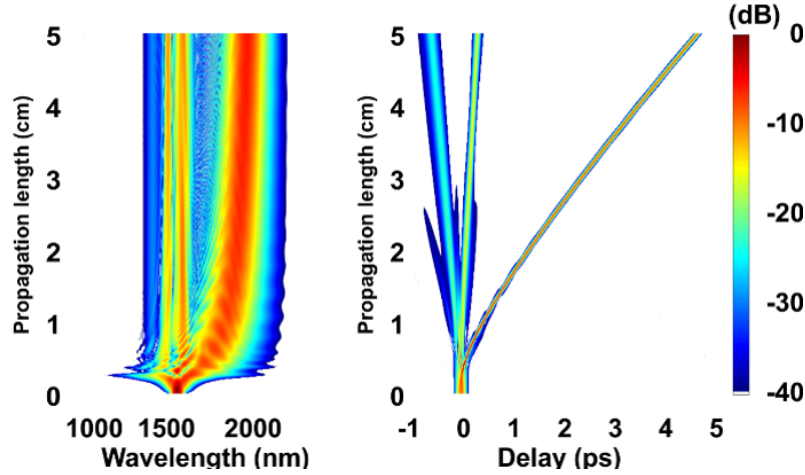


FIGURE 4.6: Numerically simulated evolution of soliton self-frequency shift along 5 cm long fiber sample (a) in spectral domain; (b) in time domain.

4.5 Experimental results and discussion

4.5.1 Soliton detuning of 68.5 THz obtained when pumped at 1560 nm

In the experimental set-up to observe SSFS, as the pump source I used Menlo Systems C-fiber HP femtosecond laser operating at 1560 nm center wavelength, with repetition rate of 100 MHz and pulse duration of 90 fs. The laser beam was coupled into the fiber using an objective lens (40 $\times$). The length of fiber samples investigated from the two fiber series NL50A and NL50C were between 2.5 cm to 6 cm. The sample lengths were restricted to below 6 cm so as to avoid modulation instability driven broadening of the soliton and spectral broadening of pulse, leading to supercontinuum generation. The output of the fiber samples were butt-coupled with a diffractive optical spectrum analyzer (OSA) through a standard SMF (Thorlabs). The OSA (Yokogawa) has a sensitivity range of 1200-2400 nm. To record soliton spectra beyond the sensitivity of OSA, a Thorlabs Fourier Transform infrared spectrum analyzer with sensitivity range of 1000-5600 nm was used. Fig. 4.7 shows an image of a fiber sample during an experiment of soliton generation in the work. The visible light is assigned to dispersive waves driven across the ZDW by the red-shifting solitons in the near-infrared. Fig 4.8. shows the soliton detuning by changing input power obtained in the tellurite suspended core fiber. The fiber sample studied in Fig.4.8 is NL50C1 and the length of the sample is fixed to 5.6 cm. When the sample length is fixed, the central wavelength of the soliton can be

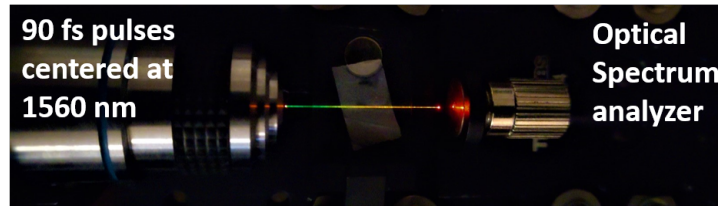


FIGURE 4.7: Soliton generation and propagation along the fabricated suspended core fiber

tuned by as a function of the input pump power, since the magnitude of Raman response depends on the pump peak power. Fig. 4.8. shows a gradual redshift of the center wavelength of soliton from the pump wavelength as the input pump power is increased. The most redshifted fundamental soliton is obtained for the input average power of 300 mW, where the center wavelength of the soliton shifts upto 2400 nm from the center pump wavelength of 1560 nm. This wide spectral shift corresponds to a detuning on 68.5 THz, which to the best of my knowledge is the spectrally widest soliton detuning attained in soft glasses as well as silica glass in the SWIR range at the time of realization of the dissertation (as can be seen from table 2.1). Importantly, this result thus serves as a proof of concept for a seed that can be tuned across the entire SWIR wavelength range. I restricted the measurements to 300 mW input power because for higher average powers than 300 mW, the fiber experienced damage as the soft glass core of the fiber has high thermal isolation. Rapid soliton detuning in such a short length of fiber as observed in this work arises from high nonlinearity of tellurite glass coupled with strong mode field confinement of the suspended core. At the same time, the dispersion characteristic of the fiber also plays a significant role. NL50C1 has the flattest dispersion profile as can be seen in Fig. 4.3 (b), with a ZDW at 1130 nm. This ZDW is the closest to the pump wavelength as compared to other fabricated fibers. The extension in the range of detuning of soliton is attributed to the flatness of the dispersion profile for wavelengths longer than the pump wavelength of 1560 nm. Further, as the soliton redshifts, it broadens in time due to dispersion it experiences at higher wavelengths. The broaden of soliton in time leads to a drop in the peak power of the soliton, consequently leading to a drop in the strength of the nonlinear response of the fiber. It is also evident that the soliton broadens spectrally as can be seen for powers higher than 160 mW in the results in Fig 4.8. This is because the redshifted Raman solitons experience modulation instability leading to decoherence on increasing the detuning of solitons. Similar decoherence of Raman solitons at near infrared wavelengths have been previously observed

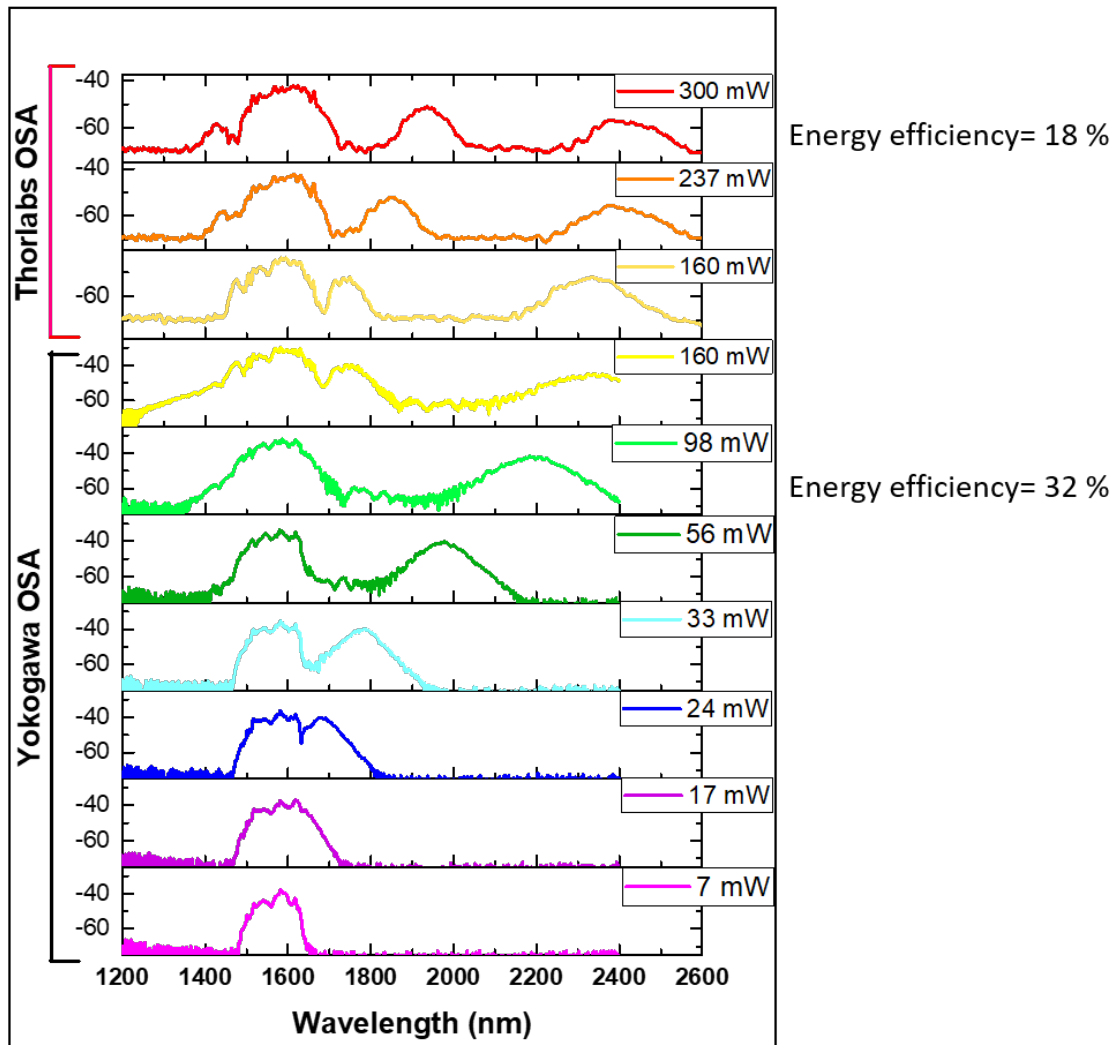


FIGURE 4.8: Soliton detuning observed in NL50C1 fiber under 1560 nm central wavelength pumping and at different average pump powers.

TABLE 4.2: Conversion efficiency of prominent soliton as a function of input power

Input power (mW)	Energy efficiency of fundamental solitons shift (%)
24 mW	38 %
33 mW	47 %
56 mW	56 %
98 mW	88 %
160 mW	62 %
237 mW	28 %
300 mW	22 %

in fibers [148]. While these results successfully obtained wide detuning of soliton from 1560 nm to 2400 nm, detuning beyond 2400 nm was limited. Soliton detuning was not only limited by the laser damage threshold of the fiber for powers higher than 300 mW, but also due to increasing dispersion and attenuation of the fiber. As the soliton detunes, the strength of nonlinearity drops due to increase in mode field diameter and MI-based broadening of the soliton. These factors collectively restrict the detuning beyond 2400 nm (center wavelength). Prominent and controllable detuning of soliton within the wavelength range of 1560-2400 nm is promising for the realisation of a SSFS based tunable source. Therefore, the conversion efficiency of SSFS determines the power scaling that can be attained by such SSFS-based tunable source. Table 4.2. illustrates the energy efficiency of the fundamental soliton for the input powers measured above for detuning. The energy efficiency was determined by integrating the peak of the soliton in the power spectra for individual input powers. While input powers were measured before the fiber sample, the output spectra gives the details of the nonlinear dynamics that occur in the fiber. Thus, the output spectra accounts for coupling loss, propagation loss and reflection at the fiber ends. The generation of soliton in the fiber was observed for a minimum input power of 24 mW (Fig. 4.8). For this power, the soliton yields 37% of the total energy. Soliton fissions from the pump for 33 mW input power and experiences Raman scattering for input powers higher than 33 mW. The fissioned soliton at 33 mW input power yields 47 % of input energy. As the soliton scatters and detunes, the energy efficiency of fundamental soliton increases upto 88 % for 98 mW input power. This is not only due to efficiency contribution of Raman scattering but also MI-induced broadening that the soliton experiences at longer wavelengths. The energy distribution

drastically changes for 160 mW input power due to the emergence of higher order soliton. Thus at 160 mW, the fundamental soliton has lower energy contribution of 62 % as compared to that at 98 mW. Increasing the power further, does continue to detune the fundamental soliton, but also decreases the conversion efficiency of the soliton to 22 % for the maximum input power of 300 mW, which can be assigned to increasing confinement loss of the fiber. The high efficiency of SSFS-based detuning in a short piece of highly nonlinear tellurite fiber shown here opens avenues to various applications that require light sources and amplifiers at SWIR wavelength. One such application for development of light sources has been demonstrated by [37] for silica fiber where they use a SSFS-based tunable seed to for a fully-fiberized mid-infrared source which can be tuned from 6 to 9 μm by difference frequency generation (DFG). Another application based on silica fiber presented by the same group shows the process of amplification and compression of seed pulses obtained from SSFS [148]. While both these cases are excellent examples of detuned solitons acting as a seed, they pose two major limitations:

1. The bandwidth of soliton detuning is limited to 2100 nm because of $-\text{OH}$ absorption in silica glass.
2. The fiber length to obtain the soliton detuning is 2.3 m, which is long enough to introduce significant chirp in the soliton, thus requiring additional steps to then recompress the pulse.

Tellurite glass based soliton detuning I present here overcomes both these limitations by using tellurite glass, which transmits well beyond 2100 nm to successfully give a wide soliton detuning from 1560 nm to 2400 nm and by using fiber lengths below 6 cm, corresponding to a relatively lesser group delay of 4.5 ps experienced by the soliton as compared to the silica fiber case.

4.5.2 Soliton detuning when pumped at 1900 nm

The soliton fission and frequency shift is strongly dependent on the spectral separation between the pump center wavelength and the ZDW of the fiber [47]. The farther the pump wavelength is redshifted from the ZDW, the shorter is the spectral shift of the central wavelength of the soliton. This occurs because when the pump wavelength is shifted farther from ZDW, it becomes difficult to satisfy the nonlinear phase modulation between the soliton and the dispersive wave [47]. Furthermore, for a pump wavelength far from the ZDW of the fiber, the soliton ceases to fission from the pump pulse [47]. In order to explore

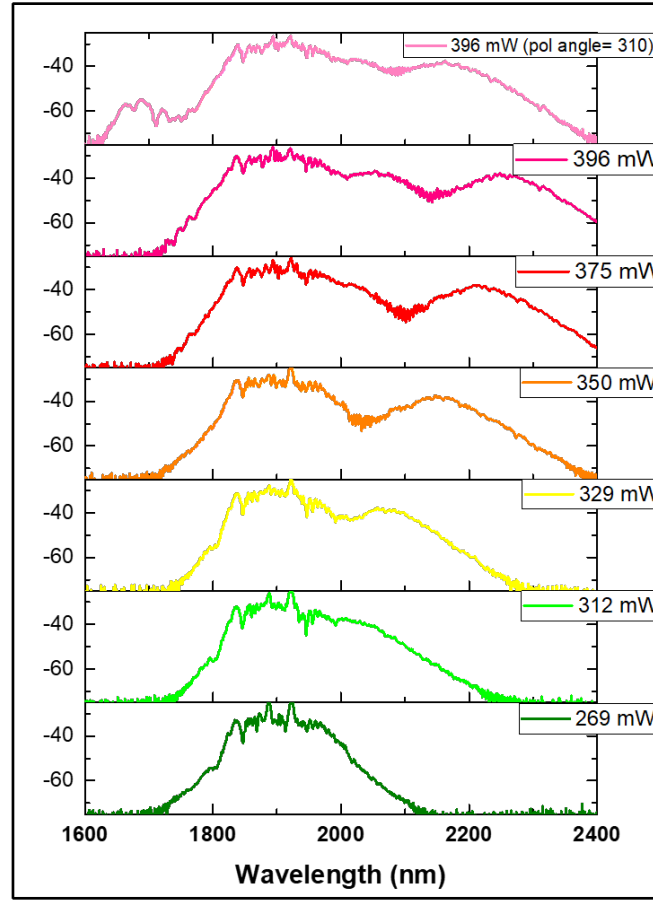


FIGURE 4.9: Soliton detuning observed in NL50C1 fiber under 1900 nm central wavelength pumping and at different average pump powers.

the range of separation between ZDW and the pump wavelength to still obtain a red-shifting soliton, I pumped the fiber with laser pulses centred at 1900 nm. I used input signal source from an in-house built, polarization maintaining, ultrafast Tm-doped fiber amplifier [149]. The amplifier was seeded with the same 1560 nm femtosecond laser as used earlier as the direct soliton driver in the suspended core fiber. The Tm: fiber amplifier has an output pulse duration of 96 fs with an average power of approximately 400 mW. Fig. 4.9 shows the soliton detuning achieved when the fiber was pumped at 1900 nm center wavelength in this conditions.

As can be seen in Fig. 4.9., the widest redshifted soliton was obtained at center wavelength of 2250 nm, when the fiber (NL5C1) was pumped at the highest amplifier power of 396 mW. This result does not exceed the result obtained

with 1560 nm pumping. For longer wavelengths, the strength of nonlinearity decreases. Thus the pump power required for the soliton to redshift is higher than that can be provided by the amplifier. Further, pumping at 1900 nm shows that the satisfactory condition of balancing of dispersion with the nonlinearity required for the soliton to fission from the pump pulse is not met as the chromatic dispersion at 1900 nm is higher than that at 1560 nm while the nonlinearity remains similar. This result affirms that the pumping conditions chosen in the previous case of 1560 nm pumping are optimal for obtaining wide SSFS-based tunability. This includes factors like the pump center wavelength – fiber ZDW spectral separation and the practical factors, like the availability of a robust femtosecond laser source at 1560 nm wavelength. I note also, that pumping at a wavelength shorter than 1560 nm would bring in other nonlinear processes such as modulation instability and four-wave mixing (thus “standard” supercontinuum generation), while pumping at longer wavelengths does not provide suitable conditions for SSFS based detuning.

4.6 DFT measurements

Dispersive Fourier transform (DFT) theory states that for a given temporal field, the dispersive stretching of the pulse with map the temporal pulse with identical intensity as that of the pulse spectrum [89]. I performed DFT analysis on our fiber to determine the noise properties of the soliton generated. I pumped 13.5 cm of fiber sample with an OPO with pulse duration of 200 fs at 1550 nm, 80 MHz repetition rate. The spectra generated from the fiber was then observed using an OSA. The signal from the fiber was time-stretched in a stretching fiber of length 170 m and $D = -91$ ps/km.nm. The stretched pulse was then recorded by the means of a photodiode and observed on the oscilloscope with frequency of 12 GHz. Total number of pulses recorded in one reading was 400. The power input into the fiber from the laser was 250 mW. Fig. 4.10 shows that after stretching the pulse in time domain, the temporal profile of the pulse mimics the spectral profile, as anticipated by DFT theory. Thus overlap in the DFT spectra and the spectra obtained through the OSA can be seen in Fig 4.10. It also shows the average of 400 DFT pulses recorded, prominently depicting the soliton peak. Interestingly, extreme redshifted rouge solitons can also be observed in the spectra between about 1650 nm and 1700 nm. I note that a strict description of this phenomenon would require a dedicated study involving preparation of appropriate statistics [150], which is out of scope of this dissertation, however the developed fiber could

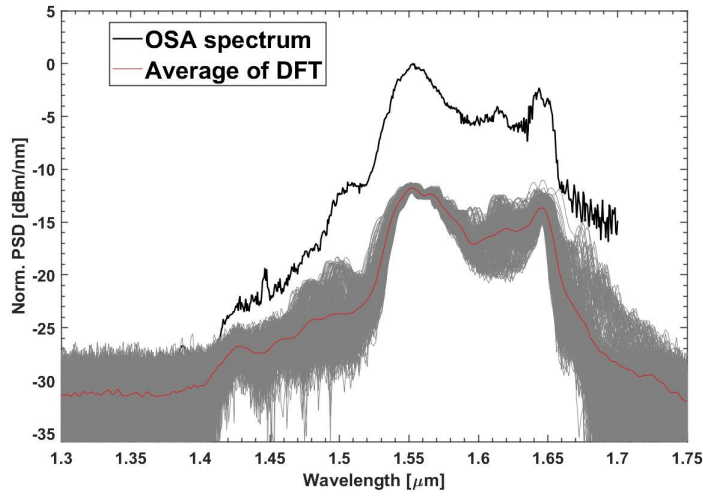


FIGURE 4.10: Coherent overlap of OSA spectra with average DFT spectra of 400 recorded pulses

be an interesting experimental platform for rouge soliton investigation. DFT measurements also reveal that the solitons possess a jitter. This is due to the intrapulse energy exchange that occurs during soliton generation and fission and additionally due to the Raman scattering of the soliton. This is in agreement with the earlier reports that compare the noise properties of anomalous and normal dispersion pumping [151] that soliton and MI based broadening rapidly deteriorates pulse coherence and introduces high levels of noise. Based on the DFT measurements, a wavelength correlation map as shown in Fig. 4.11, aids us in identifying different phenomena in SSFS. A characteristic cross across the pump depicts self-phase modulation (SPM) in the pump. Note, that the highly correlated diagonal of the map indicates the trivial information of top correlation between two identical wavelengths. The bow-like features of correlated wavelengths, indicating simultaneous increasing of intensity at wavelengths around 1650 nm and 1450 indicate onset of a redshifted soliton (Stokes component of Raman scattering) and weaker, anti-Stokes component, respectively. Notably, the wavelength area between 1560 and 1650 nm contains interleaving correlated and anti-correlated wavelengths, indicating spectrally narrow ranges where intensity increases and decreases at the same time respectively (ie. increasing at 1650 nm and decreasing at 1560 nm or 1575 nm), which can be assigned to the energy transfer process from higher frequency (shorter wavelength) to higher frequency (longer wavelength), indicative of soliton self-frequency shift.

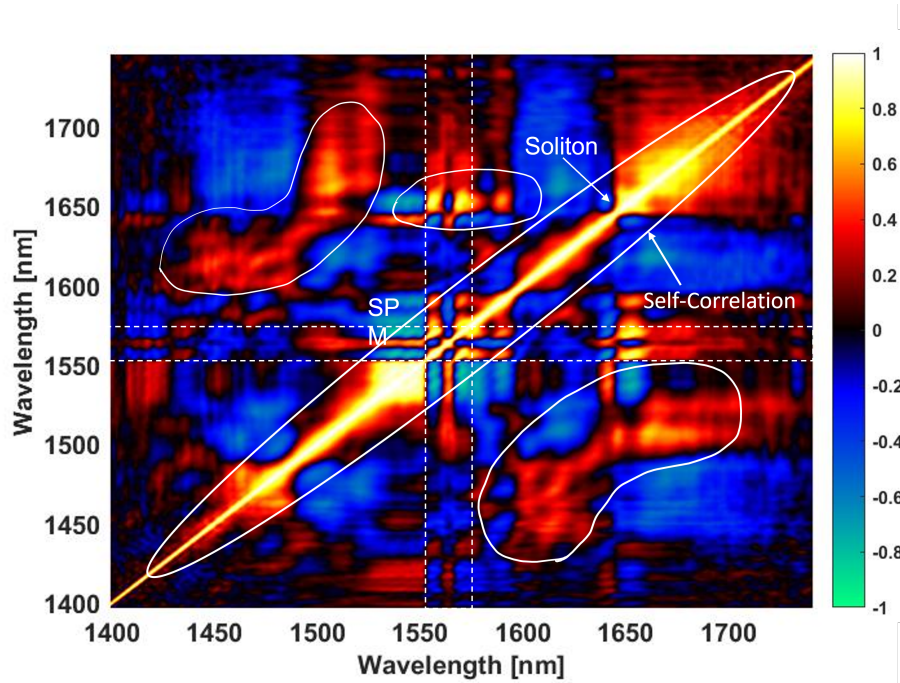


FIGURE 4.11: Wavelength correlation map showing various phenomenon in SSFS

4.7 Conclusions

Here I demonstrated a soliton self-frequency shift over a bandwidth of 68.5 THz in a short length of a highly nonlinear, suspended core tellurite fiber. The fiber when pumped at the center wavelength of 1560 nm with 90 fs pulses from a commercial mode-locked fiber laser showed an input power-based tunability across as much as 2400 nm of center wavelength shift of an isolated soliton. Highly nonlinear tellurite glass, combined with the dispersion engineering of the fiber to have a ZDW around 1200 nm and a flat anomalous dispersion for wavelengths longer than 1200 nm provided the optimal conditions for soliton generation and shift to take place in just over 5 cm of the fiber sample. This result outperforms any earlier reports of SSFS-based detuning in silica and well as soft-glass fibers. When compared to SSFS-based soliton detuning obtain in silica fiber [148], the result presented here supersede the range of soliton detuning up to 2400 nm, which is not achievable by silica fibers as they are lossy beyond 2100 nm. Another advantage of the soliton detuning of 68.5 THz obtained in this work is that it is obtained over fiber lengths 10 times shorter than that in silica fibers, which significantly reduces the chirp that is soliton attains over long fibers, requiring further recompression mechanisms. A crucial feature of these results is the input-power based tunability of solitons which

requires low peak power of femtosecond pulses to isolate soliton propagation without extending into the nonlinear regime of supercontinuum broadening. Thus, working in the low input power regime becomes practical, despite the limitation of low laser damage threshold of soft-glasses. Further, the pump power required to achieve these results can be easily obtained using commercial moderate power femtosecond laser, as the one used in this results, making it suitable for all-fiber based laser and amplifier systems.

The results presented here thus fulfil **thesis 1** of this dissertation that *shaping of nonlinearity in specialty optical fibers developed using highly nonlinear tellurite glasses enables achieving significantly improved tuning bandwidth of Raman solitons, covering the entire SWIR wavelength range, without applying complex and high peak power laser systems, compared to existing state-of-the-art fibers exploiting the silica glass technology.* The wavelength tunability throughout the SWIR range presented in this work provides a proof of concept for a fiber which can connect low power seed signals from erbium-based femtosecond seed to ultrafast amplifier systems based on Tm:ZBLAN or $H_0 : SiO_2$. This result provides a path to integrate ultrafast laser and amplifier systems as well as head towards an efficient all-fiber ultrafast systems covering the SWIR wavelength range.

Chapter 5

Real-time noise measurement of supercontinuum generated in PM and non-PM ANDi tellurite fibers

Coherence properties of supercontinuum (SC) play a crucial role in applications such as optical coherence tomography (OCT) and confocal microscopy. SC generation stemming from dispersive waves and optical wave breaking, which occurs in all-normal dispersion (ANDi) fibers, has a higher degree of coherence and a lower relative intensity noise (RIN) as compared to SC stemming from soliton dynamics in anomalous dispersion fibers [151, 152]. Recent investigation on SC in ANDi fibers showed that the degree of coherence degrades inversely to the pulse duration and fiber length due to parametric interaction between coherent and incoherent components of the SC [55]. On similar lines, Gonzalo et al. [153] showed that polarization modulational instability (PMI) introduces a power-dependent coherence degradation in ANDi fibers, which cannot be reproduced using a scalar single-polarization model of SC generation. It was recently also shown that for a PM ANDi fiber, PMI can be avoided by using suitable pump parameters and fiber length. In such a case, the technical noise from the pump dominates quantum noise and plays a prominent role in SC noise [154]. In this chapter, I describe the results of my research on the noise properties in broadband near-IR SC generated in ANDi fibers. This study was carried out on two variants of hexagonal lattice microstructured optical fiber structure developed using tellurite glasses. The fibers were designed by me and I took part in the technological processes aimed at the fabrication of the fibers. My work also involved optical characterization of all developed fibers. The fibers under the study have their main difference in the birefringence properties i.e. one of the fibers drawn is a polarization maintaining (PM)

fiber with high intentional birefringence while the other is a regular hexagonal lattice structure that does not support a particular polarization mode, hence is a non-PM fiber. I then experimentally compare the real-time noise across the entire bandwidth supercontinuum generated in these two fibers using a dispersive time-stretching technique.

Here, I demonstrate a drastic difference in the noise observed in SC generated in PM ANDi fiber in comparison to non-PM ANDi fiber. High noise observed in the non-PM fiber indicates that polarization modulational instability (PMI) plays a detrimental role with respect to the coherence of the SC generated. I measured and compared the noise properties in real-time for the two fibers with similar pump parameters and fiber lengths. This result is evidence that a PM all-normal dispersion fiber enables coherent SC generation with lower relative intensity noise as compared to their non-PM variants, which can aid to the advancement in measurement technologies such as OCT and confocal microscopy.

5.1 Design and development of PM tellurite fiber

PCFs are the medium of choice for SC generation due to their dispersion-engineering properties. It is known that all-normal dispersion (ANDi) profile of a fiber facilitates the conditions for coherent supercontinuum generation [1]. Thus these soft-glass tellurite fibers were designed to obtain coherent all-normal dispersion profile for potential in near and mid-IR transmission. On numerical modelling, the PCFs used in this work were dispersion engineered for all-normal dispersion (ANDi) profile and optimized structurally for low confinement loss as explained below. The ANDi fibers were modelled for a regular hexagonal lattice structure for suitable dispersion and confinement losses over a broad wavelength range. Such a fiber modelling has been earlier demonstrated by Saitoh et al. for silica glass PCFs [155]. The PCFs were designed on Lumerical Mode Solutions software using finite difference eigenmode (FDE) solver. The PCFs made from tellurite glass in the scope of this work were modelled in three steps:

1. *Diameter of the air-holes:* The diameter of the inner air-hole rings determines the dispersion properties and the diameter of the outer air-hole rings determine the attenuation of the whole structure. In particular, the inner most ring surrounding the core plays the most important role in

the dispersion characteristic. In this structure, it was found that the internal ring air holes diameter of $d_1 = 0.5\mu m$ showed the flattest dispersion profile in the wavelength range of 1600-3000 nm as shown in Fig.5.1 (a). Additional inner rings, around the first rings, contributed in fine tuning of dispersion profile and also were convenient from a technological point of view of fiber fabrication for soft glasses. For the outer air-hole rings, larger the diameter of the air-holes, lower the attenuation of the fiber. From a technologically practical point of view, the outer air-hole diameter was set to $d_2 = 0.8\mu m$ for the ease of fabrication.

2. *Number of rings:* The advantage of PCFs over step index fibers is that it provides a higher degree of freedom to confine light in a small core. One such way to achieve high confinement of guided modes in a PCF is by adding more number of lower refractive elements in the cladding to constrict the electric field of the modes from spreading away from the core. Thus, in this case, we increase the number of air-hole rings around the core. On determining the effect of increase in the number of rings on the confinement loss of the fundamental mode, it was seen that the long wavelength edge of the confinement loss red shifts on increasing the number of rings as seen in Fig.5.1 (b). The designed ANDi fibers were optimized to have 7 rings as the waveguide loss was obtained to be below 0.01 dB/m at the wavelength of 2800 nm, which is the long wavelength edge of the desired supercontinuum generation. The other important aspect that was determined was the ratio of number of internal rings to the number of external rings. While the second internal air-hole ring of diameter d_1 showed a slight modification to the dispersion profile, further addition of internal air-hole rings did not offer any particular advantage. In terms of outer rings with larger air-hole diameter, it was seen that with 4 outer rings were required to maintain a low confinement loss of 0.1 dB/m for wavelength below 2400 nm. Thus we optimize the structure for a ratio of 4/3 so as to obtain lowest possible confinement losses and flat all-normal dispersion over the wavelength range of 160-2800 nm.
3. *Lattice pitch:* The structure was studied for the influence of lattice pitch Λ in the range of 1.0 – 1.4 μm . With an increase in the value of lattice pitch, the dispersion dropped from $D=-50$ ps/nm/km to $D=-350$ ps/nm/km from $\Lambda=1.4\mu m$ to $\Lambda=1.0\mu m$ respectively as shown in Fig.5.1. (c). However, the effective mode area for the fundamental mode increases with

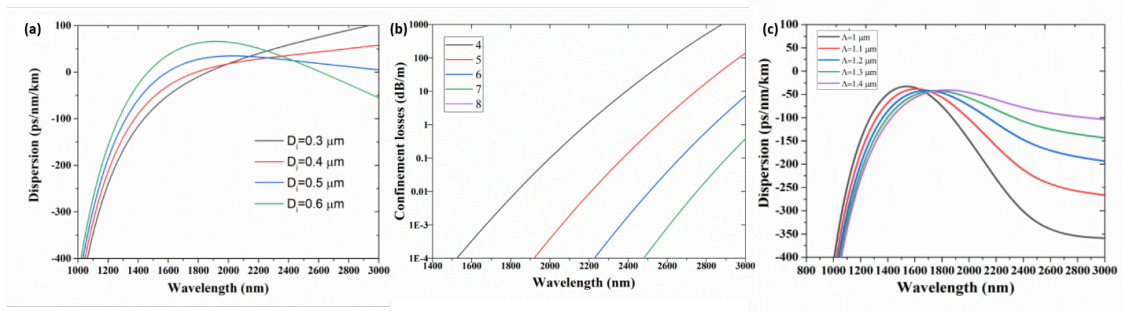


FIGURE 5.1: Numerical modelling of PCFs (a) Dispersion profiles for different diameters of inner ring air-holes (b) Effect of number of rings in a PCF on confinement losses of fundamental mode (c) Influence of lattice pitch on dispersion profile of fundamental mode

increase in lattice constant, providing decreased nonlinearity for longer wavelength range. Thus, the most convenient lattice pitch to balance the dispersion and the effective mode area is determined to be $\Lambda = 1.3 \mu\text{m}$.

The optimized structure based on the above numerical modeling is a hexagonal lattice with 7 air-holes rings around the core, out of which, 4 inner rings have an air-hole diameter of $d_1 = 0.5 \mu\text{m}$ and the outer 3 rings have an air-hole diameter of $d_2 = 0.8 \mu\text{m}$. The PCF structure has a lattice pitch of $\Lambda = 1.3 \mu\text{m}$. This structure shows all-normal dispersion, high nonlinearity, and a potential of spectrally broadening light pulses on pumping with femtosecond laser.

I designed a variant of this fiber for propagation of polarization maintained femtosecond pulses in ANDi configuration for supercontinuum generation. Like the non-PM fiber, the PM variant also has similar hexagonal structure but instead of two, this time with three air-hole sizes. The inner four rings of the structure have air-holes of diameter $d_1 = 0.5 \mu\text{m}$, the outer three rings have air-holes of diameter $d_2 = 0.8 \mu\text{m}$, optimized exactly as per modelling explained above for non-PM fiber. The only difference between the PM and the non-PM fiber design was the introduction of birefringence by modifying the structure of the inner most air-hole ring. Birefringence is introduced in the structure by varying the size of two diametrically opposite air-holes in the ring of air-holes closest of the core (as shown in Fig.5.2). The two birefringence-inducing holes have diameter d_3 and provide a geometric confinement of the fundamental mode in a particular polarization axis. This fiber was developed with the intention of studying the effect of birefringence on the noise properties of supercontinuum generated in an ANDi PCF.

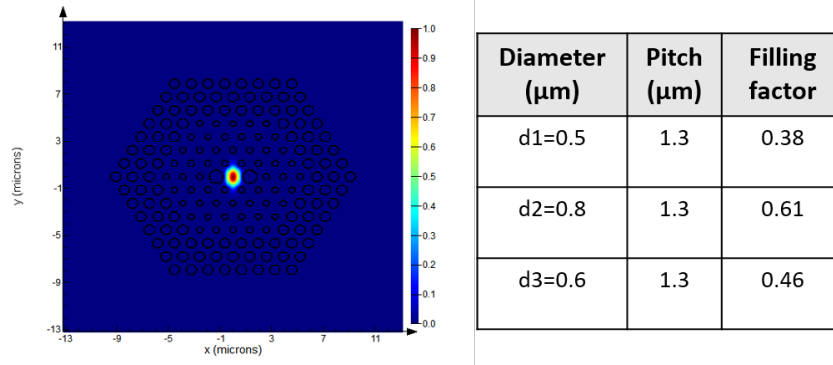


FIGURE 5.2: (left) Designed structure with fundamental mode as seen on Lumerical Mode solver; (right) Optimized structural parameters for fabrication of PM PCF

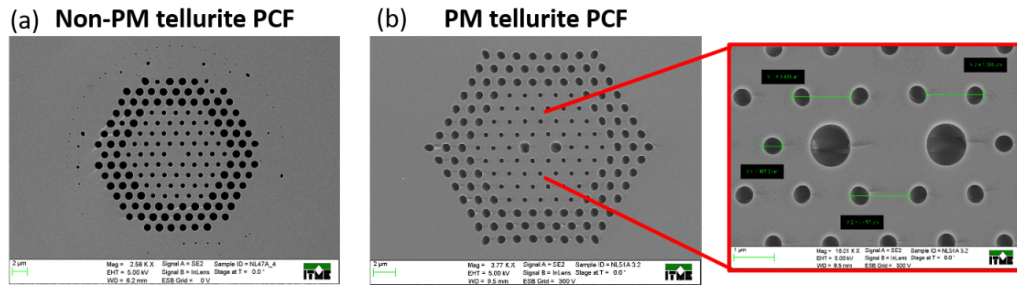


FIGURE 5.3: SEM images of (a) non-PM tellurite PCF and (b) PM tellurite PCF (inset) shows the structural change introduced near the core to induce birefringence

The design fiber with parameters outlined in Fig 5.2., contrived to have all-normal dispersion for both the orthogonal polarizations. Birefringence of the designed fiber was numerically calculated to be $\geq 2 \times 10^{-3}$, which was deemed to be sufficient to maintain polarization. The designed structure is also expected to have low confinement losses due to the two lattice pitch configuration. The PCFs were fabricated by stack and draw method as described in section 3.5.1. The different in size of the air-holes were obtained by stacking different internal diameters of capillaries in the preform. The larger holes, those in the last three rings of the structures along with the two birefringence causing air-holes, had larger internal diameter. The small air-holes were essentially capillaries with thicker walls and hence smaller internal diameter. The preform was then drawn in the presence of inert gas pressure to ensure that the air-holes sizes are maintained without collapsing of the capillaries. Fig.5.3 shows the SEM images of the two fabricated series: NL47A4 (non-PM PCF) and NL51A3.2 (PM PCF).

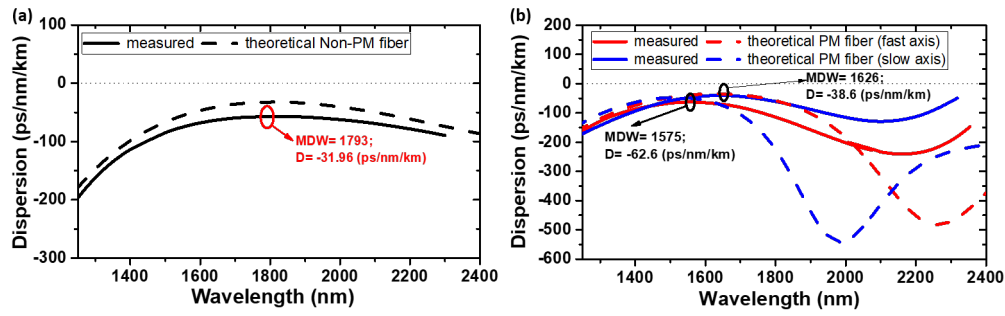


FIGURE 5.4: Measured (solid) and theoretical (dashed) dispersion plots for the two variants of regular hexagonal lattice under study (a) non-PM PCF and (b) PM PCF

5.2 Linear properties of PM and non-Pm fibers

5.2.1 Dispersion

The chromatic dispersion of the fibers was measured using Mach-Zander interferometer as described in section 2.2.2. These measured dispersion curves, as plotted in Fig. 5.4., confirmed that the fibers have all-normal dispersion. In case of the PM fiber, the axis of the fiber was identified using a half-wave plate and the dispersion was measured for the two orthogonal polarization modes. In case of the non-PM fiber, the measured dispersion profile (solid) is similar to the targeted numerical dispersion curve (dashed) that was determined while designing the fiber. The non-PM fiber has the highest dispersion value of -31.9 ps/nm/km at 1793 nm. For the PM fiber, the fast axis has maximum dispersion of -62.6 ps/nm/km at 1575 nm while the slow axis has maximum dispersion of -38.6 ps/nm/km at 1626 nm. The dispersion profile of the two axis has similar value at the pump wavelength of 1560 nm. For wavelengths longer than the pump wavelength, the dispersion profile of the fast axis is steeper than that of the slow axis. This means that the slow axis is likely to generate a broader supercontinuum as compared to the fast axis due to relatively higher dispersion values for wavelengths greater than 1560 nm, supporting the condition for optical wave breaking [156, 157].

5.2.2 Birefringence

The designed structure of the PM fiber with two large air-holes around the core facilitates propagation in one of the two orthogonal polarization modes (i.e. fast and slow axes). I measured the group birefringence (G) of the PM

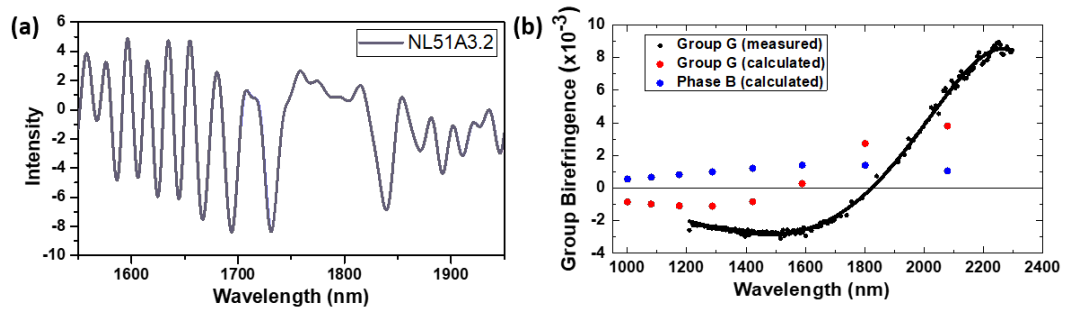


FIGURE 5.5: (a) Birefringence fringes observed when both the orthogonal modes are excited in the PM fiber (b) Plot of measured group birefringence (black) in PM fiber compared with group (red dots) and phase (blue dots) birefringence calculated from the designed fiber structure

fiber using the set-up outlined in section 2.2.5. I used a sample of PM fiber of length 54 mm and determined the axis of the fiber by adjusting the HWP and the analyzer to obtain maximum intensity on the camera. The HWP was then set to 22.5° angle to the determined axis, so as to excite both the orthogonal polarization modes (i.e. at 45°) to both the axes. The output signal was measured on an optical spectrum analyzer (OSA) where the interference fringes due to the interaction between the two orthogonal modes were recorded. Fig. 5.5. (a) shows the birefringence interference fringes recorded on the OSA. In order to measure the group birefringence from the spectral coverage of the SC source, the measured birefringence fringes were stitched together for different spectral ranges. The wavelengths at the peaks of the fringes were recorded to determine the λ_0 and $\delta\lambda$ and the group birefringence G was calculated for the length of fiber L ($=54$ mm) as $G = \frac{\lambda_0^2}{\delta\lambda \cdot L}$. Fig. 5.5. (b) shows that the value of the measured group birefringence (in black) goes from -2×10^{-3} at 1200 nm to 8×10^{-3} at 2300 nm with a zero-group-birefringence at the wavelength of 1815 nm, which corresponds to the widest observed fringe. Fig. 5.5. (b) also compares the measured group birefringence (black) with calculated group birefringence (red dots) and phase birefringence (blue dots) from the designed structure showing that fabricated fiber has higher birefringence than the designed structure.

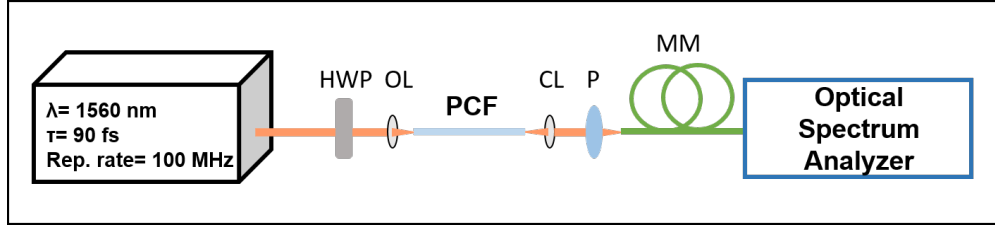


FIGURE 5.6: Schematic of the set-up used to measure supercontinuum generation in the two tellurite PCFs

5.3 SCG in PM and non-PM fiber

The fibers in this work have been designed to have key features such as high nonlinearity, effective single-mode, and all-normal dispersion. Owing to the high nonlinearity of tellurite glass, these fibers have the potential to obtain coherent supercontinuum generation in the near-IR wavelength range. Here I report a coherent pulse-preserving supercontinuum generation stemmed from self-phase modulation and optical wave breaking with femtosecond pumping a regular hexagonal lattice PCFs.

The PCFs were pumped with a compact erbium fiber-based femtosecond laser (Menlo Systems C-fiber HP) centered at 1560 nm, delivering 90 fs Gaussian pulses with repetition rate of 100 MHz. The laser pulses were coupled into the fibers using an aspheric lens of focal length of 4 mm (Thorlabs) for non-PM fiber and an objective lens of 40x for the PM fiber. Supercontinuum spectra generated in the PCFs were collimated using a similar aspheric lens of focal length 11 mm (C220TM, Thorlabs) and recorded with an optical spectrum analyser (OSA) of sensitivity range 1200-2400 nm (Yokogawa) with spectral resolution of 2 nm using a 105 μ m multimode patch cord. Outline of the set-up to measure SC generation in the two hexagonal lattice tellurite PCFs is shown in Fig. 5.6. The fabricated non-PM PCF has a flat dispersion profile in the wavelength range of 1550-1900 nm (Fig. 5.4). This enables attainment of ideal conditions for uniform optical wave breaking. The non-PM PCF of length 278 mm was used to obtain and demonstrate spectral broadening as a function of input power. As for higher powers, the spectral broadening extends beyond the range of the OSA, a Fourier transform analyser (OSA250) with a sensitivity range of 1000-5600 nm was used to obtain a complete spectra, all the while ensuring that no Fourier transform errors are recorded. Fig. 5.7. shows the experimental measurements of the evolution of supercontinuum as a function of input power. For the maximum input power of 316 mW, a broad, coherent

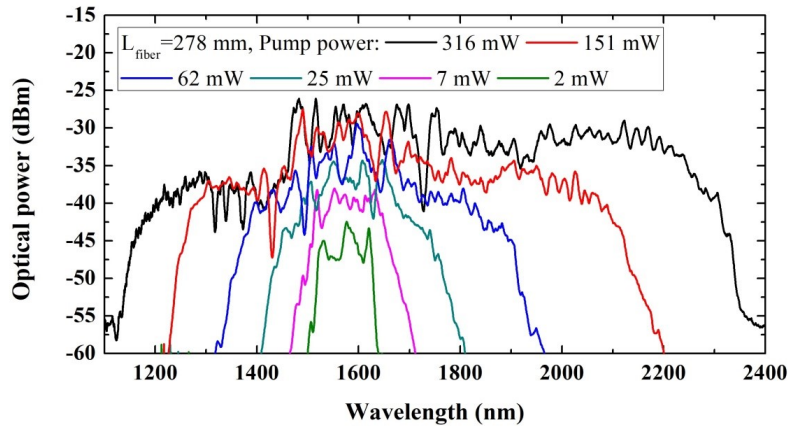


FIGURE 5.7: Supercontinuum spectra measured for the NL47A4 series fibers for different incident average pump powers.

supercontinuum was obtained from 1100 nm to 2300 nm. Arresting the fiber in normal dispersion region by dispersion engineering of its structural properties, along with high nonlinearity of the glass and the use of 90 fs pulses, the delivery of spectrally broadened coherent light pulses was ensured. Numerical simulation of pulse propagation in the developed ANDi PCF was carried out using GNLSE for an input Gaussian pulse of 90 fs, centered at 1560 nm wavelength, carrying a pulse energy of 5 nJ at 100 MHz repetition rate. A PCF sample of 4 cm of non-PM ANDi PCF was assumed for the simulations. Spectral broadening obtained with 1 nJ of pulse energy over the length of the PCF is shown in Fig. 5.8.

Supporting numerical analysis shows that the evolution of broadening is due to self-phase modulation around the center pump wavelength followed by optical wave breaking (OWB) of the pulse. The sidebands are generated due to OWB first at the trailing edge and then at the leading edge of the pulse. The leading edge of the pulse is red-shifted while the trailing edge is blue-shifted, leading to an overall octave-spanning supercontinuum generation ranging from 1100 nm upto 2300 nm. Spectral broadening towards shorter wavelengths get limited due to steep dispersion at short wavelengths and longer wavelength edge is limited by decreasing nonlinearity of the fiber. Despite a limitation, we obtain a octave spanning supercontinuum over the first 1 cm of fiber propagation for a tellurite ANDi PCF, which extends the state-of-the-art in fiber-based pulse-preserving femtosecond supercontinuum generation.

In the supercontinuum generation measurements involving the PM tellurite fiber variant, the set-up shown in Fig. 5.6. enabled for the polarization control

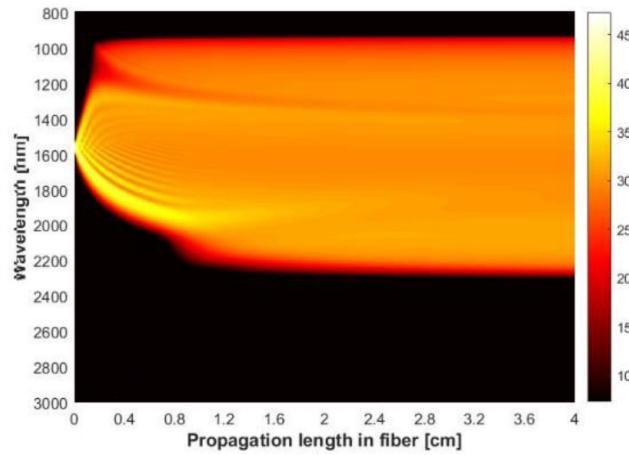


FIGURE 5.8: Evolution of SC spectra in non-PM ANDi fiber of 4 cm when pumped with 90 fs pulses of 1 nJ pulse energy centered at 1560 nm.

of light in coupled and to the fiber. The polarization of the input pulses of 90 fs, centred at 1560 nm, was optimized with respect to the axis of the PM fiber using a half-wave plate (HWP). The beam was coupled into the fiber using an objective lens and the output signal was collimated using an aspheric lens. A broadband linear polarizer was set after the collimating lens to determine the polarization extinct ratio (PER) of the fiber.

The polarization of the input pulse was aligned with the polarization axis of the fiber by using the HWP (@ 1550 nm) at the input, aligned with a linear broadband polarizer at the output by measuring the transmitted power T . Thus the fast and slow axis of the fiber are identified from the measured transmitted power and the fiber was pumped at the two orthogonal axis. Fig. 5.9. shows the experimentally measured evolution of supercontinuum when pumped at 1560 in fast axis (a) and slow axis (b). The broadest supercontinuum was obtained for the maximum available pump power of 333 mW for both the axis. The supercontinuum generated in slow is axis spanned from 1100 nm to 2135 nm which is broader than the supercontinuum generated in the fast axis with a span of 1100 nm to 2042 nm. This is in agreement with the prediction of wider supercontinuum in the slow axis due to flatter dispersion values of wavelengths red-shifted from the pump wavelength, as compared to that of the fast axis. Fig. 5.10. shows the polarization extinction ratio (PER) in supercontinuum generated with the linearly polarized pump light alignment to either slow or fast axis of the PM fiber variant. The plots in red indicate fiber pumping in the fast axis while the plots in black indicate the slow axis. The

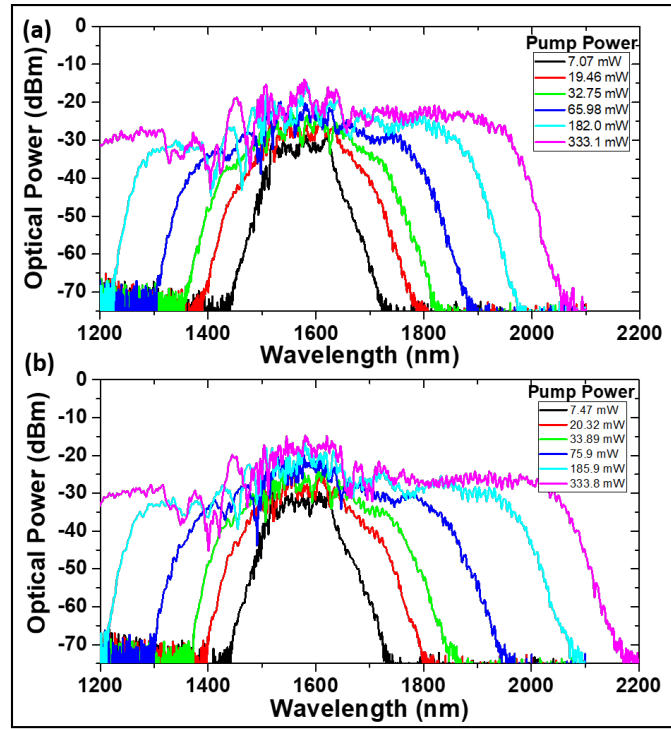


FIGURE 5.9: Spectral broadening as a function of input power in (a) fast and (b) slow axis of the PM fiber

PER was determined by changing the axis of the polarizer to align with the axis at which the fiber was pumped. When the polarizer was set to the same axis as the axis of fiber pumped, the recorded reading is denoted as max while when the axis of polarizer was orthogonal to the axis of pumping, the reading is denoted as min. The input average pump power in these readings was 330 mW. In fast axis supercontinuum generation, the maximum output power was measured to be 40.07 mW (red) and the minimum output power was 8.3 mW (light red). The power was measured using a broadband thermal power sensor (S401C, Thorlabs). When pumped in the slow axis, the max output power was 37.25 mW (black) which is lower than that of fast axis as the spectrum of slow axis is broader than that of fast axis. The PER of the fiber is 20 dB for the broaden SC generated in the fiber. This is with the exception of around the pump wavelength, where the PER is 5 dB.

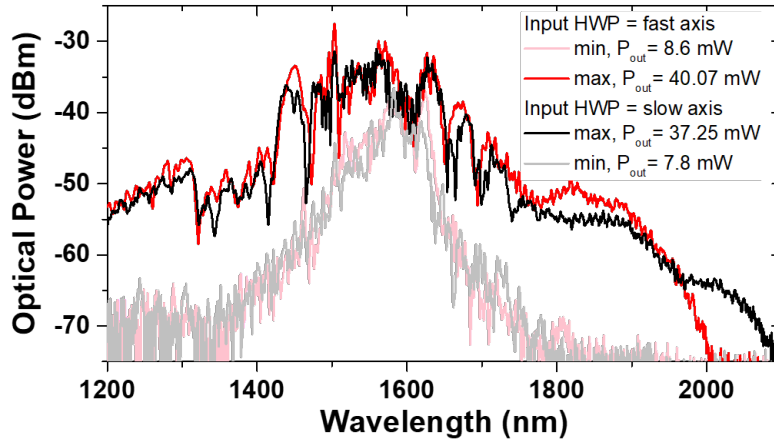


FIGURE 5.10: SC generated in fast (red) and slow (black) axes in the PM PCF. PER of the fiber is determined by recording the polarization of the SC generated for the axis of pumping (max) and the orthogonal axis (min)

5.4 DFT technique for real-time noise measurements

RIN was determined as the average of shot-to-shot spectral fluctuations over the entire bandwidth of SC generated. Here I employ the technique of dispersive Fourier transformation (DFT) to determine the noise properties of the SC generated in the two fibers. The advantage that DFT technique holds over other RIN measurement techniques is that it allows measurement of RIN across a range of wavelength in one measurement, without having to adjust filter, thus consequently increasing the accuracy of measurements. The concept of DFT method is based on the dispersive time stretching. When a laser pulse is input to a highly dispersive element, the pulse gets stretched in time due to the large GVD it experiences. DFT theory (as explained in section 2.3.10) says that when such a pulse stretches in time due to a dispersive element, the spectrum of each pulse is mapped to a temporal waveform [87]. Dispersion-compensated time stretching allows us to observe the envelope of the pulse in time domain, whose intensity essentially mimics that of the frequency spectrum. This mimicking of intensity occurs due to large linear stretching of the temporal pulse which leads to separation of the individual wavelengths whose intensity profile is similar to that of the frequency spectrum. For the conversion of oscilloscope time-base to wavelength spectrum base in DFT, the following conditions need to be fulfilled:

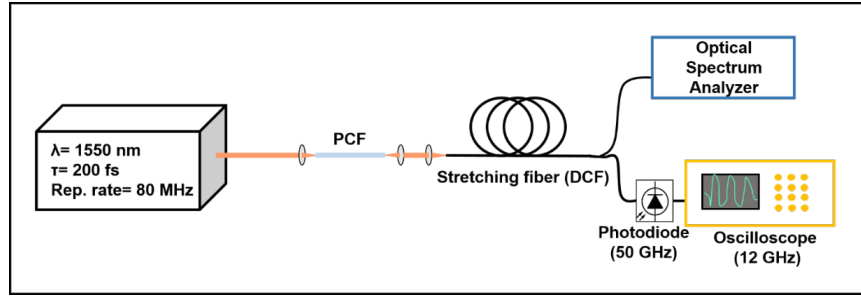


FIGURE 5.11: Schematic of experimental setup to measure real time noise in SC generated in ANDi tellurite fibers

1. The chromatic dispersion characteristic of the stretching element (dispersion compensating fiber (DCF) in our case) should be known.
2. The stretching DCF should only support linear (dispersive only) propagation. This was assured in our work by limiting the SC power at the DCF input and by monitoring the SC spectrum before and after the DCF.

I pumped the PCFs with an optical parametric oscillator (Chameleon compact, Coherent) having pulse duration of 225 fs centered at 1550 nm, 80 MHz repetition rate as shown in Fig. 5.11. The input polarization angle was controlled using a HWP and the beam was coupled into the fiber using a 40x objective lens. The SC generated from the fibers was first recorded using an optical spectrum analyzer (OSA). The signal from the fiber was then time stretched in a 170 m DCF with dispersion, $D = -83.89$ ps/nm.km at 1550 nm. The stretched pulse was recorded with a 50 GHz-bandwidth photodiode (InGaAs, U2t) and observed on an oscilloscope (Agilent) with a 12 GHz bandwidth. Total number of pulses recorded in one reading was 400 corresponding to 5 μ s time duration. Along with this, the full SC spectra were recorded with a compact spectrometer. Average pump power input in the PCFs was 250 mW. For the PM fiber, its principal axis was determined and readings were taken at the two orthogonal polarizations as well as at an offset of 45° between the two modes. Fig. 5.12 shows accurate mapping of the oscilloscope time-base into the wavelength (frequency) scale as obtained by DFT for non-PM and PM fiber by the formula [152, 158]

$$T(\omega) = \sum_{m=1}^{\infty} \frac{\beta_{m+1}z}{m!} (\omega - \omega_0)^2 \quad (5.1)$$

Where β_m and z represent the dispersion characteristic and length of the DCF stretcher respectively. The DCF stretched the pulse upto ~ 3.3 ns for the non-PM PCF and ~ 1.8 ns for the PM PCF when maximum power was coupled into

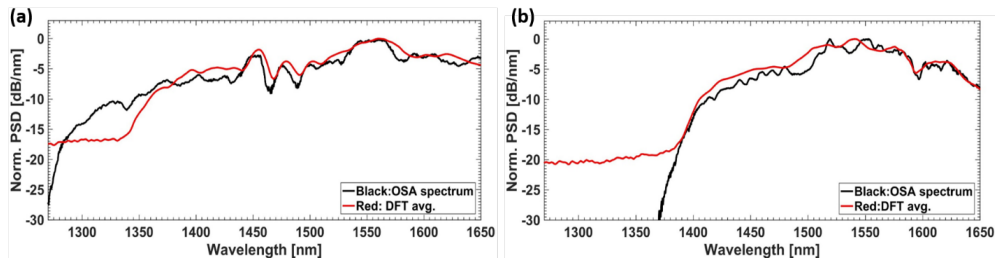


FIGURE 5.12: Overlapping spectra from OSA (black) and the DFT spectra (red) for (a) non-PM and (b) PM fiber

the PCFs. The equivalent spectral resolution of this Fourier transformed was calculated to be 5.8 nm. The mismatch between the OSA-measured spectrum and the DFT-retrieved spectrum for the non-PM fiber for wavelength less than 1350 nm is attributed to OH absorption over the significant length of the DCF stretcher used in the experiment. The DFT measured spectrum is limited at 1670 nm due to the sensitivity of the InGaAs photodiode used. Experimental results shown here demonstrate prominent intensity fluctuations in SC generated in ANDi PCFs with the length of 12.9 cm for the non-PM fiber and 12.6 cm for the PM fiber. Fig. 5.13. shows shot-to-shot measurements of 400 realizations from DFT spectroscopy. The real-time fluctuations are shown in grey while red depicts the mean of these real-time spectra. From a comparison of Fig. 5.13.(a) and (b) it is evident that the PM fiber has lower noise fluctuations (in grey) than the non-PM fiber. While supercontinuum in both the fibers stem from coherent nonlinear dynamics of SPM and OWB, the shot-to-shot noise in non-PM fiber is significantly higher than that in PM fiber. In particular, measured DFT spectra show large noise for wavelengths around the pump region and red-shifted from the pump. This can be attributed to polarization modulation instability in the non-PM fiber, which is restricted in the PM fiber due to excitation of a single orthogonal mode. The dynamic range of these measurements was 24 dB.

To further understand the role of birefringence of PM fiber in suppressing noise in SC generated, I measured SC generated in fast axis, slow axis and at 45° to both the axis. Fig. 5.13. also shows the measured DFT spectra of 400 consecutive shots each for the fast axis (b), slow axis (c) and 45° to the axes (d). When the fiber is pumped at an angle 45° to the fiber axes, the spectral broadening is narrow. Higher noise can also be seen for wavelengths redshifted from the pump wavelength for the case of 45° pumping. This is because the interaction of the two orthogonal modes possibly contributes to PMI in the fiber.

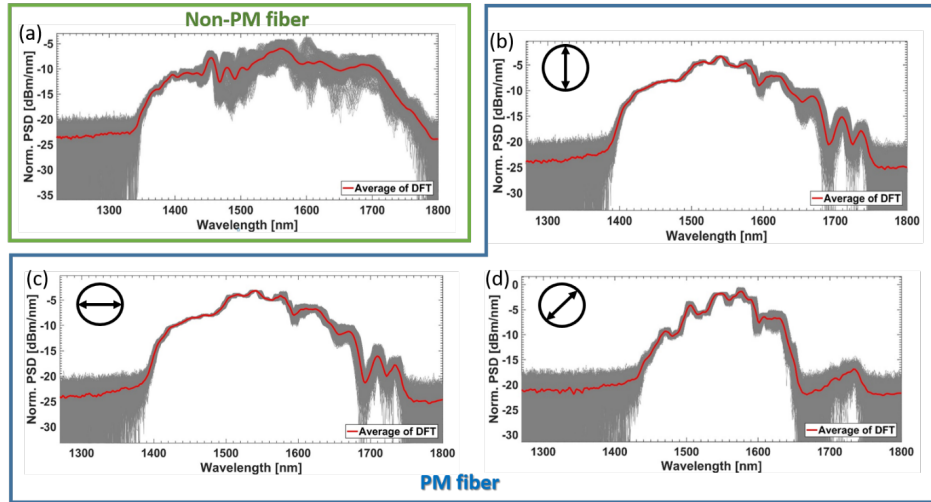


FIGURE 5.13: Shot-to-shot real-time fluctuations of 400 consecutive shots (grey) and the mean spectra (red) for (a) non-PM and (b) PM fibers.

Despite this, it is evident that when the fiber is pumped in one of the orthogonal axes, the SC has lower noise. The signal to noise ratio (SNR) is calculated as the mean of the 400 recorded pulses divided by the standard deviation of them for the two fibers. The SNR of the PM (blue) and non-PM fiber (red) plotted in Fig. 5.14. shows a significant enhancement of SNR for PM fiber as compared to the non-PM fiber, especially in the wavelength range of 1400 to 1670 nm. The difference in SNR is observed despite similar experimental conditions such same pump parameters, similar dispersion profile, and similar fiber length. This shows that, by just going from non-PM to PM type of fibers, we can reduce shot-to-shot noise in the SC spectra. The plots for real-time fluctuations (Fig. 5.13) and SNR plot (Fig. 5. 14) are limited at the wings due to the constraints of the DFT measurements. At long wavelength edge, it is accurate upto 1670 nm as the sensitivity of the photodiode reduces beyond 1670 nm of wavelength. Poor SNR at this wavelength for ANDi PM fiber can also be attributed to the loss of birefringence of the ANDi PM fiber. At the short wavelength edge, the shot-to-shot fluctuations as well as the SNR show poor agreement due to the effect of higher order dispersion of the DCF stretcher used. However, this limitation does not affect the conclusion of the role of PMI in noise of SC spectrum and the conclusion drawn here. It is to be noted that at the wavelength of 1800 nm, measured group birefringence attains a value of zero (as depicted earlier in Fig.5.6.). Thus I demonstrate and measure the noise properties of coherent supercontinuum and its dependence on the fiber

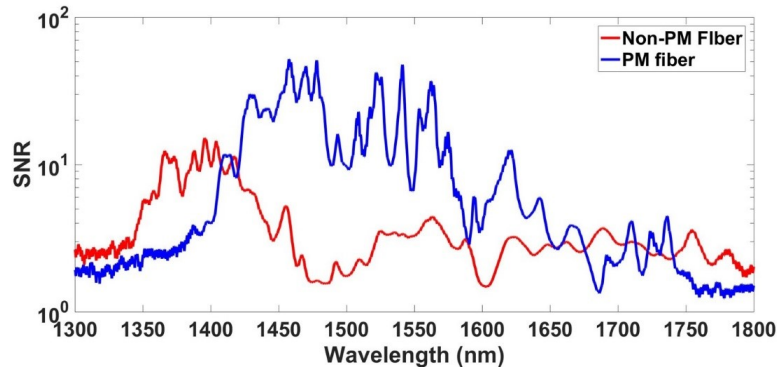


FIGURE 5.14: SNR of PM fiber (blue) is evidently better than that of the non-PM fiber (red) under similar pumping conditions, dispersion regime, and fiber lengths

geometries for ANDi fibers.

5.5 Conclusions

In this work, I demonstrate a case of supercontinuum generation in tellurite glass ANDi PCFs with real-time measurements of their noise properties. I first show a fiber-based pulse-preserving femtosecond supercontinuum generation in ANDi PCFs which extends the state of the art into near-IR wavelengths. I then show a direct comparison of SC, generated in PM-ANDi and non-PM ANDi fibers made from highly nonlinear tellurite glass, using real-time dispersive Fourier transformation (DFT) technique. The fibers used in the experiment were in-house fabricated, hexagonal lattice photonic crystal fibers (PCFs) with seven rings of air-holes surrounding the core. The dimensions of the lattice were engineered to obtain all-normal dispersion profiles. A fiber with birefringence introduced by two increased-diameter holes inside the lattice adjacent to the core was fabricated as the PM PCF variant. While most tellurite based-fibers reported have a suspended-core geometry, here I show first demonstrations of octave-spanning supercontinuum in a two lattice pitch hexagonal PCF structure as well as the first demonstration of supercontinuum in the birefringent variant of the PCF.

The DFT-based measurement and analysis of SC generation in the two PCFs show that SC generation in PM fiber has higher stability and lower noise as compared to the its non-PM variant. This is an indirect evidence that PMI contributes to coherence degradation and consequently, increase in noise, in SC generation. These results are promising and motivate further study such

as using the interferometry variant of DFT in order to assess the coherence property of SC generated in both variants of PCFs. From the application point of view, the PM ANDi fiber-based octave spanning supercontinuum outlays the advancements of low-noise broadband light sources required in amplifier systems [115], optical coherence tomography, investigating surface plasmon polaritons [159]. Thus in this chapter, I verify **thesis 3** of this dissertation that *shaping of nonlinearity in specialty optical fibers developed using highly nonlinear tellurite glasses enables achieving practical fibers enabling octave-spanning coherent supercontinuum generation without the noise-susceptible soliton dynamics and under conditions of determined state of polarization favorable to preserve low noise dynamics.*

Chapter 6

Quasi-periodic temporal pulse reshaping in femtosecond pumped graded-index multimode fiber

In this chapter, I demonstrate spatiotemporal-spectral analysis of nonlinear dynamics in a graded-index (GRIN) fiber pumped with femtosecond, high-peak power pulses. An in-house developed GRIN fiber made of highly nonlinear tellurite glass is pumped with 300 fs pulses centered at a wavelength of 1030 nm. I performed a detailed experimental characterization of the output pulse in spatial, temporal, and spectral domains. The temporal properties of the spectrally broadened, input femtosecond pulses were measured and retrieved using a second harmonic generation-based cross-correlation frequency-resolved optical gating (SHG-XFROG) setup. Spectral broadening accompanied by quasi-periodic temporal pulse reshaping was obtained owing to high peak power pumping and high nonlinearity of the fiber. This phenomenon of temporal compression and expansion of the pulses observed experimentally in the tellurite-based GRIN MMF is attributed to a complex, three-dimensional interplay between high dispersion and nonlinearity of the fiber. An interesting aspect of this results is that while most studies done in this regime show self-cleaning, I show that space-time coupling takes place such that, in the presence of temporal reshaping, spatial beam-cleaning is not observed.

6.1 GRIN fiber design, development, and properties

The designing of GRIN fiber is carried out by an in-house developed specialized method for the development of graded-index or other complex profiles of the refractive index among others for micro-lenses, optical fibers, and vortices [160–162]. The algorithm developed for designing of such optical elements consists of a threefold process to obtain the arrangement of the elements (rods) for the realization of the best fitted, graded-index profiles. In the first step, a parabolic function is established, for a specific number of rods in the diameter and a specified boundary shape. Often for fibers and lenses, the boundary shape is hexagonal or circular and not the regular rectangle. To obtain a specific boundary shape, a pixel dimension is identified and specified. The function image obtained is then dithered and pixels are clumped to form elements of the structure. This dithered image is now converted to binary image by error propagation technique. The design obtained is optimised using the genetic algorithm where a symmetric section of the fiber is selected along with the centre and a crossover of generation is performed. This crossover run helps in optimization and in obtaining the solution closest to the analytical solution of a parabolic profile (as in our case). Final step of optimization of the design occurs where every element is tested for a change in its immediate surrounding to obtain a better fit to the analytical solution. Using this algorithm of stochastic simulated annealing, a binary arrangement of two types of glasses with large number of elements is obtained so as to form the closest fit to an ideal parabolic index profile. This method of stimulated annealing was first demonstrated for the development of graded-index microlenses [163]. Over the years, this method has been optimized for nanostructurization of glasses in fiber fabrication based on the effective medium theory [164] which provides a transverse profile of a fiber designed for subwavelength size of glass rods [165, 166]. The implementation of this method described above to design the tellurite GRIN fiber used in this work was carried out by dr. hab. Rafal Kasztelan. Tellurite GRIN fiber was designed using this algorithm as shown in Fig. 6.1. (a) for two types of tellurite glasses with different refractive indices.

During the fabrication of the fiber preform, I stacked it using 10267 rods of tellurite glasses arranged according to the above design for a parabolic refractive index profile. Rods of two types of tellurite glasses- TWPNI/6 and TWZN-22 were drawn, cleaned, ionized, and vacuumed. I accomplished stacking the

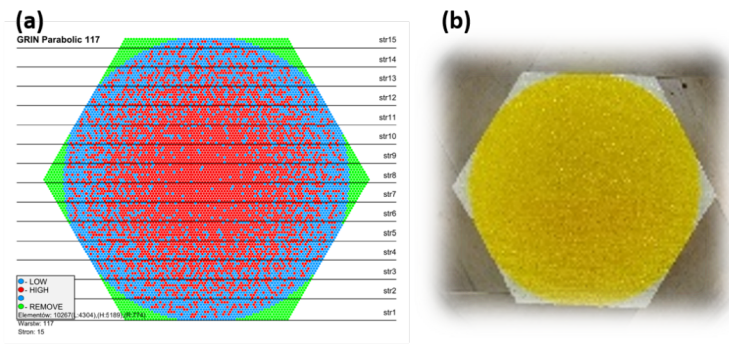


FIGURE 6.1: (a) Designed arrangement of rods of the two tellurite glasses of high and low refractive indices obtained through the algorithm (b) Stacked preform of tellurite GRIN fiber

cleaned and ionized rods from the two tellurite glasses in the mosaic designed arrangement in a clean chamber to give the preform as shown in Fig. 6.1. (b). The arranged preform was then jacketed in a tube of glass TWZN-22 and drawn into a fiber at the fiber drawing tower as described in chapter 3, section 3.5. The GRIN fiber hence developed and studied for further investigations below has a core size of $60.4 \mu\text{m}$ and SEM of the fiber is shown in Fig. 6.2 (a). Importantly, the starting diameter of each of the individual rod of about 0.5 mm , was thinned down during drawing to below 200 nm , satisfying the $\lambda/5$ sub-wavelength dimension condition. Thus, the guided modes experience a certain “effective”, continuous refractive index profile, instead of the refractive indices of the individual rods of such nanostructured core fibers [163, 166].

The chromatic dispersion of the fiber was measured using a balanced Mach-Zehnder interferometer pumped with a compact supercontinuum source (Leukos) with a spectral coverage in the near-infrared range as described in chapter 2, section 2.2.2. As can be seen in Fig. 6.2. (b), the measured chromatic dispersion remains normal at all wavelengths covered within the measurements. Modes in a parabolic GRIN fiber tend to cluster in certain degenerate groups propagating with identical propagation constants [76]. Such an equidistant propagation constants within a mode cluster leads to minimal modal dispersion [76, 167]. Thus, the dispersion of the higher order modes in the mode cluster of the fundamental modes, is very close to that of the fundamental mode. Measurement of dispersion of such a fiber, in experimental terms, gives an effective dispersion profile contributes by the fundamental mode and the higher-order propagating modes as shown in Fig. 6.2 (b). The profile also mimics the dispersion properties of the material (i.e. tellurite glass) [132, 134], demonstrating

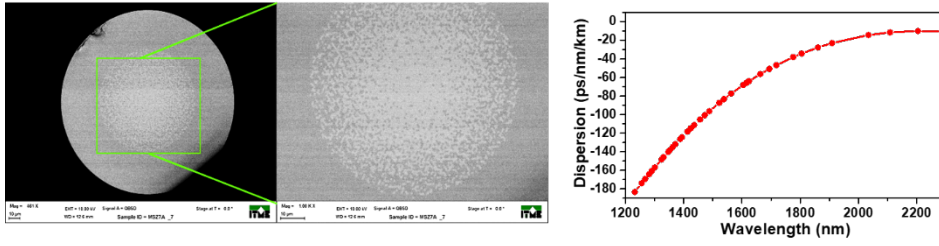


FIGURE 6.2: (a) Scanning electron microscope (SEM) image of the in-house developed GRIN tellurite fiber. (b) Measured dispersion profile of fabricated tellurite GRIN fiber

that the chromatic dispersion is prominently due to the material, with minor effect from geometry/structure of the fiber.

6.2 Experimental set-up

Fig. 6.3. shows a schematic depiction of the experimental setup used in this work to study nonlinear dynamics in the developed GRIN fiber under femtosecond pulses pumping. I pumped the GRIN fiber with a 1030 nm laser delivering 300 fs pulses at a repetition rate of 100 kHz (Jasper 20, Fluence). A half-wave plate (HWP) was used to control the polarization of the input pulse signal at the XFROG. 10 % of this beam was reflected to a delay line of the XFROG to use as a gate pulse against the output pulse from the fiber. The rest of the pulse energy was focused into the tellurite GRIN fiber (sample length 23.5 cm) using a plano-convex lens with a focal length of $f = 50$ mm. The average input power was measured after the HWP, just before the input lens. Using an input lens of focal length of 50 mm, the beam was focused into the fiber with a waist diameter at focus of $d = 19.7$ μm . For a fiber core diameter of 60.4 μm , I optimize the fiber input coupling conditions using a tight focus with the help of a three-axis translation stage on which the fiber is mounted so as to obtain improved excitation of lower order modes at the pump wavelength. The V-number of the fiber was calculated to be 93.89 which corresponds to a numerical aperture of 0.509. Thus the total number of modes that can be excited in a quadratic index profile with significant intermodal coupling was estimated at 2167 modes. The output signal from the GRIN fiber was analyzed for its spectral, spatial, and temporal properties. The power at the output of the fiber was measured to be 20 % of that at the input. This 20 % efficiency takes into account the loss of the fiber and the coupling efficiency. In order to

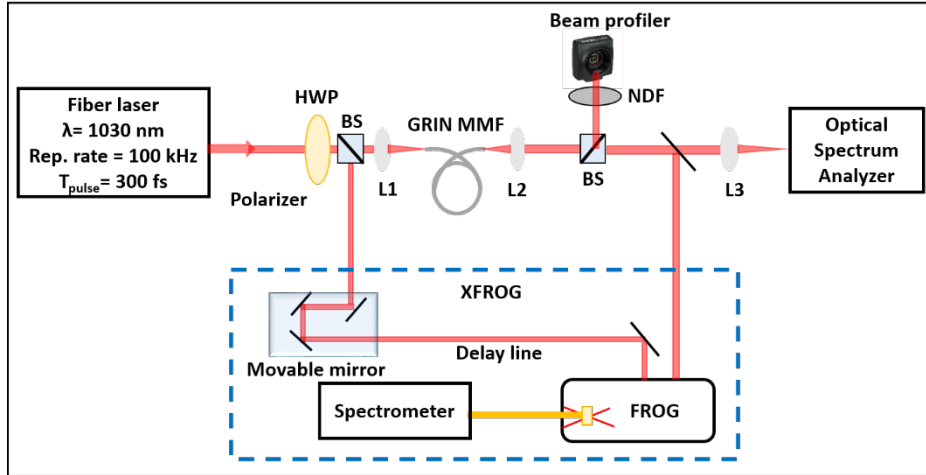


FIGURE 6.3: Experimental set-up to study pulse characteristics on propagating in a tellurite GRIN MMF with femtosecond pumping. L1,L2,L3: Lenses; BS: beam splitter; NDF: Neutral density filter

study the spatial properties of the output signal from the GRIN fiber, the signal was filtered using a neutral density filter (NDF) and captured on a CMOS beam profiler (M2MS-BC207VIS, Thorlabs) in the near-field. The spectral properties of the output signal were recorded using an optical spectrum analyzer (OSA, HP). The temporal properties of the output signal were studied using an in-house built cross-correlation frequency-resolved optical gating (XFROG) system where the stretched signal from the GRIN fiber was measured against the known gate pulse with the delay line.. These two signals were focused on a -barium borate crystal ($\beta - BBO$) crystal with a thickness of 0.05 mm for sum frequency generation, which was then recorded using a high resolution compact spectrometer (Ocean HDX, 200-1100 nm sensitivity, 0.7 nm resolution). The output signal was studied as a function of average input pump power.

6.3 Spatio-temporal-spectral (STS) analysis of the output pulse

I measured the spectra of the output signal from the GRIN fiber by coupling it into the OSA by the means of a standard multimode fiber. The OSA has a resolution of 2 nm. The sensitivity and wavelength range were kept constant throughout the measurements. The critical power of self-focusing is given by $P_{crit} = 1.86 \frac{\lambda^2}{4\pi n_0 n_2}$ [74]. For the pump wavelength of 1030 nm, the calculated P_{crit} is 1.8 MW. The highest average input power of 32 mW in the experiments

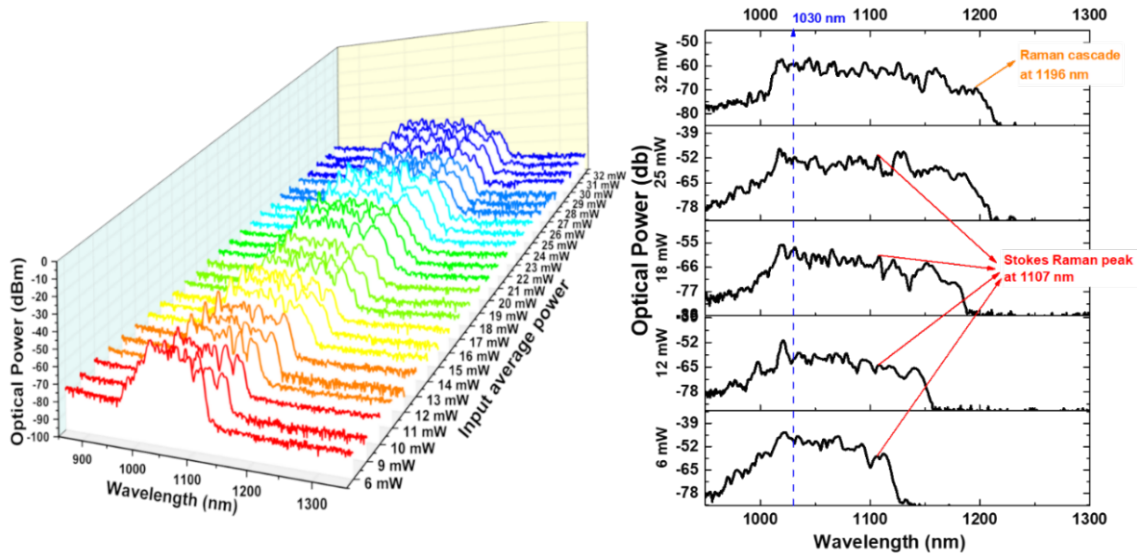


FIGURE 6.4: (a) Spectral broadening as a function of input power in GRIN MMF. (b) Spectral broadening for selected input average powers highlighting Raman peaks

corresponds to a peak power of 1.06 MW. Thus it can be safely said that the measurements were carried out well below the critical power of self-focusing. Fig. 6.4 (a) shows the measured spectral evolution of the pulses at the fiber output as a function of average input power. With an increase in the average input power, an asymmetric spectral broadening is observed as shown in Fig. 6.4.(a). At the lowest detectable average pump power of 6 mW, the spectral broadening obtained ranged from 970 to 1116 nm. As more power is pumped into the fiber, the spectral broadening in the fiber becomes asymmetric, with more spectral components at redshifted wavelengths from the pump. With further increase in average input power, the pulses' spectrum broadens to 1210 nm as seen for the highest measured average input power of 32 mW. As the input power is increased from 29 mW to 32 mW, no further significant spectral broadening is observed. To provide an insight into the spectral broadening mechanism, Fig. 6.4. (b). shows slices of measured spectral evolution for several average input powers. When an input pulse of 300 fs is injected in a highly nonlinear media such as our tellurite glass, self-phase modulation (SPM) generates new frequency components which are red-shifted at the leading edge and blue-shifted at the trailing edge of the pulse [1]. Since I operate in the normal dispersion regime, the red-shifted frequency components travel faster than the blue-shifted frequency components, thus seeing a rapid spectral broadening (due to SPM) as well as pulse broadening (due to GVD) even

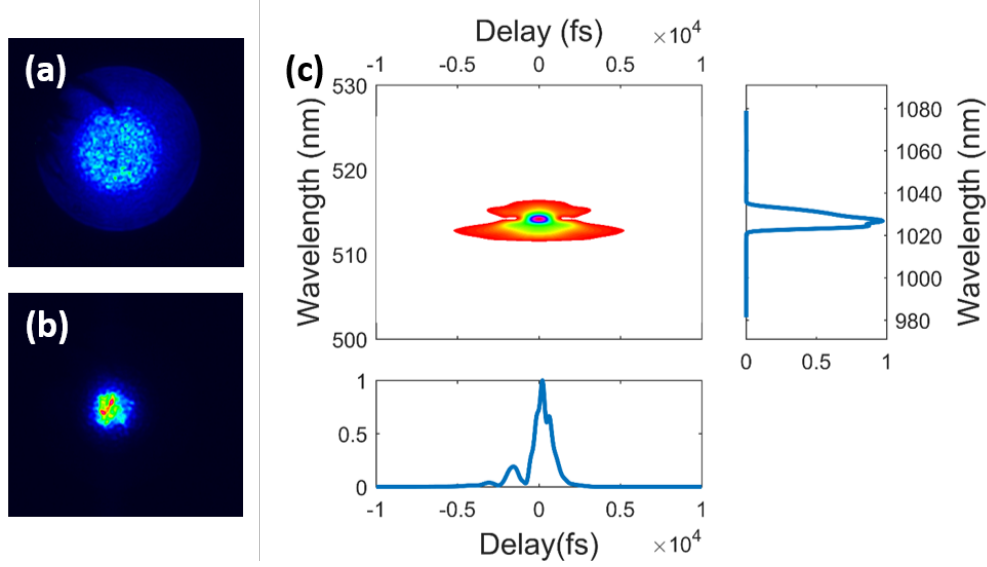


FIGURE 6.5: (a) Near-field image of an excited core b) Near-field image of spatially optimized input pump c) a spectrogram retrieved from the measured FROG signal for the input pulse from laser along with spectral and temporal subplots

at low input average powers such as 6 mW in this case. The initial broadening mechanism is also accompanied by an appearance of Raman Stokes peak at 1107 nm. It has been previously reported that the tellurite glass TWPNI/6 used primarily in the fiber core has a Raman contribution of $f_R=0.2$ and gives the first order Raman gain peak at 20.4 THz [134]. For pump at central wavelength of 1030 nm, the first order Raman gain peak occurs at 1107 nm, which agrees with the experimentally observed peaks as shown in red for selected average input powers in Fig. 6.4.(b). Further, for high average input power of 32 mW, second order Raman peak appears at 1196 nm, as shown in orange in Fig. 6.4 (b). Before going into characterization of the spatial structure of the output from the tellurite GRIN fiber used in this work, it is important to note that the physical conditions of this experiment are distinct from those of previous femtosecond pulse-driven multimode propagation in GRIN silica fibers [168], in a way that the number of modes excited in the tellurite GRIN fiber is significantly larger despite the fact, that the nonlinear response of tellurite glass is much stronger than silica. I characterized the output beam from the GRIN fiber using a CMOS beam profiler in the near field. The output beam was magnified and focused on a beam profiler using an output coupling lens that provided a magnification factor of 8 in the plane of the beam profiler. An image of such an input coupling was recorded on the beam profiler for lowest detectable average input power of 6 mW as shown in Fig. 6.5. (a) and (b).

Fig. 6.5. (a) shows the excitation of the whole core while Fig. 6.5. (b) shows the optimized input excitation for more modal content in the center of the core which showed a speckled pattern with a FWHM of $34\ \mu\text{m}$ for a input average power of 6 mW. In this measurement, I did not see the occurrence of Kerr self-cleaning [68] however I observed that after the initial growth in the diameter to up to a spatial FWHM of $52\ \mu\text{m}$ at 10 mW of average pump power incident on the fiber input facet, the beam propagates without any significant change in the diameter in the range of 10 mW to 32 mW input average powers.

In the next step, I analyzed the output pulses from the tellurite GRIN fiber in the time domain. First, the group delay profile of the input pulse from the femtosecond laser (without the GRIN fiber), was measured using frequency resolved optical gating and the result is shown in Fig. 6.5. (c). The retrieved pulse spectrum and time profile are also shown. The spectral FWHM of the pulse of 10 nm and the pulse duration of 300 fs obtained from the FROG retrieval matched the laser manufacturer specifications. In the subplot in Fig 6.5. (c) small pre-pulses extending over about 3 ps from the pulse center are also observable. When such a pulse is injected into the fiber with strong positive (normal) dispersion, it acquires further positive chirp at the leading edge. This positive chirp is visible in the spectrograms shown below in Fig. 6.7. These results were obtained with XFROG measurements of the spectrally broadened output pulses from the fiber. The pulse traces were retrieved from the measured XFROG data using the generalized projections algorithm [79, 85]. Background and noise corrections were carried out for the raw data before retrieval. The spectro-temporal evolution of the pulse was measured by XFROG for a range on average input pump powers starting from 6 mW to 32 mW. Selected spectrograms and their corresponding spectral and temporal plots are shown in Fig. 6.6. In the spectral domain of the XFROG retrieved pulses, the pulses confirm SPM-dominated broadening. The spectrum of the retrieved pulses agreed well with the spectrum measured with the OSA indicating that the entire SC bandwidth was correctly acquired in the XFROG measurements. Fig.6.6. demonstrates examples where an overlap between the OSA spectrum (orange) and the retrieved spectrum (blue) is shown to agree for spectrally broadened pulses for average input powers of 9 mW (low power; Fig.6.6. (a)), 19 mW (medium power; Fig.6.6. (b)) and 28 mW (high power; Fig.6.6.(c)). The FROG error G , defined as the RMS average across the intensity of the trace [169] is computed by the FROG software during the evaluation of projections and is listed in Fig.6.6. (d) for each average input pump power

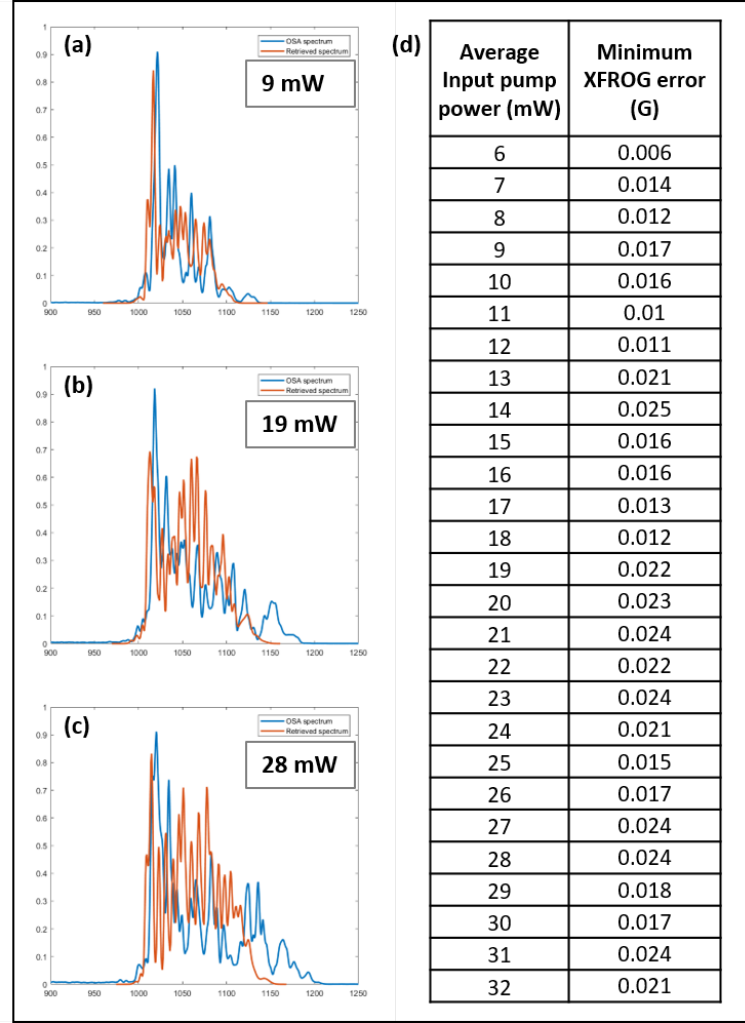


FIGURE 6.6: Spectral overlap of measured and retrieved XFROG pulse for input powers of (a) 9 mW, (b) 19 mW and (c) 28 mW. (d) Minimum FROG error of retrieved pulses for average input pump powers.

retrieved. The values of G for all powers listed are within the threshold of potential errors for the measured electric field, which additionally verifies that the XFROG traces were retrieved accurately [81]. The linear positive chirp (judging by the tilt in the spectrogram) and the corresponding temporal plot of the pulse (e.g. as seen in Fig. 6.7) is evidently due to the strong and sloped normal dispersion of the fiber. The analysis of the temporal profiles of the pulse as a function of input pump power brings forth an interesting phenomenon of pulse reshaping. I observe that after an initial expansion of the pulse in the time domain, up to 9.79 ps for the input average power of 10 mW, the pulse compresses down to 6.43 ps when the input average power is increased to 11 mW. Further, the trend observed on increasing the input pump power shows

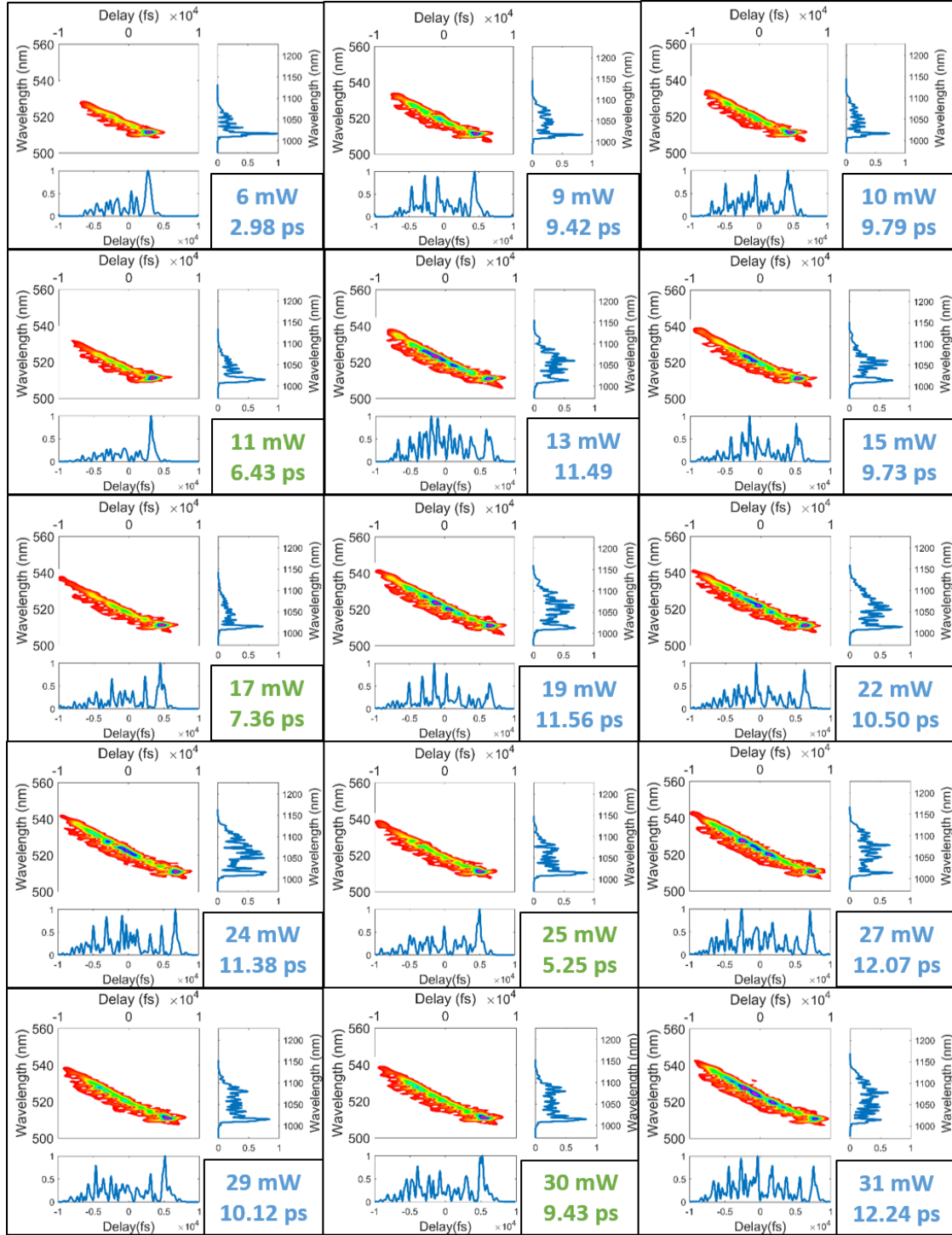


FIGURE 6.7: Spectrograms of output pulse from the GRIN fiber showing the evolution of the pulse in the spectral and time domains with increase in average incident pump power.

a quasi-periodic compression-elongation of the pulse in the time domain. Distinct compressed pulses were obtained for input average powers of 11 mW, 17 mW, 25 mW and 30 mW with pulse compressed to 6.43 ps, 7.36 ps, 5.25 ps and 9.43 ps respectively (as shown in Fig.6.7. green legends). Pulse elongation when input pump power is increased can be attributed to the GVD of the fiber imposing the linear chirp on the pulse.

The quasi-periodic pulse reshaping of pulse as a function of input average power, as deduced from the retrieved XFROG data, is depicted in Fig. 6.8 (a). To understand the underlying mechanism of the observed pulse reshaping, I plotted the spectral phase of the pulse obtained from the retrieved XFROG measurements. The phase of the spectrally broadened pulse obtained at input average power of 10 mW was taken as a reference, as shown in Fig. 6.8. (b) and the relative spectral phase was calculated for consequent data points involving increasing input power. I analyzed the relative spectral phase at different stages of pulse re-shaping. Fig. 6.8. (c) shows the four stages of pulse reshaping i.e. the pulse compression slope (range of input power for which the pulse duration measured at the fiber output decreases), compressed pulse (range of input powers for which the output pulse duration is in the proximity of a local minimum), pulse elongation slope and the elongated pulse along with their relative spectral phase profile. The pulse initially experiences a strong positive chirp causing it to elongate in time to a duration (9.79 ps at 10 mW) much larger than the original pulse (300 fs, the incident input pulse duration). The steep leading and trailing edges of this elongated pulse generate additional frequencies through SPM. Rapidly varying intensity at the edges of the pulse leads to a rapidly varying phase shift, leading to a frequency shift (corresponding to pulse broadening in the spectral domain). As the input power is increased further, the newly generated frequency components also experience with the dispersion of the fiber. When dispersion dominates SPM, a nonlinear switching is seen to occur where the pulse compresses purely due to the GVD of the fiber (for example, at input average power of 11 mW, 15 mW and 29 mW). At the pulse compression slope, shown in Fig. 6.8. (c), the spectral phase begins to flatten, followed by an almost flat relative spectral phase for a compressed pulse. A flat relative spectral phase indicates that the all the frequency components of the pulse travel at the same time with constant phase. For further pulse-elongation slope and corresponding elongation of pulse shows a strong linear chirp due to dispersion experienced by SPM-generated frequency components as shown in Fig. 6.8. Thus the spectral phase for elongating and

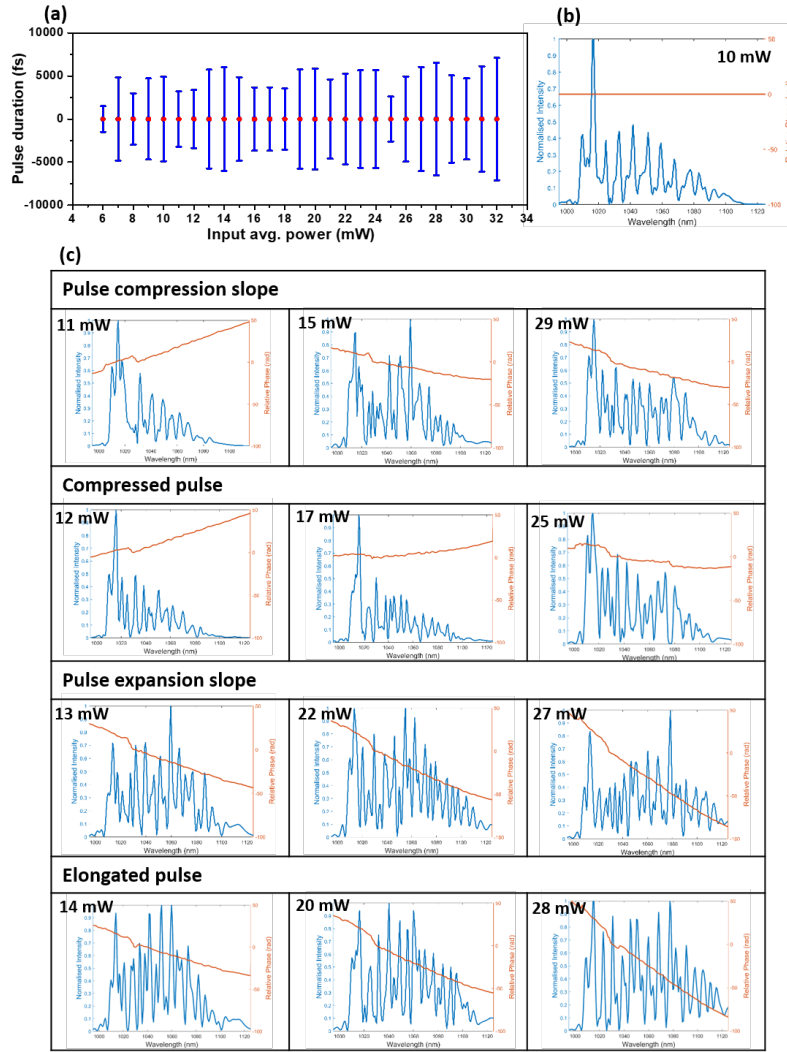


FIGURE 6.8: (a) Quasi-periodic temporal pulse reshaping as a function of input average powers. (b) Spectral phase for input average power 10 mW taken as reference. (c) Spectral phase analysis at different stage of temporal pulse reshaping

elongated pulses show a steep relative spectral phase corresponding to faster red-shifted edge and slower blue-shifted edge of the pulse.

This mechanism is analogous to pulse compressor techniques [170–172] where a nonlinearly broadened pulse can be compressed in time using dispersive elements such as gratings or prisms. A pulse compressor is essentially tasked to apply a spectral phase shift on the pulse so that the resultant spectral phase is constant. I postulate a tentative hypothesis, that here the role of introducing opposite chirp is realized by the spatial variable of the system. Specifically, as the incident input power is increased, the excited mode structure is changed in such a way, that modes with negative GVD (anomalous dispersion) dominate,

at the same time leading to the anomalous dispersion dominating over the combined GVD and SPM in shaping of the pulse in the time domain.

To summarize, here I observed a quasi-periodic pulse reshaping observed in a non-silica GRIN MMF by femtosecond pumping in normal dispersion regime. This pulse reshaping arise from the interplay between Kerr-based SPM and strong positive dispersion of the fiber. The results suggest that the presence of strong temporal dynamics prevent beam-cleaning phenomenon to occur due to space-time coupling. This opens up new areas to explore how guided modes interact together to couple in space to give beam-cleaning and in time to give pulse reshaping. Thus I show here that multimode nonlinear propagation can be exploited in simple means of shaping of femtosecond laser pulses in time domain with their basic input parameters under specific designs of fibers.

6.4 Supercontinuum generation in a tellurite glass GRIN fiber

The specialty tellurite GRIN fiber developed to demonstrate the above non-linear phenomenon, have additionally shown distinguished results for high power SC generation in the near- and mid-IR wavelengths. A collaborative study was carried out by Ekaterina Krutova from Photonics Laboratory, Tampere University, Finland, to obtain broad multimode SC in tellurite glass GRIN fiber under a set of completely different pumping conditions from the ones used above to demonstrate pulse reshaping [173]. Below I summarize the experimental results obtained by Ekaterina Krutova in the scope of our collaboration, using the tellurite GRIN fiber fabricated and characterized by me to demonstrate possible avenues and nonlinear optical applications for such GRIN MMFs in the near- and mid-IR wavelength range. The goal of this part of my research, carried out in collaboration with the partner from Tampere University work was to generate high energy density SC, for which an obvious choice was that of a MMF. Using a GRIN MMF, as in this work, gives an additional advantage of providing a high beam quality. Further, a soft glass fiber such as tellurite glass with a transmission window in the near and mid-IR as well as high nonlinearity required for SC generation is suitable for high power applications such as remote sensing in the mid-IR wavelength range. They used two different samples of the tellurite GRIN fiber from the fabricated series MS27A. For normal dispersion pumping, they used sample MS27A7, which has a core size of 89.5 μm and for anomalous dispersion pumping they

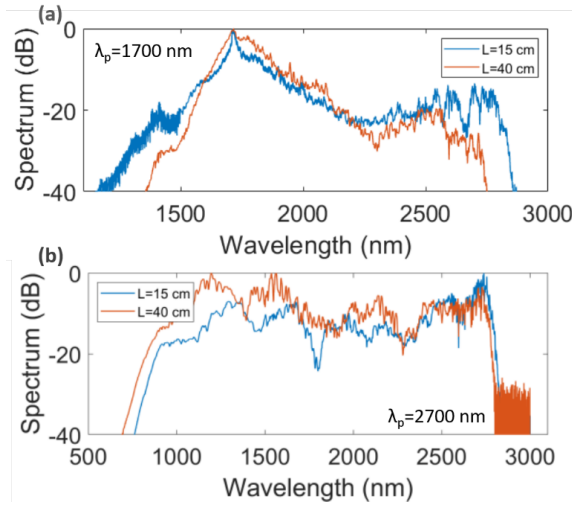


FIGURE 6.9: (Experimentally measured SC in tellurite GRIN fiber for (a) normal dispersion pumping (b) anomalous dispersion pumping [23])

used sample MS27A6 with a core size of $93.1 \mu\text{m}$. They pumped these samples using 350 fs pulses from an optical parametric amplifier (OPA) with a central wavelength tunability from 1400 nm to 4000 nm. The concept that the position of pump wavelength with respect to ZDW impact the characteristic of SC generation is exploited here to obtain broad SC by tuning the input wavelength using the OPA. In the normal dispersion regime pumping, the input pulse repetition rate was set to 66 kHz which corresponded to a peak power of about 2.2 MW. The SC dynamics were studied as a function of input wavelengths 1700 nm, 1800 nm and 1900 nm. The input pulse was coupled into the fiber with a coupling efficiency of 50 % for each pumping wavelength. The output signal obtained was a spectrally broadened pulse stemming from SPM and geometric parametric instability (GPI) in wavelengths shorter than the pump wavelength as shown in Fig.6.9.(a). The broadening in the longer wavelength is caused by soliton dynamics as the pulse broadens into the anomalous dispersion regime. As a function of fiber length, it was observed that broadening bandwidth reduced for longer fiber lengths of the same sample, which can be attributed to the attenuation experienced by the pulse as it propagates through longer fiber. Fiber sample MS27A6 of core size $93.1 \mu\text{m}$ was used for anomalous dispersion pumping at 2100 nm, 2300 nm, 2500 nm, and 2700 nm. The broadest SC of bandwidth 790 nm to 2900 nm was observed when pumped at 2700 nm as shown in Fig.6.9.(b). The coupling efficiency in anomalous dispersion regime pumping was 25 %, yet a soliton seeded dynamic lead to a

broad SC spectrum. The spectral broadening extended well into the normal dispersion regime with generated dispersive waves and SRS broadening the spectrum further. In a further study into beam cleaning dynamics, Krutova et al. show evidence of beam-cleaning effect taking place at high input powers [173].

6.5 Conclusion and future prospects

In section 6.3 of this chapter I demonstrated new dynamics leading to quasi-periodic temporal reshaping of a femtosecond pumped pulse observed for a range of average power of the incident input pulses, which cannot be assigned to mode self-cleaning effects as in the case of picosecond-scale or longer pulse propagation. The observed evolution of pulse spectral phase is consistent with alternating influence of negative GVD and combined SPM and positive GVD. With a monotonic increase of the input power, the alternation of these influences are due redistribution of energies in the excited modes which experience different chromatic dispersion. Thus the GRIN fiber acts similar to that of a classic grating pair compressor such that the grating separation is analogous to the increase in input power level as both lead to a change in the amount of chirp introduced. This in turn controls the excitation of mode structure to indirectly enables switching of phenomena dominating in the time domain shaping of the propagating pulse. In section 6.4 I summarized the results obtained by Ekaterina Krutova with the tellurite glass GRIN fiber developed by me in scope of our collaboration. These results highlight a spectrally broad SC generation spanning from 790 nm to 2900 nm in a GRIN MMF along with the observation of spatial beam-cleaning dynamics as a function of incident power [173].

The results presented here thus prove **thesis 3** of this dissertation that *multimode nonlinear propagation can be exploited for the shaping of femtosecond laser pulses in terms of their temporal, spectral as well as spatial properties with specific input parameters under graded-index designs of fibers*. The fabricated tellurite GRIN MMF shows a high degree of manipulation capabilities in terms of spectral, spatial as well as temporal propagation, making it a great potential for high power applications which require broadband light sources or spatially stable beam or all-fiber pulse compressors, under appropriate pumping conditions.

Chapter 7

Conclusions and future prospects

This dissertation is focused on nonlinearity shaping of tellurite glass micro- and nano-structured optical fibers to bring forth advancement in understanding and performance of fiber-guided nonlinear optical phenomenon such as soliton self-frequency shift, low-noise supercontinuum generation and temporal shaping of femtosecond pulses. Using numerical simulation tools, I designed and then developed in-house four specialty micro- and nano-structured fibers made from highly nonlinear tellurite glass and demonstrated targeted nonlinear pulse propagation dynamics of femtosecond laser pulses. I also carried out simulations of nonlinear propagation to support the understanding of the pulse propagation dynamics involved. By the means of these fibers developed, I demonstrated advancements of light sources by isolation of frequency-shifted soliton for a tunable laser source in the short-wave infrared wavelength range, by a low-noise supercontinuum generation in a soliton-noise suppressed regime with predetermined state of polarization, and by a multimode generation of supercontinuum in the near-infrared wavelengths along with quasi-periodic temporal reshaping of input femtosecond pulses.

7.1 Verification of the dissertation theses

In chapters 4, 5, and 6, I have demonstrated a thorough verification of the dissertation theses accomplished as per the objectives mentioned at the beginning of the dissertation. The theses achieved under the scope of this dissertation and their verification is summarized below:

The **first thesis** of this dissertation successfully achieves *shaping of nonlinearity in specialty optical fibers developed using highly nonlinear tellurite glasses to obtain significantly improved the tuning bandwidth of Raman solitons, covering the entire*

SWIR wavelength range, without applying complex and high peak power laser systems, compared to existing state-of-the-art fibers exploiting the silica glass technology.

This thesis is verified in **Chapter 4** of this dissertation. I used tellurite glass which has transmission properties throughout the SWIR wavelengths range, to design a suspended core fiber structure suitable for isolation of soliton self-frequency shift phenomenon. With numerical simulations I designed the fiber for linear properties such as flat anomalous chromatic dispersion, mode confinement area by optimizing the structural properties of the fiber such as core size, strut widths, and number and sizes of air-holes. The fabricated fiber was experimentally tested to obtain isolated soliton propagation. On pumping a short piece of fiber of 5.6 cm with 90 fs pulses at a repetition rate of 100 MHz, centered at 1560 nm of wavelength, I observed a wide soliton detuning of 68.5 THz as a function of the input pump average power. The soliton self-frequency shift of 68.5 THz corresponds to the wavelength detuning from 1560 nm to 2400 nm, i.e., covering the entire SWIR wavelength range. These results agree with the numerical nonlinear propagation of pulse in the designed fiber carried out using GNLSE. Further, to verify the nonlinear propagation dynamics required for an efficient and broadband detuning of soliton, the fiber was pumped at 1900 nm, which brought about a wide separation of pump wavelength from the ZDW of 1256 nm. The range of soliton detuning in this case was limited up to 2250 nm in the longer wavelength edge, thus confirming that pumping at 1560 nm provides an ideal separation from the ZDW for efficient soliton fission and self-frequency shift. Conveniently, 1560 nm is also a popular telecommunication wavelength at which many robust femtosecond lasers with moderate pump power are available. Further, the use of short piece of fiber to attain such wide soliton detuning prevents the pulse from attaining a strong chirp. The wide soliton detuning throughout the SWIR wavelength range, the compatibility of fiber with commercially available femtosecond lasers, and the ease of integrating a short piece of fiber make these results outperform existing silica-fiber based systems and are highly suitable for integration in all-fiberized laser and amplifier systems. These results were successfully published in Journal of Optical Society of America B [52] and presented by me at conference CLEO/Europe 2021.

The **second thesis** of this dissertation verifies that *shaping of nonlinearity in specialty optical fibers developed using highly nonlinear tellurite glasses enables achieving practical fibers enabling octave-spanning coherent supercontinuum generation without the noise-susceptible soliton dynamics and under conditions of determined state of*

polarization favorable to preserve low noise dynamics.

I demonstrated this thesis in **Chapter 5** by developing hexagonal lattice photonic crystal fibers made of highly nonlinear tellurite glass. These fibers were engineered for a flat all-normal chromatic dispersion characteristics of an effectively single mode fiber structure in the wavelength range of 1500-2400 nm using a seven rings air-hole lattice around the core. Octave-spanning coherent supercontinuum of spectral width 1100-2600 nm wavelengths was obtained by pumping the microstructured fiber with 90 fs pulses centered at 1560 nm wavelength with a peak power below 40 kW. Such broad coherent supercontinuum generation is attained due to the high nonlinearity of the glass and engineered, flattened chromatic dispersion characteristic of the fiber, enabling self-phase modulation and optical-wave breaking to occur at modest peak powers of femtosecond pulses from commercially available and feasible mode-locked fiber lasers. These experimental results also agreed with the predictions from numerically designed propagation dynamics using GNLSE.

A polarization maintaining (PM) variant of the above fiber was designed and developed by introducing structural birefringence in the fiber. This fiber was compared with the non-PM variant of the fiber for the noise properties of the supercontinuum generated. While it is known that supercontinuum generated by all-normal dispersion pumping have superior noise properties than when pumped in the anomalous dispersion regime, here I demonstrated a direct comparison of noise properties of supercontinuum generated in ANDi fibers, differing only in their polarization maintaining properties, identifying the role of polarization states under identical pumping and measurement conditions. I employed Dispersive Fourier transformation (DFT) technique and measured the shot-to-shot noise of supercontinuum spectra generated in the two fibers when injected with pulses of 225 fs centered at 1550 nm at 80 MHz repetition rate. Supercontinuum generation in PM fiber showed higher stability and lower noise as compared to the its non-PM variant. The signal-to-noise ratio (SNR) was calculated from the DFT measured spectra which showed that the SNR of the PM fiber is much enhanced as compared to the non-PM fiber. These results can be associated to the role of polarization modulation instability (PMI) in SC generation such that when PMI is suppressed in the PM variant of the fiber, the supercontinuum generated has lower noise as compared to its non-PM variant where PMI is still prevalent.

From a fundamental point of view, these results provide an indirect evidence of

the detrimental role played by PMI in the noise dynamics of ANDi supercontinuum generation. From an applications point of view, the low-noise supercontinuum generated in PM ANDi fiber is promising as low-noise broadband light sources for advancements in amplifier systems, optical coherence tomography, investigating surface plasmon polaritons. Overall, the broad pulse-preserving femtosecond ANDi supercontinuum generation demonstrated here are some of the earliest demonstrations of supercontinuum obtained with dispersion engineered non-suspended core, microstructured fiber, especially for tellurite glass fibers. These results are also first demonstration of octave-spanning supercontinuum in two-pitch lattice fibers engineered for flat dispersion as well as first demonstration of so in PM variant of hexagonal lattice fiber. The result on supercontinuum generation in the non-PM fiber has been published in the Journal of Optical Society of America B [147]. The results on measurement of noise in supercontinuum generation have been published in Optics Letter [174] and were presented by me at the conference CLEO 2020 [174].

The **third thesis** of this dissertation proves that *multimode nonlinear propagation can be exploited for the shaping of femtosecond laser pulses in terms of their temporal, spectral as well as spatial properties with specific input parameters under graded-index designs of fibers.*

This thesis is verified in **Chapter 6** of this dissertation where I reported the development and in-house fabrication of a parabolic graded-index multimode fiber made from two types of tellurite glasses. The fabricated fiber was verified for structural integration using scanning electron microscope and characterized for its chromatic dispersion properties. I then carried out experimental studies on this fiber by injecting 300 fs laser pulses centered at 1030 nm wavelength with a repetition rate of 100 kHz, to bring forth the spatial and temporal-spectral characterization of femtosecond pulse nonlinear dynamics. I observed a quasi-periodic temporal reshaping of the pulse as a function of incident average power of the pulses, which cannot be assigned to mode self-cleaning effects as in the case of picosecond-scale or longer pulse propagation. A detailed analysis of this temporal dynamics measured through cross-correlation frequency resolved optical gating revealed that the relative phase accumulation elucidate the observed pulse compression and elongation during the propagation along the fiber to be consistent with alternating influence of negative GVD and combined SPM and positive GVD. Alternation of these influences, which accompanied monotonic increase of input power, were assigned to reordering

of the structure of excited modes which experience different chromatic dispersion. The operation of the system was thus analogous to a classic grating pair compressor, in which the grating separation and thus the amount of chirp introduced to the pulse was replaced by the input power level, which controlled the excited mode structure and indirectly enabled switching of phenomena dominating in the time domain shaping of the propagating pulse.

This thesis presents one of the earliest non-silica graded-index fibers made and demonstrated for temporal pulse reshaping dynamics. I also summarized a collaborative study on the tellurite GRIN fiber developed under the scope of this dissertation which showed an octave-spanning supercontinuum generation from 790 nm to 2900 nm under multimode spatial beam-cleaning dynamics power observed in the fiber by Ekaterina Krutova from Tampere University. Thus this thesis opens avenues for high power light source applications which require targeted designing of pulses spectrally (as supercontinuum generation), spatially (as stable self-cleaned beam) and temporally (as all-fiber pulse compressors) when pumped with femtosecond pulses under specific pumping conditions. The results of supercontinuum generation in this work were presented at conferences CLEO/Europe 2021 and European Optical Society Annual Meeting (EOSAM) by Ekaterina Krutova from Tampere University [175].

7.2 Future Prospects

Shaping of nonlinearity of the fiber by shaping the linear properties of the fiber such as chromatic dispersion, birefringence, mode confinement is a strategy that will lead the evolution of fiber-based technologies. This work confirms the feasibility of using tellurite glass for the development of microstructured and nanostructured fibers in the shortwave-infrared (SWIR) range. Tellurite glass prominently holds advantage over commercially used silica glass in terms of its broader spectral transmission window in the near-infrared wavelengths and high nonlinearity of almost 10 times that of silica. This dissertation provides evidences that tellurite glass can be drawn into a wide range of designable, stable geometrical parameters of microstructured and nanostructured fibers, without recrystallization of glass. Since the in-house developed tellurite glasses show an absorption peak around 3 μm , future work in glass fabrication to reduce the OH group absorption could significantly improve the accessible spectral transmission range upto 5 μm of wavelength. Designing of tellurite glass-based fibers is successfully exploited in this dissertation to shift the ZDW

of the glass to attain desired chromatic dispersion characteristics with contribution from the waveguide dispersion. The four successful fibers made from the in-house developed tellurite glass, each tested successfully for a highly specialized nonlinear application with femtosecond pumping, proves that tellurite glass is an ideal candidate for all-fiber near and mid-IR light sources and amplifier systems.

Further, there is a current wave of translating the fiber-based light developments to feasible technologies. This dissertation opens a few paths to attain some of those technologies. The wide soliton self-frequency shift demonstrated in this dissertation under thesis 1, provides a precursor as seed of all-fiberized laser and amplifier systems since the wavelength range covered by isolated soliton is compatible with Tm:ZBLAN or Ho:SiO₂ ultrafast amplifiers. Thus, future prospects of this work would be to expand on all-fiberized systems from its current free-space coupling form. Supercontinuum generation, despite being explored for over two decades, still holds wide scope of understanding processes and knowledge that needs to be expanded. For applications such as OCT, confocal microscopy, improved coherent supercontinuum based light source is required. Thesis 2 of this dissertation highlighted how shot-to-shot noise in supercontinuum generation can be limited by using a predetermined state of polarization. However, to verify the dependence of coherence for these results still requires further interferometric studies. Thesis 3 of this dissertation opens a still little explored field of temporal dynamics in multimode fibers. By showing that a graded-index multimode fiber can act as a pulse compression-elongation system, future studies could be carried out to improve the control pulse reshaping dynamics.

Appendix A

Dispersion code

```

1  %Algorithem to process the experimental data for dispersion calculation on
2  %balanced MachZender interferometer
3  %for soft glasss fibers
4  %by Tanvi Karpate
5
6  P=xlsread('MS27A3.xlsx'); %to load the experimental data
7  wav=P(:, 1);
8  wav=wav./1000;%converting the wavelength to micrometers
9  wave=1./(wav).^2;
10 posi=P(:, 2);
11 plot (posi, wav);
12 %%
13 glass=xlsread('OPD_C230_C280_NDF');%loading the parameters of lenses used
14 OPD_samplearm=glass(1,2)./wav.^4+glass(1,3)./wav.^2+glass(1,4)
15 +glass(1,5).*wav.^2+glass(1,6).*wav.^4;
16 %optical path difference in the sample arm due to lenses used
17 L=108;%introducing the length of fiber used in the exp in mm
18 Nrel=(2.*posi-(OPD_samplearm))./L+1;
19 % calculating the relative index seen by light in the fiber
20 plot(wav, Nrel, '-o');
21 xlabel('Wavelength(\mu m)');
22 ylabel('Nrel');
23 %cftool
24
25 %%
26 [fitresult, gof, A]=Laur4(wav, Nrel);%Laurentz fitting of Nrel vs wavelength
27 D=(4*A(1,1).*wav.^3+2*A(1,2)*wav-2*A(1,4)./wav.^3)*1/300000*10^9;

```

```
28 %for laurent parameter 4
29 %D=(4*A(1,1).*wav.^3+2*A(1,2)*wav-2*A(1,4)./wav.^3
30 %-4*A(1,5)./wav.^5)*1/300000*10^9;
31 %for 5 Laurent parameters
32 %D=(6*A(1,1).*wav.^5+4*A(1,2).*wav.^3+2*A(1,3)*wav-2*A(1,5)./wav.^3
33 %-4*A(1,6)./wav.^5-6*A(1,7)./wav.^7)*1/300000*10^9;
34 %for 7 Laurent parameters
35 Disp=plot(wav, D, '-o');
36 xlabel ('Wavelength (\mu m)')
37 ylabel ('Dispersion (ps/nm/km)')
38 saveas(Disp, 'MS27A7.png')
```

Appendix B

Reconstruction of FROG and XFROG retrieved pulses

```

1  c= 3*10^8;
2  power= 14;
3  a=dlmread(['../Tanvi_MS27A3/XFROG/' num2str(power) 'mW/arecon' '.dat']);
4  %source Jasper20
5  %%
6  nowave=a(1,1);
7  nodelay=a(1,2);
8  wave=a(3:258);
9  delay=a(259:514).*4;
10 %data=a(3:258,:);
11 data=a(515:66050);
12 r=reshape(data,[256,256]);
13 r=flip(r,2);
14 r=rot90(r);
15 %%
16 ek=dlmread(['../Tanvi_MS27A3/XFROG/' num2str(power)
17 'mW/ek' '.dat']);
18 time=ek(:,1).*4;
19 t_int=ek(:,2);
20 spec=dlmread(['../Tanvi_MS27A3/XFROG/' num2str(power)
21 'mW/speck' '.dat']);
22
23 wavelength=spec(:,1);
24 w_int=spec(:,2);
25 w_int=smooth(w_int);

```

```

26 % w_int=flip(spec(:,2),1);
27 osa= xlsread(['../Tanvi_MS27A3/new_spectrum/Ms27A3_5dbscale_MMF_'
28 num2str(power) 'mW' '.csv']));
29 w_osa=osa(:,1);
30 spectrum_osa=osa(:,2);
31 spectrum=db2pow(spectrum_osa);
32 spectrum=smooth(spectrum/max(spectrum));
33 %%
34 h=figure;
35 %set(gca,'Ticklabel',22);
36 %b = get(gca,'XTickLabel');
37 %set(gca,'XTickLabel',b,'fontsize',14)
38 subplot(4,4,[5,6,9,10])
39 ax=gca;
40 colormap([1,1,1];hsv]);
41 pcolor(delay, wave, r);
42 xlim([-10000 10000])
43 ylim([500 560])
44 ax.XAxis.FontSize = 10;
45 ax.YAxis.FontSize = 10;
46 shading interp;
47 %xl=xlabel('Delay (fs)', 'FontSize', 12);
48 xl=xlabel('Delay (fs)');
49 set(xl, 'FontSize', 12);
50 set (gca, 'XAxisLocation' , 'top');
51 ylabel('Wavelength (nm)', 'FontSize', 12);
52 subplot (4,4,[13,14])
53 plot(time, t_int, 'LineWidth',2)
54 xlim([-10000 10000])
55 xlabel('Delay(fs)', 'FontSize', 14);
56 ax.XAxis.FontSize = 14;
57 ax.YAxis.FontSize = 14;
58 subplot(4,4, [7,11])
59 plot(w_int, wavelength, 'LineWidth',2)
60 set (gca, 'YAxisLocation' , 'Right' )
61 ylim([971 1227])
62 ax.XAxis.FontSize = 14;

```

```

63 ax.YAxis.FontSize = 14;
64 hold on
65 plot(spectrum,w_osa, 'LineWidth',2)
66 hold off
67 set(gca,'YScale','lin')
68 ylabel('Wavelength (nm)', 'FontSize', 14);
69 saveas(h, ['./Tanvi_MS27A3/XFROG/'
70 num2str(power) 'mW/plot_' num2str(power) 'mW' '.fig'])
71 print(gcf, '-dpng', '-r600',
72 ['./Tanvi_MS27A3/XFROG/' num2str(power) 'mW' '.png'])
73 print(gcf, '-dpng', '-r600',
74 ['./MS27A3_jasper/xfrog_jasper/' num2str(power) 'ms' '.png'])
75 close(h)
76 % OSA and XFROG spectral overlap
77 q=figure;
78 osa= xlsread(['../Tanvi_MS27A3/new_specrum/Ms27A3_5dbscale_MMF_'
79 num2str(power) 'mW_02' '.csv']);
80 w_osa=osa(:,1);
81 spectrum_osa=osa(:,2);
82 spectrum=db2pow(spectrum_osa);
83 spectrum=smooth(spectrum/max(spectrum));
84 plot(w_osa, spectrum, 'LineWidth',2)
85 %set(gca,'yscale','linear')
86 hold on
87 plot(wavelength, w_int, 'LineWidth',2)
88 ylim([950 1200])
89 hold off
90 legend('OSA spectrum', 'Retrieved spectrum')
91 saveas(q,
92 ['./Tanvi_MS27A3/new_specrum/overlap' num2str(power) 'mW' '.fig'])
93 print(gcf, '-dpng', '-r600',
94 ['./Tanvi_MS27A3/new_specrum/overlap' num2str(power) 'mW' '.png'])

```


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