MID-IR SUPERCONTINUUM GENERATION IN DISPERSION FLATTENED $AS_{38}SE_{62}$ CHALCOGENIDE PHOTONIC CRYSTAL FIBER

A PROJECT REPORT

SUBMITTED IN FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE

OF

MASTER OF SCIENCE

IN

PHYSICS

Submitted by:

AKASH KHAMARU 2K20/MSCPHY/02

KAJAL SHARMA 2K20/MSCPHY/10

Under the Supervision of

Dr. Ajeet Kumar

DEPARTMENT OF APPLIED PHYSICS

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi – 110042

DELHI TECHNOLOGICAL UNIVERSITY
(Formerly Delhi College of Engineering)

Bawana Road, Delhi - 110042

CANDIDATES' DECLARATION

We hereby certify that the project which is presented in the Major Project – II titled as "Mid-IR supercontinuum generation in dispersion flattened $As_{38}Se_{62}$ chalcogenide photonic crystal fiber" and submitted to the Department of Applied Physics, Delhi Technological University, Delhi is a record of our own, carried out during the period of January to May 2022 under the supervision of Dr. Ajeet Kumar.

The matter presented in this report has not been submitted by us for the award of any other degree of this or any other Institute/University. The work has been communicated in peer reviewed Scopus indexed conference with the following details:

Title of the Paper (I): Mid-IR supercontinuum generation in dispersion flattened $As_{38}Se_{62}$ chalcogenide photonic crystal fiber
Author names: Akash Khamaru, Kajal Sharma, Drishti Singh Tomer and Ajeet Kumar
Name of Conference: *International Conference on Current Trends in Physics and Photonics*
Conference Dates with venue: 9-11th June ; Dr. Viswanath Karad MIT World Peace University, Pune
Conference Registered (Yes/No)? : Yes
Status of paper (Accepted/Published/Communicated): Accepted
Date of Paper Publication: Yet to be Published

Place: Delhi **Akash Khamaru (2K20/MSCPHY/02)**

Date: **Kajal Sharma (2K20/MSCPHY/10)** Kajal Sharma

SUPERVISOR CERTIFICATE

To the best of my knowledge, the above work has not been submitted in part or full for any Degree or Diploma to this University or elsewhere. I, further certify that the publication and indexing information given by the students is correct.

Place: **Dr. Ajeet Kumar**

Date:

ABSTRACT

Photonic Crystal Fiber has property of generating SC due to non-linear properties and dispersion. SC has many applications like spectroscopy, hyper spectral microscopy, and spectral tissue imaging, optical coherence tomography, optical metrology, frequency comb generation, spectroscopy, and multiplexing of wavelength bisection.

In this report, we discuss about the square core photonic crystal fiber using chalcogenide glass $As_{38}Se_{62}$ as core and air holes in IR region. The designing and virtual simulation is performed by applying the Modal Analysis segment in the Electromagnetic Wave Frequency Domain (EWFD) in COMSOL Multiphysics® software, which further calculated the eigenvalue problem for the Maxwell's electromagnetic equations by an approach of vectorial finite element method (FEM). The design contains a core and a cladding. In this design, the cladding contains circular air holes whereas the core consists of square chalcogenide glass. As core matter, chalcogenide material $As_{38}Se_{62}$ was used because non-linear index of refraction that is two to three orders of magnitude higher than silicon dioxide. we observe that, at pump wavelength 3.5 μm, the nonlinear coefficient is spotted as 1290 W^{-1} km^{-1} and effective mode area as 15.3 μm^2. After calculating various useful values noted above, we moved towards our main goal is to generate supercontinuum pulse. We had taken observation of SCG at different peak powers and different fiber lengths by keeping peak pulse at constant value of 50 fs. When performed experiment, we got a maximum broadened pulse of 2000 nm to 12000 nm in 4200 W peak power and 10 mm of fiber length.

DELHI TECHNOLOGICAL UNIVERSITY

(Formerly Delhi College of Engineering)

Bawana Road, Delhi - 110042

ACKNOWLEDGEMENT

We would like to express our sincere gratitude to our guide and mentor, Dr Ajeet Kumar, for guiding and assisting us in every step of this project. We are extremely grateful to him for giving us clear direction and moral support to carry out the project.

We are expressing our gratitude to the Dept. of Applied Physics for providing us with the required labs, infrastructure and environment which permitted us to perform our task without any hinderance.

Akash Khamaru

Kajal Sharma

INDEX

TOPICS	Page No.
Candidate's Declaration & Certificate	i
Abstract	ii
Acknowledgement	iii
Contents	iv
List of Figures	vi
List of Symbols & Abbreviations	vii
CHAPTER 1: INTRODUCTION	**1**
1.1.Overview of the thesis	2
CHAPTER 2: EM WAVE AND INTERACTION WITH OPTICAL FIBER	
2.1. Electromagnetic Wave Spectrum	3
2.2. Optical Fiber Basics	4
2.2.1. Types of optical fibers	5
2.2.2. Working of optical fiber	6
CHAPTER 3: PHOTONIC CRYSTAL FIBER AND ITS PROPERTIES	
3.1. Definition-PCF	7
3.1.1. Optical properties	8
3.2. Nonlinearity	10
3.2.1. Nonlinear effects	11
CHAPTER 4: CONCEPT OF SUPERCONTINUUM GENERATION	
4.1. Definition of SCG	12
4.2. Calculation	13
4.3. Applications	14
4.4. Important Terminologies of SCG	14
CHAPTER 5: MODEL DESIGINING AND ANALYSIS OF SCG RESULTS	
5.1. Designing of PCF for SCG	16
5.2. Material selection for PCF	17
5.3. Why to choose chalcogenide fiber?	18
5.4. Step-By-Step procedure to plot SCG	19
5.5. Observations	
5.5.1. Effective mode index and area	20
5.5.2. Dispersion characteristics	21
5.5.3. Supercontinuum Generation	
5.5.3.1. SCG at different peak power	22
5.5.3.2. SCG at different fiber length	23
CHAPTER 6: CONCLUSION	**25**
REFERENCES	**26**
APPENDICES	**28**

Appendix 1 Plagiarism report
Appendix 2 Full research paper titled as "Mid-IR supercontinuum generation in dispersion flattened $As_{38}Se_{62}$ chalcogenide photonic crystal fiber
Appendix 3 Abstract acceptance mail
Appendix 4 Registration slip for proof of conference registration
Appendix 5 Paper acceptance mail
Appendix 6 Proof of SCOPUS indexing

List of Figures

Figure Number	Caption
2.1	Flow of an electromagnetic wave
2.2	The frequency spectrum of EM wave
2.3	Electromagnetic wave spectrum
2.4	Diagrammatical representation of optical fiber
3.1	Design of solid core photonic crystal fibers
3.2	Wavelength vs. Dispersion graph
4.1	Numerically designated outputs - SCG in a very small segment of fiber.
4.2	Input pulse duration
4.3	Peak power and pulse width
5.1	Proposed PCF structure
5.2	Comparing loss at mid-infrared of chalcogenide optical fibers to silica
5.3	Fundamental mode field at 2µm(left) & 6µm(right) wavelength
5.4	Plot of Nonlinear Coefficient and effective mode area of proposed fiber
5.5	Plot of dispersion with respect to wavelength at ZDW 3.59 µm.
5.6	SC spectra at different peak powers at 10 mm fiber length and peak pulse of 50 fs
5.7	SC spectra at different T_{FWHM} value at 10 mm fiber length and peak power of 4200 W
5.8	Symmetrical SC spectra at 0mm fiber length and peak pulse of 50fs
5.9	SC spectra at different fiber lengths at peak power 4200W and peak pulse of 50fs

List of Symbols & Abbreviations

Symbol/Index	Meaning/Abbreviation
SC	Supercontinuum
Fs	Femtosecond
SCG	Supercontinuum Generation
PCF	Photonic Crystal Fiber
MIR	Mid-Infrared
EM	Electromagnetic
Nm	Nanometre
TIR	Total Internal Reflection
µm	Micrometre
GNLSE	Generalized Nonlinear Schrodinger Equation
FWHM	Full Width at Half Maxima
ZDW	Zero Dispersion Length
$As_{38}Se_{62}$	Arsenic Selenide
GVD	Group Velocity Dispersion
dB	Decibel

Chapter 1

Introduction

When high-intensity laser pulse interacted with a dielectric medium leads to non-linearly evoked polarized light, that phenomenon falls within the scope of optical nonlinearity [1]. The foundational difference between nonlinear optics and classical optics is the behaviour of polarization induction at the time of interaction with electromagnetic radiation.

One of the most eminent phenomena incorporated with nonlinear optics is the formation of supercontinuum. Whenever a ultrashort laser pulse (highly intense) traverses through a non-linear medium, processes such as self-phase modulation and induced Raman scattering result in spectral broadening and temporal compression. Pulse propagation creates a spectrum containing new frequencies that are often used as wideband multi-wavelength light sources. Supercontinuum (SC) light can be produced in fabricated optical fibers by usage of a variation in distinctive sources comprising Continuous Wave fiber lasers [2], Q-switched lasers [3], picosecond fiber lasers [4] and high recurring rate lasers providing pulses with mid-100 fs [5]. The formation of supercontinuum was experimentally performed by Ranka et al. White light produced by an 800nm laser made from micro structured Air silica fiber in 2000. In 1987, Kodama and Hasegawa published a comprehensive explanation of momentum propagation called the NLSE propagation equation. We will explain in detail why this led to the development of an accurate mathematical model for simulating SCG using computational techniques.

The production of supercontinuum(SCG) in mid-infrared optical waveguides is an area of global interest. In most situations, PCFs are made up of a fine thread of fused silica with a series of small open channels encircling a central core made of glass. Despite this fact that the passage of transparency in lead silicate and silica glasses starts to narrow off ahead of 1.9 m, Supercontinuum beam has been generated out to 3 μm, though at a much lower intensity [6,7]. Other core materials must be used if SC creation is to be spread further into the mid-IR. Chalcogenide glass is one interesting contender, as it combines a huge coefficient of nonlinearity (larger than 100 times that of silica) with a transparent window that can reach out to 20 metres or beyond. Numerical and experimental experiments are being conducted around the world to study MIR-SCG from a variety of glasses such as silicon dioxide, chalcogenide and tellurite glass. Studies are investigating MIR SCG step-index fiber optics, photonic crystal fibers, and various channel waveguides.

1.1. Overview of the thesis

Our piece of work has been bifurcated into different chapters and sections/subsections for representing knowledge, learning, research methodology and outputs in a structured and well defined manner. The basic as well as theoretical nodes of our thesis are presented in the beginning list of chapters. All the results and outputs are demonstrated later in the work. The starting chapter has introduced the learner with normal presentation of the field of nonlinear optics and applications of devices which is based on nonlinearity factors.

Going ahead with a particular application named as supercontinuum generation, uses of optical waveguides and mid infrared EM spectrum are discussed to specify their tasks in advancement of science and technology. After summing up all the elements discussed earlier, we illustrate the need for our performed work and highlighted our methods, outputs and impact as brief report.

Chapter 2 emphasize the knowledge about Electromagnetic Wave and associations with optical fiber. Classifications of optical fiber are also discussed with the working.

Chapter 3 describes about photonic crystal fiber with nonlinear properties. Apart from these, Nonlinear effects are also discussed which are main aspect of this report.

Chapter 4 gives details about supercontinuum generation quantitatively and qualitatively both. This chapter also provides ideology in calculation SCG Spectra at any input parameters like pulse duration, peak power etc.

Chapter 5 gives all details about our research work that how we designed our PCF and employed it for generation of supercontinuum pulse.

Chapter 6 discusses about our conclusion of carried research work.

Chapter 2

EM Wave and Interaction with Optical Fiber

2.1. Electromagnetic Wave Spectrum

An EM wave is defined as a travelling pair of segments of magnetic and electric field and both the field vectors surround a 90^o angle in the media. Frequency f is the physical quantity responsible for determining the internal properties of the electromagnetic wave. Sometimes, the wavelength λ is often used as a characteristic quantity of EM waves due to historical advancements. This represents the propagation length in which beam travels with period of $T = f^{-1}$.

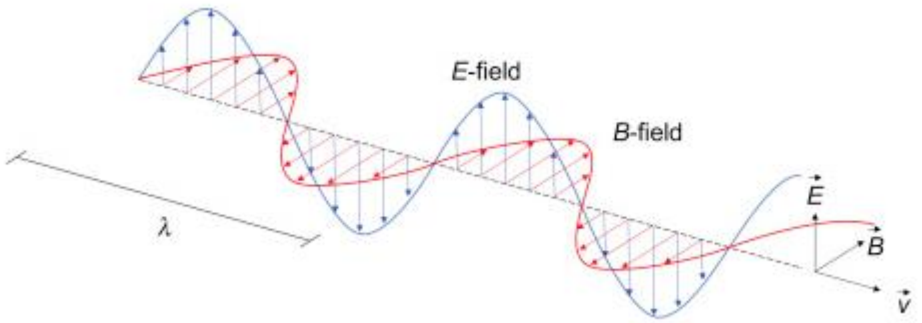


Fig 2.1: Flow of an electromagnetic wave.
Ref at [15]

The typical wavelength spectrum of waves is ranging from 10^{-15} m (1 fm; cosmic radiation) up to 10^7 m (10,000 km; high-, medium- and low-frequency AC currents). As we know only small part of all EM waves spectrum are visible to the human eye and are lie in the gap of 450 and 700 nm. Normally, the terminal point of 'light' is defined for wavelengths gap of 300 and 2000 nm.

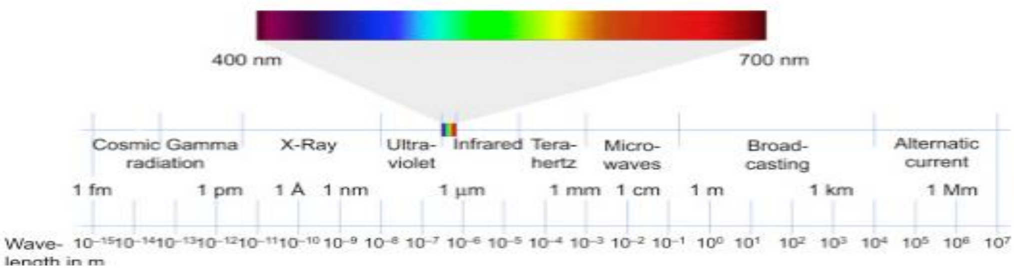


Fig 2.2:- The Frequency Spectrum of EM Waves Ref. at [15]

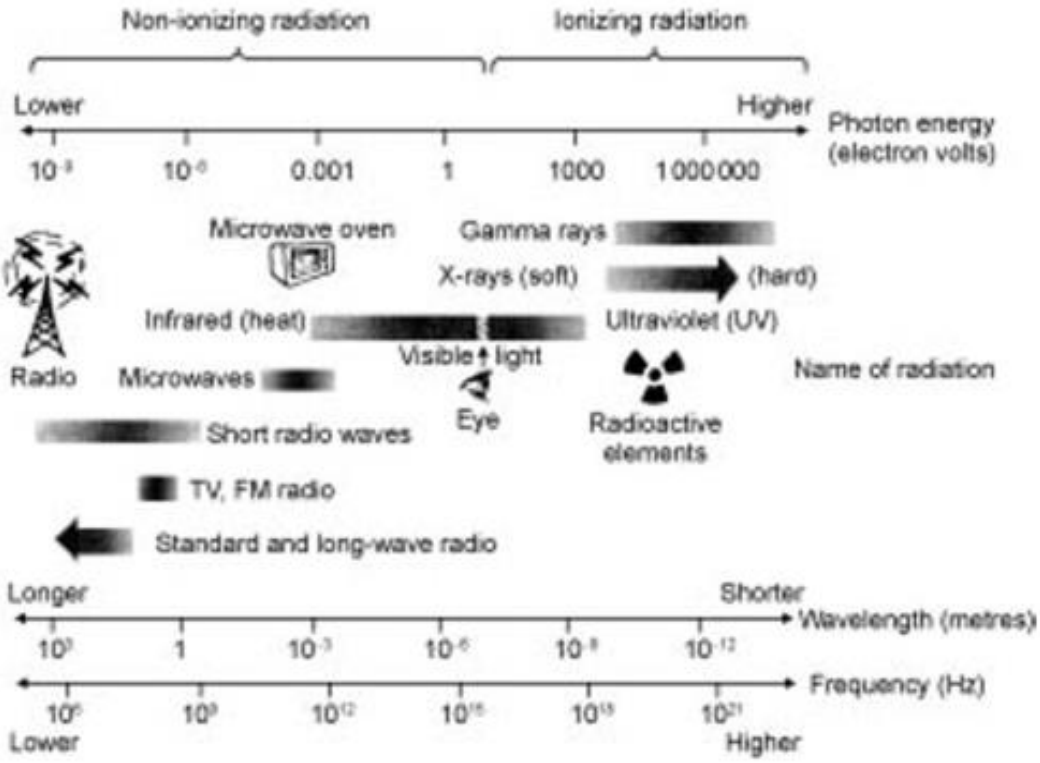


Fig 2.3: Electromagnetic wave spectrum Ref. at [16]

In vacuum, EM waves propagate at the speed of light (3×10^8 m/s), X-raysvisible part of spectrum, micro and radio waves, and light are segments of the different forms of electromagnetic waves each characterized by wavelength and respective frequency. The microwave part of the spectrum is in the range of frequency (300 to 300,000 MHz), so it is defined as non-ionizing form of EM energy.

2.2. Optical Fiber-Basics

Optical fiber is a data transmission technology that uses light pulses propagate along optical fibers, constructed of plastic/glass. Optical Fibers are prioritized for fiber optic transmission results the signal to be transmitted with less attenuation. Fiber optics are also immune to EM interference. Optic cables uses TIR (Total Internal Reflection). Fiber optics are fabricated in such a way that light propagates along with them, depending on the need for power and transmission distance. For long-distant propagation, single-mode fiber is used while multi-mode fiber is used for short-distance path. The outer layer of these fibers requires better protection than metal wires.

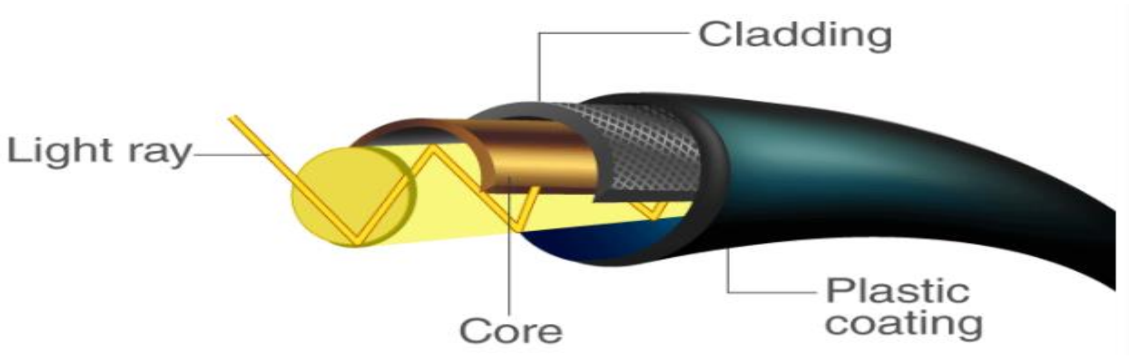
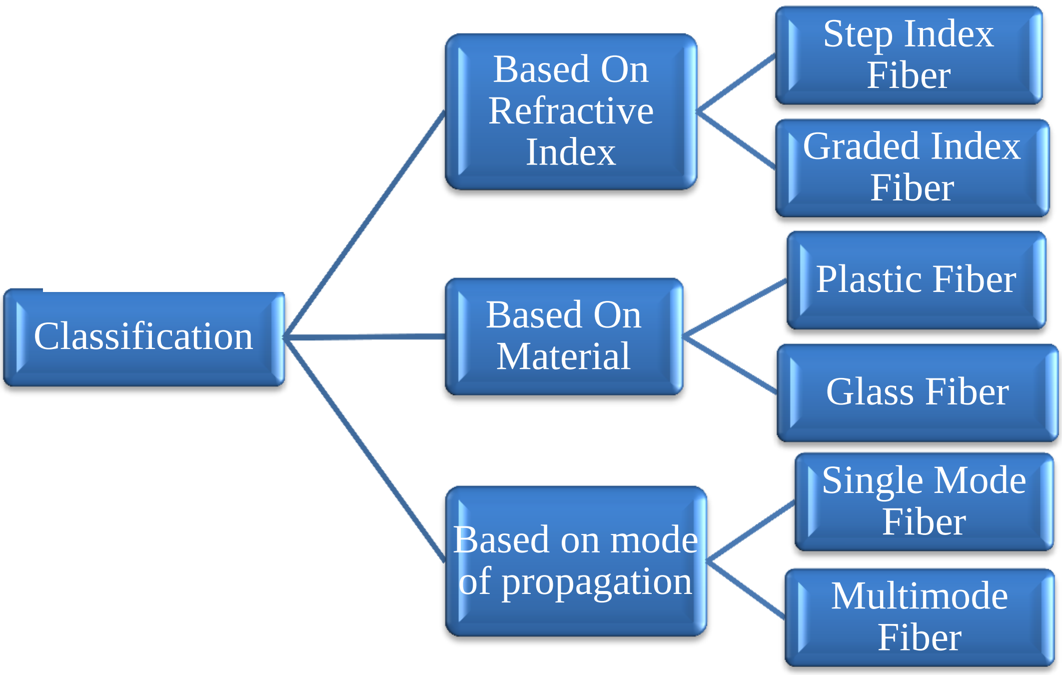


Fig 2.4: Diagrammatical Representation of Optical Fiber

Image courtesy: Circuitbread.com

2.2.1. Types of optical fibers



Four combination pairs of optic fibers on the basis of mode of propagation and refractive index are given as follows:

- Step index Single mode fibers
- Graded index Single mode fibers

- Step index Multimode fibers
- Graded index Multimode fibers

2.2.2. Working of fiber

Fiber optics operate on the principle of total reflection. Beams can carry huge amounts of data, but the problem is that they travel in a straight line. So without long straight lines with no bends, it can be very tedious to use. Instead, fiber optic cables are designed to bend all beams inward (using TIR). The beam moves continuously and reflects off the fiberglass wall to transmit data end-to-end. The optical signal degrades with distance, but depending on the purity of the material used, the losses are much lower than for metal cables. A Fibre Optic Relay System contains following components:

- The Transmitter –production of the light signals and encoding for transmission.
- The Optical Fibre – provides a defined path for transmission of pulse.
- The Optical Receiver –receiver of the transmitted light pulse and decoding.
- The Optical Regenerator – long distance propagation module.

Chapter 3

Photonic Crystal Fiber and Its Properties

3.1. Definition-PCF

Photonic crystal fibers (also known as holey fibers, micro structured fibers) have waveguide characteristics derived from very small, closely spaced air arrays rather than spatially varying glass compositions. A hole that runs the entire length of the fiber. Such air filled perforations are obtained by using a preform with (larger) holes. For example, stack capillaries and / or entire tubes (stack tube technique) and insert them into larger tubes. Typically, this preform is first a tube with a diameter of, for example, 1 mm, and then a fiber with a final diameter, for example, 125 µm.

Fig 3.1: Design of solid core PCF

Structure:- triangular pattern of air holes missing the central hole. Air holes of dimensions of a few micrometers (Image Courtesy: RP Photonics)

Mixed characteristics of optical fibers and photonic crystals they attain a collection of distinctive properties nearly impossible to get in classical fibers. PCFs can be designed in a variety of ways. There are various variables to play with, including pitch of lattice, air hole form and diameter, refractive index of the glass used, and type of lattice. Because of the freedom of design, it is possible to generate infinitely single mode fibres that are single mode over the whole optical spectrum and do not have a cut-off wavelength. In addition, PCF has two guiding mechanisms: index guiding (similar to that found in traditional optical fibres) and photonic bandgap guiding. There is a possibility in designing the desired fiber dispersion qualities by modifying the structure.

At visible wavelengths, PCFs with zero or anomalous dispersion can be developed and produced. Over a wide range, the dispersion can certainly be flattened. Nonlinear fibers work within regime of anomalous dispersion and tiny mode field regions are exceptional. Large, solid or air core single mode fibres, on the other hand, are possible.

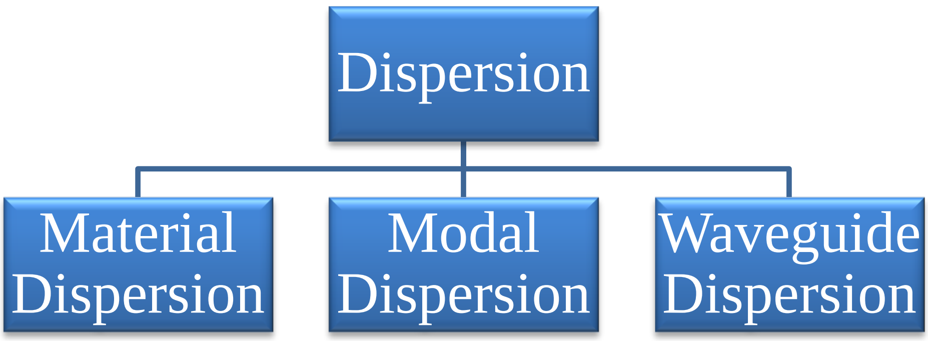
3.1.1. Optical Properties

- <u>High Birefringence</u>

Birefringence is the optical property of a material having a refractive index which is dependent on the intrinsic property of polarization and also in propagation direction of light. Linear polarized mild parallel ray and contrary heading will specific choppy effective indices of refraction (n_e & n_o) for instant and regular growing beams separately. At the factor whilst an un-captured low emission is going via cloth with a nonzero severe facet to the optical hub, the oppositely spellbound section can also additionally confront refraction at an facet in line with the normal regulation of refraction and its contrary component at a non-general factor seemed through the difference among the two compelling refractive data known as because the birefringence extent [8].

- <u>Dispersion</u>

Dispersion is the light pulse spreading outside with respect to time as it propagates down the fiber. Fiber optic dispersion includes model dispersion, material dispersion, and waveguide dispersion.



Material Dispersion	Modal Dispersion	Waveguide Dispersion
It is a process in which variable optical wavelengths traverses at different velocities, relies on the value of refractive index of the matter used for construction fibre core	Mode dispersion is a distortion mechanism that occurs in multimode fibers and other waveguides where the signal diffuses over time because the propagation speed of the optical signal is not the same in all modes.	The distribution of energy taking place from varied speeds or RIs in the fiber's core and cladding. It's impossible to debar waveguide dispersion as in the case of both modal and chromatic dispersion types.
$\tau_m = -\frac{\lambda_o}{c}\left(\frac{d^2 n_1}{d\lambda_o^2}\right)\frac{ps}{km}nm$	-----	$\tau_w = -\frac{2n_2\Delta}{c\lambda_o}\frac{B^2}{V^2}$
Material Dispersion is Directly Proportional to wavelength, hence increases.	--------	Waveguide Dispersion is Inversely Proportional to wavelength, hence decreases.

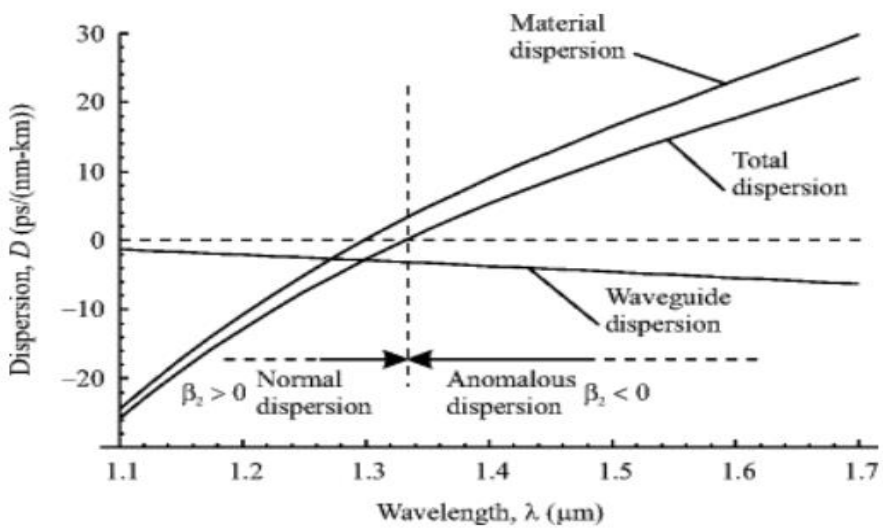


Fig 3.2: Wavelength vs. Dispersion Graph Ref. at [17]

➢ <u>Low Confinement Loss</u>

Confinement losses are referred as those observed losses from the leakage factor of the observed modes and the imperfection in structure of the PCF fiber.

➢ **Non-Linearity**

Nonlinearity in fiber takes place when traversed optical signals are very powerful, and limits the above limit of signal strength in fiber propagations.

Nonlinear coefficient is given by

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (1)$$

➢ **Effective mode index and area**

A numerical value calibrating the delay in phase per unit length in any waveguide, with relation to the delay in phase in vacuum/space is known as effective mode index.

A quantitative measure of the area which a mode of fiber envelops in the transverse extent in effective manner and is closely related to the bending loss, numerical aperture and dispersion of optical fiber.

Effective mode area is given as

$$A_{eff} = \frac{(\iint_{-\infty}^{\infty} |E|^2 dxdy)}{(\iint_{-\infty}^{\infty} |E|^4 \, dxdy)} \quad (2)$$

➢ **Zero Dispersion Wavelength**

Zero-dispersion wavelength is the wavelength or wavelengths at which material dispersion and waveguide dispersion cancel one another.

3.2. Nonlinearity

The advent of the laser spurred research into high-intense optics, leading to latest phenomena like the creation of new colors from a single colored light in a transparent crystal or the self-focusing of a single colored light optical beam in a homogeneous liquid that cannot be obtained. observed with ordinary light. The normal optical properties of the material cannot be assumed to be constant at the magnitude required to cause these types of effects, instead become the use of luminescence. Nonlinearity in optics is the science of optics in this area. The theory of optical nonlinearity is based on a well-known theory: Linear optics, especially the part discussing about the interaction of light along with the matter. Ordinary matter is a positively charged nucleus (atoms or molecules) and covered negatively charged electrons. Light contacts with substances mainly mediated by valence electrons in the outer electron shell Orbit. The basic parameters of this theory of interaction between light and matter are as follows. Photo induced electron material's polarization and extension of parameter in the non-linear area, A wide variety of optical phenomena at high intensities [9].

3.2.1. Nonlinear effects

- **Diffraction Tuning**

Diffraction gratings as a coordinating factor for synchronously excited optical parametric oscillators have many advantages. It provides an agile adjustment mechanism (compared to the temperature adjustment of nonlinear crystals) and can suppress the resonator length-dependent adjustment behaviour normally observed.

- **Self-Defocusing**

The effect of a material whose index of refraction drops with increment in optical intensity on a laser beam that is more powerful and intense in the centre than at the edges, causing the beam to defocus since the refractive index profile corresponds to that of a negative lens.

- **Generation of Spatial Solitions**

A light field that is unchanged during propagation due to the delicate balance between non-linear and linear effects in the medium. There are two different blocks of soliton.

- **Supercontinuum Generation**

Supercontinuum creation is a combination of nonlinear optical effects that spectrally broaden a laser beam that is initially almost having monochromaticity. This can be achieved, for example, by sending short, intense flashes of light through a photonic crystal fiber.

Chapter 4

Concept of Supercontinuum Generation

4.1. Definition of SCG

Supercontinuum creation is the process by which laser light is transformed into signal possessing broad spectrally induced bandwidth (that is, temporal coherence is very low). Ultra-wide continuous light spectrum is formed. This means that temporal coherence remains very low, while spatial coherence remains largely high. Spreading in spectrum is basically achieved by travelling a light pulse through a heavy non-linear device. For example, you can send an amplified ultra-short beam through a small part of glass. On the other side, a pulse can be sent with much decreased pulse energy via an optic fiber with a waveguide structure where longer propagation distances in a ultrafine effective mode region is admitted. Photonic crystal fibers are of particular interest, primarily due to their anomalous wavelength dispersion characteristics, which can allow strong non-linear interactions over fibers of considerable length. Even with moderate input power, you can get a very wide spectrum.

Fiber optics are often used to create supercontinuum. Photonic crystal fibers can be manufactured with tailor-made color dispersion characteristics and have strong mode limitations, which also increases non-linearity.

Supercontinuum light is a unique and versatile ultra-wideband source with high spectral power density and high coherence comparable to white light lasers, with several lights for light detection and illustration from frequency comb measurements, Clocked pulse generation. Steady technological advances in the development of new laser sources, the design and manufacture of optical fibers and waveguides, and the availability of highly nonlinear materials have led to the generation of supercontinuum in the unexplored parts of various nonlinear media and optical spectrum [10].

The physical mechanism behind supercontinuum production in the fiber is highly dependent on the wavelength dispersion and length of the fiber, pulse width, initial strength of the peak, and peak pump wavelength

When using femtosecond (fs) beams, spectral spread can be a result by the phenomena of self-phase modulation. In the region of anomalous dispersion, the mixing of self-phase modulation and dispersion can result in complex dynamics in soliton, such as the dividing of upper-order solitons into many basic solitons (soliton divisions).

If pumped with picosecond (ps) or nanosecond (ns) pulses, phenomenon like Raman scattering and four-wave mixing can admit a significant role.

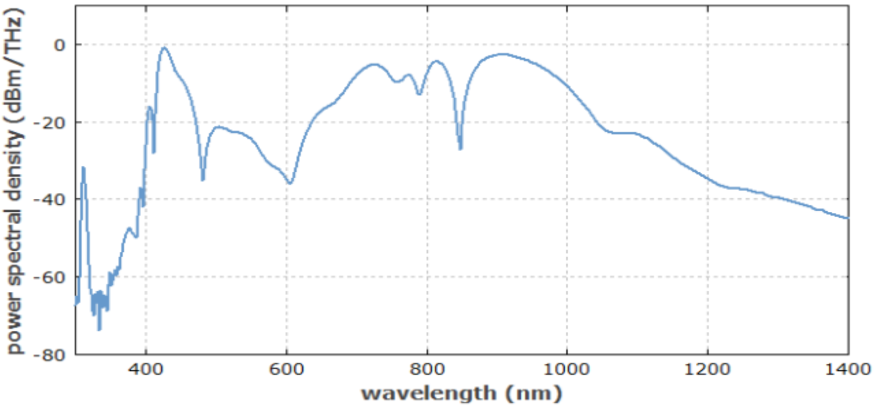


Fig 4.1:- Numerically designated outputs - SCG in a very small segment of fiber.

Image Courtesy: RP Photonics

4.2. Calculation

For recording SCG we have to simulate the generalized nonlinear Schrodinger equation (GNLSE) for output beam packet A(z:t) by applying (split-step) Fourier method [10].

$$\frac{dA}{dz} + \frac{\alpha}{2}A - \left(\sum_{n\geq 2} \beta_n \frac{i^{n+1}}{n!}\frac{\partial^n A}{\partial t^n}\right) = i\gamma\left(1 + \frac{i}{\omega_o}\frac{\partial}{\partial t}\right)A(z,t)\int_{-\infty}^{\infty} R(t')|A(z,t-t')|^2 dt' \qquad (3)$$

where, A(z;t) denotes packet of the optical beam field, t represents time and γ is representing the nonlinear coefficient. βn are coefficients of dispersion acquired by a expanding the Taylor series of the particular constant $\beta(\omega)$ around the mid frequency ω_0

The response function including the Raman and Kerr nonlinearity(s) is denoted by R(t). Where we can assume that the electronic contribution is almost instantaneous, then the R(t) is represented by well-defined functional form given in the following way

$$R(t') = (1 - f_r)\delta(t) + f_r h_r(t') \qquad (4)$$

f_r used for the fractional contribution of the retarded Raman response, and $h_r(t)$ used as Raman response function that stores all the details on the respective shaking of molecules of material as light traverses along the fiber and given by

$$h_r = \frac{\tau_i^2 + \tau_2^2}{\tau_1 \tau_2} \exp\left(-\frac{t'}{\tau_2}\right) \sin\left(\frac{t'}{\tau_1}\right) \tag{5}$$

4.3. Applications

Supercontinuum sources are generally light possesses broad optical bandwidth (ie, short temporal coherence value), but on the other hand to sufficiently collimate and focus the light for color (with some limitations). Used for purposes that require high spatial coherence. aberration). For example, such a light source is often used in combination with a monochromator as a spectroscopic adjustable light source. On comparing with tunable lasers, supercontinental sources can normally covers a much larger range of wavelengths. On the other hand, its power spectral density is much lower. Only a small amount of power can be obtained. It is transmitted via a narrowband monochromator.

4.4 Important terminologies of SCG

➢ **Pulse duration**

The pulse width τ_p is denoted as the FWHM or full width at half maxima value, the width of the time gap at which the delivered power is equal to half of the power at peak.

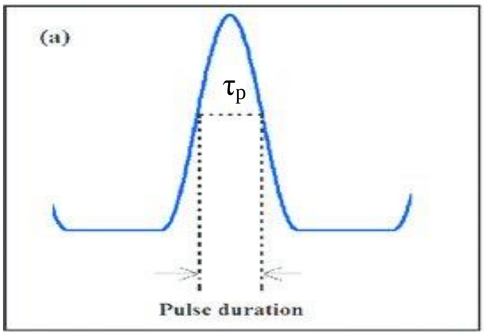


Fig 4.2: Input Pulse Duration ref at [18]

➢ **Peak power**

The peak power of a laser beam is the optical power generated at maximum extent. Due to the possibility of less pulse time with optical beams, peak strength can be very large at medium pulse energies.

$$P_p \approx 0.88 \frac{E_p}{\tau_p} \quad (6)$$

Pulse energy E_p = integration of optical power over the span of time

P_p =Peak power

τ_p = Time duration of pulse

f_s = magnitude dependent on the shape of pulse. For example, magnitude is ≈ 0.94 (Gaussian-shaped pulses) or ≈ 0.88 ($sech^2$-shaped)

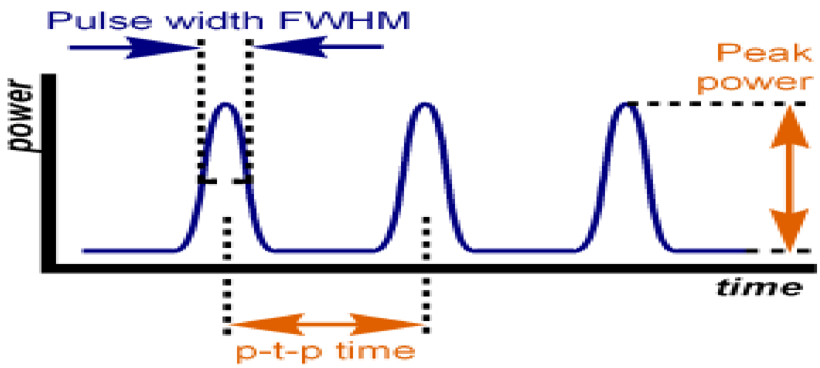


Fig 4.3 Peak Power and Pulse Width (Image Coutesy: Calctool.Org)

➢ **Pump wavelength**

It is basically the emission wavelength of the given laser. For spectral broadening, pump wavelength kept near Zero dispersion wavelength (ZDWL) which means that continuous wave light is broken down into pulses due to modulation instability.

Chapter 5

Model Designing and Analysis of SCG Results

In this chapter, we will discuss about our proposed PCF for supercontinuum generation and simulations of SCG done at different peak powers and fiber lengths. Beside of SCG, we also calculate effective mode index and respective area along with dispersion characteristics with a particular zero dispersion wavelength (ZDW) which gives strong evidence of non linearity presence in our structure and gives strength and justification to our simulated results.

5.1. Designing of PCF for SCG

Using $As_{38}Se_{62}$ chalcogenide glass as the core and air holes in the IR region, we have developed a square core photonic crystal fiber that provides very high optical nonlinearity of 1290 W^{-1} Km^{-1} at 3.5 μm and provides a flat dispersion profile. This fiber was used to numerically simulate SCG using a low power pump pulse with a duration of 3.5 μm and a duration of 50 fs. At the end of the 10 mm fiber, a pulse with a peak power of 4200 W can achieve an SC spread of approximately 200-1300 nm.

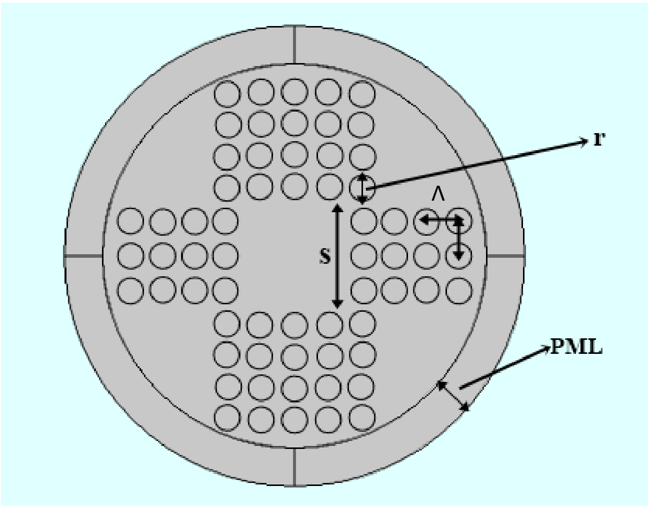


Fig.5.1. Proposed PCF Structure

Model Parameters

Our parameters consideration for designed PCF is given as following

i) Side of square core(s) = 5 μm
ii) Four array of air holes with radius (r)– 0.6 um

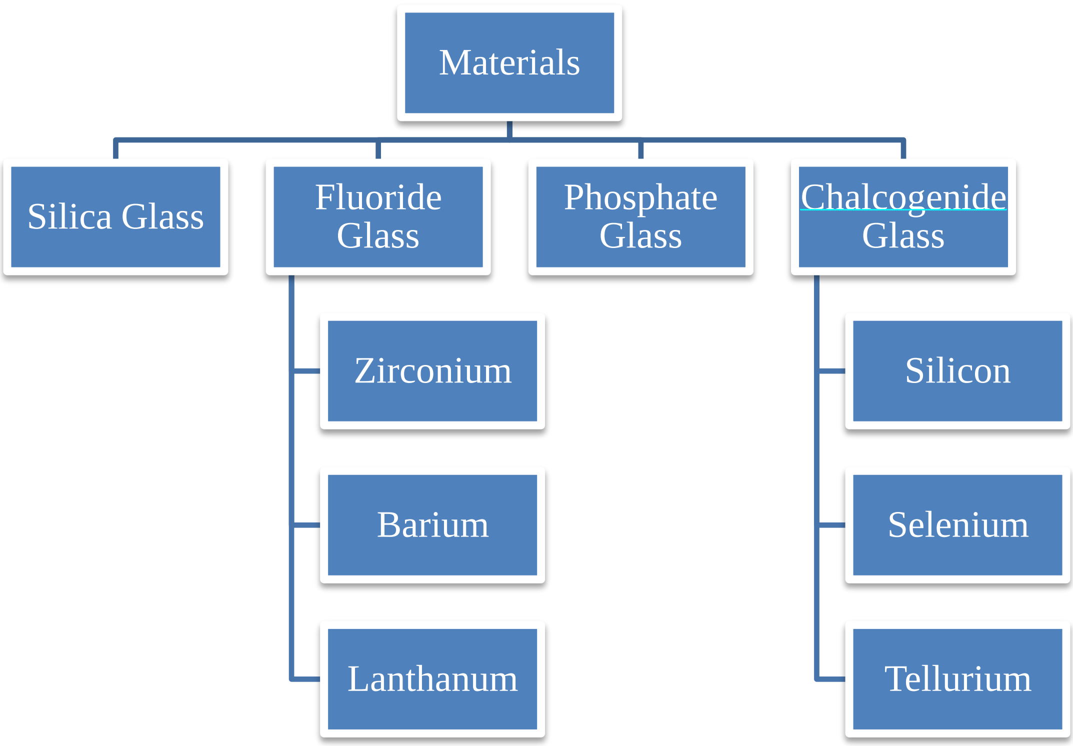
iii) Pitch (Λ) = 1.5 um
iv) PML Width = 1.8 um
v) Refractive Indices of Core and cladding is given by Sellmeier Equation

Sellmeier Equation:- Sellmeier's equation is an actual relations bridges the index of refraction and wavelength of a particular transparent medium. This equation is used for calculation of the dispersion of beam in the particular media. Equation of $As_{38}Se_{62}$ is given as follows

$$n^2(\lambda) = 3.7464 + \frac{(3.9057\lambda^2)}{\lambda^2 - 0.4073^2} + \frac{(0.9466\lambda^2)}{(\lambda^2 - 40.082^2)} \quad (7)$$

5.2. Material selection for PCF

There are several types of materials used in the manufacture of optical fibers. Fiberglass is most often made from silicon dioxide, but other materials such as fluorozircontate, fluoroaluminate, chalcogenide glass, and crystalline materials such as sapphire are suitable for long-wave infrared or other special applications. will be used.



5.3. Why do we choose chalcogenide optical fiber for Mid-Infrared Supercontinuum Generation?

In addition to the pump source, the amplification or conversion medium is very important for producing the Mid IR range of supercontinuum. In general, there are two categories of Mid IR fibers, passive and active fibers. Passive fibers are used for carrying infrared information, and active fibers use non-linear effects or rare earth doping to generate Mid IR light [11].

Permeability depends on the constituent chalcogen elements such as sulfur, selenium and tellurium [12]. As a result, As-S fibers can penetrate 1-6.5 µm [13], As-Se fibers 1.5-10 µm [14], and Tellurium fibers can penetrate 14 µm or more due to their high atomic weight. In terms of optical non-linearity, chalcogenide glass has a non-linear index of refraction that is two to three orders of magnitude higher than silicon dioxide [12].

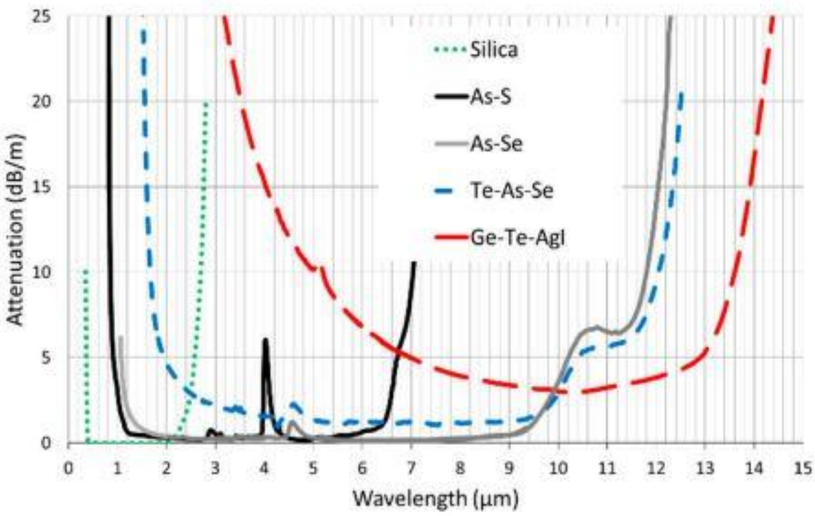
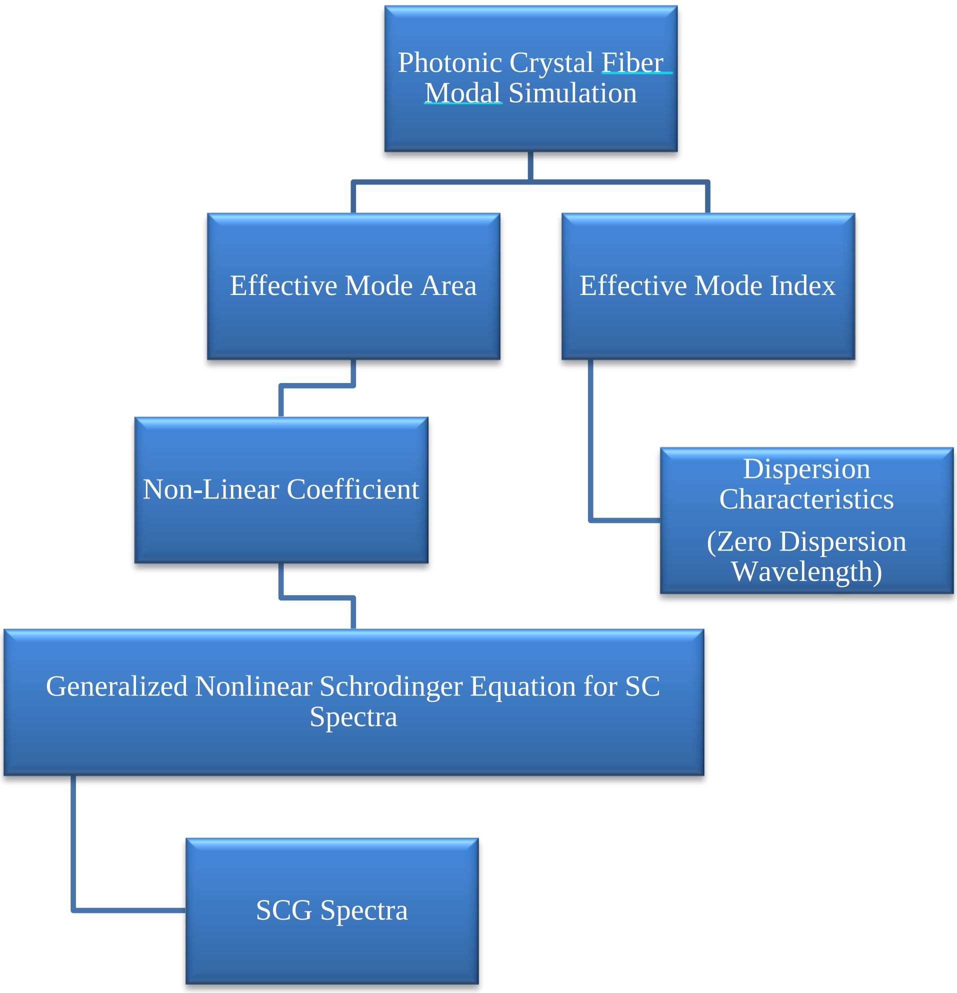


Fig 5.2. Comparing loss at mid-infrared of chalcogenide optical fibers to silica Ref. at [11]

5.4. Step By Step Procedure to calculate and plot Supercontinuum Spectra.

During the simulation process of 2D PCF structure, we travel from different milestones. It is a step-by-step process in which SCG spectra is the last executed step and gives final results. In between, we come to know about effective indices, effective area and dispersion characteristics. Main thing we have to observe is to most important effective index and zero dispersion wavelength which gives us way to find the pump wavelength suitable with this proposed PCF and performing the simulation further. is a flow diagram/flowchart for indicating simulation procedures presented below.



Both the GVD and nonlinearity of any matter are significant properties for the production of wide and efficient SCG.

5.5. Observations

In this section, we will discuss about our observations at different steps of simulation. We also pointed out things which are necessary for further calculations and observations.

5.5.1. Effective Mode Index and Area

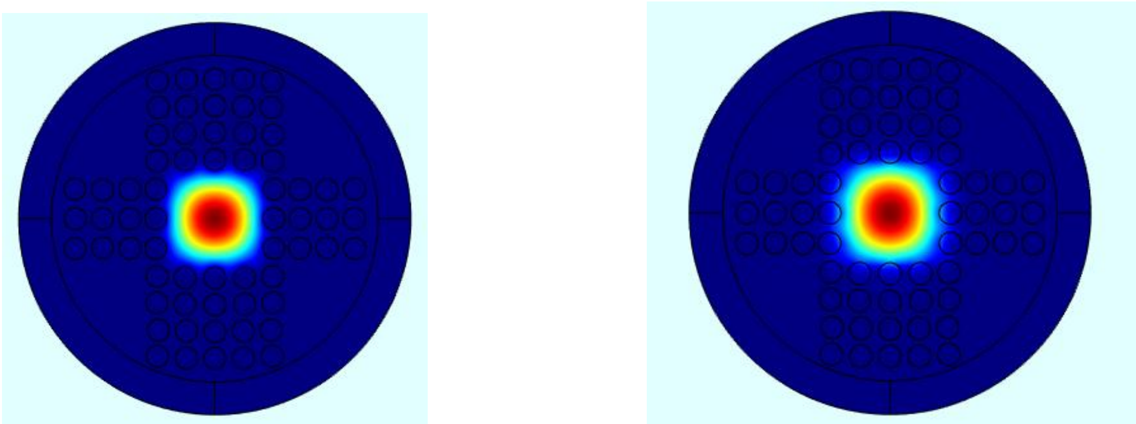


Fig 5.3. Fundamental mode field at 2μm(left) & 6μm(right) wavelength

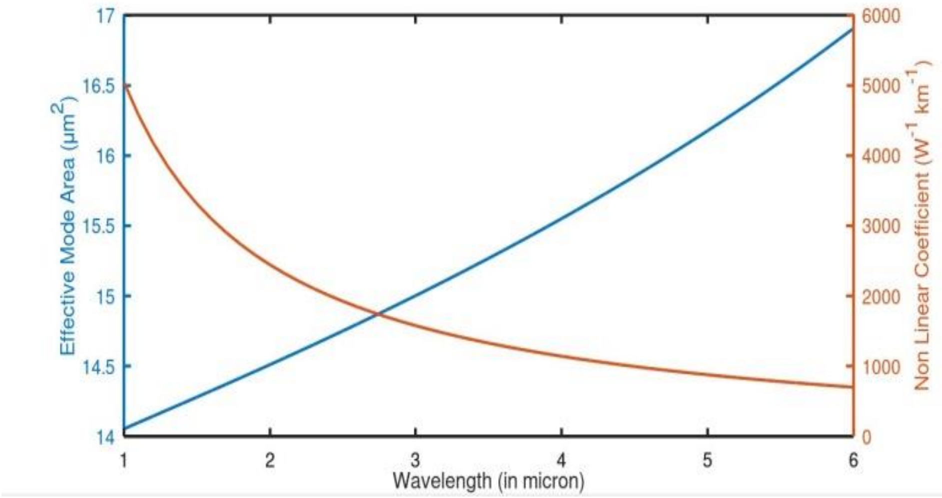


Fig 5.4. Plot of Nonlinear Coefficient and effective mode area of proposed fiber

Figure 5.4 depicts the plot of nonlinear coefficient and effective mode area versus wavelength in micron. Whole observation is taken at a passage of mid-IR bracket. From the plot, we can observe that, at pump wavelength 3.5 μm, the nonlinear coefficient is spotted as 1290 W^{-1} km^{-1} and effective mode area as 15.3 μm^2. Another observation is that effective mode area is decreasing with increment in wavelength and nonlinear coefficient is increasing with increment in wavelength. From this plot and results we can conclude that our both numerical calculated values are suitable for SCG generation. We have tried to keep the effective mode area at its smallest extent value for enhancing the nonlinearity playing inside the PCF. More the nonlinearity, more broadened SCG can be observed and used as applications in many aspects. Apart from these observations, we moved ahead with dispersion characteristics and set a goal to find a perfect zero dispersion wavelength which act as pump wavelength for our SCG simulation experiment.

5.5.2. Dispersion characteristics

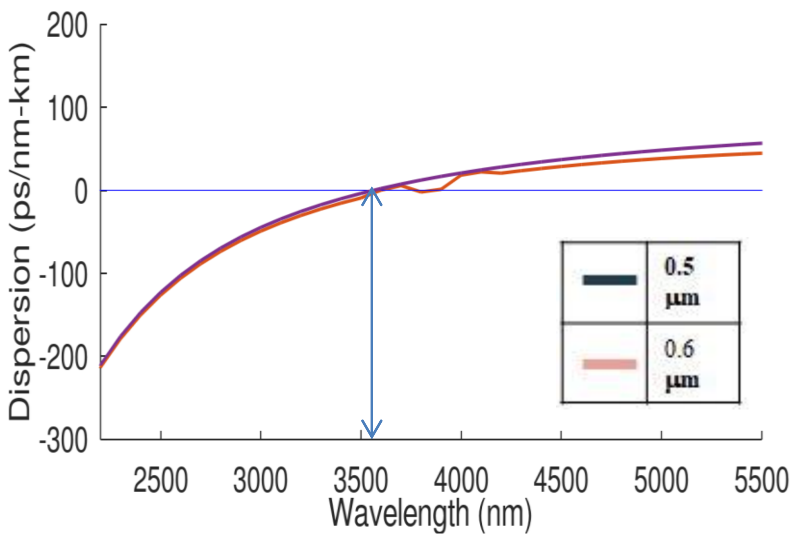


Fig. 5.5. Plot of dispersion with respect to wavelength at holes of size 0.5 μm and 0.6 μm Flattened graph and ZDW achieved at 3.59 μm at holes of 0.6 μm

Figure 5.5 depicts the flat dispersion versus wavelength with normal and anomalous dispersion values at different values of wavelength and gives us a particular point which marks transition from normal to anomalous regime which is called zero dispersion wavelength and observed at 3.59 μm. From the observed ZDW, we can perform the experiment at suitable peak pump wavelength of 3.5 μm. In next and final step, we use this pump wavelength of 3.5 μm for broadening the resulting pulse at greater extent by variating the input parameters like peak pulse power & fiber length and observe the changes in SCG.

5.5.3. Supercontinuum generation

In this subsection, SCG spectra is simulated at different peak pulses, fiber lengths by taking constant value of pump wavelength of 3.5 μm.

5.5.3.1. SCG at different peak power

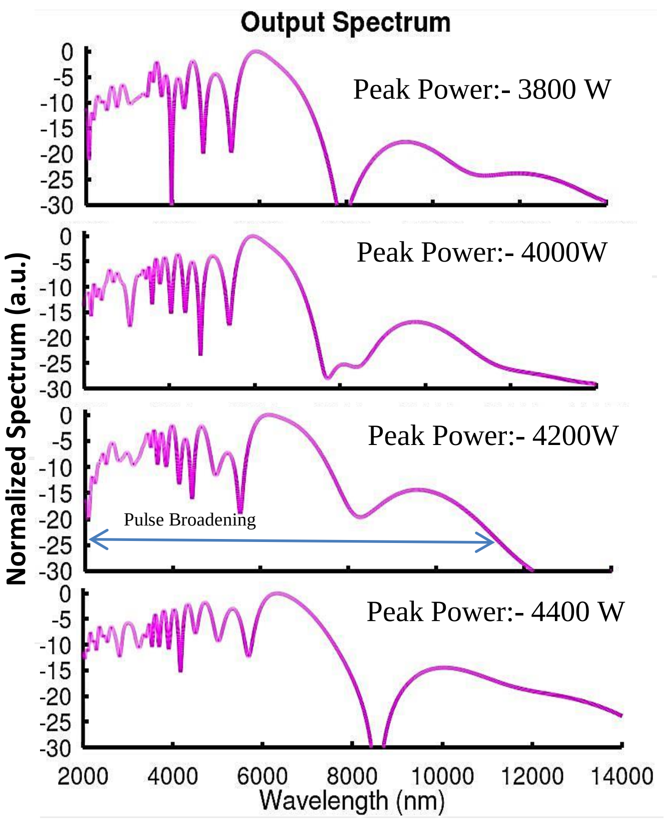


Fig 5.6. SC spectra at different peak powers at 10 mm fiber length and peak pulse of 50 fs

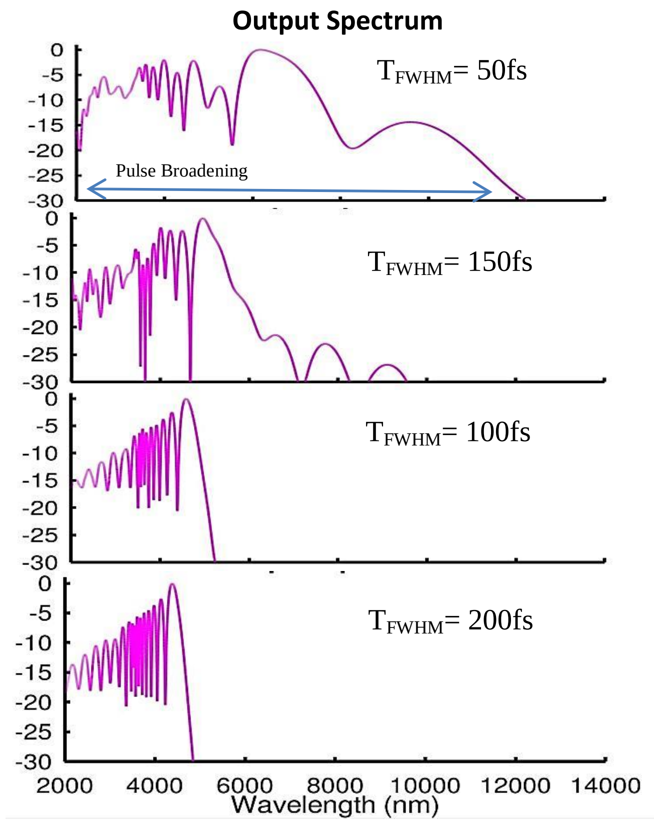
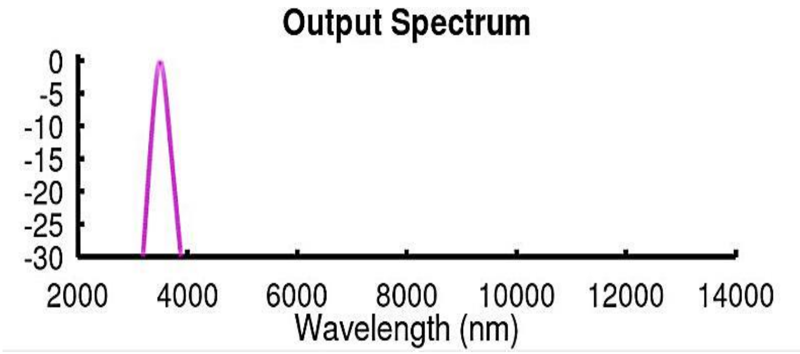


Fig 5.7. SC spectra at different T_{FWHM} value at 10 mm fiber length and peak power of 4200 W

Figure 5.6 depicts the SCG spectra at different peak powers such as 3800 W to 4400 W etc by taking constant values of peak pulse of 50 fs, pump wavelength of 3.5 μm and fiber length of 10 mm. In each of the spectra, we can see a distinct broadening from 2000 nm to 14000 nm and intensity from 0 dB to 30 dB but among these spectrum, perfect broadening is observed at 4200 W. Other observations are noted in figure 5.7 that as we increase the T_{FWHM} value, broadening is decreasing. Our main motive is to extract broadened spectra without any discontinuity. Hence, we get favourable SCG at 4200 W with the broadening from 2000 nm to 12000 nm without discontinuity.

5.5.3.2. SCG at different fiber length



Fig, 5.8. Symmetrical SC spectra at 0mm fiber length and peak pulse of 50fs

Figure 5.8 depicts an symmetrical pulse which is recorded at 0 mm length fiber by taking constant values of peak pulse 50 fs, pump wavelength 3.5 μm and peak power of 4200 W. Reason behind symmetrical pulse is the effect of only one type of non-linearity i.e., self-modulation which comes into play at 0 mm fiber length.

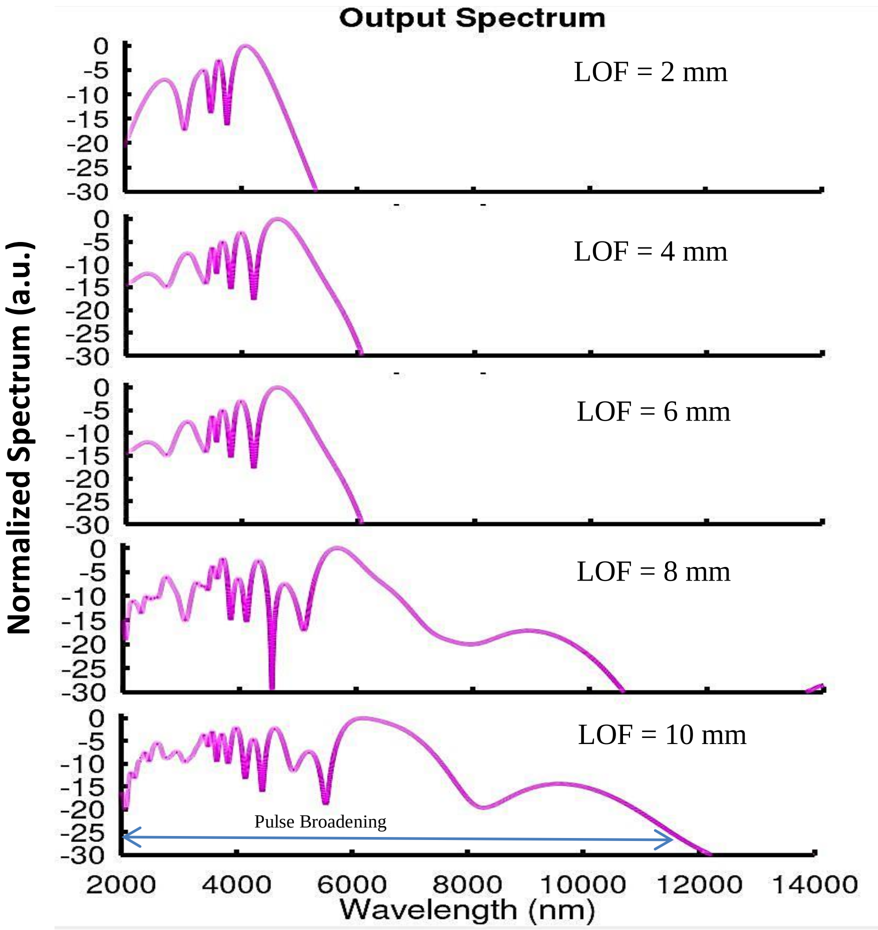


Fig. 5.9. SC spectra at different fiber lengths at peak power 4200W and pulse width (T_{FWHM}) of 50fs (LOF=Length Of Fiber)

Figure 5.9 depicts SCG spectra at different fiber lengths range from 2 mm to 10 mm by taking constant values of peak pulse 50 fs, pump wavelength 3.5 μm and peak power of 4200 W (4200 W gives a suitable SCG at previous observation, hence we have taken this particular peak power). Here we can observe that there is a transition from symmetrical pulse (given in section 5.5.3.1) to asymmetric shaped pulse which is the resultant of acting of various non-linearities like Raman scattering, cross phase modulation along with self-modulation. As we increase the fiber length, increment in broadening is observed with a maximum broadening of 2000 nm to 12000 nm in 10 mm fiber length.

Chapter 6

Conclusion

In our research work, we have presented a square core $As_{38}Se_{62}$ chalcogenide fiber and employ it for generation of supercontinuum pulse. First we go through modal analysis and calculated effective mode indices with respective areas. From the plot, we can observe that, at pump wavelength 3.5 μm, the nonlinear coefficient is spotted as 1290 W^{-1} km^{-1} and effective mode area as 15.3 μm^2. Then we plotted the dispersion versus wavelength graph which has provided us ZDW value at 3.59 μm and helped us to select 3.5 μm as pump wavelength because below 3.59 μm, dispersion curve lies in normal regime. After calculating various useful values noted above, we moved towards our main goal is to generate supercontinuum pulse. We had taken observation of SCG at different peak powers and different fiber lengths by keeping peak pulse at constant value of 50 fs. When performed experiment, we got a maximum broadened pulse of 2000 nm to 12000 nm in 4200 W peak power and 10 mm of fiber length which is very much suitable for various applications like coherence tomography, optical metrology etc.

References

[1]] P. Ma, D.Y. Choi, Y. Yu, X. Gai, Z. Yang, S. Debbarma, S. Madden, B. Luther-Davies, Low-loss chalcogenide waveguides for chemical sensing in the mid-infrared, *Opt. Express* **21 (24)** 29927–29937 (2013).

[2] B. H. Chapman, J. C. Travers, S. V. Popov, A. Mussot, and A. Kudlinski, Long wavelength extension of CW pumped supercontinuum through soliton-dispersive wave interactions *Opt. Express* **18(24)**, 24729–24734 (2010).

[3] W. J. Wadsworth, N. Joly, J. C. Knight, T. A. Birks, F. Biancalana, and P. St. J. Russell, Supercontinuum and four-wave mixing with Q-switched pulses in endlessly single-mode photonic crystal fibres *Opt. Express* **12(2)**, 299–309 (2004).

[4] A. Rulkov, M. Vyatkin, S. Popov, J. Taylor, and V. Gapontsev, High brightness picosecond all-fiber generation in 525-1800nm range with picosecond Yb pumping *Opt. Express* **13(2)**, 377–381 (2005).

[5] J. K. Ranka, R. S. Windeler, and A. J. Stentz, Visible continuum generation in air-silica microstructure optical fibers with anomalous dispersion at 800 nm *Opt. Lett*. **25(1)** 25–27 (2000).

[6] J. C. Travers, Blue extension of optical fibre supercontinuum generation *J. Opt.* **12(11)**, 113001 (2010).

[7] F. G. Omenetto, N. A. Wolchover, M. R. Wehner, M. Ross, A. Efimov, A. J. Taylor, V. V. R. K. Kumar, A. K. George, J. C. Knight, N. Y. Joly, and P. St. J. Russell, "Spectrally smooth supercontinuum from 350 nm to 3 mum in sub-centimeter lengths of soft-glass photonic crystal fibers," *Opt. Express* **14(11**), 4928–4934 (2006).

[9], R. L.Sutherland, *Handbook of nonlinear optics*. CRC press, 2003.

[10] A. Dubietis, A. Couairon, and G. Genty, Supercontinuum generation: introduction *J. Opt. Soc. Am*. **B 36,** SG1-SG3 (2019)

[8] K. Y. Yang,, Y. F. Chau,, Y. W. Huang,, H. Y. Yeh, & P. Tsai, Design of high birefringence and low confinement loss photonic crystal fibers with five rings hexagonal and octagonal symmetry air-holes in fiber cladding. *journal of applied physics*, **109(9),** 093103 . (2011).

[11] Y. Wu, M. Meneghetti, J.Troles, & J. L. Adam, Chalcogenide microstructured optical fibers for mid-infrared supercontinuum generation: interest, fabrication, and applications. *Applied Sciences*, ***8*(9)** 1637, (2018).

[12] N. Granzow, S.P. Stark, M.A. Schmidt, A.S. Tverjanovich, L. Wondraczek, P.St.J. Russell, Supercontinuum generation in chalcogenide-silica step-index fibers, Opt. Express **19 (21)** (2011) 21003–21010.

[13] J. A. Savage, Optical properties of chalcogenide glasses, *Journal of Non-Crystalline Solids*, ***47*****(1),** 101-115, (1982).

[14] M. F. Churbanov, High-purity chalcogenide glasses as materials for fiber optics. *Journal of non-crystalline solids*, **184**, 25-29, (1995).

[15] C. A. Bunge, M. Beckers, T. Gries, editors. Polymer Optical Fibres: Fibre Types, Materials, Fabrication, Characterisation and Applications. *Woodhead Publishing*; (2016).

[16] P. Pesheck, M. Lorence, editors. Development of packaging and products for use in microwave ovens. *Elsevier*; (2009).

[17] R. Ramaswami,, K. Sivarajan,, & G. Sasaki, *Optical networks: a practical perspective*. Morgan Kaufmann (2009).

[18] AH. Hamad Effects of different laser pulse regimes (nanosecond, picosecond and femtosecond) on the ablation of materials for production of nanoparticles in liquid solution. *IntechOpen;* (2016)

Appendices

Appendix 1: Plagiarism Report

turnitin

Similarity Report ID: oid:27535:17100544

PAPER NAME	AUTHOR
Final Dissertation Report II By Akash Khamaru (02) & Kajal Sharma (10) (1).pdf	Akash

WORD COUNT	CHARACTER COUNT
9418 Words	49606 Characters
PAGE COUNT	**FILE SIZE**
54 Pages	7.3MB
SUBMISSION DATE	**REPORT DATE**
May 11, 2022 12:41 PM GMT+5:30	May 11, 2022 12:43 PM GMT+5:30

4% Overall Similarity

The combined total of all matches, including overlapping sources, for each database.

- 2% Internet database
- 2% Publications database
- Crossref database
- Crossref Posted Content database
- 3% Submitted Works database

Excluded from Similarity Report

- Bibliographic material
- Small Matches (Less then 14 words)
- Manually excluded text blocks

Appendix 2: Full length research paper

Mid-IR supercontinuum generation in dispersion flattened $As_{38}Se_{62}$ chalcogenide photonic crystal fiber

A Khamaru[1], K Sharma[2], D S Tomer[3] and A Kumar[4]
Advanced Photonics Research Simulation Lab
Delhi Technological University, Delhi-110042
[1]akashkhamaru_2k20mscphy02@dtu.ac.in ,
[2]kajalsharma_2k20mscphy10@dtu.ac.in, [3]drishti_2k19phdap501@dtu.ac.in,
[4]ajeetdph@dtu.ac.in

Abstract - We have created a PCF with square shaped core using chalcogenide material $As_{38}Se_{62}$ as core and air holes in IR region, which yield very high optical non linearity of 1290 $W^{-1}Km^{-1}$ at 3.5 µm, further gives a flat dispersion profile. The fiber has been used for numerically simulate SCG using low power pump pulse width (T_{FWHM}) at 50 fs duration at 3.5 µm. At the end of 10 mm fiber, SC broadening of about 2000 to 12000 nm can be achieved with pulses of 4200 W peak power.

1. Introduction

Light is guided by photonic crystal fibers by restricting it within a recurring grid of small holes that goes the full span of the fiber. Depending on the exact arrangement of holes, they have several unique qualities like elevated nonlinearity, endlessly single mode operation, effective area, chromatic dispersion and high birefringence. PCF has property of generating SC due to non-linear properties and dispersion. Supercontinuum origin with structural coherence, wide bandwidth, and high intensity have many useful applications, such as spectroscopy, hyper spectral microscopy, and spectral tissue imaging, optical coherence tomography [1], optical metrology [2], spectroscopy, frequency comb generation [2], and multifold of wavelength division. When a nonlinear medium, like fused silica glass or PCF receives an ultrashort optical pulse, it produces a nonlinear response, the output group of spectra becomes much higher than the spectrum fed in input end, known as supercontinuum generation. Alfano and Shapiro first discovered this phenomenon in 1970s [3, 4]. Aside from the pump source, the gain medium or conversion medium is critical for the generation of supercontinua in the middle of IR region. Mid-IR fibres are divided into two types: passive fibres and active fibres. Passive fibres are used to transmit infrared data, whereas active fibres use nonlinear processes or rare-earth doping to generate Mid-IR light.

One or more chalcogen elements from Group VI A, such as Sulphur, Tellurium, Selenium, are mixed up with different metalloid elements such as (Arsenic, Germanium, Antimony, and so on, to form chalcogenide materials.) [5]. We have used the chalcogenide material ($As_{38}Se_{62}$) in our proposed design of PCF. As–S fiber can transfer from 1 - 6.5 µm, As–Se fiber can transfer from 1.5 - 10 µm, and Te-made fibers due to heavy atomic weight, can transfer beyond the 14 µm [5]. Chalcogenide material have some unique properties like broad IR transparency range and possess a nonlinear refractive index that is twice or thrice of magnitude larger than silica in the terms of optical nonlinearity. In mid-IR range and near-IR range, after exploring different methodologies, Ultra SC spectra are achieved in many works [6-10]. In the category of chalcogenide glasses, As_2Se_3 and $As_{38}Se_{62}$ have nonlinear coefficient of approximately 100 times larger than the silica glasses. $As_{38}Se_{62}$ have certain advantages and features by which we and many researchers are attracted by this material, it have huge stability against crystallization process than As_2Se_3. Apart from these features, additional features are low-loss nature and high transition temperature (165^0 C) which makes its appropriate for SC generation in Mid-IR region [11-12]. Works done by keeping $As_{38}Se_{62}$ as fiber material have several evidences. Møller et al simulated the same material PCF from 1.7-7.5 µm with pulse of 320 fs having zero dispersion at wavelength of 3.5µm[13]. Ghosh et al. reported a supercontinuum expands in range of 3.1 to 6.02 micron and 3.33 to 5.78 micron [14]. S Vyas et al. also simulate the methods of GNLSE and extracted a SC range of 2-9µm at parameters like peak pulse of 252 fs, highest peak power given as 1.33 kW and length of fiber given as 200mm [15].

In our proposed research work, we have demonstrated and simulated supercontinuum generation in IR region using chalcogenide material ($As_{38}Se_{62}$) as core material and air holes as cladding layer. We have calculated supercontinuum at pump wavelength 3500 nm and also we have taken different observation for different peak power, and fiber length.

2. Characteristics Of PCF Structure

In our proposed work, finite element method or FEM based appropriate package of software "COMSOL Multphysics" is used for simulation process of effective mode index of a particular fundamental mode and investigation of respective dispersion characteristics also. Proposed PCF is designed by wavelength dependent refractive index chalcogenide glass $As_{38}Se_{62}$ as core material whose Sellmeier equation is used and described as follows[14,15] and holes are taken of air

$$n^2(\lambda) = 3.7464 + \frac{(3.9057*\lambda^2)}{\lambda^2-0.4073^2} + \frac{(0.9466*\lambda^2)}{(\lambda^2-40.082^2)} \quad (1)$$

The Group Velocity Dispersion or GVD perform a significant aspect in SC generation because it simplifies the range of various spectral components of ultrashort pulses travel at variable phase velocities in PCF. Both GVD and nonlinearity of material are two main aspects for SCG generation.

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} \quad (2)$$

Nonlinearity of material totally depends on the nonlinear refractive index of applied material is given as follows [16]

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} \quad (3)$$

In above formula, n_2 is defined for nonlinear refractive index of $As_{38}\ Se_{62}$ glass and contains value $1.13 \times 10^{-17}\ m^2W^{-1}$ [16]. The numerical value of γ can be increased by choosing materials with large nonlinear refractive index and PCF designs with less effective mode area. λ is the pump wavelength whose value is 3.5 µm.

The effective area of travelling fundamental mode in fiber is formulated by using formula given as follows [17]

$$A_{eff} = \frac{(\iint_{-\infty}^{\infty} |E|^2 dxdy)}{(\iint_{-\infty}^{\infty} |E|^4 \, dxdy)} \tag{4}$$

Where E is the transverse distribution of electric field is extracted by simplifying eigenvalue problem from Maxwell's equations. For generation of Supercontinuum, a generalized nonlinear Schrodinger wave equation or GNLSE is solved with the help of Split-Step Fourier Method(SSFM)[18]

$$\frac{dA}{dz} + \frac{\alpha}{2} A - \left(\sum_{n \geq 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n A}{\partial t^n} \right) = i\gamma \left(1 + \frac{i}{\omega_o} \frac{\partial}{\partial t} \right) A(z,t) \int_{-\infty}^{\infty} R(t') |A(z, t - t')|^2 dt' \tag{5}$$

From the above equation we can conclude that left hand side explains the effects of linear propagation and right hand side discusses about nonlinear effects of PCF. α denotes for linear loss and the value is 0.9 dB/m [19], t denotes for time, ω_o represents n^{th} derivative of the constant of propagation β, distance is represented by z.

R(t') in the above equation describes the nonlinear Response function by consideration of nuclear and electronic contributions and the given equation of R(t') is written as follows[20]

$$R(t') = (1 - f_r)\delta(t) + f_r h_r(t') \tag{6}$$

$$h_r = \frac{\tau_i^2 + \tau_2^2}{\tau_1 \tau_2} \exp\left(-\frac{t'}{\tau_2} \right) \sin\left(\frac{t'}{\tau_1} \right) \tag{7}$$

In equations, f_r is the fractional contribution of $As_{38}Se_{62}$ chalcogenide glass whose value is 0.1. Raman parameters are defined by $\tau_1 = 23.14$ fs and $\tau_2 = 157$ fs [14].

3. Design parameter of proposed PCF

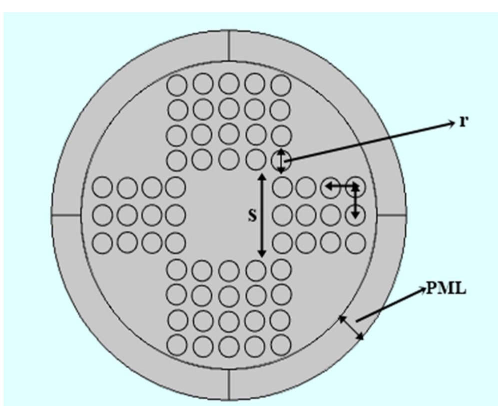


Figure 1. Proposed PCF Structure

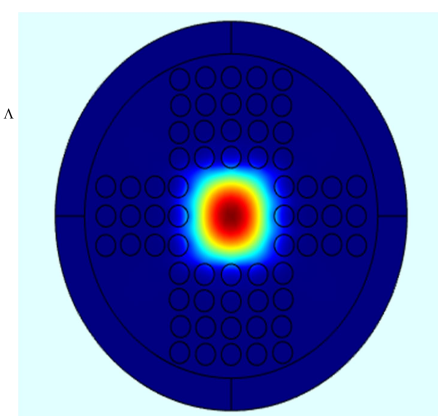


Figure 2. Fundamental mode field at 6μm wavelength

Table 1. Parameters of proposed PCF

Sr. No.	PCF Parameters		
1	r	0.6 μm	Radius Of Air Holes
2	Λ	1.5 μm	Pitch (Centre to Centre distance between holes)
3	PML	1.8 μm	Perfectly matched layer
4	s	5 μm	Side of square core

We have presented a square $As_{38}Se_{62}$ chalcogenide glass made core with length of side as 5μm with surrounded holes at four directions given in figure 1. For better flattened dispersion profile, we kept the symmetry of the fiber by keeping the diameter of air holes same in x-axis and y-axis as 1.2 μm. The centre to centre distance (pitch) of air holes is kept constant and declared by Λ whose value is 1.5 μm. Inclusion of cylindrical shaped perfectly matched layer or PML declines the reflection back effect at boundary region. Our aim is to achieve flat normal dispersion region and acquire zero dispersion wavelength which helps us to grab our pump wavelength for SC generation. Square core is taken for its high mode area which adds up to nonlinearity magnitude. After simulating for fundamental mode in square core PCF at 6μm wavelength, we get such type of output given in figure 2.

4. Results & discussions

After exploring the numerical simulations of the proposed square core chalcogenide PCF structure have acquired a wide dispersion above the anomalous region given in figure 3. A zero-dispersion wavelength is obtained at 3.59 μm with anomalous dispersion range that is well suited for pumping of the PCF with a peak pump power at pump wavelength given as 3.5 μm.

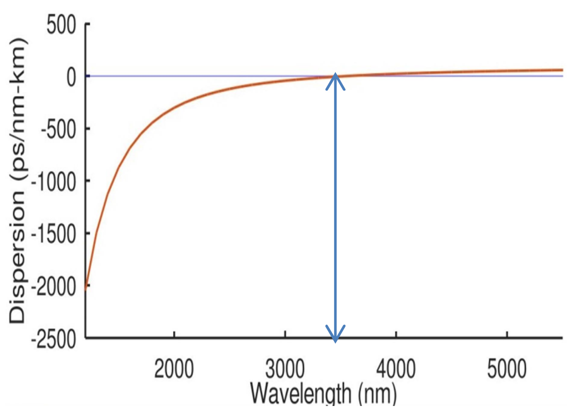


Figure 3. Plot of dispersion with respect to wavelength at ZDW 3.59 μm.

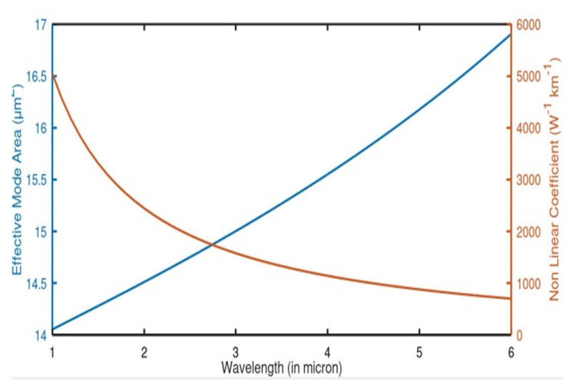


Figure 4. Plot of Nonlinear Coefficient and effective mode area of proposed fiber

Apart from dispersion flattening, there are two parameters also to taken care of. These are nonlinear coefficient and effective mode area at fundamental mode. For simulation of these parameters, we obtained a plot of nonlinear coefficient and effective mode area with respect to wavelength shown in figure 4. From the plot, we can observe that, at pump wavelength 3.5 μm, the coefficient of nonlinearity is spotted as 1290 $W^{-1} km^{-1}$ and effective mode area as 15.3 μm^2 .

After exploring the linear and nonlinear characteristics of PCF, calculating the coefficient of nonlinearity and EM area and plotting both the normal as well as anomalous dispersion regime with zero dispersion wavelength or ZDW at 3.59 μm, we have to proceed with SC generation part by extrication of GNLSE which was acquired by split step Fourier method or SSFM for input pulses at variable peak powers, different lengths of fiber etc. Figure 5 display the Supercontinuum broadening at 4000 W with the length of 10 mm fiber.

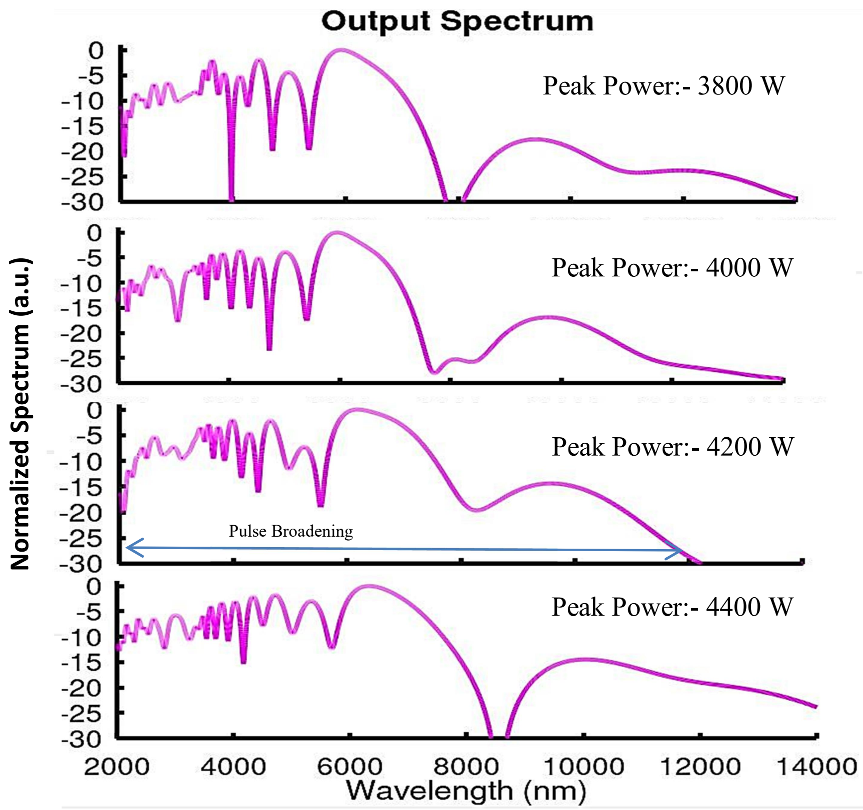


Figure 5. SC spectra at different peak powers at 10 mm fiber length and pulse width (T_{FWHM}) of 50 fs

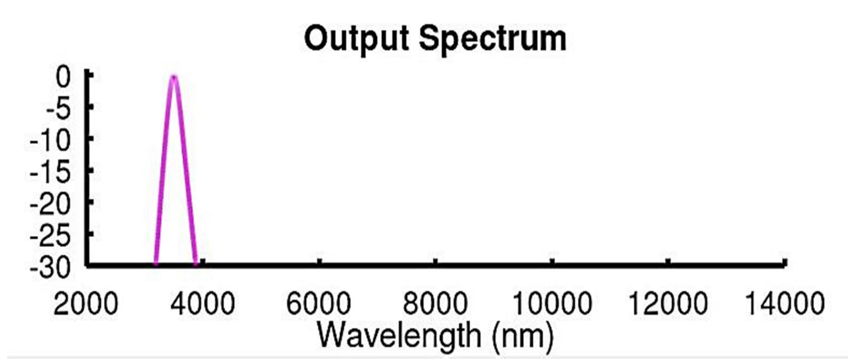


Figure 6. Symmetrical SC spectra at 0mm fiber length and pulse width (T_{FWHM}) of 50fs

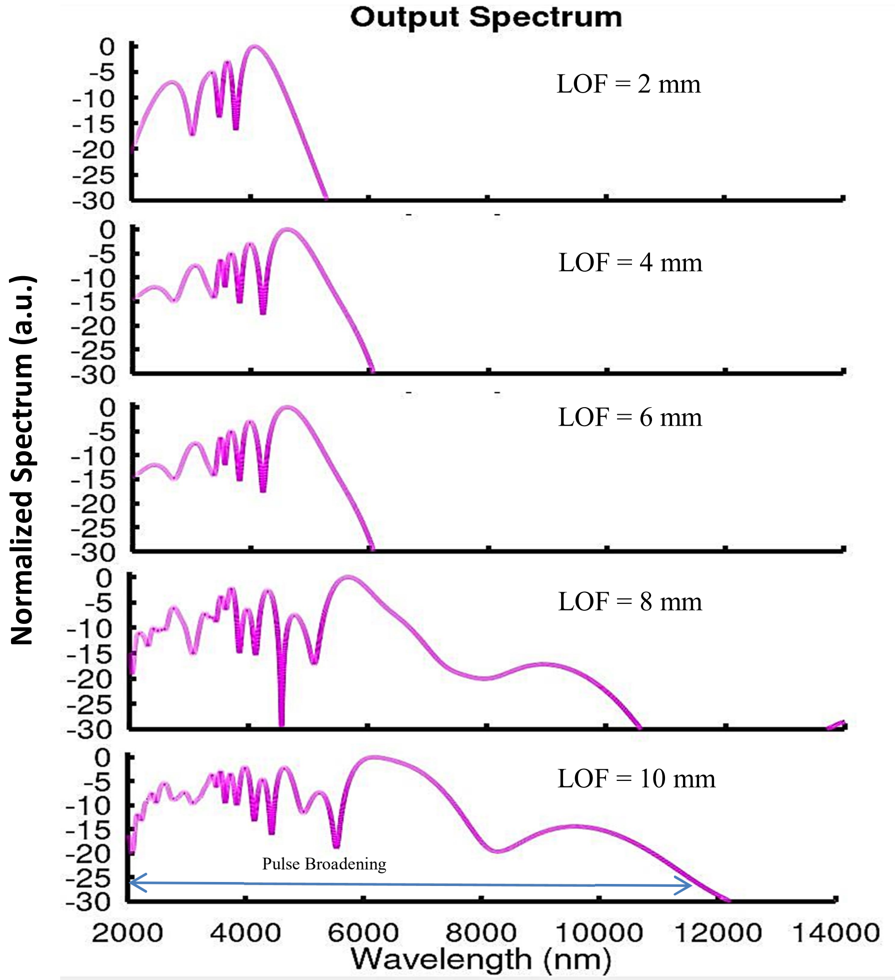


Figure 7. SC spectra at different fiber lengths at peak power 4200W and pulse width (T_{FWHM}) of 50fs (LOF=Length Of Fiber)

Figure 5 shows that at increment in peak power from 3800 W to 4200 W by keeping length of fiber and pulse width (T_{FWHM}) constant at values 10 mm and 50 fs respectively, there is a broadening in SC generated at every case. At 3800 W, there is a breakage in SC pulse and same thing happens to 4200 W. We get a best and optimized broadening at 4200 W with a broadened SC with range of 2 μm -12 μm.

Figure 7 shows that at increasing the length of fiber from and pulse width (T_{FWHM}) constant at values 4200 W and 50 fs respectively; there is a broadening in SC generated at every case. At 10 mm, we get maximum broadening of 2 μm -12.0 μm. At 0 mm, there is a symmetrical pulse which is due to only SPM (Self Phase Modulation) shown in figure 6. But when we increase the fiber length, many nonlinear effects come into play like four wave mixing, Raman scattering which diminish the symmetrical nature and offers us a broad SC spectra. Such Mid-IR SC spectra offers application in optical tomography, spectroscopy, detection of cancer cells, food quality control etc.

5. Conclusion

Our proposed design of PCF offers a broadening of Supercontinuum pulse at a range of 2-12 μm which mostly covers the mid-IR region at peak power of 4200 W having the length of 10 mm and pulse width (T_{FWHM}) of 50 fs. Along with the SC broadening, we get a high nonlinearity value of 1290 $W^{-1}km^{-1}$ at pump wavelength taken as 3.5 μm and effective mode area calculated as 15.3μm^2. From figure 7, we can understand that if we increase the peak power beyond 4000 W and below 3800 W, there is a discontinuity of SC pulse.

6. References

[1] Hartl I, Li XD, Chudoba C, Ghanta RK, Ko TH, Fujimoto JG, Ranka JK, Windeler RS Ultrahigh-resolution optical coherence tomography using continuum generation in an air–silica microstructure optical fiber. 2001 May 1 *Optics letters.* **26(9)** 608-10

[2] Ye J, Schnatz H, Hollberg LW Optical frequency combs: from frequency metrology to optical phase control 2003 Dec 8 *IEEE Journal of Selected Topics in Quantum Electronics* **9(4)** 1041-58

[3] Alfano RR, Shapiro SL Emission in the region 4000 to 7000 Å via four-photon coupling in glass. 1970 Mar 16 *Physical Review Letters* **24(11)** 584.

[4] Alfano RR, Shapiro SL Observation of self-phase modulation and small-scale filaments in crystals and glasses 1970 Mar 16 Physical Review Letters **24(11)** 592.

[5] Borisova ZU 1981 *Glassy Semiconductors* Springer: New York, NY, USA,

[6] Karim MR, Rahman BM, Agrawal GP Dispersion engineered $Ge_{11.5}As_{24}Se_{64.5}$ nanowire for supercontinuum generation: A parametric study 2014 Dec 15 *Optics Express* **22(25)** 31029-40

[7] Saini TS, Kumar A, Sinha RK Broadband mid-infrared supercontinuum spectra spanning 2–15 μm using As_2Se_3 chalcogenide glass triangular-core graded-index photonic crystal fiber 2015 Sep 15 *Journal of lightwave technology* **33(18)** 3914-20

[8] Saini TS, Kumar A, Sinha RK. Broadband mid-IR supercontinuum generation in As_2Se_3 based chalcogenide photonic crystal fiber: A new design and analysis 2015 Jul 15 *Optics Communications* **347** 13-9.

[9] Saini TS, Baili A, Kumar A, Cherif R, Zghal M, Sinha RK. Design and analysis of equiangular spiral photonic crystal fiber for mid-infrared supercontinuum generation 2015 Nov 11 *Journal of modern optics* **62(19)** 1570-6

[10] Chaitanya AGN, Saini TS, Kumar A, Sinha RK Ultra broadband mid-IR supercontinuum generation in $Ge_{11.5}As_{24}Se_{64.5}$ based chalcogenide graded-index photonic crystal fiber: design and analysis 2016 *Applied optics*, **55(36)** 10138-45

[11] Mazhorova A, Markov A, Ung B, Rozé M, Gorgutsa S, Skorobogatiy M. Thin chalcogenide capillaries as efficient waveguides from mid-infrared to terahertz 2012 Aug 1 *JOSA B* **29(8)** 2116-23

[12] Vyas S, Tanabe T, Tiwari M, Singh G. Chalcogenide photonic crystal fiber for ultraflat mid-infrared supercontinuum generation 2016 Dec 10 *Chinese optics letters* **14(12)** 123201

[13] Møller U, Yu Y, Kubat I, Petersen CR, Gai X, Brilland L, Méchin D, Caillaud C, Troles J, Luther-Davies B, Bang O. Multi-milliwatt mid-infrared supercontinuum generation in a suspended core chalcogenide fiber 2015 Feb 9 *Optics express* **23(3)** 3282-91

[14] Ghosh AN, Meneghetti M, Petersen CR, Bang O, Brilland L, Venck S, Troles J, Dudley JM, Sylvestre T. Chalcogenide-glass polarization-maintaining photonic crystal fiber for mid-infrared supercontinuum generation 2019 Sep 5 *Journal of Physics: Photonics* **1(4)** 044003

[15] Vyas S, Shiong NS, Kumar A, Sharma G, Chandna VK, Singh G. Mid-infrared supercontinuum generation using low peak pump power in $As_{38}Se_{62}$ based chalcogenide photonic crystal fiber 2021 Mar 1 *InIOP Conference Series: Materials Science and Engineering* **1119(1)** 012022

[16] Diouf M, Salem AB, Cherif R, Wague A, Zghal M. High power broadband mid-infrared supercontinuum fiber laser using a novel chalcogenide $AsSe_2$ photonic crystal fiber 2016 May 1 *Optical Materials* **55** 10-6

[17] Kalra S, Vyas S, Tiwari M, Buryy O, Singh G. Highly nonlinear multi-material chalcogenide spiral photonic crystal fiber for supercontinuum generation 2018 Apr 1 *Acta Physica Polonica* **133(4)** 1000-2

[18] Sandeep V, Takasumi T, Ghanshyam S, Manish T. Ultraflat broadband supercontinuum in highly nonlinear $Ge_{11.5}As_{24}Se_{64.5}$ photonic crystal fibres 2016 *Ukrainian journal of physical optics* **17(3)** 132-9

[19] Le SD, Nguyen DM, Thual M, Bramerie L, e Silva MC, Lenglé K, Gay M, Chartier T, Brilland L, Méchin D, Toupin P. Efficient four-wave mixing in an ultra-highly nonlinear suspended-core chalcogenide $As_{38}Se_{62}$ fiber 2011 Dec 12 *Optics Express* **19(26)** B653-60

[20] Kalra S, Vyas S, Tiwari M, Ismail Y, Yupapin P, Ali J, Singh G. Investigation of As_2S_3-borosilicate chalcogenide glass-based dispersion-engineered photonic crystal fibre for broadband supercontinuum generation in the mid-IR region 2020 Jun 6 *Journal of Modern Optics* **67(10)** 920-60

Appendix 3: Abstract acceptance mail

Fwd: Notification of Acceptance of Abstract: ICCTPP - 2022 External Inbox ×

ICCTPP Physics <icctpp@mitwpu.edu.in> Wed, Apr 20, 9:29 PM

to kajalsharma_2k20mscphy10, me, drishti_2k19phdap501@dtu.ac.in, ajeetdph@dtu.ac.in

Dear Author,

We are pleased to inform you that your abstract has been accepted for presentation in ICCTPP-2022. **Please note that you are advised to duly register for the conference AND submit the full paper before 25th May 2022**.

The guidelines for preparation of the manuscript should be as per IOP Publishing and these can be found at: https://publishingsupport.iopscience.iop.org/author-guidelines-for-conference-proceedings/

Please note that the full papers will be sent for peer review and the similarity percentage should be below 20%. We look forward to receiving your full paper. Please revert to us in case of any problems or queries.

With Warm Regards,

Organizing Committee
International Conference on Current Trends in Physics and Photonics (ICCTPP-2022)
icctpp.mitwpu.edu.in

School of Physics,
MIT World Peace University,
Pune, Maharashtra - 411038
India
https://physics.mitwpu.edu.in/

Appendix 4: Registration slip for proof of conference registration

Physics Conference Payment Status

TXNID:	20220423111212800110168486539464204
BANKTXNID:	185496752930
TXNAMOUNT:	4900.00
BANKNAME:	WALLET
GATEWAYNAME:	WALLET
STATUS:	TXN_SUCCESS
RESPCODE:	01
RESPMSG:	Txn Success
TXNDATE:	2022-04-23 23:07:49.0

Appendix 5: Paper acceptance mail

Your Submission ICCTPP 144 External Inbox ×

ICCTPP Physics <icctpp@mitwpu.edu.in>
to me

Mon, May 9, 10:56 AM (2 days ago)

Dear Akash Khamaru,

We are pleased to inform you that your manuscript Mid-IR supercontinuum generation in dispersion flattened As38Se62 chalcogenide photonic crystal fiber has been accepted for presentation in the conference. All accepted and presented papers will be included in the proceedings in Journal of Physics:Conference Series.

With Warm Regards,

Organizing Committee
International Conference on Current Trends in Physics and Photonics (ICCTPP-2022)
icctpp.mitwpu.edu.in

School of Physics,
MIT World Peace University,
Pune, Maharashtra - 411038
India
https://physics.mitwpu.edu.in/

On Thu, May 5, 2022 at 9:35 PM 2K20\MSCPHY\02\AkashKhamaru <akashkhamaru_2k20mscphy02@dtu.ac.in> wrote:

> Respected Sir,
>
> I have kept the FWHM value constant at 50 fs and modified as follows.

(whole reply of mail is attached in following pages)

DTU Delhi Technological University

2K20\MSCPHY\02\AkashKhamaru <akashkhamaru_2k20mscphy02@dtu.ac.in>

Your Submission ICCTPP 144

1 message

ICCTPP Physics <icctpp@mitwpu.edu.in> Mon, May 9, 2022 at 10:56 AM
To: "2K20\\MSCPHY\\02\\AkashKhamaru" <akashkhamaru_2k20mscphy02@dtu.ac.in>

Dear Akash Khamaru,

We are pleased to inform you that your manuscript Mid-IR supercontinuum generation in dispersion flattened As38Se62 chalcogenide photonic crystal fiber has been accepted for presentation in the conference. All accepted and presented papers will be included in the proceedings in Journal of Physics:Conference Series.

With Warm Regards,

Organizing Committee
International Conference on Current Trends in Physics and Photonics (ICCTPP-2022)
icctpp.mitwpu.edu.in

School of Physics,
MIT World Peace University,
Pune, Maharashtra - 411038
India
https://physics.mitwpu.edu.in/

On Thu, May 5, 2022 at 9:35 PM 2K20\MSCPHY\02\AkashKhamaru <akashkhamaru_2k20mscphy02@dtu.ac.in> wrote:

> Respected Sir,
>
> I have kept the FWHM value constant at 50 fs and modified as follows.
>
> I have modified following aspects:-
>
> i) The work is good and need of the hour, but saying the output mentioned in your abstract 200nm to 1300 nm in mid-infrared is wrong as it falls in the category of near-infrared.
>
> Modification:- There is a typing mistake in my paper. I have edited and changed the limit from 2000 nm to 12500 nm (2000 nm starts from Mid-IR)
>
> ii) As mentioned in figure 7, the pulse broadening (without FWHM) is up to 1200nm only, but you have reported 1300nm at length 10 mm and peak power of 4200. kindly correct this issue.
>
> Modification:- I have corrected and changed the final limit to 12000 nm
>
> iii) While measuring pulse broadening, you have ignored the most important physical parameter FWHM. Kindly incorporate at all needful places.
>
> Modification:- I have added the "pulse width (TFwhm)" in needful places
>
> Please check my modifications and reply back if there is a need of any further modifications.
> I will be highly grateful
> I will wait for your response
>
> Thank You
> Akash Khamaru
> Delhi Technological University

On Thu, May 5, 2022 at 11:24 AM ICCTPP Physics <icctpp@mitwpu.edu.in> wrote:

Dear Author,
Kindly find the review report for your manuscript. The reviewers are advising revision of your paper. Kindly revert back with the revised manuscript.

Reviewer #1

The present manuscript deals with the supercontinuum source generation using binary chalcogenide material PCF square fiber. Supercontinuum generation is when laser light is converted to light with a very broad spectral bandwidth (i.e., low temporal coherence), i.e., a super-wide continuous optical spectrum. This means that the temporal coherence is very low. The spectral broadening is usually accomplished by propagating light pulses through a strongly nonlinear device. There are many examples also in real-life practice. Therefore pulse time, pulse energy, effective mode area, FWHM etc., are a few important parameters that play a crucial role in generating supercontinuum sources. One more thing, the range of near-infrared region is approx 800 nm to 2500 nm, while the mid-infrared region is approx 1300nm to 3000nm. so keeping in mind the above description, I suggest the authors explain the following points or correct those things in your manuscript before acceptance.
1. The work is good and need of the hour, but saying the output mentioned in your abstract 200nm to 1300 nm in mid-infrared is wrong as it falls in the category of near-infrared.
2. As mentioned in figure 7, the pulse broadening (without FWHM) is up to 1200nm only, but you have reported 1300nm at length 10 mm and peak power of 4200. kindly correct this issue.
3. While measuring pulse broadening, you have ignored the most important physical parameter FWHM. Kindly incorporate at all needful places.

With Warm Regards,

Organizing Committee
International Conference on Current Trends in Physics and Photonics (ICCTPP-2022)
icctpp.mitwpu.edu.in

School of Physics,
MIT World Peace University,
Pune, Maharashtra - 411038
India
https://physics.mitwpu.edu.in/

On Mon, May 2, 2022 at 12:19 AM 2K20\MSCPHY\02\AkashKhamaru <akashkhamaru_2k20mscphy02@dtu.ac.in> wrote:

Respected Sir,

I have attached the modified full paper. Please check for any corrections/plagiarized content.
I will wait for your response.

On Sun, May 1, 2022 at 6:22 PM ICCTPP Physics <icctpp@mitwpu.edu.in> wrote:

Dear Akash Khamaru,

We have received your full paper. Kindly find attached the plagiarism report. Similarity should be strictly less than 20%, preferably in the range of 10-15%. Kindly modify the manuscript and resubmit.

With Warm Regards,

Organizing Committee
International Conference on Current Trends in Physics and Photonics (ICCTPP-2022)
icctpp.mitwpu.edu.in

School of Physics,
MIT World Peace University,
Pune, Maharashtra - 411038
India
https://physics.mitwpu.edu.in/

On Sun, Apr 24, 2022 at 9:38 AM 2K20\MSCPHY\02\AkashKhamaru <akashkhamaru_2k20mscphy02@dtu.ac.in> wrote:

Respected sir,

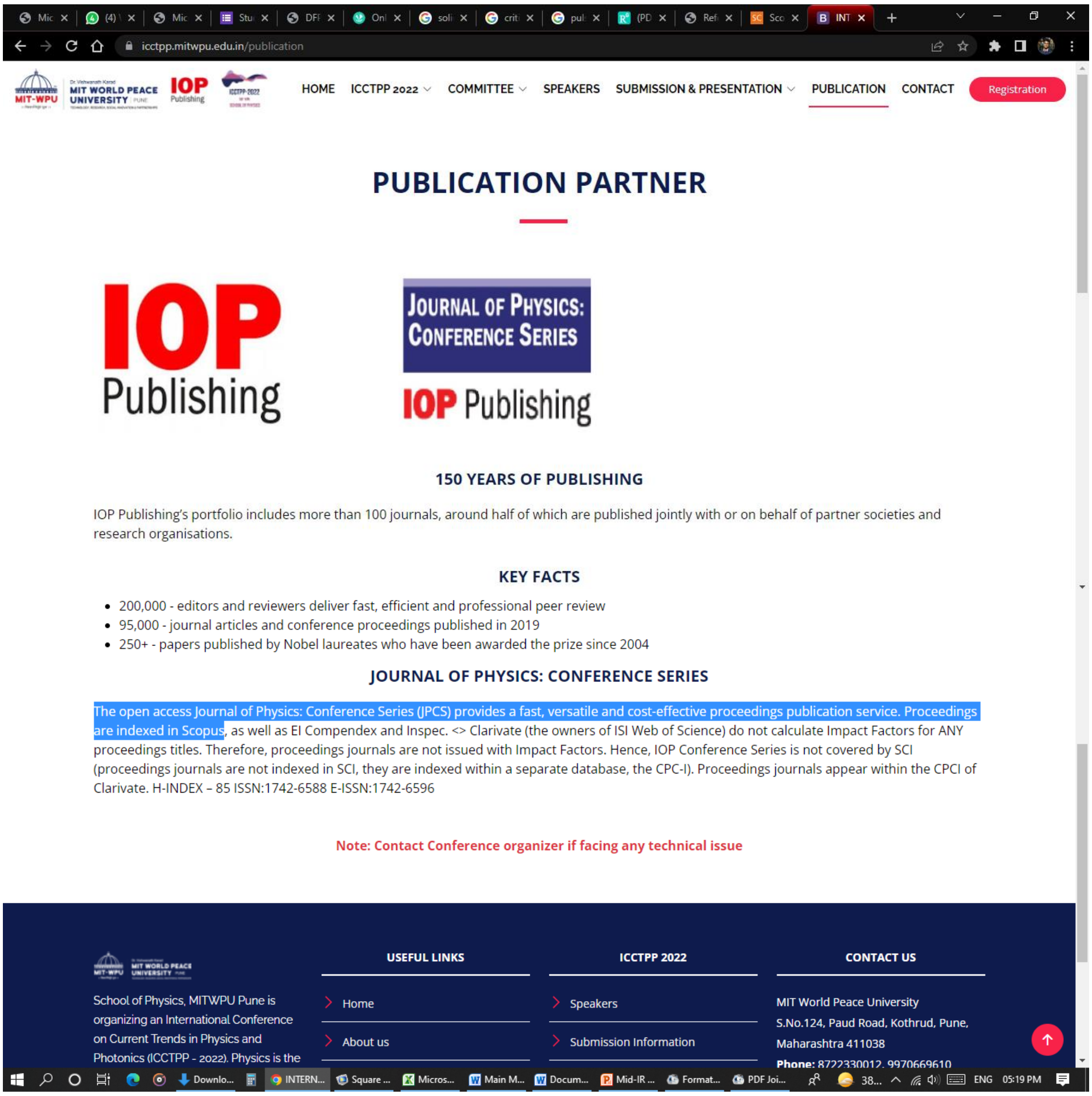
Yesterday i had registered and submitted my full paper. my abstraction id is ICCTPP144. But i didn't get any acknowledgement mail after registering. Is it a glitch or technical issue?

So, i have a request to you to check my registration status and confirm me with registration id (if any).

I have attached the fees receipt for your reference.

Thanking you,
Akash Khamaru
M.Sc. Physics
Delhi Technological University

Appendix 6: Proof of SCOPUS indexing



icctpp.mitwpu.edu.in/publication

HOME ICCTPP 2022 COMMITTEE SPEAKERS SUBMISSION & PRESENTATION PUBLICATION CONTACT Registration

PUBLICATION PARTNER

IOP Publishing

Journal of Physics: Conference Series

IOP Publishing

150 YEARS OF PUBLISHING

IOP Publishing's portfolio includes more than 100 journals, around half of which are published jointly with or on behalf of partner societies and research organisations.

KEY FACTS

- 200,000 - editors and reviewers deliver fast, efficient and professional peer review
- 95,000 - journal articles and conference proceedings published in 2019
- 250+ - papers published by Nobel laureates who have been awarded the prize since 2004

JOURNAL OF PHYSICS: CONFERENCE SERIES

The open access Journal of Physics: Conference Series (JPCS) provides a fast, versatile and cost-effective proceedings publication service. Proceedings are indexed in Scopus, as well as EI Compendex and Inspec. <> Clarivate (the owners of ISI Web of Science) do not calculate Impact Factors for ANY proceedings titles. Therefore, proceedings journals are not issued with Impact Factors. Hence, IOP Conference Series is not covered by SCI (proceedings journals are not indexed in SCI, they are indexed within a separate database, the CPC-I). Proceedings journals appear within the CPCI of Clarivate. H-INDEX – 85 ISSN:1742-6588 E-ISSN:1742-6596

Note: Contact Conference organizer if facing any technical issue

USEFUL LINKS: Home, About us

ICCTPP 2022: Speakers, Submission Information

CONTACT US: MIT World Peace University S.No.124, Paud Road, Kothrud, Pune, Maharashtra 411038 Phone: 8722330012, 9970669610

School of Physics, MITWPU Pune is organizing an International Conference on Current Trends in Physics and Photonics (ICCTPP - 2022). Physics is the

Source details

Journal of Physics: Conference Series

Scopus coverage years: from 2005 to Present
ISSN: 1742-6588 E-ISSN: 1742-6596
Subject area: Physics and Astronomy: General Physics and Astronomy
Source type: Conference Proceeding

View all documents > Set document alert Save to source list Source Homepage

CiteScore 2020
0.7

SJR 2020
0.210

SNIP 2020
0.464

CiteScore CiteScore rank & trend Scopus content coverage

i Improved CiteScore methodology
CiteScore 2020 counts the citations received in 2017-2020 to articles, reviews, conference papers, book chapters and data papers published in 2017-2020, and divides this by the number of publications published in 2017-2020. Learn more >

CiteScore 2020

0.7 = 52,411 Citations 2017 - 2020 / 72,842 Documents 2017 - 2020

Calculated on 05 May, 2021

CiteScoreTracker 2021

0.8 = 74,171 Citations to date / 96,659 Documents to date

Last updated on 06 April, 2022 • Updated monthly

CiteScore rank 2020

Category	Rank	Percentile
Physics and Astronomy — General Physics and Astronomy	#191/233	18th

View CiteScore methodology > CiteScore FAQ > Add CiteScore to your site