Design and Analysis of Supercontinuum Generation in Optical Fibers

A Dissertation submitted towards the partial fulfilment of
the requirement for the award of degree of

Master of Technology in
Microwave and Optical Communication Engineering

Submitted by
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CERTIFICATE

This is to certify that the work which is being presented in the dissertation entitled " **Design and Analysis of Supercontinuum Generation in Optical Fibers**" is the authentic work of **Priti** under my guidance and supervision in the partial fulfilment of requirement towards the degree of Master of Technology in Microwave and Optical Communication Engineering jointly run by Department of Applied Physics and Department of Electronics and Communication in Delhi Technological University during the 2015-17.

As per the candidate declaration this work has not been submitted elsewhere for the award of any other degree.

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I hereby declare that all the information in this document has been obtained and presented in accordance with academic rules and ethical conduct. This thesis is my own, unaided work. I have fully cited and referenced all material and results, that are not original to this work. It is being submitted for the degree of Master of Technology in Microwave and Optical Communication Engineering at Delhi Technological University, Delhi. It has not been submitted for any degree or examination in any other university.

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LIST OF RESEARCH WORK AND PUBLICATIONS

Publication

1. Priti, Ajeet Kumar, Than Singh Saini, **"**Broadband Supercontinuum Generation Spanning 1.5 – 13 µm in $Ge_{11.5}As_{24}Se_{64.5}$ based Chalcogenide Glass Step Index Optical Fiber", Journal of Modern Optics (Communicated – April 2017).

Conference

1. Priti, Ajeet Kumar, Than Singh Saini, "Supercontinuum generation in $Ge_{11.5}As_{24}Se_{64.5}$ based chalcogenide few-mode fiber", The International Conference on Fiber Optics and Photonics (PHOTONICS 2016), 4-8 December 2016.

ABSTRACT

Optic fiber communication is the transmission of light as a signal through an optically transparent medium which acts as channel using the principle of total internal reflection. The channel is a cylindrical waveguide of dielectric medium. The area in which the light travels is called core. Initially LED's were used as light source which were having low intensity and low coherence.

After invention of laser light for optical transmission through optical fiber, the phenomenon of nonlinear effects was discovered. The input-output power relation was no more linear and certain losses were observed and the losses increased with increase in input power. Investigation revealed that the high intensity optical light will give rise to certain nonlinear effects. This was due to response of the dielectric material to high intensity electromagnetic field. The polarization induced by electric dipoles is not linear to electric field.

The nonlinear effect give rise to two important effects called Kerr effect which is second order nonlinearity and third order nonlinearity called Pockel effect. These effects have resulted in many phenomena such as Cross-phase modulation, Self-phase modulation, Stimulated Raman Scattering, Four wave mixing etc. The effect is dependent on material and geometry of the fiber.

Super Continuum Generation or SCG is a process that is a result due to interplay between linear and nonlinear effects. It is a process where a continuous spectrum of light is generated when a high intensity short duration laser pulse is propagated through a highly non-linear fiber. The resultant spectrum will have low temporal coherence (high bandwidth) and high spatial coherence.

The project involves design and analysis of supercontinuum generation in an optical fiber. SCG has been simulated in a $Ge_{11.5}As_{24}Se_{64.5}$ Chalcogenide glass step index fiber using vectorial finite element based COMSOL Multiphysics and MATLAB.

Silica has a very low nonlinear refractive index. Silica based optical fibers display very low nonlinear coefficient. Higher optical power and longer length of the fiber are required for SCG.

Chalcogenide fibers have very high nonlinear coefficient and is transparent in near-IR and mid-IR region. Hence a chalcogenide glass fiber has been designed for generation an ultra - broadband continuum at near-IR and mid-IR region with a low peak power.

Such ultra-broadband supercontinuum spectrum is expected to have profound applications in various fields. The specific applications of mid-IR supercontinuum generation include spectroscopy, optical coherence tomography, frequency comb generation, early cancer detection, food quality control, security and sensing.

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CHAPTER 1

INTRODUCTION

The research work in this thesis is related to supercontinuum generation (SCG). SCG is the extreme broadening of the spectrum of the light pulse due to the nonlinearity of the medium. The nonlinear effects come into effect when a high intensity pulse of short duration propagates along the fiber length. Nonlinear effects are responsible for the generation of the new frequencies. These new frequencies enhance the broadening of the SCG spectra. Broadening of the SCG spectrum depends upon the structural properties of the fiber also. It mainly depends upon the refractive index difference between core and cladding. Lesser is the refractive indices difference, more will be the broadening of the supercontinuum generation spectrum. Due to its high coherence property, SCG has a wide number of applications in the fields of metrology, optical biography, bio medical research, and long distance communication with improved efficiency.

1.1 Aim of the thesis

The aim of the present thesis is to get stable and more broadening of the SCG spectra. A step index fiber is designed using a chalcogenide material $Ge_{11.5}As_{24}Se_{64.5}$ which has a high nonlinear refractive index value which is responsible for nonlinear effects occurrence. This material has very high optical as well as thermal stability even if very high intensity laser pulse is used. A SCG spectra ranging from 1.5-13 μm has been generated when a pulse of 50 fs width with a power of 4 kW is used.

Various parameters including fundamental mode, effective mode area, propagation loss, and nonlinear coefficient of the material in the fiber and PCF has been studied using COMSOL Multiphysics software. The dispersion properties of the material and effect of the pump wavelength near zero dispersion also has been studied. The various nonlinear effects such as self – phase modulation, cross – phase modulation, modulation instability, four wave mixing and Raman effect are observed using MATLAB software with COMSOL Multiphysics software. Also, various numerical techniques are also taken into the consideration. In the end, the influences of power intensity, input pulse duration and length of the fiber on SCG spectra has been studied.

1.2 Thesis organisation

The present thesis consists of six chapters. The thesis organisation is such as

- Chapter 1 contains the introduction of the supercontinuum generation and thesis organisation, aim and approach.
- Chapter 2 aims at the various types of the fibers used for the optoelectronics operations such as step index fiber, photonic crystal fiber etc.
- Chapter 3 explains the various nonlinear effects occurring inside the fiber material which are the major factors for the generation of supercontinuum spectrum.
- Chapter 4 tells about the solution of the generalised nonlinear Schrödinger wave equation (GNLSE) and explains how various parameters such as core size, pulse intensity, pulse width, dispersion etc. affect the broadening and stability of the SCG spectrum.
- Chapter 5 includes the various softwares and numerical techniques used for getting the solution of the complex partial differentiation or integral equations with the fast and efficient method. These methods and softwares have made the computation more accurate, fast and reliable. Also, it saves the time consumption.
- Chapter 6 is the last chapter of our thesis, here we conclude with the results obtained in the present research work and it contains the future work which can be performed to enhance the desired results.

CHAPTER 2

OPTICAL FIBERS AND ITS TYPES

2.1 Introduction

Optical fiber is a hollow structured waveguide made of dielectric material through which the information is guided in the form of light using the phenomenon of total internal reflection(TIR). Guiding light in a strand of dielectric material was first shown in the 19th century, in a stream of water using total internal reflection phenomenon [1]. The necessary condition for the occurance of the phenomenon of total internal reflection:

a) The light must travel from high refractive index medium to low refractive index medium.

b) The incidence angle in the high refractive index medium should be larger than the critical angle (θ_c) of the media interface.

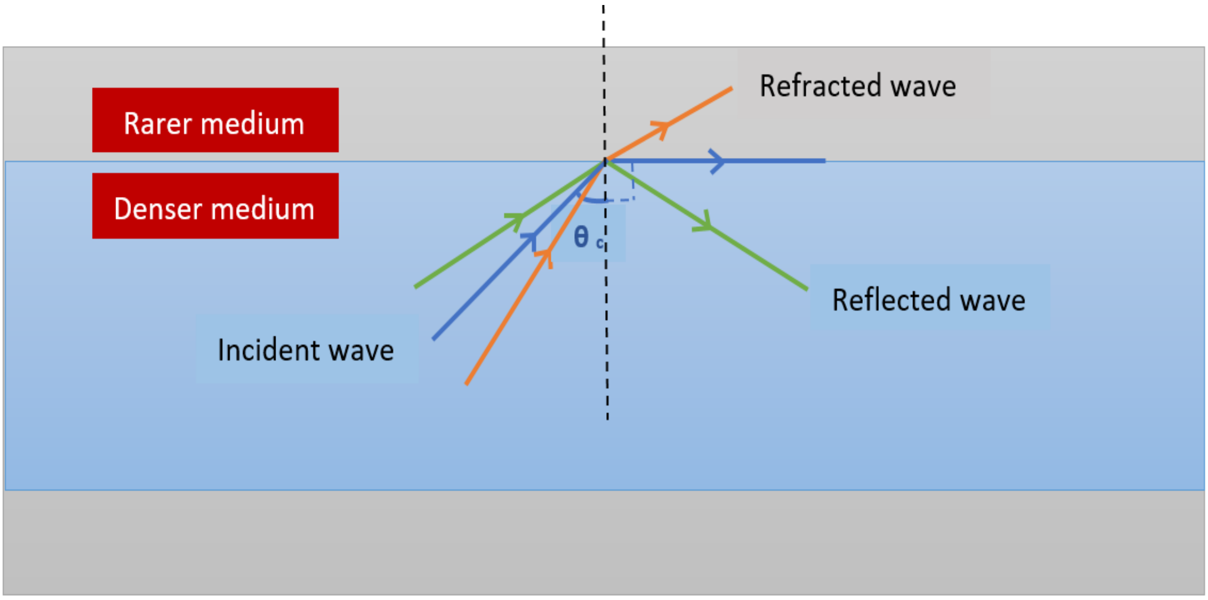


Fig.2.1 Total Internal Reflection phenomenon in an optical fiber

The difference between the core and cladding refractive indices defines the angle of entrance of the incoming wave in the fiber (which is known as numerical aperture of fiber).

2.2 Classification of the fibers

Optical fibers can be categorised based on their structure design. Fibers are categorised such as

2.2.1 Single mode fiber

Optical fibers having the core diameter of a few wavelengths of the wavelength of the light propagating into the fiber are known as single mode fibers. The core diameter is reduced in such a manner that only the fundamental mode is supported by the fiber. Due to this property, single mode fibers are used for long distance communication to increase the baud data rates.

2.2.2 Multimode fiber

Optical fibers which supports numerous modes of propagation to travel through their structure are known as multimode fibers. The diameter of the core is very large compared to the wavelength of the light travelling through it. The number of modes that can travel through the fiber depends on the diameter of the core. As the diameter of the core increases, the number of travelling modes also increases simultaneously. The multimode fibers can be divided further into two categories as follows

2.2.2.1 Step index fiber

The optical fiber in which core and cladding have constant refractive index profiles, where the core refractive index is higher than that of cladding refractive index. There is a sharp decrease in the refractive index at the core-cladding interface of the fiber as shown in the fig.2.2. Step-index fibers are generally fabricated using vapour deposition techniques [2].

Step index fiber is not preferred for supercontinuum generation mainly due to two reasons:

a) Due to more difficulty in dispersion engineering which is the basis for SCG
b) Due to large mode area.

But by using appropriate non-linear medium, dispersion properties as well as effective mode area can be altered.

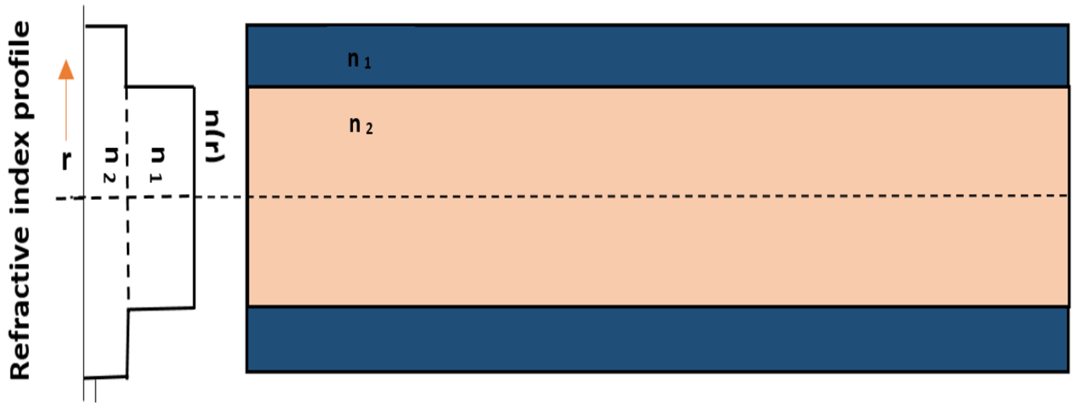


Fig.2.2. Refractive index profile of a step index fiber

2.2.2.2 Graded index fiber

Optical fibers having a gradual decrease in refractive index profile from core to the core-cladding interface are known as graded index fibers. The refracted index profile of graded index fiber is shown in fig.2.3. Graded index fibers are preferred for the telecommunication applications. Parabolic profile of refractive index offers less modal dispersion, hence resulting in long distance communication.

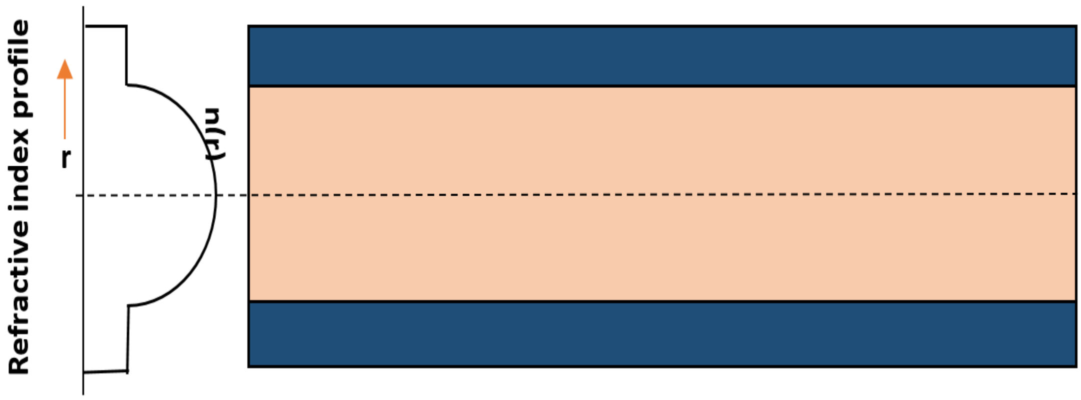


Fig.2.3. Parabolic refractive index profile of graded index fiber

2.2.3 Special purpose fiber: Photonic crystal fiber

Photonic crystal fibers use photonic crystal to form the cladding around the fiber core. These fibers obtain their waveguide properties by various glass compositions used to construct it as well as from the specially arranged air holes forming the cladding. Photonic crystal is basically a dielectric material with low loss. A defect is realized in photonic crystal fiber by removing one or more than one capillaries from its structure. Light can propagate in defects of its crystalline structure in the fiber. PCFs mainly be divided into following two classes:

a) Index guiding PCF

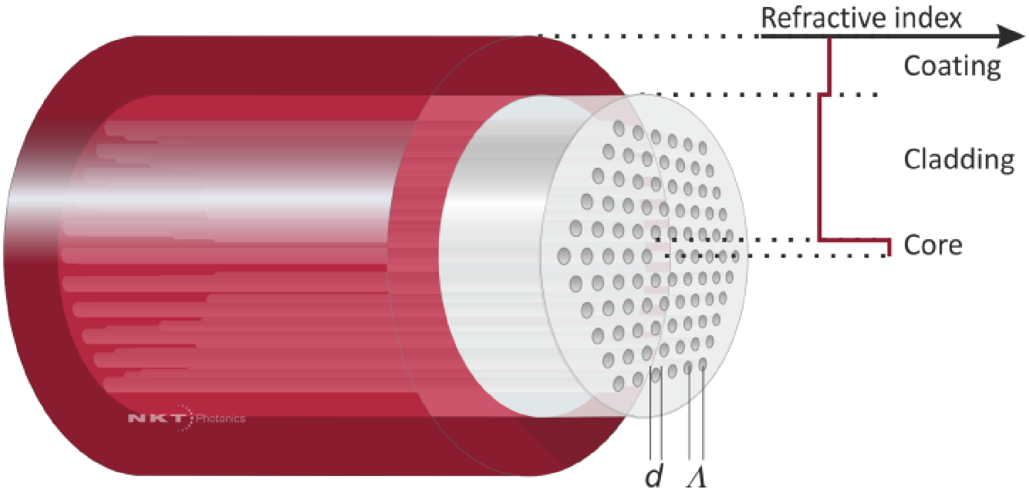


Fig.2.4(a). Side view of index guiding photonic crystal fiber and variation of its refractive index profile

(Courtesy: NKT Photonics website).

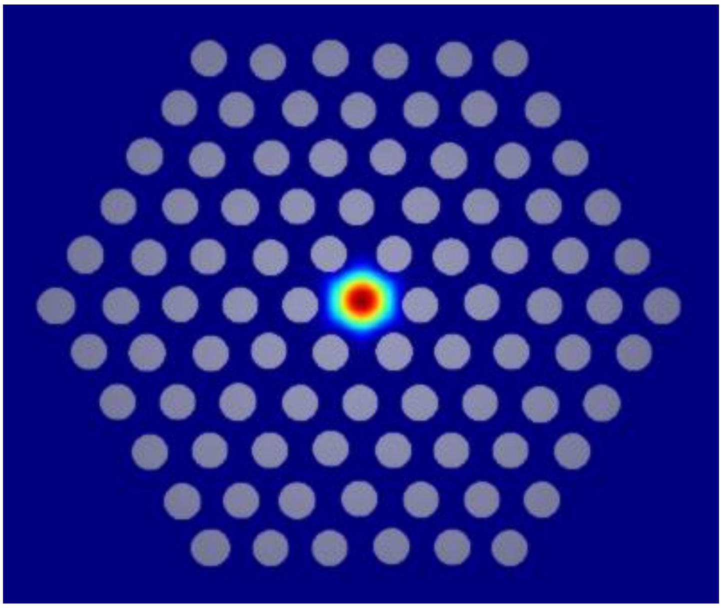


Fig.2.4(b). Fundamental mode in Index guiding PCF

(Courtesy: NKT Photonics website).

The propagation of the light through index guiding photonic crystal fiber also involves the phenomenon of 'Total Internal Reflection'. The core of PCF is filled with a solid material and cladding is having air holes which results in the difference of the refractive indices of core and cladding as shown in the figure 2.4 with the varying refractive index profile. The refractive index of core is higher than that of cladding so that the energy leakage to the cladding is minimised.

b) Band gap guiding PCF

In band gap guidance fiber, the light rays pass through the hollow core which is having low refractive index as compared to cladding. Either stack and draw technique or by extrusion method, the fiber fabrication process is completed [3]. The structure of this type of photonic crystal fiber and the fundamental mode of propagation of electric field intensity is shown in figure 2.5. Such type of fibers have very narrow pass band of approximately 100-200 nm and having a low value of non-linearity. The empty hole in the core of band gap guiding PCF can be filled with liquids [4] and gases [5] which results in the increase the nonlinearity of PCF. Hence this PCF can be used for many nonlinear applications by designing their structure for very small mode area. For the nonlinear applications, small mode area and dispersion characterstics play a vital role.

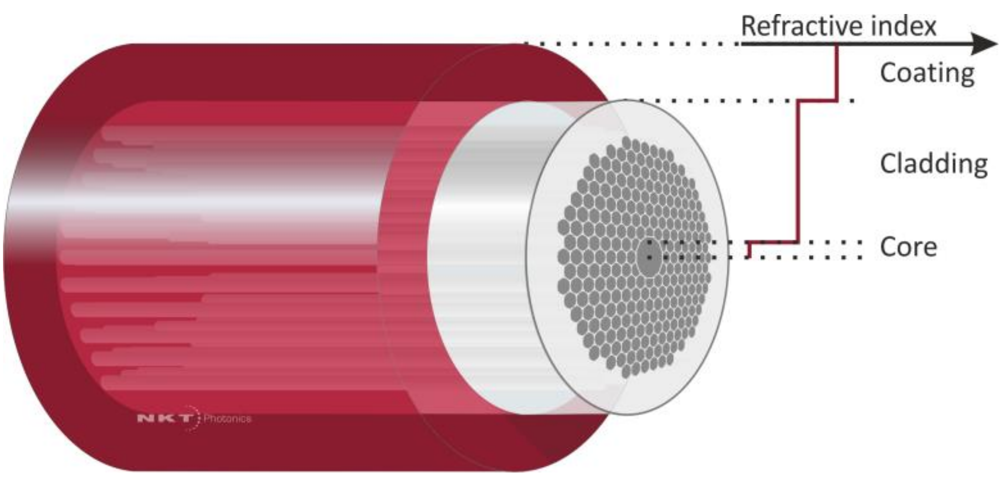


Fig.2.5(a). Side view of band gap guidance photonic crystal fiber and variation of its refractive index profile

(Courtesy: NKT Photonics website).

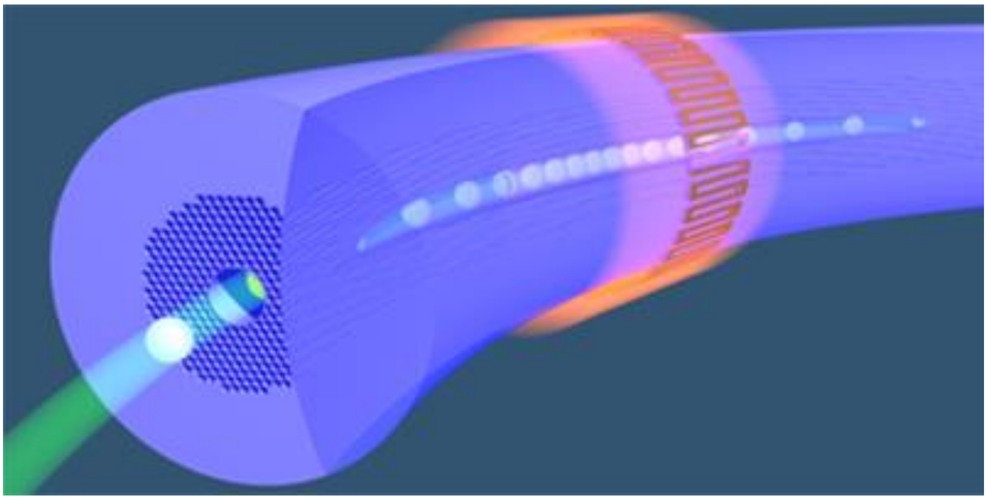


Fig.2.5(b). Fundamental mode in band gap guidance PCF

(Courtesy: NKT Photonics website).

PCF has a number of applictions in the field of realise numerous components such as add-drop filters [6], cavity fiber laser [7], fiber amplifiers [8], wavelength converters [9], power splitters [10], long periodic fiber gratings [11], wavelength demultiplexers [12].

CHAPTER 3

OPTICAL FIBER: NONLINEAR OPTICS

The light ray propagation completely depends upon the medium through which it passes. During the propagation of the light, it comes under various effects such as losses and dispersion. The dispersion occurs in a medium when the different wavelength rays travel with velocities through the medium. When the intensity of the light ray crosses a threshold value, then the medium starts to show its nonlinear behaviour. Supercontinuum generation phenomenon is a result of many non-linear effects occurring in the medium such as self-phase modulation, self-steepening, four wave mixing, cross phase modulation and modulation instability etc. Nonlinearity in a dielectric material occurs because of the dependence of refractive index of medium on the applied intensity (known as Kerr effect) and on the phenomenon of inelastic – scattering.

In the linear optics region, the induced polarisation in a dielectric medium is given by

$$P = \varepsilon_0 \chi \mathbf{E} \tag{3.1}$$

where,

P = induced polarisation,

ε_0 = permittivity of free space,

E = electric field intensity.

At high power intensity, the behaviour of the induced polarisation doesn't remain linear in nature. To take the nonlinear behaviour into account, equation 3.1 is expanded to higher order terms of electric field, E as follows

$$P = \ \varepsilon_0 \chi^{(1)} E + \chi^{(2)} E^2 + \chi^{(3)} E^3 ......] \qquad (3.2)$$

where $\chi^{(1)}$ is the first order susceptibility which takes into account the linear optical effects including linear refractive index and absorption.

$\chi(2)$ is the second order susceptibility that is related to second harmonic generation nonlinearity effect. But $\chi(2) = 0$ for silica glass which a material having the inversion symmetry at molecular level.

$\chi(3)$ is the third order susceptibility which takes into account Raman scattering and Kerr nonlinearity effect which is responsible for various nonlinear effects such as SPM, XPM and four wave mixing.

3.1 Raman Scattering

Raman scattering is inelastic scattering [13] in which energy is transferred either from the material or to the material because of molecular rotational or vibrational motion. Raman scattering phenomenon can transpire spontaneously, but this effect is relatively weak.

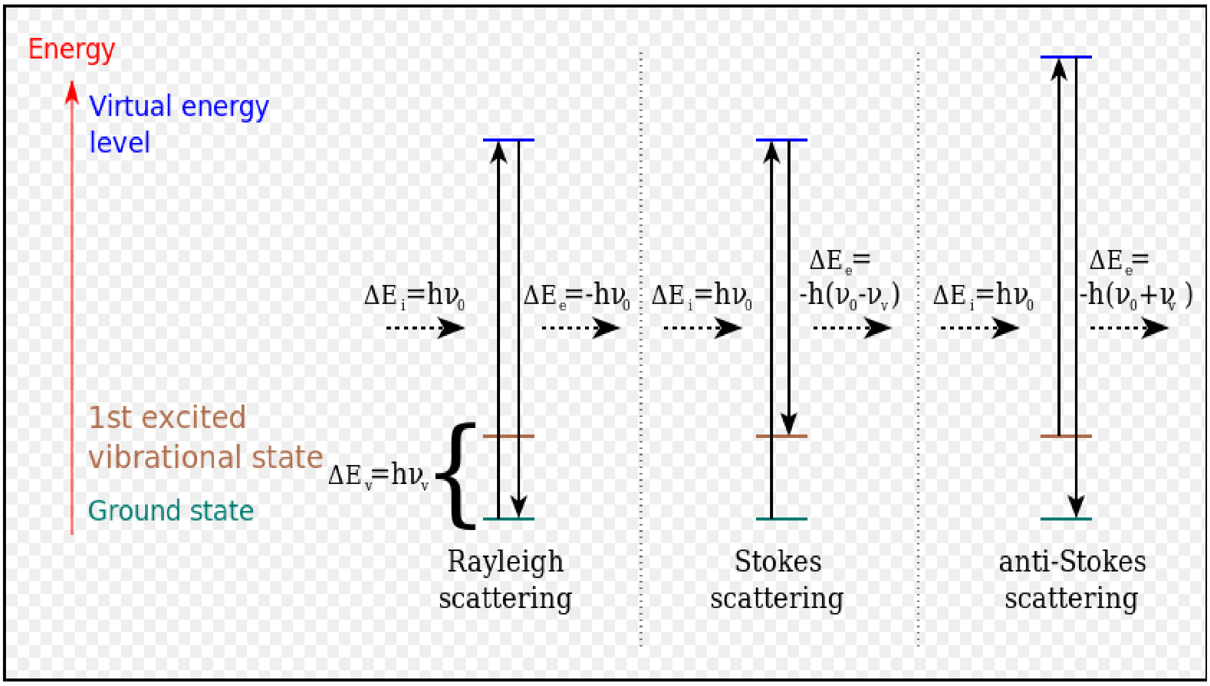


Fig. 3.1. Different possibilities of light scattering Rayleigh scattering, stokes Raman Scattering and Anti Stokes Raman Scattering.

(Courtesy: Wikipedia)

However, stimulated Raman scattering is highly efficient phenomenon which occurs when a very high intensity pulse propagates through the medium. It is an inelastic nonlinear effect.

Raman scattering is further classified in two ways such as

a) Stokes Raman Scattering:

If the molecules of the medium through which light ray is propagating are excited by a photon originated by pump source with an energy of **hυ_0**, it excites the vibrational state of the molecule of the medium. As a result of it, a photon is scattered with lower energy state of **h($\upsilon_0 - \upsilon_p$)**. This scattering is known as Stokes Raman scattering.

b) Anti – Stokes scattering:

If the molecules of the medium are already in excited sate and when a photon is incident on the molecules, a higher energy photon is generated with energy **h($\upsilon_0 + \upsilon_p$)**. This phenomenon of scattering is known as Anti-Stokes scattering. This scattering phenomenon has the application in the field of spectroscopy [14,15].

3.2 Self – Phase Modulation

Self – phase modulation is the change in the phase of optical field due to Kerr nonlinearity effect. Due the dependence of the refractive index on the intensity, the phase of the pulse is changed. The phase shift in the pulse occurring due to electric field intensity, E is given by

$$\varphi_L = \frac{2\pi}{\lambda} nL \tag{3.3}$$

At very high intensity of the pulse propagating through the medium, a nonlinear phase shift is also introduced. Hence the total phase shift in the optical field is given by

$$\varphi_T = \frac{2\pi}{\lambda}(n_1 + n_2 I)L_{eff} \tag{3.4}$$

where,

I = Intensity of the applied optical pulse,

λ = wavelength of the incident pulse,

L/L_{eff} = propagation distance.

The second term in the equation (3.4) is intensity dependent resulting in nonlinear effects and is termed as nonlinear phase shift.

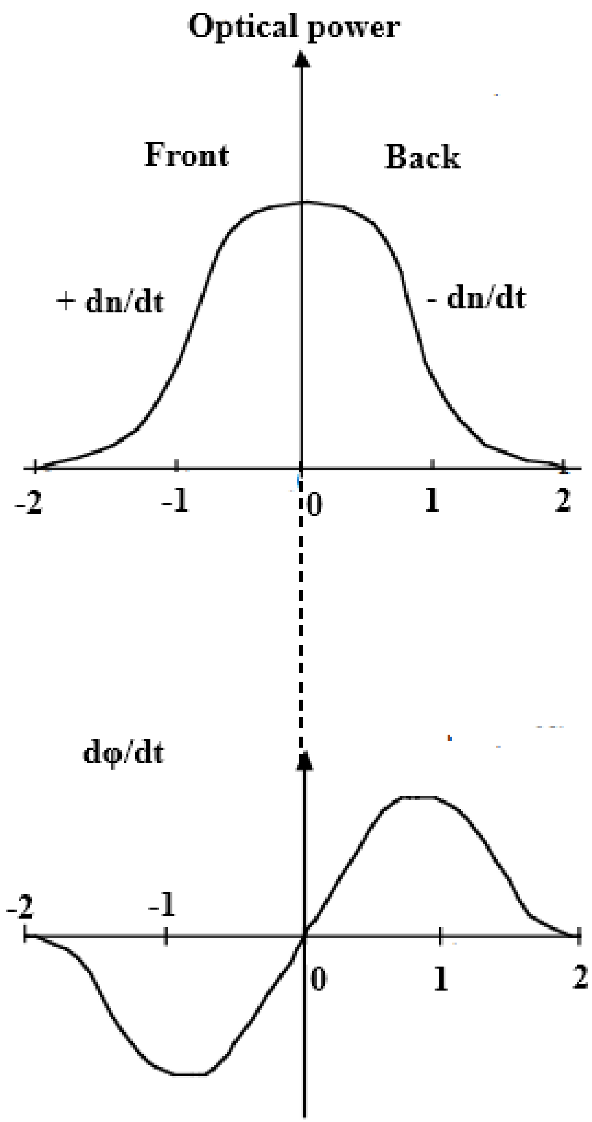


Fig. 3.2. Self-Phase Modulation

(Courtesy: S.P. Singh and N. Singh 'Nonlinear Effects in Optical Fibers: Origin, Management and Applications' PIER)

As the intensity becomes time dependent, so it generates new frequencies for the input pulsed laser light. The frequency is given by

$$\omega(t) = -\frac{d\Phi_{NL}}{dt} = -\frac{2\pi}{\lambda} n_2 I(t) L_{eff} \qquad (3.5)$$

Due to the generation of new frequencies, the bandwidth of the incident pulses is increased. In case of a bandlimited pulse, self – phase modulation results in

a) An increase in the frequency ($\omega(t) > 0$) in the trailing edge of the pulse $dI(t)/dt < 0$.
b) And a decrease in the frequency ($\omega(t) < 0$) in the leading edge of the pulse $dI(t)/dt > 0$.

Apart from this discussion, self - phase modulation is the factor which handles broadening of the spectrum of ultrashort pulses [16]. Also in anomalous – dispersion region, it handles the existence of optical solitons [17].

3.3 Self – steepening

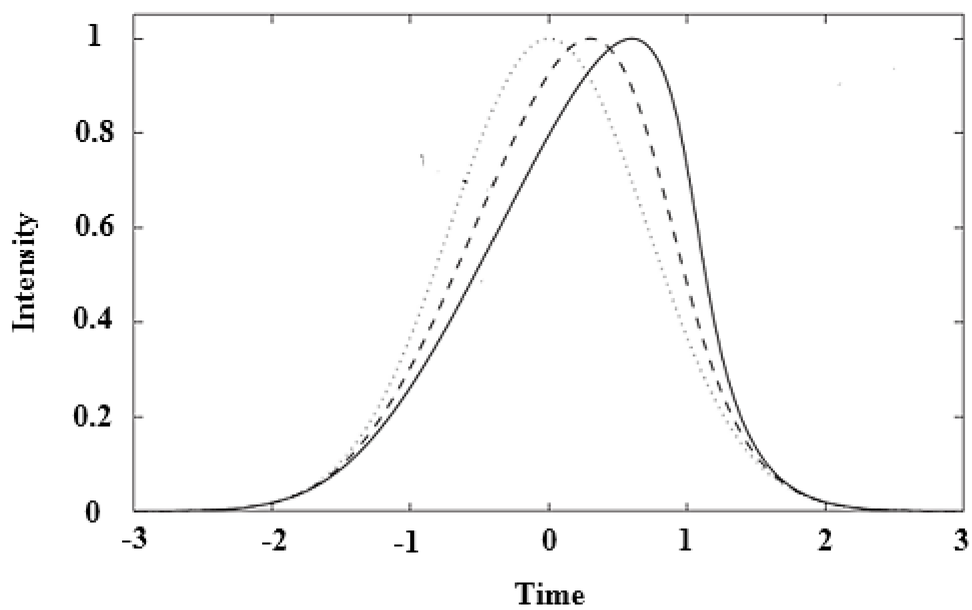


Fig 3.3. Self-Steepening of Gaussian Pulse when there is no dispersion. The dotted line is the shape of the pulse at z=0

(Courtesy: Nonlinear optics by GP Agrawal)

Reliance of the group velocity on intensity results in the self – steepening effect [18]. Due to the higher group index at the peak of the pulse travels with lower speed as compared to the rest of the part of pulse. Self – steepening effect results in the asymmetric broadening of the pulse such that the peak of the pulse start moving toward the trailing edge of the pulse. Hence it contributes to the steepening of the trailing edge as the pulse propagates. It is more significant for ultrashort pulses. It can be depicted from the figure 2.6 that with high intensity and small pulse width less than 100 fs, steepening of the pulse can occur at the short distances.

3.4 Cross – phase modulation

In cross – phase modulation, between two co-propagation fields, no energy is transferred. Hence XPM is an elastic process. When the two optical fields propagate through the dielectric medium of the fiber, they interact with each other. Hence results in a phenomenon where the intensity of one optical field changes the phase of another optical beam [19]. XPM is always accompanied by SPM. When SPM effect comes into play alone, it results in the symmetric broadening of the spectrum of pulse. But when SPM and XPM effects both simultaneously comes into the picture, it results in the asymmetric broadening of the pulse spectrum if the two pulses propagating through the dielectric medium have different group velocities.

The nonlinear phase shift in a multichannel system around the centre wavelength, λ_i is represented by

$$\varphi_{NL} = \frac{2\pi}{\lambda} n_2 L[I_i(t) + 2\sum_{i \neq j} I_j(t)] \qquad (3.6)$$

The first term in the equation 3.6 is responsible for SPM and second term for XPM. It can be seen from the above equation that XPM is two times more effective than SPM. The factor 2 in the second term of the equation results from the nonlinear susceptibility [20]. In the communication systems such as DWDM, cross – phase modulation has a major drawback that it results in the crosstalk between the channels and hence the signal is distorted. The energy of the one pulse affects the phase of the second pulse and hence symmetry of the pulse spectrum is distorted.

3.5 Four – Wave mixing

Four wave mixing is a type of Kerr effect and this effect happens when two or more different pulses having different wavelengths travel through the fiber [21]. It is a parametric process of third order. The initial and the final quantum mechanical states of the system remains identical in parametric processes [22]. Parametric processes are both second and third order susceptibility dependent in a material. In parametric processes, no energy is transferred between the medium and the propagating light wave and hence medium plays a passive role. Third order parametric process consists of the interaction of four optical pulses and the processes of parametric amplification, third harmonic generation and four wave mixing [23-26]. For the four - wave mixing process to occur, phase matching condition to be satisfied is very essential. If two pump signals of different frequencies interact with the probe light or signal light in the nonlinear dielectric medium, a new frequency known as idler frequency is generated as shown in the figure 3.4(a). The idler frequency can be given by

$$f_{idler} = f_{p_1} + f_{p_2} - f_{probe} \tag{3.7}$$

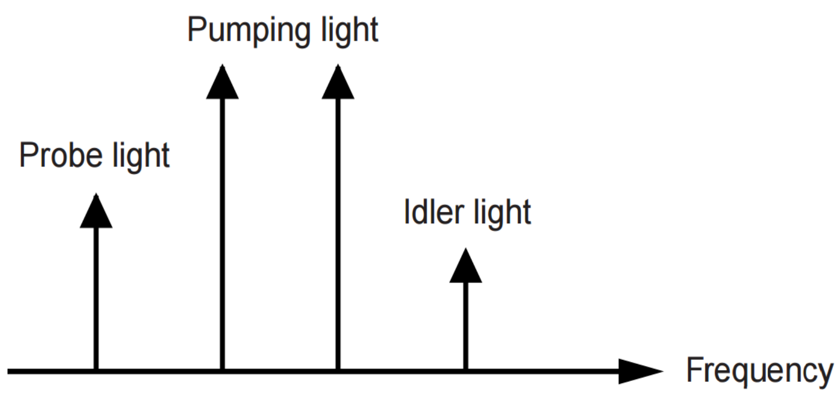
where;

f_{p_1}, f_{p_2} = pumping frequencies of the optical pulses,

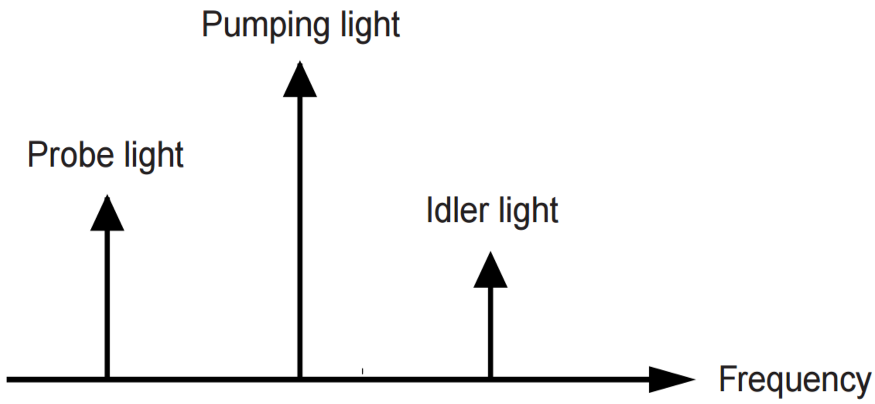
f_{probe} = frequency of the probe signal,

and f_{idler} = frequency of newly generated signal known as probe signal.

This condition is known as frequency phase matching condition.



(a)



(b)

Fig. 3.4. Schematic diagram of Four wave mixing in frequency domain; (a) 2 – channel pump wave, (b) 1 – channel pump wave (degenerated FWM)

(Courtesy: Aso, Osamu, Masateru Tadakuma, and Shu Namiki. "Four-wave mixing in optical fibers and its applications." dEp 1 (1999): 2.)

But when the frequencies of the two pumping sources is identical, then the equation for the idler signal becomes

$$f_{idler} = 2f_p - f_{probe} \tag{3.8}$$

Where; f_p is the pump frequency for the two identical signals. This condition in more refined form is known as degenerate four – wave mixing. For the efficient generation of the four – wave mixing, the pump wavelength must be close to the zero - dispersion wavelength. This process creates sidebands on the both sides of the power spectrum but only when the phase matching condition is satisfied. It has many applications such as in wave convertors and in supercontinuum generation etc.

3.6 Modulation Instability

Modulation instability is a process of nonlinear amplification of the fluctuation in the pulse envelope. This effect only occurs in the anomalous dispersion regime. It results in the fragmentation of the envelope in many ultra-short pulses and hence generates the frequency sidebands in the spectrum. The losses in the fiber results in the solitons' broadening. To compensate the fiber losses in the fiber, periodic amplification of the solitons is required so that the energy of the soliton is restored to its initial value which is necessary for the optical communication.

CHAPTER 4

NONLINEAR SCHRÖDINGER WAVE EQUATION AND FACTORS AFFECTING SUPERCONTINUUM GENERATION

The solution of the generalised nonlinear Schrödinger wave equation (GNLSE) explains the evolution of the optical pulse envelope. The generalised nonlinear Schrödinger wave equation (GNLSE) comprises of all the nonlinear effects discussed in previous chapter. The nonlinear Schrödinger wave equation used for our present work is given by [20]

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2} A - \left(\sum_{n \geq = 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial t^n} A \right) = i\gamma \left(1 + \frac{i}{\omega} \frac{\partial}{\partial t} \right) \times \left[A(z,t) \int_{-\infty}^{\infty} R(t^{`}) |A(z, t - t^{`}|^2 dt^{`} + i\Gamma_R(z,t) \right] \tag{4.1}$$

where;

A (z, t) = slowly varying pulse envelope,

z = propagation distance of the pulse,

t = related to retarded medium response,

α = propagation loss (dB/km),

β_n = n^{th} order dispersion coefficient (ps^n/sec), γ = nonlinear coefficient,

Γ_R = slope of Raman gain.

The left side of the equation (4.1) shows the linear effects of medium, while right side of equation indicates the nonlinear effects. Both linear and nonlinear effects interplay with each other to generate the supercontinuum spectrum as the pulse propagates through the material. The second term on the left side of the equation represents the losses in the fiber. The third term represents higher order dispersive properties of medium as the pulse passes through the medium. The first term in the bracket on right side of equation is related to the Kerr effect as well as to steepening effect and the second term shows the relation to the stimulated Raman scattering. The solution of the nonlinear Schrödinger wave equation gives the evolution of the pulse through medium neglecting that the inelastic scattering effect is avoided here.

4.1 Supercontinuum Generation

Supercontinuum generation is the spectral broadening of the spectrum of pulse as it passes through the nonlinear medium. The broadening of the pulse is due to many nonlinear phenomena occurring inside the nonlinear medium when a very high intensity pulse is passing through it.

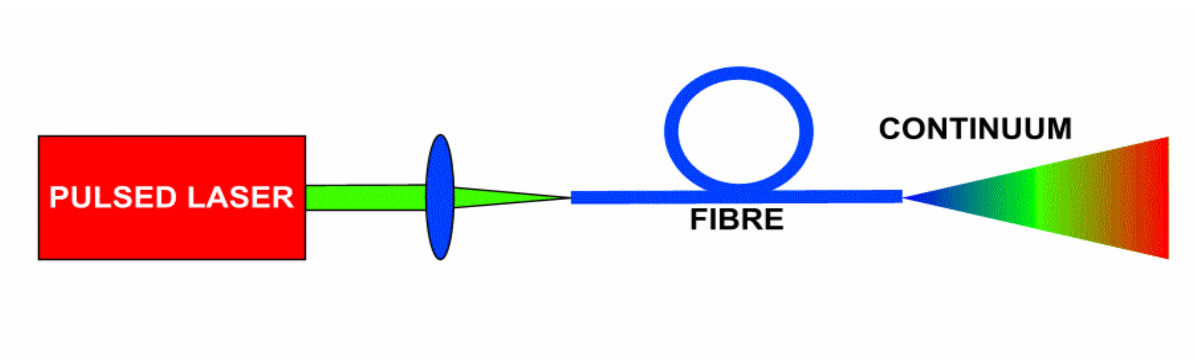


Fig.4.1. Generation of Supercontinuum Spectrum

The nonlinear phenomena occur mainly due to the dependence of the refractive index property on the intensity of the pulse. This dependence of refractive index on pulse intensity results in occurrence of many nonlinear effects such as self – phase modulation, cross – phase modulation, self – steepening, four - wave mixing and modulation instability etc. which are responsible for the generation of the supercontinuum spectrum. Supercontinuum generation phenomenon converts a high temporal and high spatial laser pulse into a pulse of low temporal coherence and high spatial coherence.

4.2 Factors affecting SCG generation

There are numeral factors on which are responsible for the occurrence of various nonlinear effects. These factors involve:

a) minimum dispersion wavelength,
b) small core area,
c) adequate fiber length,
d) Raman response parameters,
e) nonlinear coefficient of the material,
f) pulse width.
g) intensity of incident pulse light.

4.2.1 Influence of the Dispersion of Supercontinuum Generation

Dispersion is the spreading of the light as it travels down the fiber. The rays entering the fiber travels different distances and hence the velocities of different rays will be different. These different velocities become a reason for the dispersion of the pulse. In case of chromatic dispersion, both phase and group velocities of the pulse depend upon its frequency. The higher order dispersion coefficient β_n as a function of angular frequency $\boldsymbol{\omega}$ around its central frequency $\boldsymbol{\omega}_0$ [33] can be represented as

$$\beta(\omega) = \beta_0\,(\omega_0) + \beta_1(\omega_0)(\omega-\omega_0) + \frac{1}{2}\beta_2(\omega_0)(\omega-\omega_0)^2 + \frac{1}{6}\beta_3(\omega_0)(\omega-\omega_0)^3 + \cdots \qquad (4.3)$$

where,

β_0 = zero order term and holds information about the common phase shift

β_1 = first order term and holds information about the group delay per unit length (i.e.; inverse group velocity) and tells about the total time delay without affecting the pulse shape

β_2 = second order dispersion term having information of second order dispersion per unit length and total time delay affecting the shape of the pulse

β_3 = third order dispersion term having dispersion per unit length and it is an important factor for ultrashort pulses because to their larger bandwidth.

The second order dispersion coefficient term is very important factor as its value decides about the dispersion regime as follows:

a. $\beta_2 > 0$; Normal dispersion regime
b. $\beta_2 < 0$; Anomalous dispersion regime

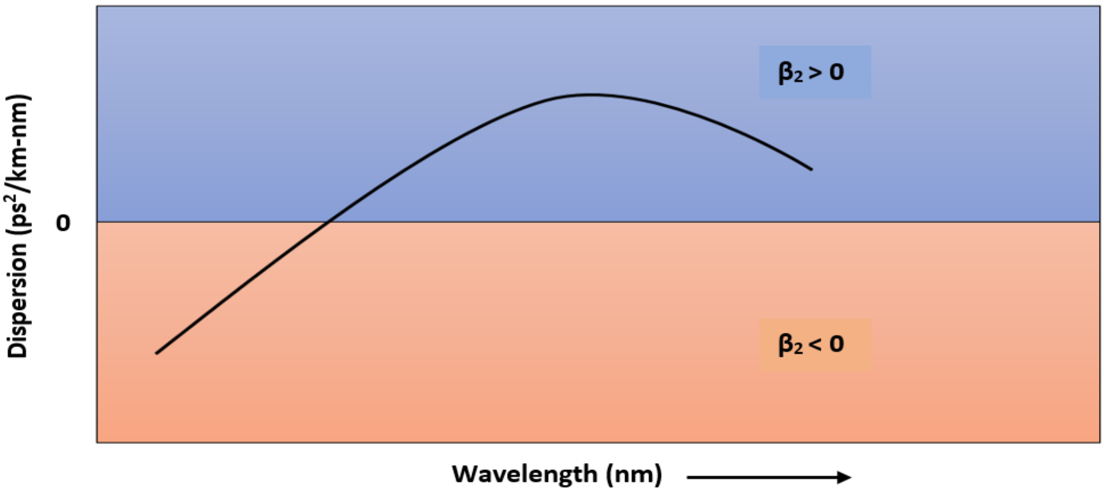


Fig.4.2. Dispersive characterstics showing anomalous and normal dispersion regime

4.2.1.1 Anomalous dispersion region

As $\beta_2 < 0$ in anomalous dispersive region, the group velocity of the pulse will increase as the frequency of the pulse will increase. It means, "the lower the frequency, the lower will be the group velocity". Hence the blue light frequency component will move with a faster speed as compared to red light component. Due the occurrence of the modulation instability effect, solitons will be formed due to the combined effect of dispersion and self – phase modulation

[34-36]. Optical solitons either do not change the shape of pulse or pulses follow a periodic evolution of pattern. SCG generates the frequency chirp which are generated due to the time dependence of $\delta\omega$. The frequency chirp that are induced by SPM process increases in magnitude with the increase in the propagation distance and hence new frequencies are generated continuously. SPM generated chirps provide the lower frequency to leading edge and higher frequency to the trailing edge of the pulse. But dispersion will nullify the above effect and select the proper pulse shape, hence the pulse propagates undistorted down the fiber. When we choose a pump wavelength in the anomalous region of dispersion, a process known as soliton fission takes place. Because of this process, higher order solitons break into many small solitons. Supercontinuum spectrum varies from pulse to pulse as it is very sensitive to even very small fluctuations in the pulse.

4.2.1.2 Normal dispersion region

As $\beta_2 > 0$ in normal dispersive region, the group velocity of the pulse will decrease as the frequency of the pulse will increase. It means, "the lower the frequency, the higher will be the group velocity of pulse". Hence the blue light frequency component will move with a slower speed as compared to red light component. When the pump wavelength is used in this region, SPM effect will be more dominating and hence it increases the broadening of the pulse. In case of SPM, the phase coherence is very high even if the broadening of the pulse is very high.

4.2.1.3 Zero dispersion at pump wavelength

Each material has zero dispersion property at a pump wavelength. Dispersion in a material can be due to two regions; either it is due to waveguide geometry or due to properties of the material used for the fabrication of the fiber. The zero dispersion wavelength (ZDW) can be achieved by changing the fiber geometry. The pump wavelength used at the zero dispersion prevents the distortion of the shape of pulse and hence results in better generation of the SCG spectra. The distortion in the pulse shape introduces the losses in the fiber leading to the loss in power and reduction in the pulse.

4.2.2 Adequate fiber length

The input power intensity and the pulse width interplay such that either dispersive or nonlinear effects dominant along the length of the fiber. Depending on these effects, there are two terms of the length which are used [20].

a) Dispersion length (L_D)

b) Nonlinear length (L_{NL})

The dispersive length and nonlinear length of the fiber are represented by [20]

$$L_D = \frac{T_0^2}{|\beta_2|} \tag{4.4}$$

$$L_{NL} = \frac{1}{\gamma P_0} \tag{4.5}$$

If the length of the fiber is taken L, then three conditions may occur as follows:

a) If $L << L_D$ and $L << L_{NL}$, neither nonlinear nor dispersive effect occur during the pulse propagation inside the fiber. This property is useful telecommunication property as the pulse propagates throughout the fiber length without changing its shape. This condition is achieved in the case of low power intensity and hence less group velocity dispersion.

b) If $L << L_{NL}$ and $L \sim L_D$, then dispersive effect is dominant and nonlinear effect can be ignored.

c) If $L << L_D$ and $L \sim L_{NL}$, then propagation of the pulse along the fiber length is governed by the nonlinear effect, SPM and dispersive effect is neglected. This is the required condition for SCG spectrum generation.

Hence both SPM and GVD interplay for the generation of SCG spectrum such that it results in the solitons formation in anomalous dispersion region and compression of the pulse in the normal dispersion region.

4.2.3 High intensity ultrashort pulse

When a pulse of very narrow width of high intensity is incident in the fiber, various nonlinear effects comes into play. Due to nonlinear refractive index of the medium, self – phase modulation occurs in the material. But SPM alone can not produce the self - broadening of the pulse up to considerable level. Cross – phase modulation is another phenomenon which is responsible for the further broadening of the spectrum. Stimulated Raman scattering also occurs inside the material due to high intensity pulse. This process generates stokes and anti – stokes band. But SRS mainly broadens the SCG spectra on the longer wavelength side (i.e., Stokes wave). Hence SRS broadens the spectra asymmetrically. Four wave mixing(FWM) is another nonlinear mechanism, which occurs only when the phase matching condition is satisfied, broadens the spectra on both sides, i.e., on shorter as well as longer wavelength side.

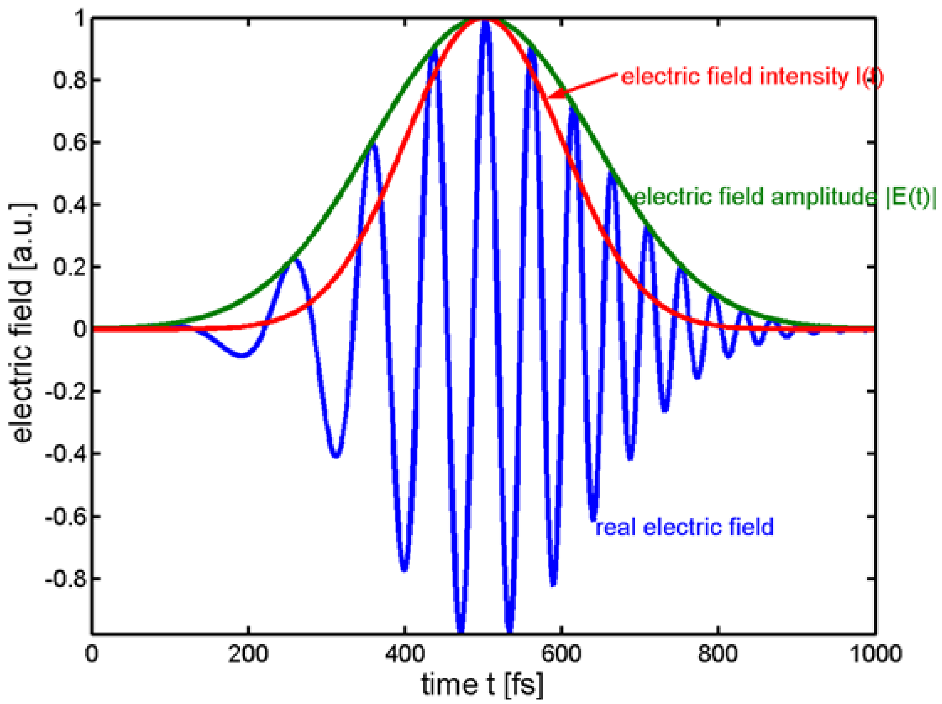


Fig.4.3. High intensity ultrashort pulse

(Courtesy: commons.wikimedia.org website).

FWM mechanism relies on the dispersion characterstics of the material. Dispersion coefficient, β_2 doesn't remain constant with the variation of the wavelength. Its variation must be taken into consideration for the higher order dispersion. This factor plats a vital role in the generation of SCG spectra. The increase in the value of β_2 reflects the more flatness of the dispersion curve and hence more stable SCG spectra can be achieved.

4.2.4 Nonlinear refractive index of the fiber material

A phenomenon known as nonlinear refraction is responsible for the occurrence of the nonlinear effects. This phenomenon happens due to the dependence of the refractive index on pulse intensity [37]. Each material has a unique value of nonlinear refractive index. It can be given by [37]

$$n(\omega, I) = n(\omega) + n_2 I \tag{4.6}$$

where,

I = optical intensity of input pulse,

$n(\omega)$ = linear part of refractive index,

n_2 = nonlinear refractive index.

Higher the value of nonlinear refractive index, larger will be the broadening of the SCG spectra.

4.2.5 Small core area

The intensity of the pulse is responsible for the occurrence of the nonlinear effects. The intensity of a pulse depends on the cross – sectional area. The nonlinear coefficient, γ must be as high as possible for the better broadening of the SCG spectra. It is given by [20]

$$\gamma = \frac{2\pi n_2}{A_{eff}\,\lambda} \tag{4.7}$$

where,

A_{eff} = effective mode area,

λ = wavelength of the pulse,

n_2 = nonlinear refractive index.

As it can be depicted from the above equation that effective mode area or core size must be small so that it results in higher nonlinearity in the fiber material. The effective mode area term is considered because the power is not uniformly contributed along the fiber length. The effective mode area can be given by [20]

$$A_{eff} = \frac{\left(\iint_{-\infty}^{\infty} |E|^2 dxdy\right)^2}{\left(\iint_{-\infty}^{\infty} |E|^4 dxdy\right)} \tag{4.7}$$

where, E is the electric field intensity.

For the nonlinear applications, the nonlinear coefficient should be large enough which can be achieved by small core area. The effective mode area of the core can be decreased by changing the design parameters of the fiber. The smaller size of the core results in the better interaction of the various optical fields and in the generation of new wavelengths. Hence it plays an important role in the generation of the SCG spectra.

4.2.6 Raman response

The ultrashort high intensity pulse when applied to the material, it interacts with the molecules of that material and affects the electronic structure of that molecule. This disturbance to molecule results in the change of the polarisation of the molecule, in other terms, changes the intensity dependent refractive index.

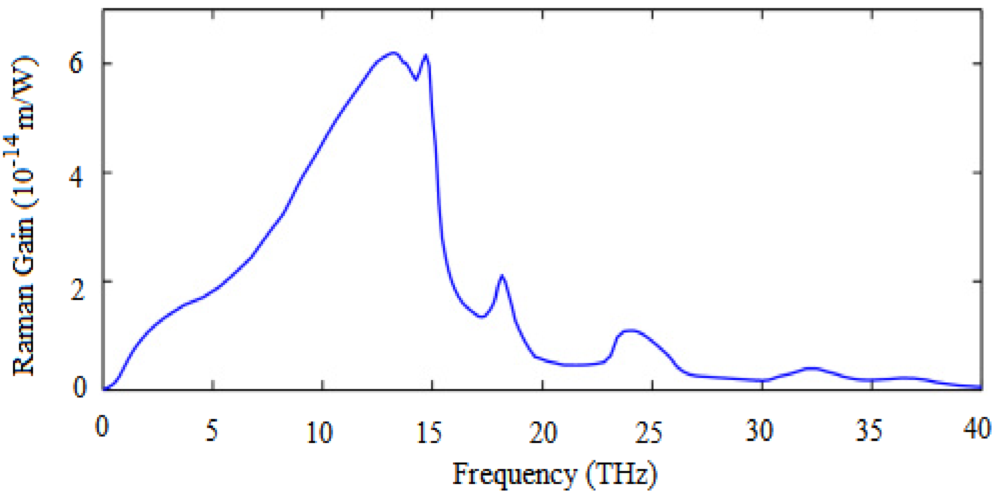


Fig. 4.4. Raman gain spectrum

(Courtesy: Nonlinear optics, GP Agrawal)

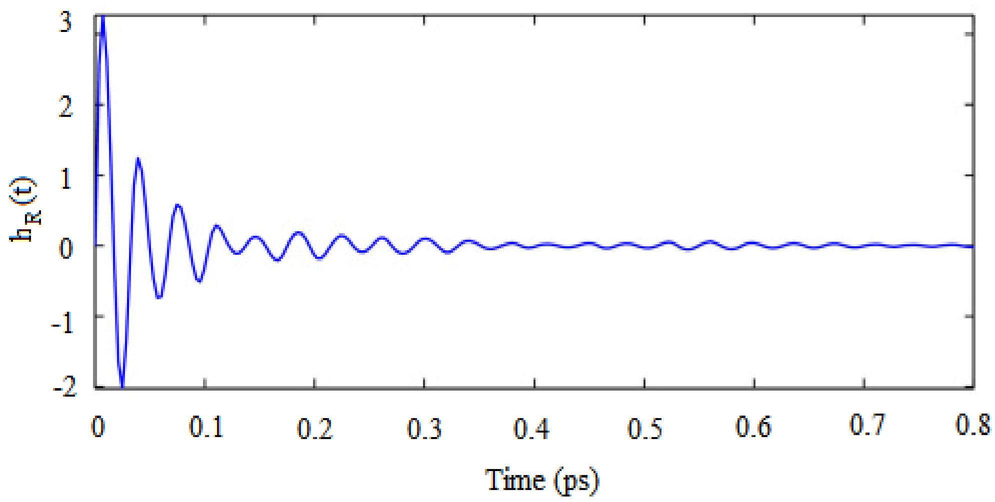


Fig. 4.5. Temporal form h_R (t)

(Courtesy: Nonlinear optics, GP Agrawal)

The disturbances induced in the fiber due to optical pulse intensity disturbs the field related to the nuclei of the molecule [38]. This process results in the further changes in the orientation of the excited molecules. This effect is known as Raman effect. Raman gain is the result optical gain caused because of stimulated Raman scattering (SRS). R(t) includes the Raman response function. Assuming the electronic contribution due to molecular vibrations is nearly instantaneous the functional form of $R(t)$ can be given by

$$R(t) = (1 - f_R)\delta(t) + f_R h_R(t) \tag{4.8}$$

where,

f_R = fractional contribution of the delayed Raman response,

$h_R(t)$ = Raman response function that keeps information on the vibration of material molecules as light pulse travels down the fiber length and represented by

$$h_R(t) = \frac{\tau_1{}^2+\tau_2{}^2}{\tau_1\tau_2{}^2}\exp\left(-\frac{t}{\tau_2}\right)\sin\left(\frac{t}{\tau_1}\right) \tag{4.9}$$

where;

τ_1 = Raman period of molecule,

τ_2 = life time of the vibrations.

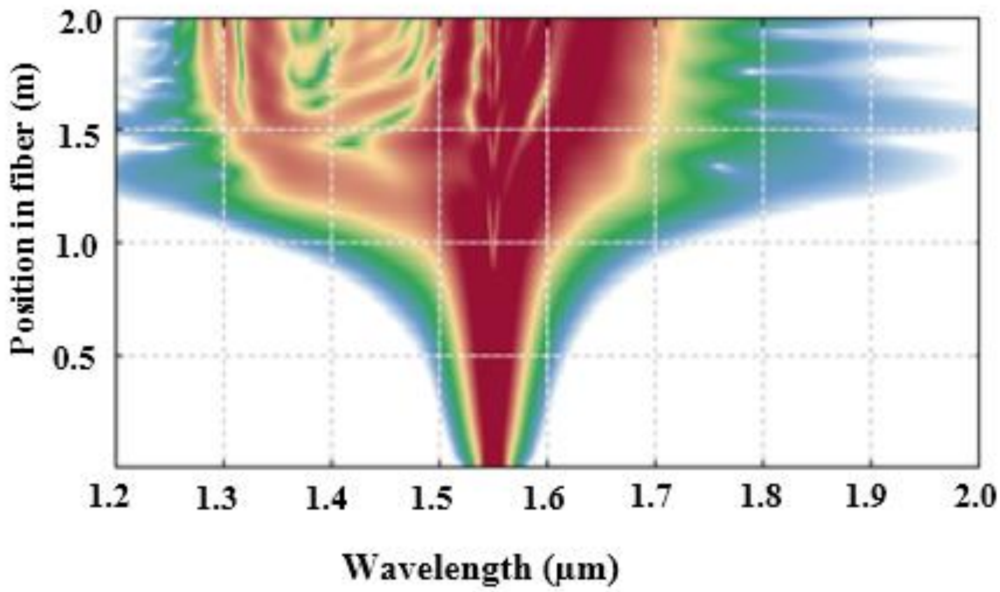


Fig. 4.6. Super Continuum generation in a fiber

(Courtesy: RP Photonics)

The spectrum of the SCG for silica at pump wavelength 1550 nm is shown in the figure 4.7.

The filters and amplifiers can be used to equalize the intensities generated by different wavelengths due to nonlinear processes. After this equalisation of the intensity, communication data rate speed can be enhanced.

CHAPTER 5

OPTICAL SIMULATION SOFTWARES AND NUMERICAL TECHNIQUES

5.1 SOFTWARES

In the present scenario, the demand of the optical communication is at the highest peak. This rapid growth in the field of optics is due to its larger bandwidth, more flexibility and more security to the data. All this is made possible only because of the work at the large scale by the research scholars throughout the world. The research work involves a high cost and not economical. In order to make research economical and to enhance the speed of research, a couple of optical softwares have been introduced. These softwares use the numerical techniques such as finite element method, variational method or Runge – Kutte method for the solution of complex equations and hence the computational speed is increased.

5.1.1 COMSOL Multiphysics software

Comsol Multiphysics uses finite element method technique for the solving the problems. This software has many applications in the field of engineering and physics applications. It is a analyser, solver and simulation software and is not platform specific. Comsol Multiphysics software holds a number of modules which can be used to provide solutions to various problems based on electromagnetics, MEMS, fluid mechanics etc. Application programming interface is also an application of this software.

Comsol Multiphysics software can be used for various fields such as

a) 2D and 3D modelling of the structures,

b) For designing of various structures such as waveguide, PCF, step index fiber, antennas etc.,
c) Frequency analysis,
d) Mode analysis on the basis of various parameters.

The parameters of the waveguide, fiber or antenna can be changed and the updated solution can be used for further simulations. Latest versions of this software also include MATLAB for programming purpose.

5.1.2 RP Fiber software

The developer of the RP fiber is RP photonics. This software is also platform independent. It provides graphic user interfaces (GUI's). RP fiber software can be used for the designing of optical devices such as high power laser, optical amplifiers, special fibers etc. This software uses script language for the designing of devices and their proper functioning.

RP fiber software is the extended version of JPLOT. It inherits all the properties of the JPOT, i.e., input commands, programs, graphical user interface and calculation techniques etc. Apart from the commands inherited from the JPLOT, RP fiber has its own inbuilt commands. These commands are used for input signal, input power, input length, and several other parameters. RP fiber contains its own inbuilt functions for the regaining the calculated results.

RF fiber works in the field of laser giving results for spontaneous, stimulated emission, also for ASE power measurements. It also provides the functions for the calculation of effective mode area, group velocity index, refractive index profile etc.

5.1.3 Optiwave software

Optiwave software is based on the finite difference time domain method. This software is used for the analysis and simulation of opto – electronics and optical circuits. This software a handful applications in the field of increasing communication demand such as it is used for the designing of the DWDM systems. This software contains modules used for the solution of optoelectronics and various electrical problems attached with it. OptiSystem, OptiSPICE, OptiFDTD , OptiFiber, OptiGrating and OptiBPM are the modules within this software which are used for various applications in the field of optoelectronics.

5.2 Numerical techniques

The numerical solution of the GNLSE leads to supercontinuum generation phenomenon. The analytical solution of this equation is not possible as it is very lengthy, time consuming method and requires the solution for the very complex equations; by using the special numerical methods [27-32], this equation can be solved. However, the experimental methods can also be used for the solution of the equation, but it is a costly method.

5.2.1 Split – Step Fourier Transform

In the present scenario, a numerical method known as Split – Step Fourier Transform is used for the solution of equation which is less time consuming and easily solved by the computer.

Split – step Fourier Transform method is a pseudo – spectral method. This numerical technique is used to solve the partial differential equations such as GNLSE. As its name suggests, this method solve the equation by splitting it in small steps and also it treats linear and nonlinear steps differently. Also Fourier transform is used again and again because this method solves linear portion of the equation in frequency domain and nonlinear portion in time domain. This method is pretty fast as it uses Fast Fourier Transform (FFT) algorithm.

The generalised nonlinear Schrödinger wave equation (GNLSE) given by equation (4.1) can be represented as

$$\frac{\partial A}{\partial z} = \dot{\mathrm{D}}A + \dot{\mathrm{N}}A \tag{4.2}$$

In the above equation, $\dot{\mathrm{D}}$ is the differential operator which takes into account the linear effects such as fiber losses and the dispersive properties of the material of the fiber. $\dot{\mathrm{N}}$ is the nonlinear operator that takes into the consideration all nonlinear effects of material and A is the amplitude of the input pulse. The linear operation is solved in the frequency domain and nonlinear operator is solved in the time domain. Linear and nonlinear effects in the fiber occur simultaneously. The whole propagation length of the fiber is divided into a number of small discrete steps. The equation will be solved after each ‘h’ step by replacing ‘z’ with ‘z + h’ after each step simulation. Each small step is solved for linear and nonlinear operators one after the other. The results of the simulations will be accurate until the small step ‘h’ is small as compared to the nonlinear length and dispersive length. The nonlinear step utilises second order Runge – Kutta numerical technique.

Split – step Fourier transform method is quite simple method. This method starts its functioning by dividing the proposed fiber into several small sectors. The pulse travels in the fiber from one sector to the another. The input field A(z, t) traverses the half distance of sector 'h/2' considering only linear effect such as dispersive effect and the rest half sector length considering the nonlinear effects only. Again in the next sector, the sequence is followed for the simulations. Therefore, nonlinear effect is considered only in the middle of the sector.

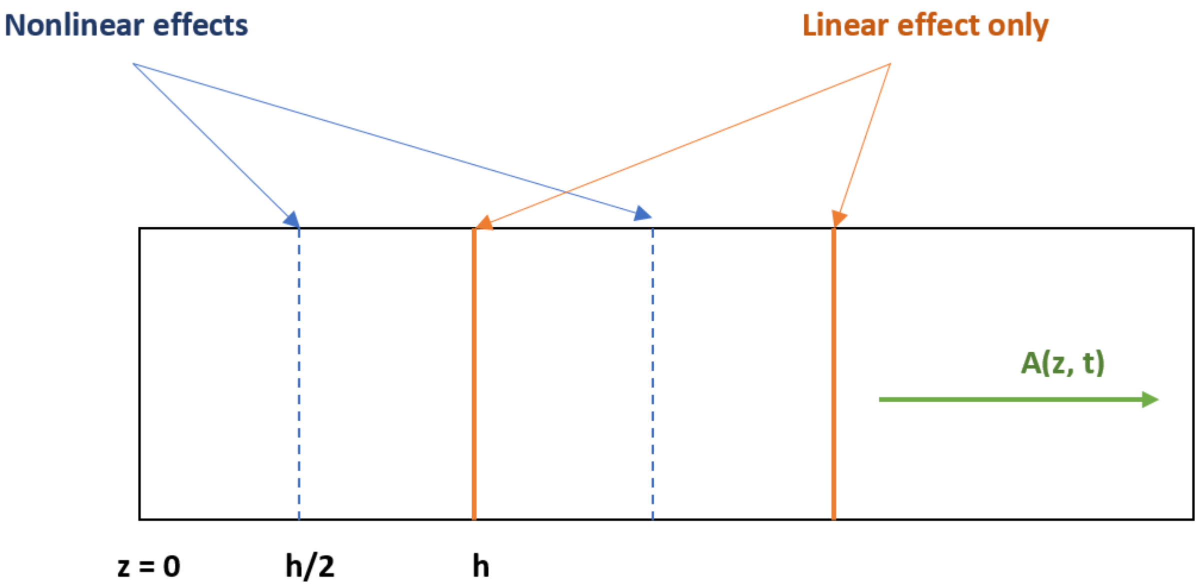


Fig. 5.1. Split – Step Fourier Transform Numerical Technique

This method has a limitation because of the small temporal window when large number of Fast Fourier Transform(FFT) operations are to be performed, otherwise this method is simple and also very fast.

5.2.2 Finite element method

Finite element method is also known as finite element analysis. This numerical technique is used to solve the partial differential equations. This numerical method is used to solve the problems related to the engineering and physics. It also solves the models that are related to the field of electromagnetics, heat flow, structural analysis etc [39]. Finite element method divides the partial differentiation equation into various algebraic equations that becomes easy to solve. As the boundary value conditions are also provided, so these problems are also known as boundary value problems. After solving all the algebraic equations, the discrete solutions are assembled together to get the solution of partial differential equation.

5.2.3 Method of moments

Method of moments numerical technique is used to solve either integral or differential or combination of both integral and differential equations. Its operation is dependent upon the large population law. This method can be applied to various number of electromagnetic problems. This method involves the steps of obtaining a suitable equation in the integral form, by using weighting and basic function, achievement of matrix form from its integral function. The parameters of the matrix equation are estimated and matrix equation is solved to get the results. In this way, the required solution can be obtained.

5.2.4 Variational method

Variational method is mainly used in the field of quantum mechanics. This numerical method provides a base for Finite element method and method of moments by converting the integral or differential equation into some variational problem. This method is quite fast and does not consume that much time for computation. Variational method provides small changes to the given system of equations and solve it using any of the methods such as least square method etc.

CHAPTER 6

BROADBAND SUPERCONTINUUM GENERATION SPANNING 1.5 – 13 µm in $Ge_{11.5}As_{24}Se_{64.5}$ BASED CHALCOGENIDE GLASS STEP INDEX OPTICAL FIBER[1]

6.1 Introduction

Supercontinuum has various potential applications in different diverse fields such as spectroscopy [40], early cancer diagnosis [41], food quality control [42], and optical coherence tomography [43]. Supercontinuum generation (SCG) is basically the broadening of spectrum of light when a very high intense laser pulse is passed through a highly nonlinear medium which is a result of several nonlinear phenomena such as self-phase modulation, stimulated Raman scattering, self- steepening, four wave mixing, cross phase modulation, and soliton fission taking place inside that material. SCG was first observed around 1970 in solid and gaseous nonlinear systems [44-46].

During the last two decades, Supercontinuum generation has become a very attractive and emerging research field due to the development of the various techniques used to obtain desirable supercontinuum sources. In most studies, supercontinuum generation has been achieved in silica fiber. But it has high material losses when used beyond 2 µm wavelength making it difficult to generate supercontinuum in mid-infrared region (MIR). MIR, also known as molecular fingerprint region, is very significant because the fundamental vibration absorption bands of most of the bio-molecules are stronger than overtones and

[1] This paper is communicated to Journal of Modern Optics.

combinational vibration absorption bands present in this region [47]. Molecular microscopy can be used to understand the structure of matter thoroughly and to perform the non-intrusive diagnostics of various systems composed of the physical, chemical and biological interest.

Research on the other non-silica glasses have been enhanced which have transparency in mid-infrared region and are able to generate supercontinuum in this region. Numerous non-silica glasses, for example tellurite, ZBLAN, bismuth, fluoride and chalcogenide have been reported for SCG in the mid-infrared domain [48-54]. Among all these non-silica glasses, chalcogenide glasses are preferred for supercontinuum generation in MIR due to their higher optical transparency, high linear and non-linear refractive indices as compared to the silica. Sulfides based chalcogenide glasses can provide MIR transparency beyond 8.5 µm, while the selenides and tellurite based chalcogenide glasses possesses MIR transparency up to 14 µm and around 20 µm respectively [55]. A few of these chalcogenide materials such as As_2S_3, As_2Se_3, $Ge_{11.5}As_{24}Se_{64.5}$ and $Ge_{11.5}As_{24}S_{64.5}$ are used to make active and passive devices in MIR. As_2Se_3 chalcogenide PCF with airholes filled by As_2S_3 rods can be used for the SCG in the mid-infrared range of 2.6 to 6.5 µm [56]. SC spectrum spanning 1.2–15 µm was generated using an 8 mm long equiangular spiral PCF structure pumped with 50 fs laser pulses of peak power of 500 W [57]. SC covering the range 1.4-13.3 µm was observed in 85 mm long As_2S_3 step index fiber with a 16 µm core [58]. Recently interest has grown in designing and optimizing planar waveguides made from $Ge_{11.5}As_{24}Se_{64.5}$ chalcogenide glasses for broadband mid-infrared SCG with appropriately tailored group velocity dispersion (GVD), including a zero dispersion wavelength (ZDW) close to the central wavelength of the pump [59,60].

In the present paper, we numerically demonstrate MIR supercontinuum generation spanning 1.5-13µm in a step index fiber having $Ge_{11.5}As_{24}Se_{64.5}$ as core material and $Ge_{11.5}As_{24}S_{64.5}$ taking as cladding material. Amongst all chalcogenide glasses, $Ge_{11.5}As_{24}Se_{64.5}$ partakes high thermal and optical stability under intense illumination [61]. The variations in the optical properties of fiber such as dispersion profile, effective mode area, nonlinearity of material have been studied by varying geometrical properties of fiber and wavelength of the pump source. Diameter of the fiber core has been optimized to keep dispersion in normal regime to get higher stability. SC generation by varying pump power, input pulse duration and length of the fiber has been investigated to obtain a wide supercontinuum spectrum ranging from 1.5-

13μm having a low dispersion of –11.36ps/nm-km at pump wavelength of 3.1μm. Such broadband SCG has potential applications in various fields such as telecommunication, ultrafast spectroscopy, pulse compression and optical coherence tomography.

This paper consists of five sections. In section-1, brief introduction of SCG and the familiar ideas of previously reported works on the topic have been discussed. Section-2 gives the design of proposed step index fiber. In section-3, the numerical methods of analysis have been discussed. Section-4 is related to the results and discussion. In the last section, the conclusion of the reported work is provided.

6.2 Fiber design

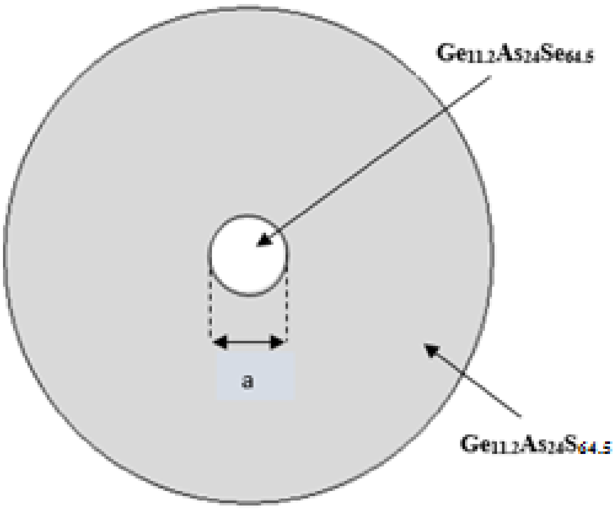


Fig.6.1(a) Transverse cross-section of step index fiber structure

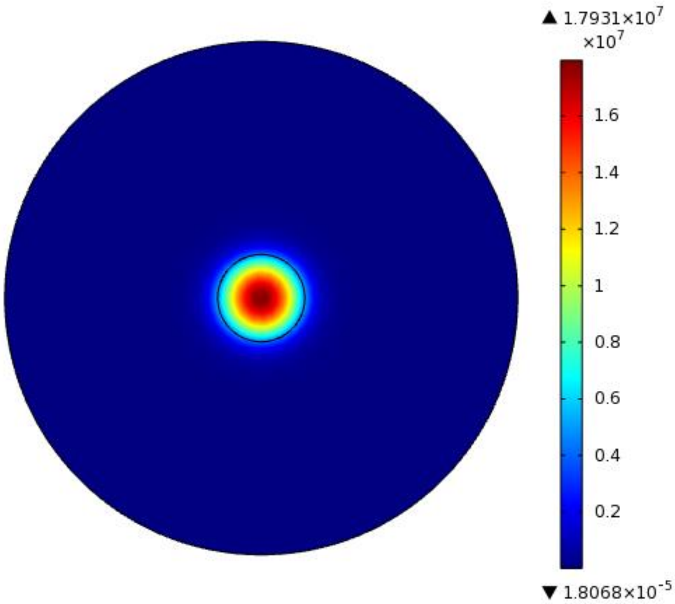


Fig.6.1(b) Transverse electric field distribution of fundamental mode at 3.1 μm

The cross-sectional interpretation of the proposed step index fiber is shown in the Fig.6.1(a). The diameter of the core is taken as 1.7 µm which is made of $Ge_{11.5}As_{24}Se_{64.5}$ chalcogenide glass material, while $Ge_{11.5}As_{24}S_{64.5}$ chalcogenide glass is taken as the cladding material.

In this paper, the chalcogenide materials are chosen to design the fiber for getting mid-infrared supercontinuum generation due to their high nonlinearity and transparency in mid-infrared domain. Fig.6.1(b) shows the transverse electric field distribution of fundamental mode in the fiber at pump wavelength of 3.1 µm. The fundamental mode with effective mode area of 6.09 µm^2 has been obtained.

6.3 Numerical method analysis

In this work, a full vectorial finite element method based commercially available software 'COMSOL Multiphysics' has been used to simulate the effective indices of the fundamental mode propagating in the core of the reported fiber.

For the calculation of wavelength dependent linear refractive index, n(λ) of the chalcogenide materials, following sellmeier equations are used [61].

The sellmeier equation for $Ge_{11.5}As_{24}Se_{64.5}$ is given by

$$n(\lambda) = \sqrt{1 + \frac{5.78525\lambda^2}{\lambda^2 - 0.28795^2} + \frac{0.39705\lambda^2}{\lambda^2 - 30.39338^2}} \quad (6.1)$$

and the selliemer equation for $Ge_{11.5}As_{24}S_{64.5}$ is given by

$$n(\lambda) = \sqrt{1 + \frac{4.18011\lambda^2}{\lambda^2 - 0.31679^2} + \frac{0.35895\lambda^2}{\lambda^2 - 22.77018^2}} \quad (6.2)$$

where, λ is the pump wavelength in micrometers.

The GVD and nonlinearity of material are two very important parameters for the generation of broad and efficient SCG. The nonlinearity depends upon nonlinear refractive index of material and given by

$$\gamma = \frac{2\pi n_2}{\lambda A_{eff}} W^{-1} km^{-1} \quad (6.3)$$

where, n_2 = 4.3 x 10^{-18} m^2/W at 3.1 µm [62] and A_{eff} is effective mode area of fundamental mode. The group velocity dispersion, D(λ) is calculated from the wavelength dependent effective refractive index (n_{eff}) as follows

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 n_{eff}}{d\lambda^2} \tag{6.4}$$

where, c is the velocity of light in free space and n_{eff} is real part of effective mode index. The effective mode area is calculated using the following equation [24],

$$A_{eff} = \frac{\left(\iint_{-\infty}^{\infty} |E|^2 dxdy\right)^2}{\left(\iint_{-\infty}^{\infty} |E|^4 dxdy\right)} \tag{6.5}$$

where, E is the transverse electric field of the fundamental mode.

SCG is obtained by numerical simulation of the generalized nonlinear Schrodinger equation (GNLSE)for output pulse envelope A(z:t) using split step Fourier method [59],

$$\frac{\partial A}{\partial z} + \frac{\alpha}{2}A - \left(\sum_{n\geq=2} \beta_n \frac{i^{n+1}}{n!}\frac{\partial^n}{\partial t^n}A\right) = i\,\gamma\left(1 + \frac{i}{\omega}\frac{\partial}{\partial t}\right) \times \left[A(z,t)\int_{-\infty}^{\infty} R(t`)|A(z,t-t`|^2 dt` + i\Gamma_R(z,t)\right] \tag{6.6}$$

where, A(z; t)is the envelope of the optical field, t is time and γ is the nonlinear coefficient. The propagation loss of the fiber is 'α' which is 0.05 dB/mm [61,63]. β_n are dispersion coefficients obtained by a Taylor series expansion of the propagation constant β(ω) around the center frequency ω_0 given by [24]

$$\beta(\omega) = \beta(\omega_0) + \beta_1(\omega_0)(\omega-\omega_0) + \frac{1}{2!}\beta_2(\omega_0)(\omega-\omega_0)^2 + \frac{1}{3!}\beta_3(\omega_0)(\omega-\omega_0)^3 + \cdots \tag{6.7}$$

R(t) represents the response function including the Raman and Kerr nonlinearities. Assuming the electronic contribution is nearly instantaneous the functional form of *R*(*t*) can be written as

$$R(t) = (1-f_R)\delta(t) + f_R h_R(t) \tag{6.8}$$

where, f_R = 0.031 for $Ge_{11.5}As_{24}Se_{64.5}$chalcogenide glass [64] which represents the fractional contribution of the delayed Raman response, and $h_R(t)$ denotes the Raman response function that contains information on the vibration of material molecules as light passes through the fiber and given by

$$h_R(t) = \frac{\tau_1{}^2 + \tau_2{}^2}{\tau_1 \tau_2{}^2} \exp\left(-\frac{t}{\tau_2}\right) \sin\left(\frac{t}{\tau_1}\right) \tag{6.9}$$

where, Raman period, τ_1 = 15.5 fs and life time, τ_2 = 230.5 fs for $Ge_{11.5}As_{24}Se_{64.5}$chalcogenide glass [64].

In the simulation, the hyperbolic secant pulse is used as an input pulse which can be expressed as:

$$A(z = 0, t) = \sqrt{P_0}\,.sech\left(\frac{t}{T_0}\right) \tag{6.10}$$

where, $t_0 = T_{FWHM}/1.763$ and P_0 is peak power of input pulse.

Fourth order Runge-Kutta interaction picture (RK4IP) method [65] is used to solve the eqn. (6.6). It is a very fast integration method and accurate as well.

6.4 Results and Discussion

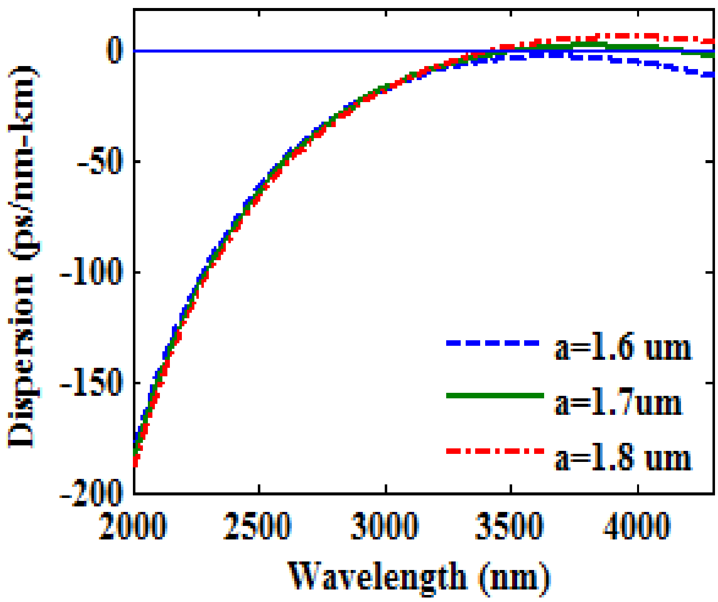


Fig. 6.2 Influence on the dispersion characterstics with the varition of core diameter of the fiber

To get the stable and efficient ultra-broadband supercontinuum spectrum in MIR region, the structural parameter (i.e. core size) has been optimized in order to get all-normal and flat-top dispersion profile. Figure 6.2 depicts the variations of the dispersion profile with variation of the diameter of the core of the fiber.

It can be observed that with the increase of the core radius, at higher wavelengths, dispersion shifts from normal regime to anomalous regime. The pump wavelength is selected in normal dispersion region in order to keep shot to shot noise free spectrum generation. A flat dispersion curve having dispersion of-11.36 ps/(nm × km) at pump wavelength of 3.1 µm have been obtained with a 1.7 µm core radius.

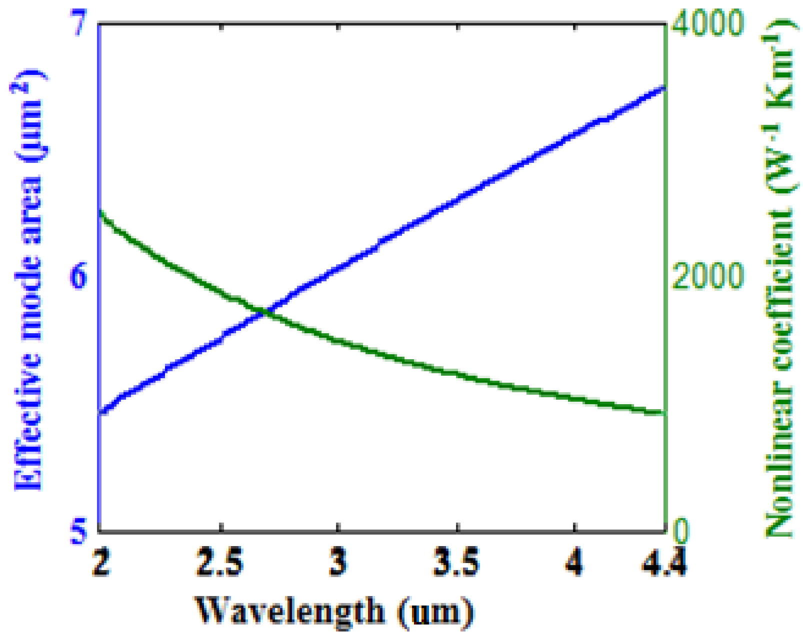


Fig.6.3 Variation of effective mode area and nonlinear coefficient with variation of wavelength

Figure 6.3 depicts the variation of effective mode area and nonlinear coefficient with the wavelength variation. The nonlinearity coefficient increases with the decrease of effective mode area. At the pump wavelength, the structue holds a nonlinear coefficient as high as 1431 $W^{-1}km^{-1}$ with effective mode area of 6.09 μm^2.

The broadening of supercontinuum spectrum using a 10 mm long fiber pumped with 50 fs input pulses at various peak power has been shown in Figure 6.4. Simulation results shows that an increase in the peak pump power results in the broadening of supercontinuum spectra. At higher peak power, SPM effect dominants over dispersion effect. With the further increase in the peak power shows no significant increase in broadening of spectrum. An ultra-broadband mid-infrared SC extending from 1.5 µm to 13 µm at 30 dB level has been generated with 4000 W peak power. The increase in the peak power leads to the more flatness of the Sc spectra.

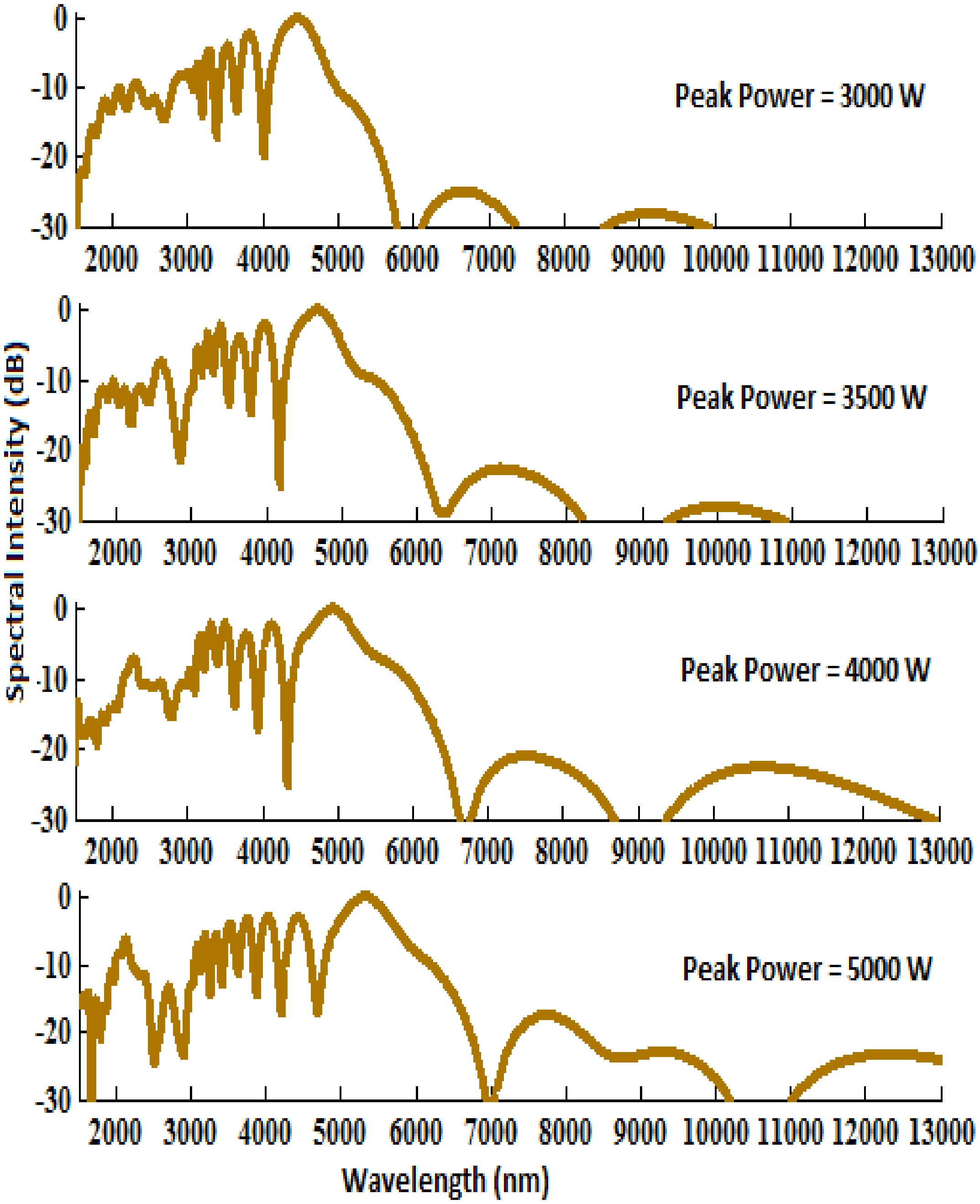


Fig.6.4 Effect of the variation in peak power on SCG spectra with 50 fs incident pulse in 10 mm length of fiber

The effect of the variation of the length of the fiber have been illustrated in figure 6.5. With the increase in the length of the fiber, broadening of the supercontinuum spectra increases.

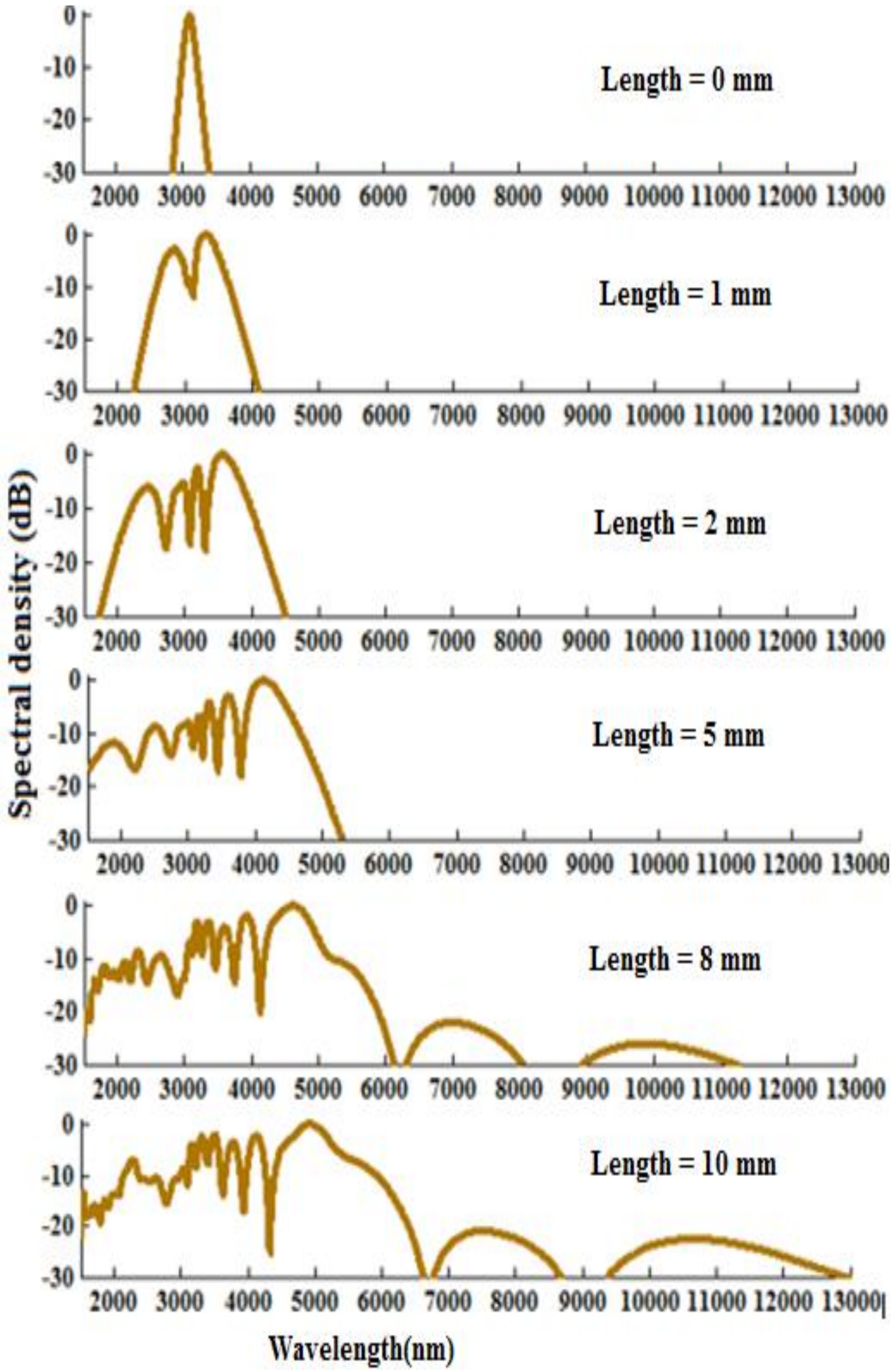


Fig.6.5 Effect of the variation in length of fiber on SCG spectra with 50 fs incident pulse of 4000 W peak power

Initially, the broadening of the spectra is symmetrical due to SPM. With the further increase in the length of the fiber, effect comes into play and results in the further increase in supercontinuum spectra. As the pulse propagates through the fiber, more and more nonlinear effects come into play and results in the more broadening of the SC spectra [66]. The relationship of the GVD and SPM effects results to a qualitatively dissimilar behaviour compared with that expected from GVD or SPM unaccompanied. Hence, the optimum SCG is obtained at L = 10 mm.

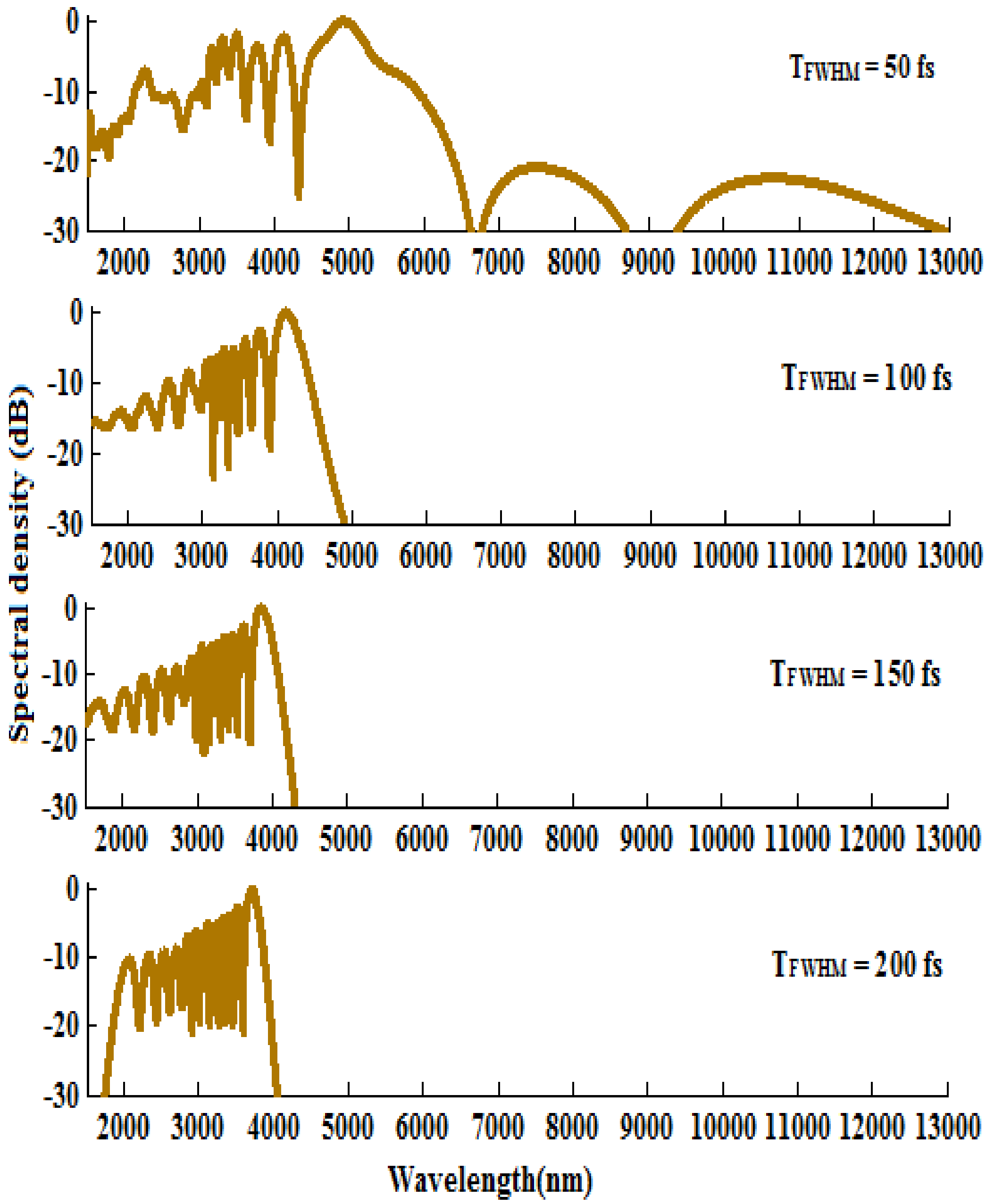


Fig.6.6 Effect of the variation in input pulse width on SCG spectra with peak power of 4000 W in 10 mm length of fiber.

Figure 6.6 illustrates effect of the pulse width on the broadening of SC spectra in 10 mm long step index fiber. The input power is kept fixed at 4000 W. The pulse width of input hyperbolic secant pulse is varied from 50 fs to 200 fs in the steps of 50 fs. It can be observed that increase in the input pulse width, T_{FWHM} results in narrowing of SC spectra. The rate of change of intensity decreases with the increase of the pulse width, thus reducing the self -phase modulation.

It can be evident from the simulations and the various results obtained that the most effective broadband supercontinuum spectrum ranging from 1.5 µm – 13 µm is obtained using only 10 mm length of the fiber pumped with 50 fs input pulse of 4000 W peak power.

6.5 Conclusions

A novel $Ge_{11.5}As_{24}Se_{64.5}$ based chalcogenide glass step index fiber structure has been reported for mid-infrared supercontinuum generation. The proposed structure inhibits a very high nonlinearity (i.e. γ = 1431 $W^{-1}Km^{-1}$) at pump wavelength of 3.1 µm with low negative dispersion of –11.36 ps/nm km. A broadband spectrum spanning 1.5 – 13 µm using a 10 mm step index fiber with a peak power of 4 kW has been simulated. Such ultra-broadband supercontinuum spectrum is expected to have profound applications in various fields. The specific applications of mid-IR supercontinuum generation include spectroscopy, optical coherence tomography, frequency comb generation, early cancer detection, food quality control, security and sensing.

CHAPTER 7

CONCLUSIONS AND SCOPE FOR FUTURE WORK

7.1 Conclusion

A novel $Ge_{11.5}As_{24}Se_{64.5}$ based chalcogenide glass step index fiber structure has been designed for mid-infrared super continuum generation. The proposed structure has a very high value of nonlinearity (γ=1431 $W^{-1}Km^{-1}$) at pump wavelength of 3.1 µm due to the higher nonlinear refractive index of the material. This design exhibits a very low and flat dispersion of – 11.36ps/nm km at pump wavelength. The pump wavelength is chosen in the normal dispersion regime for more stability of the SCG spectra. A broadband spectrum spanning 1.5 µm -13 µm has been obtained. This SCG spectra range is achieved in a 10mm length of step index fiber when a peak power of 4 kW is incident in the fiber using an ultrashort pulse laser. Such ultra-broadband supercontinuum spectrum is expected to have various applications in different fields. The applications of mid-IR supercontinuum generation involve optical coherence tomography, spectroscopy, frequency comb generation, food quality control, early cancer detection, sensing and security.

7.2 Scope for future work

Super continuum generation has been generated using step index fiber. The step index fiber can be designed to operate single mode and zero dispersion at pump wavelength. This fiber has been designed for all normal dispersion. The effective mode area has to be reduced to increase nonlinear coefficient to obtain a broader and flat spectrum. For further better results, using the same material it can be designed in PCF structure where changing the various parameters of the PCF, better results can be obtained.

Also by optimising the various parameters of PCF such as diameter of the holes, pitch of the holes, and designing of the structure affect the nonlinear properties of the material. By using a material with high nonlinear coefficient also enhances the broadening of the SCG spectra. So, different materials can also be used to get more stable and large broadening of the supercontinuum generation spectrum.

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