Chapter One

Introduction and Basic Concepts

1.1 Introduction

Optical fibers, which transmit information in the form of short optical pulses over long distances at exceptionally high speeds, are one of the major technological successes of the 20th century. This technology has developed at an incredible rate, from the first low loss single mode waveguides in 1970 to being key components of the sophisticated global telecommunication network. Optical fibers have also non-telecom applications, for example, in beam delivery for medicine, machining and diagnostics, sensing, and a lot of other fields. Modern optical fibers represent a careful trade - off between optical losses, optical nonlinearity, group velocity dispersion, and polarization effects. After30 years of intensive research, incremental steps have refined the capabilities of the system and the fabrication technology nearly as far as they can go (Poli, Cucinotta, and Selleri, 2007).

The optical fiber falls into a subset of structures known as dielectric optical Waveguides (Bass and Van Stryland, 2002). In its simplest form, an optical fiber consists of a (cylindrical) central dielectric core of refractive index n_1 cladded by a material of slightly lower refractive index n_2 ¿ ¿ n_1) (Banerjee, 2004, Agrawal, 2007, and Agrawal, 2002). This index difference requires that light from inside the fiber which is incident at an angle greater than the critical angle be totally internally reflected at the interface (Bass et al, 1995):

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) \qquad (1.1)$$

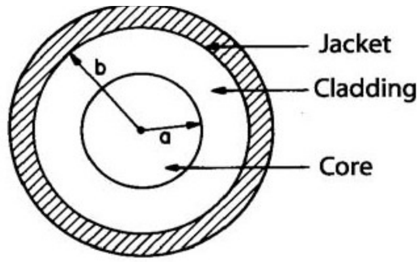

Figure (1.1): Schematic illustration of the cross section of optical fiber as (*Thyagarajan and Ghatak, 2010).*

The corresponding refractive index distribution is given as (Thyagarajan and Ghatak, 2010):

$$n = n_1 ; r < a \qquad (1.2)$$

$$n = n_2 ; r > a \qquad (1.3)$$

Where $: n_1$ and n_2 ($n_2 < n_1$) represent the refractive indices of core and cladding, respectively, and a represents the radius of the core. We define a parameter through the following equation (Agrawal, 2007, Thyagarajan and Ghatak, 2010):

$$\Delta = \frac{n_1^2 - n_2^2}{2n_1^2}$$

(1.4)

The necessity of a cladded fiber rather than a bare fiber, i.e., without a cladding, was felt because of the fact that for transmission of light from one place to another, the fiber must be supported, and supporting structures may considerably distort the fiber, thereby affecting the guidance of the light wave. This can be avoided by choosing a sufficiently thick cladding (Knight et al, 1996). The following figure shows fiber component and how the light ray entre the fiber.

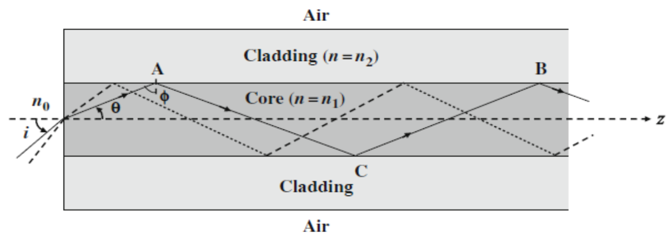

Figure (1.2): fiber consists of (core and cladding) and incident Light rays (Thyagarajan and Ghatak, 2010).

Since 1980's the researchers and engineers they are attracted by the ability to structures material on the scale of the optical wavelength (Knight et al, 1996), a fraction of micrometer or less, in order to develop new optical medium known as Photonic Crystal fibers (PCFs). Photonic crystals rely on a regular morphological microstructure, incorporated into the material, which radically alters its optical properties (Knight, 2003).

1.2 The aim of this work

In the present work, the spectral width of short laser pulses changed after propagating in hollow core photonic crystal fiber (HC-PCF) is studied experimentally. This study based on propagating diode laser pulses with microseconds pulse duration operating at 675 nm and 820 nm wavelengths with repetition rate of 1, 5 and 10 KHz for each wavelength, and the average power is 30mW and 200mW respectively, in different set of temperatures.

1.3 Fiber Types

There are several types of fibers according to two parameters that characterize an optical fiber.

The relative core–cladding index difference which is given by the relation:

$$\Delta = \frac{n_1 - n_2}{n_1} \quad (1.5)$$

And the V parameter:

$$V = k_0 a \left(n_1^2 - n_2^2\right)^{\frac{1}{2}}. \quad (1.6)$$

Where: $k_0 = \frac{2\pi}{\lambda}$, a is core radius and λ is the wavelength. The V parameter determines the number of modes supported by the fiber; these modes described the electromagnetic waves propagating along. Only a certain discrete number of modes are capable to propagating along the fiber, these modes are those electromagnetic waves that satisfy the homogeneous wave equation in the fiber and the boundary condition at the waveguide surface (Keiser, 1991). According to the supporting modes in the fiber we have two types of fiber that are single-mode fiber as the name implies only one mode of propagation and multi-mode fiber which contain many hundreds of modes. The variation in the material composition of the core gives rise to the three commonly used fiber types.

1.3.1 Multimode Step Index Fiber (Step Index Fiber)

This fiber is called (Step Index) because the refractive index changes abruptly from cladding to core. The cladding has a refractive index somewhat lower than the refractive index of the core glass. As a result, all rays within a certain angle will be totally reflected at the core-cladding boundary. Rays striking the boundary at angles greater than the critical angle will be partially reflected and partially transmitted out through the boundary. After many such bounces the energy in these rays will be lost from the fiber. The paths along which the rays (modes) of this step index fiber travel differ, depending on their angles relative to the axis. As a result, the different modes in a pulse will arrive at the far end of the fiber at different times, resulting in pulse spreading which limits the bit-rate of a digital signal which can be transmitted (Teja, 2012).

1.3.2 Multimode graded Index Fiber (Graded Index Fiber)

This fiber is called graded index because there are many changes in the refractive index with larger values towards the center. As light travel faster in a lower index of refraction. So, the farther the light is from the center axis, the grater is its speed. Each layer of the core refracts the light. Instead of being sharply reflected as it is in a step index fiber, the light is now bent or continuously refracted in an almost sinusoidal pattern. Those rays that follow the longest path by travelling near the outside of the core have a faster average velocity.light travelling near the center of the core has the slowest average velocity (Teja, 2012).

As a result all rays tend to reach the end of the fiber at the same time. That causes the end travel time of different rays to be nearly equal, even though they travel different paths (Teja, 2012).

1.3.3 Single Mode Step Index Fiber (Single Mode Fiber)

The single mode fiber has an exceedingly small core diameter of only 5 µm to 10 µm. Standard cladding diameter is 125 µm. Since this fiber carries only one mode, model dispersion does not exist. As optical energy in a single mode fiber travels in the cladding as well as in the core, therefore the cladding must be a more efficient carrier of energy. In a multimode fiber cladding modes are not desirable; a cladding with in efficient transmission characteristic can be tolerated. The diameter of the light appearing at the end of the single mode fiber is larger than the core diameter, because some of the optical energy of the mode travels in the cladding. Mode field diameter is the term used to define this diameter of optical energy (Teja, 2012). Figure (1.3) shows these types of the fiber

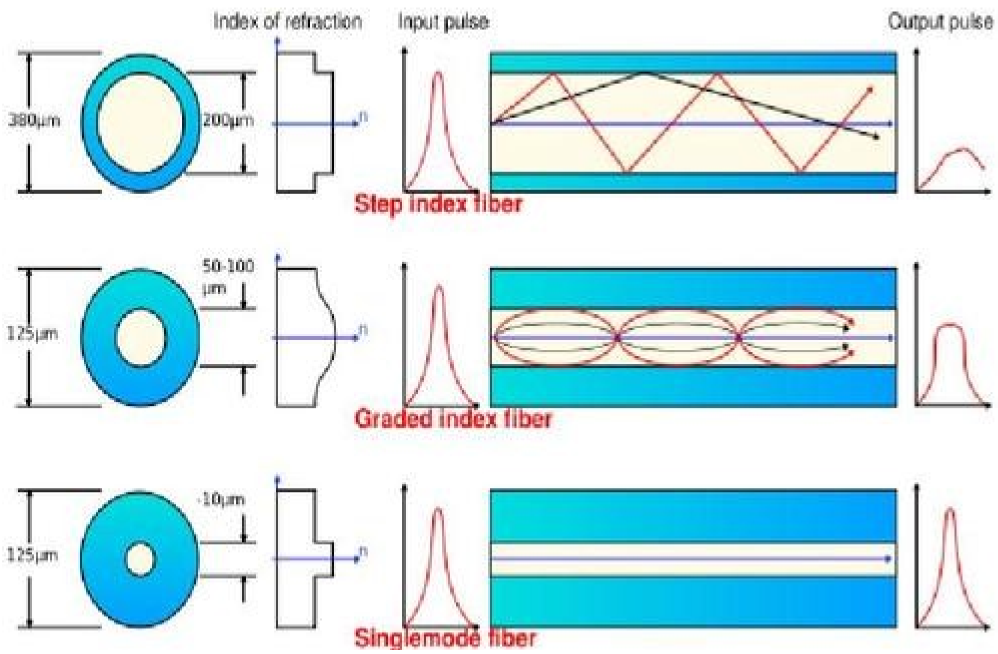

Figure (1.3): The fiber types, above multi-mode (step-index) fiber, middle multi- mode (graded-index) fiber and below single –mode (step-index) fiber (Teja, 2012).

1.4 Numerical Aperture of the Fiber

We consider light ray which is incident on the entrance aperture of the fiber with angle (i) with the axis and refracted with angle (θ) with the axis, by assuming the refractive index of outside medium $is\, n_o$ we get:

$$\frac{\sin i}{sin\theta}=\frac{n_1}{n_o} \qquad (1.7)$$

Obviously if this ray has to suffer total internal reflection at the core–cladding interface

$$\sin \varnothing (¿\, cos\theta)>\frac{n_2}{n_1} \qquad (1.8)$$

Thus

$$sin\theta<[1-\left(\frac{n_2}{n_1}\right).^2].^{\frac{1}{2}} \qquad (1.9)$$

Then we get:

$$\sin i=n_1\sqrt{2\Delta} \qquad (1.10)$$

We have assumed $n_o=1$ (the outside medium is assumed to be air).

This equation is called the numerical aperture (NA).

1.5 Attenuation

An important fiber parameter provides a measure of power loss during transmission of optical signals inside the fiber. If P_o is the power launched at the input of a fiber of length *L*, the transmitted power P_T is given by (Agrawal, 2007, and Agrawal, 2002):

$$P_T = P_o \exp(-\alpha L)$$

(1.11)

Where: α is the attenuation constantan with unit dB/km which is measure of overall fiber losses from all sources, attenuation is caused by absorption, scattering, and bending losses. Each mechanism of loss is influenced by fiber-material properties and fiber structure. However, loss is also present at fiber connections.

1.5.1. Absorption

Absorption is a major cause of signal loss in an optical fiber. Absorption is defined as the portion of attenuation resulting from the conversion of optical power into another energy form, such as heat. Absorption in optical fibers is explained by three factors (Thyagarajan and Ghatak, 2010):

1. Imperfections in the atomic structure of the fiber material.

2. The intrinsic or basic fiber-material properties.

3. The extrinsic (presence of impurities) fiber-material properties.

1.5.2. Scattering

Basically, scattering losses are caused by the interaction of light with density fluctuations within a fiber. Density changes are produced when optical fibers are manufactured. The loss spectrum of PCFs is similar to that of conventional fibers. Therefore, it can be described analogously to conventional fiber. Which described by the following equation (Poli, Cucinotta and Selleri, 2007):

$$\alpha\left(\frac{dB}{km}\right)=\frac{C}{\lambda^4}+B+\alpha_{OH}+\alpha_{IR} \qquad (1.12)$$

Where: C/λ^4 is the Rayleigh scattering which is the fundamental loss in optical fiber caused by scattering of light by random fluctuation in refractive index on a scale smaller than the optical wavelength (Al Falah, 2009), C is Rayleigh Scattering coefficient in $\left(\frac{dB}{km}\right).(\mu m).^4$, B is the loss caused by scattering due to imperfections, α_{OH} is the OH absorption loss and i α_{IR} s the infrared absorption loss (Al Falah, 2009).

1.5.3. Bending losses

Bending is geometrical effects it divided to micro and macro bending losses PCFs have a complex cladding structure, they have bending loss at short and long wavelengths unlike conventional fibers where only the long wavelength bend edge exists (Poli, Cucinotta, and Selleri, 2007), the macrobend is express as(Nielson et al, 2004).

$$\alpha_{macro} = -10\log\left(1 - \left\{\frac{1}{2\Delta}\left[\frac{2a}{R} + \left(\frac{3}{2nkR}\right)^{\frac{2}{3}}\right]\right\}\right) \quad (1.13)$$

and the microbend loss is given as :

$$\alpha_{micro} = 0.05\,\alpha_m \frac{k^4 W^6 NA^4}{a^2}$$

(1.14)

Where Δ : is the difference between core and cladding refractive index

a: core radius, R: radius of curvature of bends, k: wave vector, *NA*: numerical aperture, α_m : Attenuation constant, W: mode field radius.

1.6 Dispersion

In telecommunication systems, information is transmitted as binary data, taking the form of light pulses in optical fibers. In the field of optical waveguides, dispersion is a generic term referring to all phenomena causing these pulses to spread while propagating and they eventually overlap and light pulses could not be distinguished by the receiver(Poli, Cucinotta, and Selleri, 2007).There are essentially three causes of dispersion .

1.6.1 Chromatic (Intramodal) Dispersion

Chromatic dispersion results from the spectral width of the emitter. The spectral width determines the number of different wavelengths that are emitted from the LED or laser. The smaller the spectral width, the fewer the number of wavelengths that are emitted. Because longer wavelengths travel faster than shorter wavelengths (higher frequencies) these longer wavelengths will arrive at the end of the fiber ahead of the shorter ones, spreading out the signal.

One way to decrease chromatic dispersion is to narrow the spectral width of the transmitter. Lasers, for example, have a more narrow spectral width than LEDs. A monochromatic laser emits only one wavelength and therefore, does not contribute to chromatic dispersion. There are two types of chromatic dispersion:

1.6.1.1 Material Dispersion

GVD is an important effect because when a short pulse propagates through an optical fiber its pulse width gets broaden. The effects arise from the variation of the refractive index of the material as a function of wavelength.. This causes a wavelength dependence of the group velocity of any given mode, that is, pulse spreading occurs even when different wavelengths follow the same path (Russell, 2003.This phenomena can be understood by expanding the mode-propagation constant β in a Taylor series about the frequency ω_o at which the pulse spectrum is centered, (Agrawal, 2007).

$$\beta(\omega)=n_{eff}(\omega)\frac{\omega}{C}=\beta_0+(\omega-\omega_0)\beta_1+\frac{1}{2}(\omega-\omega_0).^2\beta_2+\frac{1}{6}(\omega-\omega_0).^3\beta_3+\dots$$

(1.15)

Where:

$$\beta_m = \left(\frac{d^m \beta}{d\omega^m} \right) \omega - \omega_0 \qquad m = (0, 1, 2 ,\ldots) \tag{1.16}$$

$$\beta_0 = n_{eff}(\omega_0) \frac{\omega_0}{C} \tag{1.17}$$

$$\beta_1 = \frac{1}{C} \left(n_{eff} + \omega \frac{dn_{eff}}{d\omega} \right) = \frac{1}{v_g} = \frac{n_g}{C} \tag{1.18}$$

$$\beta_2 = \frac{1}{C} \left(2 \frac{dn_{eff}}{d\omega} + \omega \frac{d^2 n_{eff}}{d\omega^2} \right) = \frac{d}{d\omega} \left(\frac{1}{v_g} \right) \tag{1.19}$$

Where $:\beta_0$ is the mode propagation constant of frequency ω_0 , v_g is the group velocity, and n_g is the group index. The group velocity is the speed of the envelope of an optical pulse propagating in a fiber. The coefficient β_2 determines the changes in the group velocity of an optical pulse as a function of optical frequency. This phenomenon is known as GVD and is responsible for pulse broadening. Thus, β_2 is called the GVD parameter. In general, we must retain terms up to the second-order dispersion β_2 to describe pulse propagation in dispersive media, and for ultrashort pulses or those with a wide frequency spectrum it may sometimes be necessary to also include higher order terms.

The dispersion parameter D is commonly used in place of β_2 to describe the total dispersion of a single mode fiber. It is related to $\beta_2 by$ the relation:

$$D = \frac{d\beta_1}{d\lambda} = \frac{-2\pi}{\lambda^2}\beta_2 \qquad (1.20)$$

and is expressed in unit of ps/(km.nm). Since GVD mainly comes from the combined effects of material and waveguide dispersion, D can be written as the sum of two terms.

$$D_{intra} = D_M + D_W \qquad (1.21)$$

Where D_M is the material dispersion and D_W is the waveguide dispersion.

$$D_M = \frac{-\lambda}{C}\frac{d^2 n_{eff}}{d\lambda^2} \qquad (1.22)$$

Where $n_{eff} i$ s the effective refractive index given by (Birks et al, 2004, Kuhlmey et al, 2002):

$$n_{eff} = \sqrt{f n_{air}^2 + (1-f) n_{silica}^2} \qquad (1.23)$$

Where n_{air} obtained from the following equation **(**Hirooka and Nakazawa, 2004**)**.

$$n_{air} = 1 + 0.0472326\left(173.3 - \frac{1}{\lambda^2}\right).^{-1} \qquad (1.24)$$

But When the holes of the hollow core photonic crystal bandgap fiber filled with materials other than air specially the n_{air} in equation(1.24) replaced by n_m that obtained by the following Cauchy formula (Al Falah, 2009):

$$n_m = ac + \frac{bc}{\lambda^2} + \frac{cc}{\lambda^4} \qquad (1.25)$$

Where ac, bc, cc are the Cauchy coefficients.

and n_{silica} in equation (1.23) is the refractive index of silica that get from the following Sellmeier equation (Al Fala, 2009):

$$n_{silica}(\omega) = 1 + \sum_{j=1}^{m} \frac{B_{sj}\,\omega_j^2}{\omega_{sj}^2 - \omega^2} \qquad (1.26)$$

1.6.1.2 Waveguide Dispersion

The group velocity of guided optical pulses depends on the wavelength even if material dispersion is negligible. This depends is known as the waveguide dispersion. The contribution of waveguide dispersion D_W to the dispersion parameter D is given by the equation (1.21).D_W depends on the index difference Δ.

1.6.2 Intermodel Dispersion

It results from the propagation delay differences between modes within a multimode fiber. As the different modes that constitute a pulse in a multimode fiber travel along the channel at different group velocities, the pulse width at the output is dependent upon the transmission time of the lowest and fastest modes (Al Falah, 2009).

$$D_{total}^{2}=\left(D_{material}+D_{wa\,veguide}\right).^{2}\,\Delta\lambda^{2}+D_{modal}^{2} \qquad (1.27)$$

1.6.3 Polarization Mode Dispersion (PMD)

A fundamental property of an optical signal is its polarization state. Polarization refers to the electric-field orientation of a light signal, which can vary significantly along the length of a fiber. As shown in Figure (1.4), signal energy at a given wavelength occupies two orthogonal polarization modes. A varying birefringence along its length will cause each polarization mode to travel at a slightly different velocity and the polarization orientation will rotate with distance. The resulting different in propagation modes will result in pulse spreading. This is the Polarization Mode Dispersion (PMD) (Keiser, 1991, Agrawal, 2001, Ming and Liu, 1996)

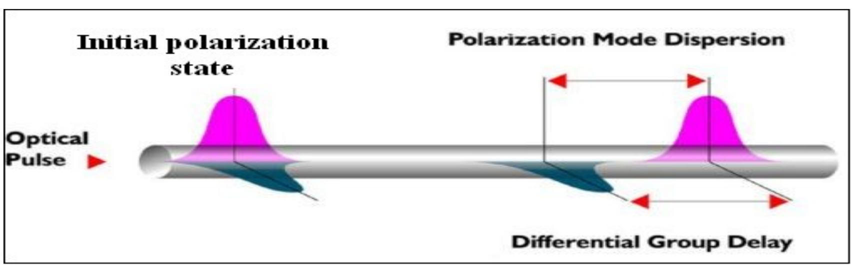

Figure (1.4): variation in polarization states of an optical pulse at it passes through a fiber (*Al Falah, 2009*).

1.7 Fiber nonlinearities

An optical fiber like any other dielectric is response to light and becomes nonlinear for intense of electromagnetic field, the response of the optical fiber depends in a nonlinear manner upon the strength of the applied optical field. the total polarization **P** induced by electric dipoles does not depend linearly on the electric field, but satisfies more general relation by expressing the **P** in a power series in **E** as (Agrawal, G., 2001, Boyd, R., 2003, Agrawal, G., 2001, Shen, 1984):

$$P=\varepsilon_0(\chi^1\cdot E+\chi^2:EE+\chi^3\vdots EEE+\ldots) \qquad (1.28)$$

Where: ε_0 is the vacuum permittivity and $\chi^j(j=1,2,\ldots)$ is jth order susceptibility. In general, χ^j is a tensor of rank j+1 of medium. The linear susceptibility χ^1 represents the dominant contribution to P, and is related to the refractive index n and attenuation coefficient α by the relations (Agrawal, 2007, Agrawal, G., 2001):

$$n(\omega)=1+\frac{1}{2}\Re[\tilde{\chi}^{(1)}(\omega)] \qquad (1.29)$$

$$\alpha(\omega)=\frac{\omega}{nC}\Im[\tilde{\chi}^{(1)}(\omega)] \qquad (1.30)$$

The term χ^2 (second order susceptibility)give rise to nonlinear effect such as sum and difference frequency generation and second harmonic generation, the term χ^3 (third order susceptibility) is responsible for nonlinear effect such as third harmonic generation, four wave mixing, two- photon absorption and nonlinear refractive index (Agrawal, 2007, Birks et al, Agrawal, 2001).

The nonlinearities in optical fiber can be classified into two categories (Agrawal, 2002, Kale, Ingale and Murade, 2013), the first one occur due to the refractive index dependence such as Self Phase Modulation (SPM), Cross Phase Modulation (CPM)and Four Wave Mixing (FWM).the second set of effect occur because of scattering effects in the fiber with the light – phonon interaction. In this category there are two main effects are stimulated Raman Scattering (SRS) and Stimulated Brillouin Scattering (SBS). In the following sections we discuss this effects briefly.

1.7.1 Nonlinear refraction

Third order susceptibility $\chi^{(3)}$ originated nonlinear effect such as third harmonic generation, four wave mixing and nonlinear refraction phenomenon which referring to intensity dependence on refractive index, can be describe as (Agrawal, 2007,Agrawal, G., 2001):

$$\tilde{n}\left(\omega,|E|^2\right)=n(\omega)+n_2(\omega)|E|^2 \tag{1.31}$$

Where $n(\omega)$ is the linear, weak- field refractive index and $n_2(\omega)$ is the nonlinear refraction coefficient. We place a bar over the refractive index n to prevent confusion with the usual, weak-field refractive index. The nonlinear refraction coefficient $n_2(\omega)$ is related to $\chi^{(3)}$ by:

$$n_2(\omega)=\frac{3}{8n(\omega)}\Re\left(\chi^3_{xxxx}\right) \qquad (1.32)$$

Where: Re stands for the real part and the optical field is assumed to be linearly polarized so that only one component χ^3_{xxxx} of the fourth-rank tensor contributes to the refractive index (Agrawal, 2007,Agrawal, G., 2001).

1.7.2 Effective length and effective area

The nonlinear effect depend on the transmission length and the area cross section of fiber, The longer the fiber link length, the more the light interaction and greater the nonlinear effect. As the light propagates along the length it is power decreases due to fiber attenuation. The effective fiber length L_{eff} is that length which power assumed to be constant. If the input power is P_0 at a distance z with attenuation coefficient α along link is described as (Singh, S. and Singh, N., 2007):

$$P(z)=P_0\exp(-\alpha z) \qquad (1.33)$$

for actual link length (L), the effective length is defined as :

$$P_0 L_{eff}=\int_{z=0}^{L} P(z)dz \qquad (1.34)$$

By using the two equations the effective link length is obtained as:

$$L_{eff}=\frac{(1-\exp(-\alpha z))}{\alpha} \qquad (1.35)$$

Also the effect of nonlinearity grows with intensity in fiber and the intensity is inversely proportional to area of the core. Since the power is not uniformly distributed within the cross-section of the fiber, it is reasonable to use effective cross-sectional area (A_{eff}).

1.7.3 Self Phase Modulation (SPM)

Self Phase Modulation (SPM) is nonlinear effects of light- matter interaction. (Singh, S. and Singh, N., 2007). SPM generates additional frequency components due to the picture of amplitudes and independent on the intensities. The amplitude contributions from SPM interfere with those amplitudes which are already present in the pulse. The spectrum will become broader when the interference is constructive in the spectrum wings otherwise the spectrum pulse will compress if the interference is destructive. (Rudiger Paschotta, 2013). In the systems with high- transmitted power the SPM effects are more pronounced because the chirping effect is proportional to transmitted power (Singh, S. and Singh, N., 2007). When an ultrashort or short pulse of light traveling in the fiber the medium refractive index will varying due to Kerr- effect, this refractive index variation will produce a phase shift in the pulse(Agrawal and Andersolsson, 1989).

The phase $\varnothing$ is given by:

$$\varnothing = \frac{2\pi}{\lambda} nL \tag{1.36}$$

Where: λ is wavelength of optical pulse propagation in fiber with length L and refractive index n and n L is called optical path length.

For high power transmitted in fiber the n and L are replaced by n_{eff} and L_{eff} respectively equation (1.36) become:

$$\phi=\frac{2\pi}{\lambda}n_{eff}L_{eff} \tag{1.37}$$

Or

$$\phi=\frac{2\pi}{\lambda}(n_L+n_{nl}I)L_{eff} \tag{1.38}$$

Where: $n_{eff}=n_L+n_{nl}I$; n_L is the linear refractive index and n_{nl} is nonlinear refractive index.

The total phase shift is given by(Masuda, 2008):

$$\phi=\phi_l+\phi_{nl} \tag{1.39}$$

There are two important applications of SPM concept in solitons and in pulse compression.

1.7.4 Cross Phase Modulation (CPM or XPM)

Is nonlinear phenomenon occurring when two or more optical pulse propagates simultaneously, the CPM is always accompanied by SPM and occurs because the nonlinear refractive index seen by an optical beam depends not only on the intensity of that beam but also on the intensity of the other co-propagating beams (Alfano et al, 1989). Asymmetric spectral broadening and distortion in the pulse shape may causes due to CPM. The effective refractive index on nonlinear medium in terms of the input power (P_o) and the effective cross section area (A_{eff}) is given by:

$$n_{eff}=n_l+n_{nl}\frac{P_o}{A_{eff}} \tag{1.40}$$

If the fiber modes are affected by the nonlinear refractive index, the mode shape does not change but the propagation constant becomes power dependant

As $K_{eff}=K_l+K_{nl}P$ (1.41)

Where: K_l is linear portion of propagation constant and K_{nl} is nonlinear portion of propagation constant. The nonlinear phase shift is given by:

$$\varnothing_{nl}=\int_0^L (K_{eff}-K_l)\,dz \tag{1.42}$$

L is the fiber length by using equation (1.38) and (1.41) we found:

$$\varnothing_{nl}=K_{eff}P_oL_{eff} \tag{1.43}$$

When two optical powers propagate simultaneously the nonlinear phase shift of the first channel ($\varnothing_{nl}^1$) depends on the signal powers of the two channels, $\varnothing_{nl}^1$ is given by:

$$\varnothing_{nl}^1=K_{eff}L_{eff}(P_1+2P_2) \tag{1.44}$$

For N- channel transmission system the nonlinear phase shift of ith channel can express as (Singh, S. and Singh, N., 2007):

$$\varnothing_{nl}^i=K_{eff}L_{eff}\left(P_i+2\sum_{n\neq i}^{N}P_n\right) \tag{1.45}$$

The factor 2 indicates that CPM is twice as effective as SPM for the same amount of power (Singh, S. and Singh, N., 2007). The first term in the equation (1.45) represents the SPM contribution and the second term that of CPM. The CPM phenomenon is used in optical switching and pulse compression.

1.7.5 Four Wave Mixing (FWM)

The Four Wave Maxing (FWM) process originates from third order nonlinear susceptibility χ^3, (Gupta and Ballato, 2007), suppose there are three optical fields with carrier frequencies $\omega_1, \omega_2 \wedge \omega_3$ copropagate inside the fiber simultaneously a fourth field will generate with frequency ω_4 due to χ^3 , which is related to the other frequencies by the relation:

$$\omega_4 = \omega_{1\pm}\omega_{2\pm}\omega_3 \qquad (1.46)$$

.In quantum mechanics the FWM occurs when photons from one wave or more are annihilated and new photons are created at different frequencies, the net energy and momentum are conserved during the interactions. The FWM process is used to reduce the quantum noise through squeezing phenomenon.

1.7.6 Stimulated Raman Scattering (SRS)

Stimulated Raman Scattering (SRS) is nonlinear effect in optical fiber causes by inelastic scattering phenomenon due to χ^3 leading to generate new spectral lines, SRS arises when the light interact with vibrational modes of the constituent molecules in the scattering medium; equivalently to light scattering from optical phonons (Frazão et al, 2009, Ruffin, 2004) when the light incident at any molecular medium there is scatter light can be observed spectroscopicaly, the energy levels of this process seen in figure (1.5):

*Figure (1.5): Energy level diagrams shows (a) Raman Stokes scattering and (b) Raman anti-Stokes scattering(*Birks et al,*2004).*

The incident optical field scatters to small fractions of new frequencies by Raman effects, those frequency component shifted to lower and higher frequencies are called stocks and anti- stocks lines. The amount of frequency shift is determined by the vibrational modes of molecules (Bhagwat and Gaeta, 2008).

1.7.7 Stimulated Brillouin Scattering (SBS)

Stimulated Brillouin scattering is nonlinear effects arises from the interaction of light with propagating density waves or acoustic phonons (Ruffin, A. 2004, Dossou, Szriftgiser and Goffin, 2008, Schneider,Hannover, and Junker, 2006). Even though SRS and SBS are very similar in their origin, different dispersion relations for acoustic and optical phonons lead to some basic differences between the two. A fundamental difference is that SBS in single mode fibers occurs only in the backward direction whereas SRS can occur in both directions (Agrawal, 2007, Frazao, O. et al, 2009).

1.8 Thesis layout

This research work organized into four chapters, chapter one is introduction of fiber technology and basic concepts and the aim of this research, photonic crystal fiber technology and propagation of short laser pulses in PCF are describes in chapter two briefly, chapter three is discussed the experimental part, chapter four included the results and the experiments results discussion the conclusion of this research work and the future research suggestions.