University of Basrah

Soliton and Supercontinuum Generation in Photonic Crystal Fibers

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In

Physics

1440/Ramadan May/2019

بســم الله الرحمــن الرحيــم

قالوا سبحانك لاعلم لنا الا

ماعلمتنا انك أنت العليم الحكيم

صدق الله العلي العظيم

سورة البقرة الاية (32)

My homeland

Iraq

And

My mother

Supervisor Certification

We certify that this thesis entitled" Soliton and Supercontinuum Generation in Photonic Crystal Fibers" submitted by **Mohammed Salim Jasim** was prepared under our supervision at the Department of Physics, College of Education for Pure Sciences, University of Basrah in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics.

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Abstract

The present thesis contains a theoretical study of the soliton and supercontinum generation phenomena in photonic crystal fibers and its appearance and continuity in the fibers depending on the photonic crystal parameters. The study depends on the effect of the photonic crystal arrangement especially the holes number, hole- hole spacing and holes diameter on the effective refractive index and the effective mode area of the photonic crystal fiber, and the effect of the fiber parameters on the pulse like the absorption, dispersion and nonlinearity studied also. As the soliton and supercontinuum generation appearance depending on the balance between the dispersion and the nonlinearity, the effect of these parameters on the soliton and supercontinum is studied too. This study focused on studying factors affecting both interaction between solitons and supercontinuum generation, and the dynamics of these phenomena on the photonic crystal fibers and the pulse characteristics too. The work is based on general nonlinear Schrodinger equation (GNLSE) and nonlinear Schrodinger equation (NLSE) solving by using the Split-Step Fourier method (SSFM) by Math Lab System. Many of photonic crystal fibers arrangements with different hole-hole spacing, holes diameter and holes number were studied. The effect of these arrangements on the photonic crystal fibers properties viz., the dispersion, effective refractive index, effective mode area and the nonlinearity of the optical fibers were studied numerically using the Finite Differences in Frequency Domain (FDFD) technique. The study showed that thesis that arrangements strongly affect the optical fiber properties and in turns affects the propagation of optical pulses in the photonic crystal fibers, and shows that the soliton dynamics depends on the pulse power, temporal width, nonlinear effects of soliton, nonlinearity, and its dispersion effect, so the supercontinuum generation (S.C.G) depends on some of these parameters such as pulse power, wavelength, time width, duration time pulse, and nonlinear effects too.

CONTENTS

List of Symbols

Meaning of Symbol	Symbol
Attenuation constant	α
Carrier frequency	ω
Critical angle	θ_c
Center carrier frequency	$\omega_\circ$
Charge density	ρ
Current density	J
Nonlinear Schrodinger Equation	NLSE
Dispersion length	L_D
Dispersion coefficient	**D**
Disable (scale unite)	dB
Distance between air hole	Λ
Diameter air hole	d
Effective area	A_{eff}
Effective refraction index	n_{eff}
Electric field	E
Electric displacement field	D
Electric field amplitude	A(z, t)
Electric polarization	P
Fractional contribution of delayed Raman	f_R
Group velocity dispersion	β_2

Meaning of Symbol	Symbol
Group velocity	V_g
Gaussian intensity pulse widths	$T_\circ$
Linear refractive index	$n_\circ$
Linear part of NLSE operator	$\hat{L}$
Linear susceptibility	$\chi^{(1)}$
Linear polarization	$\mathrm{P_L}$
Fiber length	L
Magnetic field	H
Magnetic displacement	B
Medium permeability	μ
Magnetic polarization	M
Nonlinear refractive index	n_2
Nonlinear part of NLSE operator	$\widehat{N}$
Third-order susceptibility	$\chi^{(3)}$
Second-order susceptibility	$\chi^{(2)}$
Nonlinear polarization	$\mathrm{P_{NL}}$
Nonlinear coefficient	γ
Nonlinear length	L_{NL}
Pulse intensity	$\|u\|^2$
Power pulse	$P_\circ$
Pulse distribution intensity	$F(x, y)$
Permittivity	ϵ

Meaning of Symbol	Symbol
Propagation velocity of light in vacuum	c
Propagation constant	β
Reflective index in core	n_{co}
Reflective index in clad	n_{cl}
Raman response function	h_R
Soliton order	N_s
Vacuum permittivity	$\epsilon_\circ$
Vacuum wave number	$k_\circ$
Vacuum permeability	$\mu_\circ$
Wave number	k
Wave intensity	I
Wavelength	λ
Number of points	N_p

List of Acronyms

Definition	Attribute
Continuous wave	CW
Cross-phase modulation	XPM
Coherent Anti-Stokes Raman scattering	CARS
Finite Difference Frequency - Domain	FDFD
Full-width at half -maximum	FWHM
Four-wave maxing	FWM
General Nonlinear Schrodinger Equation	GNLSE
Group Velocity Dispersion	GVD
Microstructure Optical Fibers	MOFs
Modulation instability	MI
Multi-mode fiber	MMF
Mode-field diameter	MFD
Nonlinear Schrodinger Equation	NLSE
Optical Soliton Fiber Communication	OSFC
Optical coherence tomography	OCT
Optical Soliton Fiber Communication	OSFC
Optical fiber communication	OFC
Photonic crystal fiber	PCF
Photonic Crystal Fibers	PCFs
Photonic Band-Gap	PBG
Photonic Crystal	PC

Definition	Attribute
Polarization Mode Dispersion	PMD
Supercontinuum	SC
Stimulated Brillion scattering	SBS
Stimulated Raman scattering	SRS
Single-mode fiber	SMF
Self-phase modulation	SPM
Split-Step Fourier Method	SSFM
Time-division multiplexing	TDM
Ultra-short pulse	USP
Wavelength division multiplexing	WDM
Wavelength division	WD
Zero Dispersion Wavelength	ZDW

CHAPTER ONE

OPTICAL FIBER

Chapter One

Optical fiber

1.1: Introduction

Optical fibers (OFs) are made of two types materials from glass or plastic with thickness around human hair, they are builds to guide light inside the fiber. Light is transmitted along the fiber based on total internal reflection. Can be used in various industrial and medical applications. OFs were constructed for the number of reasons viz., the light cannot traverse through air without losses for long distances, losses that can be reduced by guiding through optical fiber. As light traverse distance in a transparent material and meets another transparent material part of the light is reflected and part is transmitted into the second transparent material. Transmitted light changes its direction as it enters the second material. This is the fact of refraction which depends on the fact that light travels at two different speeds in both materials [1]. An optical fiber comprises: the core that is the smallest part carries the light. It is usually made of glass, and some are made of plastic. The glass is made of pure silicon dioxide (SiO_2), the cladding that is surrounding the core having lower refractive index to meet the total refraction condition if it is made of glass the cladding and core are made together of silicon dioxide-based material permanently in a fused state, and the coating protects the optical fiber. It absorbs scrapes, nicks and shocks. Optical fiber is very fragile without coating [2], it is shown in Fig (1.1). Fig (1.2) which is shows the total reflection of light beam as it traverses a fiber.

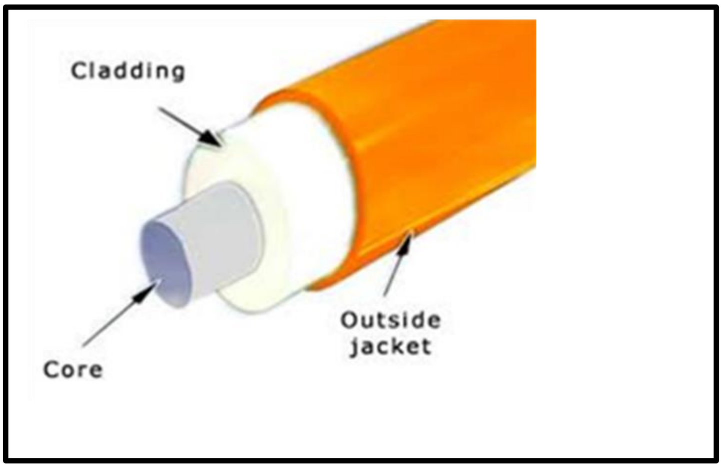


Figure (1.1): Optical fiber structure [2]

A periodic optical nanostructure is called a photonic crystal (PC) that affects the photons motion in similarly to how the properties of semiconductors enable the creation of electronic devices. PC has a band gap that permits some wavelengths of light to pass through but not others, allowing the control over the behavior of light. Such materials control propagation light and open up the new way to routes of ultra-compact, high selectivity of wavelength optical devices [2, 3]. The idea of a PC is new, although it is for long time prior to Yablonovitch [2]. This opened the door wide enough for advancement for the manufacturing of photonic component due to its amazing properties. Such devices based on photon having several advantages compare to electronic one for such as (i) light speed in dielectric material larger than the electron’s in metallic wire, (ii) larger bandwidth of dielectric material compare to that of metals and (iii) less energy loss in photons as compare to electron’s. Laser pulse interaction with a nonlinear photonic crystal fiber represents one of the modern problems. The formation of optical soliton was found out in the case of self-action of laser pulse and dual-waves interaction or with cubic nonlinear response or with combined nonlinearity. Under certain conditions soliton appears on input parameters of layered structure, wavelength of an optical radiation and light intensity of laser pulse [4]. A stable wave structure that based on a specific equilibrium of dispersive (linear) and self-focusing (nonlinear) is called soliton. When solitons unchanged post collisions together, so that they retained their magnitudes, shapes, and speeds. Solitons are found in many non-linear physical phenomena [5]. In optics solitons where studied widely as a result of their use applications in fibers distortion less signal transmission and other nonlinear applications in systems of optical communication. Optical solitons properties which fix their shape in order to realize the propagation over ultra-long distances and with ultra-large capacity [6]. Optical bit rate of communication system based on soliton usually determined via time interval between optical solitons, these characteristics are important to increase the information bit rat and to improve the stability of soliton propagation in the optical soliton [7]. As their interval decreased their optical solitons interact strongly. The study of interaction of optical solitons is necessary in nonlinear optical fibers, when the nonlinear effects and dispersion proportional on normalized distance of propagation [8].

1.2: Types of optical fiber

Optical fibers are classified according to the following [3]:

1.2.1: Based on the relative refractive index of core and clad, the (OFs) are also classified such as:

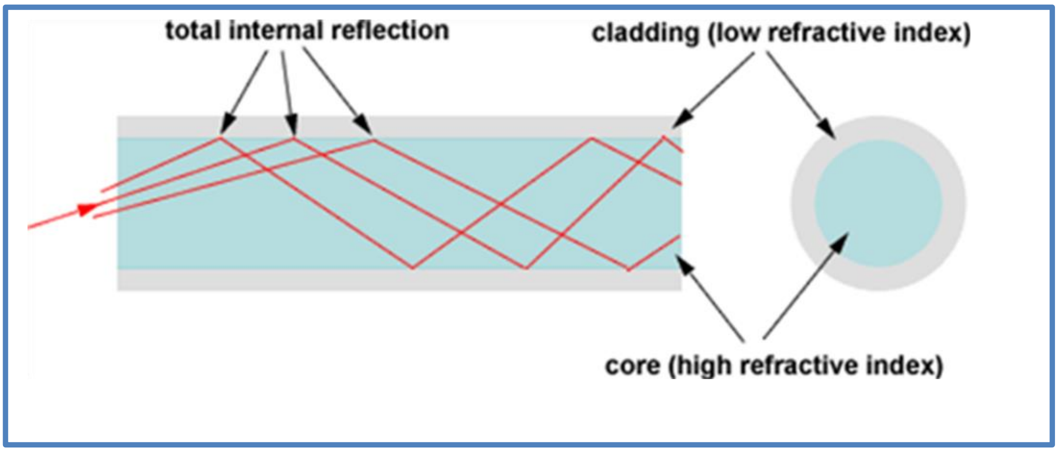


Figure (1.2): Transmission of light wave along optical fiber [3]

A-Step index fibers:

When core refractive index is constant from the core center to interface between core and cladding the optical fibers are called step index fibers [1], as show in Figure (1.3) shows that type.

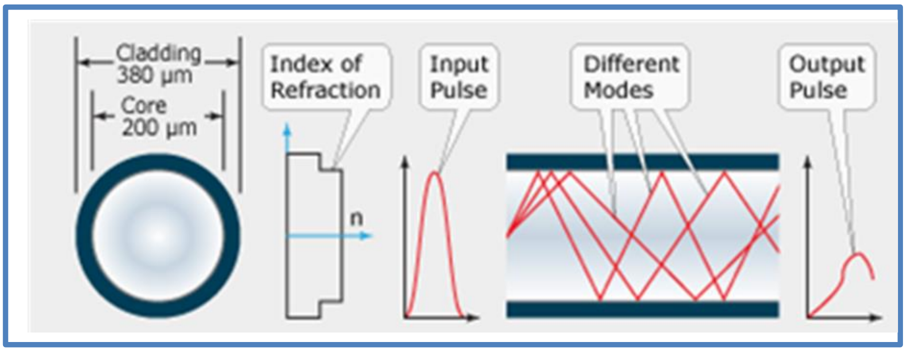


Figure (1.3): Step index optical fiber [1]

B-Graded index fibers:

When the refractive index of material that fiber and core are made vary with distance from center of fiber to interface between core and cladding we have graded index fibers [2], as shown in Fig (1.4).

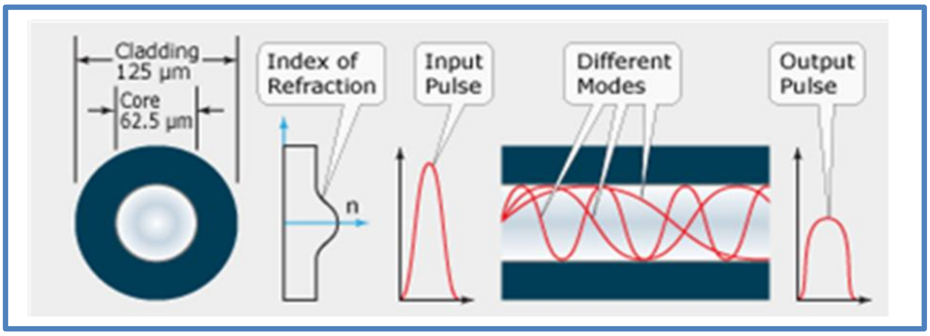


Figure (1.4): Graded index optical fiber [1]

The comparison between step and graded index fibers as given in table (1.1).

Table (1.1) Comparison between step index and graded index fibers [1-5]:

Step Index Fiber	Graded Index Fiber
1. Index of refraction is uniform in the core and cladding but they are not equal. 2. High pulse distortion. 3. Single and multimode mode can traverses the fiber. 4.Simply manufactured . 5. High numerical aperture. 6. High Attenuation. 7.Low bandwidth. 8. It suffer losses due to reflection.	1. Index of refraction not uniform along core and decreasing toward interface. 2. Low pulse distortion. 3. Only multimode can traverse the fiber. 4. Not easy to Manufacture. 5. Small numerical aperture. 6. Low Attenuation. 7. High bandwidth. 8. It not suffer from reflection losses.

1.2.2: Classification of optical fibers based on propagating types of modes

A-Single mode fibers (SMFs):

Single mode fiber has narrow diameter that can carry one mode (or signal), it requires a narrow spectral width light source. SMFs are used mainly in applications for sending data at multi-frequency Wave-Division-Multiplexing (WDM) [2], this case one cable is needed. It gives a high transmission rate up to 50 times more distance than multi-mode with high cost. SMFs have a much smaller core compare to multi-mode these properties reduces or eliminates distortion [4].

B-Multi-mode fibers (MMFs)

This type of fibers has light waves follows various paths, or modes, with long cable runs, multiple paths of this causes signal distortion at the receiving end that result in retransmission this imposes the usage of shorter runs. Due to the use of large core it allows the use of lower cost electronics and light sources such as LEDs [3]. Both types are illustrated in figure (1.5).

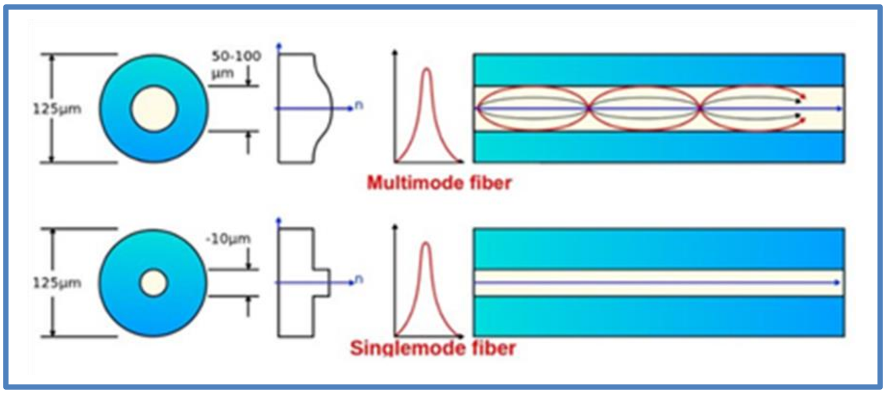


Figure (1.5): The single- mode and multi-mode fibers [4]

The comparison between single and multi-mode fibers as given in table (1.2).

Table (1.2) Comparison between single mode and multimode Fibers [1-5]

Single mode	Multimode
1. Single mode of propagation is supported. 2. Its core diameter of the order of (5 to 10) μm. 3. Very small transmission losses. 4. Broad bandwidth. 5. Laser diode is required as source. 6. It is used for long distance, usage in communications. 7. Step index fiber. 8. Glass made.	1. Multi-mode propagation supported. 2. Its core diameter is the order of (50 to 100) μm. 3. High transmission losses. 4. Narrow bandwidth. 5. LED can be used as sourse. 6. Short distance use in communication. 7. Step or graded index fiber. 8. Plastics made.

1.3: Propagation of light in optical fiber

Light travels along the fiber via total reflection successively. The physical phenomenon known as total internal reflection is responsible for light pulses to travel along the fiber by successive reflections. However, only with the appearance of devices capable of converting electronic pulses into pulses of light, it was possible to transmit information through the fiber. Light, while propagating in the fiber, can be seen as an electromagnetic phenomenon, and the whole propagating mechanism, which can be described by the electromagnetic optical fields associated to it, is governed by Maxwell equations. When light passes from one medium (material) to another it changes speed. When light speeds up as it passes from one material to another, the angle of refraction is bigger than the angle of incidence. At the interface between two materials, the angle of refraction cannot be greater than 90°. When the angle of refraction is equal to 90°, the angle of incidence is called the critical angle (θ_c). At any angle of incidence greater than the critical angle, the light cannot pass through the surface - it is all reflected [4].

1.4: Optical absorption

The repeaters number depends on the amount of attenuation suffered by the passage through in the fiber material. Let the power launched at the input of a fiber of length L, be P_o, the output power P_t is given by [3]

$$P_t = P_\circ e^{(-\alpha L)} \quad (1.1)$$

α is the attenuation constant (absorption factor), $(\frac{1}{km})$, which can calculated using the following formula

$$\alpha = -\frac{10}{L}\log\frac{P_t}{P_\circ} \quad (1.2)$$

The absorbed light energy is transformed into other forms of energy for example, to heat. Absorption of light by optical fibers material can be intrinsic or extrinsic.

1.4.1: Intrinsic absorption

This type of absorption is caused by basic fiber-material properties. If the fiber material is absolutely pure, in the absence of imperfections or impurities, all absorption are intrinsic. Due to its low intrinsic material absorption at the wavelengths of operation, silica fibers are mainly used in communications. Absorption of light particle (photon) interacts with an electron and excites it to a higher energy level. Intrinsic absorption usually minimized by the suitable composition of materials that core and cladding are made of. Moreover, fibers made of fluoride glasses [1].

1.4.2: Extrinsic absorption

Impurities cause an extrinsic absorption introduced to the material of fiber. Iron, nickel, and chromium impurities, they are introduced to the fiber while fabrication. Also losses are caused by the presence of transition metal impurities known as impurity absorption [5].

1.5: Dispersion

Information is encoded in digital communication systems, in the form of electric pulses transformed into optical pulses which are transmitted from the transmitter to the receiver, usually, using optical fibers. The larger capacity of the system is the larger number of pulses that can be sent per unit time and still be resolvable at the receiver end. Pulses spread out as they travel along the fiber this dispersion phenomenon is called pulse dispersion. Represent the main problem affecting the optical communication system performance that arises as the frequency components of the signal pulses travels with different velocities, determining the broadening of the pulse. Dispersive pulse broadening and loss are directly proportional to the length of the link [6].

The state of polarization of the light is another reason for dispersive distortions in single-mode fibers, i.e., a light pulse of finite duration by necessity has a nonzero spectral width. When different frequency components, propagates at different velocity gives rise to differential transit time and to signal distortion called delay distortion [7]. Pulse dispersion and fiber losses are most important factors that limit a fiber capacity [8]. Due to the following reasons pulse distortion occurs:

i- Intermodal.
ii- Material.
iii- Waveguide .
iv- Polarization Mode .

Pulse dispersion is shown in figure (1.6).

(a)
(b)
(c)
(d)

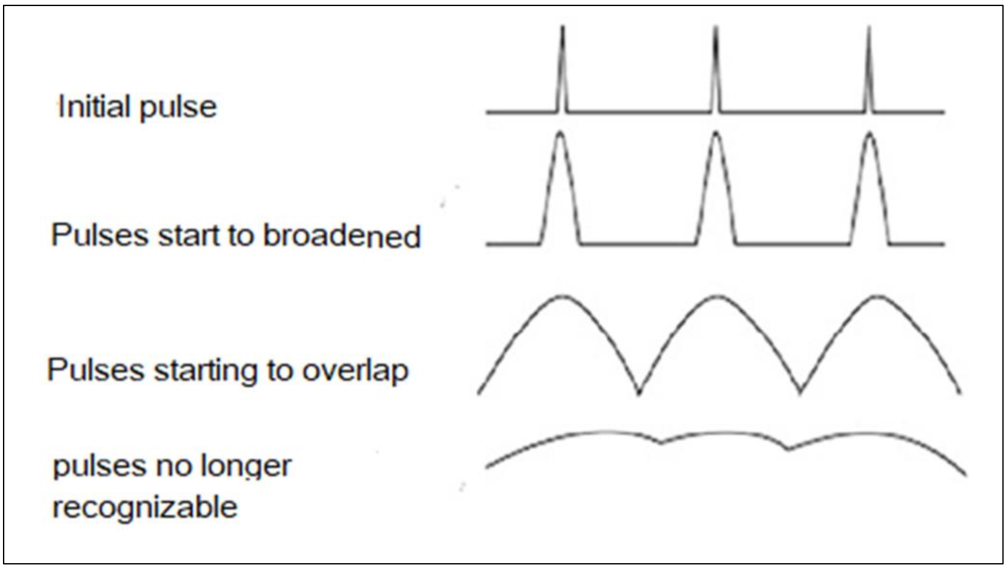


Figure (1.6): Pulse intensity distribution with time at different distance. (a) Initial pulses, (b) pulses start to broadened, (c) pulses starting to overlap, (d) pulses no longer recognizable [6]

1.6: Nonlinear effects

A- Optical Kerr effect

The optical nonlinear Kerr effect occur due to interaction of intense electric field with a medium instantaneously response which lead to a change of refractive index [9]. It can be written as:

$$n = n_\circ + n_2 I \ldots\ldots.. \qquad (1.3)$$

$n_\circ$ is the linear refractive index in the absence of the pulse, I is the intensity of the electric field, and n_2 is the nonlinear refractive index that can be written as:

$$n_2 = \frac{3x^{(3)}}{4c\epsilon_\circ n_\circ^2} \qquad (1.4)$$

$\epsilon_\circ$ is the vacuum permittivity and $x^{(3)}$ is the third-order susceptibility. The Kerr nonlinearity gives rise to different effects, depending on the shape of the field injected into the fiber [10]. There are two types of Kerr effect:

i- Kerr electro-optic effect:

Kerr electro-optic effect, (DC Kerr effect) is the special case in a slowly varying external electric field, across the sample material in this case the sample becomes birefringent, so that the medium having different refractive indexes with respect to the polarization of incident light when applied. The difference in index of refraction,Δn, is given by [11]

$$\Delta n = \lambda K \Delta E \tag{1.5}$$

Where λ and E are the incident light wavelength of the light and its strength of the electric field, and K is the Kerr constant.

ii- Magneto-optic Kerr effect:

The phenomenon magneto-optic Kerr effect (MOKE) occurs when light suffer reflecting a magnetized material a slight rotation of its plane of polarization as it is reflected [12].

B- Self-phase modulation

The change in refractive index determines a corresponding change in the constant propagation [6]. The phase, $\Delta\varphi_{NL}$, of a signal propagating in the fiber is related to the distance as follows [13]:

$$\Delta\varphi_{NL} = n_2 I(t)\frac{2\pi}{\lambda}L = n_2 I k_\circ L = \gamma p L \tag{1.6}$$

$$\gamma = n_2 2\pi/\lambda A_{eff} \tag{1.7}$$

The change in phase of optical pulse can be written as:

$$\Delta\varphi = (n_\circ + n_2 I)k_\circ L = \Delta\varphi_L + \Delta\varphi_{NL} \tag{1.8}$$

$k_\circ$, L, represents the vacuum wave vector and the fiber length, respectively. p is the light power, and A_{eff} is the modal effective area of the guided mode. Self-phase modulation (SPM) phenomenon occurs when the power variation within the pulse leads to its own phase modulation [14], see Fig. (1.7).

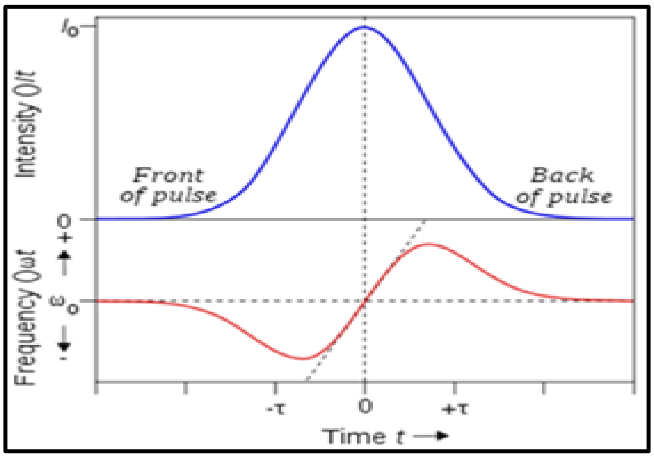


Figure (1.7): Function of self-phase modulation of moving pulse (blue curve) moves through a self-frequency shift (red curve) through a non-linear medium. Further, the front of the pulse is also shifted to lower frequencies and again to higher frequencies [6]

C- Cross-phase modulation

When two or more optical fields having different wavelengths propagate simultaneously inside a fiber, they interact with each other through cross-phase modulation (XPM). The XPM- induced coupling among multiple optical fibers, XPM is another effect originated from the nonlinear refractive index [13], or is the change in the optical phase of a light beam caused by the interaction with another beam in a nonlinear medium, specifically a Keer medium. This can be described as a change in the refractive index [10].

D- Four-wave mixing

The parametric interaction among waves viz., four-wave mixing (FWM) satisfy a given phase relationship called phase matching [15]. If three optical fields with frequencies $\omega_i (i = 1,2,3)$ propagate inside a fiber simultaneously, it appears that the third-order polarization vector will have several components, viz., three input fields components with the frequencies, the others have an angular frequency ω_4 given by [16]:

$$\omega_4 = \omega_1 \pm \omega_2 \pm \omega_3 \quad (1.9)$$

In the absence of the frequency ω_4 in the fiber, a new field component is created at this frequency. If the frequency ω_4 is already present in the fiber, it will be affected by the nonlinear interaction between the fields at ω_i, which causes crosstalk in communication systems multichannel [17].

E- Self-Focusing and Self-Defocusing

The propagation of light in a homogeneous medium, optical diffraction occurs, a geometrical effect leading to a spatial broadening the beam propagation direction, depends on refractive index of the media [18]. Self-focusing is a nonlinear optical phenomenon refers to the nonlinear process counteracts against diffraction-induced natural spreading of an optical beam and contract diffraction when power exceeds a critical value. Of origin self-focusing in the nonlinear refractive index, $n = n_\circ + n_2 I$, where any increase in the intensity , I, leads to n_2>0, this produces a convergent wave front through the nonlinear phenomenon of self-phase modulation (SPM) during the beam propagation in the medium. The beam is then said to be self-focused the sufficiently intense beams. For nonlinear media with n_2< 0, SPM imposes a diverging wave front. So that beam is said to be self-defocused [19], leads to spatial broadening of a beam. Figure (1.8) shows the self-focusing and self-defocusing of a Gaussian beam.

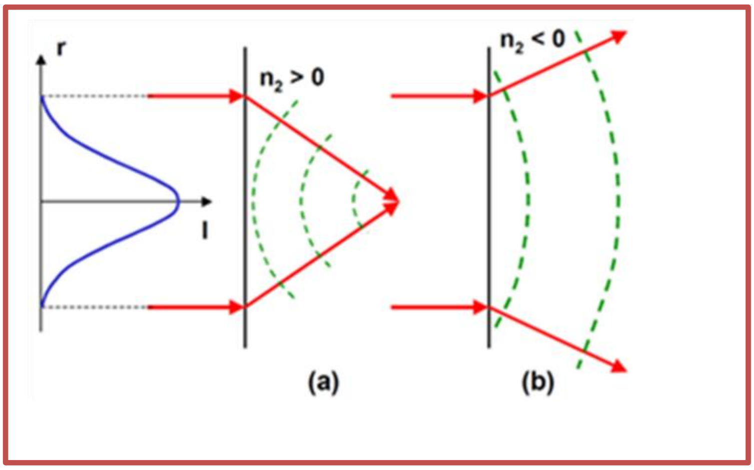
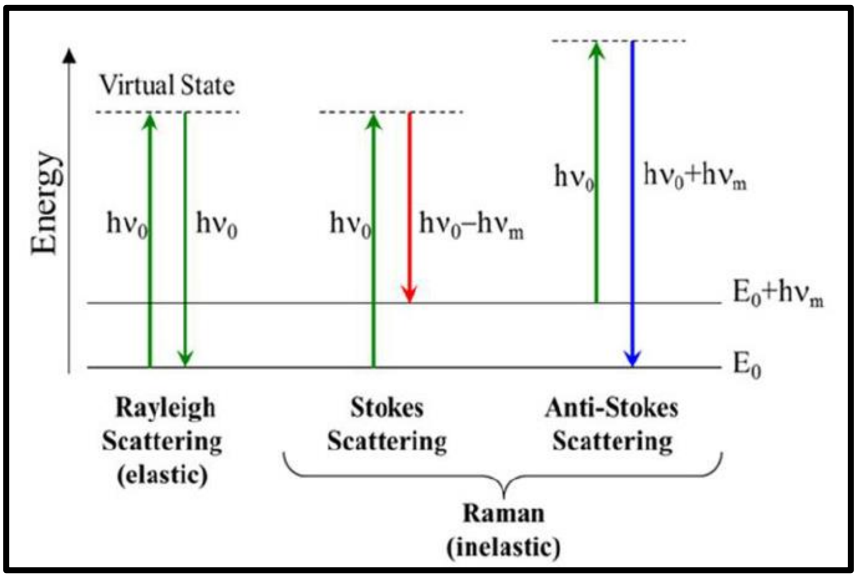


Figure (1.8): (a) Self-focusing and (b) self-defocusing of a Gaussian beam [4]

F- Stimulated Raman scattering

When light is scattered in a medium there are two possibilities: there may exist energy exchange with the material (Raman scattering), or such an exchange may not occur (Rayleigh scattering). The Raman scattering meanwhile, leads to two possible outcomes: absorption of energy by the material when an optical photon hit it (Stokes) or loss of energy (anti-Stokes) [20]. At the beginning, the Raman scattering is a spontaneous process of coupling of light with the molecular vibrations of the medium in which it propagates. Nonetheless, the stimulated Raman scattering (SRS) takes place when an excess of Stokes photons that were previously generated by spontaneous Raman scattering are present or added to the excitation beam. This third-order phenomenon then creates a Stokes band on the longer wavelength side [10], SRS redistributes the energy from the higher frequency components to the lower ones of the pulse. As a result, the spectrum is shifted to longer wavelengths and loses symmetry, this phenomenon is known as self-frequency shift (since no other pulse is involved), figure (1.9) shows Rayleigh and Raman scattering.



Figure(1.9): Diagram of quantum energy transitions for Rayleigh and Raman Scattering [21]

1.7: Soliton

The term soliton in optics, refer to any optical field that is not changed during propagation as a result of a balance between nonlinear and dispersive effects in the medium. Soliton phenomenon was due first to John Scott Russell in 1834[22]. Optical Soliton refers to a beam of light or pulse propagation in a non-linear optical medium with constant shape and velocity. Solitons are widely used in non-linear optical fibers in communications, optical switching computing, etc., [10], of localized optical structures during the past two decades have been widely investigated [23-26]. The soliton compensates linear pulse dispersion by nonlinear pulse compression [27]. Figure (1.10) shows comparison between propagation of regular pulses with optical solitons pulses.

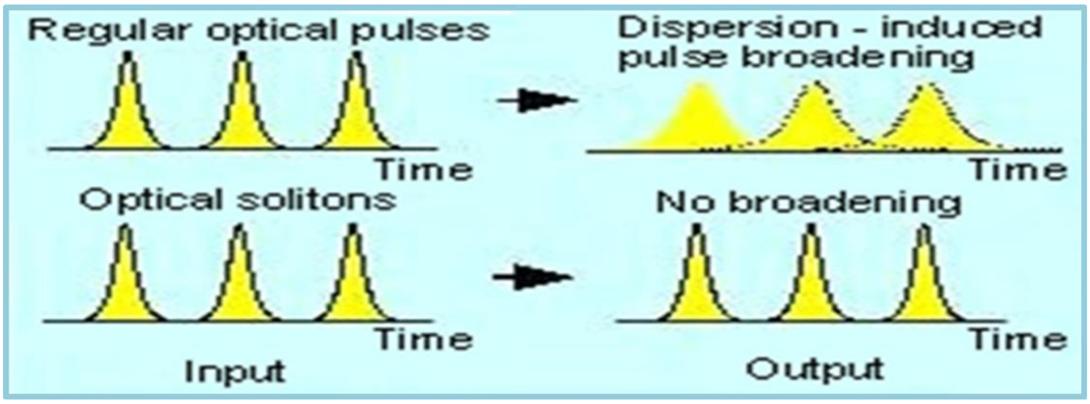


Figure (1.10): Waveform evolution of regular optical pulses and optical soliton pulses during optical propagation [28]

Due to technical advances, optical solitons have been evolves since 1973 in the direction of optical transmission applications since the discovery of solitons in optical fibers [25]. The transmission of "ideal solitons" during 70’s and 80's of the last century was considered where solitons propagate in optical fibers with constant dispersion and nonlinearity values so that its amplitude and width remain identical over propagation distance. Optical fibers exhibit loss, which reduces nonlinearity [24]. Such losses breaks dispersion and nonlinearity balance reducing the distortion of soliton propagation. Solitons are either temporal or spatial, according to the confinement of light in time or space during propagation, when optical pulses that maintain their shape we have temporal solitons, while self-guided beams that remain confined in the transverse directions orthogonal to the direction of propagation are spatial solitons [29]. Both soliton types evolve from a nonlinear change in the refractive index of an optical material induced by the light intensity. This is optical Kerr effect in nonlinear optics, when the self-focusing of an optical beam balances its natural diffraction-induced spreading spatial soliton is formed [30]. When the natural dispersion-induced broadening of an optical pulse counteracts leads to a temporal soliton. So that, the pulse (or the beam) propagates through a medium without change in its shape and is said to be self-localized or self-trapped [22].

Spatial soliton belongs to the discovery of the nonlinear phenomenon of self-trapping of continuous-wave (CW) optical beams in a bulk nonlinear medium. Stable spatial solitons were observed during 1980’s using nonlinear media in which diffraction spreading was limited to only one transverse dimension [26].

Optical fibers was discovered in 1973 to support another kind of temporal solitons when the group-velocity dispersion (GVD) is normal [23]. To clarify the distinction, standard pulse-like solitons are called bright solitons. Temporal dark solitons draw much attention during the 1980's. When the refractive index is lower in the high intensity region (self-defocusing nonlinearity) spatial dark solitons can form in optical waveguides and bulk media. Examples include Bragg solitons, quadratic solitons, vortex solitons spatiotemporal solitons, vector solitons [27].

1.8: Specifications the optical soliton

For the effects due to nonlinearity and dispersion are destructive in optical fiber communication (OFC) but useful in Optical Soliton Fiber Communication (OSFC) systems [29-31]

1- The soliton type pulses are highly stable.

2-Their transmission rate is more than 100 times better than that in the best linear system.

3-They are not affected by the imperfections in the fiber geometry or structure.

4-Soliton can be propagated without any distortion if the nonlinear characteristics like amplitude, intensity of the pulse-depending on velocity and the dispersion characteristics like frequency-depending on velocity of the media, are balanced.

5-This format is the only stable form for pulse propagation through the fiber in the presence of fiber nonlinearity and dispersion in all optical transmission lines with minimum loss.

6-In dispersion managed fibers, a large pulse width is allowed, pulse height is reduced and nonlinear interactions between adjacent pulses as well as among different wavelength channels are reduced.

7- Not only in the field of communications, soliton also find applications in the construction of optical switches.

1.9: Supercontinuum Generation (SCG) in Photonic Crystal Fibers

The generation of new frequency components and spectral broadening are inherent features of nonlinear optics. The generation of supercontinuum is feasible by sending very short pulse of the order of a few femtoseconds long. Photonic crystal fibers (PCFs) have high nonlinearity and have zero or anomalous group velocity dispersion around 1550 nm, such fibers will enable the generation of supercontinua [32]. SC generation when narrow-band incident pulses undergo extreme nonlinear spectral broadening to yield a broadband very or white light spectrally continuous output. SCG was first reported by Alfano and Shapiro in bulk glass [33, 34]. The emergence of photonic crystal fibers, combining tailored dispersion properties and enhanced nonlinearity, has led to record spectral expansion [35, 36]. As a simple way to create multi-wavelength optical sources for dense wavelength division multiplexing telecommunications applications, the spectral slicing of broadband SC spectra has been used. The ease with which SC generation in PCF has been observed experimentally has actually made it relatively difficult to understand in clear physical terms. A supercontinuum is an optical pulse with a broad spectrum which is extended over hundreds of nanometers. Particular techniques include optical coherence tomography and coherent anti-Stokes Raman scattering (CARS) micro-spectroscopy [37, 38]. CARS are a nonlinear optical process to produce stronger signal as compared to spontaneous Raman scattering [39]. Figure (1.11) shows supercontinuum generation in PCF.

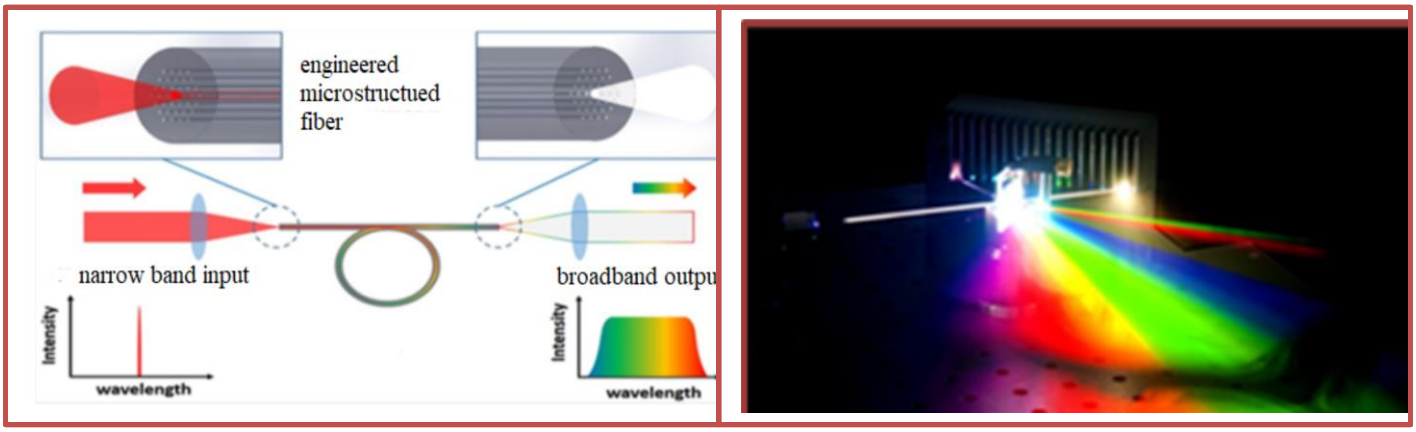


Figure (1.11): On the left side illustrates the SCG theoretically and on the right side illustrates the SCG in the laboratory [40]

The progress in photonic crystal fibers makes the supercontinuum generation relatively simple [41]. The physics behind the process generation of supercontinuum in photonic crystal fibers has been studied. Generation of continuum is based on the stimulated Raman scattering [42], self-phase modulation [43], four-wave mixing [44] and solitons [45], etc. Supercontinuum properties depend on the (a) input pulse and (b) PCF parameters [46].

Generation of supercontinuum in silica and non-silica [47] fibers experienced rapid growth with the advent of photonic crystal fibers (PCFs) [48]. The freedom design of PCFs makes it possible for SC generation wider range of source parameters compared to bulk media or conventional fibers [43].

1.10: Literature review

The idea of guiding light through total internal reflection dates back to the late nineteenth century, when spectacular luminous fountains celebrated the technological progress in many universal exhibitions across the globe. The first successful demonstrations of light guidance and imaging in an unclad glass fiber had to wait until the late 1920s. Optical fiber is a flexible, transparent fiber made by drawing glass (silica) or plastic to a diameter slightly thicker than that of a human hair. Fibers are used instead of metal wires because signals travel along them with less loss. In addition, fibers are immune to electromagnetic interference, a problem from which metal wires suffer excessively [49]. Optical communications came as the laser was invented in 1960 which permitted to emit light in a narrow wavelength spectrum. Allowing to work at different frequencies by utilizing the wave properties of light. During 1964, a Shanghai engineer named Charles K. Kao has carried out research on different materials and was convinced by his research. The attenuation was caused by impurities and that it should be theoretically possible to reduce the attenuation to at least 20dB/km. In September 1970 laboratories announced single-mode fibers with attenuation at the 633 nm (Helium-Neon laser) below 20dB/km. A team at the Physical institute built the first semiconductor laser diodes, which allowed continuous-wave beams to be emitted at room temperature allowing lasers to be used as light sources more easily [50], and used in networks began to be deployed for submarine and trunk systems in the 1980s in Japan to meet the demand for broadband communication. Fiber-to-the-home (FTTH) services were first introduced in 2001. Their provision to subscribers has spread rapidly over the access networks. The number of FTTH subscribers in Japan exceeded 23 million at the end of 2012. The optical reflectometry is a promising technology for use in optical fiber monitoring in communication systems. Operators can perform tests from central offices (or remotely via a network) without installing any equipment in the customer’s house. Photonic crystals have been observed in one form or another since 1887. Eli Yablonovitch and Sajeev John published two milestone papers on photonic crystals in 1987[51]. One-dimensional photonic crystals in the form of periodic multi-layer dielectric stacks (such as the Bragg mirror) were studied extensively. A detailed theoretical study of one-dimensional optical structures was performed by Bykov [52] who was the first to investigate the effect of a photonic band-gap on the spontaneous emission from atoms and molecules embedded within the photonic structure. Bykov also speculated as to what could happen if two- or three-dimensional periodic optical structures were used [53]. The concept of three-dimensional photonic crystals was then discussed by Ohtaka in 1979[54]. These papers concerned high-dimensional periodic optical structures, i.e., photonic crystals. Yablonovitch's main goal was to engineer photonic density of states to control the spontaneous emission of materials embedded in the photonic crystal. After 1987, the number of research papers concerning photonic crystals began to grow exponentially. Due to the difficulty of fabricating these structures at optical scales, early studies were either theoretical or in the microwave regime, where photonic crystals can be built on the more accessible centimeter scale. By 1991, Yablonovitch have demonstrated the first three-dimensional photonic band-gap in the microwave regime [55]. The structure that Yablonvitch was able to produce involved drilling an array of holes in a transparent material, where the holes of each layer form an inverse diamond structure – today it is known as Yablonovite. Thomas Krauss demonstrated a two-dimensional photonic crystal at optical wavelengths [56]. This opened the way to fabricate photonic crystals in semiconductor materials by borrowing methods from the semiconductor industry. Techniques use photonic crystal slabs, which are two dimensional photonic crystals "etched" into slabs of semiconductor. Total internal reflection confines light to the slab, and allows photonic crystal effects, such as engineering photonic dispersion in the slab. Researchers around the world are looking for ways to use photonic crystal slabs in integrated computer chips, to improve optical processing of communications—both on-chip and between chips. Two-dimensional photonic crystals are commercially used in photonic crystal fibers [57] (otherwise known as holey fibers, because of the air holes that run through them). Photonic crystal fibers were first developed by Russell in 1996[49], and can be designed to possess enhanced properties over (normal) optical fibers. Studies has proceeded more slowly in three-dimensional than in two-dimensional photonic crystals. This is because of more difficult fabrication. Attempts have been made, however, to adapt some of the same techniques, and quite advanced examples have been demonstrated [58] for example in the construction of "woodpile" structures constructed on a planar layer-by-layer basis. Three-dimensional photonic structures from self-assembly—essentially letting a mixture of dielectric nano-spheres settle from solution into three-dimensionally periodic structures that have photonic band-gaps. It was realized in 1995 that natural and synthetic opals are photonic crystals with an incomplete band-gap [59]. The first demonstration of an "inverse opal" structure with a complete photonic band-gap came in 2000 [60]. The ever-expanding field of biomimetics—the study of natural structures to better understand and use them in design—is also helping researchers in photonic crystals [61,62]. Hasegawa and Tappert [63,64], who predicted the existence of optical solitons in 1973 and the same was confirmed experimentally by Mollenauer and his group in 1980 [39]. For communication applications, optical soliton is modified so that it is more immune to external perturbations by applying proper variation of the fiber dispersion profile. In 1964 Jones and Stoicheff [65] reported using a continua generated by a maser to study induced Raman absorption in liquids at optical frequencies [66]. When the maser emission was in a single sharp spectral line, as they were described, allowed the first Raman absorption spectroscopy measurements to be made. In 1970 Alfano and Shapiro reported the first measurements of frequency broadening in crystals and glasses using a frequency doubled Nd:Glass mode-locked laser[34]. In 1976 Lin and Stolen reported a new nanosecond source that produced continua with a bandwidth of 110-180 nm centred on 530 nm at output powers of around a kW [67]. Lin and Nguyen reported several continua, most notably one stretching from 0.7-1.6 μm using a 315 m long GeO doped silica fibre with a 33 μm core [68]. The optical setup was similar to Lin's previous work with Stolen, except in this instance the pump source was a 150 kW, 20 ns, Q-switched Nd:YAG laser. Indeed, they have so much power available to them that two thirds was attenuated away to prevent damage to the fiber. Fujii et al. repeated Lin's 1978 setup with a mode-locked Nd:YAG with peak power of the pulses was reported as being greater than 100 kW and they achieved better than 70% coupling efficiency into a 10 μm core single-mode Ge doped fiber [69]. It was realized that self-phase modulation could not account for the broad continua seen, but for the most part little else was offered as an explanation. In 1982 Smirnov et al., [70] reported similar results to that achieved by Lin in 1978, using multimode phosphosilicate fibers pumped at $0.53\mu m$ and 1.06 μm, they saw the normal Stokes components and a spectrum which extended from the ultraviolet to the near infrared. If the nanosecond pulses consisted of sub-nanosecond spikes in a nanosecond envelope, it would explain the broad continuum. Very short pulses resulting in the broad continuum was studied a year later when Fork et al., [71] reported using 80 fs pulses from a colliding mode-locked laser [72]. The laser's wavelength was 627 nm and they used it to pump a jet of ethylene glycol. They reported very small chirps across the continuum. These observations and others led them to state that self-phase modulation was the dominant effect by some margin. Noted that their calculations showed that the continuum remained much larger than self-phase modulation would allow, suggesting that four-wave mixing processes must also be present. They stated that it was much easier to produce a reliable, repeatable continuum using a femtosecond source. Over the ensuing years this source was developed further and used to examine other liquids [73]. Nakazawa etal., reported using the two transitions in Nd:YAG at 1.32 and 1.34 μm to pump a multimode fiber simultaneously at these wavelengths [74]. Alfano, Ho, Manassah and others carried out a wide variety of experiments, though very little of it involved fibers [75]. In 1987 Gomes et al., [76] reported 53-Cascaded stimulated Raman scattering in a single mode phosphosilicate based fiber. The applicability of supercontinua for use in wavelength division multiplexed (WDM) systems for optical communications was investigated heavily during the 1990s. In 1993 Morioka et al., [77] reported a 100 wavelength channel multiplexing scheme which simultaneously produced one hundred 10 ps pulses in the 1.224-1.394 μm spectra region with a 1.9 nm spectral spacing. They produced a supercontinuum using a Nd:YLF pump centered on 1.314 μm which was mode-locked to produce 7.6 ps pulses. They then filtered the resulting continuum with a birefringent fiber to generate the channels. Morioka, Mori and Saruwatari, continued development of telecommunications technologies utilizing supercontinuum generation throughout the 1995s up to the present day. Their research included: using a supercontinua to measure the group velocity dispersion in optical fibers [78]. The first demonstration of a fiber-based supercontinuum pumped by a fiber-based laser was reported by Chernikov et al., [79] in 1997. They made use of distributed back-scattering to achieve passive Q-switching in single-mode ytterbium and erbium-doped fibers. In 2000 Ranka et al., [80] used a 75 cm PCF with a zero dispersion at 767 nm and a 1.7 μm core diameter. They pumped the fiber with 100 fs, 800 pJ pulses at 790 nm to produce a flat continuum from between 400 and 1450 nm. Herrmann et al., provided a convincing explanation of the development of femtosecond supercontinua, specifically the reduction of solitons from high orders down to the fundamental and the production of dispersive waves during this process [81]. Other areas of development since 2000 have included: supercontinua sources that operate in the picosecond, nanosecond and CW regimes; the development of fibers to include new materials, production techniques and tapers; novel methods for generating broader continua; novel propagation equations for describing supercontinuum in photonic nanowires [82] and the development of numerical models to explain and aid understanding of supercontinuum generation. In 2007 A. Boh Ruffin and D.A. Nolan, studied supercontinuum generation in fiber lasers and in optical fibers pumped by different light sources which include fs and ps pulse sources, and CW amplified spontaneous emission (ASE) light sources. In 2009 Driben, Husakou and Herrmann, reported supercontinuum generation in aqueous colloids containing silver nanoparticles [83]. Numerically study low-threshold supercontinuum generation using the significant enhancement of non-linearity in aqueous colloids with silver nanoparticles. In 2010 Dudley and Taylor, reported supercontinuum generation in short dispersion-shifted fiber by a femtosecond fiber laser. The supercontinuum generation has been obtained in short conventional dispersion-shifted fiber using the femtosecond pulses from a passively mode-locked erbium-doped fiber laser. In the experiment, the supercontinuum spectrum of >300 nm has been observed by injecting 70-fs pulses into a several-meter dispersion-shifted fiber [37]. In 2012 Hernandez-Garcia, and Estudillo-Ayala, reported the experimental study of broadband spectrum generation in a piece of standard fiber using as the pump a train of noise like pulses, or sub nanosecond packets of sub ps pulses with randomly varying amplitudes [84]. In 2013 Buczynski, Siwicki, and Stepien with others, reported experimental demonstration of supercontinuum in an in-house fabricated, all-solid, flat-top normal dispersion photonic crystal fiber, Presented study comprises characterization of developed fiber in terms of microstructure design, attenuation and dispersion characteristic, followed by experiment and numerical analysis of supercontinuum generation spanning an octave from around 900 nm to 2400 nm under 1530 nm excitation with 70 fs pulses [85]. In 2014 Castello-Lurbe, Torres-Company, and Silvestre, theoretically find the third order dispersion that optimizes the spectral broadening induced by optical wave-breaking, it produces supercontinuum spectra spanning beyond 2/3 of an octave in a silicon waveguide pumping at 1550 nm [86]. In 2016 Bagratashvili ,Gordienko, Mareev, Minaev, Ragulskaya and Potemkin, found that supercritical fluids are a unique source of multi-octave supercontinuum radiation, which is generated upon filamentation of an intense femtosecond laser pulse [87]. In 2017 Dubietis, Tamosauskas, Suminas, Jukna, and Couairon, reported nonlinear propagation of intense femtosecond laser pulses in bulk transparent media leads to a specific propagation regime, termed femtosecond filamentation, which in turn produces dramatic spectral broadening, or super-broadening, termed supercontinuum generation [88]. In 2019 Habib, Markos, Adamu, Antonio-Lopez, and Amezcua-Correa, reported Broadband supercontinuum generation spanning 0.58-5.0 μm is numerically presented [89].

1.11: The aim of the study

The goal of the present work is the study of the propagation of short laser pulse in photonic crystal fibers; investigate the effect of (PCF) arrangements on the pulses propagation and on the optical fibers properties (its dispersion and nonlinearity). Study the conditions needed to achieve soliton waves in PCF with the effect of the PCF parameters, hole-hole spacing, holes diameter and number of holes drilled in PC. The second part of the study of soliton is the solitons interactions to obtain single giant soliton. That by solving the Nonlinear Schrodinger equation (NLSE) using the Fast-Fourier transform method.

Study the supercontinuum generation in PCFs by solving General nonlinear Schrodinger equation (GNLSE) with the effect of the PCF parameters, the pulse conditions and Raman scattering effect on PCFs.

Finally goal we study the PC arrangement to obtain an optical fiber with proper specification that serves a special application of PCFs.

Chapter Two

The Equation of the Propagation of Gaussian Pulse in Photonic Crystal Fiber

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The Equation of the Propagation of a Gaussian Pulse in Photonic Crystal Fiber

2.1: Introduction

Pulse propagation in photonic crystal fibers is usually modeled by the nonlinear Schrodinger equation (NLSE) [10, 90]. Hence, the NLSE forms the basis for optimizing existing fiber links and suggesting new fiber communication systems in attempts to achieve high bit-rate data transmission. Recently, much experimental progress has been made in creating ultra-short pulses that would allow very high data transmission in one channel [91,92]. However, for describing the propagation of these very narrow pulses, the validity of the NLSE as a slowly varying amplitude approximation of Maxwell's equations is questionable. The breakdown of the NLSE has been discussed[90], for instance, in the context of self-focusing of ultra-short pulses [93]. The reason for this breakdown is that the basic assumption that is made in the derivation of the NLSE as an approximation of Maxwell's equations is that the pulse's spectrum is localized around the carrier frequency [94]. This assumption is violated by short pulses. One approach to describe the propagation of short pulses is to incorporate higher order terms in the cubic nonlinear Schrodinger equation, especially in order to account for Raman scattering [95,96]. A different way is to work in the Fourier domain, but in this case the term arising from the nonlinear part of the polarization in Maxwell's equation will lead to convolution integrals that might be diffcult to treat analytically and numerically [96]. A new method recently was evolved study short pulses by Alterman and Rouch [97], but this equation is formally an integral equation as it assumes the inversion of a differential operator. Still, it can be solved numerically very efficiently. Simultaneously, numerical schemes have been developed in order to compute the solution of the full Maxwell's equations [98]. The basic idea is to make use of the fact that the pulse is broad in the Fourier domain. This approach leads to a different partial differential equation than the NLSE. Ultra-short pulse laser is a very important light source in the fields of optoelectronics, ultrafast optical measurements, optical chemistry, and ultrafast spectroscopy. Pulse compression process is found to be one of the best techniques to obtain ultra-short pulses by means of optical fibers [10]. Relying on the composition and material characteristics, numerical solve of electromagnetic wave equations necessity adjustable [99]. The recent work widespread research work on pulse compression in PCF is mainly motivated by nonlinear applications in telecommunication, optical metrology, optical coherence tomography (OCT) and sensors. Among these applications, the pulse compression at 1.55μm wavelength has many applications in telecommunications, ultra-broadband SC generation and biotelemetry. PCFs also called holey fibers or micro structured fibers commonly consist of a fused silica core surrounded by a regular array of air holes running along the fiber length [100]. They have the advantage of design flexibility in controlling the mode propagation properties. By varying the arrangement and size of the air holes, the fiber dispersion can be tailored in broad ranges [101]. Therefore, PCF is very much suitable for pulse compression in telecommunication window. In order to generate ultra-short pulses in PCFs requires a much high pump power and a short input pulse width. In general tapering can be done by reducing the pitch and radius very much suitable for pulse compression applications. Fiber tapering provides a convenient way to reduce the mode-field diameter (MFD) of fibers, thereby allowing for a better pulse compression [10].

2.2: Derivation and solving of the nonlinear Shrodinger equation

2.2.1: Maxwell's equations

The subject of ultrafast and nonlinear optics are much understood and described by the propagation of laser light in an optical medium. In what follows the derivation of the general propagation equation for laser light in a passive optical medium. This description includes the major effects that act on continuous beams as well as short pulses with high intensities, ignoring amplification and loss. To describe evolution properly of real beams, diffraction is included i.e., it is not necessarily make the plane wave approximation [91]. Any assumptions and limitations are explained through the steps of the derivation. Starting with four Maxwell's equations that describe the electromagnetic fields of light (the electric), E, the displacement, D, the magnetic, H, and the magnetic density, B. Using the following procedure to derive the wave equation [102,103].

$$\nabla \times \nabla \times E = \nabla \times \left(-\frac{\partial B}{\partial t}\right) \tag{2.1}$$

$$\nabla \times \nabla \times E = -\frac{\partial}{\partial t}(\nabla \times B) \tag{2.2}$$

Since $(B = \mu H = \mu_\circ H + M)$ and $(D = \epsilon E = \epsilon_\circ E + P)$

Vacuum permittivity $\epsilon_\circ = 8.85\times10^{-12}$ F/m , vacuum permeability $\mu_\circ = 4\pi\times10^{-7}\, {}^{H}/_{m}$, induced electric polarization is (P), and the induced magnetic polarization is (M). For a nonmagnetic medium i.e., M=0 such as optical fibers [10] so that:

$$\nabla \times \nabla \times \mathrm{E} = -\mu_\circ \frac{\partial}{\partial \mathrm{t}}(\nabla \times \mathrm{H}) \tag{2.3}$$

By using the magnetic field equation in Maxwell's equations in equation (2.3) one will gets:

$$\nabla \times \nabla \times E = -\mu_\circ \frac{\partial}{\partial t}\left(J + \frac{\partial D}{\partial t}\right) \tag{2.4}$$

For charge-free and isotropic fibers as the propagating medium, i.e., $\rho = 0 , J = \sigma E = 0$

$$\nabla \times \nabla \times E = -\mu_\circ \frac{\partial}{\partial t}\left(\epsilon_\circ \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t}\right) \tag{2.5}$$

$$\nabla \times \nabla \times E = -\frac{1}{c^2}\frac{\partial^2 \mathrm{E}}{\partial t^2} - \mu_\circ \frac{\partial^2 \mathrm{p}}{\partial t^2} \tag{2.6}$$

Making use of the following identity

$$\nabla \times \nabla \times E = \nabla(\nabla \cdot \mathrm{E}) - \nabla^2 \mathrm{E} \tag{2.7}$$

and since $[\, \nabla . D = \epsilon\, (\nabla . E) = 0 \,]$ leads to

$$\nabla \times \nabla \times E = -\nabla^2 \mathrm{E} \tag{2.8}$$

Using equation (2.8) in equation (2.6) leads to the following wave equation [96]:

$$\nabla^2 E - \frac{1}{c^2}\frac{\partial^2 E}{\partial t^2} = \mu_\circ \frac{\partial^2 P_L}{\partial t^2} + \mu_\circ \frac{\partial^2 P_{NL}}{\partial t^2} \tag{2.9}$$

The polarization can be defined as linear (P_L) and nonlinear (P_{NL}) as follows [103]:

$$P_L(r,t) = \epsilon_0 \int_{-\infty}^{+\infty} \chi^{(1)}(t-\tau) \,.\, E(r,\tau) d\tau \tag{2.10}$$

$$P_{NL}(r,t) = \epsilon_0 \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} \chi^{(3)}\,(t-t_1, t-t_2, t-t_3) E(r,t_1)\, E(r,t_2)\, E(r,t_3)\, dt_1\, dt_2\, dt_3 \tag{2.11}$$

($\boldsymbol{P}_{NL}$) is treated as a small perturbation with respect to polarization ($\boldsymbol{P}_L$) and the wave equation will have the following form [102]:

$$\nabla^2 E(\omega) = -\frac{\omega^2}{c^2}\epsilon(\omega)\, E(\omega) \tag{2.12}$$

$$\nabla^2 E(\omega) + \frac{\omega^2}{c^2}\epsilon(\omega)\, E(\omega) = 0 \tag{2.13}$$

Equation (2.13) in the frequency domain (ω). Writing electric field in to two parts one in the transverse F(x, y) dimensions and the other in propagation dimension A ($z, \omega - \omega_\circ$) [12,4] :

$$\boldsymbol{E}(r, \omega - \omega_\circ) = F(x,y) A(z, \omega - \omega_\circ) e^{+i\beta_\circ z} \tag{2.14}$$

(F(x,y)) is the intensity distribution of pulse transverse to the direction propagation and the wave vector before perturbation is ($\beta_\circ$) .

Substituting for $\nabla^2 E$ and E in equation (2.13) one gets:

$$\frac{\partial^2 F}{\partial x^2} + \frac{\partial^2 F}{\partial y^2} + [\,\epsilon(\omega) k_\circ^2 - \beta^2]\, F = 0 \tag{2.15}$$

$$2i\beta_\circ \frac{\partial A}{\partial z} + \left(\tilde{\beta}^2 - \beta_\circ^2\right) A = 0 \tag{2.16}$$

Since ($\tilde{\beta} = \epsilon(\omega)\frac{\omega^2}{c^2}$) and ($\frac{\partial^2 A}{\partial z^2}$) is the second derivation of A(z, ω) which vary slowly with respect to (z) and writing the definitions [12]

$$\Delta(n + \Delta n)^2 \approx n^2 + 2n\Delta n \tag{2.17}$$

$$\Delta n = n_2|E|^2 + \frac{i\alpha}{2k_\circ} \tag{2.18}$$

$$\tilde{\beta} = \beta(\omega) + \Delta\beta \tag{2.19}$$

One gets:

$$\frac{\partial A}{\partial z} = i(\beta(\omega) + \Delta\beta - \beta_\circ)A \tag{2.20}$$

Writing the propagation constant $\beta(\omega)$ and $\Delta\beta(\omega)$, the amount of variation in the wave vector post perturbation as Taylor progressions, the higher terms are neglected while the first and second terms are kept in deriving equation (2.21) and (2.22), one get the followings [97] :

$$\beta(\omega) = n(\omega)\frac{\omega}{c} = \beta_o + \beta_1(\omega - \omega_o) + \frac{1}{2}\beta_2(\omega - \omega_o)^2 + \cdots \tag{2.21}$$

$$\Delta\beta(\omega) = \Delta\beta_\circ + (\omega - \omega_\circ)\Delta\beta_1 + \frac{1}{2}\Delta\beta_2(\omega - \omega_\circ)^2 + \quad \ldots \tag{2.22}$$

By using the definitions ($\omega - \omega_\circ = i\frac{\partial}{\partial t}$) and ($\Delta\beta_m = \frac{d^m\beta}{d\omega^m}$) in equation (2.20) , where (m=1,2,,…)

$$\frac{\partial A}{\partial z} = i\left[\beta_\circ + i\beta_1\frac{\partial}{\partial t} + \Delta\beta_\circ + i\frac{\partial}{\partial t}.\frac{\partial\beta_2}{\partial t} - \beta_\circ\right]A \tag{2.23}$$

$$\frac{\partial A}{\partial z} = -\beta_1\frac{\partial A}{\partial t} + i\Delta\beta_\circ - \frac{\beta_2}{2}.\frac{\partial^2 A}{\partial t^2} \tag{2.24}$$

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + i\frac{\beta_2}{2} . \frac{\partial^2 A}{\partial t^2} = i\Delta\beta_\circ A \qquad (2.25)$$

Since ($\Delta\beta = \Delta\beta_\circ$) i.e. [4]

$$\Delta\beta(\omega) = \frac{\omega_\circ^2 n(\omega) \iint_{-\infty}^{+\infty} \Delta n(\omega) \, |F(x,y)|^2 dx\, dy}{c^2 \beta_\circ \iint_{-\infty}^{+\infty} |F(x,y)|^2 dx\, dy} \qquad (2.26)$$

Where :

$$\beta_1 = \frac{1}{\mathrm{v}_g} = \frac{n_g}{c} = \frac{1}{c}\left(n + \omega \frac{dn}{d\omega}\right) \qquad (2.27)$$

$$\beta_2 = \frac{1}{c}\left(2\frac{dn}{d\omega} + \omega \frac{d^2 n}{d\omega^2}\right) \qquad (2.28)$$

By using equations (2.14), (2.25) and (2.26) with taking the reverse of Fourier transformation of A:

$$A(z,t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} A(z, \omega - \omega_\circ) \, e^{-[(\omega-\omega_\circ)t]} d\omega \qquad (2.29)$$

so that equation (2.25) becomes:

$$\frac{\partial A}{\partial z} + \beta_1 \frac{\partial A}{\partial t} + \underbrace{i\frac{\beta_2}{2} . \frac{\partial^2 A}{\partial t^2}}_{\text{(GVD)}} + \underbrace{\frac{\alpha}{2} A(z,t)}_{\text{Absorption}} = \underbrace{i\gamma |A|^2 A(z,t)}_{\text{Nonlinearity}} \qquad (2.30)$$

Nonlinear Schrodinger equation (NLSE) represented by equation (2.30), that describe the propagation of an optical pulse in a physical medium. Equation (2.30) is a nonlinear partial differential equation of the first order in position and of the second order in time. α, is the loss parameter of the medium, γ, is the nonlinear coefficient, β_1 is the inverse a group velocity dispersion ($V_g{}^{-1}$) and β_2 is the group velocity dispersion.

It is assumed in the derivation of the NLSE that the material respond nonlinearly to incident optical field instantaneously. Ultra-short pulses causes delayed nonlinear responses in the material due to the Raman effect.

Raman effect physical origin is the molecular vibration in material. NLSE can be written as including the Raman response of the medium silica GNLSE [104]:

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A + i(\beta(\omega) - \beta_\circ)A + i\gamma\mathcal{F}\left(A\int_0^\infty R(\tau)\ \left|A(z,t-\tau\right|^2 dt\right) \quad (2.31)$$

Fourier transform is denoted by $\mathcal{F}$ and the nonlinear response function R(τ) is given by [105] :

$$R(t) = (1 - f_R)\big(\delta(t)\big) + f_R h_R\,(\tau_1^{-2} + \tau_2^{-2})\tau_1 e^{(\frac{-t}{\tau_2})} \sin\left({}^{t}/_{\tau_1}\right) \quad (2.32)$$

In the right hand side of equation (2.32) the instantaneous electronic response is represented by the first term, the delayed Raman response is represented by the second term. f_R is the Raman contribution, $\delta(t)$ is the instantaneous delta function response, Raman cross sections h_R, ${}^{1}/_{\tau_1}$, is the phonon frequency, ${}^{1}/_{\tau_2}$, represented the band width of Lorentzian line.

The following formula in silica agrees well with experimental observations [106].

$$h_R = (\tau_1^{-2} + \tau_2^{-2})\tau_1 e^{(\frac{-t}{\tau_2})} \sin({}^{t}/_{\tau_1}) \ldots \quad (2.33)$$

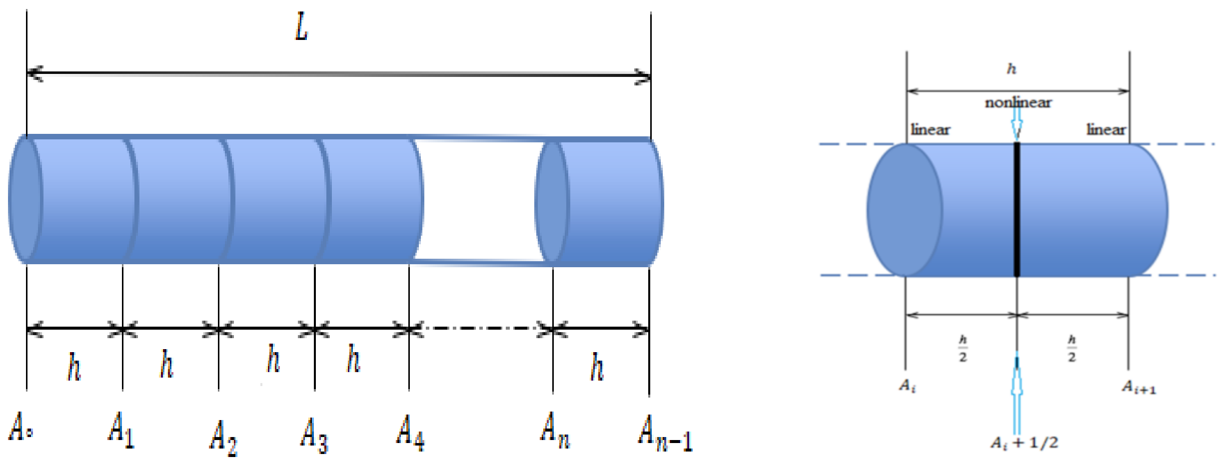
h_R the Raman cross section is a function and contains information of the silica molecules vibration (within the PCF) when light passes through the fiber. The following experimental value of f_R, τ_1 and τ_2, but an analytical form of h_R exists given by [106]:

Where $f_R = 0.18$, $\tau_1 = 12.2\ fs$, $\tau_2 = 32\ fs$.

Equation (2.31) is the generalized nonlinear Schrodinger equation (GNLSE) in the frequency domain. Analytical solution of equation (2.31) is difficult to be obtained while numerical solution is possible.

2.2.2: Split-Step Fourier Method

The numerical solution of NLSE will be discussed in this section, viz., equation (2.30). Agrawal was the first to suggest a solution of NLSE using the split step Fourier method propagating along optical fibers. It is a spectral method used in various studies to solve the NLSE by dividing the optical fiber into small parts (A) called the split-step method since each cell has part (A_i) [4, 105] as shown in Fig (2.1a) and is divided into two parts as in Fig (2.1b). The first part represents the linear effects only in the NLSE. The nonlinear effects are the second part of the cell is studied then both parts are added to each other and soon for the rest (A_i) cells [107].



(a) (b)

Fig (2.1): (a) Optical fiber is divided to a parts , (b) each part is divided once more to two linear and nonlinear parts.

To carry out the solution of equation (2.30) suppose the following [10,108]:

$$\frac{\partial A}{\partial z} = (\hat{L} + \hat{N})A \tag{2.34}$$

The linear parts of the NLSE can be written as follows [105]:

$$\hat{N}A = i\gamma|A|^2\, A \tag{2.35}$$

$$\frac{\partial A}{A} = (\hat{L} + \hat{N})\, \partial z \tag{2.36}$$

$$\ln\frac{A}{A_\circ} = (\hat{L} + \hat{N})z \tag{2.37}$$

$$A = A_\circ\, e^{(\hat{L}+\hat{N})z} \tag{2.38}$$

$$A(\mathrm{z}+\mathrm{h},\mathrm{t}) = \mathrm{A}(\mathrm{z},\mathrm{t})\mathrm{e}^{(\hat{\mathrm{L}}+\hat{\mathrm{N}})\mathrm{z}+\mathrm{h}} \tag{2.39}$$

The propagated distances (z) can be divided in to small segments (z+h), for each of length h as in the figure (2.1). Each individual segment of length h is subdivided to two parts of equal lengths, one is the linear operator that operates over each sub-segment in the frequency domain, while other is nonlinear operator that operates locally only at the central point [102]. The equation (2.39) becomes:

$$A(z+h,t) = A(z,t)e^{(\hat{L}+\hat{N})h} \tag{2.40}$$

$$A(z+h,t) = A(z,t)e^{\hat{L}h}e^{\hat{N}h} \tag{2.41}$$

Dispersion term is only and taken by neglecting the nonlinear one so that the linear part of equation is:

$$\frac{\partial A(z,\omega)}{\partial z} = -\frac{i}{2}\omega^2\beta_2 A(z,\omega) \tag{2.42}$$

Integrating equation (2.42), accordingly taking the exponential for the terminals of equation, one gets [108]:

$$A(z,\omega) = A(0,\omega)e^{-\frac{1}{2}\omega^2\beta_2 z} \tag{2.43}$$

Solve for the nonlinear part as :

$$\frac{\partial A}{\partial z} = i\gamma\left|A(z,t)\right|^2 A(z,t) \tag{2.44}$$

By integrating equation (2.44), taking the exponential for the terminals equation, one gets [10]:

$$\mathrm{A(z,t) = A(0,t)e^{i\gamma|A|^2 z}} \tag{2.45}$$

Expressed the linear part by Fourier formula and solving numerically leads to:

$$e^{\frac{h}{2}\hat{L}}A(z,t) = F^{-1}\{e^{\frac{h}{2}\hat{L}}F\{A(z,t)\}\tag{2.46}$$

Fourier transformation from time domain to frequency domain, applying $\hat{L}$, the linear operator, that apply inverse Fourier transform one gets amplitude in the time domain.

Defining nonlinear operator by equation (2.35) so that:

$$A_{i+\frac{1}{2},L}(z,t) = A_{i+\frac{1}{2},R}(z,t)e^{h\hat{N}} \tag{2.47}$$

The value of field amplitude is ($A_{i+\frac{1}{2},L}(z,t)$) at a finitesimal point ($i+\frac{1}{2}$). (over each segment of length h consists) the following summarizes what has been done three steps [107] :

Step 1:

$$\left.\begin{aligned}
&\mathrm{A_i(z,\omega) = F\{A_i(z,t)\}}\\
&\mathrm{A_{i-}(z,\omega) = A_i(z,\omega).e^{-\frac{1}{2}\omega^2\beta_2 h}}\\
&\mathrm{A_{i-}(z,t) = F^{-1}\{A_{i-}(z,\omega)\}}
\end{aligned}\right\} \tag{2.48}$$

Step 2:

$$\left.\mathrm{A_{i+}(z,t) = A_{i-}(z,t).e^{i\gamma|A|^2 Ah}}\right\} \tag{2.49}$$

Step 3:

$$\left.\begin{aligned} \mathrm{A_{i+1}(z,\omega)} &= \mathrm{F\{A_{i+1}(z,t)\}} \\ A_{i+1}(z,\omega) &= A_{i+1}(z,\omega).\,e^{-\frac{1}{2}\omega^2\beta_2 h} \\ A_{i+1}(z,t) &= F^{-1}\{A_{i+}(z,\omega)\} \end{aligned}\right\} \quad (2.50)$$

Where (F) indicates the Fourier transformation (FT) and (F^{-1}) is the inverse (FT). Applying these footsteps beginning from the input represented by the incident pulse (A_o), step by step, until the end of fiber (A_N).

CHAPTER THREE

PHOTONIC CRYSTAL FIBERS

Chapter Three

Photonic crystal fiber

3.1: Introduction

Development of optical integrated circuits faces problems such as unavailability of such materials that can be manufactured for optimal photon confinement and trapping without losses [109]. Various active research on photonic crystals were carried out post the pioneer works of Yablonovitch and John [51, 55]. Due to several features such as the ability to manipulate and control the propagation as electromagnetic waves in small spaces have attracted much research [110]. Such structures will be useful in optical filters, optical limiters, low-loss optical waveguides, optical switches, dielectric reflecting mirrors, etc., [111]. Using quantum cascade laser and optical parametric oscillators were used in the measurement of transmission through PC [112] and optical parametric oscillators [113]. PCs have the nature of periodicity in its constituent and possesses forbidden bands at specific frequency (wavelength) where propagation of light is prohibited, as shown in Fig (3.1). PCs classification are based on their dimensions viz., one, two, and three dimensions based on its periodic layers arranged within the structure.

3.2: Photonic band gap Mode

A structure that might manipulate light beams in the same way semiconductors control electric currents is called photonic band gap (PBG) crystal. Electrons of energy lying in the electronic band gap cannot be supported by semiconductor. PC similarly cannot support photons in the photonic band gap. Light processing occurs when it is prevented propagation in crystal. Such revolution in photonics should is similar to the revolution made the manufacturing the usual transit consist of dielectric materials, that serve as electrical insulators or through which an electromagnetic field propagated with low loss. Holes of the order of light waveguide are drilled into the dielectric in a structure mimics lattice-like repeatedly identical in regular fashion. If precisely built resulting holey crystal will have a photonic band gap, so that a range of frequencies within which a specific wavelength of light is blocked [102,109].

3.2.1: Photonic band gap principle

Material with periodic arrangement of the permittivity is called photonic band gap (PBG) materials, with semiconductor physics viz., a lattice of crystal that corresponds with a PBG periodic arrangement of the atoms potential [114]. Materials having PBG are also called photonic crystals (PC). The permittivity periodicity mimics the same role of propagating photons inside the structure than the potential of atom for the electrons. The geometry and index contrast of the PC determine many of its optical properties as it does for conduction properties of semiconductors. Photonic crystal waveguides are a special case of resonant device, where light is confined in two lateral directions, and is allowed to propagate in the third direction. Traditionally this was achieved by placing line defects in an otherwise uniform crystal. Photonic crystal heterostructures, however, are also suitable for this function. Light in the center crystal, which acts as the core, will be blocked by the side claddings, and can only propagate in the vertical direction. Here again, photonic crystal heterostructures have the advantage of offering more degrees of freedom in tuning the dispersion relations of both the core and cladding. As a consequence, single-mode propagation can be obtained in a guide with a wider core, allowing more efficient end coupling to the waveguide. This frequency range is calculated using an analogy with the band structure, or by calculating the spectrum [115].

3.2.2: Photonic band gap Classifications

Method of the fabrication is depending on the number of dimension of the photonic band gap.

3.2.3:1D Photonic band gap Crystals

The "one-dimensional" term imply that the periodicity of dielectric is in one direction. It is made of alternating layers of materials, having different dielectric constants, with a space, a. Its photonic band gap increase as the dielectric contrast of the material increase [115-116]. See figure (3.1a).

3.2.4: 2D Photonic band gap Crystals

The periodicity along two axes of a photonic crystal makes two dimensional, such as the one shown in Fig (3.1b). One can imagine the columns to be infinitely tall, the case of finite extent in the third direction. For certain values of the column spacing, this crystal can have photonic band gap in the xy plane. Inside this gap, no extended states are permitted, and incident light is reflected. Unlike the multilayer film, this two – dimensional photonic crystal can prevent light from propagating in any direction within the plane [57, 117].

3.2.5: 3D Photonic band gap Crystals

Photonic crystal in three-dimensional makes the manipulate and control photo interaction with matter possible. It offers possibilities of controlling light with the aid of three dimensional nature structure [58, 118], see figure (3.1c).

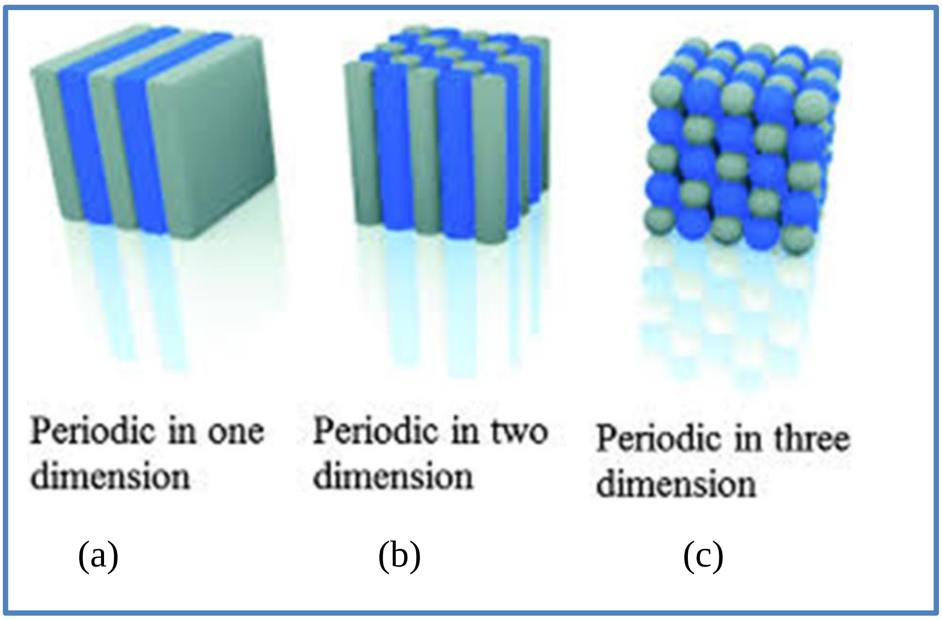


Figure (3.1): Photonic crystals (a) 1D (b) 2D and (c) 3D [115].

3.2.6: Applications for Photonic crystals

Photonic crystals can be used in various applications are attractive optical materials for controlling and manipulating light flow [54, 58, 60, 115]:

1- One dimensional photonic crystals are widespread used.

2- In the thin-film optics from low and high reflection coatings on lenses and mirrors to color changing paints and inks.

3-Higher-dimensional photonic crystals are of great interest for both fundamental and applied research.

4-The two dimensional ones are beginning to find commercial applications.

5- The first commercial products involving two-dimensionally periodic photonic crystals are already available in the form of photonic-crystal fibers, which use a micro-scale structure to confine light with radically different characteristics compared to conventional optical fiber for applications in nonlinear devices and guiding exotic wavelengths.

6-The three-dimensional PCs are still far from commercialization. It might offer additional features such as optical nonlinearity required for the operation of optical transistors used in optical computers, when some technological aspects such as manufacturability and principal difficulties such as disorder are under control.

7- Formation of a narrow band filter for selecting a particular wavelength.

8- Pulse shaping and compression using Bragg soliton eff ects.

9- Photonic crystal defects which can slow or even stop light pulses propagating in the crystal.

10- The use of temporal solitons - stable pulses which result from combination of Kerr nonlinearity and chromatic dispersion. By using these effects, the ultimate goal of nonlinear photonic crystal technique - All-optical processing of light pulses [119].

3.3: Photonic crystal fiber

Photonic-crystal fiber (PCF) is a new class of optical fiber based on the photonic crystals properties. As a result of its ability to confine light in hollow cores not in conventional way of optical fiber, PCF is now finding applications in highly sensitive gas sensors, high-power transmission, fiber lasers, nonlinear devices and fiber-optic communications. PCF categories Bragg fiber, hole-assisted fiber, photonic-band gap includes fiber. It is possible to consider Photonic crystal fibers as subgroup of general optical micro-structured class of fibers, since light is directed by structural, and not only by refractive index differences. PCFs are generally divided into two main categories:

3.3.1: Index-Guiding fibers: Have a solid core like conventional fibers. Light is confined in a solid core by making a modified total internal reflection mechanism.

3.3.2: Photonic Band-Gap (Air Guiding) Fibers: This type of band-gap with periodic microstructure elements. Its core has a lower refractive index compare to surrounding photonic crystal cladding. The following parameters can be manipulated: diameter and shape of hole, lattice pitch, type of lattice, and refractive index. Two guiding mechanisms are available in PCF: index guiding mechanism and photonic band gap by manipulating the structure. It is possible to design desired dispersion wavelengths and fabricated. Dispersion might be flattened along a very large range. Combining anomalous dispersion with small mode field areas results in outstanding nonlinear fibers. It is also possible to achieve large solid (air) core single mode fibers [120]. The idea of a photonic crystal fiber was presented for the first time by Yeh and Yriv [121].

3.3.3: Guidance mechanisms in photonic crystal fibers

If the realizing defect in a structure through removing central capillary, electromagnetic wave guiding in a photonic crystal fiber is considered as a mechanism of modified total internal reflection. To carry one fundamental mode is possible through a network of air capillaries through leaking. This is the mode with the smallest diameter, close to the size of the defect, i.e., to the lattice constant of the periodic structure [122].

3.3.4: PCF Type

Photonic crystal fibers are fabricated by stacking tubes of macroscopic silica in an array, inserting them into larger tube of silica and drawing resulted in optical fibers [123].

A- Solid core PCF

The first PCF design with solid core, which is surrounded by a hexagonal air channels guidance of light in solid-core PCF is explained by total internal reflection at interface between the core and the cladding [124]. The square at long wavelengths of effective index of the cladding equal the mean value of silica and air indices squared. Microstructure a details come at shorter wavelength into play and reducing effective index ratio of core and to cladding i.e., only first mode is guided inside the core no matter how short is the wavelength of light [125]. Fundamental mode with larger transverse effective wavelength so that no coupling is possible with outside space through cladding microstructure is possible. It is possible according to this feature to design very large-area single mode (SM) core, allowing of higher total power to carry in (SM) regime as a result of lower intensity-related nonlinear effects. Endlessly single mode (ESM) is one of the most important advantages of solid core PCFs with respect to the standard fibers [126]. See figure (3.2).

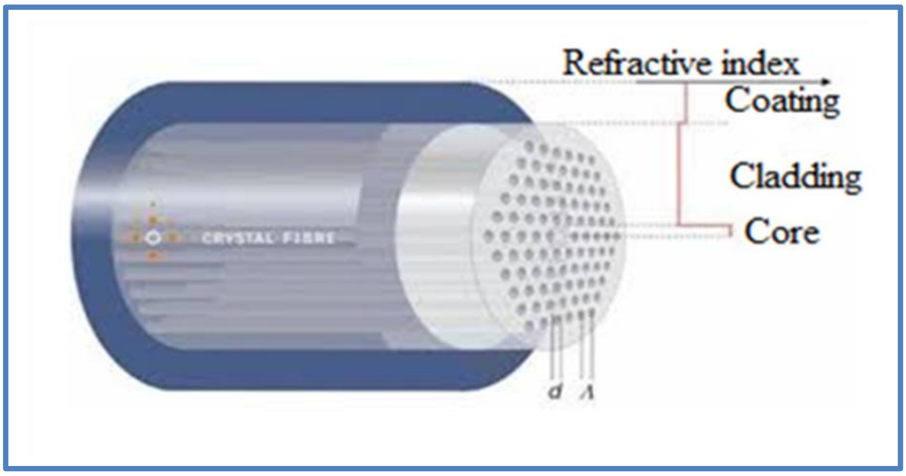


Figure (3.2): Most common design of PCF with solid core and micro-structured cladding [126].

B- Hollow core fiber

Hollow core (HC) fibers on the contrary to solid core PCF guides light through a true photonic band-gap. A correctly designed HC fiber does light cannot propagate through microstructured fiber cladding in the absence of coupling between cladding and core, light of specific wavelength is totally reflected at all angles and so that it is restricted to the region inside the air core. The GVD in (HC) (PCF) decreasing as wavelength, passing zero at zero dispersion wavelength (ZDW) close to the upper band-gap. . In fact, it is particularly intriguing to study the new light-guiding mechanisms offered by PCFs and the innovative properties related to the presence of the PBG [101,126]. See figure (3.3).

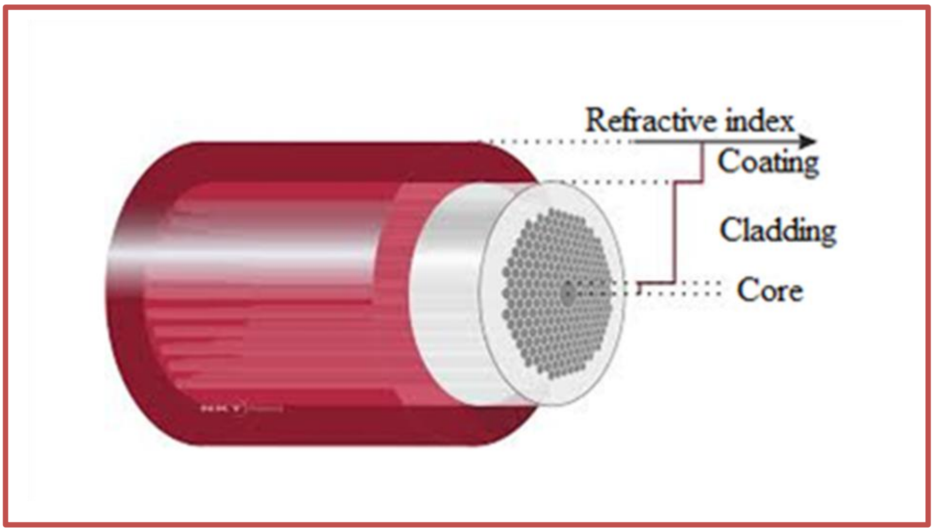


Figure (3.3): Schematics of hollow core PCF [126].

3.3.5: Advantages of photonic crystal fiber

The following PCF advantages due to its flexibility of design compare to the conventional optical fiber [125,127]:

A- Dispersion controlled.

B- Single mode with single polarization.

C- Large scale fiber single mode.

D- Short operating wavelength.

E- Large birefringence.

F- Effective mode area and nonlinearity.

3.3.6: Applications of photonic crystal fiber

A- Residual dispersion compensation in optical transmission [103].

B- The use in dispersion compensating fibers. [128].

C- Optical fiber pressure sensor [129].

D- Supercontinuum generation and flat dispersion profile for mid-infrared [130].

E- Broadband supercontinuum generation which is used in detection of cancer, dermatology, dental and ophthalmology [131].

3.3.7: Parameters effects of on the photonic crystal fiber

Optical fibers are the micro-structured optical fibers (MOFs). They are made of a hexagonal along length air holes along of a silica fiber surrounding the core of solid silica. Light is guided through it via the total internal reflection and its band gap effect PCF depends on many parameters viz., the distance between the air holes, number of holes and diameter of air hole [132].

3.4: <u>The effective refractive index</u>

An evanescent fields are belong to guided mode optical forces among two adjacent dielectric structure occurs [133]. In dielectric materials linear lossless may be obtained from the device's dispersion relation directly as a function of the structures of degrees of freedom (gap) [133-135].

The modes effective refractive indices and effective refractive index differences between the modes are important characteristics of few-mode optical fibers. Reflection spectrum measurement of few-mode fiber, discrete information of effective refractive indices of the modes can be obtained at their resonance wavelengths [136]. The refractive index of a material, n, at low light [137], is usually written as:

$$n = \frac{c}{v} \tag{3.1}$$

(v) is the velocity of light in a medium and (c) is the velocity of light in the vacuum. When light interacts with matter, a new refractive index is defined. The new reflective index called effective refractive index [138] and can be calculated by Sellmeier's equation [139]:

$$n_{eff} = n(\lambda) = \sqrt{1 + \frac{A\lambda^2}{\lambda^2 - D} + \frac{B\lambda^2}{\lambda^2 - E} + \frac{C\lambda^2}{\lambda^2 - F}} \tag{3.2}$$

Where, A, B, C, D, E, F, are Sellmeier's factors, are constants depend on the material, and experimentally computed, for pure silica (SiO_2) the values are:

A= 0.069675, B=0.408218, C= 0.890815, D=0.0047701, E= 0.0133777, F= 98.02107 [4] and (λ) is the wavelength measure by (microns).

3.5: Effective mode area

The effective area of mode is frequently used in fiber context optics. Modes of waveguides the fibers have smooth transverse profiles. Mode area generally is not straightforward, viz., for complicated mode shapes. The mode effective area can be written as [140].

$$A_{eff} = \frac{\left(\iint |E|^2 dx\, dy\right)^2}{\iint |E|^4 dxdy} \tag{3.3}$$

E is the electric field and

$$|E|^2 = E \, . \, E^* \tag{3.4}$$

E^* is the complex conjugate.

3.6: Solving the wave equation

To figure out propagation of an electromagnetic wave through photonic crystal fibers one must use an approximate method, Finite Difference Frequency- Domain (FDFD), which is called Yee algorithm to solve curl Maxwell's equations [141], was rewritten by Costa et al., [142]. Dividing medium to grid points, Yee grid, that solved in the limited differences by finite different frequency domain (FDFD). The electric and magnetic fields are divided into the directions of the coordinates, as illustrated in figure(3.4). Using the (FDFD) method in the large quantity of boundary conditions available when electromagnetic performing calculations making it an ideal way for 3D shapes [141]. The method finite difference generally depends on the approximation of derivatives as follows [143]:

$$\frac{df(x)}{dx} \approx \frac{f(x+\Delta x)-f(x-\Delta x)}{2\Delta x} \tag{3.5}$$

Function will be denoted by the symbol (u) at a point at a specific location which having coordinates with the formula as follows [144]:

$$u(i\Delta x, j\Delta y) = u_{i,j} \tag{3.6}$$

Indicators (i, j) are the grid points in the x, y directions in the photonic crystal fiber respectively, ($\Delta x, \Delta y$) represent step size for position (x, y).

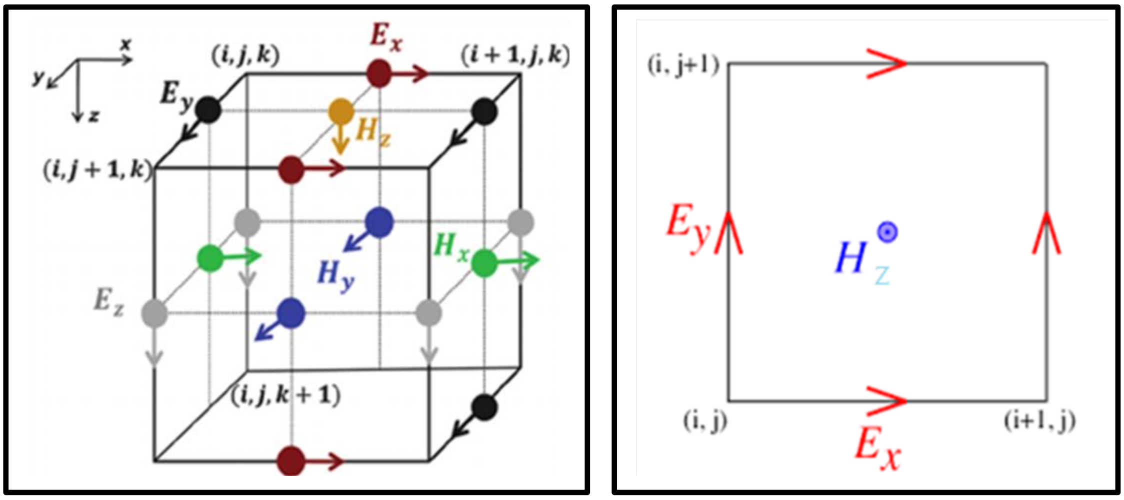


Figure (3.4): Yee grid used defining positions of the electric and magnetic field nodes. The components of electric field and that of magnetic field are assigned to cell edges and a faces respectively [145]

Formula of the first derivative of function (u) relative to (x) are as follows:

$$\frac{\partial u}{\partial x} = \frac{u_{i+1,j}-u_{i,j}}{\Delta x} + o(\Delta x) \qquad \text{(Forward)} \tag{3.7}$$

$$\frac{\partial u}{\partial x} = \frac{u_{i,j}-u_{i-1,j}}{\Delta x} + o(\Delta x) \qquad \text{(Backward)} \tag{3.8}$$

$$\frac{\partial u}{\partial x} = \frac{u_{i+1,j}-u_{i-1,j}}{2\Delta x} + o(\Delta x)^2 \qquad \text{(Central)} \tag{3.9}$$

By the same trend, first derivative for (y) can be written, the second derivative for the (x, y) coordinates are:

$$\frac{\partial^2 u}{\partial x^2} = \frac{u_{i+1,j} - 2u_{i,j} + u_{i-1,j}}{(\Delta x)^2} + o(\Delta x)^2 \quad (3.10)$$

$$\frac{\partial^2 u}{\partial y^2} = \frac{u_{i,j+1} - 2u_{i,j} + u_{i,j-1}}{(\Delta y)^2} + o(\Delta y)^2 \quad (3.11)$$

Extracting the clad effective refractive index will be done through finding constant isolation of the medium $(\varepsilon(\omega, k))$, k is the wave vector, the refractive index can be defined in the form:

$$\mathrm{n} = \sqrt{\varepsilon\,\mu} \quad (3.12)$$

Where (μ) is the medium magnetic permeability and since the $(\mu \approx 1)$, consider $(n = \sqrt{\varepsilon})$, can be make up (n) by (n_{eff}) from equation $(n = n_\circ + n_2 I)$. The polarization waves of the electromagnetic field scattered in the direction (z) will show only Cartesian compounds $(E_x E_y H_z)$, the wave vectors are restricted to the plane (xy) meaning $(H_z = 0)$, $(K_z = 0,\ z = 0)$, the (u) function is to replace the electric field and the solution method becomes as follows :

$$\frac{\partial^2 \mathrm{E_x}}{\partial \mathrm{x}^2} + \frac{\partial^2 \mathrm{E_y}}{\partial \mathrm{y}^2} + \frac{\omega^2}{\mathrm{c}^2}\varepsilon_{\mathrm{i,j}}\mathrm{E_{x,y}} = 0 \quad (3.13)$$

Solution of equation (3.13), can be written as follows :

$$\frac{\mathrm{E_{i+1,j}} - 2\mathrm{E_{i,j}} + \mathrm{E_{i-1,j}}}{(\Delta \mathrm{x})^2} + \frac{\mathrm{E_{i,j+1}} - 2\mathrm{E_{i,j}} + \mathrm{E_{i,j-1}}}{(\Delta \mathrm{y})^2} + \frac{\omega^2}{\mathrm{c}^2}\,\varepsilon_{\mathrm{i,j}}\mathrm{E_{i,j}} = 0 \quad (3.14)$$

$$\mathrm{E_{i+1,j}} = -(\Delta \mathrm{x})^2 \left(\frac{\mathrm{E_{i,j+1}} - 2\mathrm{E_{i,j}} + \mathrm{E_{i,j+1}}}{(\Delta \mathrm{y})^2}\right) + 2\mathrm{E_{i,j}} - \mathrm{E_{i-1,j}} - (\Delta \mathrm{x})^2 \frac{\omega^2}{\mathrm{c}^2}\varepsilon_{\mathrm{i,j}}\mathrm{E_{i,j}} \quad (3.15)$$

To solve the last equation and find the value of $(E_{i+1,j})$ it is assumed that the value of $(i = 0)$ at the beginning before entering the pulse into the fiber then the $(E_{i,j} = E_{ini})$, where E_{ini} represents the electric field of the pulse entered the photonic crystal fiber.

3.7: The effect of coefficient of photonic crystal

To study pulse propagation of laser in PCFs, start with solving the wave equation (2.13), which represents the electric field of laser pulse propagating through PCF.

Where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ (3.16)

Photonic crystal is investigated by studying the effects of the various parameters of the photonic crystal i.e. the air hole diameter (d), the number of air holes (N), and the hole-hole distance (Λ), as shown in Fig (3.5).

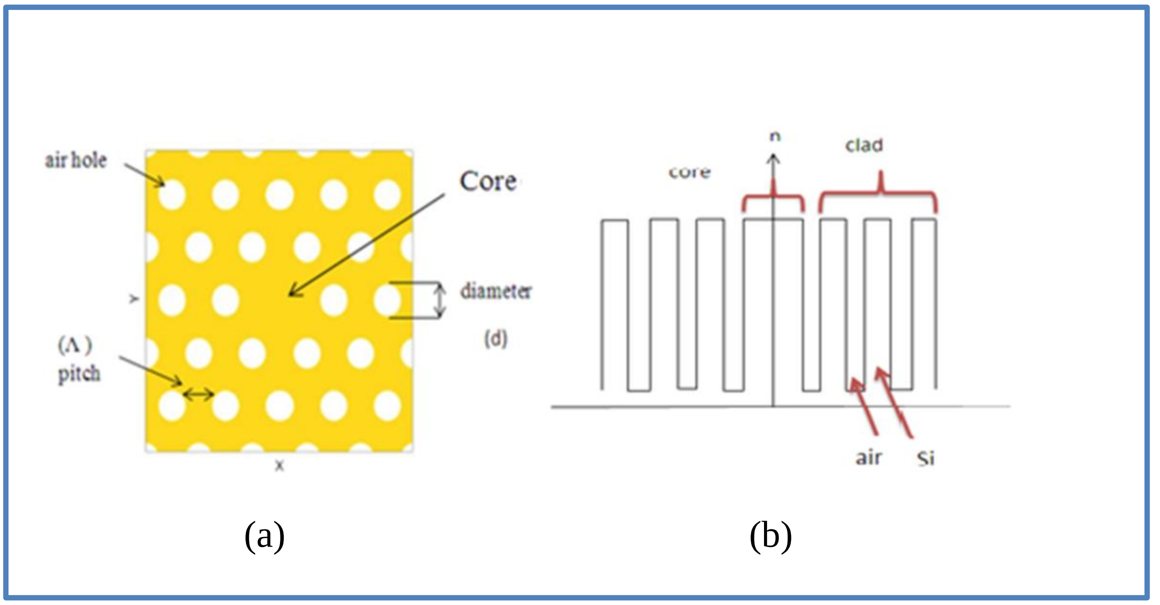


Figure (3.5): Shows (a) photonic crystal fiber consists of material and air hole drilled, (b) refractive index in photonic crystal fiber [4].

This study includes the spectra of the dispersion and the effective refractive index, the dispersion coefficient, the group velocity, and the shape of the output pulse, moreover, the effect of that on the possibility of obtaining isolated waves. In order to investigate the effect of the diameter of the air holes, values in the range (d= 0.5, 0.8, 1) μm were chosen for them based on theoretical and experimental studies, while the pitch and the number of air holes were fixed. A relationship between the dispersion curve and the wavelength within the mentioned range was observed in which increasing the diameter of the holes leads to the shifting the zero dispersion towards the shorter wavelengths, as shown in figure (3.6). On the other hand, the effective refractive index of the core does not affected within the mentioned range of the diameter of the holes, while the effective refractive index of the cladding varies with the diameter, d, in which the difference between the refractive indices of the core and the cladding is increased by increasing the diameter of the holes, as shown in figure (3.7).

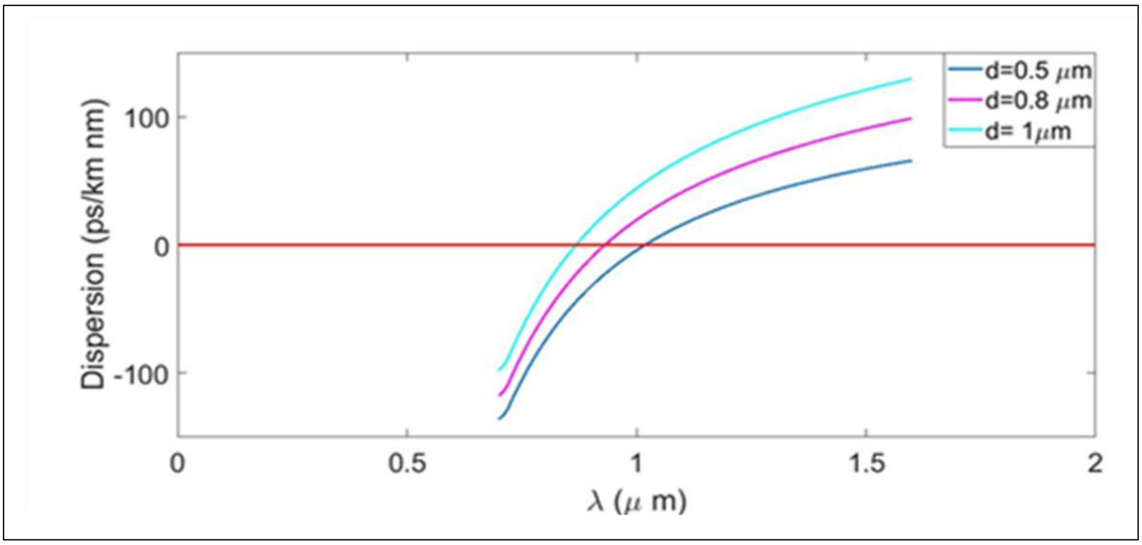


Figure (3.6): Variation of dispersion against wavelength for diameter air hole as d(μm) = (0.5, 0.8, 1), Λ= 3 μm, and N= 6

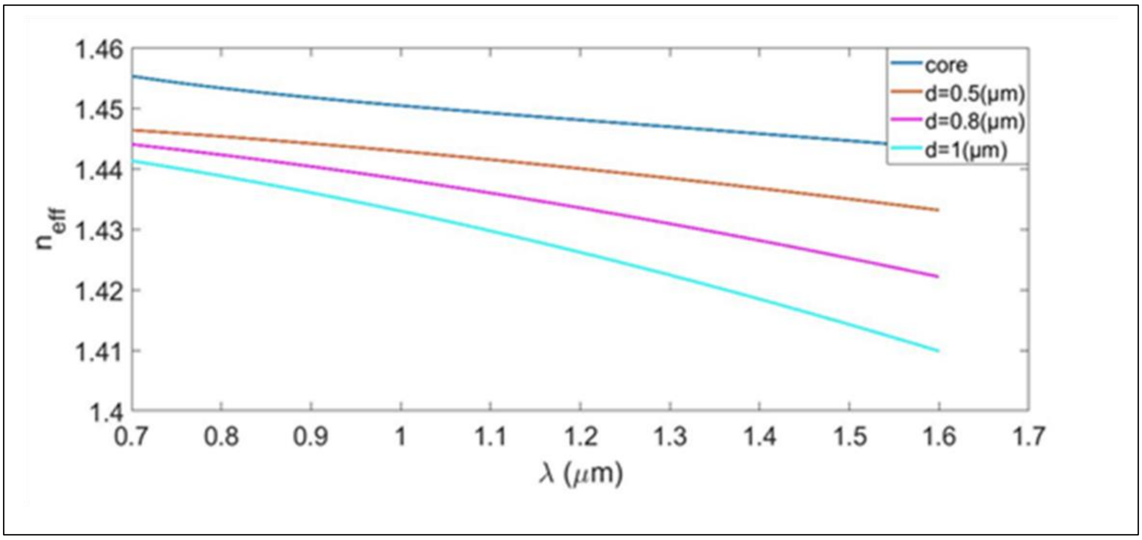


Figure (3.7): Variation of effective refractive index against wavelength for diameter air hole vary as d(μm) = (0.5, 0.8, 1) , Λ = 3 μm and N= 6.

While investigating the effect of the holes pitch on the dispersion and the effective refractive index within the dispersion curve values in the range of (Λ=3, 3.5, 4)μm, it was found when the air hole pitch increases, the dispersion curve shifts toward the longer wavelengths and the wavelength of zero dispersion increases, as shown in figure (3.8). On the other hand, while investigating the relationship between the effective refractive index and the pitch, it was noticed that the effective refractive index of the core remains almost constant for all the pitch values within the range mentioned previously, while the effective refractive index of the core and the cladding is reduced with increasing pitch as shown in figure (3.9).

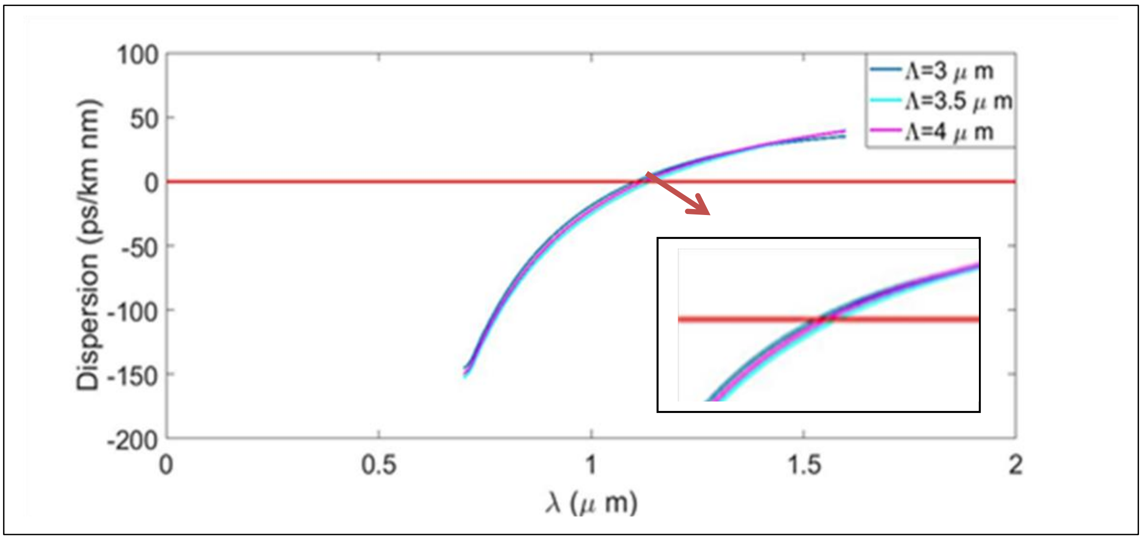


Figure (3.8): Variation of dispersion against wavelength for pitch vary as Λ(μm) =3, 3.5, 4, d= 0.3μm and N= 6.

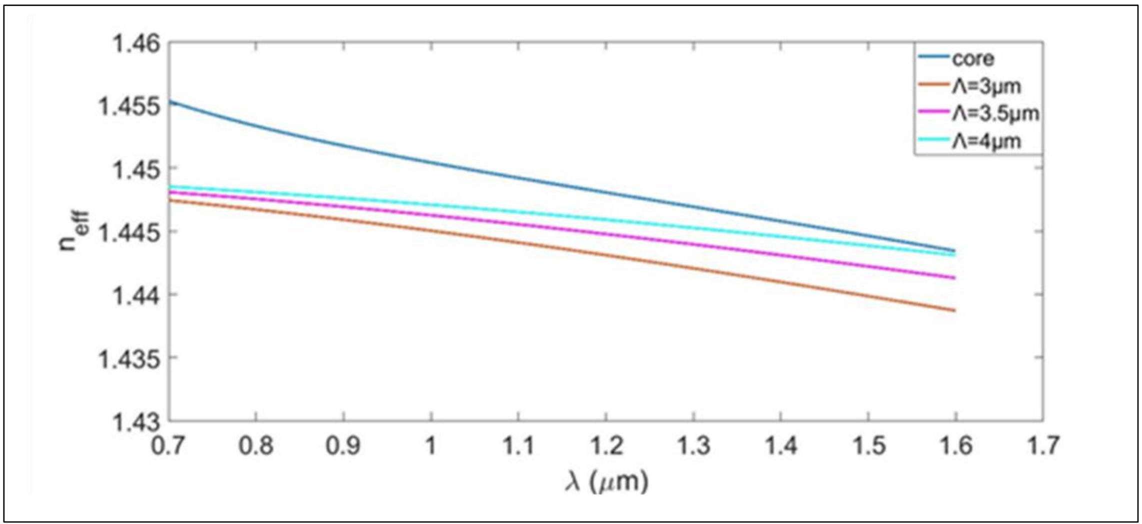


Figure (3.9): Variation of effective refractive index against wavelength for pitch vary as Λ (μm)=3, 3.5, 4, d= 0.3μm and N= 6.

In figure(3.10) and (3.11) the effect of the number of the air holes on the dispersion curve and the effective refractive index are observed at certain values of the number of holes of (N=5, 8, 12), were selected while the air holes pitch and diameter of the holes were fixed at the (Λ=3μm) and (d=0.3μm), respectively. It is noticed that the curves intersect and match each other. Moreover, one point of zero dispersion at wavelength (λ=1.2μm), were observed. In addition, while the holes pitch increases, the dispersion curves shift toward long wavelengths. Regarding the relationship between the effective refractive index and the number of holes, it was noticed that the difference between the effective refractive indices of the core and cladding decreases by increasing the number of holes, while for large number of holes, it was noticed that the curves match each other. The refractive index of the core remains constant for all values of number of gaps, as shown in figure (3.11).

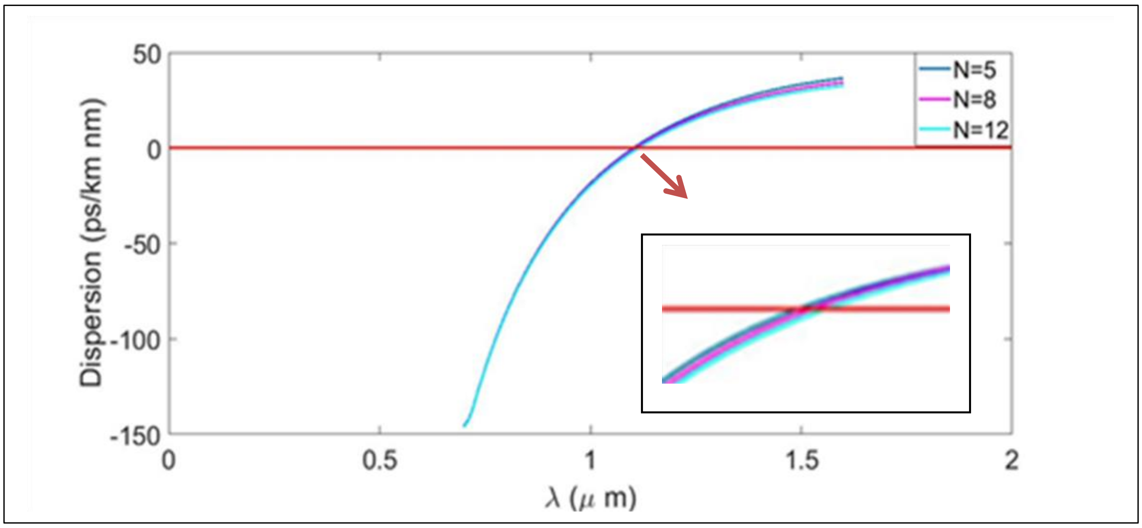


Figure (3.10): Variation of dispersion against wavelength for the number of air holes vary as N=5, 8, 12, Λ=3μm and d=0.3μm.

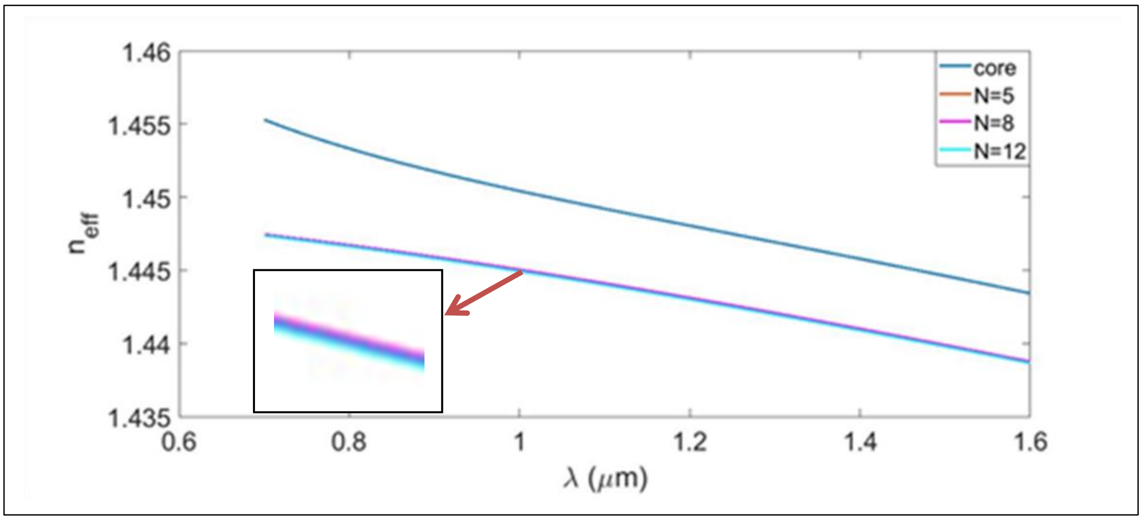


Figure (3.11): Variation of effective refractive index against wavelength for the number of air holes vary as N=5, 8, 12, Λ=3μm, and d=0.3μm.

3.8: Determination of the two points for zero dispersion wavelength (ZDW)

The selections of the photonic crystal parameters make it more flexible for many applications, the choice of the holes diameters, hole-hole spacing and the holes numbers gives a unique dispersion, effective area, effective refractive index and nonlinearity.

As the dispersion plays the major role affects the propagation of the laser pulses (message) in the communication system, where, the pulses suffer a broadening with time. To overcome this, the communication system must works at a wavelength range in a way that keeps the dispersion curve close to zero. To solve this advantage the engineers must use pulses with a wavelength close to that gives zero dispersion (ZDW) in the dispersion curve of the optical fiber. Figure (3.12a) shows how to choose the propagation wavelength (λ) [106]. This gives some restriction on the choice of the laser type used.

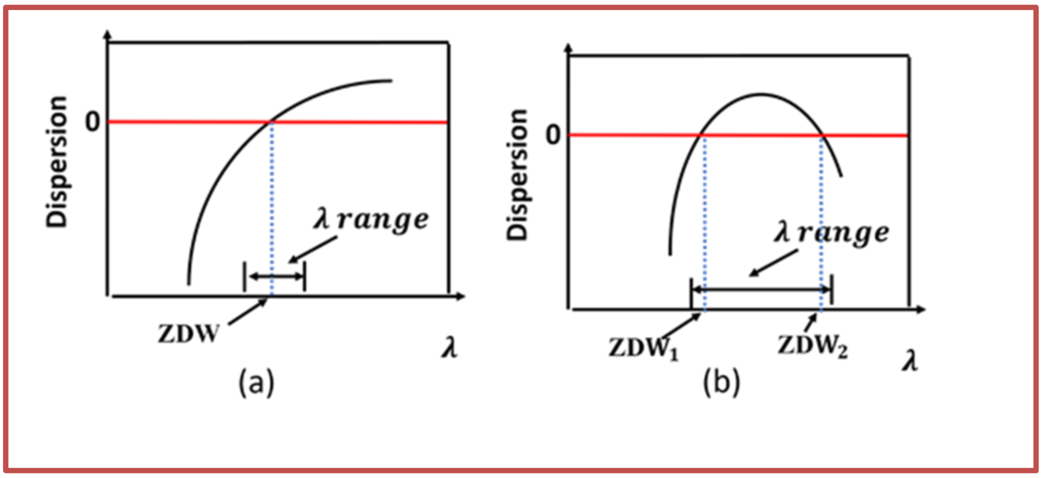


Figure (3.12): The wavelength selection range for (a) one ZDW, (b) two ZDWs [106]

The photonic crystal can be customized to have a dispersion curve with two ZDWs. In this case, the range of the wavelength will be extended to be $ZDW_1 \leq \lambda \leq ZDW_2$ as can be seen in figure (3.12b).

When (N=6), (Λ= 1.2, 1.3, 1.4, 1.5) μm and (d=0.6, 0.65, 0.7, 0.75) μm , one will notice two point of the dispersion, figure (3.13) shows it.

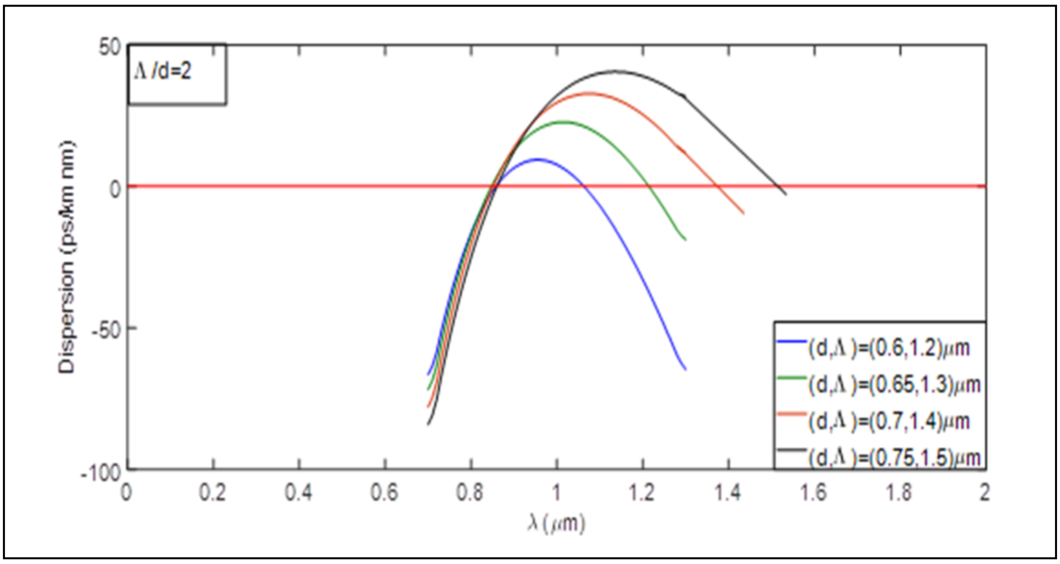


Figure (3.13): Dispersion curves when N=6, Λ= (1.2, 1.3, 1.4, 1.5) μm and d= (0.6, 0.65, 0.7, 0.75) μm.

Where curves intersect and one above the other and thus get the first ZDW at (λ=0.8) μm near for all curves, while when the dispersion increase the curves diverge from each other, that lead to different ZDW, whenever (Λ) and (d) increase the range of wavelengths between the two ZDW of each curve increased too.

Now, when (N=11), (Λ= 1.2, 1.3, 1.4, 1.5) μm and (d=0.6, 0.65, 0.7, 0.75) μm , one will notice two points of the dispersion as shown in figure (3.14).

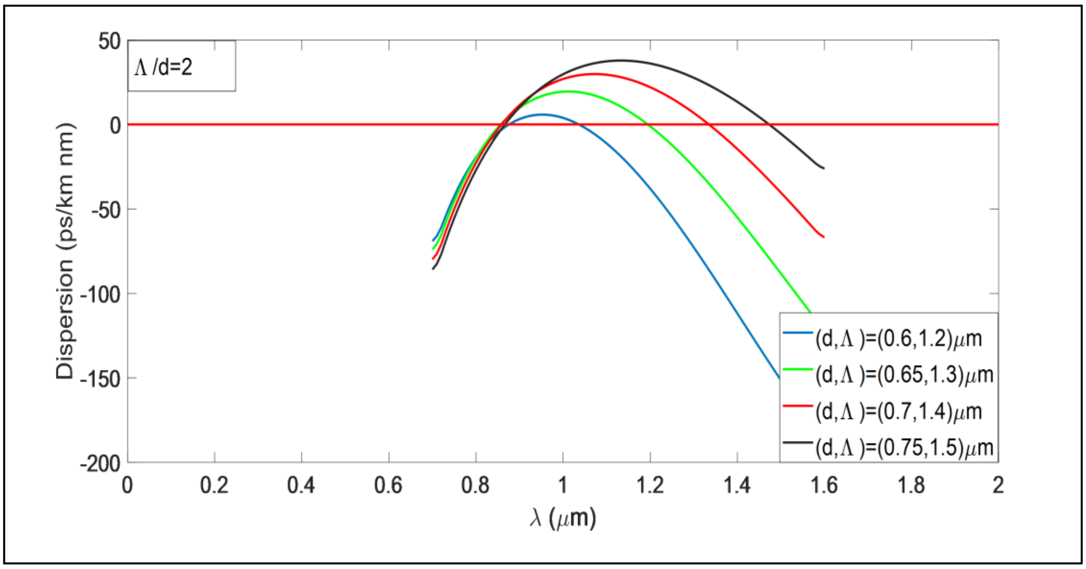


Figure (3.14): Dispersion curves when N=11, Λ= (1.2, 1.3, 1.4, 1.5) µm and d= (0.6, 0.65, 0.7, 0.75) µm.

By increasing the number of holes (N=11), for the same values both (Λ and d), one notice the curves are slightly lower compared to the previous case, and therefore will show the first ZDW shifting toward right, as well it is clear when Λ and d decrease the dispersion decrease too.

CHAPTER FOUR

OPTICAL SOLITONS

Chapter Four

Optical Solitons

4.1: Introduction

Optical solitons resulted on the condition that total refractive index seen by a beam is :

$$n = n_{\circ} + n_2 |A|^2 \tag{4.1}$$

Where $n_{\circ}$ is the linear index of the medium, $n_2$is the medium Kerr index, and A is incident electric field. The medium total refractive index increases as the increase of amplitude. Solitons are either temporal or spatial [23].

4.1.1: Spatial soliton

Solitons can propagate in nonlinear media with a constant shape. They occur in physics including Bose– Einstein condensates, nonlinear optics, plasma physics and hydrodynamics. An optical wave-packet, in optics, as it propagate naturally spread in a medium, due to spatial diffraction or chromatic dispersion. By eliminating such broadening via a nonlinear process, a stable localized wave-packet in time or space or both forms, this is known as an optical soliton. Self-trapped optical beams is spatial optical solitons which propagate in a nonlinear medium with no diffraction, remains spatially invariant while propagation via self-focusing that balance the natural diffraction [151-152]. It can be figured as follows: an optical beam induces a waveguide that guides itself via propagation confined in an optical fiber.

The idea of spatial solitons is illustrates in figure (4.1). The equalizes expanding wavefront due to diffraction by the converging wavefront because of self-focusing so that soliton is borne with a plane wave front.

Soliton solutions are known to be stable. Perfect balance between the nonlinear (self-focusing) and linear (diffraction) prevents any fluctuations field that destroys soliton. when fluctuation lead to bit of soliton widening, self-focusing comes in to effect so that soliton retain its shape.

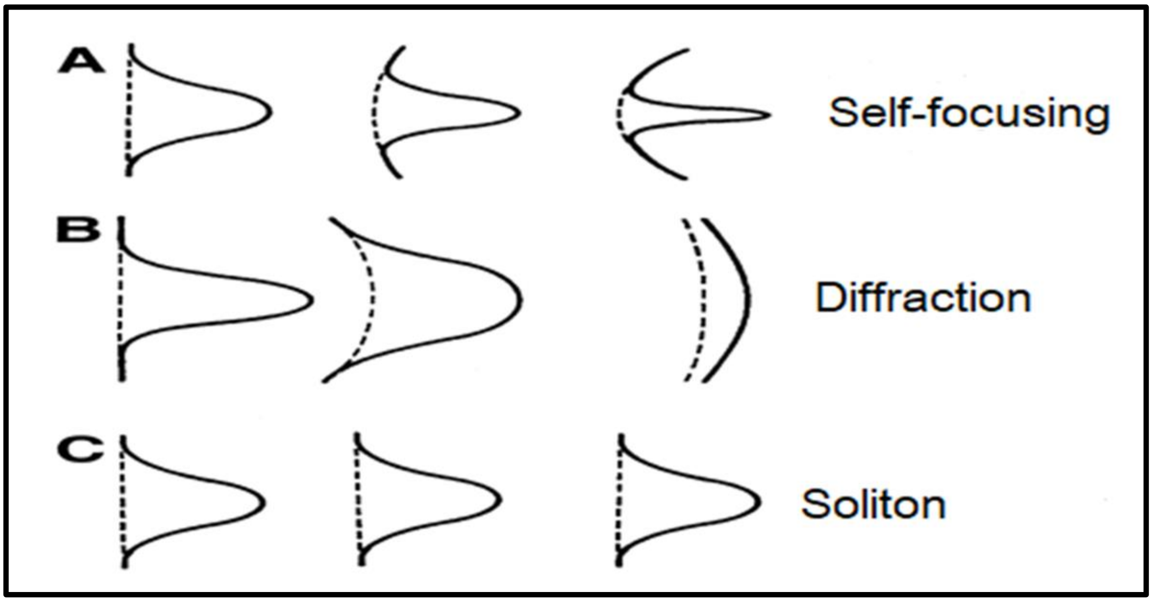


Figure (4.1): Linear and nonlinear effects on Gaussian pulses [153]

4.1.2: Temporal soliton

Limits transmission bit rate in optical fibers since the generated pulse have certain bandwidth together with dependence of fibers refraction indexes on its frequency (or wavelength). Such effect leads to group velocity dispersion that can be written in terms of the following delay dispersion parameter D [154]

$$\Delta\tau \approx DL\,\Delta\lambda \tag{4.2}$$

$\Delta\tau$ is the temporal width of pulses, L is the fiber length and $\Delta\lambda$ is the wavelength bandwidth. Such dispersion can be balanced using fiber having, D, of different signs in different parts of fiber, in modern communication system so that the pulses broadening and shrinking while propagating. It is possible to remove such a problem completely with temporal solitons. Soliton solutions are only possible in the region of anomalous dispersion, so that higher frequency waves travel faster compare to the low frequency ones. Self-phase modulation on the other hand, produces a chirped pulse without changing [10].

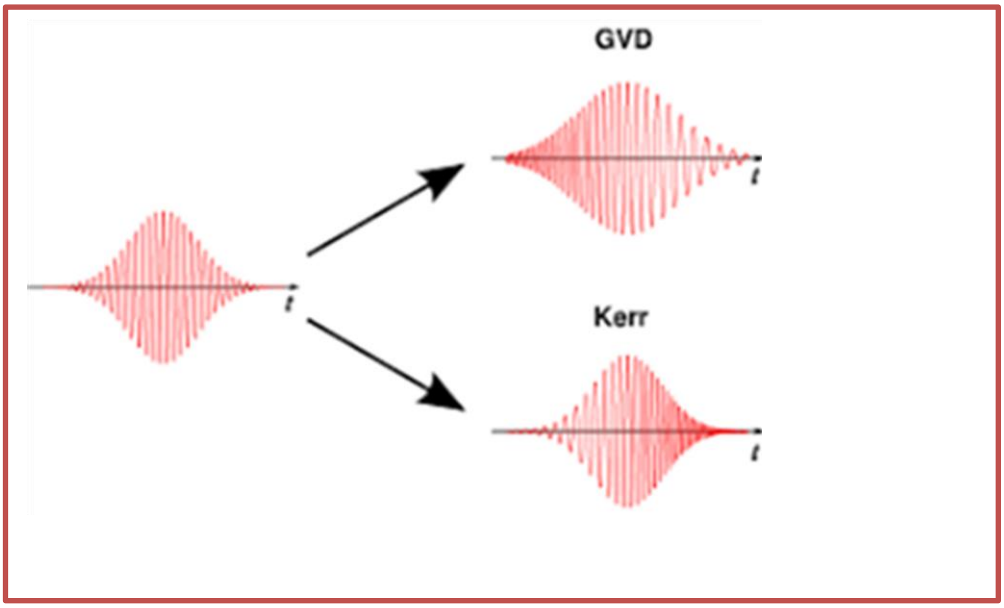


Figure (4.2): Linear and nonlinear effects on Gaussian pulses [154].

When pulse propagate in a fiber with positive D where the dispersion is anomalous i.e higher frequency components propagate faster compare to the lower frequency, so that it arrives before at the end of the fiber. So that signal suffers wider chirp, (upper of the figure (4.2)). Consider a medium that suffers nonlinear Kerr effect only, its refractive index does not depend on frequency: hypothetically post propagation it gets a chirped pulse through ideal medium with neglecting dispersion, so no broadening (upper of the figure (4.2)). The two effects introduce a frequency changes in two opposite directions. A pulse can be made where frequency two effects will balance each other. For higher frequencies, linear dispersion make them propagate faster, while nonlinear Kerr slow them down. So that pulse does not change while propagating, these are temporal solitons.

4.1.3: Conditions for soliton

The conditions for soliton are [153]:

A) Anomalous dispersion region must. That is β_2<0.

B) Pulse input has to be chirped hyperbolic secant pulse.

C) The dispersion length (L_D) should equal the nonlinear length (L_N), $L_D = L_{NL}$.

D) Chirp due to group velocity dispersion (GVD) should exactly cancel. chirp due to the self-phase modulation (SPM).

4.1.4: General properties

Precise definition of a soliton is hard:

1. Permanent wave form.

2. Localization through moving.

3. Strongly interaction with another solitons and retain identity.

4.2: Solitons in photonic crystal fibers

Solitons propagation can be simulated at various conditions. Two pulse types will be used in this section, viz., “sech” and Gaussian. Split-step Fourier method (SSFM) is used as a numerical method to simulate the wanted performance. It is assumed that dispersion is anomalous (β = -1), and there are no losses ($\alpha = 0$) [109].

4.2.1: First-order soliton :

$sech$ shape pulses written as:

$$u(0,\tau) = N_s sech\ (\tau) \tag{4.3}$$

With N_s is the pulse order. For $N_s = 1$ leads to

$$u(0,\tau) = \text{sech}(\tau) \tag{4.4}$$

This pulse is called the fundamental soliton and its profile against the fibers length and time is shown in figure (4.3).

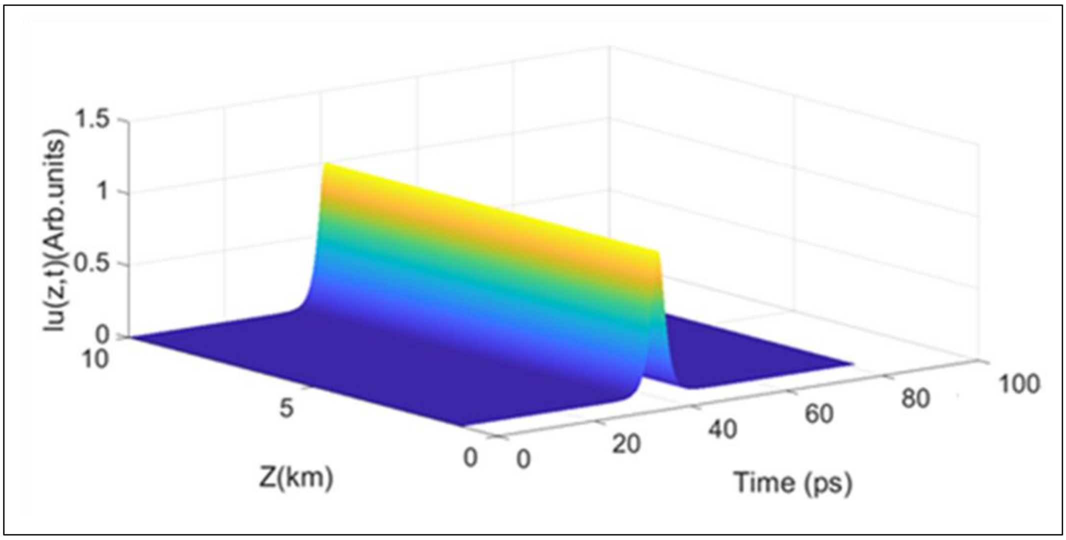


Figure (4.3): First – order soliton propagation along a fiber link, and time.

Figure (4.3) shows that the soliton does not suffer dispersion and its amplitude is the same along the fiber. Due to its unchanged shape along the fiber, this pulse is called the fundamental soliton. The pulse shape does not change, because that the fiber nonlinearity exactly compensates the group velocity dispersion (GVD) effect. Even if N_s is not exactly equal to 1, i.e., if N_s lies between 0.5 and 1.5, this happens, because the optical soliton is remarkably strong and stable against perturbations [10].

4.2.2: Third-order solitons

The pulse equation of the third-order soliton ($N_s = 3$) is

$$u(0,\tau) = 3\,\mathrm{sech}(\tau) \tag{4.5}$$

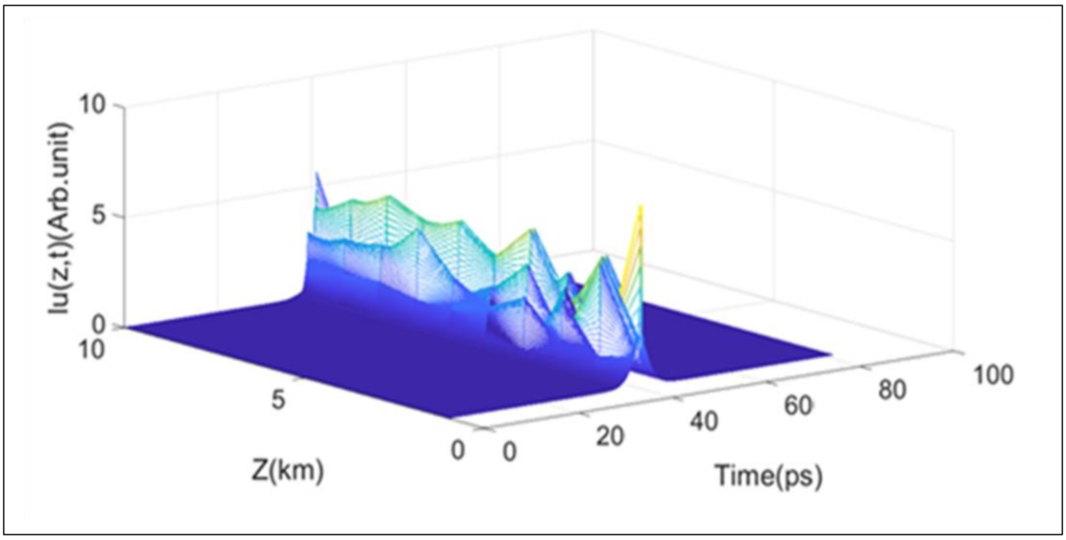


Figure (4.4): Propagation of the third-order soliton along a fiber link.

Figure (4.4) shows that the third-order soliton has a periodic behavior, and also does not tend to the fundamental soliton. The third-order soliton recovers its initial pulse shape with the same period of the second-order soliton. The third order solitons prove that, for N_s higher than 1.5, the pulse does not tend to the shape of the fundamental soliton.

4.3: Applications of optical soliton

1: Soliton Amplification

Loss of energy occurs as a result of the pulse propagation along the fiber such effect leads to soliton broadening. Generally loss is compensated through amplification. There are two types of soliton amplifications viz., lumped and distributed. In the first an optical amplifier retains soliton energy to its input level post propagation through a certain distance. In the second two methods usually applied, i.e., stimulated Raman scattering and erbium-doped fibers by periodic pumping along the fiber length[155].

2: Pulse Compression

Compressing of optical pulses is widely used in nonlinear fiber optics. Dispersive and non-linear effects have led to producing very short pulses less than 5 fs. Compressing of pulse can be carried out via., two types, one based on nonlinear fiber optics and the other is grating-fiber. Compression occurs via., interplay between GVD and SPM. Dispersion-decreasing fibers (DDFs) are helpful for pulse compression. So that a train of ultra-short pulses can be generated by DDFs pulse compression mechanism.

3: Soliton Bit Rate

Large number of systems of commercial wave-length division multiplier (WDM) systems, due to the use of appropriate use of solitons replaces the traditional non-return to zero (NRZ) and return to zero (RZ) modulations. NRZ is a binary modulation with square pulses so that the signal is on for a 1 bit and off for a 0 bit. In RZ one pulse is shorter than the bit time. In NRZ and RZ systems the Four-Wave Mixing (FWM), Kerr nonlinearities (SPM), and Cross Phase Modulation (XPM) are the unwarranted effects which restrict at high speeds the performance and distorting signals. A conventional WDM system without introducing too much nonlinearity enhances the power. The NRZ and RZ systems are, known as linear systems. NRZ system while encoding digital signals if two are close together, the intensity signal does not drop back to 0 between the individual bits as it does with solitons. The conventional NRZ or RZ modulation formats are preferred to the soliton based technology [156].

4: Timing Jitter

Soliton pulses in an ideal soliton in a fiber are possible to separate from each other. One digit of information bit each soliton pulse can be carried and it is separated from others. It is possible soliton pulse width is narrower than the bit rates in a larger bandwidth in comparison to a linear pulse having the same bit rate. Soliton timing jitter as a result of amplified noise or due to interactions with neighboring solitons is however, the major detrimental factor to the use of optical soliton communication which is responsible for bit rate error. By dispersion compensation we can control the soliton jitter by reducing the average dispersion close to zero [155].

5: Spatial Soliton

The importance of optical spatial solitons is widely acclaimed. By advent of self-trapping of light when laser beam is focused on the edge of a photo-sensitive material creates its own waveguide that is further guided by this waveguide. The refractive index of the medium is altered by the diffracted light beam. The beam creates a channel dynamically via., the passage of time, that controls the diffraction and guides the beam through the material. The propagation of an optical beam solitons can be formed in a non-linear medium without any diffraction effect. Spatial solitons with varieties of dimension were observed in various non-linear media [9].

4.4: <u>Advantages of soliton based communication</u>

A: Solitons are unaffected by an effect called phase modulation dispersion (PMD).

B: Solitons are well matched with all optical processing techniques.

C: The solitons are controlled properly [16].

D: The particle nature of solitons.

E: Solitons tend to stay together [19].

F: Solitons replaces the traditional NRZ with RZ modulations [1].

4.5: The effect of photonic crystal fiber on the Gaussian pulse propagation through the fiber

In chapter two NLSE was solved using SSFM. This chapter presents the effect of the properties of photonic crystal fiber parameters on the Gaussian pulse such as the absorption, dispersion, and nonlinear effects. Assume a Gaussian pulse of power (1mW), and width (FWHM=50ps), enter a fiber with length of (100km). The dispersion phenomena within fiber length can be defined with characteristic length for the dispersion is given by [112]:

$$L_D = \frac{T_\circ^2}{|\beta_2|} \tag{4.6}$$

For assuring to obtain the dispersion phenomena within the distance under the study, one can normalized the quantities of the study which is the fiber length, pulse time, and pulse amplitude, where the distance (Z) [102], can be written as:

$$Z = \frac{L}{L_D} \tag{4.7}$$

While the time (t) is defined as:

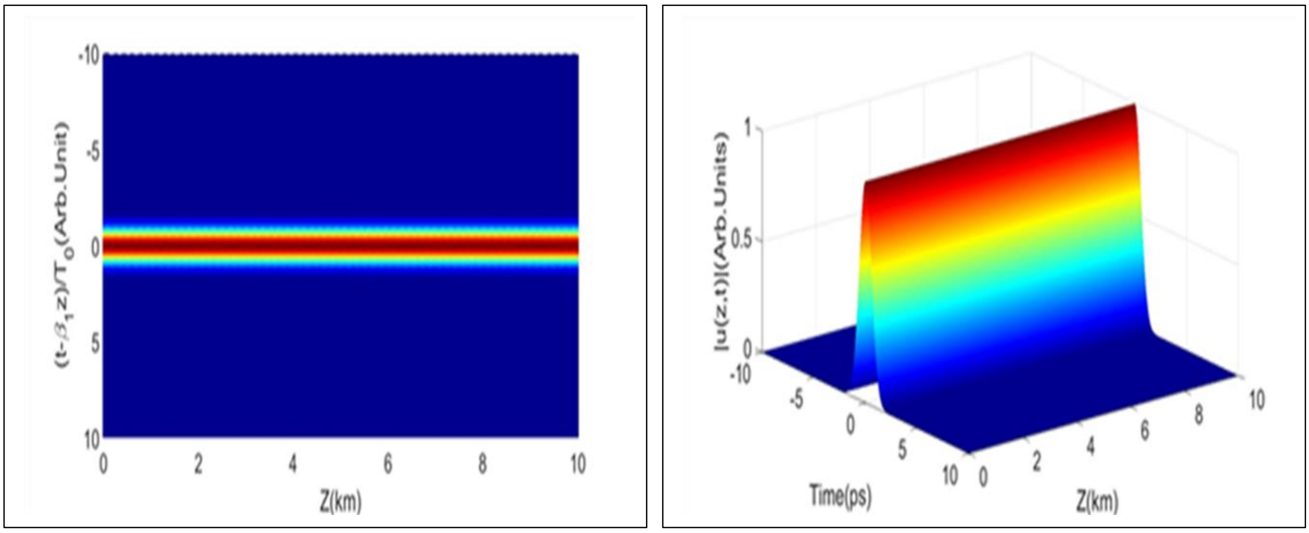
$$t = \frac{t}{T_\circ} \tag{4.8}$$

And pulse amplitude is given by:

$$U = \frac{A}{A_\circ} \tag{4.9}$$

where ($T_\circ$) and ($A_\circ$) are the width and amplitude of the pulse respectively.

The first proposed numerical result obtained by using the parameter of the optical fiber by neglecting α and have a balance between the effects of β_2 and the one that come from γ, where α is the attenuation, β_2 group velocity dispersion, and γ is the nonlinear effect. When the Gaussian pulse is not subjected to attenuation, dispersion, and nonlinear effects, thereby assumes that pulse keep with the same shape without any change, as shown in figure (4.5), with the distance and time, where (4.5a) shows that the intensity of the soliton will be constant along the propagation distance inside the fiber, and with a certain width at time. While (4.5b) is a three-dimensional plot of the pulse shape with the distance and time inside the fiber.

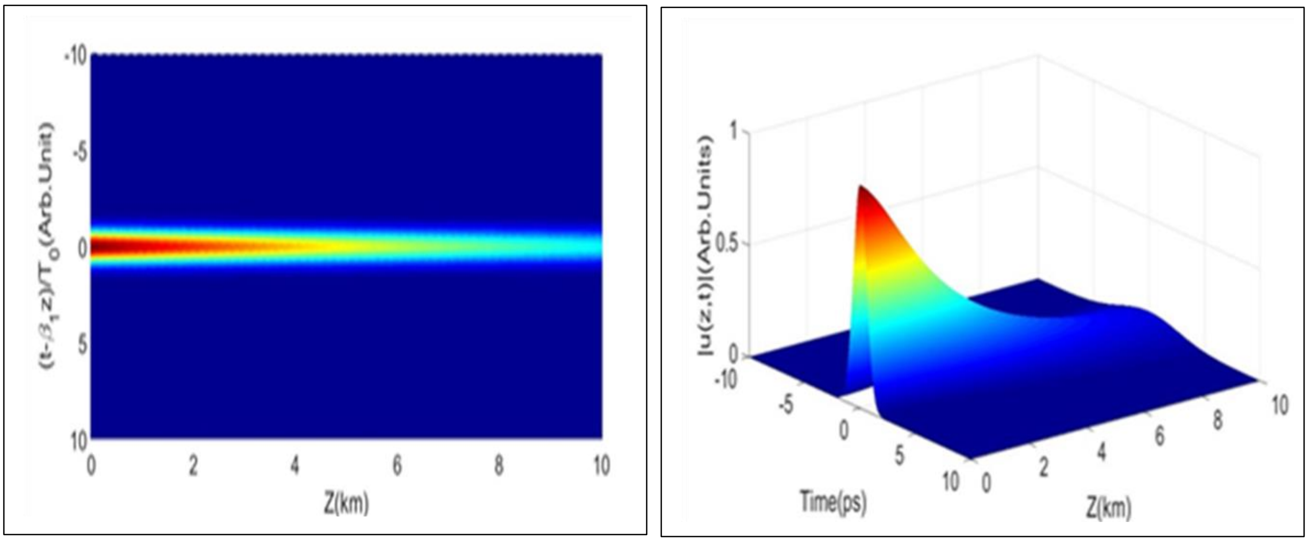


(a) (b)

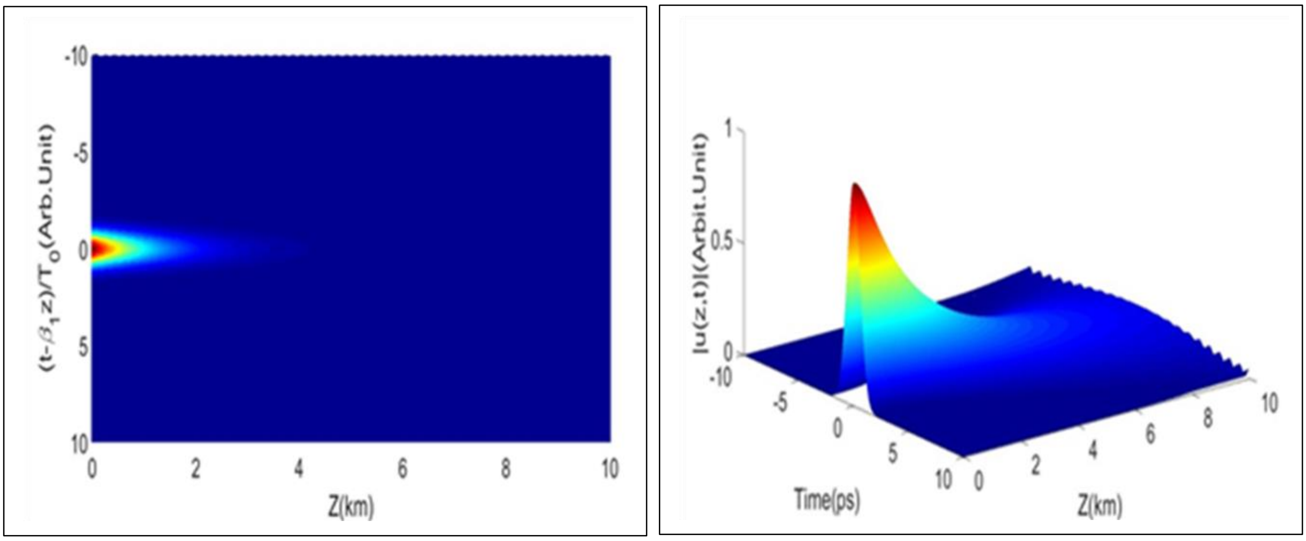
Fig (4.5): The propagation of a Gaussian pulse neglecting α and have a balance between the effects come from β_2 and the come from γ.

4.5.1: The effect of α on the pulse

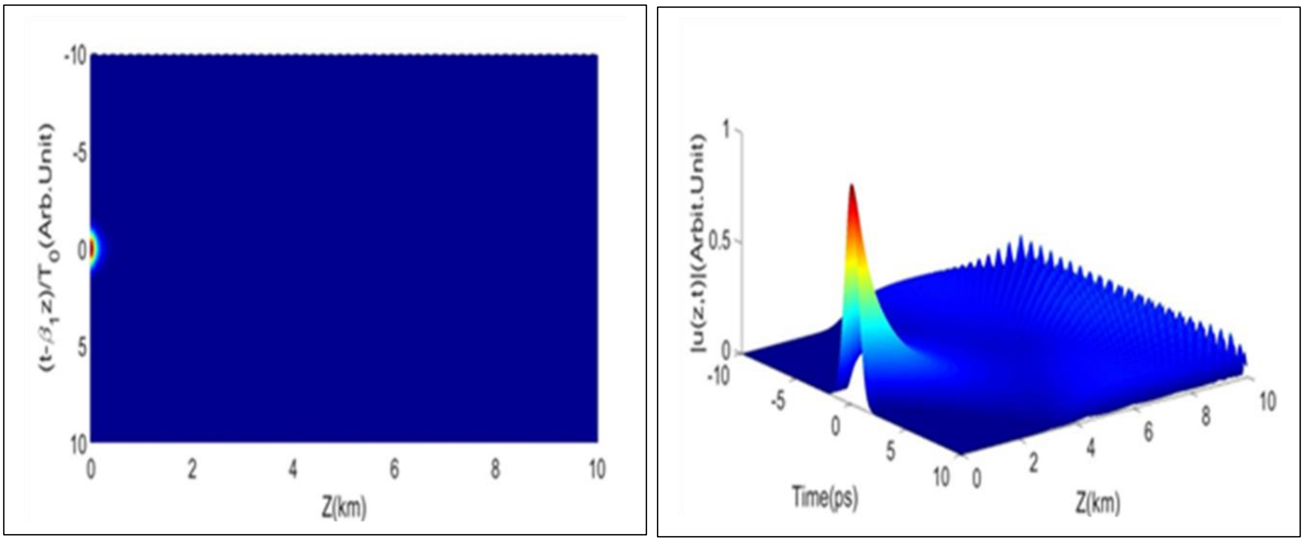
When a Gaussian pulse passes into the medium and the medium suffers no nonlinearity or the nonlinearity is very small (γ=0.000003 W^{-1} km^{-1}) and (GVD) for the medium was (β_2=0.00006 ps^2/km) small also taking different values of the absorption coefficient (α) one can notice that with increasing (α), the attenuation will increased, and the pulse intensity decreases and may be disappear for high (α) values. As can be seen in figure (4.6).



(a)



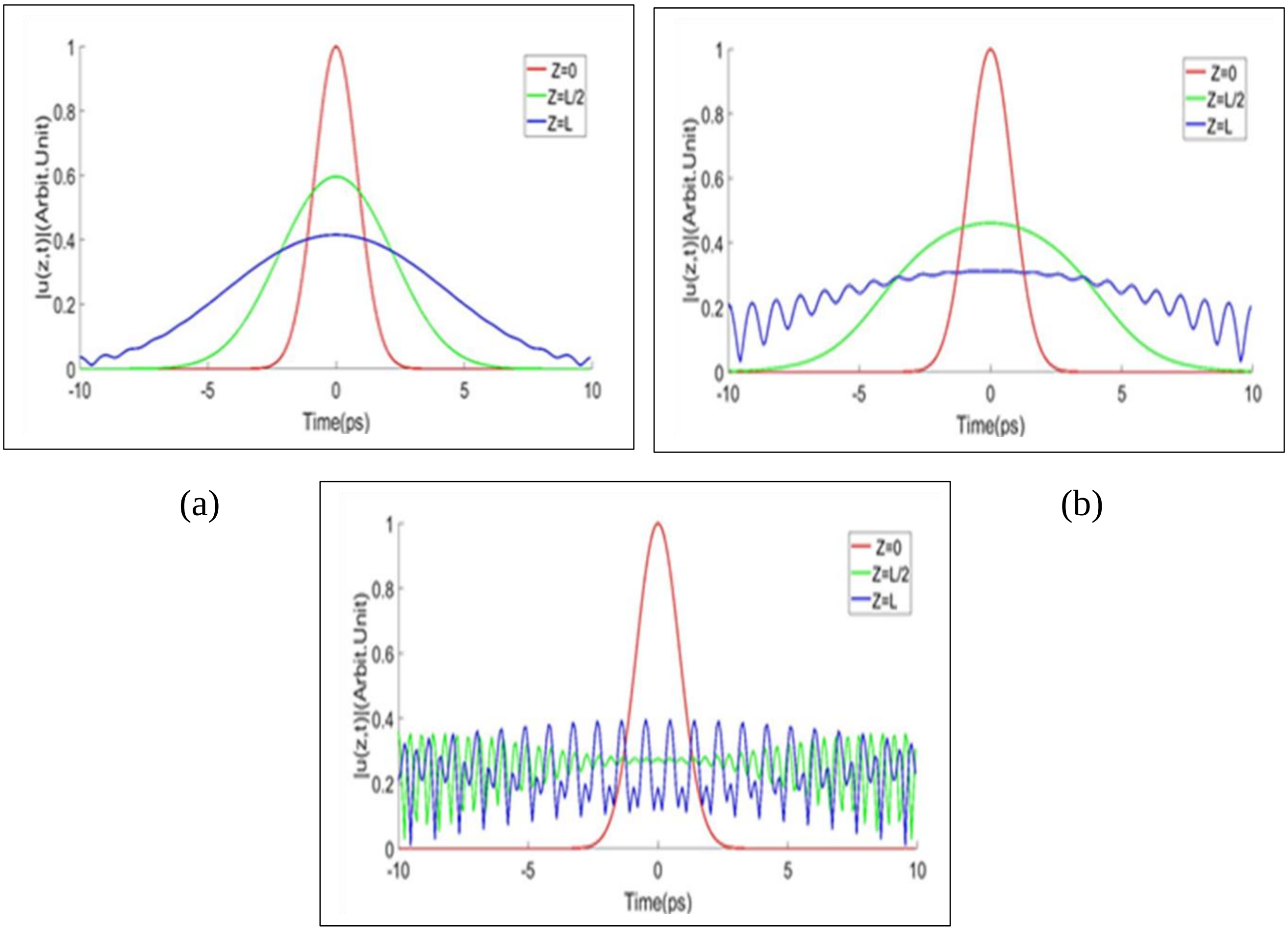
(b)



(c)

Figure (4.6): The propagation of a Gaussian pulse in the fiber and picture for change the pulse intensity with distance and time for (a) α=0.0002dB/km , (b) α=0.002dB/km, (c) α=0.02dB/km.

For more explanation of pulse behavior, the pulse intensity profile can plotted in two dimensional with time at different distance inside the fiber. Figure (4.7) shows the intensity profile with time at different distance at the entrance, at the mid-length and at the output.



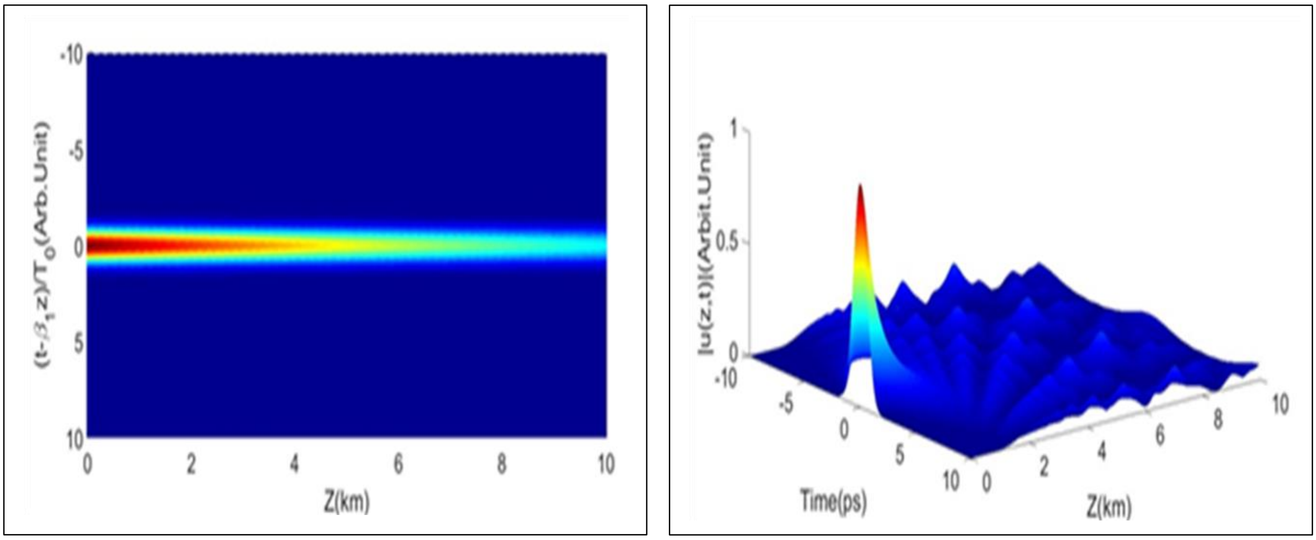
(a) (b)

(c)

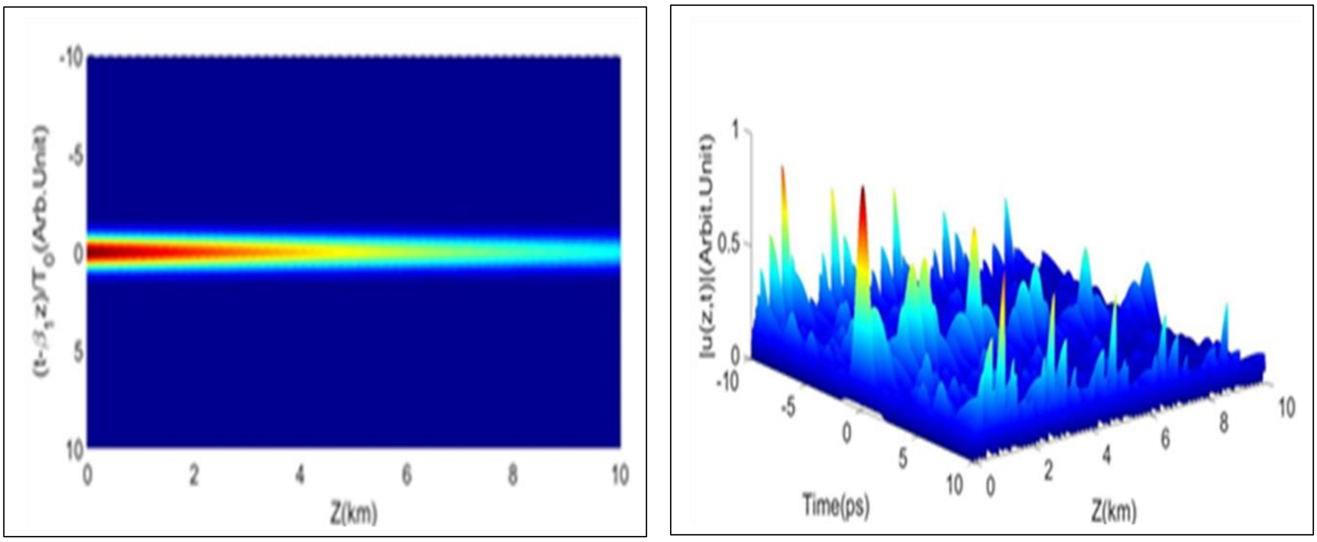
Figure (4.7): Evaluation of the intensity of the Gaussian pulse in the optical fiber with the time for (a) α=0.0002dB/km, (b) α=0.002dB/km, (c) α=0.02dB/km. At z=0, z=L/2, z=L

4.5.2: The effect of β_2 on the pulse

To study different effect of the dispersion the attenuation and nonlinearity will fixed at small values (α= $0.0002{}^{dB}/_{km}$, γ=0.00003W^{-1} km^{-1}), and taking three different values of β_2 {β_{21} = 0.006 (ps^2)/km, β_{22}=0.06 (ps^2)/km , β_{23}=0.6 (ps^2)/km}, and as we saw in the figure (4.5) the pulse conserves its shape as it propagates along the fiber, but now it suffers a reduction, similar to what happen in figure (4.6), as can be seen in figure (4.8), where for β_{21} = 0.006 (ps^2)/km, it is clear that the pulse shrinks with time and its intensity decreased with the propagation distance figure (4.8a). If we increase β_2 0.06 (ps^2)/km, the intensity also shrinks with time, and decreases with the distance, while we have complex shape or distribution will appears an in fig (4.8b). If we increase β_2 more, the intensity distribution have more complexity, see figure (4.8c). Figure (4.9) shows the two dimensional intensity distribution with time for three simulations z=0, z=L/2, z=L.



(a)



(b)

Figure (4.8): The propagation of a Gaussian pulse in the fiber and picture for change the pulse intensity with distance and time for (a) β_2=0.006 (ps^2)/km,(b) β_2=0.06 (ps^2)/km) , (c) β_2=0.6 (ps^2)/km).

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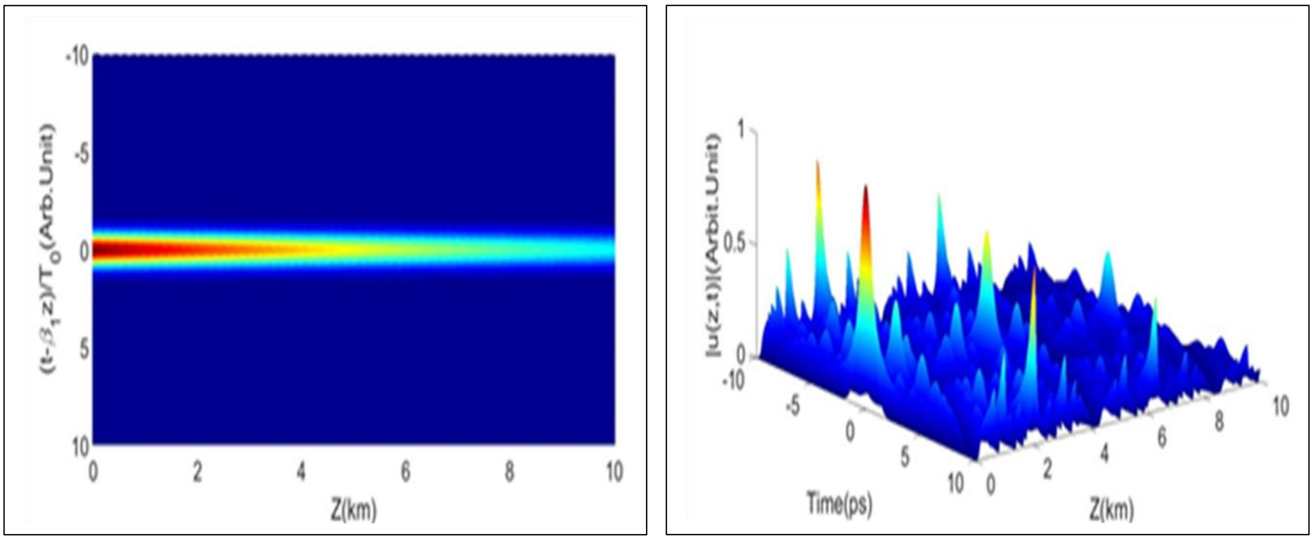

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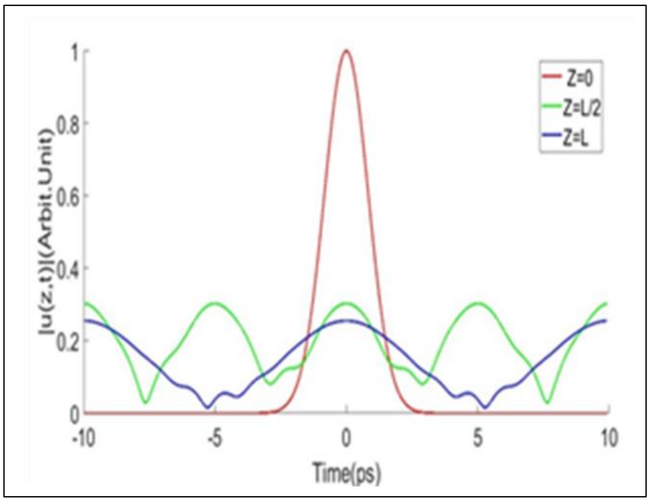
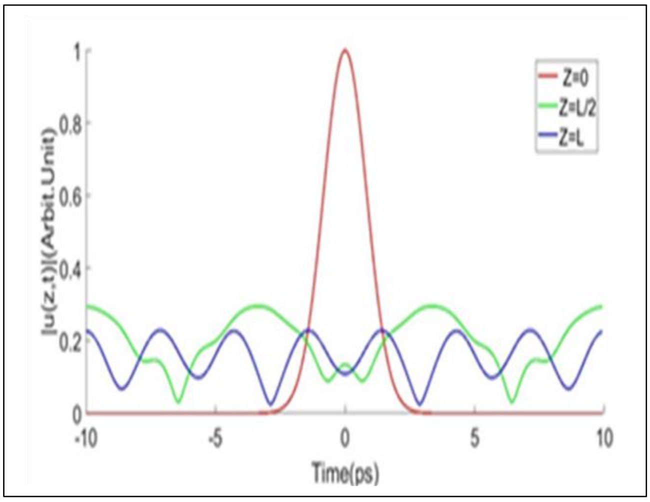


(a)



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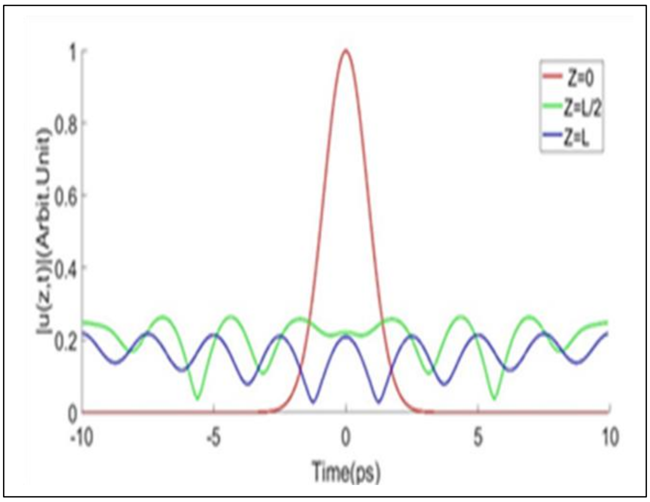
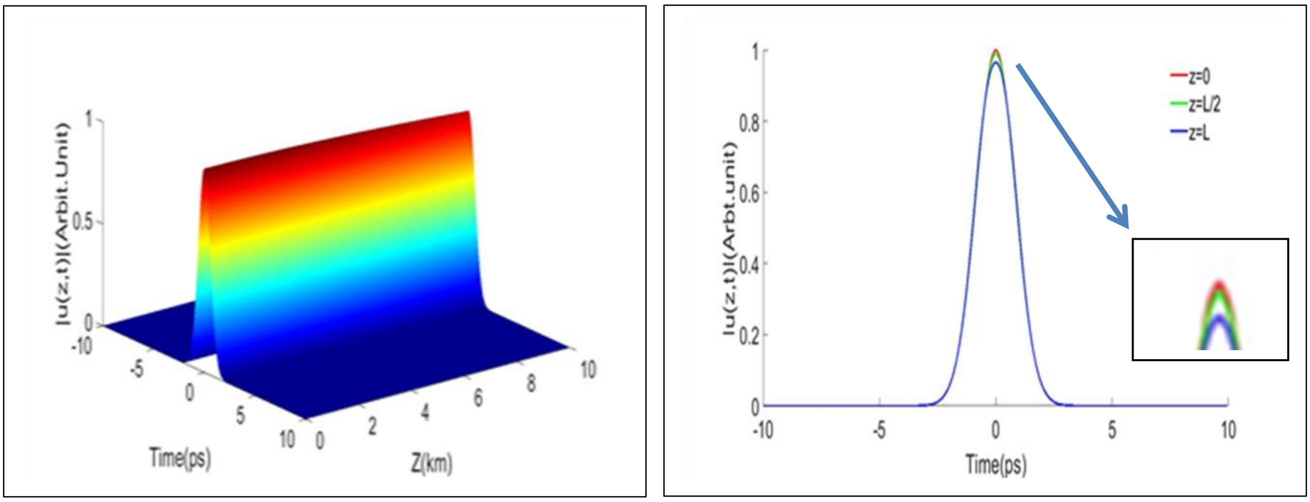


(c)

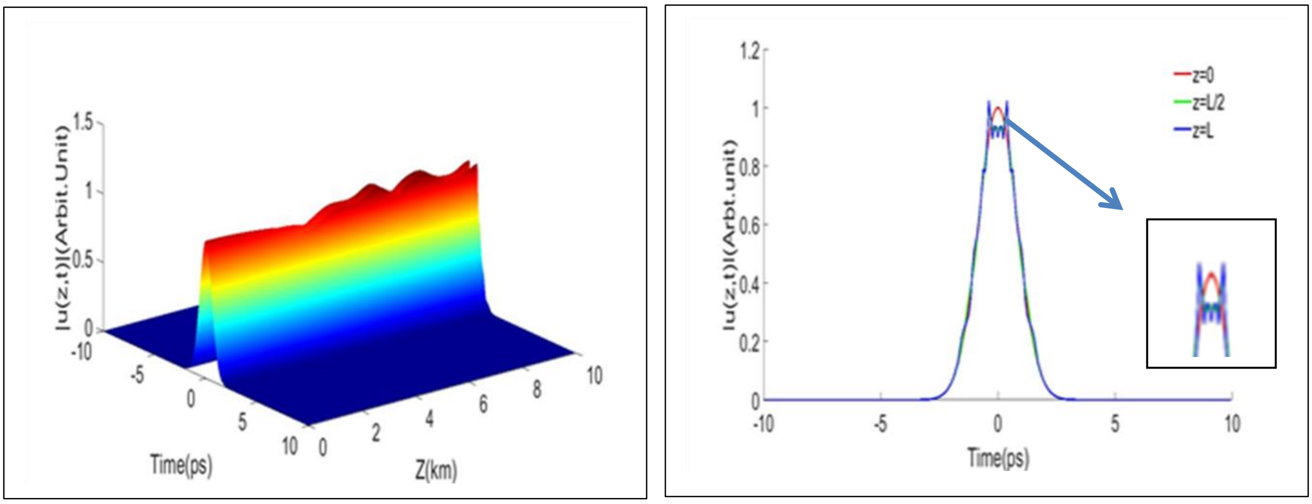
Figure (4.9): Evaluation of the intensity of the Gaussian pulse in the optical fiber with the time for (a) β_2=0.006 (ps^2)/km, (b) β_2=0.06 (ps^2)/km, (c) β_2=0.6 (ps^2)/km. At z=0, z= L/2, z=L.

4.5.3: The effect of γ on the pulse

Now to study effect of the nonlinear effect the attenuation and dispersion will fixed at small values (α=0.000002 dB/km, β_2=0.0000006 (ps^2)/km), and taking different values of γ($\gamma_1 = 0.003W^{-1}km^{-1}$,$\gamma_2 = 0.03W^{-1}km^{-1}$,$\gamma_3 = 0.3W^{-1}km^{-1}$), For $\gamma_1 = 0.003W^{-1}km^{-1}$one can notice that the pulse intensity decreases with the propagation in the fiber, i.e. the dispersion is dominates, see figure (4.10a), when increase nonlinear effect of ($\gamma = 0.03W^{-1}km^{-1}$), the intensity increases with the distance in the fiber comparing with the pulse intensity at the entrance, with appearing of increasing and decreasing in the intensity of a periodic manner, see figure (4.10b), now if the nonlinear effect becomes $\gamma = 0.3W^{-1}km^{-1}$, it is clear that the periodic frequency appears was increased, see figure (4.10c).



(a)



(b)

Figure (4.10) The propagation of the Gaussian pulse in the fiber and picture for change the pulse intensity with distance and time for (a) γ=0.003(W^{-1} km^{-1}), (b) γ=0.03(W^{-1} km^{-1}), (c) γ=0.3(W^{-1} km^{-1}).

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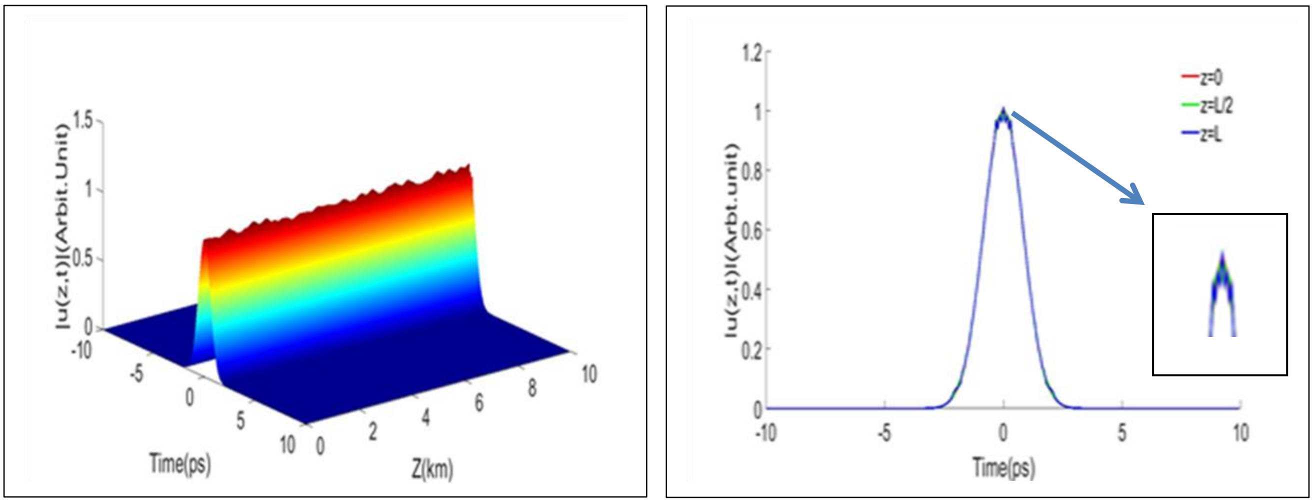

(c)

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CHAPTER FIVE

SOLITONS INTERACTION

Chapter Five

Solitons Interaction

5.1: Introduction

In this chapter the changes that occur when two solitons interact are introduced. What is the effect that the two solitons get in the medium? Will they interact when they meet or will they pass through each other without causing any effect?

Optical solitons can maintain their speed, shape and amplitude as they traverses long distances when used in communication systems based on fibers [10,157]. Solitons with particle-like feature as they collide with each other. As a result of unavoidable dispersion in optical fibers, the optical pulses propagation speeds are not equal with different wavelengths, which can make optical pulses expand in the time domain [158]. Self-phase modulation can generate in fibers, as a result of nonlinear effects that causes phase changes along the front and back edges of optical pulses [159-160]. Since the frequency and speed of propagation at optical pulses back edge are higher than at the front one, pulse width compressed. As pulse broaden balance the pulse compression effects leads to formation of optical solitons which are stable as they propagate [161]. Optical solitons properties that keep constant shape enable them to realize the propagation with ultra-large capacity over ultra-long distances [153].

5.2: Interacting between solitons

To increase the amount of information carried by fiber light pulses should be close to each other. Interactions enhancement could also possibly increase optical capacity of communication networks. As solitons propagate in an optic fiber, they can attract, repel and interact. Likening the interactions to those of molecules, it suggest that the temporal motion of solitons and energy associated with the interactions can lead to new optical effects in new of laser systems classes [162]. Fig (5.1) shows four types of interaction between two solitons viz., collision, attraction / repulsion and trapping/dragging [163].

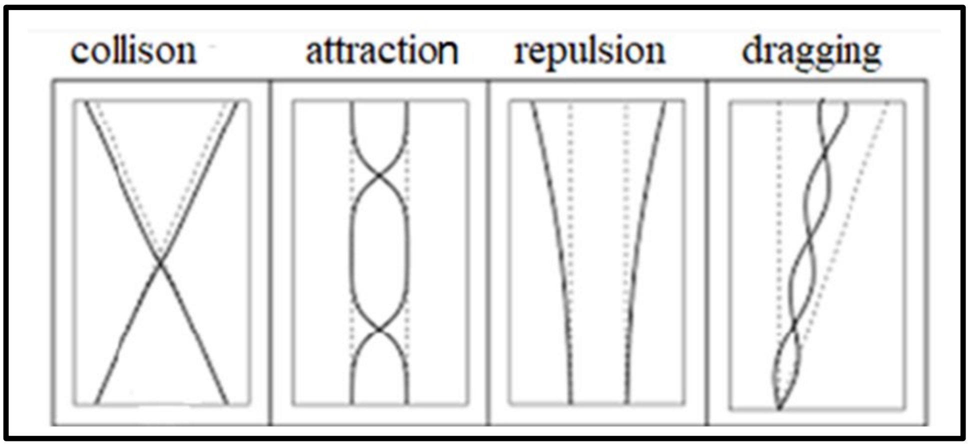


Figure (5.1): The common interaction soliton geometries. Dot lines are soliton paths in the absence of interaction. [153].

In the real world the communications are not perform using just a single pulse, at each time. A train of pulses is constantly propagated through a communication link. In order to propagate a train of solitons, they need to be well sufficiently separated. This means that apart, each soliton occupies only a fraction of the bit slot. However, the interaction between solitons is inevitable. When interaction is symmetric no net change in the propagation angle. When orthogonally-polarized solitons collide angle change result. Same-polarization and in phase solitons will attract each other while those solitons with a relative phase π will repel. Trapping and dragging occurs where two solitons overlap, former being phase-sensitive and the latter phase-insensitive [164]. Suppose the two solitons equation can be written as [10]:

$$u(0,t) = \mathrm{sech}(t - q_\circ) + r\,\mathrm{sech}[r(t + q_\circ)]e^{i\theta} \tag{5.1}$$

Where $q_\circ$ is the initial separation, θ is the relative phase and r is the relative amplitude between the two solitons.

5.3: Theoretical treatment

The propagation of soliton analyzed along a nonlinear medium by solving numerically the NLSE which was explained in section (2.35) for a pulse propagating along a fiber [109]

$$i\frac{\partial A}{\partial z} = -\frac{i\alpha}{2}A + \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \gamma\,|A|^2 A \tag{5.2}$$

Where A is the pulse amplitude, the coefficients α, β_2 and γ are the attenuation, group velocity dispersion and nonlinear effects in the fiber respectively, while $|A|^2$ represent pulse power and z is the direction propagation of pulse. If one suppose ($\alpha = 0$) i.e., no losses in the fiber, so the equation (5.2) becomes [109]

$$i\frac{\partial A}{\partial z} = \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \gamma\, |A|^2\, A \qquad (5.3)$$

And one can normalize equation (5.3) by using the following variables

$$\mathrm{U} = \frac{\mathrm{A}}{\sqrt{\mathrm{P}_\circ}}\ , \xi = \frac{\mathrm{z}}{\mathrm{L_D}}\ , \tau = \frac{\mathrm{T}}{\mathrm{T}_\circ} \qquad (5.4)$$

So that NLSE can be written as:

$$i\frac{\partial U}{\partial \xi} = sgn\ \frac{\beta_2}{2}\frac{\partial^2 A}{\partial t^2} - \mathrm{N}_s^2|U|^2 U \qquad (5.5)$$

Where $sgn\ \beta_2 = \pm 1$ depend upon the GVD signal, N_s, represents the order of soliton given by:

$$N_s^2 = \frac{L_D}{L_{NL}} \qquad (5.6)$$

Where (L_D) is the dispersion length, and (L_{NL}) is the nonlinear length are given by:

$$L_{NL} = \frac{1}{\gamma P_\circ} \qquad (5.7)$$

$$L_D = \frac{T_\circ^2}{|\beta_2|} \qquad (5.8)$$

Equations (5.7) and (5.8) lead to:

$$N_s^2 = \frac{\gamma P_\circ}{|\beta_2|}T_\circ^2 \qquad (5.9)$$

For the anomalous system ($\beta_2 < 0$) and let $u = N_s U$ (5.5) becomes

$$i\frac{\partial u}{\partial \xi} = \frac{1}{2}\frac{\partial^2 u}{\partial t^2}\ |u|^2 u \qquad (5.10)$$

Depending on pulse power ($P_\circ$) and width ($T_\circ$), pulse propagating along the fiber can be governed by group velocity dispersion effect or nonlinear effect. The behavior of the pulse can be divided in to following cases [153]:

1-For $(L_D) > (L_{NL})$

Nonlinear effects are neglected since it effects are very small compare to the dispersion effect, i.e., dispersion effects are dominant along fiber.

2- For $(L_D) < (L_{NL})$

Dispersion effects are neglected so that nonlinear effects are dominated along the fiber.

3- For dispersion length (L_D) = nonlinear length (L_{NL})

Nonlinear effects and dispersion effects have no effects on pulse propagation, so that pulse have the same shape along the fiber and called soliton.

N is independent of β_2 but the pulse propagating depend strongly on (GVD). For the normal dispersion case the pulse broadening, while in the anomalous dispersion case don't has broadening viz., the pulse has the same shape along the fiber.

5.4: Factors affecting the interaction between the solitons

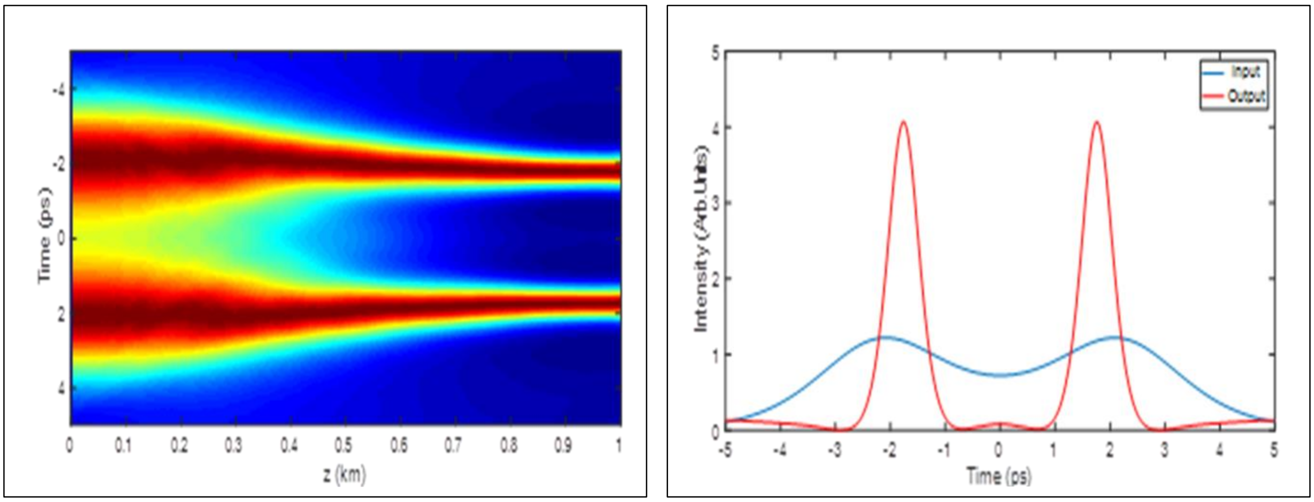
There exist number of parameters that might affect on the interaction between solitons so that affect the interaction mechanism are studied in details as follows:

5.4.1: The effect of pulse power, (p_o).

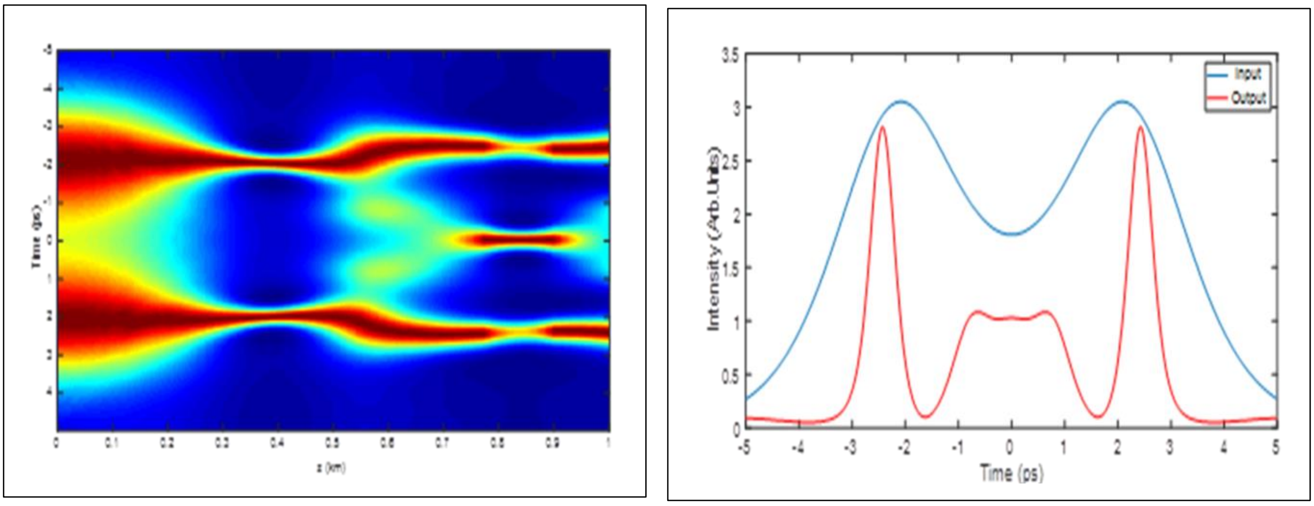
To figure out the effect of pulse power all parameters were set constants as shown in table (5.1) while the powers of the pulse were varied in the range (0.5-3.5) Watt. It is noticed that interaction condition is satisfied with the increase of power. When the power equals 0.5Watt and less each pulse make its own soliton. For power of 2.5 Watt and more, the interaction between the two waves become so clear that one can conclude that the single soliton might change into number of solitons as power increased in short distance compare to the low power. It is noted too that the soliton bifurcate into number of solitons as power increase and in a short time and it is noted that as the power increased that the height of the input curve becomes higher than the output power, as shown in Fig (5.2).

Table (5.1): Parameters for solitons interaction

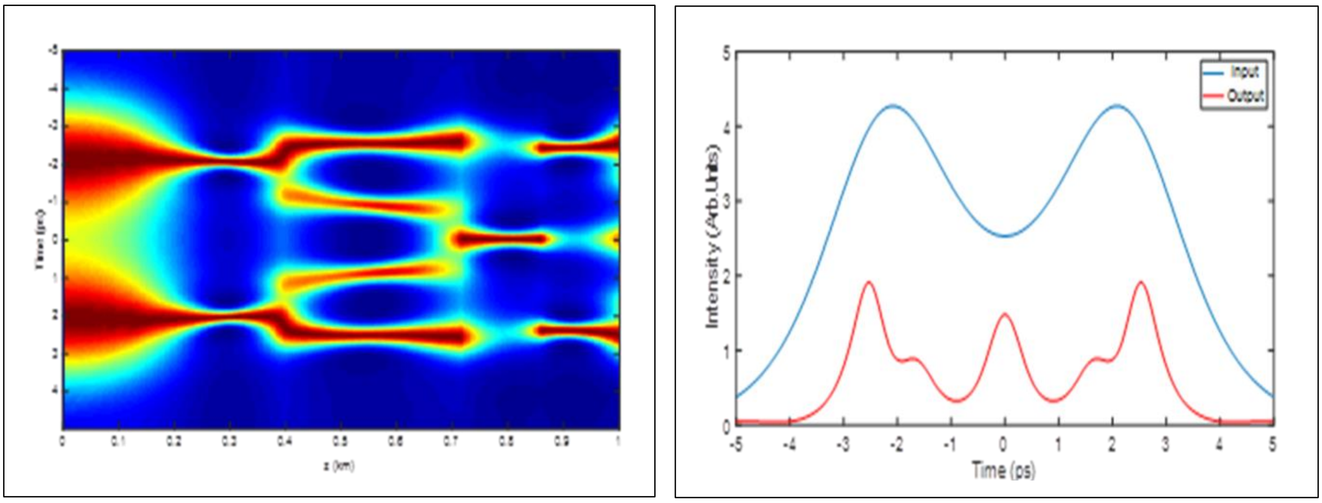
Parameter	Value
N_p	512
T_O	1.5 ps
γ	3 $W^{-1}km^{-1}$
β_2	-2.5 $\frac{ps^2}{km}$
L	1km



(a)



(b)



(c)

Figure (5.2): Shows the interaction between two solitons to form a single soliton after a time of 1.5 ps for two pulses

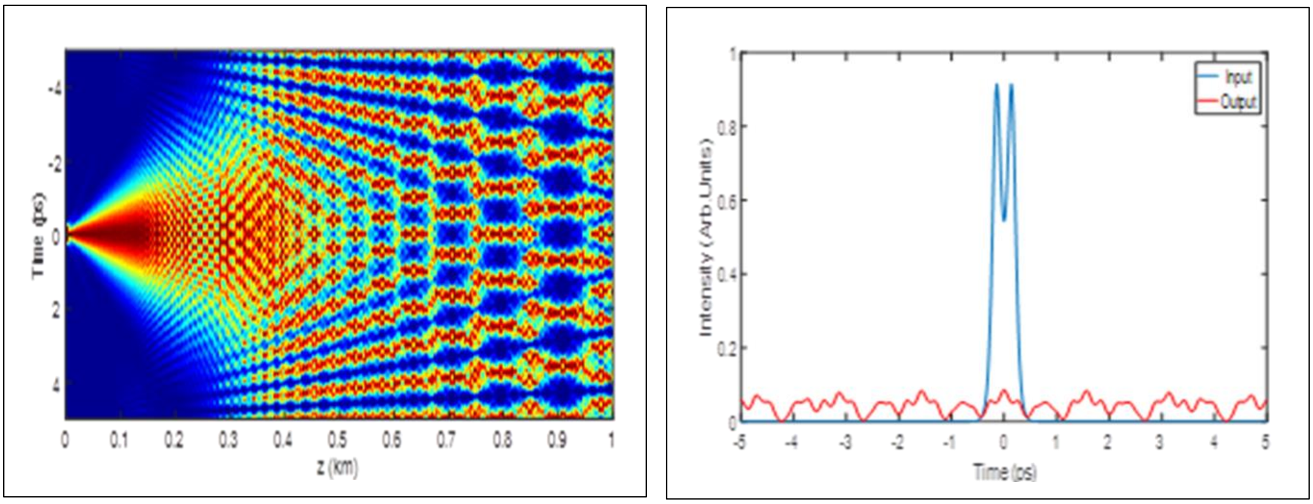
(a) P_o=1W, (b) P_o=2.5 W, (c) P_o=3.5W.

5.4.2: The effect of pulse temporal width, (T_o).

To study the effect of time variation on the interaction among solitons, all parameters are kept constant, as shown in table (5.2) and varying the time in the range (0.1-1.5) ps , where it can be seen that the pulse broadened because of the dispersion parameter in the entrance of the fiber, then changes to a structure of intensities progress with time as the pulse propagate down the fiber. Fig (5.3a) shows that the behavior while at other region both pulse interact to make a single soliton of the first degree then evolved to a soliton of the third degree as shown in Fig(5.3b, 5.3c),as the pulse continue propagating down the fiber. While when pulse temporal width increased the two pulses make single soliton too and the distance covered by the soliton inside the fiber required for the interaction will increased as the two pulse temporal width increased. Also as the time becomes high of the order of 1.5 ps no interaction between the soliton occur i.e both solitons continue propagating separated, the input pulse curve will decrease gradually in comparison with output pulse curve, as shown in Fig (5.3d, 5.3e, 5.3f).

Table (5.2): Parameters for solitons interaction

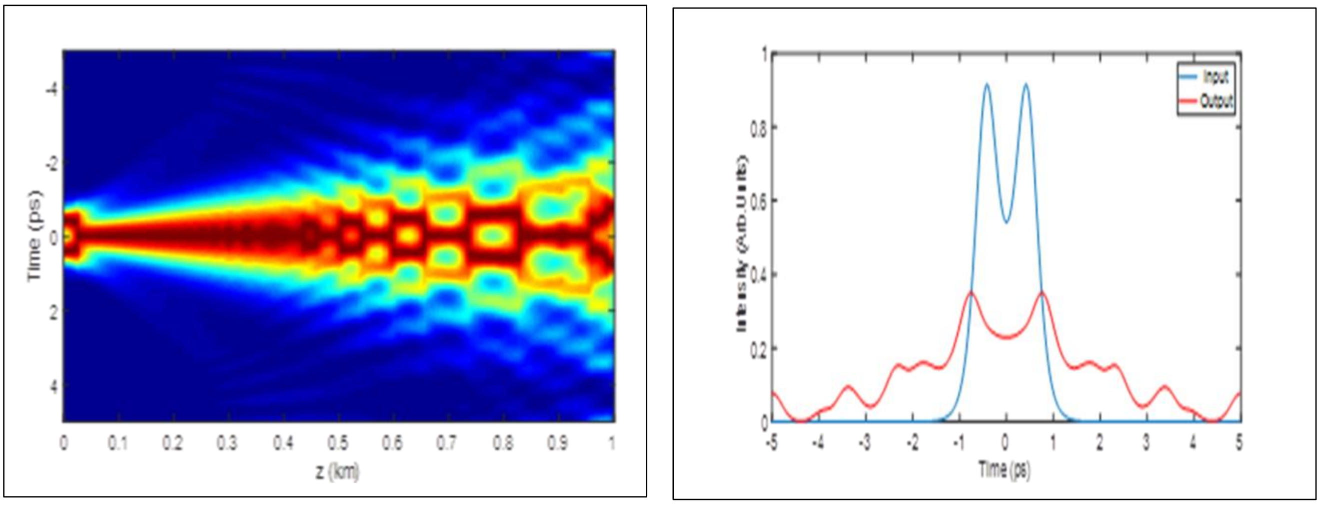
Parameter	Value
N_p	512
P_O	0.75W
γ	$3\ W^{-1}km^{-1}$
β_2	$-2.5\ \frac{ps^2}{km}$
L	1km



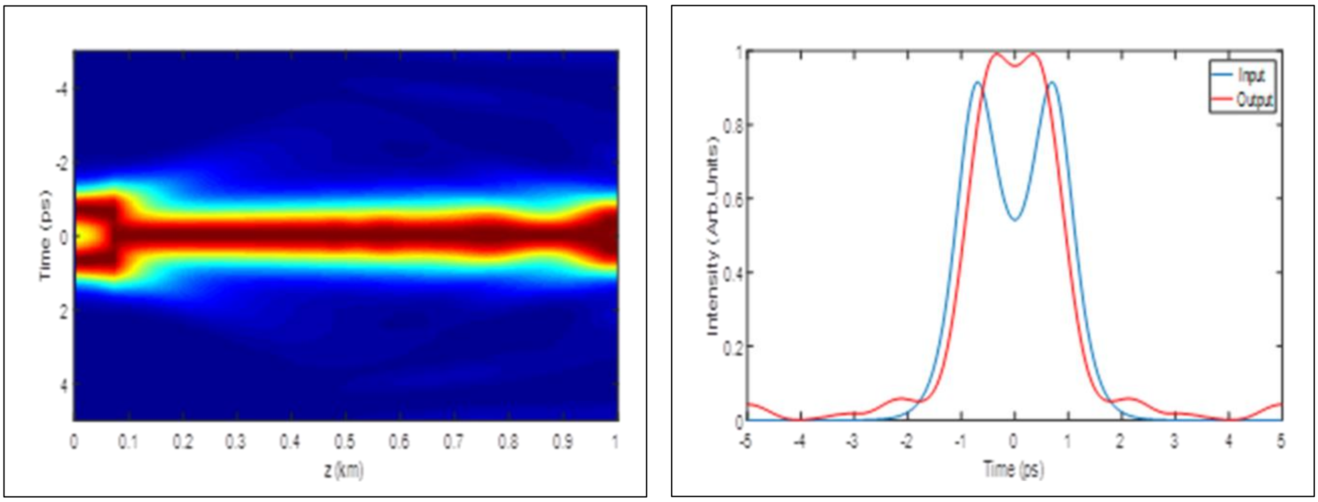
(a)

Figure (5.3): Shown the interaction between two solitons to form a single soliton in the power P_o=0.75W for two pulses in the time: (a) T_0=0.1ps, (b)T_O=0.3ps, (c)T_O=0.5ps , (d)T_O=0.8ps , (e)T_O=1.2ps, (f)T_O=1.5ps.

Continue



(b)



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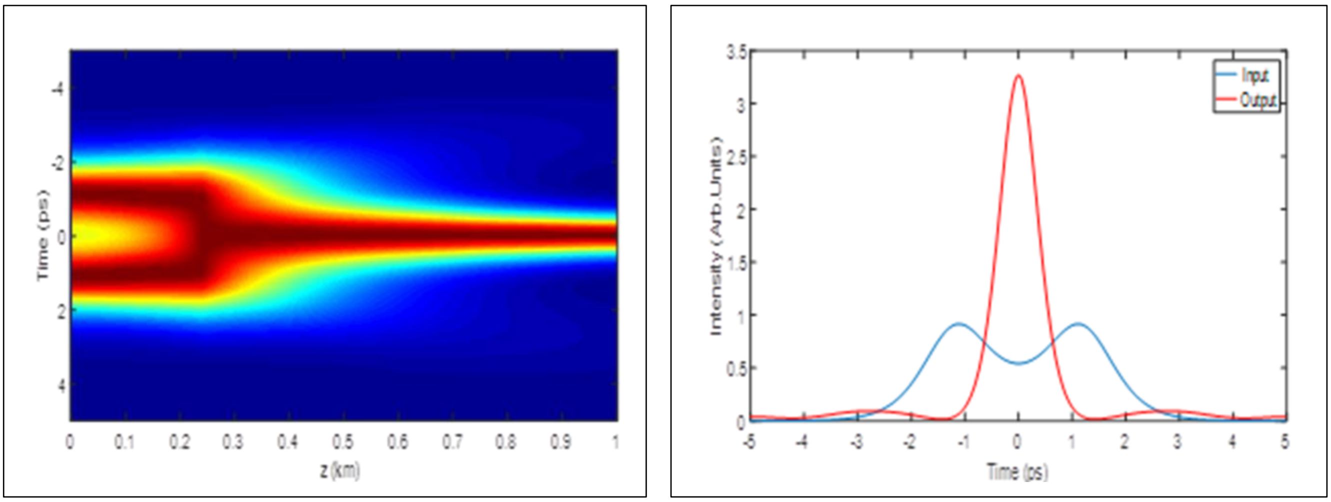

(d)

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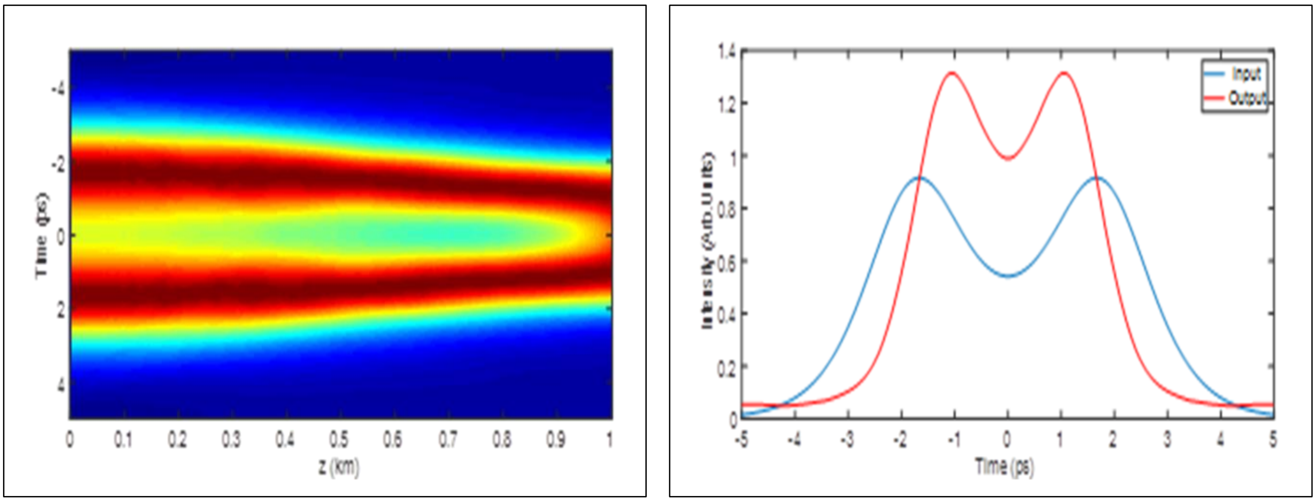
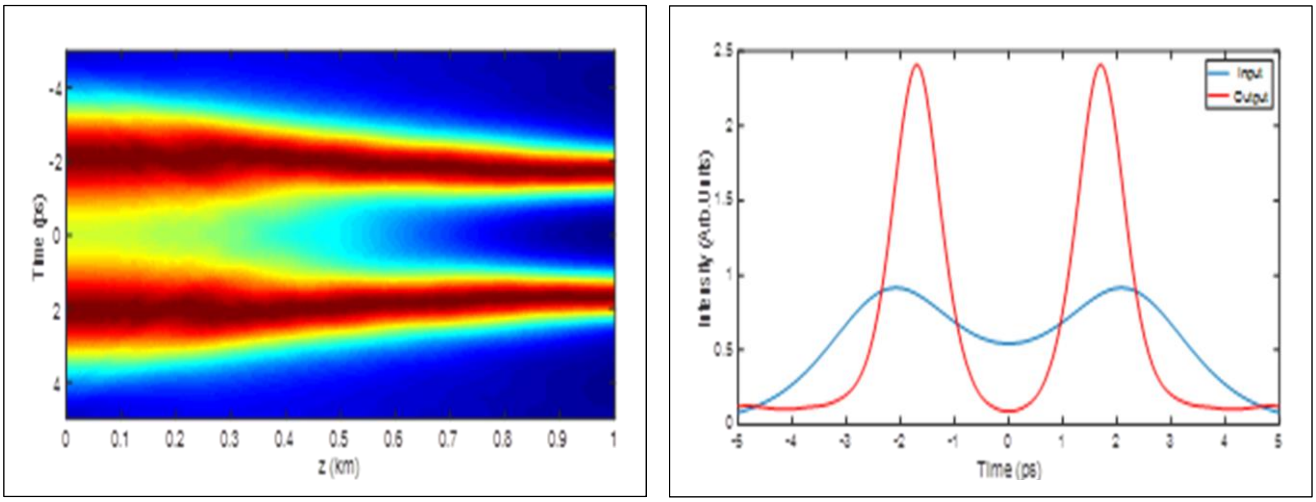


(e)



(f)

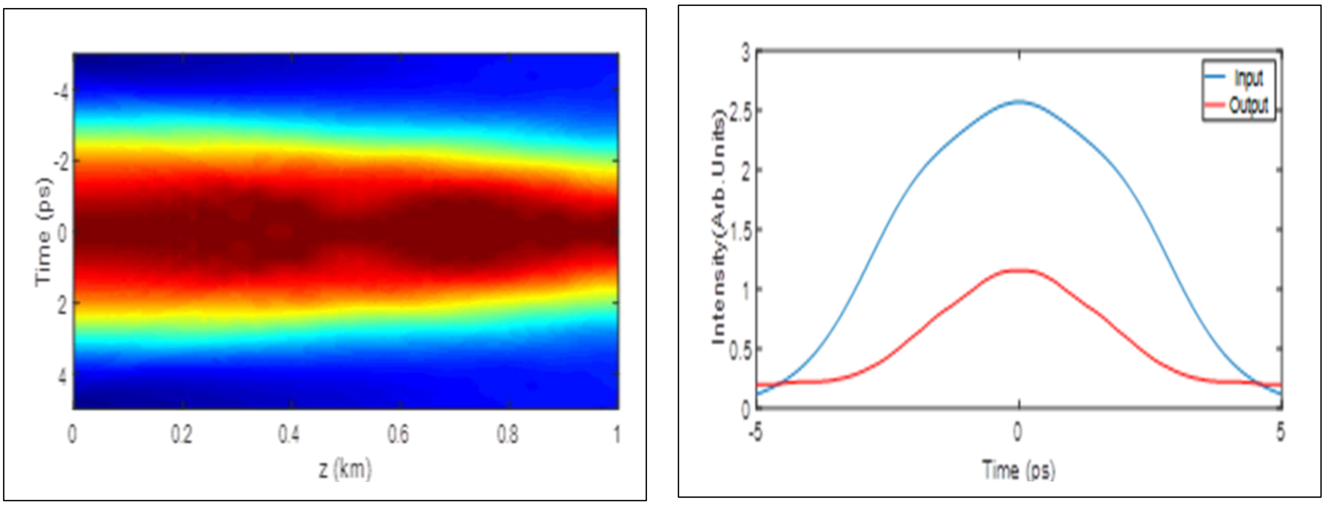
Continued

5.4.3**:** The effect of nonlinearity on the interaction between solitons, (γ).

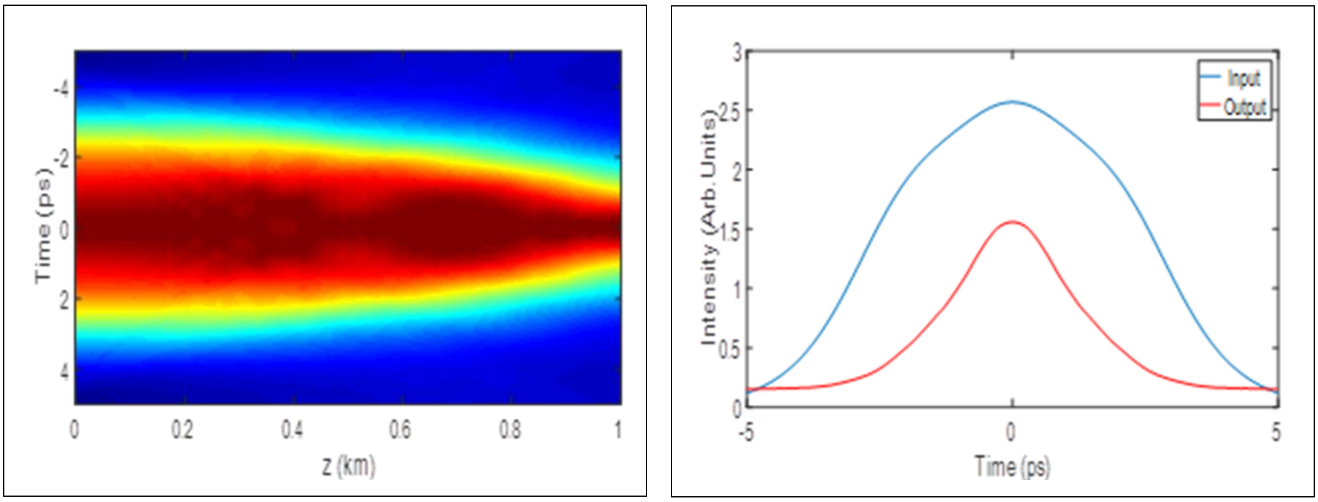
To study the effect of nonlinearity on soliton interaction inside the fiber all parameters are kept constant as shown in table (5.3), while varying the nonlinear effect (γ) value. It is noted that the distance required for the interaction inside the fiber to occur will be large relatively for low nonlinearity effect as shown in Fig (5.4a, 5.4b). As the nonlinearity effects increased the interaction among solitons will occur in short distance and fast in time as it is shown in Fig (5.4c-5.4h). The effect of dispersion on interaction where the interaction results in multiple solitons, the output pulse curve shows dispersion as a result of the nonlinear effects.

Table (5.3): Parameters for solitons interaction

Parameter	Value
N_p	512
P_O	0.75W
T_O	1.5 ps
β_2	-2.5 $\frac{ps^2}{km}$
L	1km



(a)

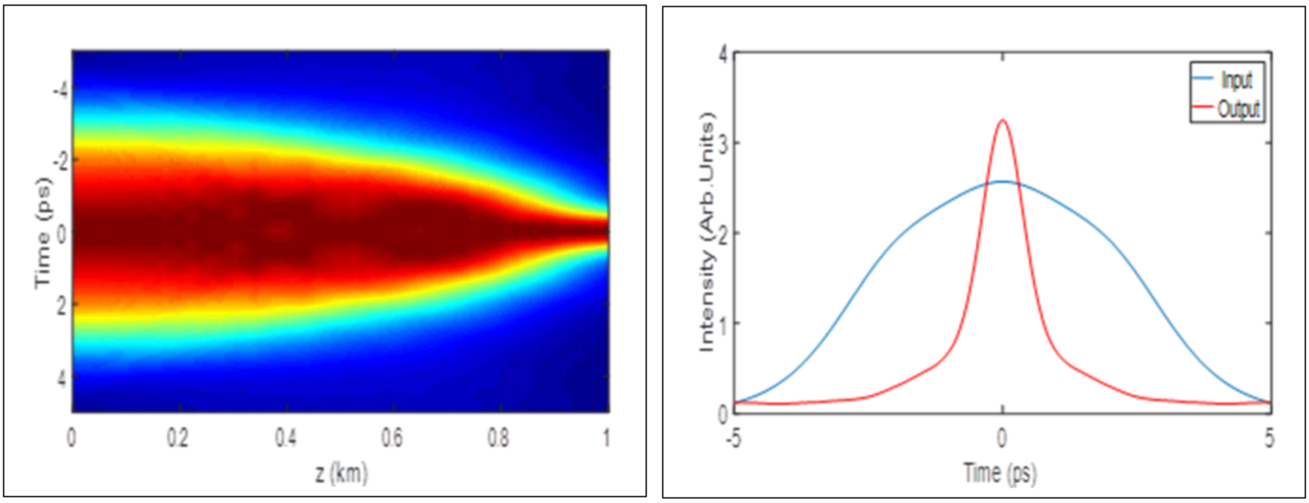


(b)

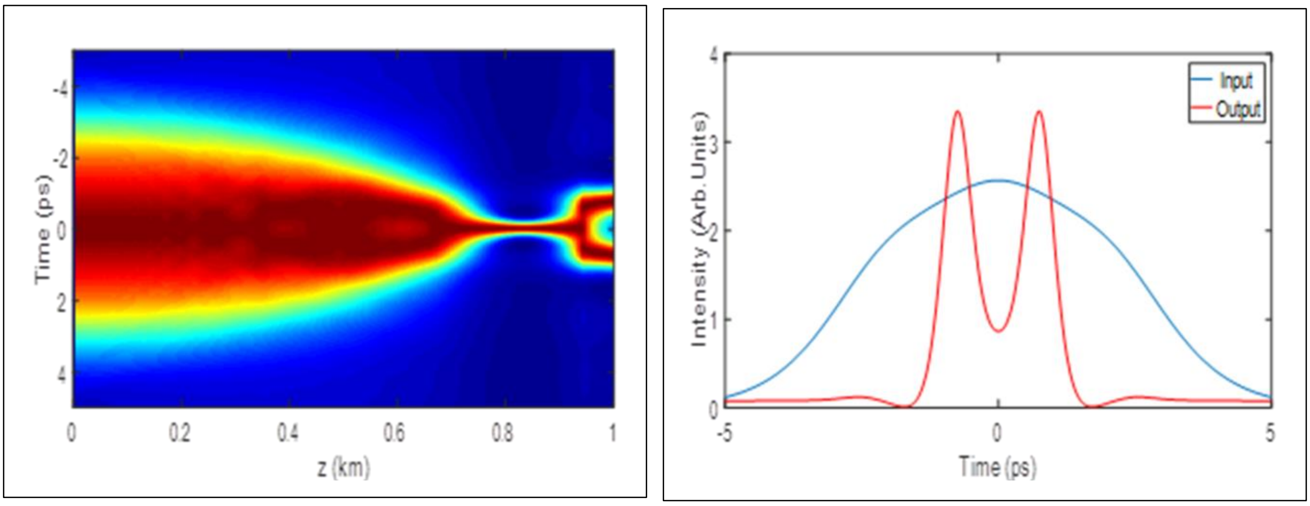
Figure (5.4): Shown the interaction between two solitons to form a single soliton after a time of 1.5 ps and power 0.75 W for two pulses, when γ ($W^{-1}km^{-1}$)

(a)γ =0.1, (b) γ =0.5, (c) γ =1, (d) γ =2, (e) γ =4, (f) γ =6, (g) γ =8, (h) γ =10.

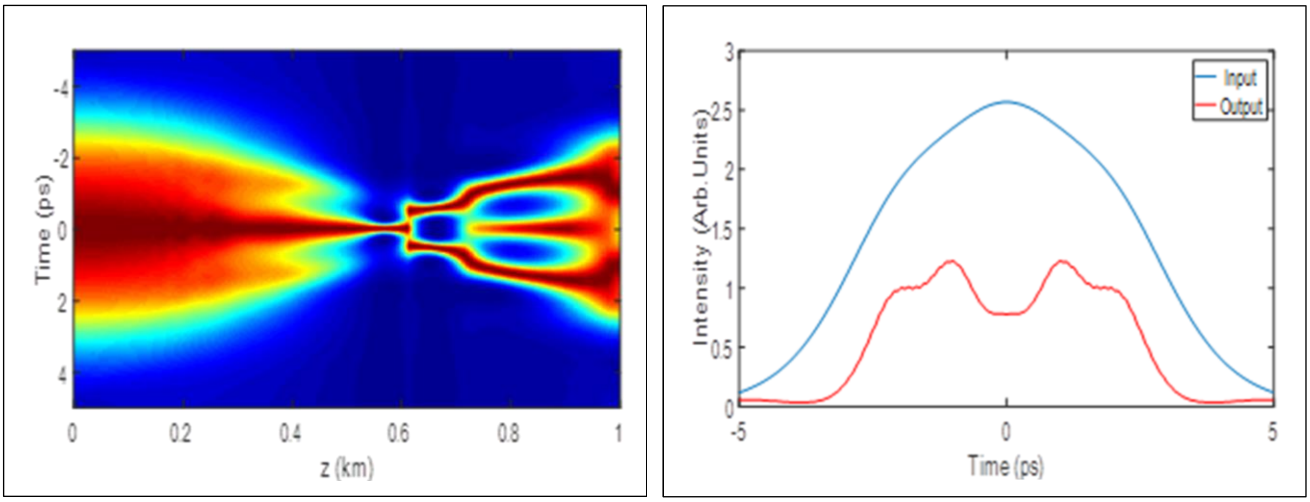
Continue



(c)



(d)



(e)

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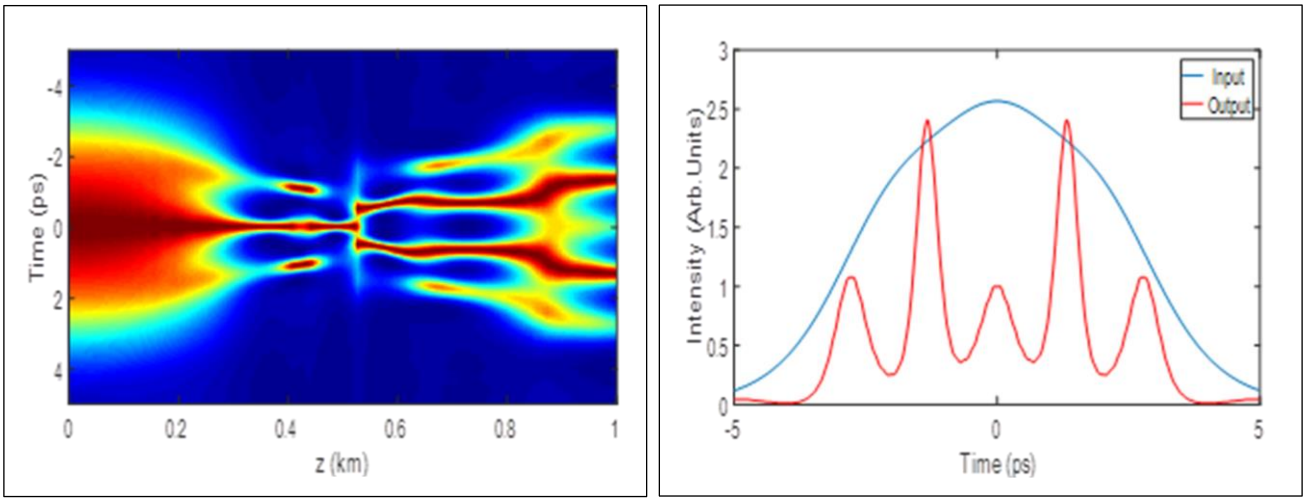
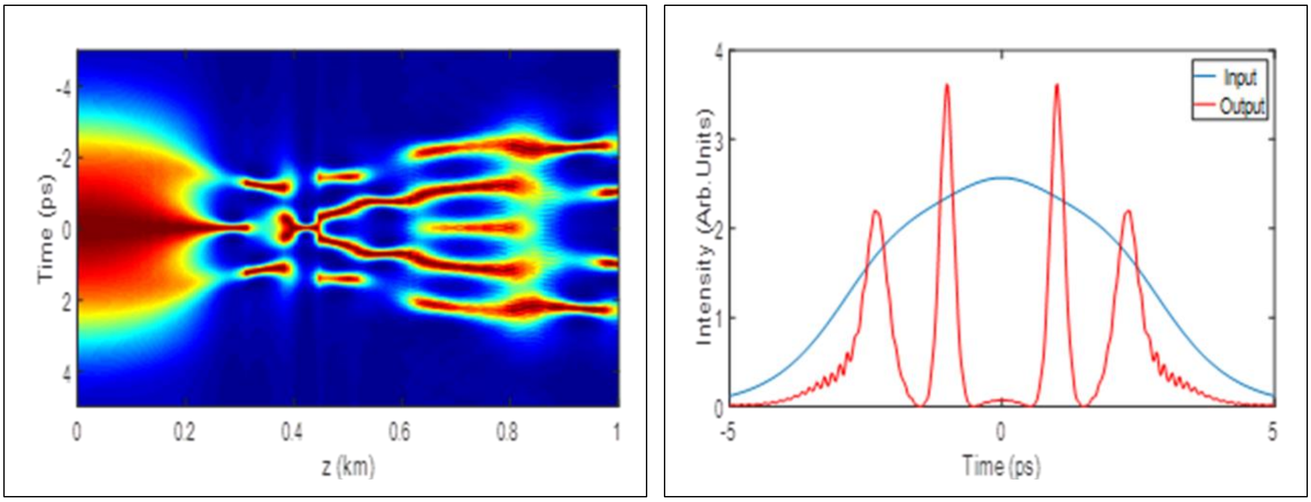
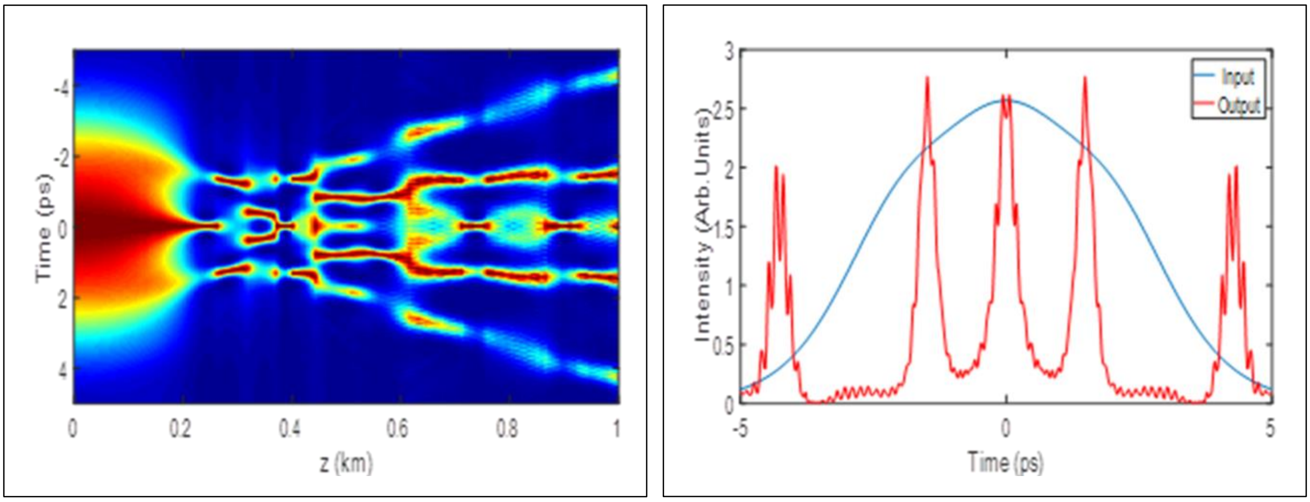


(f)



(g)



(h)

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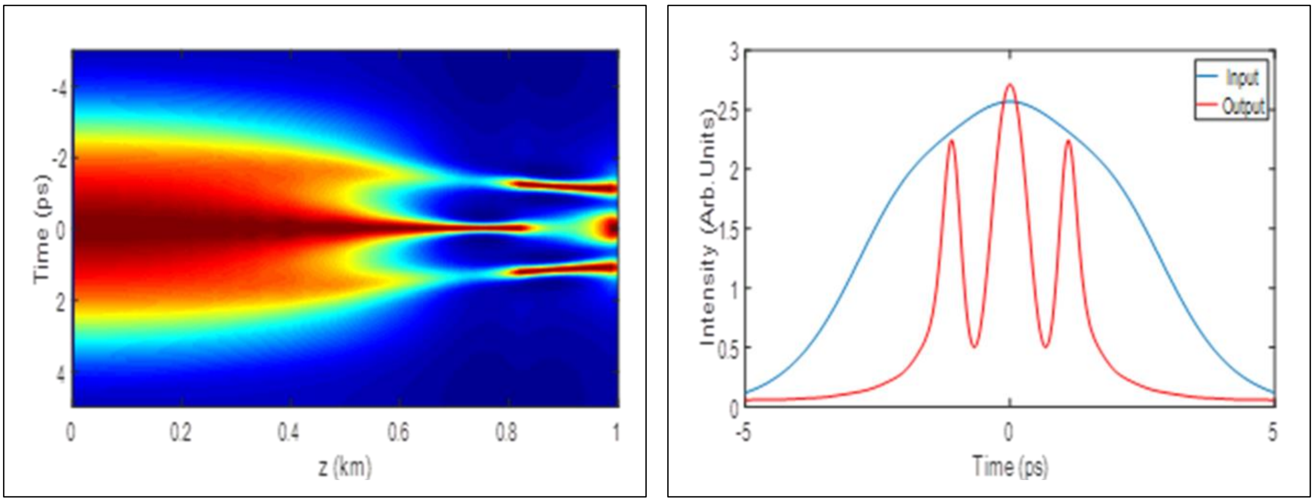
5.4.4: Dispersion effect on the solitons interaction, (β_2).

To study the effect of dispersion on solitons interaction inside fiber all parameters were kept constant as shown in table (5.4), and varying the parameter, $\beta_{2,}$ in the range (-1) $\frac{ps^2}{km}$ to (-5) $\frac{ps^2}{km}$. It can be seen that no effect is seen to occur for low β_2 value; a dispersion to the solitons occurs as shown in Fig (5.5a) followed by dispersion processes. The difference between input and output pulses curve increased with the increase of β_2 as can be seen in the other Figures (5.5b) and (5.5c).

Table (5.4): Parameters for solitons interaction

Parameter	Value
N_p	512
P_O	0.75W
T_O	1.5 ps
γ	3 $W^{-1}km^{-1}$
L	1km

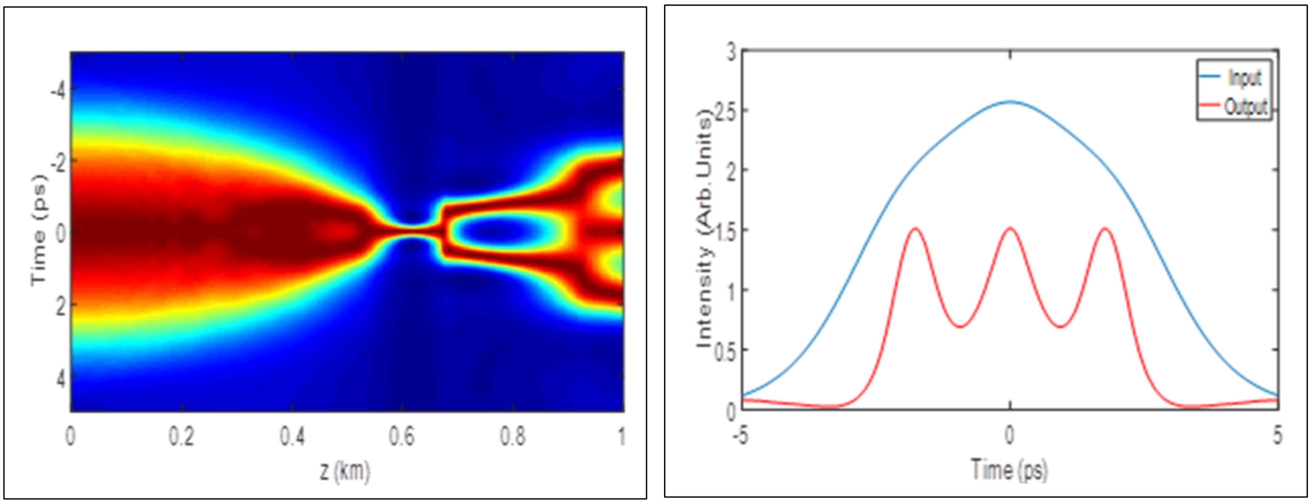


(a)

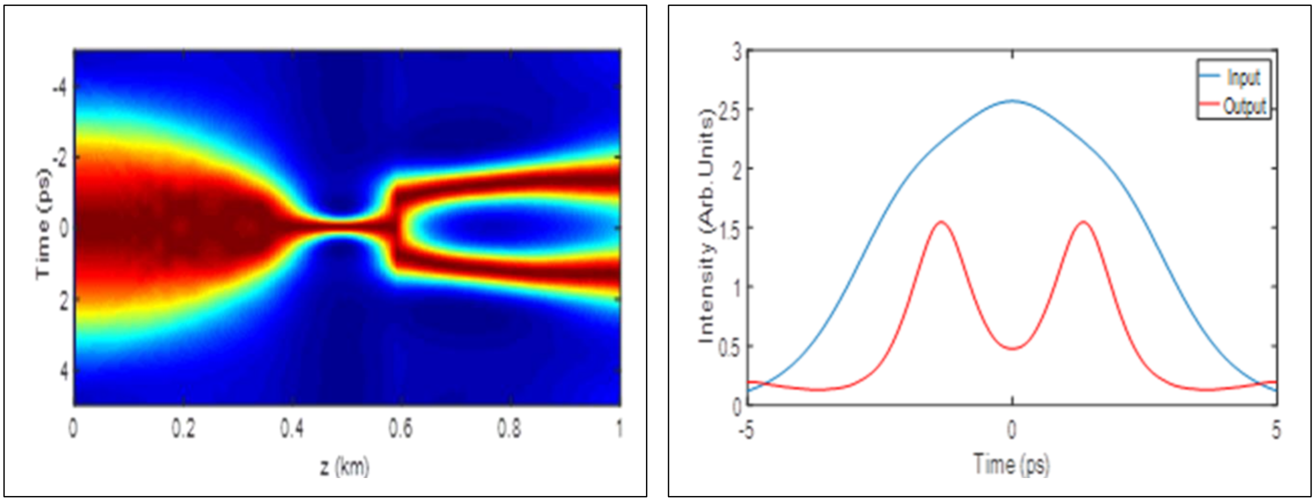
Figure (5.5): Shown the interaction between two solitons to form a single soliton after atime of 1.5 ps and power 0.75 W for two pulses when beta

(a) β_2=-1$\frac{ps^2}{km}$, (b) β_2=-3 $\frac{ps^2}{km}$, (c) β_2=-5 $\frac{ps^2}{km}$.

Continue



(b)



(c)

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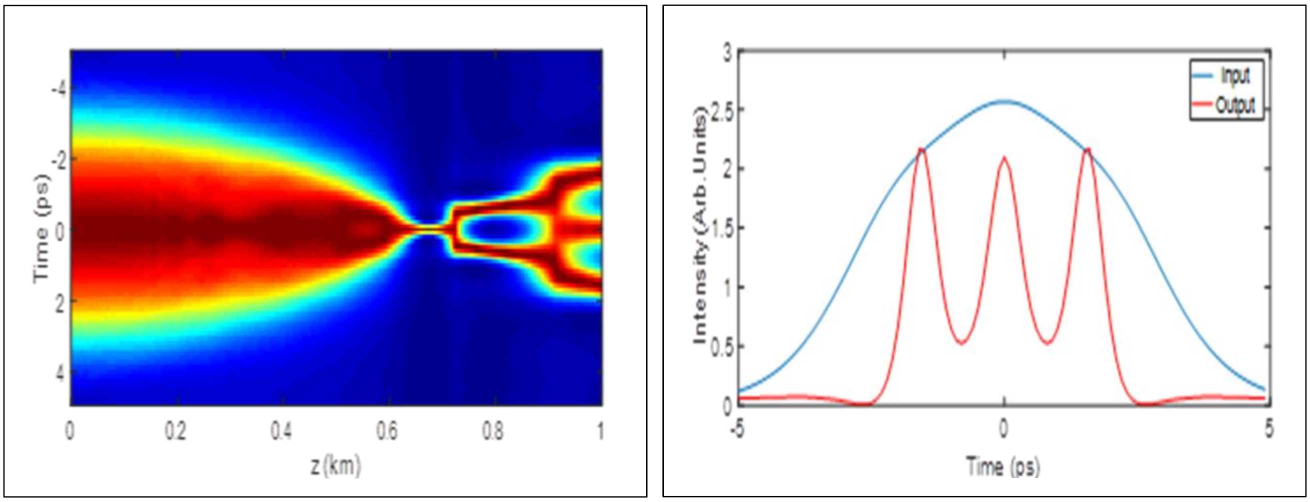
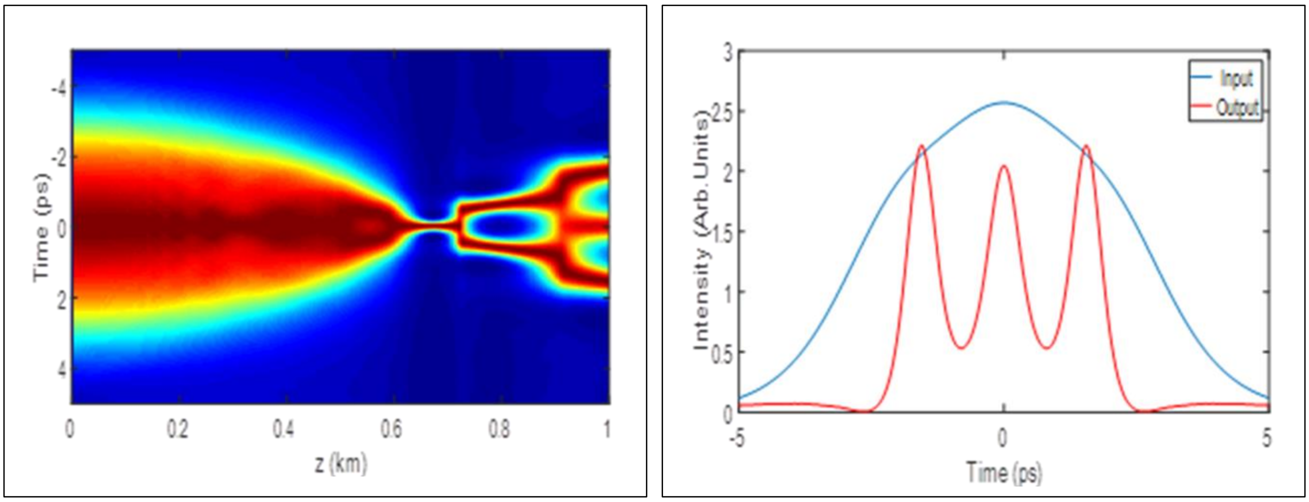
5.4.5: Degree or order effect on the solitons interaction, (N_s).

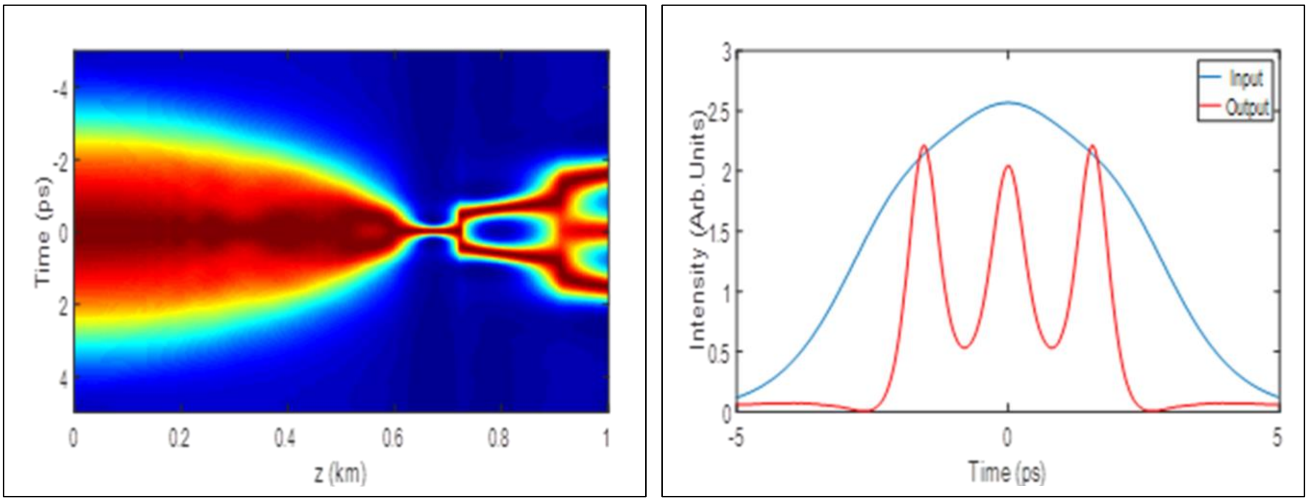
By the variation of soliton degree, N_s, and keeping the rest parameters values constant it appears that it has no effect on the interaction process between solitons in the range used (100-2000) m, it has result that is shown in the Fig (5.6).



(a)



(b)



(c)

Figure (5.6): shown the interaction between two solitons to form a single soliton after a time of 1.5 ps and power 0.75 W for two pulses, when the order soliton

(a) N_s=100 , (b) N_s=350 , (c)N_s=900

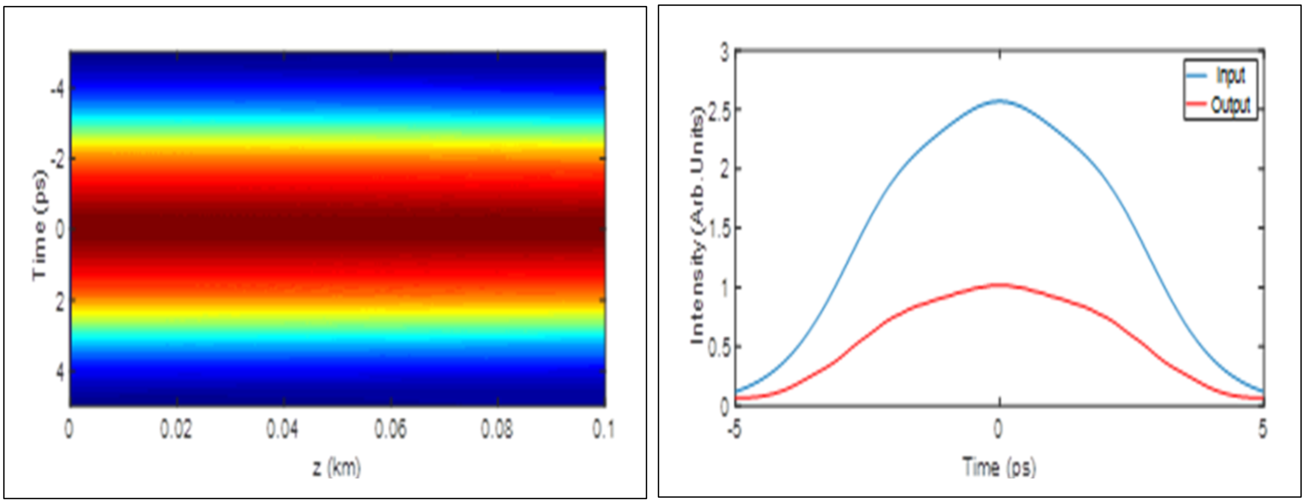
Continued

5.5: Choice of suitable Fiber length at the solitons interaction, L.

To choose the appropriate fiber length the following must be done Fixing all parameters values as shown in table (5.5) and varying the fiber length, it appears that the fiber length is of valuable importance for the interaction process as the case with other parameters. As the fiber length increased the probability of interaction is feasible where soliton can propagate as single ones for long distance. But for a certain fiber length the interaction process can occur as a certain point of the fiber with the effect of other parameters for the interaction to occur. It is also noticed that the input pulse curve is higher than the output pulse at certain points as shown in Fig (5.7).

Table (5.5): Parameters for solitons interaction

Parameter	Value
N_p	512
P_O	0.75W
T_O	1.5 ps
γ	$3\ W^{-1}km^{-1}$
β_2	$-2.5\ \frac{ps^2}{km}$

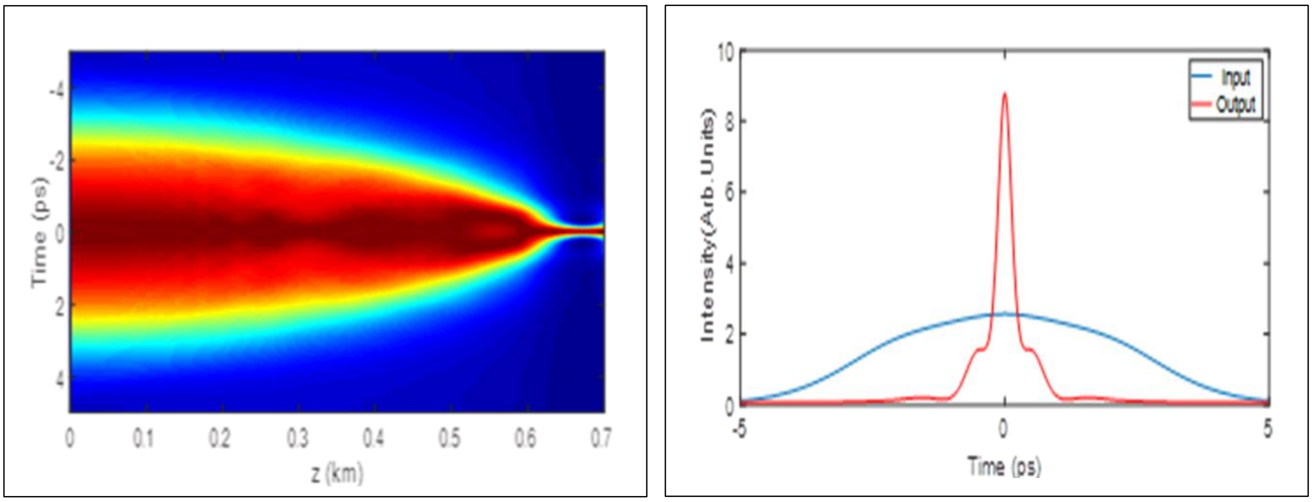


(a)

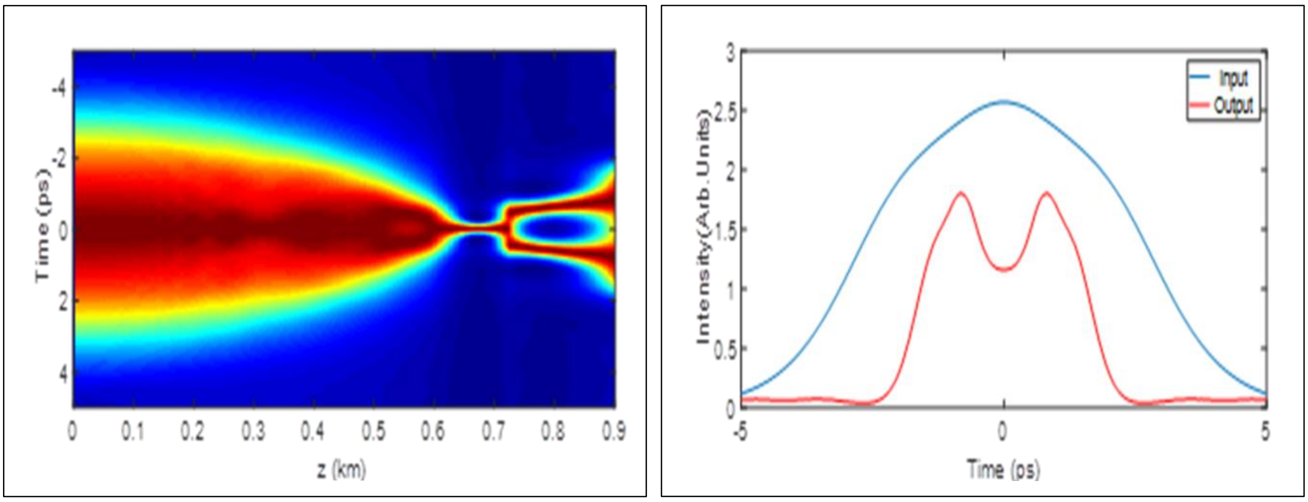
Figure (5.7): Shown the interaction between two solitons to form a single soliton after a time of 1.5 ps and power 0.75 W for two pulses, when fiber length :

(a) L=0.1km, (b) L=0.7km, (c) L=0.9km, (d) L=1km.

Continue



(b)



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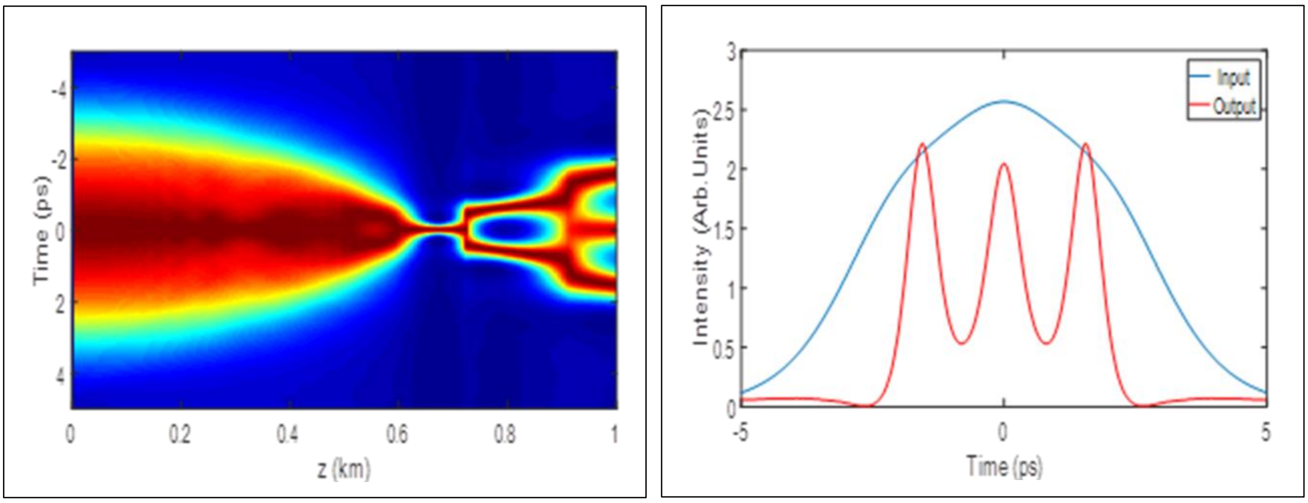

(d)

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CHAPTER SIX

SUPERCONTINUUM GENERATION

Chapter Six

Supercontinuum generation

6.1: Introduction

When narrow-band and short laser pulses enter an optical nonlinear medium, they might suffer very large spectral broadening so that they convert into a continuous broadband spectrally output, such a process is called generation of supercontinuum (SCG). For the generating of supercontinuin photonic crystal fibers (PCFs) is favored. The flexibility in design of dispersion characteristics high nonlinearity enhanced interest in SCG research, both theoretically and experimentally [165]. SCG is the generation of continuous broad spectra during propagation of high power short pulses in nonlinear media [166]. The nonlinear effects responsible for the SCG are four-wave mixing, solitons [45], stimulated Raman scattering [43], self-phase modulation [46], etc. Supercontinuum light broad as a lamp, bright as a laser. As ordinary light is not spatially coherent, coupling it into a fiber is real problem leading to low- power, low-brightness source with reasonable beam quality. SC spectra are generated using femto-second pumping or pulses in the pico-second in PCF of highly nonlinear and in the regime of anomalous group velocity dispersion (GVD) in a fiber. For optical communications the SC light-wave should possess low noise and high stability. To reduce increase stability and noise, SC might be generated in the normal GVD regime where spectral broadening is mainly dominated through four wave mixing, cross phase modulation, Raman scattering and self-phase modulation [167,168]. Most SC experiments lead to an output in the mW-range [169]. PCFs are ideal media for SCG since dispersion can be tailored to make continuum generation possible in a specific region.

6.2: The physics of supercontinuum generation

Inducing a broadband electronic polarization is the physics behind SCG in a dielectric medium via the use of an intense light pulse obtained from a laser with high power. Highest peak powers are usually associated in laser with the short pulse in the pico and femto regime so that, SCG resulted with pulsed pumping. Although this is not necessary, this isn’t so intense continuous laser sources might be used [170].

6.2.1: Supercontinuum and Solitons

To explain SCG based on self-phase modulation is an over-simplification. The physics of the SC arises from interaction among SPM and linear dispersion. Soliton physics are essential in obtaining the true physical picture of SC. Most known optical soliton is invariant fundamental soliton, another class soliton of higher-order, soliton of higher order undergoes a process called as soliton fission. The perturbations that might leads to higher-order soliton breakup lead to ejected fundamental solitons. For each ejected soliton, higher-order dispersion leads to a resonant transfer of energy to shorter wavelengths while Raman scattering leads to a continuous shift self-frequency to longer wavelengths [37].

6.2.2: Soliton fission

The first experiments on the generation of SC in fibers injected with high-power pulses in the spectral visible region into were conducted in silica-based optical fiber with zero GVD at wave-length around 1.3μm. In particular, Lin and Stolen [69], using visible kW peak power nanosecond pulses to generate a SC covering a range of 200 THz on long-wavelength side. Observed broadening was due to stimulated Raman scattering and SPM. These experiments make it clear the importance of the mutual interaction between Raman scattering and SPM, and role of cross-phase modulation (XPM) and variety of four-wave-mixing processes. Many experiments on fission soliton were performed by Schütz [171], Beaud et al., [172], Islam et al., 1989 [173], 1989 [174] and Gouveia-Neto et al., 1988[175]. Such experiments prove that soliton fission can leads to an equivalent form of SCG, allowing broadband spectral over the wavelength range of telecommunications. Numerical simulations make it clear that the SCG occur in three phases:

1- Fission at distinct fundamental soliton components.

2 - Propagation of these solitons.

3 - Spectral broadening and temporal compression.

This first phase associated with longer wavelengths continuous shift via., Raman soliton self-frequency shift and generation of dispersive waves on the short-wavelength side.

6.2.3: Modulation instability

Modulation instability (MI) is a nonlinear phenomenon in which a weak perturbation of a continuous wave (CW) grows exponentially as a result of the interplay between dispersion and nonlinearity. It can also be interpreted in terms of a phase matched four-wave mixing (FWM) process. Basically, a negative linear phase mismatch value must exist to compensate for the positive nonlinear one. MI, leads to the breakup of a continuous wave (CW) or quasi-continuous wave fields, which becomes a train of fundamental solitons. It is important to stress that the solitons generated in this regime are fundamental, as several papers on CW and quasi-CW supercontinuum formation have accredited short wavelength generation to soliton fission and dispersive wave generation as described above [176].

6.3: Applications for supercontinuum generation

Main applications will be review in this section of spectral broadening effect and SC generation in optical fiber communications.

1:Time-division multiplexing(TDM)-to-wavelength-division multiple-xing WDM-to- time-division multiplexing (TDM) conversion

It is possible to combine low-speed data channels into a single high-speed optical telecom line, multiplexing in wavelength and in time there are two approaches.

2: All-optical analogue-to-digital conversion

All-optical analogue-to-digital conversion, signal processing and switching important technologies which might open new technologies in data transmission in ultra-high-speed through overcome bit rate limits.

3: Pulse train generation at high repetition rates

Ultra-short pulse train of high repetition rate can be produced. The effect of induced instability is utilized modulation, i.e. growth of small intensity modulation amplitude of CW radiation as a result of modulation instability (MI).

4: Multi-wavelength optical sources

One of the most important applications of SC to the field of telecommunications is the design of multi-wavelength sources is an important for ultra-broadband WDM.

5: Pulse compression and short pulse generation

The foundation of optical telecom systems is based on ultra-short optical pulses. Where transmitted information along telecom lines are encoded using amplitude and phase of such pulses.

6.4: Numerical method

To investigate the SCG along a fiber with properties that was described before the optical pulse propagation along this fiber is modeled via modified general nonlinear Schrödinger equation (GNLSE) [177]:

$$\frac{\partial}{\partial z}A(z,T) = -\frac{\alpha(\omega)}{2}A(z,T) + \sum_{n\geq 2}\beta_n \frac{i^{n+1}}{n!}\frac{\partial^n}{\partial t^n}A(z,T) + i\gamma\left(1+\frac{1}{\omega_\circ}\frac{\partial}{\partial T}\right)\int_{-\infty}^{\infty} R(T')|A(z,T-T')|^2\, dT' \qquad (6.1)$$

Different parameters appear in this equation were introduced in chapter two, it is assumed that input pulses possess horizontal or vertical polarization during while launch into fiber, i.e., neglecting cross phase modulation between pulses of two different polarizations. The NLSE is solved using the split-step Fourier method, due to its high accuracy and simplicity, by rewriting the GNLSE in the form:

$$\frac{\partial A}{\partial z} = (\widehat{D} + \widehat{N})A \qquad (6.2)$$

Operator $\widehat{D}$ takes into account losses and linear terms within a linear medium while operator $\widehat{N}$ takes into account for all nonlinear effects. $\widehat{D}$ and $\widehat{N}$ are defined as follows:

$$\widehat{D} = -\frac{\alpha}{2} + \sum_{n\geq 2} \beta_n \frac{i^{n+1}}{n!} \frac{\partial^n}{\partial t^n} \qquad (6.3)$$

$$\widehat{N} = i\gamma\left(1 + \frac{1}{\omega_\circ}\frac{\partial}{\partial T}\right)\int_{-\infty}^{\infty} R(T')|A(z, T - T')|^2 \, dT' \qquad (6.4)$$

As optical pulses propagate along PCFs, nonlinear effects and dispersion simultaneously act along fiber length. In the SSFM it is assumed that over a small distance, h, the dispersive and nonlinear effects independently act. This simplifies problem encountering a negligible error. The propagation from z to z + h is carried out by two steps, viz., first only considering linear effects while the second, the nonlinear effects. First part is solved using a Fast Fourier transform (FFT) algorithm that requires careful step size Δz consideration a long the fiber and the time resolution Δt used for the temporal window.

6.5: <u>Results and discussion</u>

There are number of parameters that might have effect on the supercontinum generation so that number of these parameters effects on the supercontinum generation mechanism are studied in details. Different conditions would result in distinct SC generation processes. In order to control the SC generation progress, not only the parameters of the properties of fiber (the material of fiber, geometry parameters) but also be carefully considered pump source (pump wavelengths, pulse duration, and the pump power level). Suppose that if there is a L=0.15 m length of a highly nonlinear PCF structure, with hole diameter d=1.4μm, pitch (Λ) = 1.6μm, and ZDW around 780 nm, fractional Raman contribution f_r=0.18, using the global table for group velocity dispersion (GVD), as shown in the table (6.1):

Table (6.1): Parameters for group velocity dispersion [35]

Parameter	Value ($\frac{ps^2}{km}$)
β_2	-11.830
β_3	8.1038×10^{-2}
β_4	-9.5205×10^{-5}
β_5	2.0737×10^{-7}
β_6	-5.3943×10^{-10}
β_7	1.3486×10^{-12}
β_8	-2.5495×10^{-15}
β_9	3.0524×10^{-18}
β_{10}	-1.7140×10^{-21}

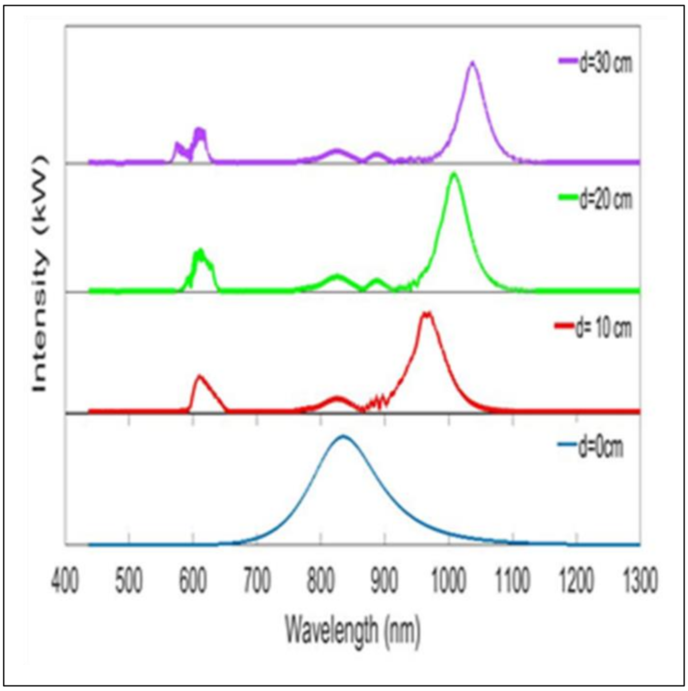
The femtosecond laser-pumped SC usually exhibits a broadband continuum range due to the high pulse peak power and short pulse duration, while the system of the femtosecond pump source itself is complex. It is also hard to configurate a femtosecond pumped SC source with an all-fiber architecture [35]. The CW-pumped SC could obtain a high average power and high spectral power density output. However, compared with the pulse-pumped SC, the CW-pumped SC has a relatively narrow spectral range. In fact, the picosecond fiber laser is an ideal SC pump source. On the one hand its high pulse peak power is helpful for exciting the nonlinear effects on the other hand it is feasible to form a high power all-fiber picosecond laser, then to form an SC source with all fiber architecture [178].

6.6: The spatial and temporal evolution of Supercontinuum Generation

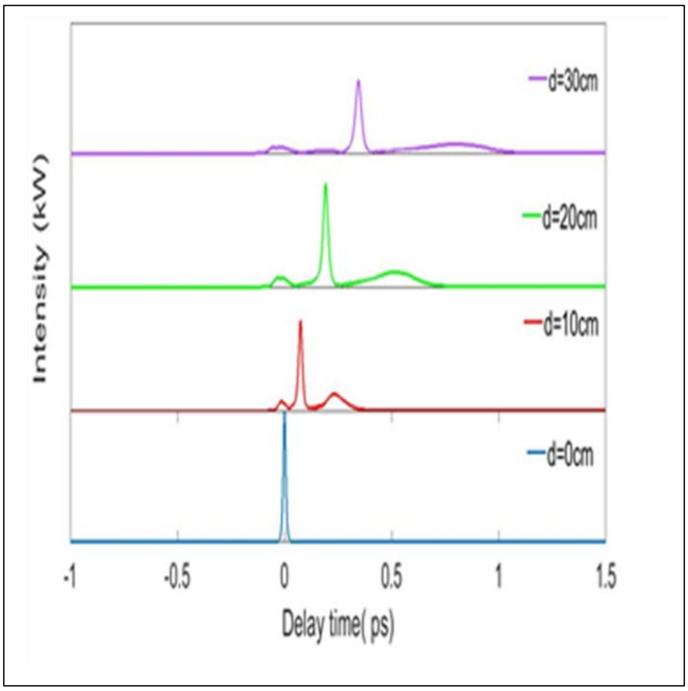
For the numerical simulation of SCG, a 10000 kW power and 0.02 ps time width pulse as input incident on a PCF of length 30 cm, using table (6.1) and table (6.2). solving eq. (6.1), the simulation results of the intensity spectrum inside the fiber is shown in figure (6.1a), and the temporal evolution of the intensity is shown in figure (6.1b). It can be seen that a short intense pulse (10000 kW, 0.02 ps) penetrates PCF will disappear after a short distance inside the fiber and converted into a broadened spectrum. The pulse will give rise to a more than 2 ps of a broadened spectrum of light in the visible range. It is clear that the broadening in the spectrum with increasing the distance inside the fiber. This is what happen to the time period also. It can be seen that the output is more complex. The physical point of this phenomenon becomes from the interaction between many physical processes, viz. dispersion, nonlinearity, effective refractive index, Raman scattering, etc. So, it is difficult to explain what happen exactly until now [35]. Another point of view is the intensity difference between many parameters used in the simulation is large so it is convenient to deal with the logarithmic scale for all next.

Table (6.2): Parameters for SC generation

Parameters	Values
Duration input (T_o)	0.02 ps
Fiber length (L)	30 cm
Nonlinear effects (γ)	0.11 $W^{-1}km^{-1}$
Losses (α)	0 $\frac{dB}{km}$
Fractional Raman contribution (f_r)	0.18
Width of time window	12 ps
Wavelength (λ)	850 nm



(a)



(b)

Figure (6.1): (a) the spectrum of the SC intensity at traveling distance inside the PCF of (0, 10, 20, 30) cm. (b) the temporal intensity distribution of the SC at traveling distance inside the PCF of (0, 10, 20, 30) cm.

6.7: Factors affecting the Supercontinum Generation

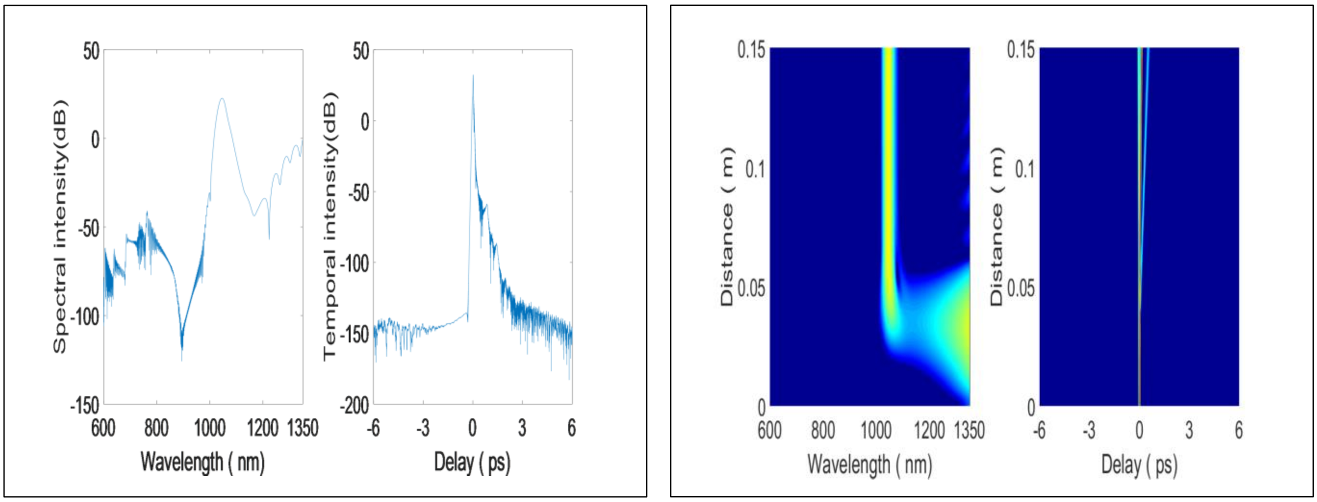
There are number of parameters that might have effect on the SC generation so that number of these parameters effect on the SC mechanism are studied in details:

6.7.1: The effect of pulse power

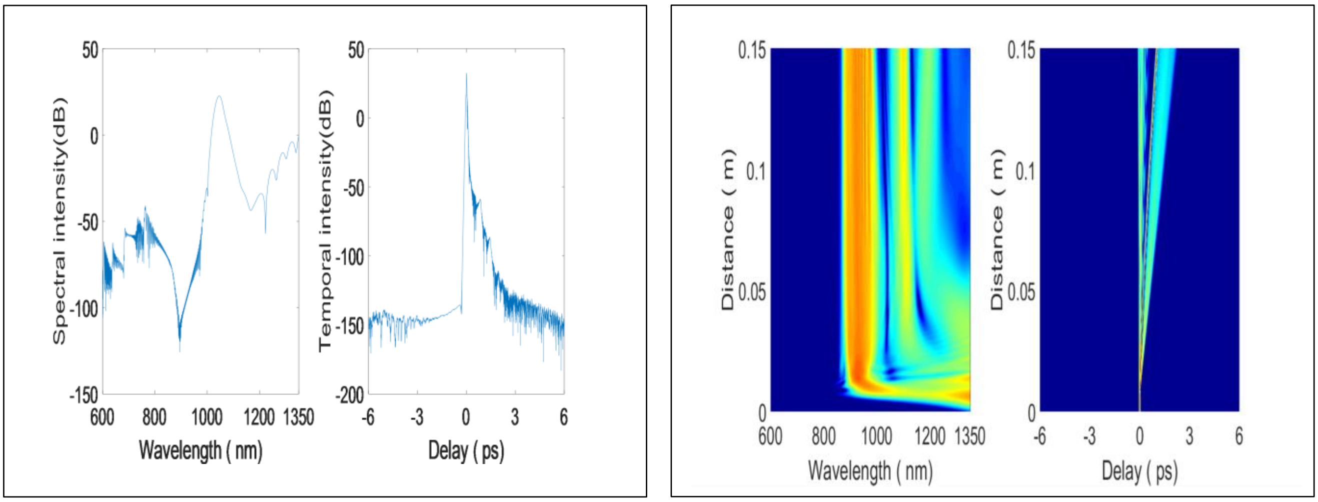
To figure out the effect of pulse power, all parameters were set constants as shown in table (6.3) while the power of the pulse was varied in the range (1000-10000) Watt. In Fig (6.2) at left, the SC output spectrum (intensity in dB against the wavelength) and the temporal output (intensity in dB against the delay time) (a) for input power 1000 W and (b) for 10000W. While the evolution of the SC with the distance inside the PCF and time, and with distance and the delay time at the right. The delay time is taken at the center of pulse width as a reference point, are shown on a logarithmic scale to illustrate the fine structure of the spectrum generated, and it can be seen clearly that this is very complex. One notice when the power increases the individual soliton are ejected from the input pulse in an ordered fashion one by one. The ejected solitons are arranged by peak power with the highest peak power (shortest) solitons exhibit the largest group velocity difference relative to the pump power.

Table (6.3): Parameters for SC generation

Parameters	Values
Wavelength (λ)	1550 nm
Duration input (T_o)	0.015 ps
Width of time window (T_{width})	12.5 ps
Nonlinear effects (γ)	0.11 $W^{-1}km^{-1}$
Losses (α)	0 $\frac{dB}{km}$
Fiber length (L)	0.15 m
Fractional Raman contribution (f_r)	0.18



(a)



(b)

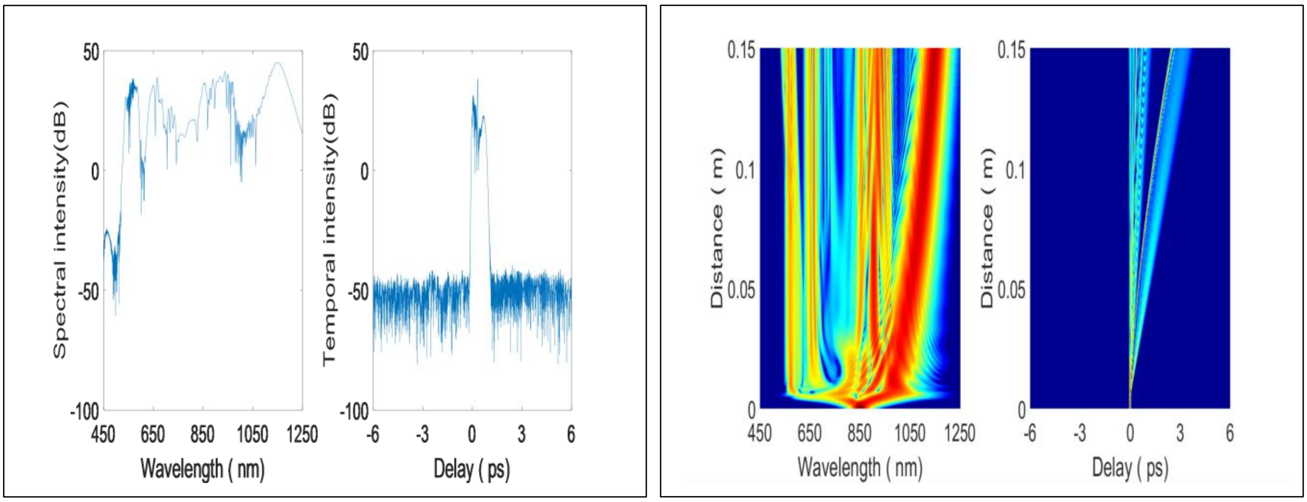
Figure (6.2): The results of the numerical simulation. Left the spectral and temporal SC output (dB). Right the SC evolution with the distance versus the wavelength and with delay time. (a) at 1000W, (b) at 10000W.

6.7.2**:** The effect of pulse wavelength

By fixing all parameters values as shown in table (6.4) and varying the wavelength, it appears that the wavelength is of valuable importance for the SC process as the case with other parameters. Figure (6.3) represent both the spectral and temporal intensity using logarithmic density scale, the result obtained, showing the fiber output characteristics for selected pump wavelength as indicated. From the figure (6.3) it is possible to broadly identify three different regimes of spectral broadening. For a normal GVD pump wavelength of 450 nm far from ZDW, SPM is the dominant nonlinear process, and the approximately symmetric temporal and spectral properties are typical of those expected from the interaction of SPM and normal GVD of the fiber. As the pump wavelength approaches the ZDW but still lies within the normal GVD regime, the initial spectral broadening due to SPM transfers spectral content into the vicinity of the ZDW and across into the anomalous GVD regime. This can be seen to some extent for 650nm pump, but is more apparent for a 750nm pump. For pump wavelength exceeding 800nm, the energy transferred into the anomalous GVD regime increases, and soliton dynamic play an increasingly important role. Specifically, the spectral and temporal SC characteristic exhibit clear signatures of soliton fission and dispersive wave generation as seen in Fig (6.3) the SC spectral and temporal intensity in one dimension against wavelength and delay, left column, while the distance dependence on wavelength in three dimensions are shown in the right column.

Table (6.4): Parameters for SC generation

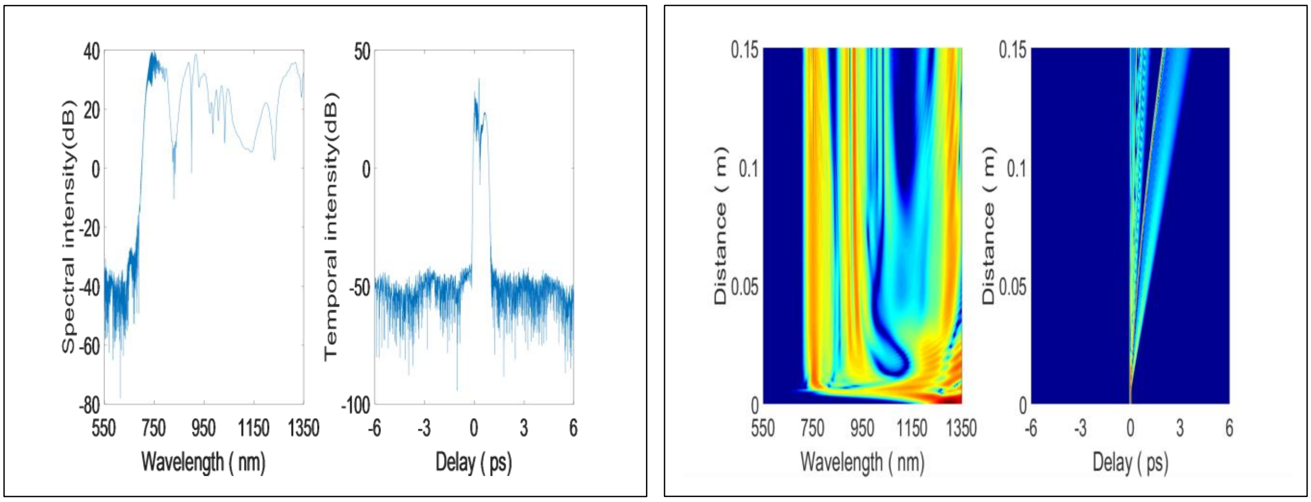
Parameters	Values
Power ($P_{\circ}$)	10kW
Duration input (T_o)	0.015 ps
Width of time window (T_{width})	12.5 ps
Nonlinear effects (γ)	0.11 $W^{-1}km^{-1}$
Losses (α)	0 $\frac{dB}{km}$
Fiber length (L)	0.15 m
Fractional Raman contribution (f_r)	0.18



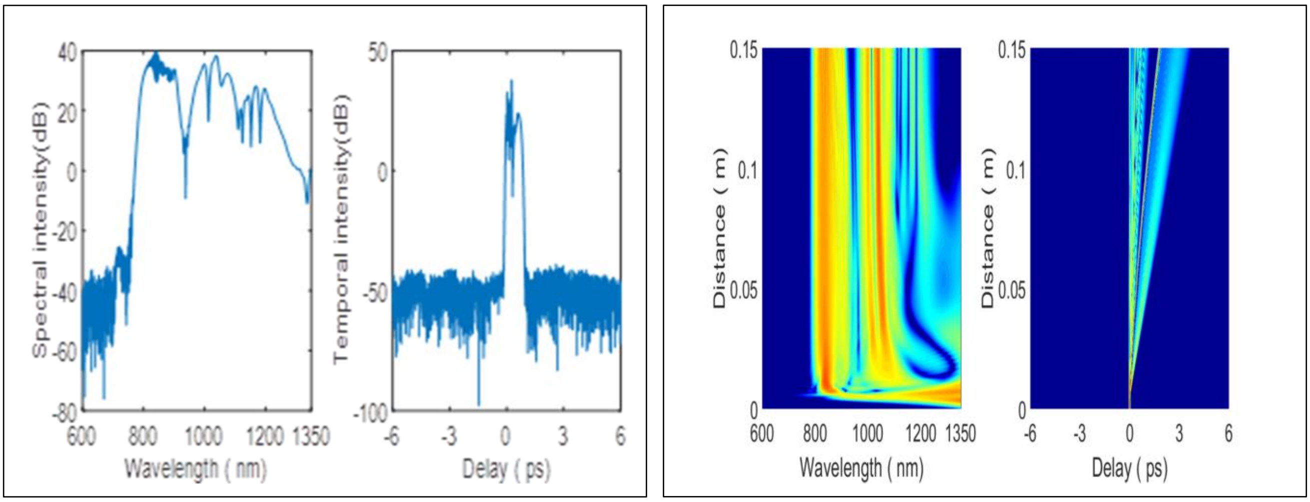
(a)

Figure (6.3): The effect of the wavelength on the SC generation. Left the spectral and temporal SC output (dB). Right the SC evolution with the distance versus the wavelength and with the delay time. (a) λ=850nm, (b) λ =1300nm, (c) λ =1550 nm.

Continue



(b)



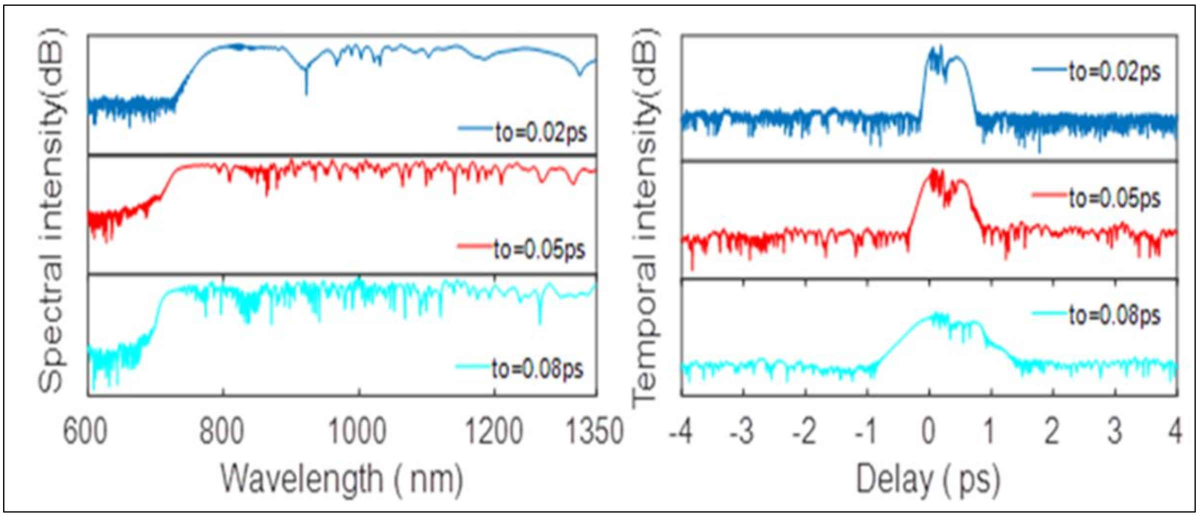
(c)

6.7.3: The effect of Duration input (T_o)

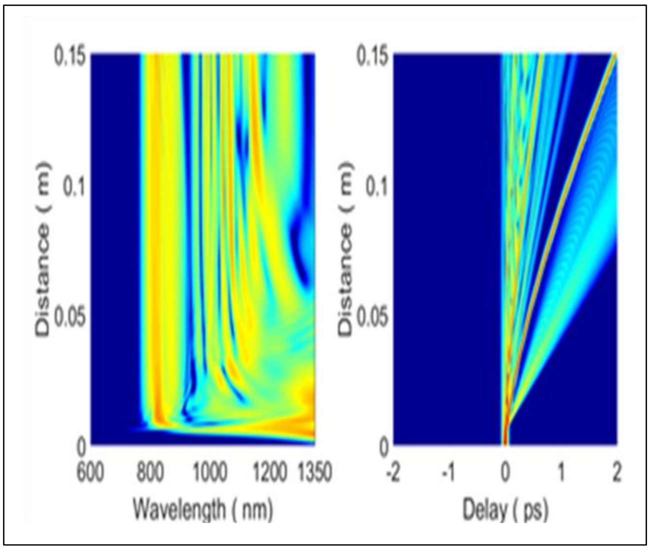
To study the effect of input pulse repetition (T_o) on the SC generation, all the parameters are kept constant while varying the input pulse duration, as shown in table (6.5). Some dependence on the output SC characteristics with pulse duration can also be observed in the long pulse regime. Fig (6.4) shows simulation results for spectral and temporal characteristics for pulses in the range (0.02-0.08) ps, the physical mechanisms underlying the spectral broadening do not differ over this range, some differences in the spectral and temporal characteristics nonetheless be observed. For shorter input pulses, separated solitons are more distinctly observed both in the temporal trace and in the spectrum. It is easy to see from Fig (6.4) how noise and smoothing effects would be expected to become more prominent for longer pulses.

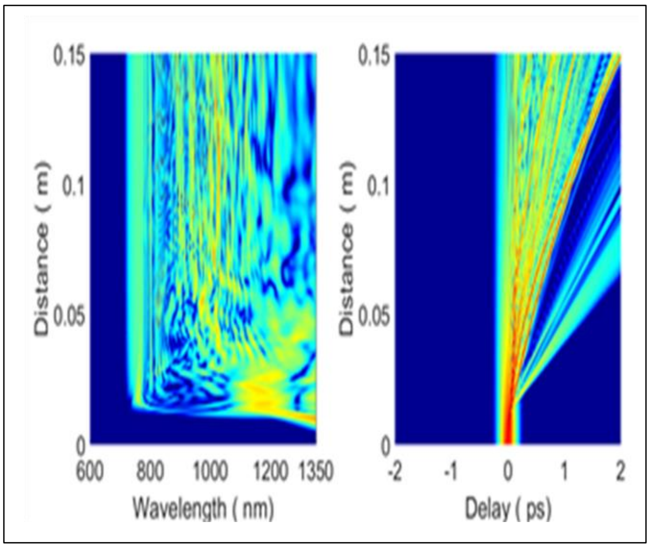
Table (6.5): Parameters for SC generation

Parameters	Values
Power ($P_{\circ}$)	10kW
Wavelength (λ)	1550 nm
Width of time window (T_{width})	12.5 ps
Nonlinear effects (γ)	0.11 $W^{-1}km^{-1}$
Losses (α)	0 $\frac{dB}{km}$
Fiber length (L)	0.15 m
Fractional Raman contribution (f_r)	0.18



(a) (b)





(a) (b) (a) (b)

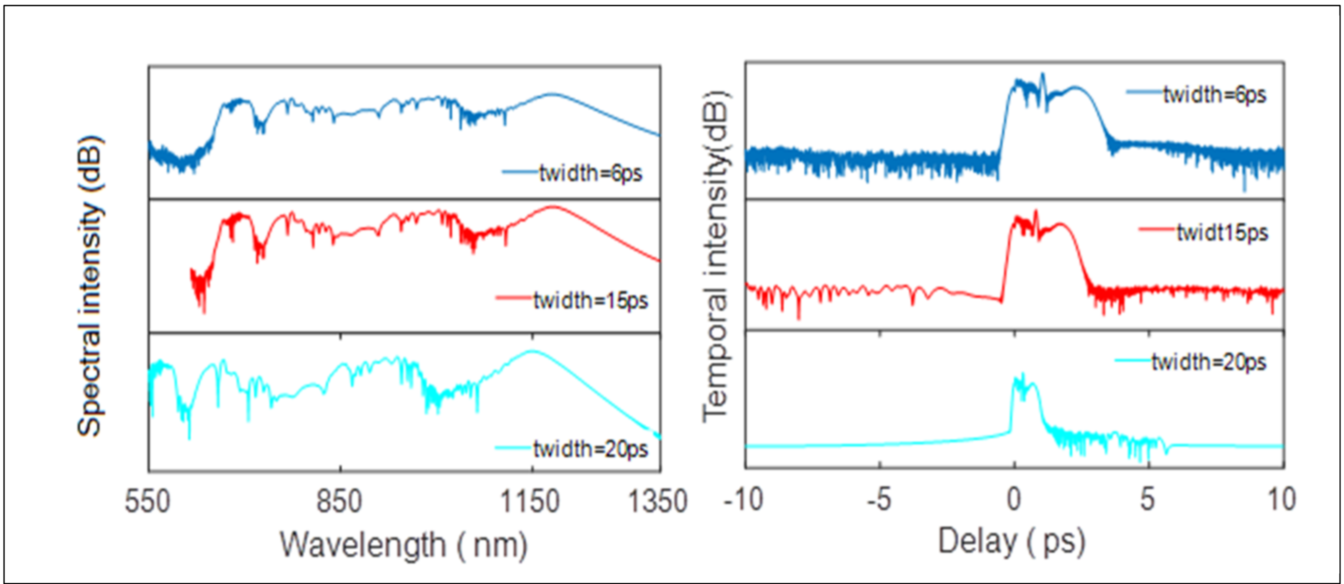
Figure (6.4): The effect of Duration input on the SC generation. Upper row is the spectral and temporal SC output (dB). Lower row is the SC evolution with the distance versus the wavelength and with the delay time. (a) T_o=0.02ps, (b) T_o =0.05ps, (c) T_o =0.08 ps.

6.7.4: The effect of Width of time window (T_{width})

To study the effect of time variation on the SC generation, all the parameters are kept constant, as shown in table (6.6) and varying the time in the range (6-20) ps, SC generation with anomalous GVD regime pumping dominated by soliton – related propagation effects. The most important of these is the initial dispersive perturbation that induces the pulse breakup. Raman and higher – order dispersion introduce comparable perturbation.as shown in Fig (6.5).

Table (6.6): Parameters for SC generation

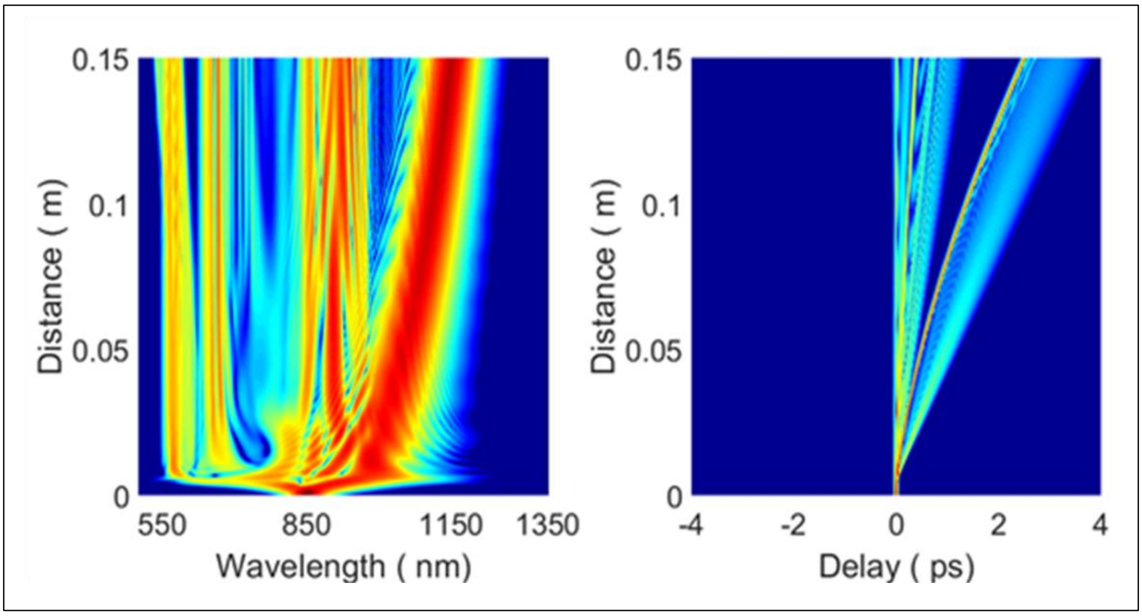
Parameters	Values
Power ($P_\circ$)	10kW
Wavelength (λ)	1550 nm
Duration input ($T_\circ$)	0.015 ps
Nonlinear effects (γ)	0.11 $W^{-1}km^{-1}$
Losses (α)	0 $\frac{dB}{km}$
Fiber length (L)	0.15 m
Fractional Raman contribution (f_r)	0.18



(a) (b)

Figure (6.5): The effect of the pulse width on the SC generation. Upper row is the spectral and temporal SC output (dB). Low row is the SC evolution with the distance versus the wavelength and with the delay time. (a) $t_{width} = 6ps$, (b) $t_{width} = 15ps$, (c) $t_{width} = 20ps$.

Continue



(a) (b)

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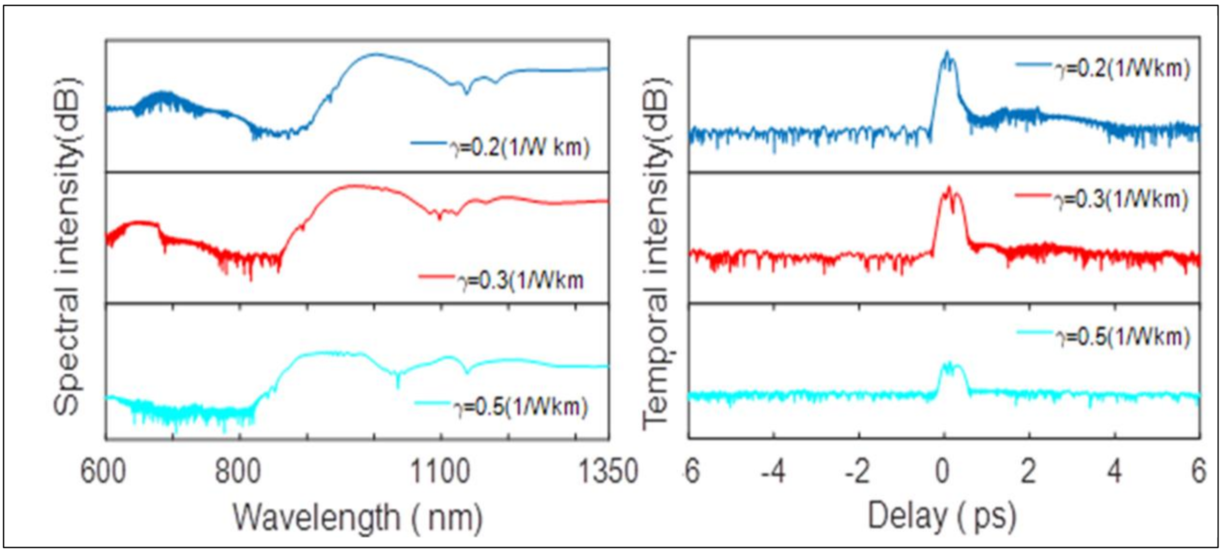
6.7.5: The effect of nonlinearity on the SC generation

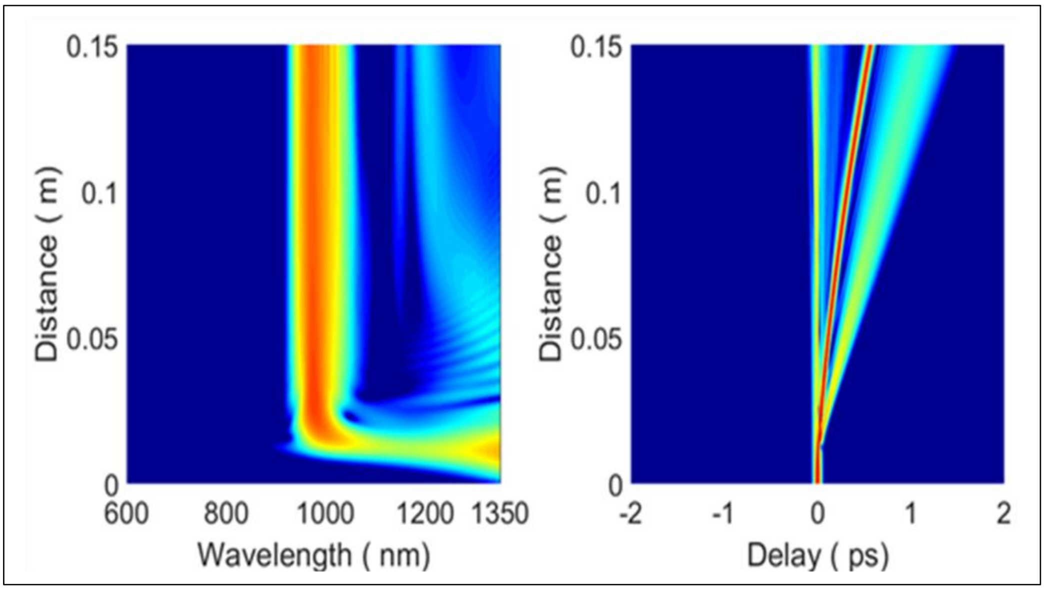
To study the effect of nonlinearity on soliton interaction inside the fiber all parameters are kept constant as shown in table (6.7), while varying the nonlinear effect (γ) value. Although white-light SC generation is perhaps the most spectacular manifestation of nonlinear optical propagation effects in PCFs, one notice when the nonlinear effects are increase the intensity decrease so decreases the noise, as shown in Fig (6.6).

Table (6.7): Parameters for SC generation

Parameters	Values
Power ($P_\circ$)	10kW
Wavelength (λ)	1550 nm
Duration input ($T_\circ$)	0.015 ps
Width of time window (T_{width})	12.5 ps
Losses (α)	$0\,\frac{dB}{km}$
Fiber length (L)	0.15 m
Fractional Raman contribution (f_r)	0.18



(a) (b)



(a) (b)

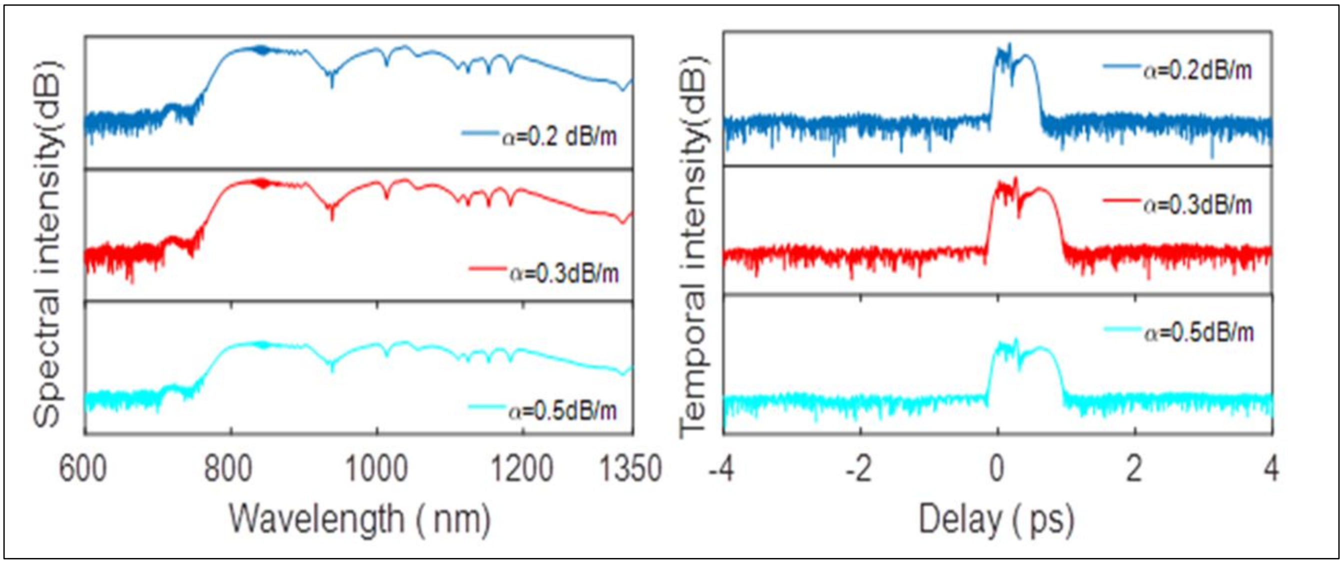
Figure (6.6): The effect of the nonlinear on the SC generation. Upper row is the spectral and temporal SC output (dB). Lower row is the SC evolution with the distance versus the wavelength and with the delay time. (a) γ= 0.2$W^{-1}km^{-1}$, (b) γ =0.3 $W^{-1}km^{-1}$, (c) γ =0.5$W^{-1}km^{-1}$.

6.7.6: The effect of losses on the SC generation

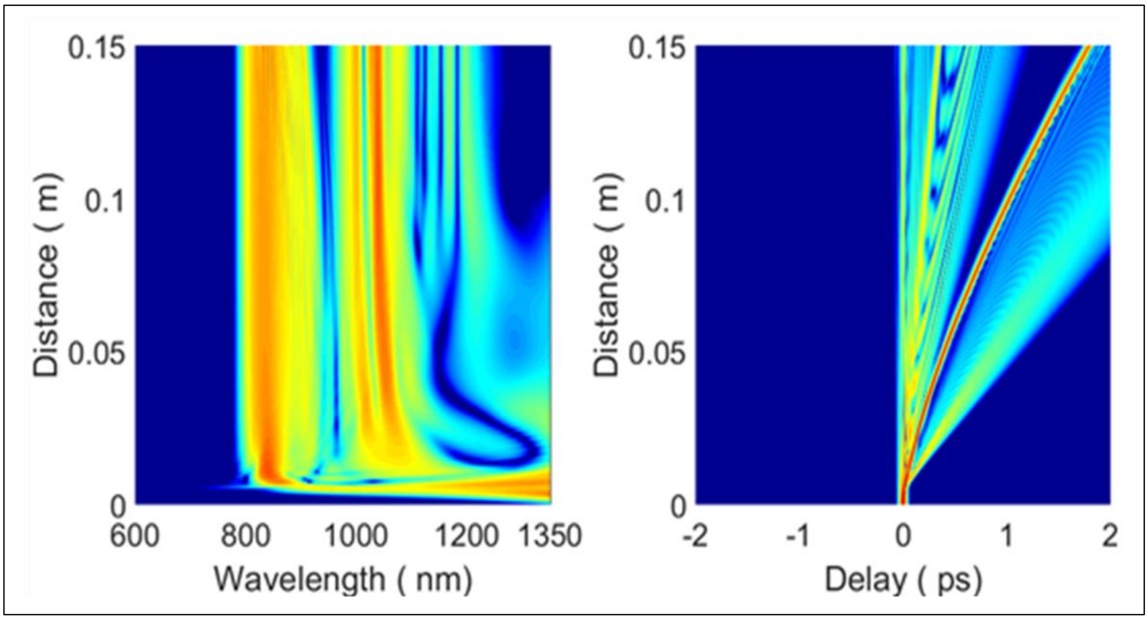
By fixing all parameters values as shown in table (6.8) and varying the losses, one can noticed that not effect of the losses within the range (0.2-0.5)$\frac{dB}{m}$ with other parameters, as shown in Fig (6.7).

Table (6.8): Parameters for SC generation

Parameters	Values
Power ($P_\circ$)	10kW
Wavelength (λ)	1550 nm
Duration input ($T_\circ$)	0.015 ps
Width of time window (T_{width})	12.5 ps
Nonlinear effects (γ)	0.11 $W^{-1}km^{-1}$
Fiber length (L)	0.15 m
Fractional Raman contribution (f_r)	0.18



(a) (b)



(a) (b)

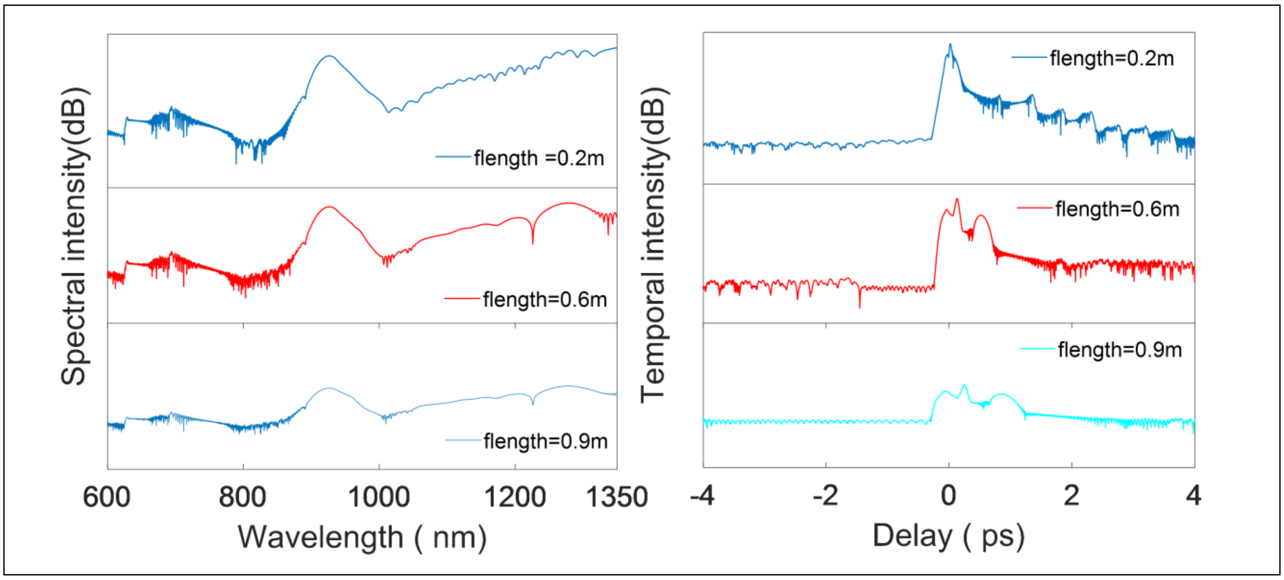
Figure (6.7): The effect of losses on the SC generation. Upper row is the spectral and temporal SC output (dB). Lower row is the SC evolution with the distance versus the wavelength and with the delay time. (a) α= 0.2 dB/m , (b) α =0.3 dB/m (c) α =0.5dB/m.

6.8: Choice of suitable Fiber length in the Supercontinuum Generation

Fixing all parameters values as shown in table (6.9) and varying the fiber length, it appears that the fiber length is of valuable importance for the fission solitons process as the case with other parameters. As the fiber length increased the probability of SC characteristics is clear for long distance. This effect can be understood in a straightforward way by considering the relative distance scales associated with the process of modulation instability and soliton fission, as shown in Fig (6.8).

Table (6.9): Parameters for SC generation

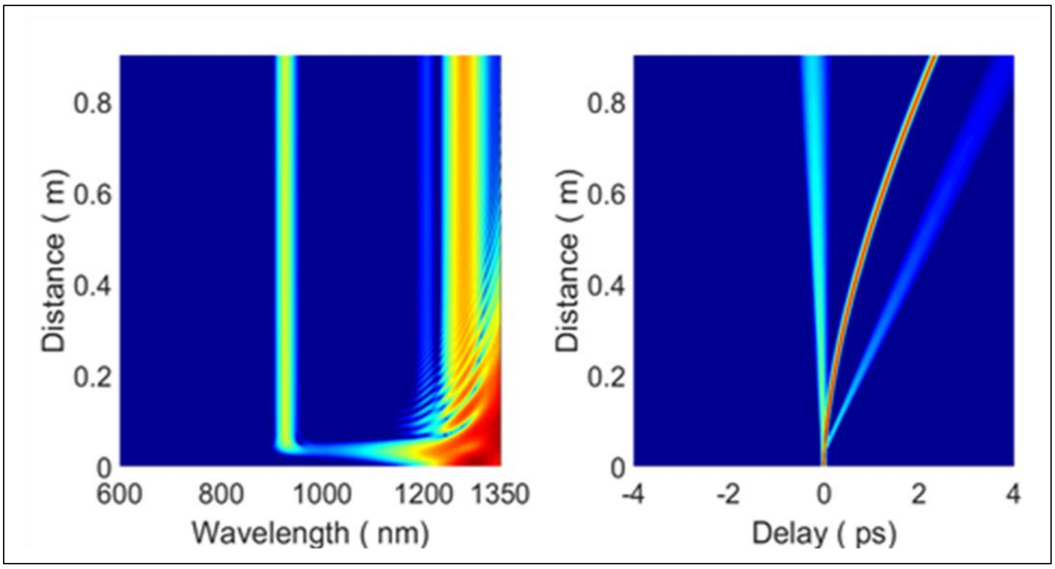
Parameters	Values
Power ($P_\circ$)	10kW
Wavelength (λ)	1550 nm
Duration input ($T_\circ$)	0.015 ps
Width of time window (T_{width})	12.5 ps
Nonlinear effects (γ)	0.11 $W^{-1}km^{-1}$
Loss(α)	0 $\frac{dB}{km}$
Fractional Raman contribution (f_r)	0.18



(a) (b)

Figure (6.8): The effect of fiber length on the SC generation. Upper row is the spectral and temporal SC output (dB). Lower row is the SC evolution with the distance versus the wavelength and with the delay time. When the fiber length. (a) (L) = 0.02m, (b) (L) =0.06m, (c) (L) =0.09 m.

Continue



(a) (b)

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CHAPTER SEVEN

CONCLUSIONS AND FUTURE WORK

Chapter Seven

Conclusions and future work

7.1: Conclusions

Three major problems are targeted in this work. The first is the photonic crystal fibers viz., the effect of those fibers on the wave or optical pulse propagation along the fiber and effect of the photonic crystal coefficients on the fiber itself. The second is the study of solitons and its affected on by number of linear and nonlinear effects and mechanism of interaction between solitons and coefficient effects on the solitons interaction. The last is an extensive or detailed study on supercontinuum through the study of the effects of number of parameters on the occurrence of supercontinuum. Basing on these three problems this study can conclude as follows:

1- As the absorption level increased, it reduces the propagating pulse intensity more.

2- As the chromatic dispersion level increased so do pulse width temporally and its intensity is reduced.

3- As the nonlinearity increased inside the fiber medium it lead to changes of propagating pulse shape and high level on nonlinearity the pulse shape differ completed in comparison with the input pulse.

4- The values of the effective index of the photonic crystal fiber depends largely on the properties of the photonic crystal viz., number of air holes drilled in the fiber, distance between these holes to their diameters ratio.

5- The difference between refractive index of the cladding that is made of holes drilled and the core refractive index depends on the properties of the photonic crystals mention in point (4).

6- Soliton also depends on the properties of the photonic crystal mentioned before. There exist number is conditions should be meeted to make a soliton viz., Anomalous dispersion should be available ; The input pulse should have either a sech a Gaussian shape; Dispersion length (L_D) should equal the nonlinear length (L_N) i.e. $L_D=L_N$; group velocity dispersion effects must equalizes the nonlinear effects.

7- It appears that the interaction between solitons occur under certain condition and due to number of parameters viz., input pulse power, effect of temporal width, dispersion and nonlinear effects along the fiber length. It is also proved that soliton order has no effect on the solitons interaction were the fiber length varied from 100m to 2000m where no effect of changing the soliton order appears to occur.

8- When studying the phenomenon of supercontinuum in photonic crystal fibers using the general nonlinear Schrodinger equation it is found that there exist number of parameters that it is possible to affect the occurrence of the supercontinuum viz., pulse power and wavelength effects. It is found too there is no effect of the dissipation on supercontinuum phenomena occurrence in photonic crystal fibers within special parameters.

7.2: Future work

1- Studying the propagation of a short laser pulse in Hollow PCFs.

2- Studying the soliton and supercontinuum generation experimentally in the lab.

3- Studying the effect of Stokes and anti-Stokes solitons.

4- Scrutinying study of the solitons interaction problem.

5- Repeating this study for chirped laser pulses.

6- Studying the propagation of ultra-short pulses (fsec) in PCFs.

7- Trending toward more Nano-scales PCFs.

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PAPERS ABSTRACT

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The Effect of the Nonlinearities on Gaussian Pulses Propagation in Photonic Crystal Fiber

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The Effect of the Nonlinearities on Gaussian Pulses Propagation in Photonic Crystal Fiber

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Abstract: Nonlinear effects are attributed to the dependence of the susceptibility on the electric field, which becomes important at high field strengths, in optical fibers impose different limitations on the communications link, and an understanding of such effects is almost a prerequisite for actual light wave system designers. On the other hand, they offer a variety of possibilities for all-optical signal processing, amplification and regeneration, in the nonlinear regime, is introduced and shows the influence and consequences of the nonlinear effects of the propagation Gaussian pulse in photonic crystal fibers. In this paper, one reviews the effects - both detrimental and potentially beneficial - of optical nonlinearities in photonic crystal fibers.

Keywords: Kerr effect, Raman scattering, Brillion scattering, Nonlinear Schrodinger equation.

1. Introduction:

Photonic crystal fibers (PCFs) are fibers with an internal periodic structure made of capillaries, filled with air, laid to form a hexagonal lattice. Light can propagate along the fiber in defects of its crystal structure. A defect is realized by removing one or more central capillaries. PCFs are a new class of optical fibers. Combining properties of optical fibers and photonic crystals they possess a series of unique properties impossible to achieve in classical fibers [1]. The interaction of optical signal with different medium leads to nonlinear optical effects [2]. Nonlinearities of fibers mode of photonic crystals are divided into two classes first class due to refractive index modulation of silica by changes of intensity in signal or Kerr effect. Such effects lead to self-phase modulation (SPM), cross-phase modulation (XPM), and four wave modulation (FWM). The second class is nonlinearities because of stimulated scattering processes, Stimulated Raman Scattering (SRS), Stimulated Brillion Scattering (SBS) [3]. Linearity's because both classes responded to the materials from dynamic or

Study the Effect of Some Photonic Crystal Arrangements on the Dispersion and Effective Refractive Index of Photonic Crystal Fiber

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Abstract: ***The recent optical fibers are the microstructure optical fibers (MOFs). They are consistingof a hexagonal arrangement of air holes along the length of a silica fiber surrounding a central core of solid silica. They can guide light through the total internal reflection mechanism and photonic band gap effect. PCFs contain axially air channels which provide alargedegreeoffreedomindesignto achieveavarietyof peculiar properties,numerous PCF-based sensors have been proposed, developedand demonstrated fora broad range of sensing applications,PCF is depends on different parameters such as the diameter of air hole, number of holes, and the distance between the air holes. This paper presents the results of the customizing of a photonic crystal fiber. This customizing is essential to know the actual parameters of the PCF for its use in the application.***

1. Introduction

Fibers made of photonic crystal (PCs) are fibers having internal periodic structure made of fine tubes[1] filled with air, laid to form a hexagonal lattice. To confine the propagating light in a narrow region the photonic structure is used in the graphene layer for the sake of enhancing light–matter interaction[2]. They much attention have been paid in recent years to PCFs due to these flexible structure, easy on-chip integration, outstanding light confinement capability, and compact size [3]. There exist several parameters to manipulate lattice pitch, air hole shape and diameter, refractive index of the glass, and type of lattice[4]. Freedom of design allows one to obtain endlessly single mode fibers, which are single mode in all optical range and a cut-off wavelength does not exist[5].Moreover, there are two guiding mechanisms in PCF, there are index guiding mechanism (similar to the one in classical optical fibers) and the photonic bandgap mechanism. The holey Fiber (also called the index guided fiber) light is guided in the solid core made of pure silica by modified total internal reflection mechanism [6-8],light guidance in solid-core PCF can still be well explained with the total internal refraction of light on the interface between the core which has refractive index of silica and the cladding which has lowered effective refractive index due to air holes [9], this type shown in figure (1a).

While Photonic Band-Gap Fibers follows Photonic Band Gap Mechanism and here the light is guided in air holes. When replacing central part of the array of air holeswith a bigger hole of much larger diameter in comparison to the surrounding holes, so obtained fiber is called the Photonic band-gap fiber. The structure periodicity of is broken, sodefect introduced causes a change in its optical properties[11-12].Figure (1b) illustrates the Photonic Band Gap Fiber.

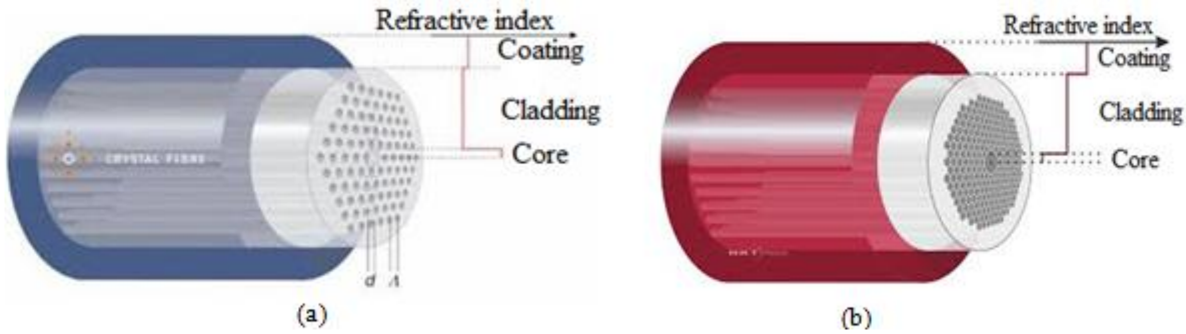

Figure 1: PCF microstructured cladding (a) solid core and (b)hollow core PCF [10]

2. Theory

The nonlinear Schrödinger equation (NLSE) is approximately describes the propagation of an optical signal, through a fiber[13], by neglecting, third and fourth order dispersion coefficient of the medium so the equation appeared in the form (1):

$$\frac{\partial A}{\partial z} = -\frac{\alpha}{2}A(z,t) - \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial t^2} + i\gamma|A|^2 A \dots (1)$$

Where theapproximation slowly-varying envelope is used with assumptiveinstantaneous nonlinear response. A(z, t) is the electric field amplitude complex envelope of the optical signal at a retarded time (a temporal frame of reference moving with the group velocity of the pulse), t, and after propagating a distance, z, and α, β_2, and γ arethe medium parameters of in which the pulse is propagating.$\beta_2$is the second-order dispersion coefficient, while α is the loss parameter, and γ isthe nonlinear coefficient.

The effect of attenuation and dispersion on the propagation of a short Gaussian pulse in optical fibers

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Abstract: Fiber optics being the most important in many of applications like medicine and communication. Manny factors affect the light propagation through it, like attenuation, dispersion and nonlinear effects. In this paper the effect of attenuation and dispersion on the propagation of a Gaussian pulse in optical fiber was studied by theoretical simulations. Nonlinear Schrodinger equation was solved by split step Fourier method using MATLAB. The study focused on the pulse intensity distribution with time and its distribution along the fiber under the effect of attenuation and dispersion. The pulse propagation is affected strongly with varying these parameters.
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Keywords: optical fibers, attenuation, dispersion, soliton

Introduction:

An optical fiber is a very clear glass capable of carrying the light pulses as information in the communication system. The two main elements of an optical fiber are its core and cladding. The core made of silica glass is the light transmission area of the fiber. The cladding is the layer completely surrounding the core. The difference in refractive index between the core and cladding is less than 0.5 percent. Optical fiber played a very important role due to its wide properties like high bandwidth, long distance transmission, and high level of security [1-4]. Dispersion is the main performance limiting factor in optical fiber communication. Dispersion greatly hampers the performance of optical fiber communication. When a pulse travels through an optical fiber it becomes broadened due to dispersion. The dispersion is proportional to the length of the fiber. Dispersion is a consequence of the physical properties of the transmission medium [2,5,8-9].

Attenuation:

Attenuation is one important characteristic of an optical fiber, since it determines the repeater spacing in a fiber transmission system. The lower the attenuation, the greater will be the required repeater spacing and lower will be the cost of that system. Representing by $P_\circ$ the power launched at the input of a fiber of length L, the output power is given by [7]:

$$P_t = P_\circ EXP\,(-\alpha L) \quad (1)$$

where α is the attenuation constant (absorption factor), (1/km), and it's a gauge to losses the energy during upload the signal (pulse) in optical fiber [9-10]. Usually, the fiber attenuation is given in dB/km, using the relation [7]:

$$\alpha = -\frac{10}{L} Log\, \frac{P_t}{P_\circ} \quad (2)$$

Absorption is the way by which the energy of a photon is taken up by matter, typically the electrons of an atom. Thus, the light energy is transformed to other forms of energy for example, to heat. The absorption of light during wave propagation is often called attenuation [7].

Dispersion:

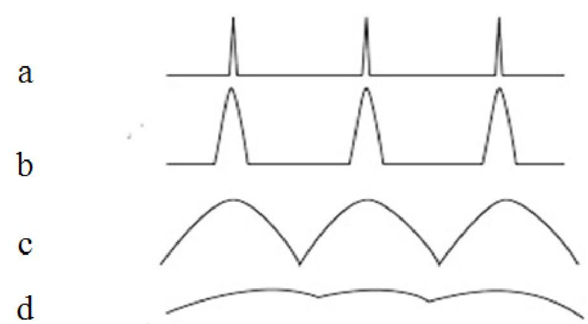

Figure (1): Distribution of pulse intensity with time at different distance. (a) initial pulses. (b) pulses start to separate (c) starting to overlap (d) pulses no longer recognizable [3].

Dispersion is defined as pulse spreading in an optical fiber. As a pulse of light propagates through a fiber, elements such as numerical aperture, core diameter, refractive index profile, wavelength, and laser line width cause the pulse to broaden. Dispersion

الخـلاصـــة

تضمنت الاطروحة المقدمة دراسة نظرية لكل من ظاهرتي الموجة المنعزلة والتوسع الطيفي الفائق وآَلية ظهورهما واستمراريتهما في الالياف أعتماداً على معاملات البلورة الفوتونية. أعتمدت هذهِ الدراسة على تاثير ترتيب البلورة الفوتونية خصوصاً عدد الفجوات والمسافة بين الفجوات وقطر الفجوات على معامل الانكسار الفعال ومساحة النمط الفعال في الياف البلورة الفوتونية، وتاثير معاملات الليف على النبضة مثل الامتصاص والتشتت والتاثيرات اللاخطية والتي تم دراستها أيضاً . مثل هذهِ الموجة المنعزلة والتوسع الطيفي الفائق أظهرا أعتمادهما على التوازن بين التشتـت والتأثيرات اللاخطية ، تاثير هذه المعاملات على الموجة المنعزلة والتوسع الطيفي الفائق تم دراستهما أيضاً.

ركزت هذه الدراسة على أثر تلك العوامل على كل من التفاعل بين الموجات المنعزلة والتوسع الطيفي الفائق ، وديناميكية هذه الظواهر في الياف البلورة الفوتونية وخصائص النبضة أيضاً. أستند هذا العمل على معادلتي شرودنكر اللاخطية واللاخطية العامة واللاتي تم حلهمـا باستخدام طريقة فورير ذات المراحل المنفصلة والتي تعرف أيضاً بالطريقة الطيفية عن طريق أستخدام برنامج الماتــلاب.

أن العديد من الياف البلورة الفوتونية تم ترتيبها بإختلاف في كل من (المسافة بين الفجوات وقطر الفجوات وعدد الفجوات) والتي تم دراستها. ان ترتيب البلورة الفوتونية وهي عدد الفجوات الهوائية المحفورة والمسافة بين الفجوات وقطر تلك الفجوات على معاملات الليف مثل الامتصاص والتشتت واللاخطية ومساحة النمط الفعال واللاخطية أضافة الى معامل الانكسار الفعال أو المؤثر في كل من قلب الليف وغلافه وتم حسابها عددياً في ليف البلورة الفوتونية بأستخدام طريقة الفروقات المـحدودة في نطاق التردد.

هذهِ الدراسة أوضحت ان هذا الترتيب له الاثر الفعال في خصائص الليف وانتقال ذلك الاثر على أنتشار النبضة الضوئية في الليف وان ديناميكيات الموجة المنعزلة تعتمد على كل من قدرة النبضة الداخلة وعرضها والتاثيرات اللاخطية وتاثير التشتت أيضاً ، كذلك فان التوسع الطيفي الفائق يعتمد على بعض هذه المعاملات متمثلةً بكل من قدرة النبضة و الطول الموجي و عرض النبضة ودوريتها والتاثيرات اللاخطية أيضاً.

جامعة البصرة

الموجة المنعزلة وتوليد التوسع الطيفي الفائق في الياف البلورة الفوتونية

الطالب

محمد سالم جاسم

بأشراف

أ.د.جاسب عبد الحسين مشاري

أ.م.د.حسن عبد الله سلطان

قسم الفيزياء

أطروحة تقدم بها الى

مجلس كلية التربية للعلوم الصرفة/جامعة البصرة

وهي جزء من متطلبات نيل شهادة الدكتوراه فلسفة في الفيزياء

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