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EFFECT TWO ZERO DISPERSION WAVELENGTHS AND RAMAN SCATTERING IN THE THIRD-ORDER SOLITON OF SOLID CORE PHOTONIC CRYSTAL FIBERS TO PRODUCE SUPERCONTINUUM GENERATION

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ABSTRACT Fiber optics have been greatly enhanced by photonic crystal fibers based on microstructure air-glass designs. Such fibers enable highly tight light that is confined in a small mode shape region resulting in significantly improved alternative options between light and dielectric medium. Photonic crystal fibers, on the other hand, allow light to be guided via air core instead of glass. Photonic Crystal Fibers (PCFs) that consist of dielectric materials is a don't ever and an ever field in more modern application. The Split-Step Fourier method (SSFM) was used in this work to create a fiber photonic crystal, which was suggested and validated using Matlab software. The impact of two-zero-dispersion on the Soliton in solid-core photonic crystal fibers has been studied by investigating the interplay between Raman Effect and second-order-dispersion. The number of soliton pulse increase with an increase in pitch. When the magnitude of the Gaussian pulse increases proportionally, the pulse constriction is also noticeable. Furthermore, these results show that Raman Effect has an important role in making the impulses are sharp at their end, and the two-zero dispersion allows the field to work freely within the visible light region. These findings are incredibly useful in learning more about photonic crystal fiber and improving data speeds in modern applications. It has been discovered that the proposed photonic crystal fibers of two–zero-dispersion wavelengths (TZDWs) can be used to effectively tailor the properties of third-order Soliton as well as the possibility of producing supercontinuum generation whereby many modern applications are depending on it including medical and industrial. In addition, supercontinuum generation and Soliton have an important role in modern communication systems.

Keywords: Photonic Crystal Fibers (PCFs), Tow Zero Dispersion Wavelength (TZDWs), Third Order Soliton, Raman Effect, Split-Step Fourier (SSTF), supercontinuum generation.

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1. INTRODUCTION

Waves are optical solitons created in PCFs as a result of the conflicting effects of linear and nonlinear effects. The nonlinear Schrödinger equation (NLSE) has been used to comprehend such pulses through theoretical investigations and numerical simulation (Agrawal, 2013; Amiranashvili et al., 2013), which has been succeeded in comprehending certain elements of nonlinear pulses propagations such as dispersive wave emission (Krupa et al., 2019). Microstructure fibers or PCFs have a solid core encircled by a continuous sequence of air-holes in the propagation path that change the boundary condition of the fiber core. These holes can be fabricated with a certain degree of flexibility to design this relationship beyond material dispersion (Maidi et al., 2021; Pisco & Galeotti, 2021; Amiranashvili et al., 2014). Silica in PCFs has proven to be particularly effective at shedding optical soliton light, which has a broad array of applications (Nixon, 2011).

To stress its parameters-dependent character, dispersion is sometimes referred to as chromatic dispersion or Group Velocity Dispersion (GVD) (Chakravarthi et al., 2012). PCFs have a very flexible structure that enables easy modification of the zero-dispersion wavelength (ZDW) and other characteristics. PCFs' capacity to closely confine light, as well as their variable design structure, improve nonlinear and dispersion features (Habeb, 2018). The effects of TZDWs on soliton behavior in PCFs are important to be examined since PCFs with TZDWs are tuned for distinct dynamics. Nonlinear phenomena in PCFs with TZDWs have been explored previously by Cheng et al (2012). Researchers use the nonlinear behavior of a variety of solid materials, optical fibers, nanowires, and other techniques to produce soliton. The characteristics of the produced spectra are influenced by a variety of factors including dispersion profile, the amount of nonlinearity, pulse width, and others (Ung & Skorobogatiy, 2011; Foster et al., 2008).

The location of the ZDW medium is critical among the parameters that determine and influence the soliton spectral effect since it is induced by a variety of structures (Fujii & Tanabe, 2020). This situation motivates us to research the mechanisms of nonlinear pulse propagation in solid core PCFs with TZDWs, as well as the impact of TZDWs on solid core PCFs soliton. Several approaches were utilized in this study as shown in Figure 1. The contribution of this research include:

(i) Achieving a wider visible spectral range for photonic crystal fibers in two-zero dispersion by controlling the distance between the two air holes (pitch).
(ii) Achieving soliton in a second-order dispersion by interplaying with the Raman and the pitch control.

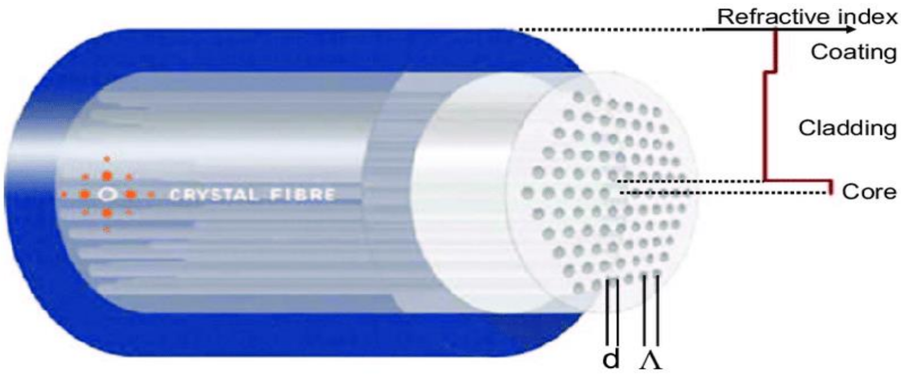

Figure 1. Solid core PCFs with microstructure cladding are the most prevalent design.

1.1 Dispersion

In digital communication systems, data is contained using electric pulses that are converted into optical pulses and transferred from the transmitter to the receiver via optical fibers. The larger the system's capacity, the more pulses can be supplied per unit time while remaining fixable at the receiver end. Pulses disperse as they pass along the fiber and this phenomenon is referred to as pulse dispersion. Represent the major issue influencing the operation of an optical communication system that develops when the frequency components of signal pulses move at different speeds, causing the pulse to expand. The length of the link determines the amount of dispersive pulse broadening and loss (Hasan, Ahmed, & Mohiuddin, 2011). Another cause of dispersive distortions in single-mode fibers is the position of the polarization of the light whereby a light wave of finite time must have a nonzero width of spectral. Differential transit time and signal distortion, often known as delay distortion, occur when various frequency components transmit at varying speeds (Ferreira, 2008). The two significant issues that limit fiber capacity are pulse dispersion and fiber losses (Dubey & Shukla V, 2014). Pulse distortion arises for some reasons such as polarization mode, waveguide, intermodal, and material. The dispersion of the pulse is shown in Figure 2.

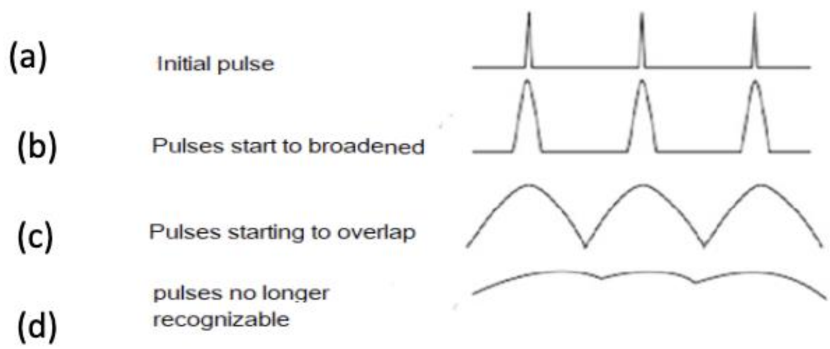

Figure 2. At various distances with time, the intensity of the pulses changes, (a) Original pulses, (b) pulses begin to broaden, (c) pulses begin to overlap, and (d) pulses become unintelligible

1.2 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 hole's diameters, hole-hole spacing, and holes numbers gives a unique dispersion, effective area, effective refractive index, and nonlinearity.

As dispersion plays a major role, it affects the propagation of the laser pulses (message) in the communication system in which the pulses suffer a broadening with time. To overcome this, the communication system must work at a wavelength range in a way that keeps the dispersion curve close to zero. To solve this disadvantage, the engineers must use pulses that have a wavelength close to the zero dispersion (ZDW) in the dispersion curve of the optical fiber. Figure 3a. shows how to choose the propagate wavelength (λ). This gives some restrictions on the choice of the laser type used.

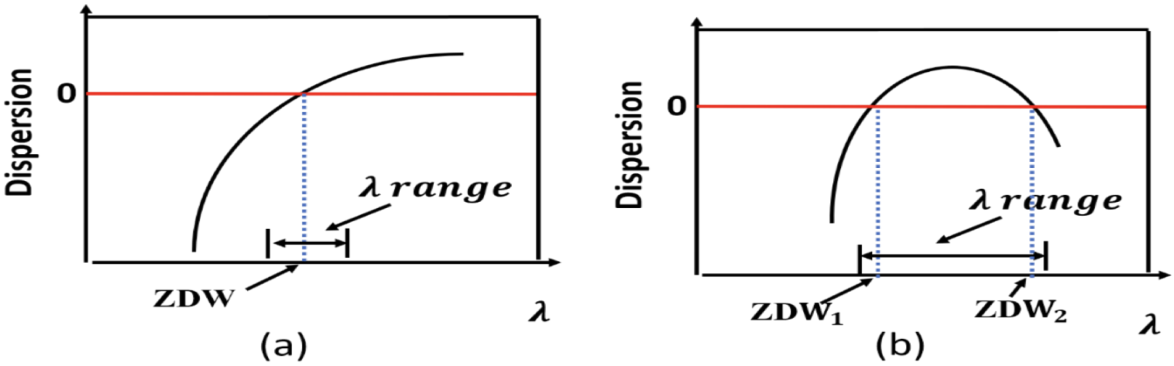

Figure 3. The wavelength selection range for (a) one ZDWs, (b) two ZDWs.

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 ZDW1 ≤ λ ≤ ZDW2 as seen in Figure 3.(b)

1.3 Raman Scattering with a Stimulus

When light is emitted in a medium, one of two things can happen either energy is exchanged with (Raman scattering) or without the material (Rayleigh scattering). In the meantime, Raman scattering can result in energy absorption (Stokes) or loss of energy (anti-Stokes) when an optical photon strikes the material (Sadeghpour & Dalgarno, 1992). Raman scattering begins as a natural process of light coupling with the molecules of the material through which it travels. However, when an excess of Stokes photons was generated by spontaneous Raman scattering are absent or supplied to the excitation laser, stimulated Raman scattering (SRS) occurs. On the higher wavelength side, these third-order phenomena form a Stokes band (Singh, Sharma & Kaler, 2009), and SRS redistributes energy from the higher component of frequency of the pulse to the lower component. Self-frequency shift occurs when the spectrum shifts to a higher wavelength and loses its symmetry (since no other pulse is involved). Figure.4 shows the Raman scattering and Rayleigh.

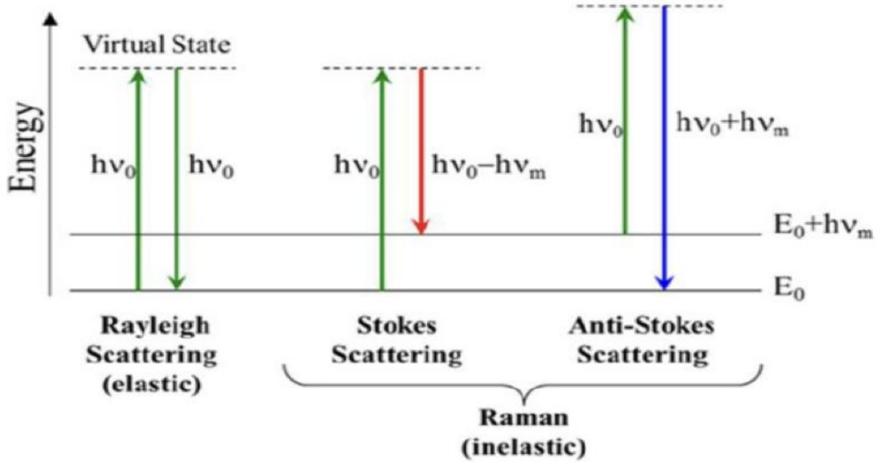

Figure 4. Diagram of Rayleigh and Raman Scattering quantum energy transitions

1.4 Soliton

In optics, a soliton is any optical field that does not change during propagation due to a balance between nonlinear and dispersive effects in the medium. John Scott Russell was the first to notice the Soliton phenomenon in 1834 (Singh, Sharma & Kaler, 2009). A light beam or wave propagating in a nonlinear optical medium with continuous shape and velocity is referred to as optical soliton. Solitons are used widely in nonlinear optical fiber communications, switching computing of optical, and many other applications (Hansson et al., 2020). Over the last two decades, specialized optical structures have attracted a lot of attention (Akhmediev et al., 2012; Melnik, Tcypkin & Kozlov, 2018; Malomed et al., 2016; Li et al., 2018). By compressing nonlinearly, the soliton compensates for linear pulse propagation (Lee et al., 2008). Figure.5 shows how normal pulses and optical solitons pulses propagate differently.

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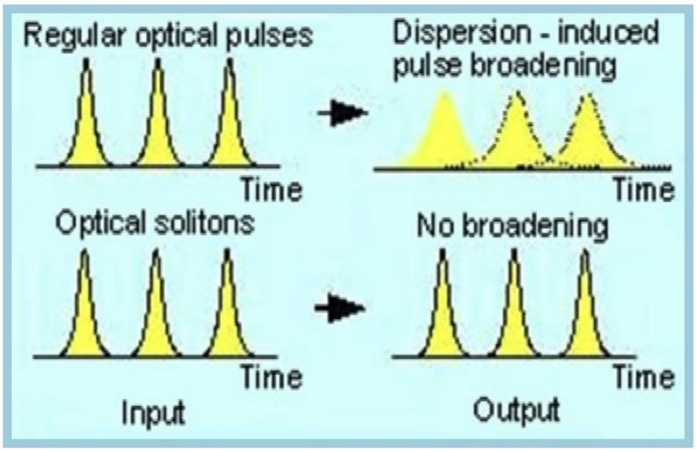

Figure 5. Waveform transformation of standard optical signals and optical soliton pulses throughout optical propagation

Since the discovery of solitons in optical fibers in 1973, optical solitons have progressed in the path of optical communication applications due to technological advances (Malomed et al., 2016). Even during the 1970s and 1980s, the propagation of "ideal solitons" was assumed in which solitons propagate in optical fibers with constant dispersion and nonlinearity values so that their amplitude and width stay identical over propagation distance loss in optical fibers to reduce nonlinearity (Melnik et al., 2018). These losses impede dispersion and nonlinearity balance and reduce soliton propagation distortion. Solitons are classified as either temporal or spatial based on the confinement of beam laser in time or space during propagation. Temporal solitons are optical pulses that keep their shape throughout propagation, whereas spatial solitons are self-guided structures that are still confined in a transverse direction, orthogonal to the direction of propagation (Boyd, 2020). Both categories of soliton arise from a nonlinear alteration in the refractive index of an optical material caused by beam laser intensity. When the self-focusing of an optical beam balances its natural diffraction-induced spreading spatial soliton, this is known as the optical Kerr effect in nonlinear optics (Shah et al., 2020). A temporal soliton occurs when the natural dispersion-induced expansion of the optical wave counteracts. As a result, the pulse (or beam laser) propagates across a material without changing its shape and is described as self-localized or self-trapped (Akhmediev et al., 2012).

The observation of the nonlinear phenomena of continuous-wave (CW) optical beams laser self-trapping in a bulk nonlinear material is known as a spatial soliton. During the 1980s, stable spatial solitons were discovered utilizing nonlinear media with only one transversal dimension of diffracting spread (Duan et al., 2012).

When the group-velocity dispersion (GVD) is uniform, optical fibers were discovered in 1973 to allow another type of temporal solitons (Akhmediev et al., 2018). Standard pulse-like solitons are referred to as bright solitons to explain the distinction. During the 1980s, temporal dark solitons garnered a lot of interest. In optical waveguides and bulk media, spatial dark solitons can arise when the refractive index is lower in the high intensity zone (self-defocusing nonlinearity). Bragg solitons, vector solitons, spatiotemporal solitons, quadratic solitons, spatiotemporal solitons, and vortex solitons are some of the examples (Lee et al., 2008).

1.5 Specifications of the Optical Soliton in Optical Fiber Communication Systems

The consequences of dispersion and nonlinearity in optical fiber communication systems (OFCS) are destructive, but they are advantageous in OSFCS (Boyd, 2020; Shah et al., 2020); Luan et al., 2006).

(i) Soliton waves are extremely stable.
(ii) Their transmission rate exceeds that of the best linear system by more than a factor of 100.
(iii) Deformations in fiber shape or structure have no effect on them.
(iv) Soliton can always be transmitted without deformation if the nonlinear features of the pulse such as amplitude and intensity, and the dispersion features of the fiber such as frequency are matched.

(v) In all optical transmission lines with minimal loss, this style is the only stable phase for signal propagation in the fiber in the absence of fiber nonlinearity and dispersion.

(vi) Large signal widths are allowed in the dispersion-controlled fibers, wave height is minimized, and nonlinear interaction between neighboring waves as well as between different wavelength bands is reduced.

(vii) Soliton is used in the development of optical switches as well as in the networking industry.

2. MATHEMATICAL MODEL

Starting with four Maxwell's equations that explain light's electromagnetic fields and some algebra, one may arrive at the propagation wave equation illustrated in the formula below (Sakret al., 2019).

$$\nabla^2 E(w) + \frac{w^2}{c^2}\,\epsilon(w)E(w) = 0 \qquad (1)$$

Eq. (1) is in the frequency domain (Writing electric field (E) into two parts one in the transverse dimensions and the other in the propagation dimension and the wave propagation in photonic crystal fiber is generally governed by the NLSE (Sutherland, 2003).

As a first stage, one numerically built a PCFs utilizing the approach of completely vectorial effective indexing to explore an effect of TZDWs on the dynamical soliton. The PCFs are made up of a hexagonal shape with a series of 1 m air-holes across the whole length of the fiber. The dispersion coefficients for the second-order dispersion coefficients are in (ps^2)/km units. The nonlinear coefficient is at 0.003 $w^{-1}km^{-1}$. A pitch value changing of range (1.2-1.5) um characterizes the fiber cladding. The NLSE is used to model the constructed fiber mathematically (Agrawal, 2013):

$$(2)\frac{\partial A}{\partial z} - sgn\,(\beta_2)\frac{1}{2}\frac{\partial^2 A}{\partial T^2} - i\,\gamma|A|^2 A + \frac{1}{2}\alpha A = 0$$

The formula uses anomalous dispersion (β_2<0). Where A slowly varying the amplitude of the pulse envelope, β_2 = dispersion of the 2nd order, α = fiber loss, γ = nonlinear coefficient, sgn (β_2) is equal to '+' or '-' depending on whether $\beta_2>0$ or $\beta_2<0$. Usage of anomalous dispersion ($\beta_2<0$). Two function lengths representing dispersion (L_D) and nonlinearity will be added to further evaluate NLSE (L_{NL}) according to the formula below (Wartak, 2013):

$$= \frac{T_\circ^2 \, 2\pi}{|D|\lambda^2}$$

$$(3) L_D = \frac{T_\circ^2}{|\beta_2|}$$

$$(4) L_{NL} = \frac{1}{\gamma P_\circ}$$

Where $P_\circ$ is the initial power and $T_\circ$ is the duration value of the initial pulse or usually known as the full width of the half-max pulse (FWHMP) to illustrate the respective effect. These two measurements define how far a pulse must propagate. For numerical analysis normalize variables, Physically L_D is the length of propagation by which the Gaussian pulse widens by a $\sqrt{2}$ because of group velocity dispersion (*GVD*). Normalize variables for numeric processing are shown below:

$$\frac{A}{\sqrt{P_\circ}} \qquad (5) U =$$

$$\frac{T}{T_\circ} \qquad (6) t =$$

T_o denotes the full width at *half-maximal pulse. (FWHMP)* of the magnitude put pulse. Eq. (1), after a simple algebra shall take the form is given by:

$$(7) \qquad \frac{\partial U}{\partial z} - i\left(sgn(\beta_2)\left(\frac{1}{2L_D}\right)\right)\left(\frac{\partial^2 U}{\partial t^2}\right) + i\left(\frac{1}{L_{NL}}\right)|U|^2 U + \left(\frac{1}{2}\right)\alpha U = 0$$

Here $\alpha = 0$

Normalize the z vector as follows:

$$(8) \mathcal{L} = \frac{z}{L_D}$$

And the number of algebraic stages, Eq. (6) becomes:

$$(9)\left(\frac{\partial U}{\partial \mathcal{L}}\right) - i\left(\frac{sgn(\beta_2)}{2}\right)\left(\frac{\partial^2}{\partial t^2}\right) + i\, N^2 |U|^2 U = 0$$

where N denotes the soliton order, which is often referred to as:

$$(10) N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_\circ T_\circ^2}{|\beta_2|}$$

During pulse propagation, neither dispersive nor nonlinear effects play a significant role when PCFs length L is such that L≪ L_{NL} and L≪ L_D. In this regime, the PCFs are only a transporter of optical pulses. This regime is beneficial for optical communications. When the FCF length is L≪ L_{NL} but L≈ L_{LD}, GVD governs the pulse evolution and nonlinear effects play a minimal role. When the fiber and pulse characteristics are such that dispersion is dominant, the dispersion-dominated regime is used as follows:

$$\ll 1 \qquad (11)\quad N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_\circ T_\circ^2}{|\beta_2|}$$

When the PCFs length L is such that L≪ L_D but L≈ L_{NL}, self-phase modulation (SPM) governs pulse evolution in the fiber resulting in pulse spectral widening. Whenever nonlinearity is dominant, the nonlinearity-dominated regime is used as follows:

$$\gg 1 \qquad (12)\quad N^2 = \frac{L_D}{L_{NL}} = \frac{\gamma P_\circ T_\circ^2}{|\beta_2|}$$

In Eq. (9), whenever there is a fundamental soliton, and for other cases of the soliton, Nth order soliton will be used as indicated in the diagram.

3. RESULT AND DISCUSSION

In this theoretical study, the MATLAB simulation ODE 45 program was used, where it could reach the wavelength of zero-dispersion and can be changed to the visible and near-infrared spectral range for photonic crystal fibers. This brings us to many applications at different levels of the spectrum that occur when the distance between air holes increases, which can exhibit exceptionally significant waveguide dispersion. This results in anomalous dispersion in the visible and near infrared wavelength region as shown in Figure.6.

The wavelength of zero-dispersion can be changed to the visible spectral range for photonic crystal fibers that occur when the distance between the air holes increases from 1.3 um to1.5um, which can exhibit exceptionally significant waveguide dispersion. This results in anomalous dispersion in the visible wavelength region as shown in Figure.6.

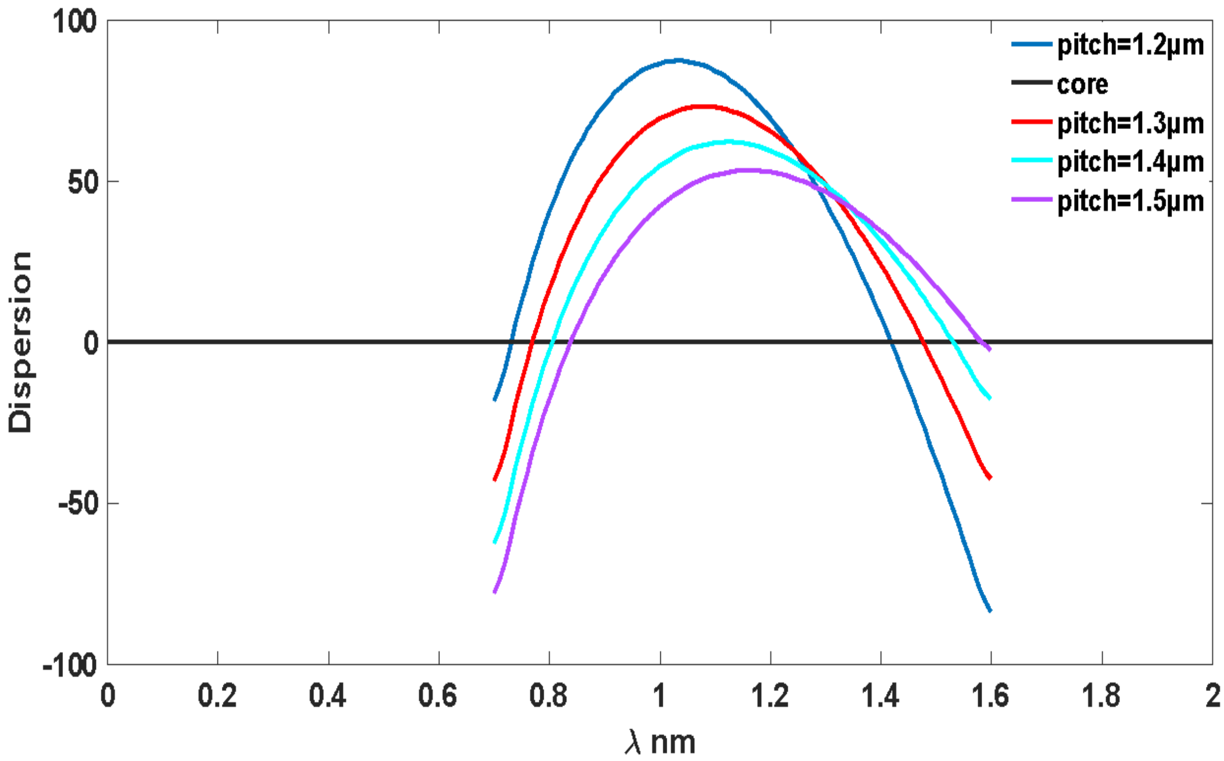

Figure 6. Variation of total TZDWs with λ for four different sets of Λ(1.2,1.3,1.4,1.5)um

From Figure.6, one can conclude that the spectrum is extended into the longer wavelength region by combining the positive wavelength dispersion gradient with the anomalous dispersion area. The soliton dynamics start after that, and the Raman Effect causes the soliton self-frequency to appear. Following that, the soliton dynamics, and due to the Raman Effect, soliton self-frequency emerges. Figure. 7 shows that meanwhile the lagged lower frequency components tend to move quicker as a fiber exhibits the gradient of positive dispersion at the 2nd-zero dispersion wavelengths as explained by Fig.3, higher frequency components travel quicker once the rise in dispersion reaches saturation, and the pulse is broken down into its constituent parts. As a result, the 2nd-zero dispersion wavelength prevents energy from migrating into the visible spectrum zone.

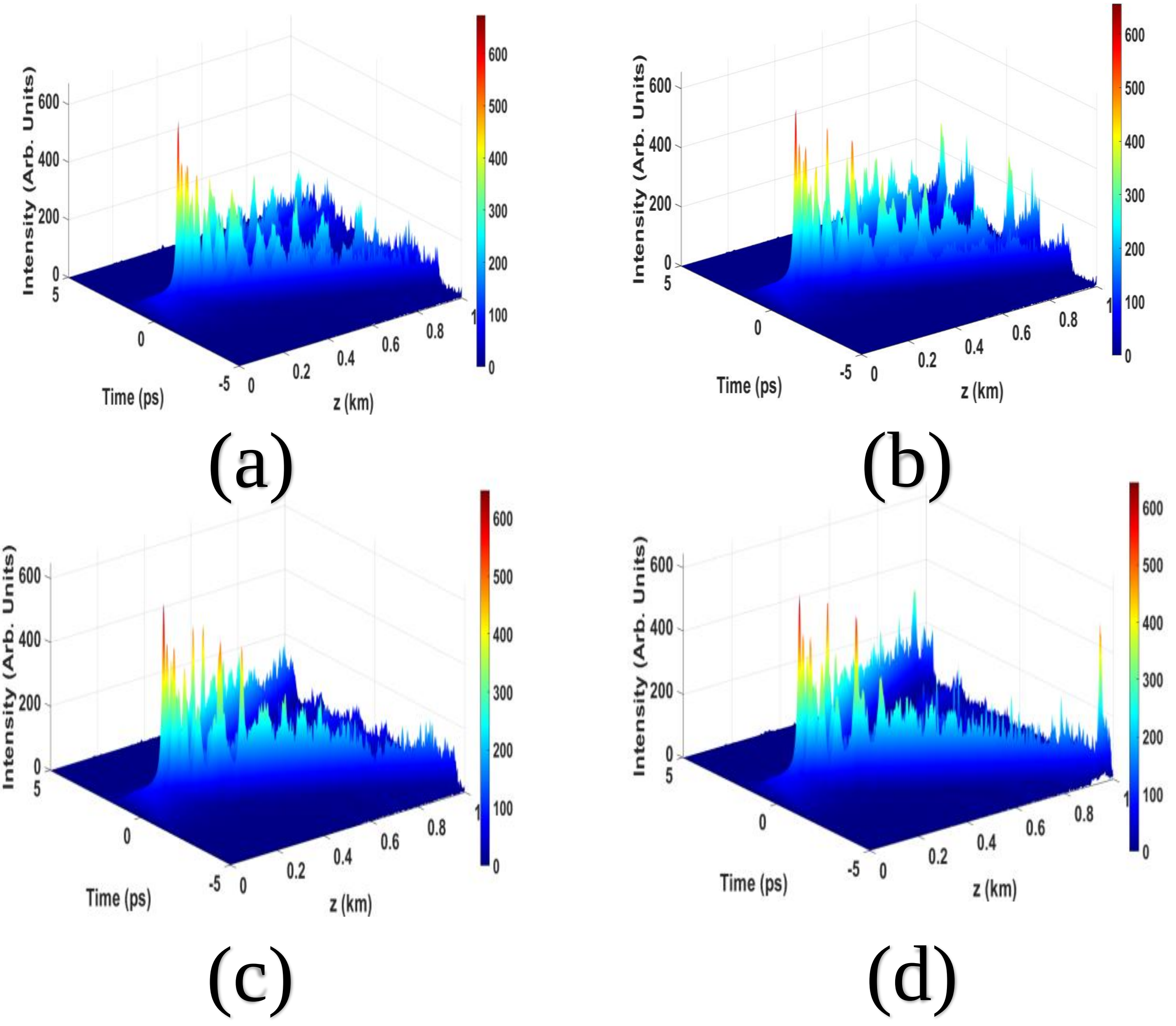

Figure 7. Temporal evolution of ultra-short higher-order (N = 3) soliton propagation, when a- Λ =1.2um,b- Λ= 1.3um,c- Λ=1.4um,d- Λ=1.5um

Solitons were formed as a result of this balancing act. The interplay between the negative dispersion slope and Raman scattering resulted in peculiar nonlinear spectral soliton dynamics. Despite the fact that the pulse is pushed in a dispersion zone that is peculiar, normal dispersion occurs in a segment of the pulse. High frequencies travel faster than the low-frequency component in the anomalous dispersion area, just as they do in positive launching conditions. This mechanism suppresses the phenomenon of soliton self-frequency shifted in the deeper long wavelength region, which is combined with the purely negative 2^{nd}-order dispersion gradient.

Solitary waves are formed by spectral components traveling with normal dispersion. As a result of the soliton interplay, the spectrum can be somewhat stretched into the longer wavelength area. The fiber exhibits radically different characteristics when the pulse is sent towards the 2nd wavelength of the zero dispersion.

4. CONCLUSIONS

In solid core PCFs, the soliton's impact on the 2nd-zero dispersion wavelength is studied numerically. The inquiry is predicated on the distance between air holes in PCFs. The wavelength of the pump is selected to lie inside the anomalous dispersion area. The gradient of the dispersion, as well as the symbol of 2nd-order dispersion, have been found to distinguish between the various launching conditions. In soliton, the Raman phenomenon is also important. One conclusion is that the solid core PCFs with TZDWs, in which extra constraints are imposed by the pitch, as well as third-order soliton conditions and associated dynamics, were able to show different levels of soliton transmitted through the PCFs by simply controlling the pitch (1.2, 1.3, 1.4, 1.5). Each type of soliton level has its own application depending on the design by the engineers. It was also verified in this study the possibility of obtaining a spectral expansion from a third-order soliton, which is used in many modern applications.

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