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**ORIGINAL ARTICLE**

# Study Effect Self-Frequency Shift of A Soliton in A Liquid Core Photonic Crystal Fibre

***Mohammed Salim Jasim AL-Taie[1]***

[1]Gifted Guardianship Committee, Directorate of Education, Misan, Iraq

*Corresponding author: msjadr72@gmail.comt

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## Abstract

In this study, the dispersion curve family reveals that changing the liquid core fluoro-ethylene increases the dispersion curve and causes the curve to flatten at sugar solution 60% with the second zero dispersion point of the wavelength as the refractive index rises. The two zero dispersion wavelength shifts toward the visible region, and it's clear that Soliton's intensity at the second zero dispersion point is around 10% to 25% of its maximum. These peaks are further subdivided into low amplitude dispersive waves depending on the liquid core used at the anomalous region of the fiber. When a soliton approaches the second point of zero dispersion, the refractive index rises. A broadband continuum named "supercontinuum" will emerge as a result of soliton fission, dispersive wave radiation, and soliton self-frequency shifting. This type of expansion is important in many modern applications, such as medical, industry, and communication systems.

**Keywords:** photonic crystal fiber; self-frequency shift; Raman effect; Solton; Supercontinuum generation.

## Introduction

PCFs (photonic crystal fibers) are an excellent medium for soliton (Artega-Sierra, Antikainen, Agrawal & Govind, 2018). The photonic cladding characteristics may be tweaked to modify the fiber's dispersion qualities (Vladimirov, Tlidi & Taki, 2021). The zero dispersion wavelength (ZDW) of a silica-based photonic crystal fiber may be moved into the visible region, allowing a variety of pulsed sources to be employed efficiently for broadband supercontinuum production over the visible and near-infrared spectrum (Amin et al., 2022). The ability to selectively fill photonic crystal fibers with diverse media opens up a variety of nonlinear optics options (Kasztelanic et al., 2018). The soliton self-frequency shifting (SSFS) process occurs when a single optical pulse's center frequency redshifts while passing through a photonic crystal fiber (PCF) due to nonlinear and inelastic photon scattering from the molecular lattice (Zhang et al., 2020), Due to the process' inherent nonlinearity, the SSFS rate is increased by raising the pulse's power density (Rusanen, Frolov, Weckström, Kinoshita & Arikawa, 2018).

Utilized for guiding construction. Having transverse measurements of such a select few micrometres, made as well as the index guide by core photonic crystal fiber or by confining other nonlinear phenomena fibers (Islam et al.,2021), Indeed, index guiding by core is beneficial in this regard and was used as a technique of gaining two zero dispersion anomalous, a requirement in support of the development of bright solitons (Alotaibi & Carr, 2019). As a result, longitudinal confinement of light can be kept by balancing (anomalously) dispersive pulse broadening with the Kerr effect's nonlinear phase shift. The core used in this study is normally made up of liquids uniform in diameter. Two zero-dispersion wavelengths are joined to the un-taped fiber, both at their extremities by a transition region. (TZDWs) on both the shorter (1st) and longer (2nd) wavelength ends separate the spectral regions of anomalous dispersion. A cancelation of a soliton's red-shift occurs when the soliton's self-frequency shift leads to the state of solitary attaining the second zero dispersion wavelength (Sun et al.,2022). at longer wavelengths, as well as intense. In a usually dispersive area, resonant emission of minimal-amplitude waves (scattering waves) occurs (Al Mohtar et al., 2017). As a result, the second point of zero dispersion wavelength effectively indicates the spectral region in which a soliton can red-shift to its maximum value. This property was already utilized to limit a red-shifting pulse's ultimate wavelength to a fixed amount that is in-dependent of the input power (Carpeggiani et al.,2020). While enhancing the Soliton self-frequency shift rate with tighter light concentration, differing liquids of the core This procedure may potentially be slowed by reducing the maximal red-shift achievable (Robichaud et al., 2022). One of the most appealing aspects of Soliton is its high climate control self-frequency shift based sources, and while the limitation on the range of wavelengths that can be achieved reduces the source's efficiency, Essentially, by modifying the liquid core of fiber, the shorter fiber length needed for a specific red-shift allowed by faster shift speeds might be advantageous (Christ, Ang, Li, Johannes, Kowalsky & Menzel, 2022), thus avoiding the trade-offs implied by shorter second Zero dispersion wavelengths show that in a core with a suitable liquid, there is an ideal degree of tapering beyond which the benefits of increased nonlinearity are no longer realized due to fiber dispersion behavior, Liquid core photonic crystal fibers have additionally been utilized for the amplification of a variety of nonlinear processes, including the trapping and visible-shifting of dispersion wavelengths and the construction of a coherence wideband continuously by a soliton with visible light. The soliton self-frequency shifting, as well as the longitudinally variable dispersion of the liquid core fiber, are crucial factors in each of these concepts (Lühder, Schneidewind, Schartner, Ebendorff-Heidepriem & Schmidt, 2021). In this paper, one looks at a way of creating an ideal liquid core profile that improves the SSFS rate while avoiding the second zero dispersion wavelength's limitations, The foundation of future reconfigurable and adaptable optical systems with unparalleled performance will be the selective filling of diverse materials. The optical nonlinearity discrete system, as well as the dispersion, spatial coupling, and spatial organization of a waveguide array.

## Materials and Methods

### *Linear and nonlinear in liquids core photonic crystal fiber*

This Several wavelengths propagate through the fiber concurrently for short pulses, even if nonlinear effects can be ignored. The term dispersion refers to the wavelength dependency of the propagation constant $\beta(\omega)$, in a Taylor series, developing $\beta(\omega)$ gives us (Rao, LIU & Zhao, 2022)

$$\beta(\omega) = \beta0 + \beta1(\omega - \omega0) + 1/2\ \beta2(\omega - \omega0)2 + \ldots \quad (1)$$

and

$$\beta n = (dn\beta(\omega)\ /d\omega n\ )\ \omega - \omega0 \qquad (n = 0, 1, 2, \ldots) \quad (2)$$

Inverse of the group velocity, $vg$, is $\beta_1$ in this case. When the definition of $\beta_2$ is added to the equation, the result is

$$\beta 2(\omega) = d\beta 1 \,/\, d\omega = (d/d\omega)(1/\,vg(\omega)) = -\,(1/\,v2\,g)\,(dvg/\,d\omega) \qquad (3)$$

The group- velocity- dispersion (GVD) is defined as the change in group- velocity as a function of frequency. It is critical to distinguish between two distinct dispersion regions. When $\beta 2 > 0$, During the so normal dispersion regimes, the red portions travel quicker than the blue. In the anomalous dispersion regimes, the inverse is true for the region containing $\beta 2 < 0$.

The wavelength where $\beta 2$ equals zero is referred to as the zero dispersion wavelength (ZDW) (Zhang et al., 2022), In our current study, there are two zero-dispersion, which gives a broader scope to work at multiple points where the dispersion is zero. can been adjust the GVD to the various applications. Another definition of the GVD is also used throughout the description (Khalyapin, 2021).

$$D = -(2\pi c \,/\, \lambda^2)\,\beta_2 \qquad (4)$$

The wavelength is denoted by λ.

When nonlinear effects play a significant role in the liquid core of the fiber, the response of the nonlinear effect is characterized by the function R(t) defined by the generalized nonlinear Schrödinger equation (GNLSE), includes Raman phenomena as well as the self-steepening phenomenon (Hernandez et al., 2022).

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

$T = t - z/vg$ in a co-propagating time frame. In this study, Equation (5) is used to simulate propagation in the selectively filled PCF. It is numerically solved using a split-step Fourier method by trying to plug in all of the photonic crystal fiber parameters used, such as the calculated dispersion coefficients $\beta n$ (Ibarra-Villalon, Pottiez, Gómez-Vieyra, Lauterio-Cruz & Bracamontes-Rodriguez, 2021).

The function $R(t)$ in the generalized nonlinear Schrödinger equation describes the retarded response of the nonlinear liquids. The response function $R(t)$ is influenced by a number of physical factors, and the function can be expressed as (Mei, Steinmeyer, Yuan, Zhou & Long, 2022).

$$R(t) = fe\delta(t) + fRhR(t) + fmhm(t) \qquad (6)$$

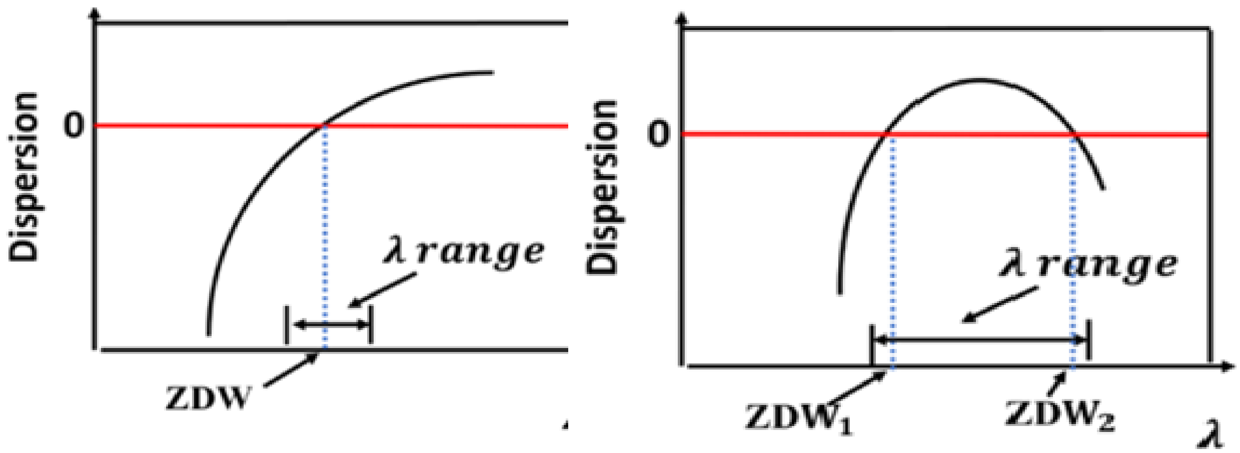
The initial contribution is provided by electron motion caused by incoming light. The answer takes only a few femtoseconds since the electrons are closely bonded. This effect can be considered instantaneous when the material is illuminated with pulses of several hundred femtoseconds in length, and the temporal dependence can be written as $\delta$ -function.

Raman effects provide the second part. The temporal responsiveness is represented by the function $hR(t)$. It is a material feature as well, and in (Hernandez et al., 2022; Mei, Steinmeyer, Yuan, Zhou& Long, 2022), a general version of $hR(t)$ is proposed as

$$h_R(t) = \frac{\tau_1^2 - \tau_2^2}{\tau_1\tau_2}\exp\left({}^{-t}/{}_{\tau_2}\right)\sin\left({}^{t}/{}_{\tau_1}\right) \qquad (7)$$

The Raman line shift and line width are the parameters $r_1$ and $r_2$, respectively. The molecular reorientation causes the third part, only gases and liquids can have this effect. The incoming light aligns the thermally directed particles in the medium, resulting in a relatively high polarizability (Dahal, Allemeier, Isenhart, Cianciulli & White, 2021). As dispersion plays a major role, it affects the propagation of the laser pulses (messages) in different systems, where 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 advantage, the engineers must use pulses that have a wavelength close to that which gives the zero dispersion (ZDW) in the dispersion curve of the optical fiber. Figure. 1a shows how to choose the propagation wavelength (λ). This places some restrictions on the choice of the laser type used.




(a) (b)

**Figure 1.** The wavelength selection range for (a) one ZDW, (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 $ZDW_1 \leq \lambda \leq ZDW_2$ as can be seen in Fig. 1b. After demonstrating that an optimal liquid of core exists through a series of simulations, one can investigate how progressively broadening the soliton shifting at the proper rate can result in a higher redshift than a normal profile.

## Results and Discussion

### *Identifying the second zero dispersion wavelength*

The effect of liquids in fluid-filled fibers having a delayed response on soliton dynamics was investigated. a hexagonal photonic crystal fiber was designed, with a radius of 0.4 μm, the distance between the air holes is 1.5 μm, and it has a liquid core, where seven types of liquids were used, starting with tetra fluoro ethylene to sugar solution 60% and depending on the Matlab program ODE45, the results were reached where it turns out that the dispersion curve family reveals that changing the liquid core fluoro ethylene increases the dispersion curve and causes the curve to flatten at sugar solution 60%. Figure. 2 shown the refractive index rises with different liquids core, and the TZDW shifts toward the visible region, explained that in Figure. 3

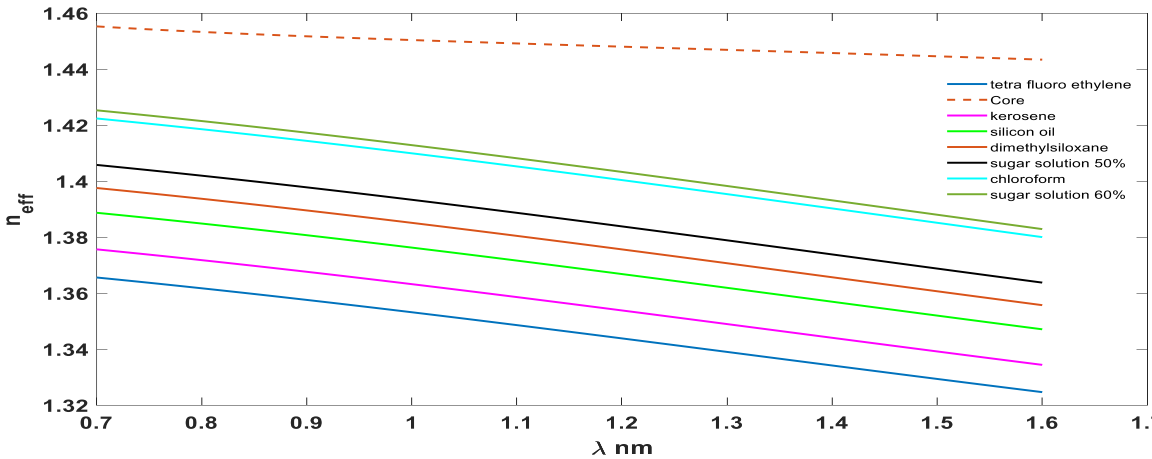



**Figure 2.** Show the refractive index with different liquids core

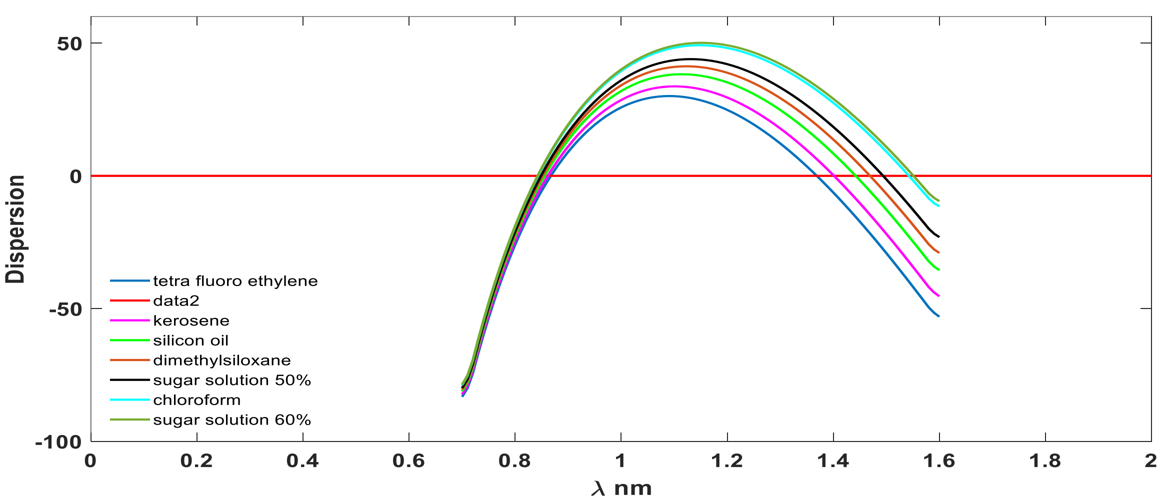



**Figure 3**. Explain the curve shifted toward the visible light.

The effect of changing the liquid fibre core on the refractive index was determined from the Figure 2 result, which in turn led to a change in the locations of the two zero dispersion points Figure 3 shown that. It appears that the liquid with the highest refractive index and two-zero dispersion points in it crawling towards the longer wavelengths, one know the disparity is due to anomalies between the manufacturer's dispersion curve as well as the true PCF component dispersion, especially in the 2nd ZDW area, because this stabilisation frequency is independent of input power. If the original dispersion slope is essentially red-shifted, the relative dispersion slope will also be red-shifted, It is possible to determine the 2nd ZDW to be around 1.630nm.

***Self-frequency shift of solitons in liquid core fibres***

To confirm the reliability of estimate, numerical models of soliton dynamics using a mathematical formulation in the nearby area of the 2nd ZDW were performed. In actuality, this approach is limited to employs the nonlinear Schrödinger equation (NLSE), which includes the Raman scattering , as well as the 2nd and 3th order the coefficients of dispersion (β_2 and β_3), which are obtained from a Taylor series of the transmission constant at the normalising frequency of the a soliton. Variations in the stabilisation wavelength and amplitudes at ZDW (respectively δλ and δI) have been studied by varying the liquid core of photonic crystal fiber. In Figure 4, For bigger differences, numerical spectrum are displayed., and it is clear that such Soliton amplitude at the Zero-dispersion wavelength maintains about 10-25 percent This corresponds to a ZDW position inaccuracy of roughly 0.1 nm, Figure 4 show the change in relative intensity with respect to time, while Fig. 5 explained the relative intensity with respect to the distance for different core liquids which is used in this study.

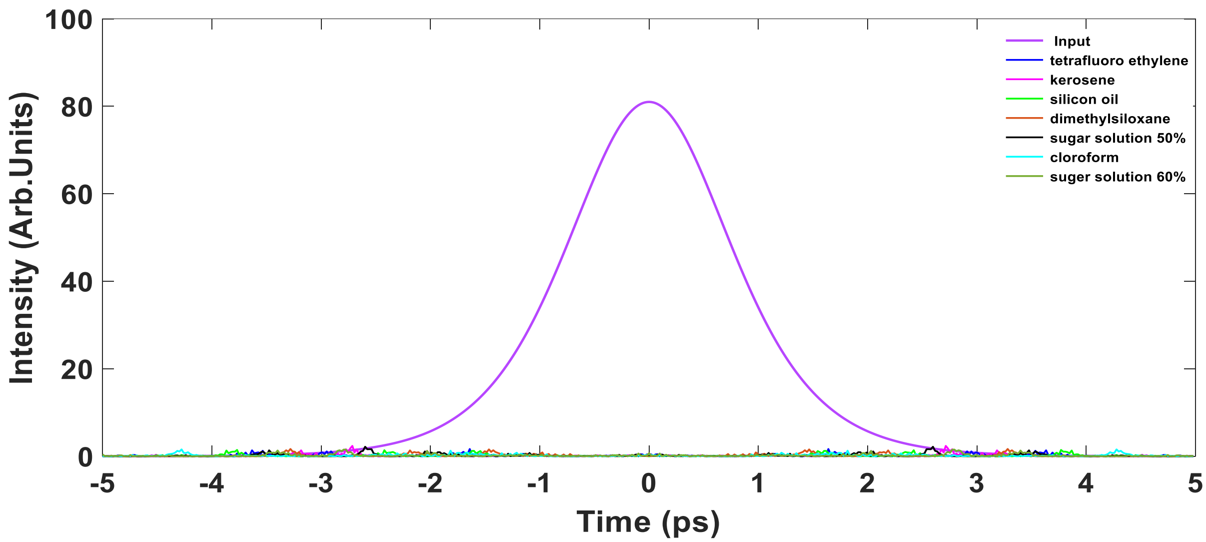



**Figure 4.** shows the intensity with respect to the time for different liquids core

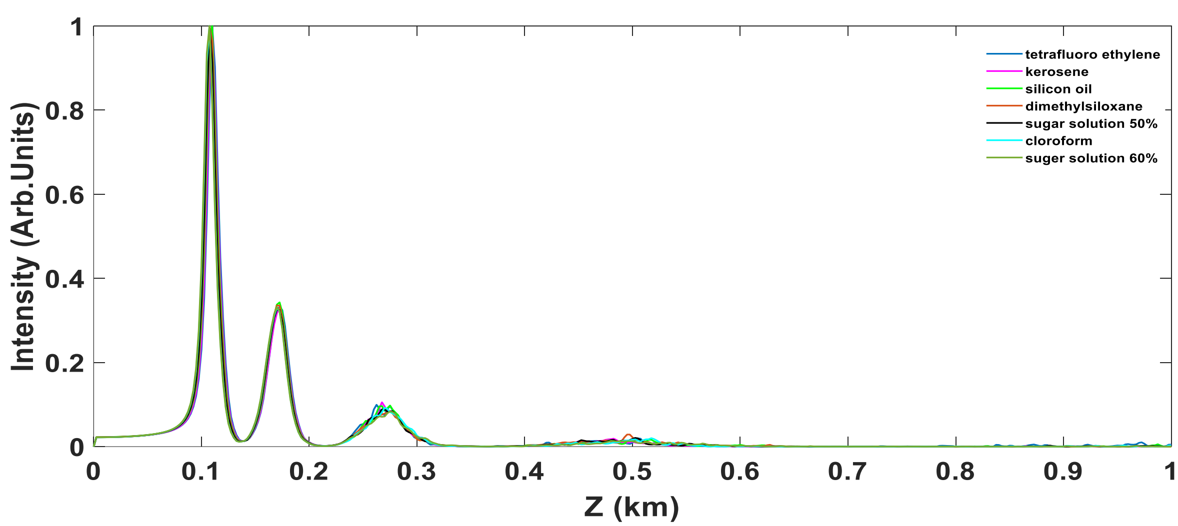
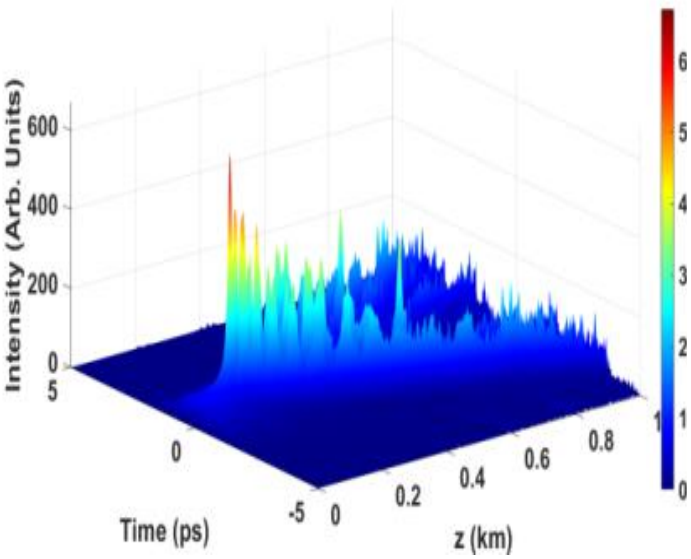
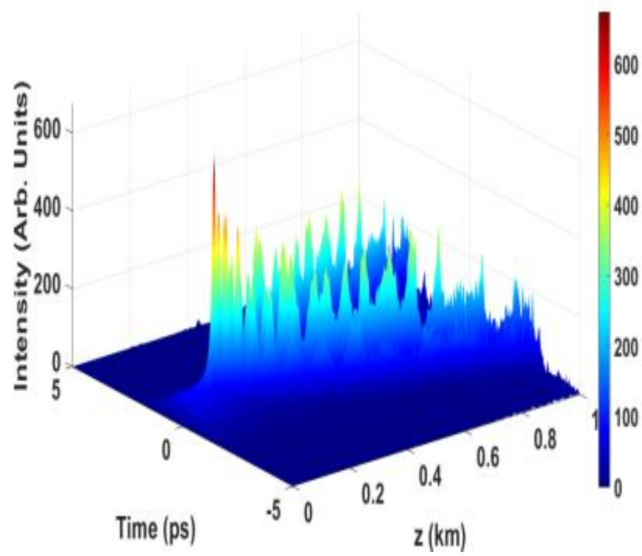



**Figure 5.** shows the intensity with respect to the distance for different liquids core

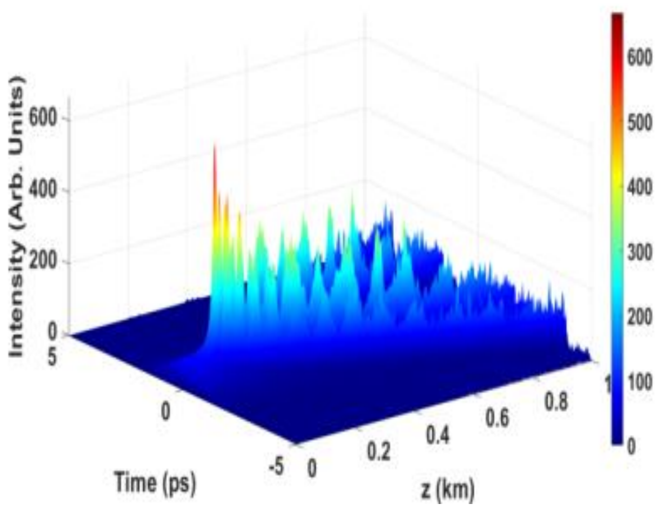
Pumping wavelengths are chosen because they fall in the anomalous dispersion region and are close to their, results in Fig. 6 depict the spectral and temporal evolution of a soliton launched near the first ZDW. At ZDW, there are changes in the stabilising wavelength and amplitudes. (respectively δλ and δI) have been studied by varying the liquid core of photonic crystal fiber. In Figure 6, For bigger changes, actual spectrum is provided.




(a)




(b)

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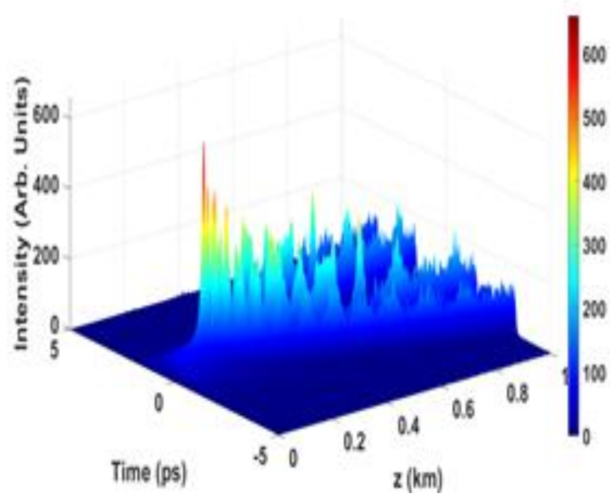


(d)

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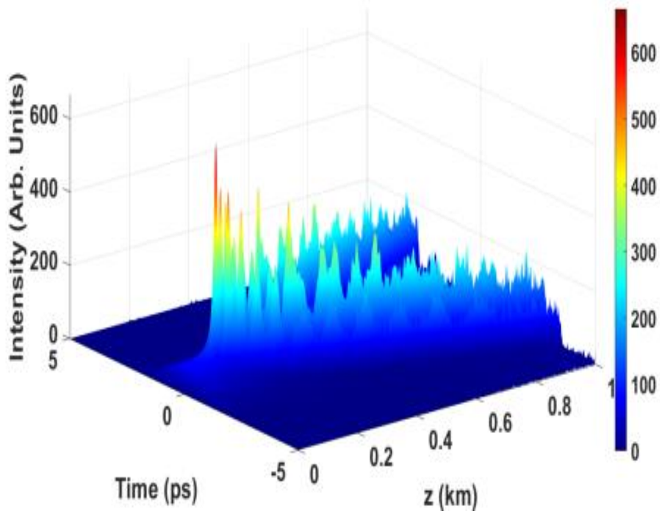
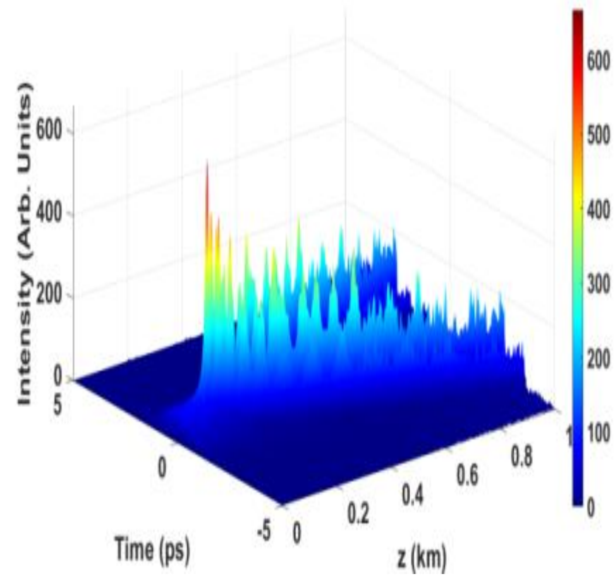
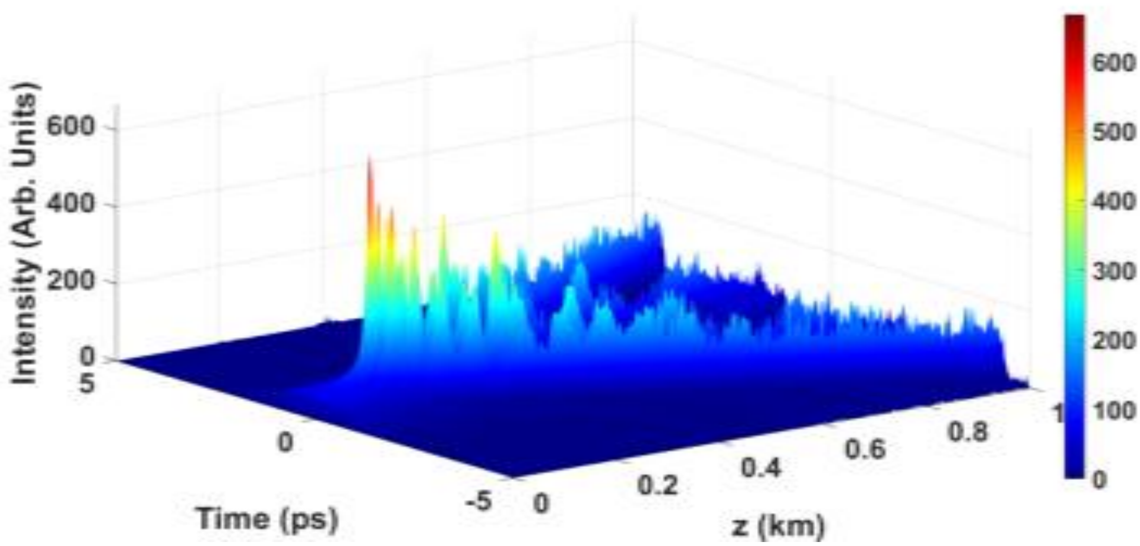



(e)




(f)




(g)

**Figure 6.** Explained Soliton fission with different liquids core

The soliton spectrum evolves in three stages: initial soliton fission and diffraction wave generation, higher-order soliton compaction and Raman self-frequency shift. Figure. 6 depicts the dynamic behavior of Soliton during the initial phase, when the spectral broadening is more symmetrical about the pump wavelength. The relative detuning between the ZDW of the fiber and the type of core material is crucial to the dynamics of soliton in PCFs. by using liquid core with laser pulses the Soliton spectra evolve differently depending on the liquid core used at the anomalous region of the fiber, according to the previously reported results. These peaks are further subdivided into low amplitude dispersive waves. As the liquid core's refractive index rises, the high-frequency components support the expansion while the low-frequency components narrow. Individual nonlinear contributions are numerically examined to gain a better understanding of the underlying soliton dynamics, higher-order dispersion, Raman scattering and modulation instability all make higher-order solitons sensitive to disturbance. (see Figure 6).

Soliton fission is conceivable with a modified liquid core with a high enough refractive index order. The geometrically widening is enhanced further as the pulse grows, with identifiable peaks forming in the higher and lower frequency ranges. A higher-order soliton of order N emits N basic solitons in decreasing order of peak intensity. These solitons are subsequently exposed to SSFS, resulting in the formation of a supercontinuum. Furthermore, the Raman contribution causes them to shift to various wavelengths, while dispersion causes them to change to distinct temporal locations. When a soliton approaches the ZDW, certain energy is transferred into the typical dispersion region, resulting in a dispersive wave (DW). A broadband continuum known as the supercontinuum will form as a result of soliton fission, dispersive wave radiation, and SSFS.

## Conclusion

Soliton dynamics in photonic crystal fiber are complicated. The implications of this difficulty on the statistical features of the soliton spectra have only recently been demonstrated, but there is obviously a lot of motivation in studying more about the physical mechanisms that cause Soliton instabilities, particularly perturbations in dispersion from a first period of modulating unstable.

The major purpose of this study was to investigate into the influence of two-zero dispersion in the liquid core on the self-frequency shift of the red-shifted ejection solitons created during picosecond continuous generation in a two-zero dispersion wavelength (TZDWs) in photonic crystal fibres (PCFs). for different types of cores Various distributions for the soliton peak were observed depending on the type of liquid. Liquid core plays a critical role on the second ZDW, according to extensive simulations. The physical process that causes this uniformity for soliton frequency and amplitude is straightforward: For particular liquids of core and in a mode related to the onset of dispersive wave transmission, the much more strenuous solitons in the distributing Raman-shift towards the zero dispersion wavelength first, loosing energy to the scattering wave preference.

This finding is important for understanding Soliton's noise properties in fibers with two ZDWs, and it could also have practical implications. The usage of a two-ZDWs PCF may be advantageous in generating intensity stabilised ultrafast pulses from an initial pico-second supply excitement for operations including such microfluidic devices where non-resonant excite is achieved with ultra-short impulses.

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