Supercontinuum Generation by Controlling Pitch in Photonic Crystal Fibers

Mohammed Salim Jasim Al-Taie

Gifted Guardianship Committee, Directorate of Education, Misan, Iraq
****Email: mohammed.altaie@iraqiggc.edu.iq.***

ABSTRACT: The influence of varying the distance between air holes (pitch) on the geography of solitone propagation through the photonic crystal fiber has been tested, and the study depends on the Split-Step Fourier method and the results that were reached by using the MATLAB program. The first-order solitone was tested with the change in pitch, and it was found that there is a clear decay in the amplitude of the resulting pulse with the increase in pitch . While increasing the pitch in the case of second-order solitons, it was noticed that the pulse would split into multiple-order solitons down to higher-order solitons with the increase in pitch, while in the case of third-order solitons, solitonic fission leads to the supercontinuum generation with increasing the pitch, where the supercontinuum generation was reached in this way depending on a very small energy source compared to the high energies approved to generate this type of spectrum by the previous methods. In this study, observed that when the pitch values increased in the third-order soliton, this result led to the use of supercontinuum generation (ScG) which has many applications such as medical and industrial applications and has an important role in modern communication systems.

Keywords: Photonic Crystal Fiber, Split-Step Fourier, Soliton Pulse, Pitch, Supercontinuum Generation.

توليد التوسع الطيفي الفائق من خلال التحكم بالمسافة بين الفجوات في الياف البلورة الفوتونية

محمد سالم جاسم الطائي

الملخص: تم اختبار تأثير اختلاف المسافة بين ثقوب الهواء على جغرافية انتشار السوليتون من خلال ألياف البلورة الفوتونية ، وتعتمد الدراسة على طريقة الخطوة المنقسمة لفورييه والنتائج التي تم التوصل إليها باستخدام برنامج ماتلاب تم اختبار السوليتون من الدرجة الأولى مع التغيير في المسافة بين الفجوات الهوائية ، حيث وجد أن هناك اضمحلالا واضحًا في سعة النبضة الناتجة مع زيادة المسافة. بينما في حالة السوليتونات من الدرجة الثانية ، لوحظ أن النبضة ستنقسم إلى سوليتونات متعددة الترتيب وصولاً إلى السوليتونات ذات الترتيب الأعلى مع زيادة المسافة بين الفجوات الهوائية ، بينما في حالة السوليتونات من الدرجة الثالثة ، يؤدي الانشطار السوليتوني إلى توليد التوسع الطيفي الفائق مع زيادة المسافة بين الفجوات ، حيث تم الوصول إلى التوسع الطيفي الفائق بهذه الطريقة اعتمادًا على مصدر طاقة صغير جدًا مقارنةً بالطاقات العالية المعتمدة في توليد هذا النوع من الطيف بالطرق السابقة. في هذه الدراسة لوحظ عند زيادة قيم المسافة بين الفجوات التي تؤثر على السوليتون من الدرجة الثالثة ، يتم الحصول على التوسع الطيفي الفائق الذي له العديد من التطبيقات منها الطبية والصناعية ، وله دور مهم في أنظمة الاتصالات الحديثة.

الكلمات المفتاحية: ألياف البلورة الفوتونية ،طريقة الخطوة المنفصلة لفورييه ، نبضة سوليتون, المسافة بين الفجوات الهوائية, التوسع الطيفي الفائق.

1. Introduction

A solid-core photonic crystal fiber is defined as a fiber with a silica backdrop and air holes in the cladding area. The core is engineered to have a high refractive index compared to the cladding, and laser light is guided through the fiber in the same manner that it is guided in traditional fibers, through a modified total internal reflection process [1]. This structure allows a PCF to be built with better properties than a traditional optical fiber. These characteristics include an indefinite single module, controllable dispersion qualities, and a high nonlinear factor [2]. Because of these characteristics, the PCF can be used as optical amplifiers, fiber lasers, super continuum generation, and all-optical wavelength transfer, among other applications [3]. The PCF's nonlinearity properties can be improved by achieving a limited effective mode region [4]. The PCF nonlinearity can be improved by a few degrees by decreasing the effective mode region. As the nonlinear coefficient is increased, the fiber becomes a perfect candidate for optical applications, and the detection of nonlinear effects becomes possible at the shortest fiber lengths [5-7]. It is therefore possible to achieve a well-guided mode that is limited to a narrow region by varying the sizes of the air-holes within the cladding region. PCFs are used in parametric amplifiers as nonlinear mediums[8]. By appropriately adjusting the air-hole diameters, one may construct an appropriate mode area that results in the required nonlinearity [9-10]. Optical parametric amplifiers in fiber are used in a variety of applications, including signal processors, converters of optical wavelength, and line amplifiers. To assure manufacturing, a new PCF with a radius suitable for airholes (d=0.5)μm was designed with low dispersion, high nonlinearity, decreased confinement loss, and improved mode region characteristics. The PCF structure, which has a wide range of applications in optical communications, was created using a modeling methodology specific to this study. The propagation of the first, second and third-order solitones was controlled by controlling the distance between the air holes (Λ) .

2. Photonic Crystal Fibers (PCFs)

This form of PCF is made up of a patrol system of air holes rings with a solid core in the middle that runs through the length of the fiber, as shown in Figure 1.

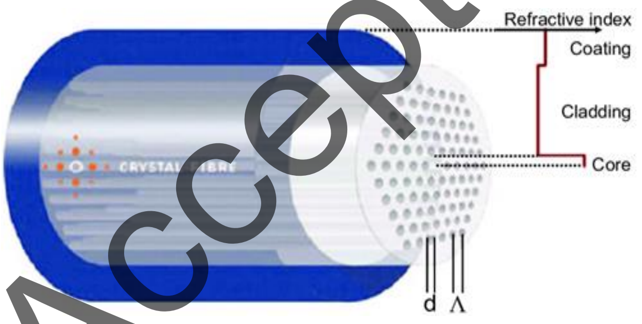


Figure 1. Solid-core PCF with microstructure cladding is the most prevalent design.

They are made of pure silica, and their aim is to lower the cladding's effective refractive index, resulting in a total internal reflection guidance system [11]. (Figure 1,a) illustrates the cross section of the solid core. (Figure 1,b) shows the variation in refractive index with radial size.

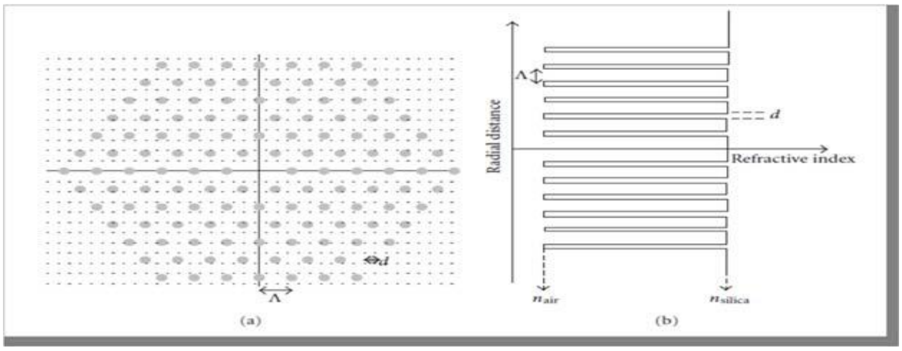


Figure 2. (a) Solid-core fiber cross-section and (b) refractive index profile[12]

One of the most appealing features of (PCFs) is their ability to remain single-moded over a broad wavelength range, unlike ordinary single-mode fibers, which become multi-moded for wavelengths under their single-mode cut-off wavelength. PCFs with this benefit are known as Endlessly Single-Mode (ESM) – PCFs [13]. The cladding's limited air-filling fraction is needed for a low index-contrast equivalent waveguide, which is required for single-mode operation. At lower wavelengths, the effective index of the cladding would be similar to the refractive index of the silica. This property would reduce the wavelength and maintain the single-mode over a broad wavelength range [14]. The improved optical guiding conditions ensure that PCFs are ideal for the desired application through the following effects:

A-Effective AreaA_{eff}

The light carrying region is commonly referred to as the effective mode area. Electric-field (E) propagation occurs within the core for the fundamental propagating mode; as a result, the effective mode region (EMA) of a PCF can be calculated using equation 1[15].

$$A_{eff} = \frac{\left(\int\int |E_t|^2 dxdy\right)^2}{\int\int |E_t|^4 dxdy)} \qquad (1)$$

B-Non Linear effect (γ)

The nonlinear effects would be worthwhile with a high optical power density supplied by a limited effective field. The effective region and even the nonlinear coefficient of the PCF background material in relation to the operating wavelength are all directly related to the nonlinear effectiveness or nonlinearity. An Equation should be used to look at the nonlinear effect [15].

$$\gamma = \frac{n_2 2\pi}{\lambda A_{eff}} \qquad (2)$$

C-Material Dispersion

Since the phase index fiber model is made of pure silica glass, the material dispersion (in the core region) can be approximated using the Sellmeier principle. The wavelength dependency of a material's refractive index is caused by the interaction of the optical mode with ions, gases, or electrons in the material. The dispersion of the materials is determined by [16].

$$D = -\frac{\lambda}{c}\frac{d^2 n}{d\lambda^2} \qquad (3)$$

In this study, one cares about the pulse that takes the form of sech^2 pulses, which is known as soliton.

3.Soliton In Photonic Crystal Fibers

The interesting phenomenon of optical solitons, which are solitary optical waves that spread in a particle-like manner over long distances, has been the subject of intensive research in recent decades owing to its critical position in groundbreaking applications such as mode-locking [17], frequency combs [18-19], and supercontinuum generation [20, 21], among others [22- 24]. One of the specific challenges is the interaction of a laser pulse with a nonlinear photonic crystal. Many papers deal with (i) building an all-optical switcher based on this relationship, (ii) light translation on photonic crystal defects, and (iii) photonic crystal use in different laser systems [25]. The main aim of this study is to investigate in depth the relationship between soliton formation and parameters, as well as to discover a method for regulating soliton parameters and soliton displacement in photonic crystals. The (NLSE) governs pulse propagation within a waveguide[26]. Mathematically, it is expressed as[27]:

$$i\,\frac{\partial A(z,t)}{\partial Z} = \frac{i\alpha}{2}A(z,t) + \frac{\beta_2}{2}\frac{\partial^2 A(z,t)}{\partial T^2} - \gamma\,|\,A(z,t)\,|^2\,A(z,t) \qquad (4)$$

Where $A\,(z,t)$ denotes the slowly varying pulse envelop amplitude, β_2 = 2nd- order dispersion, α= losses of fiber, γ = effect of nonlinearity. The effects of fiber losses, nonlinearity, and dispersion on pulses transmitting through the fibers are described by the three components on the right side of equation (4). Depending on the incoming pulse characteristics - peak intensity (Po=1) watt and starting width (To=1) ps, dispersive or nonlinear effects prevail along the fiber. The dispersion length (L_D) and nonlinear length (L_N) values of the fiber over which dispersive or nonlinear effects are relevant for pulse evolution are used to determine length scaling. Mathematically-based [28-29].

$$L_D = \frac{T_\circ^2}{|\beta_2|} \qquad (5)$$

$$L_{NL} = \frac{1}{\gamma\beta_\circ} \qquad (6)$$

The split-step Fourier method (SSFM) is used to perform the numerical simulations. Abnormality is suspected in the dispersion (β_2 = - 3) $ps^2 km^{-1}$, furthermore, there are no losses. (α = 0) $dBkm^{-1}$. nonlinear effects (γ= 1)$W^{-1}Km^{-1}$, where the parameters for the photonic crystal fibers are the distance between holes (d=0.5) μm, wavelength (λ=1.55)nm, number of air-holes (n=8), and diameter of the air hole (Λ=1.2,1.8,2)μm. The results are reached using the MATLAB program.

4.Simulation Results

The effect of the distance between air holes (Λ) on different-order solitons has now been studied and analyzed.

4.1 First-order soliton

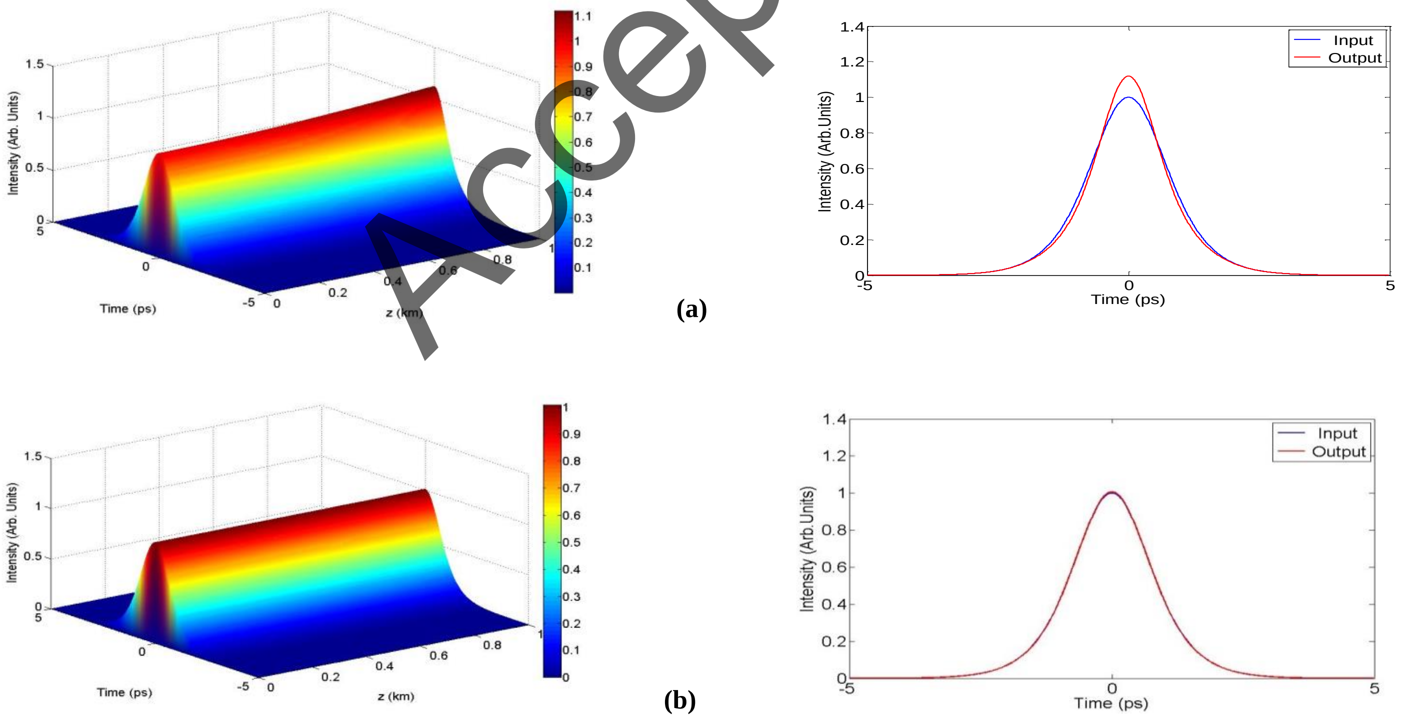
Sech, pulses of the form are used, i.e, having the following form [30].

$$A(0,t) = N\ Sech(t) \qquad (7)$$

The order of the pulse is represented by N. When N=1 is used, just generate the first-order.

$$A(0,t) = \ Sech(t) \qquad (8)$$

If the pulse has the form of a "Sech" and N = 1, it is referred to as the fundamental soliton, and Figure (3- a,b,c) below shows its propagation along the fiber. The distance between air holes (Λ) first-order solitone has been controlled as Λ =(1.2, 1.8, 2)μm. And the radius of the air holes is constant, equal to 0.5 μm As shown in the following results.



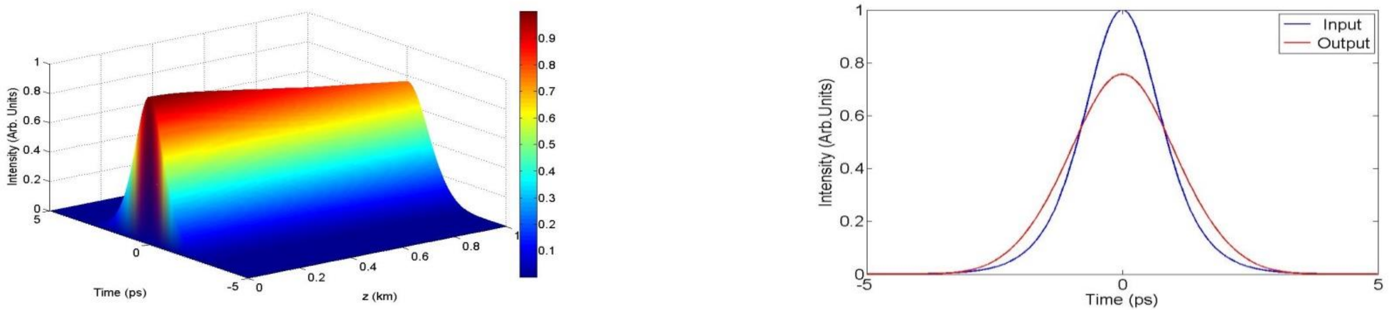
(a)

(b)

Figure 3. Shows the amplitude of the output pulse in three and two diensions, first- order soliton, with different pitch

a- Λ =1.2μm, b- Λ =1.8 μm,c- Λ =2 μm

Continue



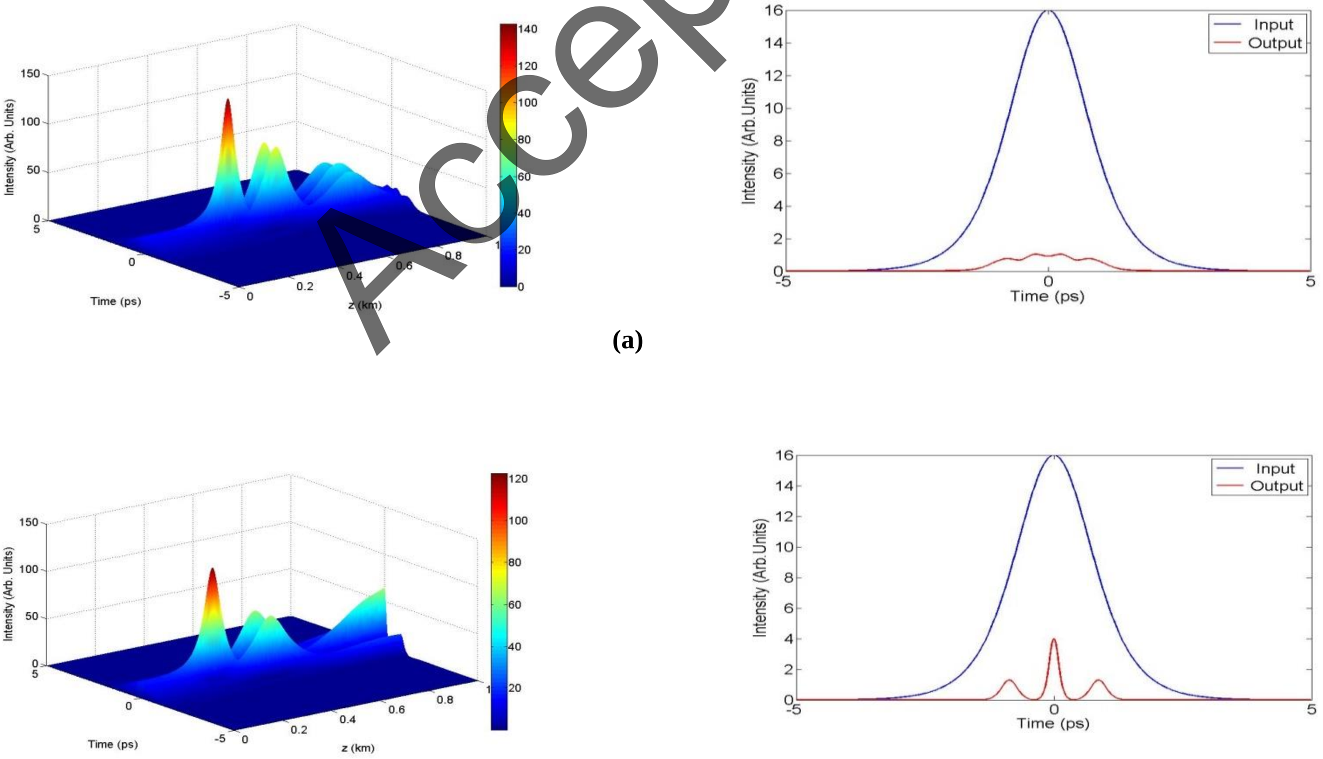
(b)

Continued

Through the results of the change in the diameter of air holes in figure 2, it is clear that there is a decrease in the amplitude level of the outgoing pulse and that this decrease is gradually decreasing as the diameter of air holes increases. There is also a clear capsizing in the 3D pulse; rather than the widening at the end of the pulse appearing as the diameter of the holes increases, the expansion begins from the beginning of the pulse spread. The reason for this is that by increasing the diameter of the holes, the distance traveled by the light propagation through the fiber will lose part of its power, which leads to a decrease in the amplitude of the pulse coming out.

4.2 Second – Order Soliton

In the second order of soliton where N=2As in the 3D soliton, the pulse displays convexities and concavities with distance and time with the change in the diameter of air holes, and that increasing this same diameter of air holes has a clear influence on modifying the pulse strength, and that the output pulse steadily diminishes as the diameter of air holes increases, as seen in the 2D soliton. Figure 4 shows that.

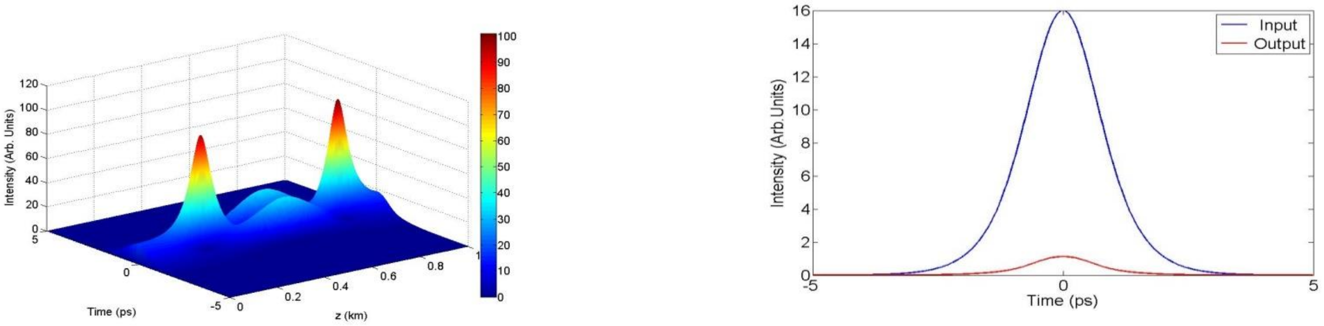


(a)

(b)

Figure 4. Explain the amplitude of the output pulse in three and two dimensions for a second order- soliton, with different pitch. a- a- Λ =1.2μm, b- Λ =1. 8 μm,c- Λ =2 μm

Continue



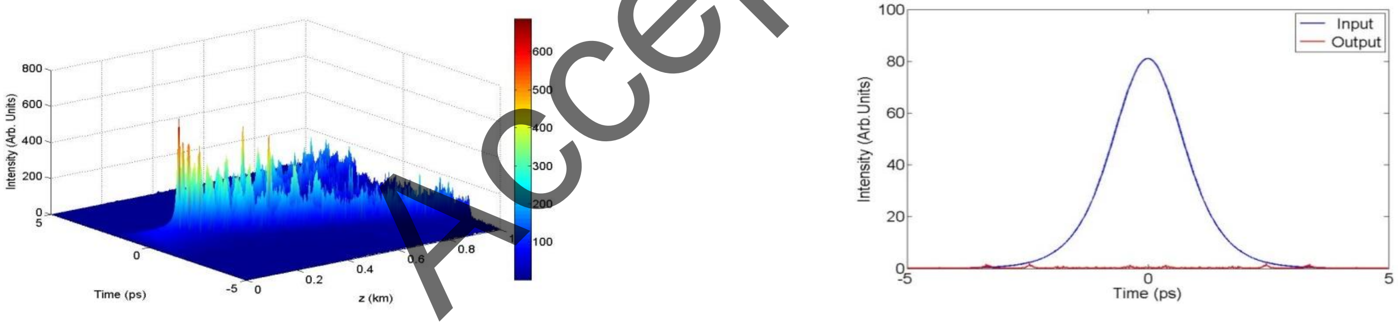
(c)

Continued

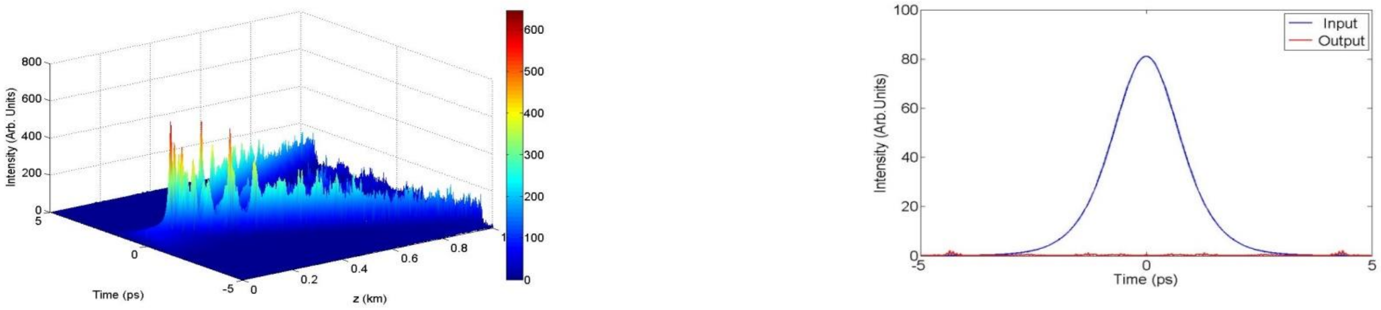
The N=2 soliton spectral components are separated in time as a function of a perturbation introduced at Λ=(1.2,1.8) μm. Since the perturbation lowers Λ=2 μm, only partial spectral re-compression appears. Optical pulses in a nonlinear and dispersive medium that show periodic oscillations in their temporal and spectral forms are classified as second-order. when only the pitch effect is considered, demonstrates the power evolution of pulse shapes. Within two soliton periods, the soliton decay can be seen.

4.3 Third – Order Soliton

When it comes to the third-order soliton, with N=3 the pulse exhibits bifurcations, showing the formation of a supercontinuum by soliton fission across time and distance with air- hole changes Λ=(1.2,1.8, 2) μm, with increased pitch, the output strength steadily diminishes to the point of vanishing, as shown in Figure 5.



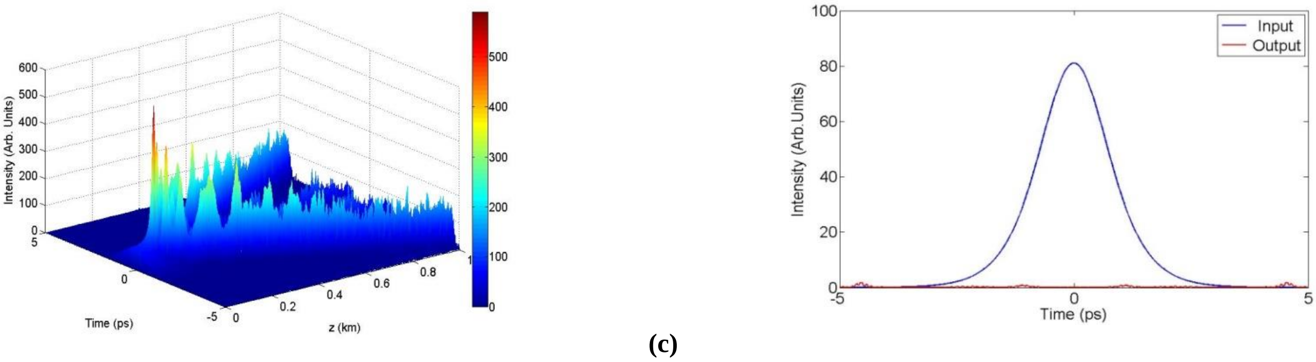
(a)



(b)

Figure 5. Explain the amplitude of the output pulse in three and two dimensions with different pitches.
a- a- Λ =1.2μm, b- Λ =1. 8 μm, c- Λ =2 μm

Continue



(c)

Continued

Higher-order solitons are structurally unstable, according to one study, and a perturbation in the modified nonlinear Schrödinger equation (NLSE) can produce significant changes in the nonlinear dynamics of pulse amplitude. In figure 4 it can be observed Positive chirp is produced by SPM, while negative chirp is produced by GVD (D>0). The amount of positive chirp created by SPM is greater than the amount of negative chirp generated by GVD due to the higher intensity; it cannot be canceled out entirely. As a consequence, the pulse begins to chirp in a constructive manner.

Conclusions

The aim of this study was to look into the decay of various orders of soliton, which was caused by changing the distance between the air holes. To complete this mission, a systematic modeling effort for soliton propagation in photonic crystal fibers was undertaken. The split- phase Fourier approach was used to create a simulation tool (SSFM). It turns out that when soliton is in the first order, there is an inversion occur in the form of solitone, as well as a decrease in pulse intensity as the distance between air holes increases Λ=(1.2,1.8, 2) µm.

In the case of second-order solitone, distortions appear when the distance between air holes is (Λ=1.2 and 1.8) µm, but the contours of the pulses appear with a decrease and regularity of the pulse of the output when Λ= 2 µm.

When the distance between air holes changes in the case of the third-order solitone in the super continuum generation phenomenon, is clear as well as the chirps are evident as the distance between air holes increases and the intensity level of the pulse decreases. The main properties of this study are useful for nonlinear microscopy and spectroscopy applications.

Conflict of interest

The author declares no conflict of interest.

Acknowledgment

This project would not have been possible without the support of people and institutions. in specialy Many thanks to professor, H.A. Sultan, who read my numerous revisions and SQU Journal for Science which supported me with the the previous project, this encouraged me to present my new project.

References

1. Novoa, D., Y, Joly.; Specialty Photonic Crystal Fibers and Their Applications, Crystals journal. 2021,11,739,1-4.

2. Mohammed Salim Jasim. Effect the Radius of Air Holes in Photonic Crystal Fiber on Soliton Propagation with Different Orders, Research & Reviews: Journal of Material Sciences.2022, 10, 5,44-52.

3. Jasim, M,S.; The refractive index and dispersion of the sensors are dependent on the parameters of the photonic crystal fibers, Insights Herbal Med.2022 1,1, 40-44.

4. Russell , P. Photonic Crystal Fibers., J. Lightwave Technol. 2006, 4729–4749 .

5. ALTAIE, Mohammed.; Effect two zero dispersion wavelengths and raman scattering in the third-order soliton of solid core photonic crystal fibers to produce supercontinuum generation. *Malaysian Journal of Science*. 2022,41,2, 55-68.

6. Pakarzadeh , H. Parametric amplification in tapered photonic crystal fibers with longitudinally decreasing zero-dispersion wavelength, Optik-Int. J. Light and Electron Optics. 2015, 126, 5509–5512 .

7. Jasim, M,S., Sultan, H, A., Emshary, C, A.;The Effect of the Nonlinearities on Gaussian Pulses Propagation in Photonic Crystal Fiber, IOP Conference Series: Materials Science and Engineering.2019, 571 ,1, 012121.

8. . Mussot ,A., Kudlinski , A; Habert ,R; Dahman , I; Mélin , G; Galkovsky ,L; Fleureau ,A; Lempereur ,S; Lago , L; Bigourd , D; Sylvestre ,T; Lee , M,W; Hugonnot ,E. 20 THz-bandwidth continuous-wave fiber optical parametric amplifier operating at 1µm using a dispersion-stabilized photonic crystal fiber, Opt. Ex- press.2012, 20, 8,28906–28911.

9. Mohammed, S, J, Al-Taie. Optical Properties of Photonic Crystal Fibers with Fluid Cores, SQU Journal for Science. 2022, 27,2,119-124 .

10. Lee , J,H., Yusoff, Z; Ibsen , M; Belardi ,W; Monro ,T, M; Richardson ,D, J. A Holey Fiber-Based Nonlinear Thresholding Device for Optical CDMA Receiver Performance Enhancement, IEEE Photonics Technol. Lett. 2002,14 6, 876–878.

11. Zsigri, B. Photonic crystal fibers as the transmission medium for future optical communication systems, Ph. D. Thesis. Technical University of Denmark, 2006.

12. AL-TAIE, Mohammed Salim Jasim. Supercontinuum generation by frequency chirp in photonic crystal fibers. Indian Journal of Physics, 2023, 1-6.

13. Birks, T. A; Knight, J. C; Russell, P. St J. Endlessly single-mode photonic crystal fiber. OPTICS LETTERS, 1997, 22, 13, 961-963.

14. Md. I. I., Kawsar. A; Shuvo. S.; Sawrab. C.; Bikash. K. P.; Md. S. I.; Mohammad. B. A. M.; Sayed. A. Design and Optimization of Photonic Crystal Fiber Based Sensor for Gas Condensate and Air Pollution Monitoring, Photonic Sensors. 2017, 7, 3, 234–245.

15. Jin, J. Finite-element Methods for Electromagnetics; 2nd ed. , John Wiley and Sons, 2016.

16. Mohammed, S, J, Al-Taie. Study Effect Self-Frequency Shift of A Soliton in A Liquid Core Photonic Crystal Fibre, MALAYSIAN JOURNAL OF APPLIED SCIENCES. 2022, 7, 2, 64-74

17. Grelu, P. & Akhmediev, N. Dissipative solitons for mode-locked lasers. Nature Photon. 2012, 6, 4, 84-92.

18. Herr, T. et al. Temporal solitons in optical microresonators. Nature Photon. 2014, 8, 7, 145–152.

19. Cundiff, S. T. & Ye, J. Colloquium: Femtosecond optical frequency combs. Rev. Mod. Phys. 2003, 7,5, 325–342.

20. Mohammed Salim Jasim Al-Taie.;Theoretical Analysis of The Super-Gaussian Pulse Propagation in Solid-Core Photonic Crystal Fiber,Journal of Nature, Life and Applied Sciences.2022, 6, 2, 110 – 119.

21. Jasim, Mohammed Salim. "Effect of Some Parameters on Optical Soliton Pulses in Photonic Crystal Fibers." CURRENT APPLIED SCIENCE AND TECHNOLOGY. 2023,23,5, 10-55003.

22. Leo F. et al. Temporal cavity solitons in one-dimensional Kerr media as bits in an all-optical buffer. Nat. Photonics.2010, 4,5, 471-476.

23. Reeves, W. H. et al. Transformation and control of ultra-short pulses in dispersion-engineered photonic crystal fibres. Nature .2003, 4, 2, 511-515.

24. JASIM, Mohammed; AL-ABOODY, Nadia. A Theoretical Study of the Supercontinuum Generation for the Photonic Crystal Fibre. In: Proceedings of 2nd International Multi-Disciplinary Conference Theme: Integrated Sciences and Technologies, IMDC-IST 2021, 7-9 September 2021, Sakarya, Turkey. 2022.

25. Trofimov ,V., Lysak ,T; Matusevich O; Sheng Lan,.Parameter Control of Optical Soliton in One-Dimensional Photonic Crystal, Mathematical Modelling and Analysis .2010, 1,5 ,517–532.

26. Sutherland, R, L. Handbook of Nonlinear Optics, 2nd Edition, Marcel Dekker, New York, USA, 2003,235-238.

27. Agrawal, G.P. Nonlinear fiber optics, Fifth edition, Elsevier/Academic Press, Amsterdam, 2013, 142-149.

28. Ambaye,C., Zhang a; Wu,G, Y. The Evolution and perturbation of Solitons in Dispersive Nonlinear Optical Fiber, IOSR- J. Elec. and Comm. Eng. 2014, 9, 3, 119-126.

29. Sakoda,K.”Optical properties of Photonic Crystals,2nd Edition,National Institute for Materials Science Nanomaterials Laboratory ,Japan.2005, 327-332

30. M. Wartak,” Computational photonic an introduction with MATLAB” Cambridge University Press. 2013, 248-257.