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Numerical Study of High-Order Soliton Generation in Photonic Crystal Fibers: Effect of the Pulse Shape and Its Duration

[1*]S. N. Abd Ali, [2]H. A. Sultan

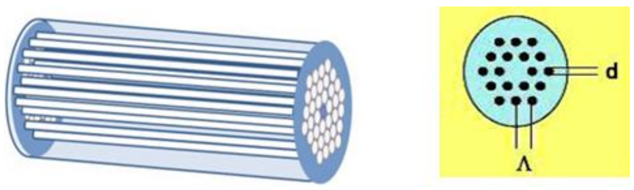
[1,2]Department of Physics, College of Education for Pure Sciences, University of Basrah, Basrah, Iraq
*Corresponding Author's E-mail: safe.almodares@gmail.com

***Abstract* - High-order soliton generation in photonic crystal fibers was simulated using split-step Fourier method (SSFM) and MATLAB. The input pulse shape was studied for various types, super-Gaussian, chirped and pulses obtained from a train of individual Gaussian pulses. The study shows that the order of soliton generated depends on pulse shape, input power and dispersion and nonlinear parameters of the photonic crystal fiber.**

Keywords: Photonic crystal, Fibers, Soliton, Gaussian beam.

I. INTRODUCTION

The rapid progress in the field of optical communications has led to the manufacture of a new generation of optical fibers characterized by specifications that cannot be found in traditional fibers known as photonic crystal fibers, also called microstructure fibers (MFs). The central region, which represents the core, is surrounded by a cladding containing capillary tubes, and light is scattered through these fibers by total internal reflection or by the effect of the photon band gap by creating a defect in its structure [1,2] as in Fig. (1).



(a) (b)

Figure (1): Photonic crystal fiber representation (a) longitudinal and (b) transverse view, is the distance between the air holes, d is the diameter of the air holes [3]

Soliton waves are defined as a type of optical pulse that can propagate for long distances through optical fibers without distortion, meaning that the pulse will propagate without divergence or focusing and maintain its shape during the propagation path, so it appears as if it is isolated [3,4] as in Fig. (2).

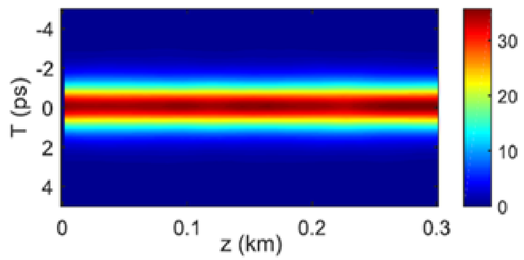


Figure (2): 2D- diagram of isolated wave intensity (first-order soliton)with Time, T, and distance, z, in optical fiber [3]

When a Gaussian beam of high intensity is propagated through a nonlinear medium, the response of this medium to it is in the form of an inhomogeneous distribution of optical density in addition to the nonlinear refractive index, so the medium will affect the beam that it travels through, either in the form of self-assembly of the beam, so the intensity of the beam is the greatest value in its center The value of the refractive index becomes large at the center and gradually decreases towards the two ends of the beam, so the medium acts as a light focus lens for rays, and this effect is called self-focusing, or the opposite occurs, so the value of the refractive index is as great as it can be at both ends of the beam and gradually decreases at the center of the beam, so the medium acts as a lens scattered of the rays This effect is known as self-defocusing [4].

In optical fibers, if the dispersion effect overcomes the nonlinear effect, the beam will continue to extend and if the nonlinear effect exceeds the dispersion effect, the beam will tend to be more centered (focused). When the nonlinear effect equals the dispersion one, the beam will be transmitted without divergence or focusing along the propagation path, and this type of wave is known as soliton [3,4].

The soliton can be classified into orders according to the value of the parameter N. The soliton order can be obtained from the following equation [13]:

$$N^2 = \frac{L_D}{L_{Nl}} = \frac{\gamma P_0 T_0{}^2}{|\beta_2|}$$

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L_D is the dispersion length, L_{NL} is the nonlinear length, γ is the nonlinearity coefficient, P_0 is input pulse power, T_0 is the pulse width in time, and β_2 is the inverse of the group velocity.

At N=1, i.e. single-order soliton wave as in Fig.4a, and high-order soliton wave when N≥2, the second order at N=2 as in Fig.3b, and N =3, Fig. 3c.

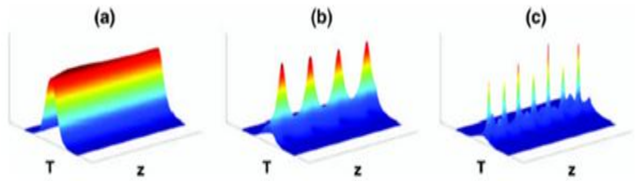

Figure (3): 3D plot of soliton wave with time T and distance z (a) Single-order, (b) second-order, and (c) third-order soliton [4]

The special and unique properties of photonic crystal fibers make them suitable for many applications such as optical communications and medical applications; they have attracted wide interest from many researchers in linear and nonlinear optics studies. First-order soliton is suitable for general optical communication, while high-order soliton is useful in order to achieve secure communications. It is useful too in the medical disintegration of kidney stones and in fighting cancerous tumors [4].

In the last decade, the soliton generation in photonic crystal fibers was studied by many researchers, in 2016, Doaa et al [4] presented a theoretical study on the factors affecting the propagation of a Gaussian pulse through the fibers of the photonic crystals including the effect of the properties of these fibers on the pulse travels through it, and the effect of the photonic crystal parameters on the properties of the photonic crystal fiber itself. S. Sharma et al [6] carried out 2018 a study of short-range soliton wavelength tunable in photonic crystal fibers. The first-order soliton was studied theoretically by Z. S. Abdul-Hussein et al in photonic crystal fibers. This study contained three main axes, namely the effect of the photonic crystal coefficients on the scattering and nonlinear properties, the relationship between the crystal coefficients needed to find an isolated wave, and the interaction between the isolated waves. [1]. In 2019, M. S. Jasim et al conducted a theoretical study on the generation of first-order soliton and super continuum generation in photonic crystal fiber [7]. Muhammad Sufi Rosla, et al presented in the year 2020 a study on an overview of the transmission temporal of an isolated wave (Soliton) in nano wires and optical crystal fibers [8]. Saili Zhao and X. Sun conducted a study on the dynamics of isolated wave (Soliton) in fully normalized dispersion photonic crystal fibers and frequency-dependent nonlinear Kerr effects in 2020 [9]. D. Krishna et al in 2020 conducted a study of the hybrid crystal fibers with a small ellipsoidal air gap as an effective source of spectral expansion [10]. Y. Yang and his group presented in 2021 a study on the effect of the scattering curve on the spectral tunnel of the isolated wave (Soliton) in the photonic crystal fibers [11]. In 2021, researcher Fan San conducted a study on the propagation of soliton waves in optical fibers was described by the generalized Kudryashov refractive index using a high-order nonlinear Schrödinger equation [12].

In this paper, a study of high-order soliton generation in photonic crystal fibers, the study is focused on the effect of the pulse type, duration, and intensity distribution on the generation of high-order soliton. Super Gaussian pulse of different orders, chirped pulses, and finally the study and using a chain of successive pulses to generate high-order soliton were examined.

II. THEORY

Electromagnetic light waves problems can be explained by Maxwell's equations, which are partial differential equations that express the behavior of the electric and magnetic fields and their interaction with material mediums and their transformation from one form of energy to another, which are written in the following form [4]:

$$\nabla . \vec{D} = \rho \qquad (1)$$

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial T} \qquad (2)$$

$$\nabla . \vec{B} = 0 \qquad (3)$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial T} \qquad (4)$$

Where ($\vec{E}$) the electric field. ($\vec{H}$) Magnetic field. ($\vec{D}$) Electrode flux intensity. ($\vec{B}$) Magnetic flux intensity. ($\vec{J}$) Electric current density. (ρ) The volumetric density of electric charge. (T) is the time.

The pulse traveling through a nonlinear and dispersed medium is described by the nonlinear Schrödinger equation (NLSE), which is derived from Maxwell's equations [4].

By taking the convolution of eq. (2)

$$\nabla \times \nabla \times \vec{E} = -\frac{\partial}{\partial T}(\nabla \times \vec{B}) \qquad (5)$$

From eq. (5) we get the wave equation, which is written as follows:

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$$\nabla^2\vec{E} - \mu_\circ\epsilon_\circ\frac{\partial^2\vec{E}}{\partial T^2} = \mu_\circ\frac{\partial^2 P}{\partial T^2} \qquad (6)$$

Where (P) the electric polarization. ($\mu_\circ$) magnetic permeability. ($\epsilon_\circ$) electrical permittivity. By using the wave eq. (6), it is possible to arrive at the nonlinear Schrodinger equation that describes the behavior of a light beam traveling in a material medium, it is written in the following form [4,13]:

$$\frac{\partial A}{\partial Z} = -\frac{\alpha}{2}A(z,T) - \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + i\gamma|A|^2A \qquad (7)$$

Where (A) amplitude of the pulse.($|A|^2$) intensity of the pulse.(Z) The direction of propagation. (β_2) The inverse of the group velocity modeling and simulation [12].

$$\frac{\partial A(z,T)}{\partial z} + \frac{i}{2}\beta_2\frac{\partial^2 A}{\partial T^2} + i\gamma|A|^2A = 0 \qquad (8)$$

$$A(z,\omega) = \int_{-\infty}^{+\infty} A(z,T)e^{i\omega T}\,dT \qquad (9)$$

Where (ω) is the central frequency of the optical pulse.

$$\frac{\partial A}{\partial z} - \frac{i}{2}\beta_2\omega^2 A(z,T) = 0 \qquad (10)$$

$$A(z,\omega) = A(0,\omega)\exp^{\left(\frac{i\beta_2\omega^2 z}{2}\right)} \qquad (11)$$

Whereas eq. (9) and (10) can be used to analyze eq. (8) in the Fourier domain to arrive at an expression that describes the resulting waveform in eq. (11). Nonlinear Schrodinger equation is difficult to be solved analytically, so it is solved by numerical methods such as the Split-Step Fourier method (SSFM) [], which depends on dividing the fiber into small cells, then the each cell will be separated into two parts, the linear part to solve the linear term of eq. (8), while the second is for the nonlinear term of eq. (8), at the end the results are collected [13].

So we will rewrite eq. (8) in the following form:

$$\frac{\partial A}{\partial z} = (\hat{D} + \hat{N})\,A \qquad (12)$$

Where $\hat{D}$is the operator of the linear operator, $\hat{N}$ is the nonlinear operator, i.e.:

$$\hat{D} = \frac{i}{2}\beta_2\frac{\partial^2}{\partial T^2} \qquad (13)$$

In the same way, the operator of the nonlinear part , N, is given by the equation:

$$\hat{N} = i\gamma|A|^2 \qquad (14)$$

The solution to eq. (11) leads to:

$$A(z+h,T) = \exp[h+z(\hat{D}+\hat{N})]A(z,T) \qquad (15),$$

When (h) is too small, then eq. (12) can be written as:

$$A(z+h,T) = A(z,T)\exp(h\hat{D})\exp(h\hat{N}) \qquad (16)$$

Finally collecting the two parts gives:

$$A(z+h,T) \approx \exp\left(\frac{h}{2}\hat{D}\right)\exp\left(\int_z^{z+h}\hat{N}(z')dz'\right)\exp\left(\frac{h}{2}\hat{D}\right)A(z,T) \qquad (17)$$

III. RESULTS AND DISCUSSION

Super Gaussian input pulse:

To study the effect of the Super Gaussian pulse on the generation of high-order solitons, pulses were used as shown in Fig. (4) for several values of (m).

The super Gussian pulse function is given by the following equation:

$$A_{in} = \sqrt{Po}\exp\left(-T^2/2{T_0}^2\right)^{2m} \qquad (18),$$

Where T is the simulation time, T_0 is the pulse duration at FWHM, and m is the super Gaussian pulse order P_0 is the input power.

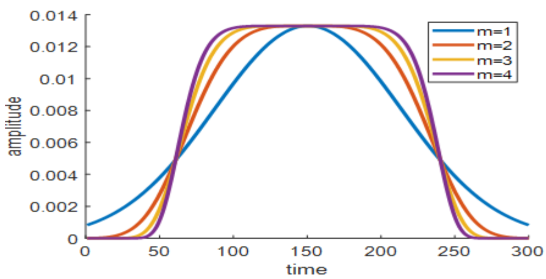

Figure (4): Super Gaussian pulse with different parameter m = 1,2,3,4

The effect of standard Gaussian beam (m=1) was previously studied in details [2,13]. To generate high-order soliton, and based on the previous studies, the following values of the pulse duration, dispersion and nonlinearity of the photonic crystal fiber was chosen as: the values of the pulse width time T_0= 1 ps, linear effects coefficient β_2=-25 ps^2/km and nonlinear effects coefficient were fixed at γ= 1 w^{-1}/km and the input power were chosen as:m=1, the value of the input power isPo= 0.5W, when m=2 the value of the power becomes Po= 0.22 W,when m reaches a value of m=3 the value of the power is Po= 0.067 W and at value of m=4 the value of the power is Po= 0.55 W. It is clear that the propagation of super Gaussian pulse in photonic crystal fiber can generates high-order soliton depending on the super Gaussian order, m.

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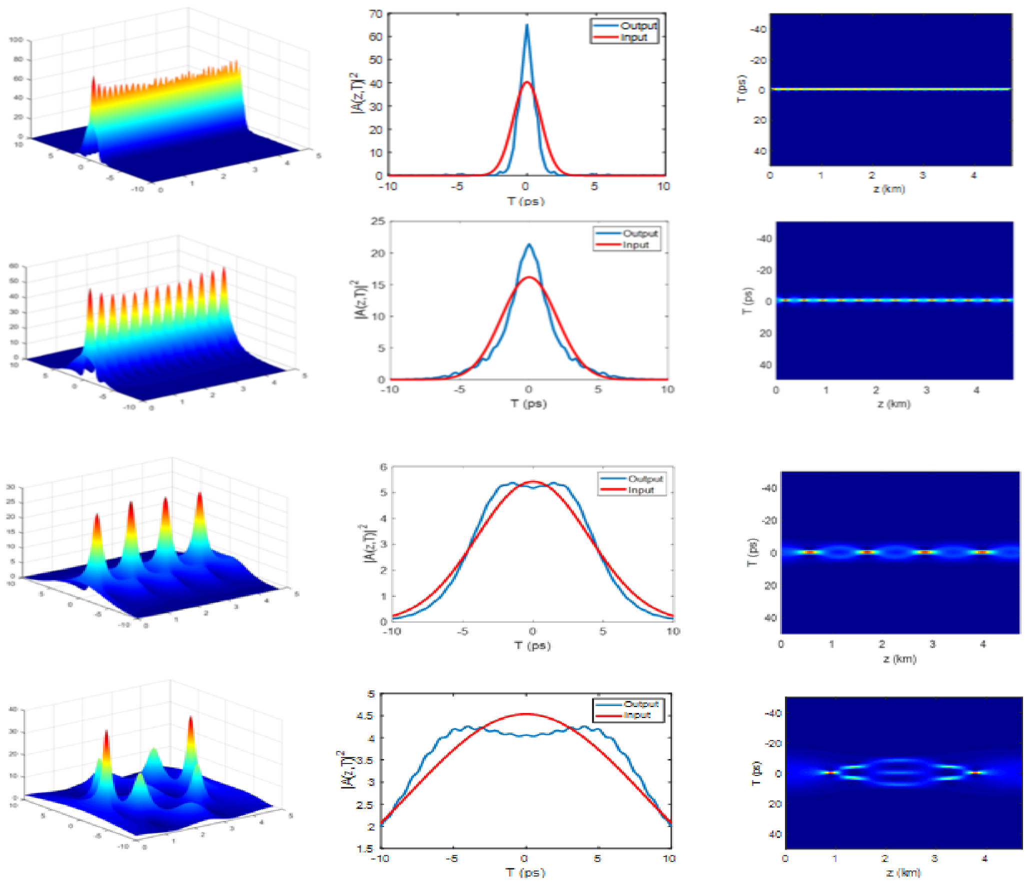
The simulation results at the above parameters and the high-order soliton generated is shown in fig. (5) for soliton order N=2,3. It can be seen that the period of high-order soliton is depends on the value of m for N=2 at m=1-3 and N=3 at m=4, as a samples example of soliton generated.

The photonic crystal fiber was chosen of 5 km length, Fig 5 (b) is the intensity distribution on time for input-output pulse, the output distribution is at the fiber end.



(a) (b) (c)

Figure (5) Samples of High order soliton (a) 3D view, (b) input vs output pulse, and (c) 2D representation generated in photonic crystal fiber at ϒ = 1W^{-1}/Km, β₂ = -25 ps^2/km,T_0= 1 ps, with super Gaussian pulse of m=1, 2, and 3 respectively

Chirped Gaussian pulse:

In the case of chirped pulse as input pulse, given by eq. (19), a multi-distortion Gaussian pulse can be generated, as shown in Fig. (6) for several values of the chirped factor, C.

Fig. (6) shows examples of chirped Gaussian pulse used in this study for C= -(1, 2, 3, 4, 5).

$$A_{in} = \sqrt{P_o}\, exp\left(-(1+1iC)\, T^2/2{T_0}^2\right) \qquad (19)$$

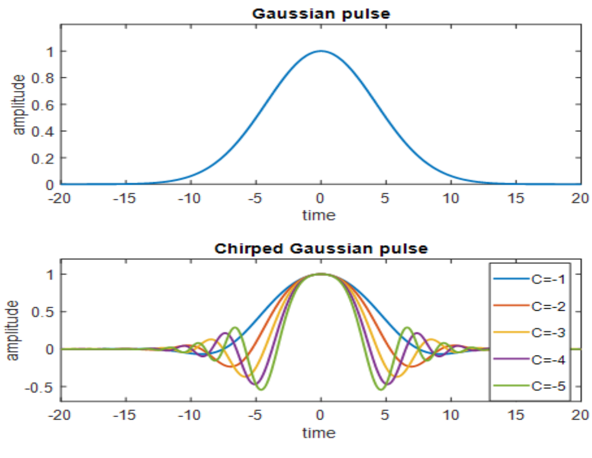


Figure (6): Normal and chirped Gaussian pulse with different parameter C = -(1,2,3,4,5)

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At value of dispersionβ_2=-25 ps^2/km and the nonlinearity factorγ= 1 w^{-1}/km were fixed, and the values for the power Po, and the pulse width time T_0 were chosen based on the value of the distorted pulse coefficient (C). it was found that when C=-1 was the value of the power Po = 0.25 w and the time of the pulse width T_0 = 10 ps and when the value of C=-2 is the value of the power Po= 0.36 w and the time of the pulse width T_0 = 8 ps and at value C=-3 the value of power is Po= 0.41 w and the time of the pulse width T_0 = 12 ps and where the value of C=-4 becomes the value of the power Po= 0.47 w and the time of the pulse width T_0= 10 ps When the value of C=-5 the value of the power Po= 0.52 w and the time of the pulse width T_0 = 10 ps in order for the intensity of the pulse to maintain its shape with both distance and time, forming a high-order isolated wave, it was studied for a group of shapes shown in Fig. (7) both distance and time, forming a high-order isolated wave, it was studied for a group of shapes shown in Fig. (6).

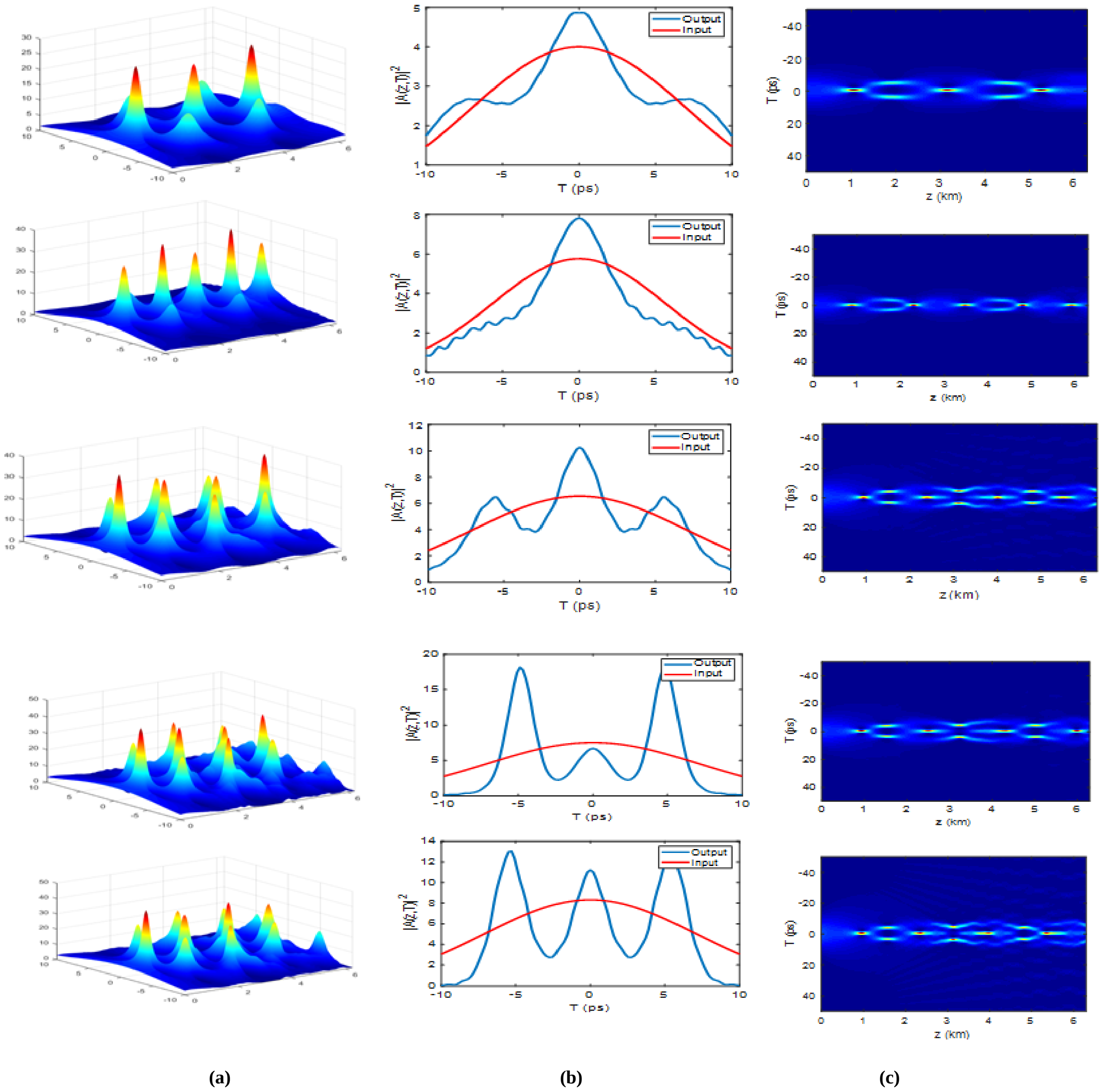

Figure (7): Samples of High-order soliton(N=3)in the photonic crystal fiber at Υ = 1 W^{-1}/Km, β_2 = -25 ps^2/km (a) 3D plot of the soliton with time (t) and distance (z).(b) Comparison of the $|A_{in}|$ and $|A_{out}|$. (c) 2D drawing of the propagation pattern, when C= -1, -2, -3, -4 and -5

Train of Gaussian beams:

If the input is a series of pulses (train), the effect of these trains on the soliton generated in the photonic crystal fiber, were studied for various shapes of trains used. Fig. (8) shows samples of trains.

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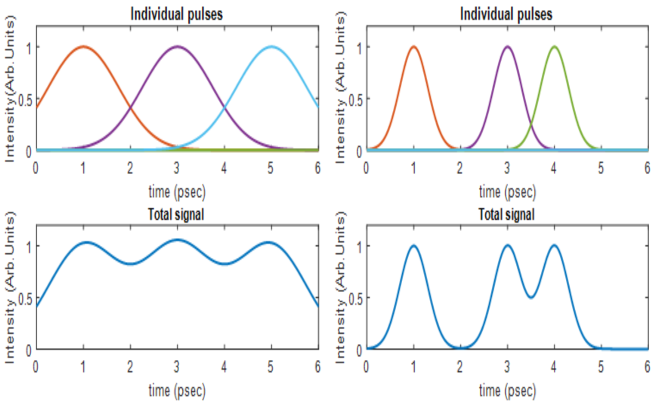
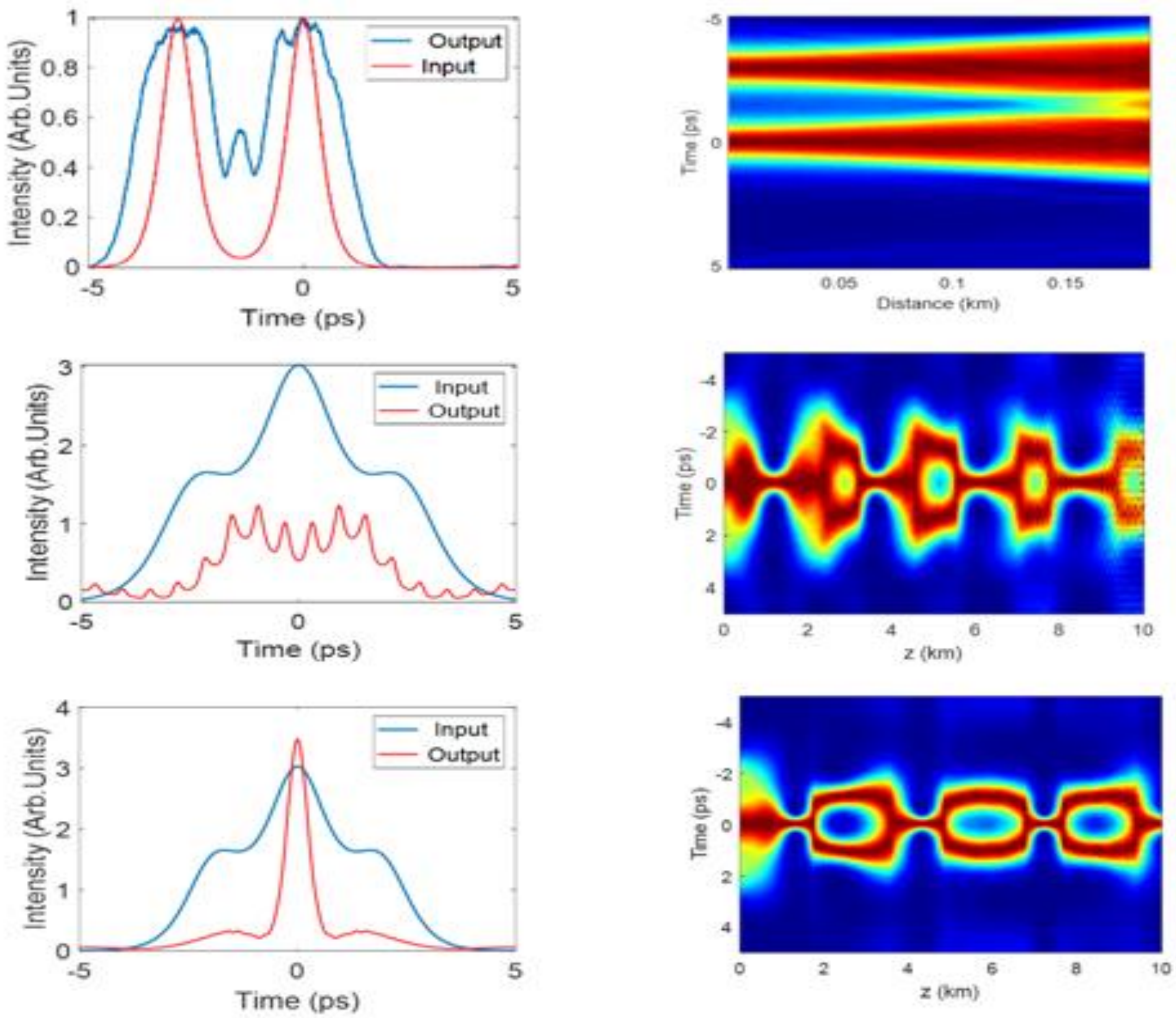


Figure (8): Samples of pulses train, individual pulses (upper), and resulted pulse (down) used in the study

Where the values of the pulse width time T_0= 1 ps, linear effects coefficient β_2=-2.5 ps^2/km, and nonlinear effects coefficient γ= 1 w^{-1}/km were fixed, and power values were chosen ranging between *Po* = (0.1-1.3) w It was found that when *Po* = 1 w the intensity of the pulse maintains its shape during propagation with both distance and time as a high-order isolated wave. After that, the value of the power *Po*= 1 w, the coefficient of linear effects β_2=-1.19 ps^2/km, and the coefficient of the nonlinear effects of γ= 1 w^{-1}/km were fixed, and values for power were chosen ranging between *Po* = (0.1-1.3) w It turns out that when T_0= 1 ps, the intensity of the pulse maintains its shape during propagation with both distance and time as a high-order isolated wave as in the fig. (9).



(a) **(b)**

Figure (9): The soliton in the photonic crystal fiber. (a) Comparison of the incoming and outgoing pulse. (b) Two-dimensional plot of the propagation of a soliton

IV. CONCLUSIONS

In this work, the effect of many input pulse shapes, durations and power on the generation of high-order soliton (N=2 and 3) were studied numerically. The study proved that those pulse parameter in addition to the photonic crystal parameters (dispersion and nonlinearity) can determine the generation of high-order soliton and its order (N=2 or N=3).

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