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RESEARCH ARTICLE

Optimize Nonlinear Effects on Fundamental and High-order Soliton in Photonic Crystal Fiber

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Abstract Nonlinear effects in optical fibers are mainly caused by two sources: inelastic scattering behaviour or the intensity sensitivity of the medium's refractive index. The propagation process in photonic crystal fibers is more complex than the propagation process of first-order solitons, second-order solitons, and third-order solitons. This article discusses the effects of propagation on first-, second- and third-order solitons. A popular approach to supercontinuum generation through soliton fission is the higher-order soliton technique for spectral generation.

Keywords: Photonic crystal fibers (PCFs), supercontinum generation (SCG), soliton, nonlinear effects (NLE).

Introduction

A soliton is any answer to a long-term equation that represents a wave that is localized. (even when it moves), and has the ability to interact strongly with other solitons while maintaining its identity, even though an exact definition of a soliton is difficult to come by [1]. In other words, a soliton is a bundle of waves or momentum that maintains its shape even when moving at a constant speed. The rejection of dispersive and complex effects in the middle causes the formation of a soliton [2]. One way to conceptualize each wave packet as being made up of plane waves at various frequencies is to consider dispersion, a process that determines a wave's phase and amplitude dependent on its frequency [3]. Due to dispersion, waves of different frequencies travel at different speeds, and the shape of the pulse changes over time. It's worth noting that the spread simply rearranges itself the phase relationships between the remaining frequency components in the pulse's original spectrum; it does not introduce any new frequency elements [4]. However, nonlinear factors can change the phase shift during the pulse, thereby producing additional frequency components in the pulse spectrum (this effect is called self-phase modulation in optics). As shown in Figure 1.

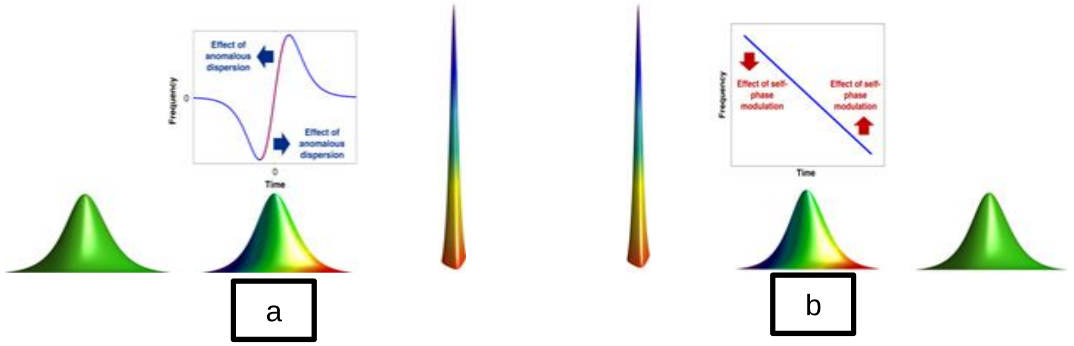

Figure 1. shown the change of phase shift during the pulse, to produce additional frequency components in the pulse spectrum by (a) dispersion (b) self-phase modulation

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If the initial pulse has the proper form, nonlinear processes can accurately cancel dispersion, producing a pulse with a consistent shape that defined a soliton [1, 5]. While there are a number of partially differential nonlinear dispersive formulae that provide soliton solutions, the Schrodinger nonlinear equation which describes the waves of light in fiber optics more crucially is the most essential one (among those that characterize physical systems) [1, 6], Since a soliton is a constant wave that is both confined (although they were moving) and capable of intense interaction with other solitons while maintaining its identity, it is generally understood to refer to any solution of a nonlinear equation [7]. In other words, a soliton is a bundle of waves or momentum that maintains its shape even when moving at a constant speed. The cancellation of dispersion and nonlinear effects in the medium leads to the formation of solitons [8]. One way to conceptualize each wave packet as being made up of plane waves at various frequencies is to consider dispersion as a process that determines a wave's phase and amplitude dependent on its frequency [9]. Due to dispersion, waves of different frequencies travel at different speeds, and the shape of the pulse changes over time [10]. It is essential to note that dispersion just rearranges the phase relationships between the remaining frequency components in the pulse's original spectrum; it does not introduce any new frequency elements [11]. However, nonlinear factors can change the phase shift during the pulse, thereby producing additional frequency components in the pulse spectrum (this effect is called self-phase modulation in optics).

When a pulse has the correct form, nonlinear processes can exactly cancel out dispersion, creating a soliton, or pulse with a consistent shape [11–12]. While several partial differential nonlinear dispersive formulas provide soliton solutions, the Schrodinger nonlinear equation—which describes the waves of light in optical fibers more crucially—is especially significant (among those that characterize physical systems) [13–14].

Materials and Methods

This paper represents a theoretical study of the propagation mechanism of a single-order and multiple-order optical soliton spread through a solid-core photonic crystal fiber Its dimensions are the diameter of the air holes, the distance between the holes, and the number of holes are (d=0.5μm,Λ=3 μm N=6) respectively, such that the pulse preserves its message throughout distance and time. The Matlab program was relied upon to process and clarify the diffusion mechanism, and the equation adopted in the program is the nonlinear Schrodinger equation (NLSE) [15]. which can be stated mathematically as [16].

$$i\left({}^{\partial A(z,t)}/_{\partial Z}\right) = \left({}^{i\alpha}/_{2}\right)A(z,t) + \left({}^{\beta_2}/_{2}\right)\left({}^{\partial^2 A(z,t)}/_{\partial T^2}\right) - \gamma \mid A(z,t) \mid^2 A(z,t) \qquad (1)$$

Here β2 is the second-order dispersive coefficient, α is the loss of fibers, and γ is the coefficient of nonlinear-ity, A (z, t) is the slowly changing pulse amplitude. The effects of fiber loss, dispersion and nonlinearity on pulse propagation in the fiber are represented by the three terms on the right of the equation above, respectively. Depending on the type of incident light, which has a peak intensity of 1 watt and a starting duration of 1 ps, either dispersive or nonlinear-effects are most significant in the fiber. The parameters of the fiber's dispersion length (LD) and nonlinear length (LN), over which effects of dispersions or nonlineariiness are significant for the evolution of pulses, provide the length scale, which is based on math.

$$\mathrm{L_D} = {}^{\mathrm{T}_\circ^2}/_{\mid \beta_2 \mid} \qquad (2)$$

$$L_{NL} = {}^{1}/_{\gamma\beta_\circ} \qquad (3)$$

Fourier split-step technique (SSFM) is applied to the numerical simulations. With α = 0, there are no losses and the dispersion is thought to be abnormal (β2 = - 3). Their values (1,2,3) $W^{-1}Km^{-1}$, however, will alter due to nonlinear influences, and depend on Mathlab software is used to compute the findings.

Results and Discussion

We numerically explore the low-power pulse's propagation characteristics using Equation (1) to examine the influence of the nonlinear effects on fundamental and high-order soliton on the development of a trapped soliton. As the next sections demonstrate. When using sech,pulses with the following form are employed.

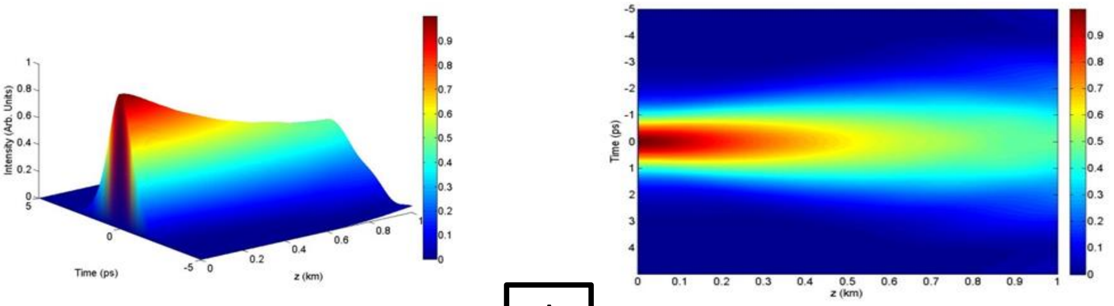
$$A(0,t) = N\, Sech(t)$$

where N represents the pulse's order. Just generate the first pulse while using N=1.

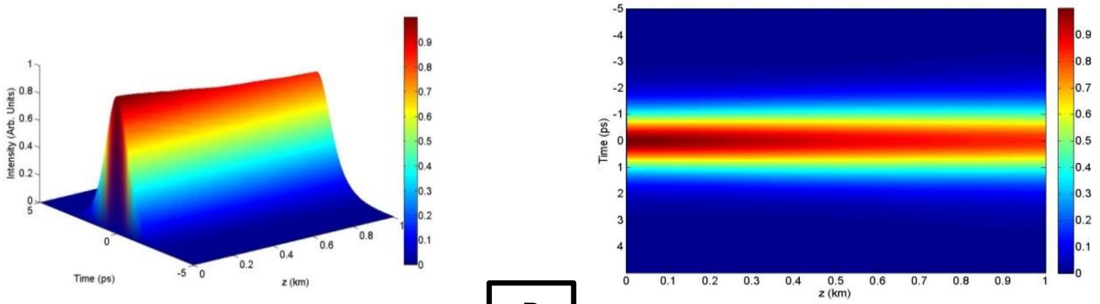
$$A(0,t) = Sech(t)$$

The basic soliton is the pulse that has a "Sech" form and N = 1. The progression of this pulse along the fiber is seen in the schematics below.

When nonlinear effects are valued differently (1,3,5) W^{-1} km^{-1}, As illustrated in Figures 1-A, B, and C, the pulse in the case of the first-order soliton will essentially remain unchanged over time and space, but there will be discernible increases in the output pulse's intensity as the value of nonlinear effects rises, as indicated in Figures 1-D and E, until it surpasses the input pulse's value, as shown in Figure 1-F.



A



B

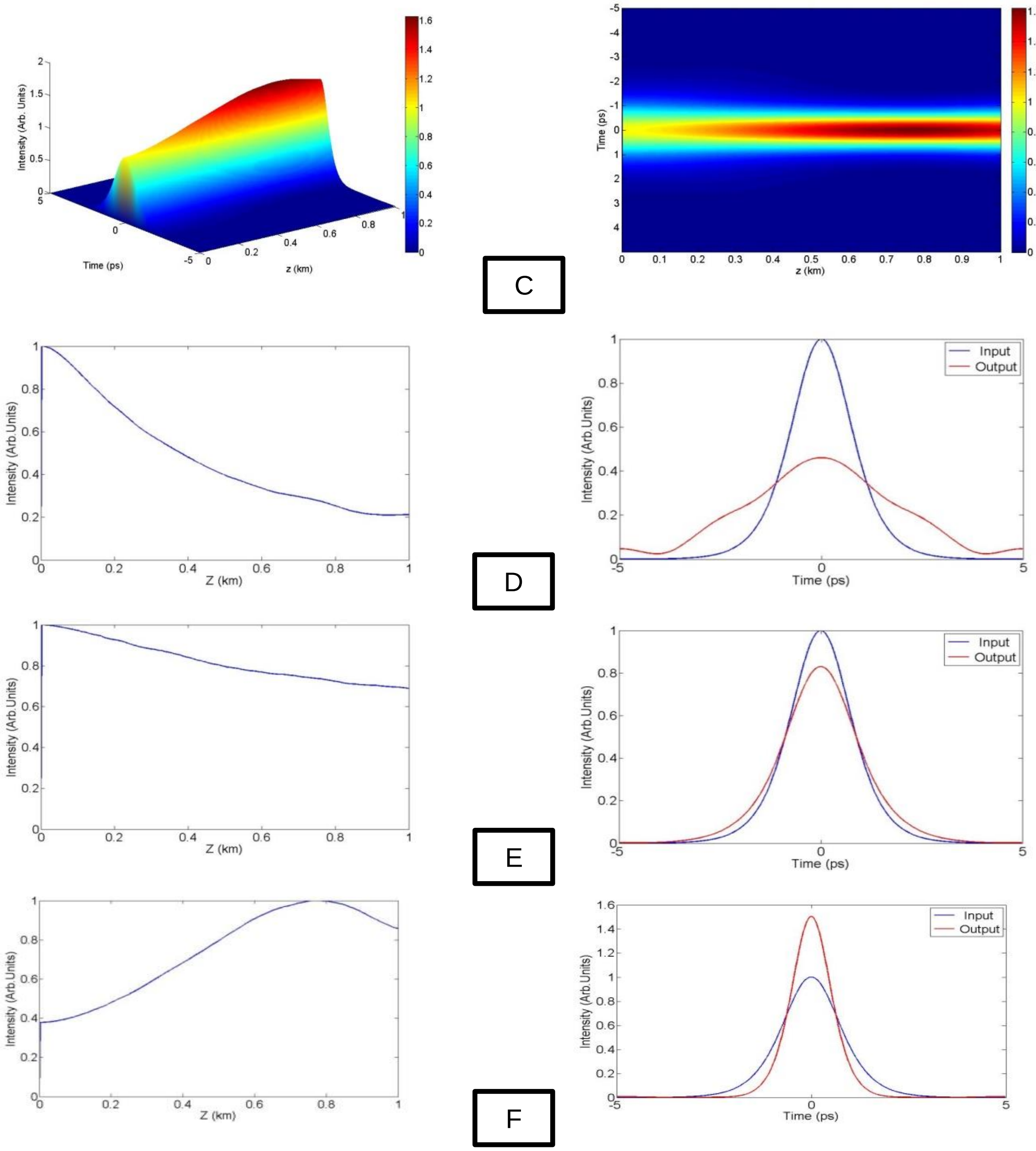
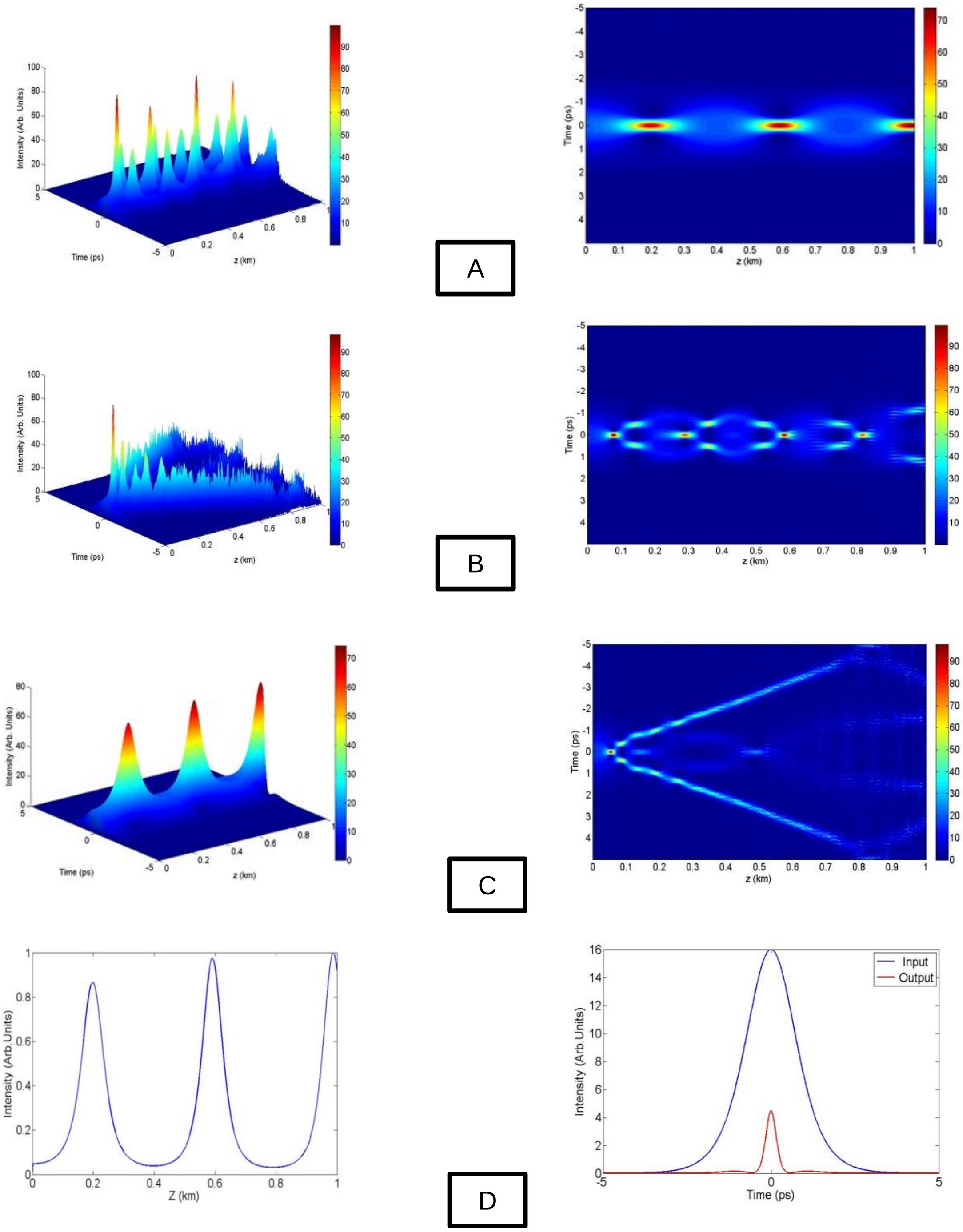
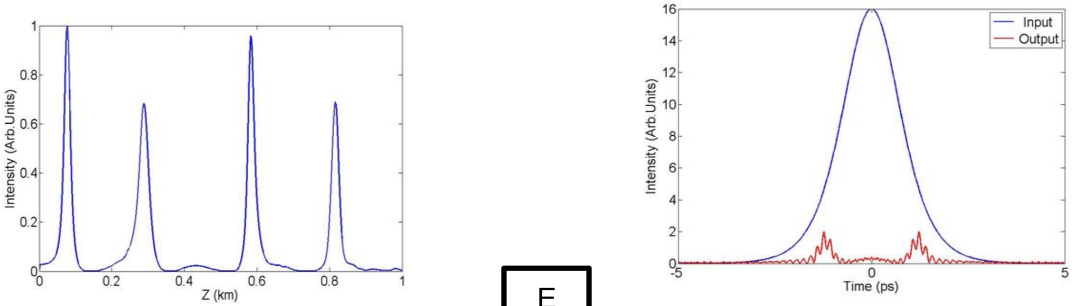


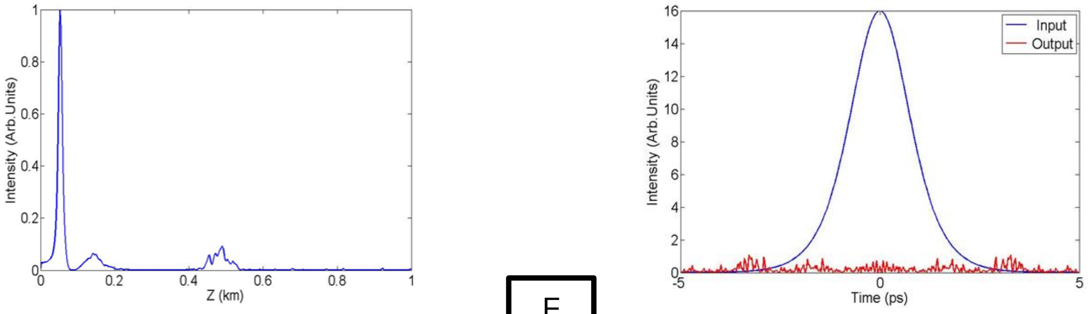
Figure 2. First-order soliton propagation along a PCF fiber with nonlinear effects, A-when $\gamma = 1\ w^{-1}Km^{-1}$,B-when $\gamma = 3\ w^{-1}Km^{-1}$,C-when$\gamma = 5\ w^{-1}Km^{-1}$, and the pulse and features of the same parameters are displayed in figures D, E, and F

In the second soliton order, during the change of nonlinear effect value, the pattern appears bumpy with distance and time, as shown in Figure (2-A, B, C)). Furthermore, the intensity of the mode changes and the output mode decreases until it reaches the chirp stage, as shown in Figures (2-D, E, F).


A
B
C
D
Intensity (Arb. Units)
Time (ps)
z (km)
Z (km)
Intensity (Arb.Units)
Time (ps)
Input
Output

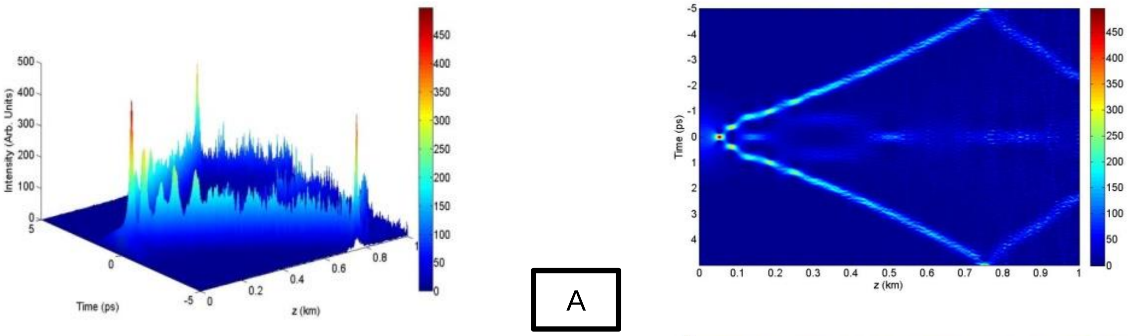


E

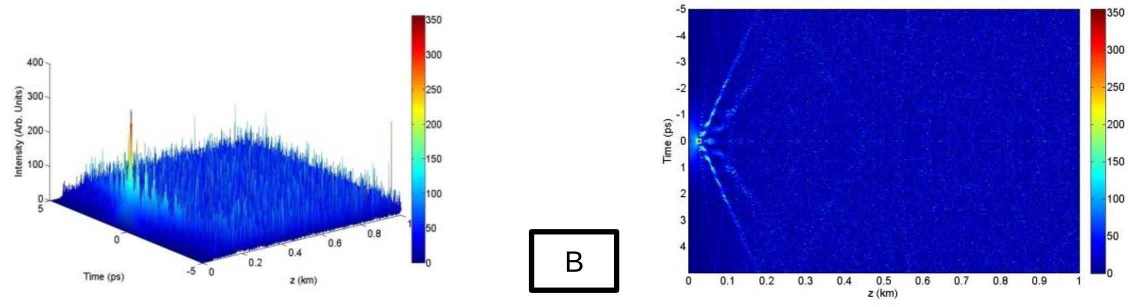


F

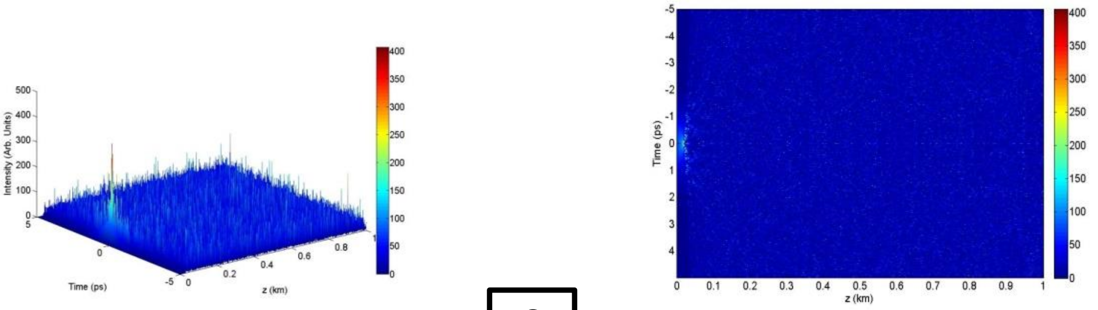
As evident in Figures 3 (A, B, and C), the third-order soliton's pulse exhibits a variety of bifurcations that demonstrate the generation of the supercontinuum by soliton fission with distance and time, and the output intensity decreases to a point that is almost imperceptible with increased nonlinear effects Figure 3 (D, E, and F)



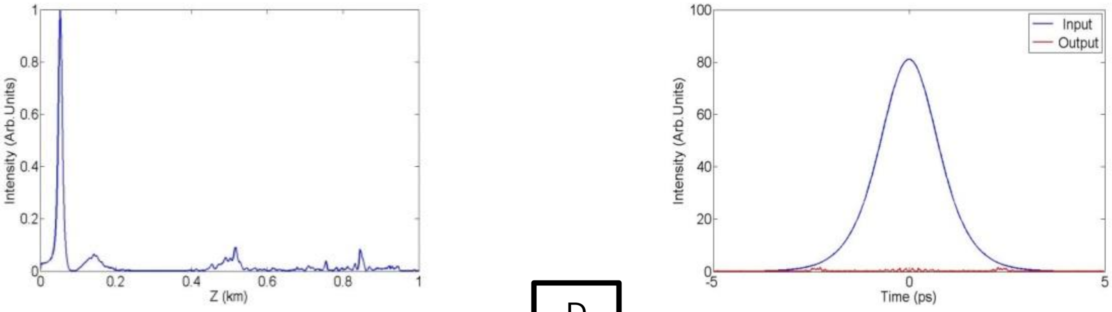
A



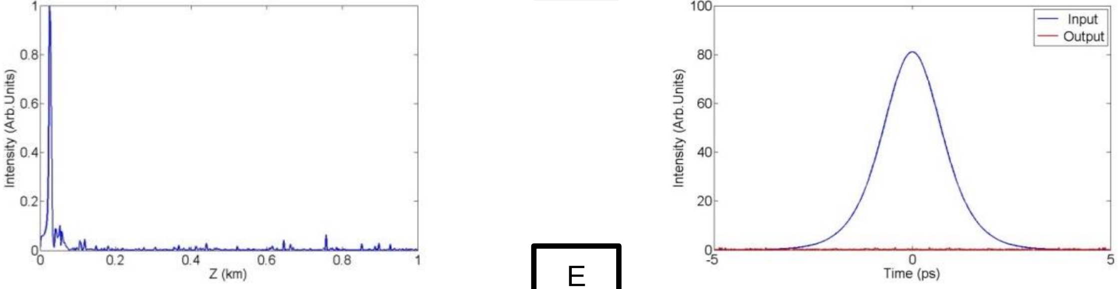
B



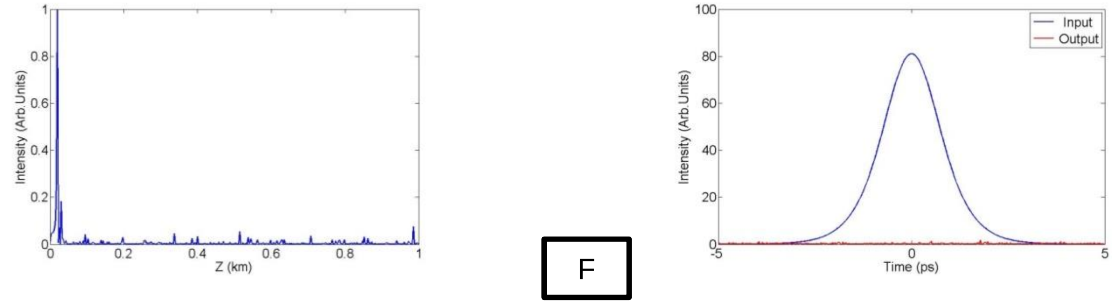
C



D



E



F

Figure 4. Third-order soliton propagation along a PCF fiber with nonlinear effects, A-when $\gamma = 1\ w^{-1}Km^{-1}$,B-when $\gamma = 3\ w^{-1}Km^{-1}$,C-when$\gamma = 5\ w^{-1}Km^{-1}$, and the pulse and features of the same parameters are displayed in figures D, E, and F

Conclusions

The impact of nonlinear effects on fundamental and high-order soliton was examined. Observe that nonlinear effects lead to basic soliton pulse displacement, but significant spectral expansion leads to high-order effects when they follow other higher-order effects. The data's spectrum properties reveal that the high nonlinear component splits apart while flailing around the beat. Nonlinear effects, while one of the components involved in soliton-based telecommunication transmission, can provide a wide variety of frequencies that are supported by the supercontinuum source for WDM systems when combined with other higher order components. effects. In this way, nonlinear effects contribute to the accessibility of diode lasers for the low-power production of wide spectrum components.

Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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References

[1] Al-Taie, M. S. J. (2022). Optical properties of photonic crystal fibers with fluid cores. *Sultan Qaboos University Journal for Science (SQUJS)*, *27(*2), 119-124.

[2] Mollenauer, L. F., & Gordon, J. P. (2006). *Solitons in optical fibers: Fundamentals and applications.* Elsevier.

[3] Jasim, M. S. J. A. T. (2022). Study effect self-frequency shift of a soliton in a liquid core photonic crystal fibre. *Malaysian Journal of Applied Sciences, 7*(2), 64-74.

[4] Mani, B., Chitra, K., & Sivasubramanian, A. (2014). Study on fundamental and higher order soliton with and without third-order dispersion near zero dispersion point of single mode fiber. *Journal of Nonlinear Optical Physics & Materials*, *23*(03), 1450028.

[5] Uddin, M. H., Zaman, U. H. M., Arefin, M. A., & Akbar, M. A. (2022). Nonlinear dispersive wave propagation pattern in optical fiber system. *Chaos, Solitons & Fractals*, *164*, 112596.

[6] AL-Taie, M. S. J. (2023). Supercontinuum generation by frequency chirp in photonic crystal fibers. *Indian Journal of Physics*, 1-6.

[7] Biswas, A., Milovic, D., Savescu, M., Mahmood, M. F., Khan, K. R., & Kohl, R. (2012). Optical soliton perturbation in nanofibers with improved nonlinear Schrödinger's equation by semi-inverse variational principle. *Journal of Nonlinear Optical Physics & Materials*, *21*(04), 1250054.

[8] Malomed, B., Torner Sabata, L., Wise, F., & Mihalache, D. (2016). On multidimensional solitons and their legacy in contemporary atomic, molecular and optical physics. *Journal of Physics B: Atomic, Molecular and Optical Physics*, *49*(17), 170502.

[9] Akhmediev, N., Soto-Crespo, J. M., Vouzas, P., Devine, N., & Chang, W. (2018). Dissipative solitons with extreme spikes in the normal and anomalous dispersion regimes. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *376*(2124), 20180023.

[10] Jasim, M. S. (2023). Effect of some parameters on optical soliton pulses in photonic crystal fibers. *Current Applied Science and Technology,* 10-55003.

[11] Kjellman, J. Ø., Stabile, R., & Williams, K. A. (2017). Broadband giant group velocity dispersion in asymmetric InP dual layer, dual width waveguides. *Journal of Lightwave Technology*, *35*(17), 3791-3800.

[12] Jasim, M., & Al-Aboody, N. (2022, January). A theoretical study of the supercontinuum generation for the photonic crystal fibre. *Proceedings of 2nd International Multi-Disciplinary Conference Theme: Integrated Sciences and Technologies,* IMDC-IST 2021, 7-9 September 2021, Sakarya, Turkey.

[13] Jasim, M. S., Sultan, H. A., & Emshary, C. A. (2019, July). The effect of the nonlinearities on gaussian pulses propagation in photonic crystal fiber. *IOP Conference Series: Materials Science and Engineering* (Vol. 571, No. 1, p. 012121). IOP Publishing.

[14] Eid, M. M., Habib, M. A., Anower, M. S., & Rashed, A. N. Z. (2021). Highly sensitive nonlinear photonic crystal fiber based sensor for chemical sensing applications. *Microsystem Technologies*, *27*, 1007-1014.

[15] Nosratpour, A., Razaghi, M., & Darvish, G. (2018). Computational study of pulse propagation in photonic crystal semiconductor optical amplifier. *Journal of Nanophotonics*, *12*(3), 036015-036015.

[16] Fehenberger, T., Millar, D. S., Koike-Akino, T., Kojima, K., Parsons, K., & Griesser, H. (2020). Analysis of nonlinear fiber interactions for finite-length constant-composition sequences. *Journal of Lightwave Technology, 38*(2), 457-465.