Square Lattice Elliptical-Core Photonic Crystal Fiber Soliton-Effect Compressor at 1550nm

Ashkan Ghanbari[a], Alireza Kashani Nia[b] Ali Sadr[c]
[a]*Islamic Azad University, Tehran Central Branch,*
[b]*Faculty of Electrical Engineering, Islamic Azad University,Tehran Central Branch,*
[c]*Faculty of Electrical Engineering, Iran University of Science and Technology*
ghanbari.ashkan@yahoo.com, Ali.Kashaniniya@iauctb.ac.ir, sadr@iust.ac.ir
Corresponding author:*Ashkan Ghanbari*

***Abstract*- In this paper, we investigate the evolution of supercontinuum and femtosecond optical pulses generation through square lattice elliptical-core photonic crystal fiber (PCF) at 1550 nm by using both full-vector multipole method (M.P.M) and novel concrete algorithms: symmetric split-step Fourier (SSF) and fourth order Runge Kutta (RK4) which is an accurate method to solve the general nonlinear Schrodinger equation (GNLSE). We propose a novel square lattice PCF structure featuring a minimum anomalous group velocity dispersion (GVD), nearly zero third-order dispersion (TOD) and enhanced nonlinearity for efficient soliton–effect compression of femtosecond optical pulses and supercontinuum generation(SCG) with lowest input pulse energies over discrete distances of the fiber.**

***Index Terms*-** Multipole, Photonic, Soliton, Compression, Supercontinuum, Dispersion.

I. INTRODUCTION

Due to the advent of huge applications in different fields of science and technology, generation of ultrashort laser pulses has always been considered of great interest. One of the best techniques to acquire ultrashort pulses using optical fibers is known to be Pulse compression process [1], [2]. Mollenuar et al discovered pulse compression in fiber as a technique for ultrashort pulses generation [3]. The discovery of this technique rapidly developed it in numerous fields of nonlinear optics encompassing ultrafast physical processes such as ultrahigh-data rate optical communication, optoelectronic terahertz time domain spectroscopy, etc. One of the techniques for achieving optical pulse compression is to spectrally broaden the laser pulse using self-phase modulation (SPM) in a waveguide, it will be then compressed outside the waveguide employing passive and active dispersion compensation devices. The disadvantage of this technique is that the required dispersion

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compensation causes the system to be complex [1], [2]. Another method for generation of ultrashort pulses employs higher order solitons that are formed in a waveguide [4], [5]. In recent years, photonic crystal fibers (PCFs) have received a great deal of scientific attention because of their numerous and invaluable nonlinear applications in sensor and communication fields. The arrangement of air holes in the cladding region gained more importance due to optical properties of photonic crystal fibers (PCFs) such as highly nonlinearity, large mode areas, high numerical aperture, adjustable zero dispersion, etc [6]. Whereas PCFs with square lattice arrangement of air holes in the cladding can also compensate the dispersion and can be useful for ultra flat dispersion [7].To make the effective refractive index and consequently the propagation characteristics of photonic crystal fiber (PCF) appropriate for different cases, the cladding’s microstructure can be accordingly changed. This change in microstructure can be achieved by making changes into the size of the air holes. The considerable changes of air hole diameter, pitch and design of PCF have helped in several fields such as, optimization of the pump spectra for obtaining flat Raman gain, narrow or broad supercontinuum spectra and, etc. The nonlinear optical applications of all kind of PCFs such as fiber laser, supercontinuum generation(SCG), parametric amplifier, pulse compression, etc. are the main motivating items for recent widespread studies on PCFs [8]. Among the mentioned applications, the combination of promoted nonlinearity and managed dispersion is the one which makes the supercontinuum generation (SCG) or soliton compression possible at the short and long wavelengths in PCFs and has resulted in many researches due to its variety of applications [5,8,9].

Recently, The pulse compression and Supercontinuum generation have been obtained by utilizing only triangular PCFs in different wavelength regimes in the range of 1.06(μm) to 1.55(μm)[10]. Also , only a few theoretical works were done in the square lattice PCFS in which all of them are related to the dispersion compensation in these kind of waveguides [7],[11]. But according to our researches, soliton-effect compression and supercontinuum generation of low-energy 1550 nm ultrashort optical pulses in highly nonlinear square lattice photonic crystal fibers has not been studied so far . Ultrashort pulses generation at 1550 nm can be specifically employed in material processing, bio-photonic sensors, military applications, Spectroscopy and so on [8], [9]. Reducing the required energy for generating the ultrashort optical pulses has been always of a great importance and an increase in nonlinearity of PCFs is needed to achieve that. Generally there are two different ways to improve the nonlinearity of PCFs. First, the design of PCF can be modified with applying large air hole size in order to gain high nonlinearity and large dispersion and small pitch. The second way is to use non silica technologies such as Silicon (si), SF6, TF10, CS2, etc to improve nonlinearity. Consequently a considerable diminution in the required pulse’s input energy will be achieved [8].

In this paper we focus on designing a novel structure of photonic crystal fiber consisting of a silica elliptical core surrounded by square- lattice of air holes in the cladding and also use the soliton-

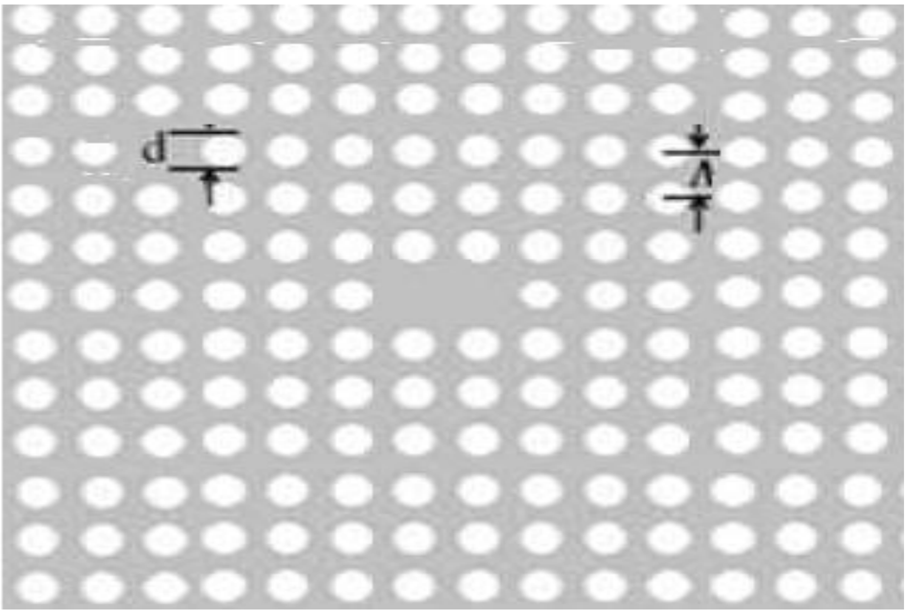

Fig.1. The proposed square lattice PCF schematic.

effect for laser pulses compression and supercontinuum generation in these kind of waveguides.

II. DISPERSION OF SQUARE LATTICE ELLIPTICAL CORE PHOTONIC CRYSTALS FIBER

Dispersion affects the ultrashort pulses propagation in a way that leads to broadening the pulse in the time domain. Hole pitch (Λ), wavelength (λ), and normalized air holes diameter ($\frac{d}{\Lambda}$) are three factors on which photonic crystal fibers dispersion depends [1], [2]. The dependency of photonic crystal fiber's dispersion on wavelength, pitch (Λ), and normalized air holes diameter ($\frac{d}{\Lambda}$) allows for shifting the zero dispersion point [1]-[6]. Silica owns well-known optical properties and is one of the most important materials for fabrication of optoelectronic devices [1]. As seen in Fig. 1, we consider a elliptical silica core photonic crystal fiber with a square lattice of circular and six equally spaced air holes, where d is the hole diameter, Λ is the hole pitch, MN_r is number of missing rings in the center of the PCF, , N_r is the number of rings ($N_r = 6$ is considered here). The refractive index of silica is considered to be 1.45. In the center, 3 air holes are omitted ($MN_r = 3$) creating a elliptical shape central high index defect acting as the fiber core.

The total dispersion in PCFs is calculated from the following formula [5]-[8],

$$D_t(\lambda) = \underbrace{\frac{-\lambda \partial^2 \operatorname{Re}[n_{eff}(\lambda)]}{c \partial \lambda^2}}_{D_W} + \underbrace{\frac{-\lambda \partial^2 n_S(\lambda)}{c \partial \lambda^2}}_{D_m} \qquad (1)$$

Where, n_S , is the refractive index of pure silica (or any other materials), λ is the corresponding wavelength, c is the velocity of light in a vacuum and n_{eff} is the effective refractive index. Full-vector multipole method (M.P.M) can be used to analyze the dispersion properties of silica PCFs. To achieve this purpose, we use CUDOS MOF software[1] which solves the mode equation obtained from Maxwell equations, using multipole method and is a popular software for designing PCFs. By implementation of general data relevant to fiber in the software such as, number of missing air holes, number of air hole rings, wavelengths range, desired hole pitches and hole diameters size, type of material which is used in fiber and etc, we can calculate the values of effective refractive index, n_{eff}, for different wavelengths. As seen in equation (1), the waveguide dispersion (D_w) has to be added to the material dispersion (D_m) to obtain the total dispersion. In the case of pure silica, n_S , can be directly derived from the Sellmeier formula as below [5]-[9] ,

$$n_s^2(\lambda) = \frac{0.696166\lambda^2}{\lambda^2 - 0.0684043^2} + \frac{0.4079426\lambda^2}{\lambda^2 - 0.1162414^2} + \frac{0.897479\lambda^2}{\lambda^2 - 9.896161^2} + 1 \qquad (2)$$

The second-order dispersion (or so-called group velocity dispersion (GVD)) of the PCFs is then can be calculated directly by equation (3) [9],

$$GVD(\beta_2)(\lambda) = -\frac{\lambda^2}{2\pi c} D_t(\lambda) \qquad (3)$$

In Fig. 2, we have plotted the GVD as a function of wavelength in the short wavelength infrared(SWIR) region of the spectrum for the largest possible value of normalized air hole size ($d/\Lambda = 0.8$) and two pitches (Λ). As seen in Fig. 2, there is a minimum and nearly flat region of negative GVD which is shifted to higher wavelengths by changing the pitch (Λ). By choosing the proper pitch (Λ), this region can be centered at desired wavelengths. As illustrated in Fig. 3, by choosing the values $\Lambda = 1.5\mu m$ and $d/\Lambda = 0.8$, the minimum and nearly flat region can be centered at 1550 nm. The importance of nearly flat region is in soliton - effect pulse compression is due to its results as smaller third- order dispersion. It is noteworthy that after attaining certain values of hole pitch ($\Lambda = 1.5\mu m$) and normalized air hole size ($d/\Lambda = 0.8$) the fiber is not theoretically single mode at 1550nm (it supports 4 modes). But it should also be mentioned that, the single mode operation of fiber in the theoretical higher order modes regime is still possible. This is because the second and higher order modes still have extremely high attenuation close to fundamental mode. So, they are difficult to excite, leaky and strongly uncoupled from the fundamental mode. For this reason, also in this situation, the fundamental mode is considered the only propagated mode in the PCF and the fiber

[1] . The CUDOS MOF software is licensed and published by university of Sydney

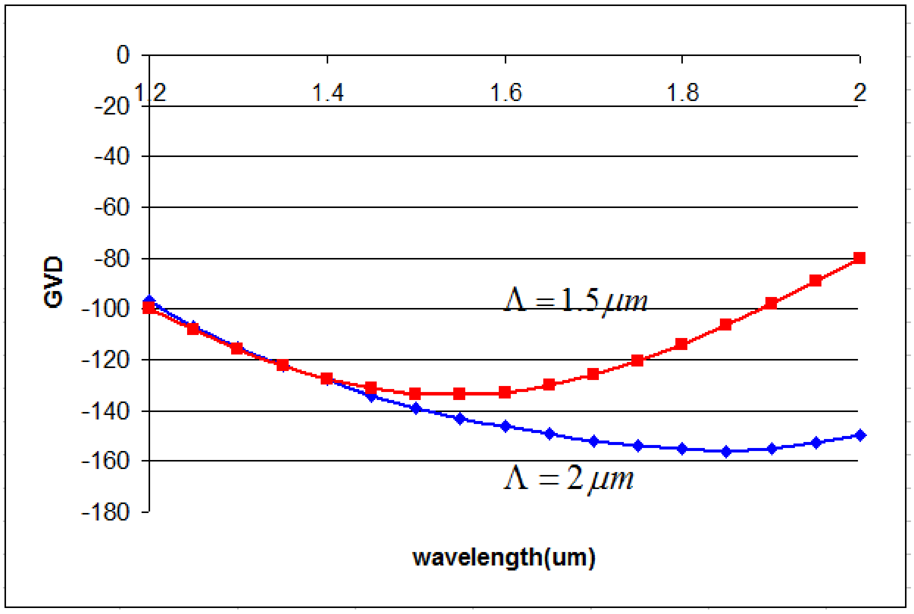

Fig. 2. GVD (ps^2/km) of the proposed PCF as a function of wavelength for $\frac{d}{\Lambda} = 0.8$ and several pitches.

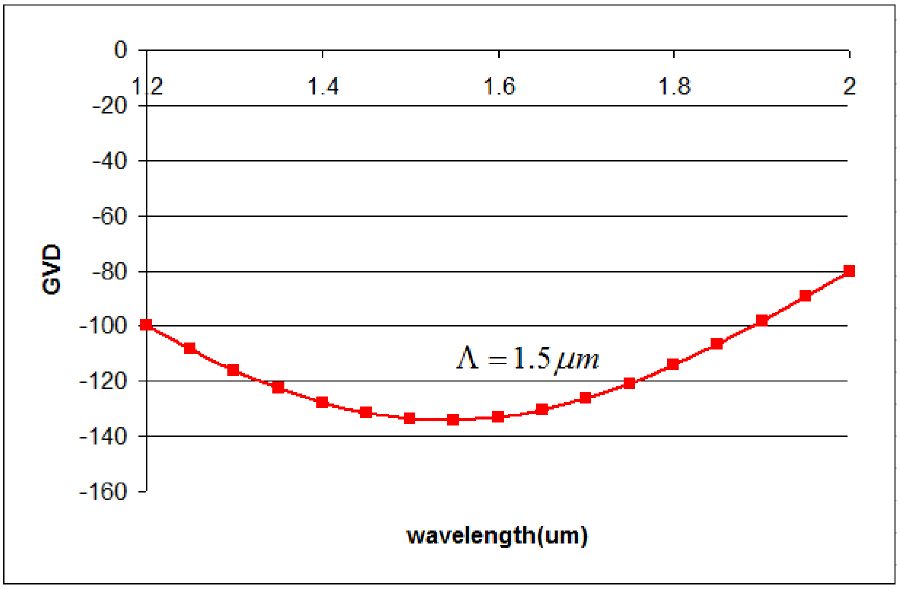

Fig. 3. GVD (ps^2/km) of the proposed PCF as a function of wavelength for $\frac{d}{\Lambda} = 0.8$ and $\Lambda = 1.5\mu m$.

is effectively single mode. When considering the propagation of pulses with femtosecond duration, the third-order dispersion will be of great importance and must be included in the generalized nonlinear Schrodinger equation (GNLSE). In Fig. 4 we have plotted the third order dispersion (TOD) as a function of wavelength in

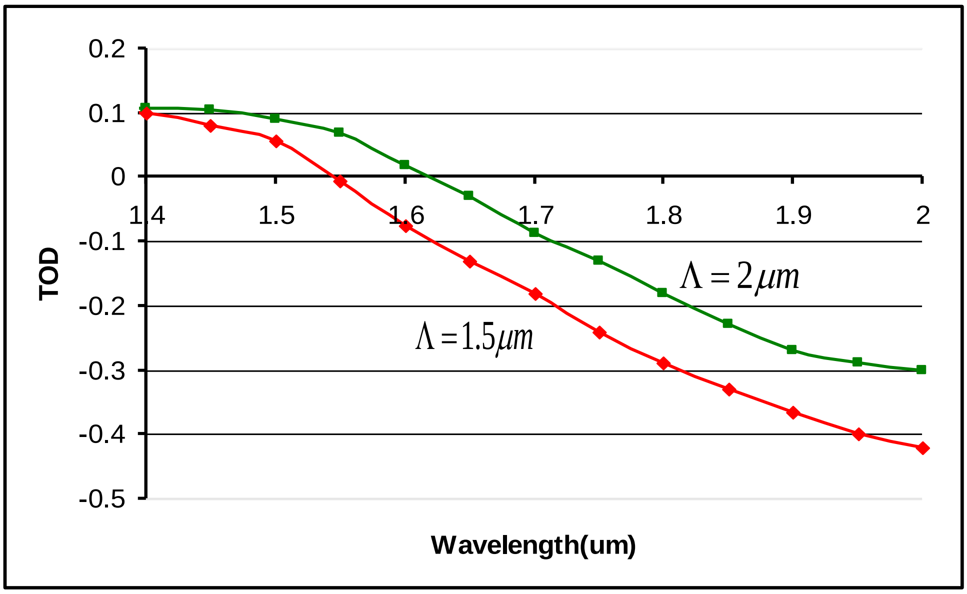

Fig. 4. TOD (ps^3/km) of the proposed PCF as a function of wavelength for $\frac{d}{\Lambda} = 0.8$ and several pitches.

the same region of the spectrum as GVD for $d/\Lambda = 0.8$ and two pitches. This Figure shows that the slight positive TOD ideally required for soliton-effect compression would be provided by the square lattice PCF in the wavelength region where a minimum and nearly flat anomalous GVD can be found.. The silica square lattice PCF can be known to be appropriate for the soliton-effect compression technique according to the fact that the ratio of the higher-order dispersions to GVD would be small at the 1550 nm wavelength.

III. SOLITON–EFFECT COMPRESSION IN THE PROPOSED PCF STRUCTURE

In this compression method, the fiber itself plays the role of the compressor. Through an interaction between self-phase modulation (SPM) and GVD, the input pulse propagated in the anomalous GVD regime of the fiber would be compressed. This compression mechanism is due to a basic characteristic of the higher order solitons which act in a periodic evolutionary manner such that they start each period with an initial narrowing phase. The input pulses can be compressed by a factor depending on the soliton order, N, provided that the fiber length is selected appropriately [1]-[4].

Fig. 5 shows the effective area for the proposed PCF. The smaller the effective area is, the higher the intensity goes. Smaller effective area also ends in an increased nonlinear phase shift and shorter nonlinear length. The effective area of the fundamental mode for the proposed PCF with the values of $\Lambda = 1.5\mu m$ and $\frac{d}{\Lambda} = 0.8$ is calculated to be 2.8 μm^2.

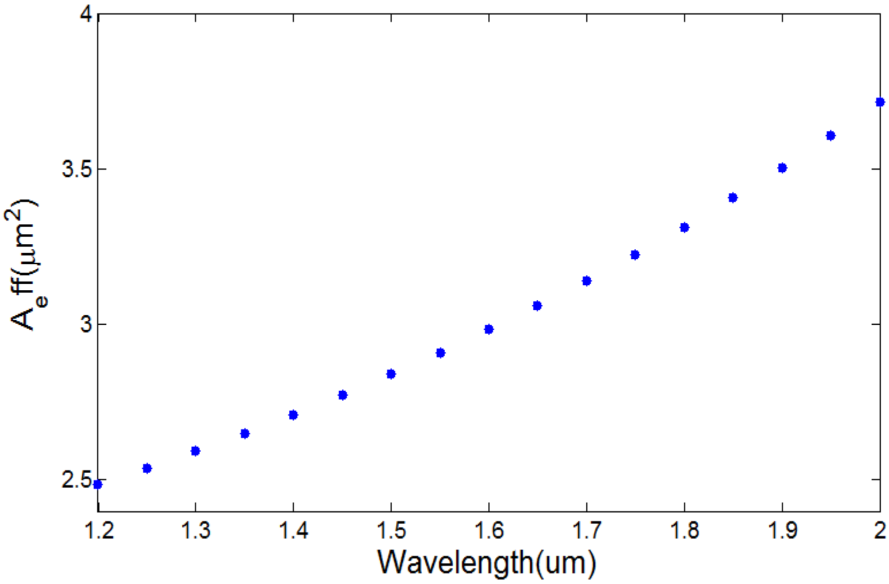

Fig. 5. Effective area of the fundamental mode for the proposed PCF .

Modeling the wave propagation in the fibers can be realized considering general nonlinear schrodinger equation (GNLSE) that includes, GVD, Third order dispersion (TOD), Raman effect, self-steepening , self phase modulation (SPM). Such equation can be written as below [2], [12]-[14],

$$
\begin{aligned}
&\frac{\partial A}{\partial z} = -\frac{i\beta_2}{2T_0^2}\frac{\partial^2 A}{\partial t^2} + \frac{\beta_3}{6T_0^3}\frac{\partial^3 A}{\partial t^3} - ..\\
&\ldots -\frac{\alpha}{2} + i\gamma(1-f_R)(|A|^2 A + \frac{i}{\omega_0}\frac{\partial(|A|^2 A)}{\partial t}) + ..\\
&.. + i\gamma f_R(A\int_0^\infty h_R |A(z,t-t')| dt' + \ldots\\
&.. + \frac{i}{\omega_0}\frac{\partial}{\partial \tau}[A\int_0^\infty h_R |A(z,t-t')| dt'])
\end{aligned}
\tag{4}
$$

Where, t stated as the reduced time, T_0 as the initial pulse width of optical pulses (note that, in this paper we will consider the FWHM value as, $T_{FWHM} = 1.76T_0$) and A(z,t) as the pulse amplitude. $\alpha(m^{-1})$ is linear loss coefficient β_2, β_3 are GVD and Third-order dispersion respectively. ω_0 is the central angular frequency, $s.s = {}^{1}\!/\!{}_{\omega_0}$ is responsible for self-steepening and γ states as the nonlinear coefficient defined by equation (5),

$$
\gamma = \frac{n_2\omega_0}{cA_{eff}} \tag{5}
$$

Where $n_2(m^2/W)$ is the nonlinear refractive index (silica has a nonlinear refractive index of $3.2\times10^{-20}\, m^2/W$), A_{eff} is the modal effective area, and c denotes the speed of light. f_R is the relative strength of Kerr and Raman interactions and finally, $h_R(t)$ is the Raman response function. An analytical form of $h_R(t)$ also exists which is given by equation (6). Experiments show that, f_R, τ_1 and τ_2 are $f_R = 0.18$, $\tau_1 = 12.2fs$ and $\tau_2 = 32fs$ respectively which are derived from [1], [2], [14].

$$h_R(t) = \frac{\tau_1^2+\tau_2^2}{\tau_1\tau_2^2}\exp(-t/\tau_2)\sin(-t/\tau_1) \tag{6}$$

Employing the normalized time, $\tau = \frac{t}{T_0}$, normalized distance, $\xi = \frac{z}{L_D}$, and the normalized pulse amplitude , $U(z,\tau) = \frac{N_p A(z,\tau)}{\sqrt{P_0}}$, equation.(4) can be written as equation (7),

$$\begin{aligned}\frac{\partial U}{\partial \xi} &= -\frac{i\,\mathrm{sgn}(\beta_2)}{2}\frac{\partial^2 U}{\partial \tau^2} + \frac{\beta_3}{6|\beta_2|T_0}\frac{\partial^3 U}{\partial \tau^3} - \ldots \\ &\ldots - \frac{\alpha L_D}{2}U + i\bar{N}U - \frac{i}{\omega_0 T_0}\frac{\partial(\bar{N}U)}{\partial \tau}\end{aligned} \tag{7}$$

Where, N_p is soliton order ($N_p = (\frac{\gamma P_0 T_0^2}{|\beta_2|})^{0.5} = 1$ for the fundamental soliton), P_0 implies the peak power of the input pulse, and $\bar{N}$ is defined by equation (8),

$$\bar{N} = \frac{N_P N(z,\tau)}{P_0} \tag{8}$$

The delayed response, $N(z,\tau)$, is defined by equation (9), [14]

$$N(z,\tau) = (1-f_R)|A|^2 + f_R(A\int_0^\infty h_R\,|A(z,\tau-\tau')|d\tau') \tag{9}$$

and L_D is the dispersion length defined by equation (10),

$$L_D = \frac{T_0^2}{|\beta_2|} \tag{10}$$

The novel concrete algorithms: symmetric split-step Fourier (S-SSFM) and fourth-order Runge Kutta (RK4) is used to simulate the Generalized Nonlinear Schrodinger Equation (GNLSE) which is an accurate method for solving the GNLSE (specially see[12]-[14]).We also used a chirp-free secant hyperbolic pulse at the input as below,

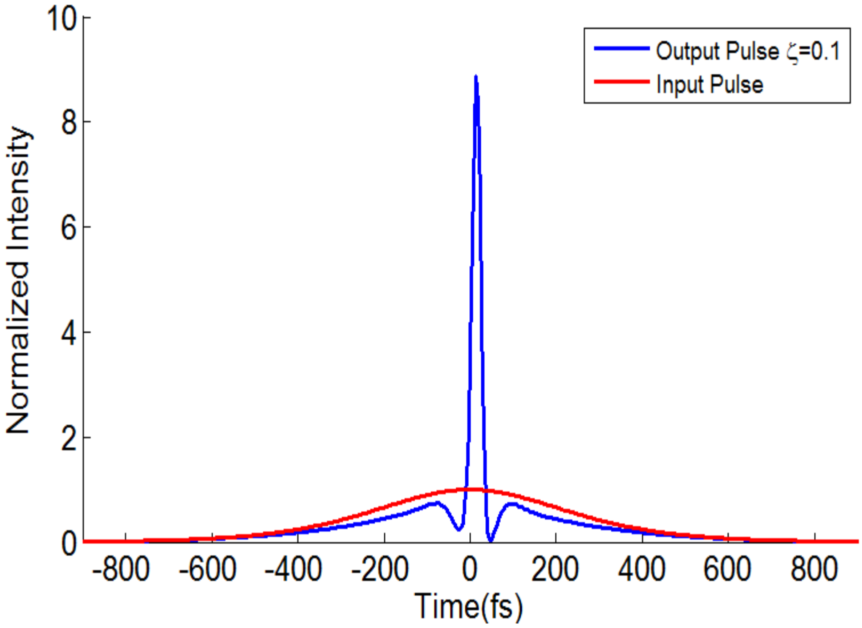

Fig.6. Output compressed pulse at a wavelength of 1550 nm and normalized propagation distance of $\xi = 0.1$. Input pulse is also shown.

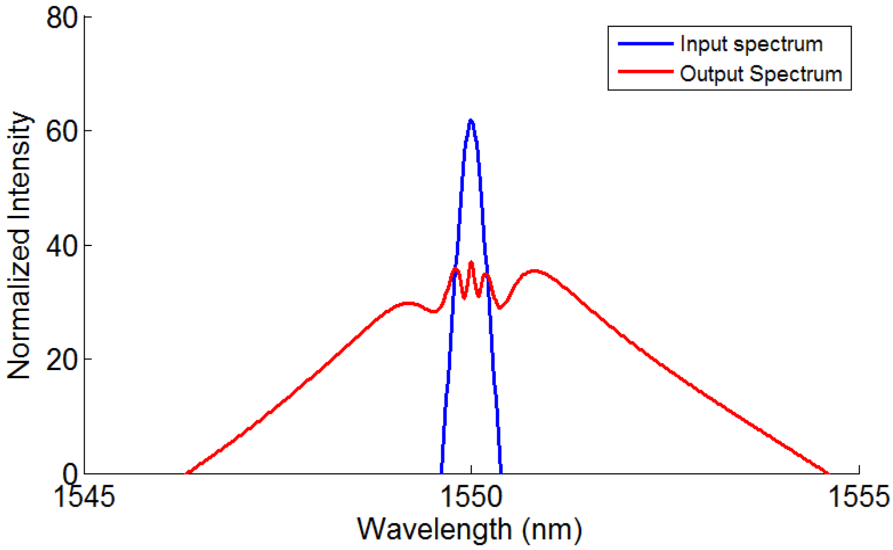

Fig.7. Spectrum of the output compressed pulse at a propagation distance of $\xi = 0.1$.The Input Spectrum is also shown.

$$U=N[\text{sech}(\tau)] \tag{11}$$

The photonic crystal fiber designed for this work is made of pure silica. In this work , we consider $\Lambda = 1.5\mu m$ and $\frac{d}{\Lambda} = 0.8$ for the proposed photonic crystal fiber structure and use a 300-fs input pulse at a pump wavelength of 1550 nm . The utilization of GVD, TOD, Linear Loss, SPM, Self-steepening, and Raman effect in GNLSE simulation, yields an output compressed pulse of 20 fs

TABLE I. COMPARISON BETWEEN NOVEL DESIGNED PCF PARAMETERS AND PREVIOUS TRIANGULAR DESIGNS

Kind of PCF / **Parameters**	**Novel Designed PCF**	**Silica Triangular PCF**	**Silica Triangular PCF**	**Silica Triangular PCF**	**Silica Triangular PCF**	**Silica Triangular PCF**
$\beta_2(ps^2/km)$	-147	-18.15	-37.4	-770	69.8	-12.7
$\beta_3(ps^3/km)$	-0.007	0.001	Not Listed	Not listed	-0.025	0.008
$A_{eff}\ [\mu m^2]$	2.8	1.1	20	44	Not listed	Not Listed
$\gamma(w.km)^{-1}$	47	21	6.4	2	0.926	45
$\lambda[nm]$	1550	850	1550	1550	800	850
Soliton order(N)	N=7	N=7	Not Listed	N=3	N=9	N=15
Reference	This work	[14]	[15]	[16]	[17]	[2]

which is shown in Fig. 6. This corresponds to the excitation of a higher order soliton of order N = 7, for a peak power of P = 1702 w (corresponds to input energy of 510 pJ) , and large nonlinear coefficient of $\gamma \approx 47(w.km)^{-1}$. The compressed pulse was obtained for a propagation distance of $\xi = 0.1$. In Fig.6, we can see a weak delay of optical pulse due to full linear and nonlinear effects. The spectral evolution at the normalized propagation distance of $\xi = 0.1$ is shown in Fig.7. We can see a self frequency shift to lower frequencies (higher wavelengths) because of dominate intrapulse Raman scattering process. In this situation, with increasing the normalized distance ($\xi = \frac{z}{L_D}$), the Spectrum will get broader and two main spectral peaks appear on both sides of the profile . Fig. 7 also clearly shows the supercontinuum effect at the propagation distance of $\xi = 0.1$ where the output spectrum has broadened to more than an octave.

A. Comparison between Square Lattice PCFs Propagation Characteristics with Triangular Lattice PCFs.

In this section, the results from designing the square lattice elliptical core photonic crystal fiber (PCF) and conventional triangular PCFS in Table I are compared. Comparing the parameters obviously indicates that, the proposed PCF which is designed in this article has ideal conditions in nonlinear applications particularly SC-generation and soliton- effect optical pulses compression as well as the other works (triangular lattice PCFs designs). This fiber presents very low third order dispersion value in addition to higher nonlinear coefficient in the wavelength of 1550nm. Consequently, these features result in boosting the quality and output optical pulses compression and also a significant decrease in required energy for nonlinear applications in these kinds of novel waveguides.

IV. CONCLUSION

We have numerically investigated the soliton-effect compression of femtosecond optical pulses in a square lattice elliptical core PCF in the short wavelength infrared region of the spectrum (especially at 1550 nm). It has been shown that by adjusting the geometrical parameters of the PCF such as pitch (Λ) and normalized air holes diameter ($\frac{d}{\Lambda}$), we are able to center a minimum and nearly flat region of large negative GVD at 1550 nm and finally calculate the smaller higher-order dispersions which are ideally needed for efficient soliton-effect compression of optical pulses. As well as the other types of PCFs (silica Triangular PCFs), the novel structure has a larger nonlinear property and require less amount of energy for nonlinear applications. By using a 300 fs input pulse with a low energy of 510 Pj (corresponds to peak power of 1702 w), a compressed pulse of 20 fs can be obtained for the proposed PCF with considering, $\Lambda = 1.5\mu m$ and $\frac{d}{\Lambda} = 0.8$ at the normalized propagation distance of $\xi = 0.1$.

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