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Analysis of Dispersion and Nonlinear Property in Doping Defected Core Spiral Photonic Crystal Fiber

Japatosh Mondal[1*], Md. Sajjad Hossain[2] and Mohammad Shaifur Rahman[3]

[1]Department of Electrical and Electronic Engineering, Bangabandhu Sheikh Mujibur Rahman Science and Technology University, Gopalganj 8100, Bangladesh.
[2]Department of Electrical and Electronic Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh.
[3]Department of Electrical and Electronic Engineering, Khulna University of Engineering and Technology, Khulna 9203, Bangladesh.

Authors' contributions

This work was carried out in collaboration between all authors. Author JM designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Author MSH managed the literature searches. Author MSR managed the analyses of the study. All authors read and approved the final manuscript.

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ABSTRACT

We propose a novel nearly zero-dispersion fiber (NZDF) at the operating wavelength based on GeO_2 doped SiO_2 square defected core spiral photonic crystal fiber (dd-SPCF). The 2-D finite element method with perfectly matched layer boundary condition is introduced to investigate the guiding properties using COMSOL Multiphysics 4.2.0.150. The angular displacement and diameter of circular air holes of spiral arms in the designed dd-SPCF have been tuned to offer near zero dispersion as well as low effective area. The proposed dd-SPCF shows promising dispersion characteristics (-0.000169 ps/km-nm) with very low effective area (2.6516 μm^2) and high nonlinear

**Corresponding author: E-mail: jmondal.eee@bsmrstu.edu.bd;*

76.44 $W^{-1}km^{-1}$ parameter at operating wavelength 1.55 μm, making it a suitable candidate for chromatic dispersion controller and nonlinear optical applications.

Keywords: Chromatic dispersion; spiral PCF; zero dispersion; non linear coefficient.

1. INTRODUCTION

Photonic crystal fibers(PCFs), comprising of a central defected region circled with compound air-holes that run along the fiber distance end to end, are not possible to be formed in conventional optical fibers. It is because PCFs bear some unique features [1] which now a day are inviting sincere attentions from various concerned communities. Tailoring ability of the air hole arrangement and its diameter of a PCF provide freedom in the design of the microstructure cladding where light is guided by means of modified total internal reflection (MTIR) and the air holes are used to reduce the index of the cladding region. A number of interesting PCFs designs has been offered to get nearly-zero dispersion and ultra-flattened chromatic dispersion. Among them, the conventional PCF designs with uniform optimized air-holes [2-5], a PCF with two defected air-hole rings [6-7], GeO_2 doped defected SiO_2 square core hexagonal PCF [8-9], nonlinear PCFs with several kinds of air hole with different diameters [10-11], equiangular spiral PCF with a defect air-hole at the center [12], square PCFs with ultra-flattened chromatic dispersion and low confinement losses [13] have been reported. Dissimilar arrangement of air holes [3,6] and doping materials [8] give different dispersion characteristics. So, the task of controlling the chromatic dispersion is a very important problem in dispersion controllers [10], nonlinear systems [14] or designing practical optical communication systems [15]. However, it is difficult to control, the dispersion and the low confinement loss, simultaneously in a wavelength, which is highly required for the design of a near zero dispersion PCFs around 1550 nm wavelength.

The rapid development of optical fiber network and the ever increasing data rates compel serious residual chromatic dispersion in transmission distances. In addition, optical sources of different wavelengths are being widely used nowadays for optical communication. Hence, the best approach is nearly zero dispersion for a large bandwidth of wavelengths. To serve this, NZDF [8], a fiber that contains zero dispersion properties has to be launched. The chromatic dispersion can be customized by arranging the air hole size, shape and large index contrast of PCF. A soft glass equiangular spiral PCF carries the potentials to be considered as pertinent for the supercontinuum generation (SCG) due to its higher nonlinearity [12] around $5250W^{-1}km^{-1}$ pumped at near infrared wavelength of 1064 nm. But, SCG in highly nonlinear soft glass, schott SF_6, bismuth oxide, and tellurite PCFs using long pump pulses (ns) in visible region is difficult possibly because of the low damage threshold of these glasses. Silica is superior in the visible region due to its few orders of magnitude higher damage threshold than the above mentioned nonlinear materials [16]. Therefore, in this work, we have engineered the spiral PCF design architecture in silica material to achieve nearly zero dispersion fiber (NZDF) with higher nonlinearity in the visible region. K. Saitoh and M. Koshiba showed the chromatic dispersion 0.304 ps/km-nm, at operating wavelength 1550 nm, of their proposed the defected core photonic crystal fiber, [17]. Saeed Olyaee and Mahdieh Izadpanah presented index-guiding PCF that showed dispersion 0.00046 ps/km-nm but non-linear coefficient was absent there [5]. Recently GeO_2 doped SiO_2 square defected core hexagonal PCF exhibits dispersion characteristics 0.0001787 ps/km-nm with very low effective area (3.03 μm^2) at 1550 nm has been reported [8]. To improve the above result, a PCF containing GeO_2 doped defected SiO_2 square in the core with spiral air hole arms dd-SPCF is proposed in this paper. The existence of the demonstrated central defected air-hole [8] that controls the waveguide dispersion from positive to negative value for different doping concentration of GeO_2 in central core. Likewise, the square core fiber improves image scrambling into the spectrograph with increased capture area. This types of fiber offer homogenized output distribution over broad application wavelengths 300 nm to 2400 nm that deliver a top hat beam profile, which in turn reduces the size and complexity of the laser delivery system. A square-core optical fiber makes a better match with laser diode output beams allowing greater coupling efficiency.The simulation of the structure shows ultrahigh nonlinearity 76.44 $W^{-1}km^{-1}$, and dispersion characteristics -0.000169 ps/km-nm with very low effective area 2.6516 μm^2 at 1500 nm wavelength. The above properties of the proposed dd-SPCF are suitable for such applications as optical parametric amplification, wavelength conversion, ultra short soliton pulse transmission, SCG and so on. The factors of the design methodology of the proposed structure are given in Section 2. The simulation methodology and simulation results are explained in Section 3 and Section 4 respectively, while the conclusions are given in Section 5.

2. DESIGN METHODOLOGY

The cross section of the proposed dd-SPCF structure is shown in Fig. 1. It has 6 arms and the starting air holes of each arm form a single spiral of radius r_o with equal angular displacement from previous one is increased by θ. The radii of subsequent rings are enhanced by geometric progression of following manner (r_o, r_o+2p, r_o+4p,…..); where p represents the distance factor to control the pitch. The air-hole pitch is labeled Λ. Each arm contains 4 air holes which are denoted by d_1, d_2, d_3 and d_4 respectively. The central core region is perturbed by a GeO_2 doped SiO_2 square with side a. The host material is regular silica. The insertion of the extra GeO_2 doped SiO_2 square in the core region is the novel concept of the present design. The existence of the central defected air-hole has the function to control the waveguide dispersion properties of the fiber as will be demonstrated later on. The outer circle is required to represent the thickness of perfectly matched layer (PML) for simulation the PCF by using Finite Element Method (FEM). The NZDF can be fabricated by the sol-gel method [18] which gives well-arranged air holes. To analyze, Λ =1.4, r_o=1.3 μm, θ=60°, a=1 μm, d_4=0.6 μm, d_3=0.48 μm, d_2=0.32 μm and d_1=0.416 μm are reported for the optimized structure. The spiral-shape structure is compact for tight light confinement and large nonlinearity; small effective area can be obtained by changing the GeO_2 doped SiO_2 square side in the core region.

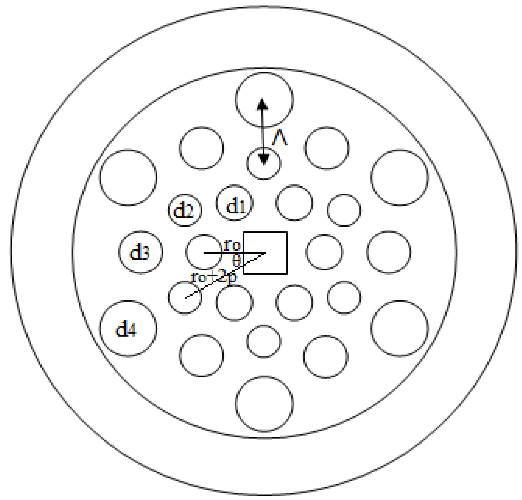

Fig. 1. Structure of the proposed dd-SPCF for NZDF

3. SIMULATION METHOD

The fiber is simulated by Finite Element Method (FEM) with Perfectly Matched Layer (PML) absorbing boundary condition. The COMSOL software 4.2.0.150 version is used as a simulation tool. For numerical analysis, 11 μm computational windows with maximum and minimum element size 1.43 μm and 0.066 μm respectively, are arranged in a triangular mesh over the cross section of the fiber. With the help of circular PML boundary conditions, the computation was carried out by 418 boundary elements and degree of freedom 21605 where the computer took about 17s to run the simulation. The FEM directly solves the Maxwell equations to approximate the best value of the effective refractive index. Once the modal effective refractive index, n_{eff} is obtained by solving an eigen value problem drawn from Maxwell equations using the COMSOL software 4.2.0.150 through which chromatic dispersion, effective area and confinement loss of PCFs can be easily calculated.

The dispersion of microstructured fibers can also be divided into two types; one is material dispersion, $D_m(\lambda)$ expressed as

$$D_m(\lambda) = -\lambda / c(d^2 \,\mathrm{Re}[n_{eff}]/d\lambda^2) \quad (1)$$

Where $R_e[n_{eff}]$ is the real part of effective refractive index n_{eff}, λ is the wavelength, c is the velocity of light in vacuum. Refractive index of SiO_2, GeO_2 and GeO_2 doped SiO_2 can be found from Sellmeier's equation [19].

$$n^2 = 1 + \sum_{i=1}^{3} \frac{A_i \lambda^2}{\lambda^2 - l_i} \quad (2)$$

$$n^2 = 1 + \sum_{i=1}^{3} \frac{[SA_i + X(GA_i - SA_i)]\lambda^2}{\lambda^2 - [Sl_i + X(Gl_i - Sl_i)]^2} \quad (3)$$

where A_i and l_i are the oscillator strength and oscillator wavelengths of SiO_2 and GeO_2 respectively. So far, SA, Sl, GA, Gl are the Sellmeier coefficients for the SiO_2 and GeO_2 glasses and X is the doping concentration of GeO_2 and the material dispersion based on Sellmeier's equation has been taken into account explicitly in the effective index of the PCF.

The effective area A_{eff} is calculated as follows [20].

$$A_{eff} = (\int_{\infty}^{\infty}\int_{\infty}^{\infty} |E|^2 dxdy)^2 / \int_{\infty}^{\infty}\int_{\infty}^{\infty} |E|^4 dxdy \quad (4)$$

Then using effective area we calculate the nonlinearity parameter by [21].

$$\gamma = 2\pi n_2 / \lambda A_{eff} \quad (5)$$

where nonlinear refractive index, n_2 for GeO_2 doped SiO_2 can be calculated as [21].

$$n_2 = 2.507 + 0.505\Delta \quad (6)$$

where relative index difference, $\Delta = \left(n_1^2 - n_0^2 / 2n_1^2\right)$; n_0 is the refractive index of pure silica and n_1 is its value when the fiber core is doped GeO_2.

The confinement loss L_c is obtained from the imaginary part of n_{eff} as follows:

$$L_c = 8.686 + K_o \, \mathrm{Im}[n_{eff}] \quad (7)$$

where $I_m[n_{eff}]$ is the imaginary part of the refractive index, $k_o = 2\pi/\lambda$ is the wave number in the free space.

4. SIMULATION RESULTS

The refractive index, n_2 for silica fiber varies in wide range from 2.23 to $3.95\times10^{-20}\,m^2/W$ depending on the type of fiber and doping techniques. To get large range of variations in n_2 values, core is doped with other materials such as GeO_2 and fluorine. By using the doping materials, the refractive indices of fibers differ by a small amount which is typically less than 1%. These doping concentration level affect n_2 values to make dispersion shifted fiber. Our Proposed dd-SPCF is doped with GeO_2 whose refractive index value n_2 varies almost linearly due to relative refractive index of the core, $\Delta = 0.02$.

The wavelength dependence of Silica glass, GeO_2 and GeO_2 doped SiO_2 based on sellmeier's equation is shown in Fig. 2. Moreover, the continuous increment of the doping concentration of GeO_2 in the defected core downshift the chromatic dispersion from positive to negative values has been reported [8]. But Fig. 3 shows wavelength dependence of chromatic dispersion of the proposed NZDF for optimum design parameters keeping the doping concentration of GeO_2 doped SiO_2 defected core at 45.47%.

Dispersion curve is illustrated through contour plot of electric field distribution over the dd-SPCF cross section shown in Fig. 4. Material dispersion is the only factor to dominate the total dispersion at lower wavelength (750 nm) shown in Fig. 4(a) because at that time the field is fully confined in the core and intaracts with the materials solely. The dispersion curve can not be manipulated by the change of core diameter prior to the first zero dispersion wavelengths (ZDW). As shown in Fig. 4(b), with the increase of wavelength, field starts to interact with the first ring of air holes and waveguide dispersion starts to increase simultaneously. Hence, material dispersion is nullified by waveguide dispersion to first ZDW. If wavelength increases more, material dispersion begins to dominate again and field distribution starts to interact with the upper portion of the first air hole ring and enter into the silica material between the two successive holes of the second ring.

As a result, material dispersion dominates the whole process and the increasing pattern of dispersion curves down into a flat portion. When the core size is smaller, nonlinear tends to be higher because of its small effective area.

Afterwards, Group velocity dispersion curve moves slowly to normal dispersion region with the excessive reduction of the core size but it does not reach ZDW. As the core size increases the GVD curve stretches up, and the nonlinearity decreases. Therefore, a tradeoff between high value of nonlinearity and larger bandwidth of anomalous dispersion is needed towards a high nonlinearity with zero-dispersion PCF.

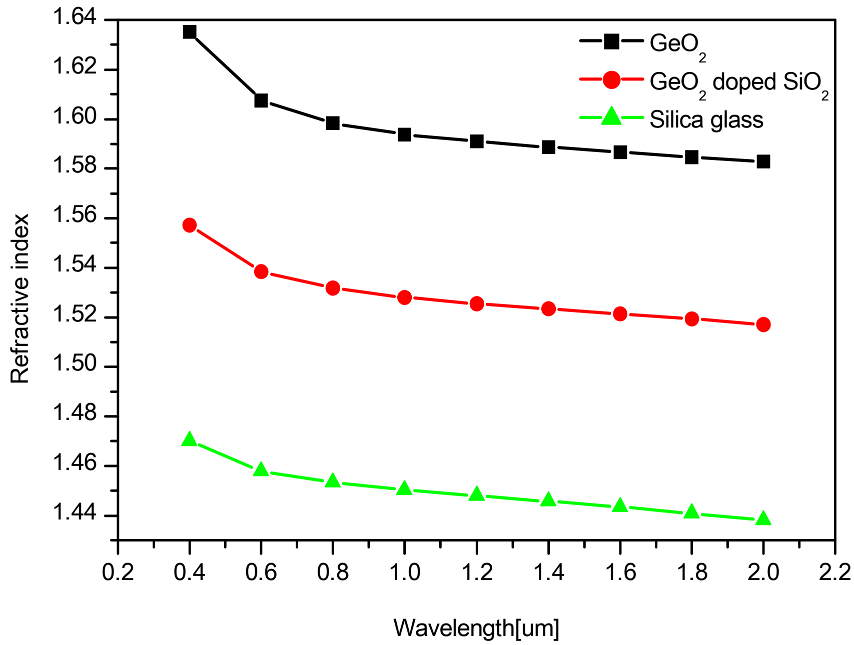

Fig. 2. Plot of refractive indices as functions of wavelength for Silica Glass, GeO_2 and GeO_2 doped SiO_2 square defected core with GeO2 doping conc. X= 45.47%

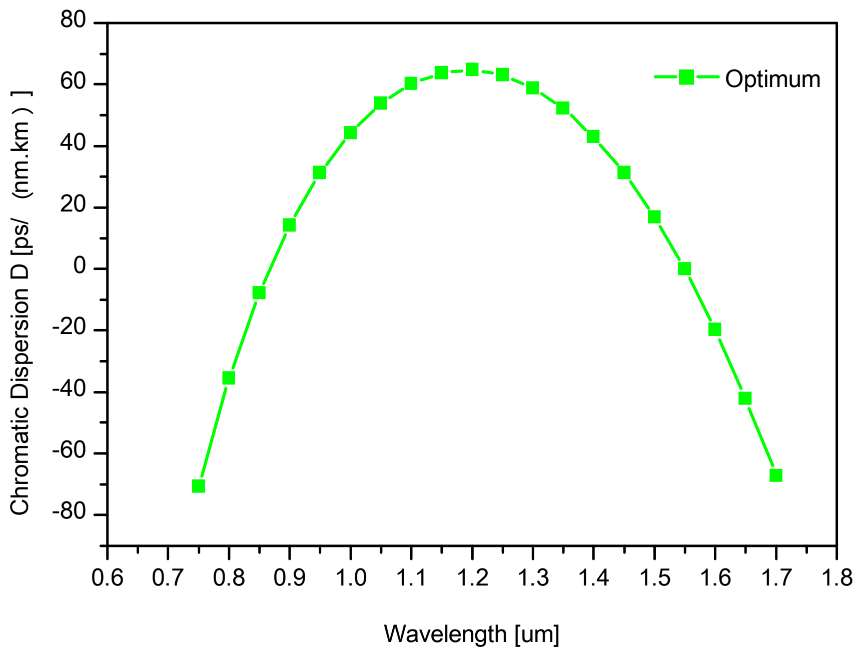

Fig. 3. Dispersion curve of the proposed NZDF for optimum design parameters

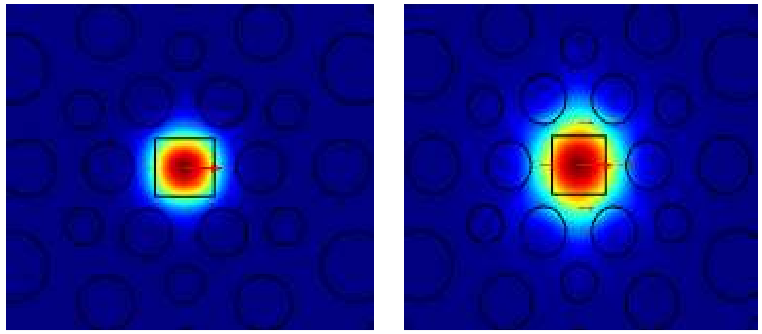

Fig. 4. Contour plot of electric field at (a) 750 nm, and (b) 1550 nm wavelengths

In Figs. 5 to 9 we show the variation of the design parameters Λ, *d*, *a* to the total dispersion curve of the PCF to investigate the parameter dependence of the dispersion, effective area, nonlinear properties and confinement loss of proposed dd-SPCF keeping the doping concentration of defected core constant at 45.47%.

In this proposed dd-SPCF design, near zero dispersion PCF can be efficiently structured by optimizing the geometrical parameters, such as air-hole diameters, pitch and square side. To account forthis issue, air-hole dimension, d is varied up to +2% aroundthe optimum values and the results are shown in Fig. 5. Compared to Fig. 6, we found that the chromatic dispersion of the proposed dd-SPCF seems sensitive to possible variations for the design parameter pitch Λ, while insensitive to the structural tolerances of the air-hole sizes and defected rings in the cladding at operating wavelength. Fig. 7 shows the variation of dispersion due to variation of the defected square core side 'a' of the dd-SPCF. According to these numerical results, there exists an optimized set of design parameters that is Λ, d, a and X that lead to zero and ultra-flattened total chromatic dispersion. This design significantly reduces the ring number of air-holes, but the designing procedure becomes more sensitive because several geometrical parameters X, Λ, d and a, are needed simultaneously to tune the dispersion behavior of the dd-SPCF.

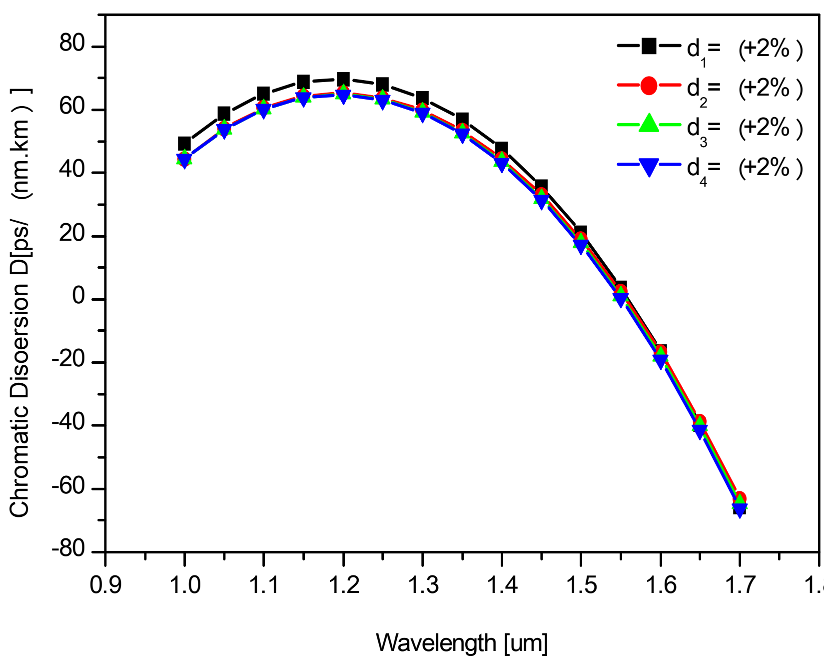

Fig. 5. Variation of dispersion versus wavelength as a function of air hole diameter, d

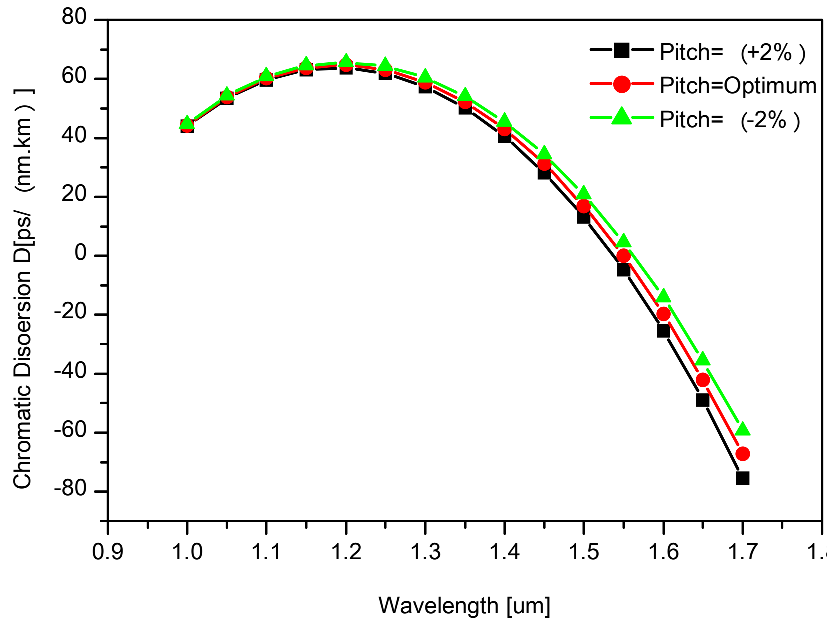

Fig. 6. Variation of dispersion versus wavelength as a function of pitch, Λ

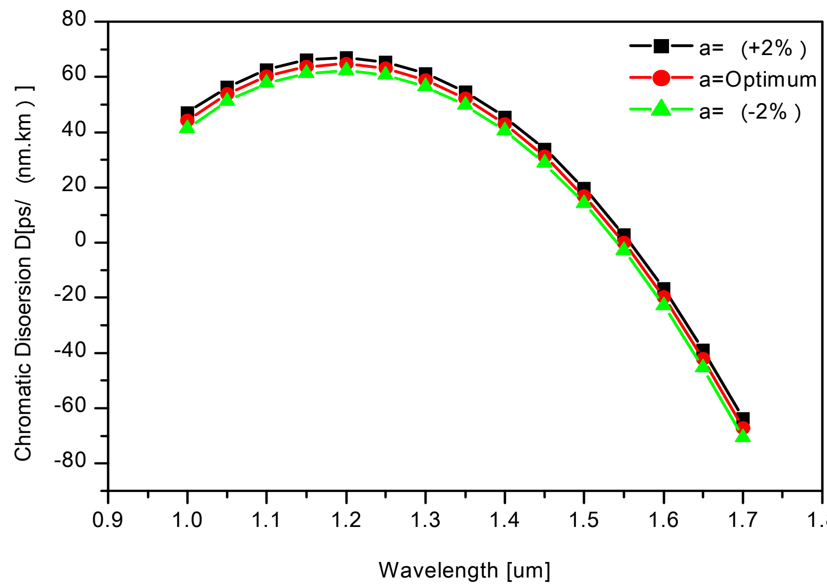

Fig. 7. Variation of dispersion versus wavelength as a function of core side, a

In practical applications, however, only the near-zero dispersion characteristics may not be enough for justifying the usefulness of the fiber. Our proposed dd-SPCF structure has small effective mode area (2.6516 μm^2) compared to that of conventional fibers (about 85 μm^2), and high nonlinear gain $76.44 W^{-1} km^{-1}$ for nonlinear applications. Fig. 8 shows the effective area and nonlinearity as a functions of the wavelength.

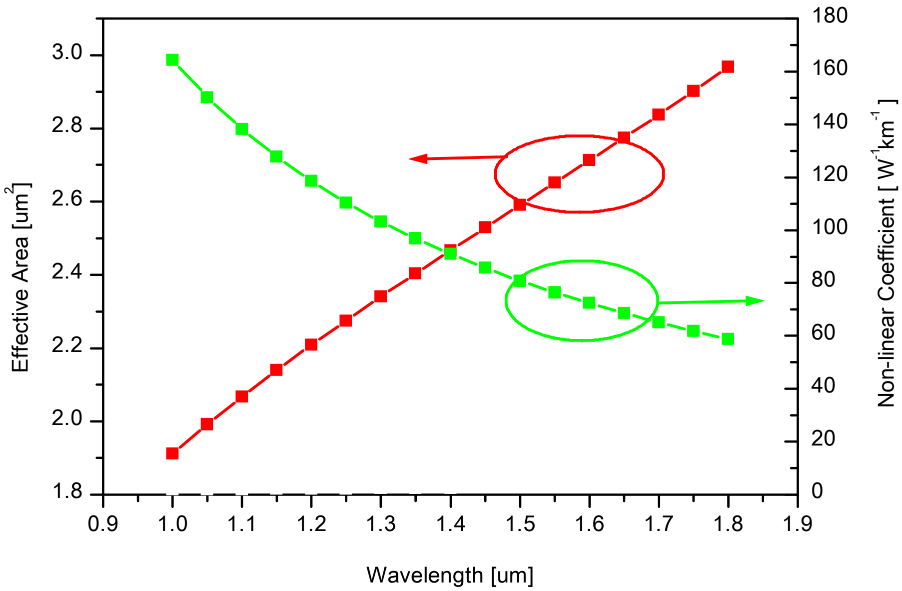

Fig. 8. Effective area and non-linear coefficient versus wavelength of the proposed dd-SPCF for optimum design parameters

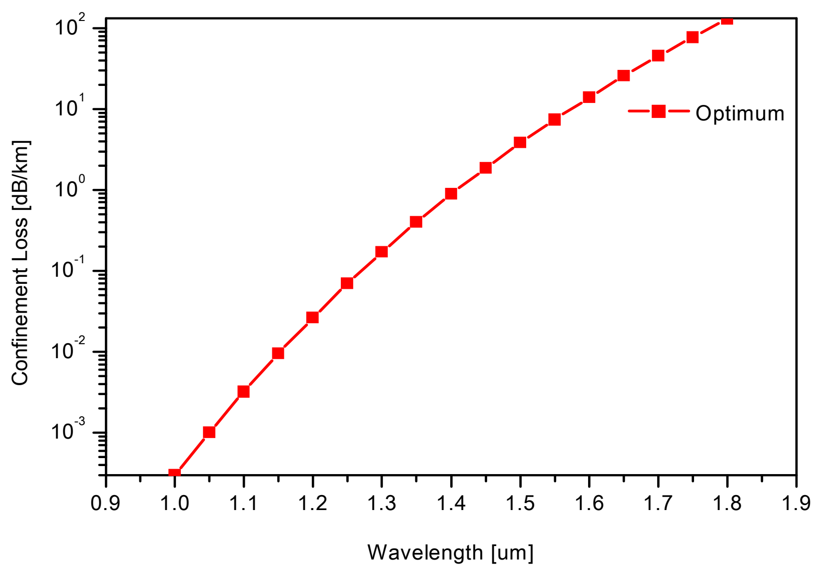

Fig. 9. Confinement loss of the proposed dd-SPCF for optimum design parameters

The nonlinear gain increases with increasing n_2 by using the Eq. 5. As the effective area increases, the nonlinear gain decreases as in Fig. 8. From Fig. 9 it is shown that confinement loss is 0.0746 dB/km at 1.55 µm that increases from lower wavelength to higher wavelength. At operating wavelength we get small effective area with high nonlinear gain, which can be used for Super Continuum Generation, Four Wave Mixing and other nonlinear applications such as soliton pulse transmission, laser tuning, nonlinear spectroscopy to biomedical imaging and frequency metrology.

The numbers of air-hole diameter of spiral arms, square core side and pitch are varied up to ±2% at operating wavelength 1550 nm and the effect on desirable PCF properties is summarized in Table 1.

Table 1. Variation of design parameters of ±2% at operating wavelength

PCF properties	d_1	d_2	d_3	d_4	a	Λ
Chromatic dispersion (ps/km-nm)	±3.69	±2.46	±1.10	±0.327	±2.88	±4.61
Effective area (μm^2)%	1.64	0.06	0.015	0	0.37	0.98
Non-linear coefficient ($W^{-1}km^{-1}$)%						
Confinement loss (dB/km)%	±0.29	±5.92	±10.96	±7.06	±8.12	±12.38

Table 2. Comparison between properties of the proposed NZDF and other NZDFs at operting wavelength

PCFs	Dispersion (ps/km-nm)	Wavelength (nm)	Effective area (μm^2)	Nonlinear coefficient $\left(W^{-1}km^{-1}\right)$	Number of design parameters
dd-SPCF	-0.000169	1550	2.6516	76.44	4
Ref. [5]	0.00046	1550	2.6	-	-
Ref. [8]	0.0001787	1550	3.03	67.23	4
Ref. [17]	0.304	1550	>3.03	-	-

From Table 1, it is clear that if the size of first air holes of each arm, d_1 is modified up to $\pm$2% keeping all parameters constant, chromatic dispersion also changes to $\pm$3.69 but for d_4 this change happens to $\pm$0.327. It has been seen, the size of air hole of several rings near the center core influences the dispersion response significantly. Also it is evidently prevalent that square core side 'a' that made the core defected dominantly influences the dispersion level than the air-holes pitch Λ. In the outermost cladding, a high value air filling fraction is chosen for better field confinement and also to reduce the confinement loss. In addition, the radius of starting air holes of each spiral arm manipulates the effective area. The value of non-linear coefficient is mostly digressed by the radius of starting air holes of each ring and it is inversely proportional to the effective area.

Finally, a comparison is made between properties of the dd-SPCF and some other fibers designed for dispersion managed applications. Table 2 (above) compares those fibers taking into account the near zero dispersion, effective area and nonlinear coefficient at operating wavelength and number of design parameters including number of rings in the cladding.

5. CONCLUSION

A truly near-zero dispersion and nonlinear characteristics of GeO_2 doped SiO_2 square defected core PCF is modeled. It is found that GeO_2 doping concentration in defected core is used to get low dispersion, while the square defected core is for small effective area and low confinement loss. The proposed NZDF shows small effective area 2.6516 μm^2 and high nonlinear gain $76.44 W^{-1}km^{-1}$ at operating wavelength 1.55 µm. In this wavelength the dispersion and confinement loss are equal to -0.000169ps/ (km-nm) and 0.0746 dB/km respectively. Therefore, this fiber appears as an effectual partner in the field of telecommunication. Since it offers better results than standard optical fiber, it does not require dispersion compensation in optical domain. Along with these advantages, it also works with nonlinear optic applications.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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