A Theoretical Investigation of a Photonic Crystal Fibre with Ultra-Flattened Chromatic Dispersion with Three Zero Crossing Dispersion Wavelengths

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Abstract: This paper presents a novel non-defective core photonic crystal fiber (PCF) which was found to produce three zero dispersion wavelength (ZDW), which may lead to a very powerful spectral densities compared to that of single or double ZDW PCFs. More so, the presented PCF design not only has the three ZDW achieved for the PCF, but also, been able to achieve a high negative chromatic dispersion (-220.39 ps/km.nm), and ultra-flatted chromatic dispersion of ±0.9 ps/km.nm within operating wavelength range of 1.53 to 1.8 μm. These characteristics may be helpful for applications in the fields of supercontinuum generation (SCG), soliton pulse transmission, and detecting or sensing and optical communication systems. The propagation properties of the proposed PCFs: effective index, confinement loss and chromatic dispersion, are well researched making use of full vectorial finite element method (FEM).

Keywords: Zero dispersion wavelength, chromatic dispersion, photonic crystal fibers.

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1. Introduction

Photonic-crystal fiber (PCF) is another class of optical fiber in light of the properties of photonic crystals. They comprise of a silica core, encompassed by an occasional cluster of air-holes running along the whole length of the fiber. On account of its capacity to confine light in hollow cores or with repression qualities unrealistic in traditional optical fiber, PCF is presently discovering applications in fiber-optic interchanges, fiber lasers, nonlinear devices, high-power transmission, very sensitive gas sensors, and different areas [1-6].

Designs [3] and [4] proposed PCFs that yield ultra-flattened chromatic dispersion by using novel techniques. [3] showed the possibility to design a four-ring PCF with flattened dispersion of ±0.5 ps/nm.km over the wavelength range 1.19 to 1.69 μm. More so, the design, with five rings, achieved flattened dispersion of ±0.4 ps/nm.km over the wavelength range 1.23 to 1.72 μm. Lee et el. [5] proposed an annular core photonic quasi-crystal (PQC) fiber that has a 6-fold symmetric quasi periodic array of air holes with a central core to achieve a nearly zero ultra-flattened chromatic dispersion (CD). However, their design is not a true effective index guidance (EIG) PCF because of the introduction of the defective core with an air hole. More so, their design made used of six air-hole rings which makes the design too bulky and complex. Lu et el. [6] also proposed an oblong shaped core using a 3-contiguous air hole in the fiber core to achieve a nearly zero flattened CD. The downside of their design is the introduction of the defective core using the 3-contiguous air holes, making the design a false EIG PCF. More so, making use of eleven air-hole rings is will make the design too bulky. Hasan et el. [7] controlled CD by inserting circular air holes in the core. They also achieved an ultra-highly negative CD by the use of an elliptical air hole in the core. In view of these, the core becomes defective, making the design a false EIG PCF. Moreover, the use of octagonal, instead of hexagonal, lattice PCF in their design causes the design to be too bulky with air holes. Olyaee et el. [8] simultaneously reduced CD and confinement loss (CL) by making the hole diameters of the outer rings bigger in a six air hole rings PCF. They demonstrated a reduced CD by omitting the holes in the six corners of cladding in the hexagonal structure. However, the PCF design becomes bulky due to the higher number of air hole rings. Moreover, the use of finite-difference time-domain (FDTD) numerical method makes their simulation results relatively less accurate than using the preferred FEM method. Akowuah et el. [9] made use of three air hole rings and introduced extra smaller air holes in between the main holes in each ring, belonging to the first and third rings. This made it possible for them to achieve a 2 ZDW, nearly zero and negative CD. Increasing the number of ZDW has a known ability to enhance the power spectral densities, which find it useful in SC generation applications [10,14].

Taking note of all the challenges faced by the above reviewed PCF designs, it is deduced that getting a particular PCF design to fulfill all the desires of the optical properties is a very difficult task. In view of this, more novel PCF designs are needed to be in place to concentrate more effort tailored to a particular requirement. In this light this paper proposes a novel PCF design to achieve a 3 zero dispersion wavelength.

2. Design methodology

Chromatic dispersion (D) has two components: Material (D_m) and Waveguide (D_w) dispersions. A positive D depicts anomalous dispersion regime [12]. In the other hand, a negative D is said to be normal [13].

Material dispersion is caused by the interaction between the light and ions, molecules or electrons in the material. It refers to the wavelength dependence of the refractive index of the material.

Waveguide dispersion depends among others on the core diameter and on the refractive index contrast between the core and the cladding. Generally, conventional optical fibers have dispersion characteristics close to the material dispersion of silica due to their small waveguide dispersion resulting from a low index contrast between the core and the cladding [16,17].

This paper makes use of the usual formula from the real part of the effective index $Re(n_{eff})$ and the material (silica) dispersion given by Sellmeier's formula [15] is directly included in the calculation [17-19]:

$$D = -\frac{\lambda}{c}\frac{\partial^2 \mathrm{Re}(n_{eff})}{\partial \lambda^2} \qquad (1)$$

where c is the velocity of light and is λ the operating wavelength. The D_m component comes from silicon material used in the fibre. The D_w component comes from how the arrangement of the air-holes in the silicon material are made in an attempt to guide the waves, like light, passing through it. Chromatic dispersion CD is calculated by adding the material dispersion (D_m) to the waveguide dispersion (D_w), as shown in equation 2.

$$CD = D_m + D_w \tag{2}$$

where

$$D_m = -\frac{\lambda}{c}\frac{\partial^2 n_{silicon}}{\partial \lambda^2} \tag{3}$$

and

$$D_w = -\frac{\lambda}{c}\frac{\partial^2 \left[\mathrm{Re}(n_{eff}) \mid n_{silicon}(\lambda) = const.\right]}{\partial \lambda^2} \tag{4}$$

D_m is calculated by applying Sellmeier type expansion [15,17] for $n_{silicon}$, where $n_{silicon}$ is affected by wavelength in dispersive media. Contrary, D_w is affected by hole-size, pitch, wavelength and the number of air-hole rings in the material. From equation 4, since $n_{silicon}$ is constant, D_m is not considered. In view of latter, the effective index n_{eff} of a guided mode only explicitly depends on the design parameters, like the size of the air-holes and pitch.

3. Simulation and results

The proposed PCF structure consists of a regular 3-ring hexagonal lattice of air holes with a missing hole in the center, in a silica background. The silica has a refractive index of 1.45. That of the hole is 1.

The diameter and radius of air holes are denoted by d and r, respectively. The hole-to-hole spacing, called the pitch, is also denoted as Λ. The computational window in the directions of x and y is Wx and Wy, which are 16.0 μm and 14.6 μm respectively.

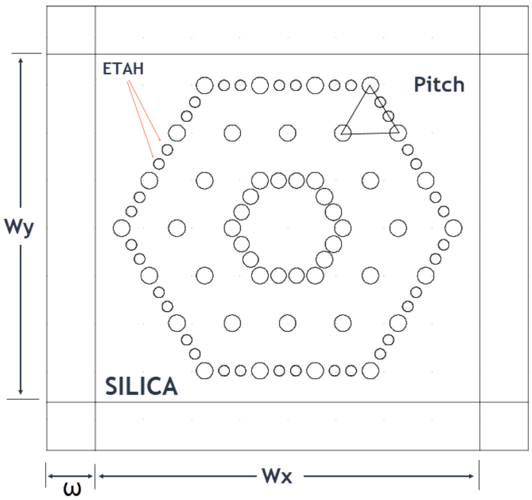

Fig. 1. Cross-sectional diagram of the proposed 3-ring PCF of 36 main air-holes, no ETAH in the second ring, and ETAH in first ring greater than ETAH in third ring

The perfectly matched layer (PML) of the PCF has been subdivided into 8 regions $\alpha_{jmax} = 8$, and the thickness of the PML is 2 µm. Next, the PCF structure has been supplied with extra-twin air holes (ETAH) which are located in-between the main holes in the same air hole rings such that the spaces between all the holes are the same. Moreover, the diameter of ETAH at the first ring should be greater than the ETAH at the third ring, with ETAH in the second ring removed. This is illustrated in Fig. 1 above.

The idea of incorporating ETAH in the same rings is adapted from the study done in [7], where extra air holes (EAH) were added to the PCF design structure to achieve a lower confinement loss. This is intentional to allow our PCF design to also achieve low losses.

The geometric figure to help in locating the centers of the two extra twin air holes is as shown in Fig. 2. It is worthy to know that all holes do not merge with their neighboring air holes.

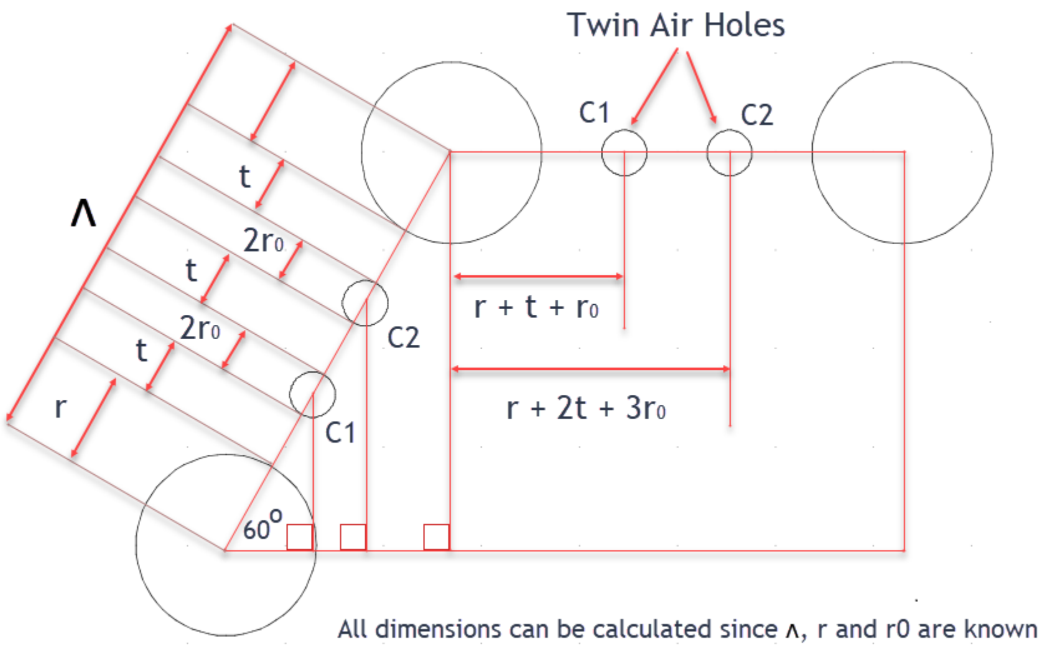

Fig. 2. Geometric view of ETAH location

The adaptability offered by PCFs, has created a lot of enthusiasm for these fairly unusual structures. These fibers can be intended to have various unusual properties, low CL and unusual dispersion properties over wide wavelength range.

The cross-sectional diagram of the proposed PCF is as shown in Fig. 3.

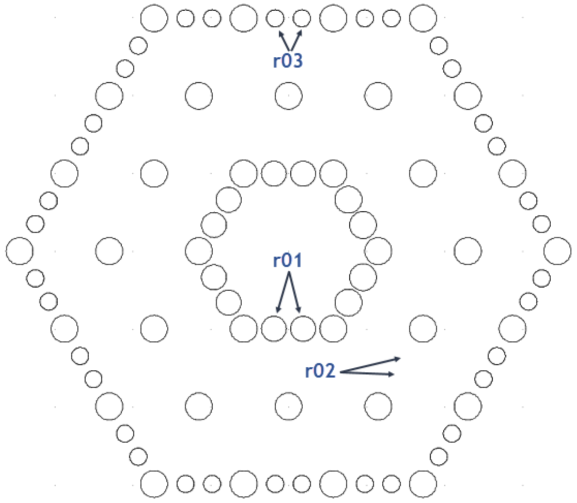

Fig. 3. Cross-sectional diagram of the proposed PCF without ETAH in the second ring, and also $r_{01} > r_{03}$

From Fig. 4, it is observed that not only has the three ZDW been achieved for the PCF, but also, been able to achieve a high negative dispersion with (a) parametric values, and an ultra-flatted CD of ±0.9 ps/km.nm within operating wavelength range of 1.53 to 1.8 μm with (c).

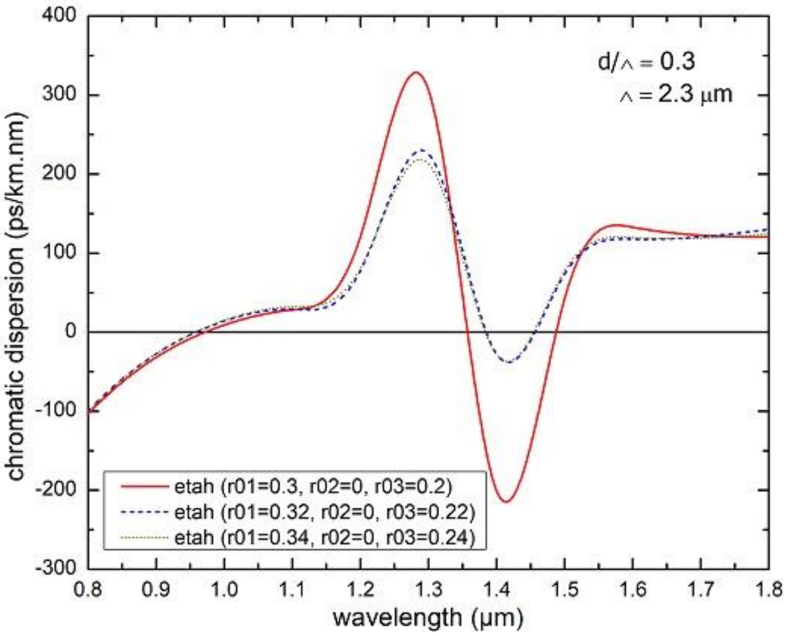

Fig. 4. Variance of CD with λ, when d/Λ = 0.3, Λ = 2.3 μm, for
(a) r_{01} = 0.3 μm, r_{02} = 0 μm, r_{03} = 0.2 μm,
(b) r_{01} = 0.32 μm, r_{02} = 0 μm, r_{03} = 0.22 μm, and
(c) r_{01} = 0.34 μm, r_{02} = 0 μm, r_{03} = 0.24 μm

To underpin the novelty of our proposed PCF design, the ETAHs in the second ring were reduced to zero while maintaining those in the first and third rings. More so, the sizes of the ETAHs in the first ring were always made slightly lower than those of the third ring. As shown in Fig. 4, by carefully varying the sizes of the ETAHs, maintaining the conditions above, our design is able to achieve 3 ZDWs which may find useful in application areas like SCG, since according to [13] and [14] such PCFs may lead to stronger power spectral densities compared to single and double ZDW PCFs. The proposed PCF has also recorded a significant large negative CD (-220.39 ps/km.nm) accounted for by the carefully reduction of both the sizes of ETAHs in the first and third rings, and still maintaining the conditions where the sizes of ETAHs in the first ring are slightly greater than those of the third ring with those of the second rings still being reduced to zero, and an ultra-flatted CD which may be found useful in application areas like long distance secure data transmission and dispersion compensating fibers [13, 14].

The insertion of EAHs in the rings of PCF further reduces the confinement loss [5]. More so, upon further investigations the PCF was found out to produce two ZDW by carefully varying the sizes of the EAHs in the rings [5]. Since it is more beneficial to have PCFs with more ZDW, our approach sought to vary the sizes of our ETAHs in all the rings in order to produce more than two ZDWs.

Table 1 shows the summary in comparison of the proposed PCF to others.

Table 1. Proposed PCF verses Other PCFs

PCF	**CD [ps/km.nm]**	**Comments**
[5] Lee et el.	Variation of +/-0.11 for 1.15 – 1.65	D core, BD (4 R)
[6] Lu et el.	Variation 0.82+/-0.3 for 1.12 – 1.51 λ	D core, BD (11 R)
[7] Hasan et el.	-608.93 (average) Absolute CD variation of -12.7 for 1.46 – 1.625 λ	DE core, BD (6 R)
[8] Olyaee et el.	< 2.5, Variation 0.8 for 1.1 – 1.7 λ	BD (R > 3)
[9] Akowuah et el.	~	Less BD (3 R), 2 ZDW, higher CL
Proposed PCF	±0.9 ps/km.nm for 1.53 – 1.8 λ	Less B (3 R), 3 ZDW, ~ D core

Abbreviations: D – Defective (Air-hole), BD – Bulky Design, R - Air-hole rings, DE – Defective (Elliptical air-hoe), ~ D core – True EIG PCF (Non-defective)

4. Conclusion

A novel PCF have been proposed to easily yield three ZDWs. More so, the proposed PCF design not only has the three ZDW achieved for the PCF, but also, been able to achieve a high negative chromatic dispersion (-220.39 ps/km.nm), and ultra-flatted chromatic dispersion of ±0.9 ps/km.nm within operating wavelength range of 1.53 to 1.8 μm. These characteristics may be helpful for applications in the fields of supercontinuum generation, soliton pulse transmission, and detecting or sensing and optical communication systems.

With the introduction of smaller ETAH in the structure of the proposed PCF, one may be tempted to conclude that they may be very difficult to be fabricated. However, with the sol-gel fabrication method [18], coupled with the surfaced nanophotonics technology [20-22] the proposed PCFs can be fabricated easily.

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