Octagonal Photonic Crystal Fibre with Golden Ratio Principle as a Dispersion Compensating

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***Abstract*—An octagonal 5-layer air-hole dispersion compensating photonic crystal fibre is presented in this paper. The design is based on the golden ratio principle where the pitch to air hole diameter ratio is kept at 1.618. Numerical analysis using full-vector Finite Element Method (FEM) with a perfectly matched layer boundary condition is used to investigate optical properties of the Photonic Crystal Fibre (PCF). At its optimum pitch value, high negative dispersion of −295 ps/(nm.km) and low confinement loss of 0.00755 dB/km is achieved at 1550 nm wavelength. Similarly, the proposed PCF also yields negative dispersion and low confinement loss on the E+S+C+L+U wavelength bands and partially on the O band with optimum pitch. These properties point to the suitability of the proposed PCF for potential application as a dispersion compensating fibre.**

***Index Terms*—Chromatic dispersion, confinement loss, dispersion compensating fibre**

I. Introduction

There is an ever-increasing demand for high-speed long haul transmission links, made possible using fibre optic technology. However, information carrying capacity of the fibre is still very much limited by pulse broadening due to chromatic dispersion [1]. To overcome this difficulty, dispersion compensation techniques become indispensable, with chirped in-fibre Bragg gratings [2], planar light wave circuit dispersion equalizer [3] and dispersion compensating fibres (DCFs) [4]. Among techniques that have been used. DCFs are generally preferred for dispersion compensation due to its reliability, simplicity and suitability for broadband dispersion compensation [4].

Since the first introduction of photonic crystal fibre (PCF), many advancements have been made to improve structure of such fibres to suit different applications [5]. Design flexibility of PCFs allows one to manipulate several parameters such as lattice type, lattice pitch, air hole diameter and shape as well as the refractive index of the material, to obtain unique and desirable dispersion properties that are impossible to achieve with conventional fibres [6]. High negative dispersion is one advantageous property of PCFs that makes it useful for mitigation of chromatic dispersion in long haul transmission links. This has led to surging developments of PCF-based DCFs within the past decade [1], focusing on designing PCFs with high negative dispersion property with minimal loss.

Many PCF designs can be found in the literature. Ani *et al*. [7] proposed a circular lattice PCF producing an average negative dispersion of −124.0 ps/(nm.km) with confinement loss of less than 10^{-6} dB/km. In [8], a double-hole assisted core encapsulated in a square lattice cladding has been proposed, with negative dispersion of −150 ps/(nm.km) and loss of less than 10^{-5} dB/km. High negative dispersions of −506 ps/(nm.km) and −558.96 ps/(nm.km) in the 1460 to 1675 nm wavelength range, have been demonstrated using a modified octagonal PCF [9] and a decagonal PCF structure [10], respectively. However, losses are a bit higher; in the order of 10^{-1} dB/km [9] and 10^{-2} dB/km [10].

Ahmed *et al*. [11] presented a square lattice PCF that exhibits an ultrahigh negative dispersion of −1083 ps/(nm.km) at 1550 nm wavelength, although the confinement loss; important property for DCF, has not been investigated. Meanwhile, an octagonal structure PCF with negative dispersion coefficient of −3339 ps/(nm.km) with confinement loss in the order of 10^{-2} dB/km has been reported by Roy *et al*. [12].

The above literatures [7]-[12] indicate that for DCF, the design is a trade-off between negative dispersion and confinement loss; whereby to obtain higher negative dispersion would inevitably lead to higher loss. Additionally, design complexity also needs to be taken into account. Although the designs in reference [7]-[12] exhibited high negative dispersion and low confinement loss, the designs contained multiple air hole sizes and complex geometrical structure that would make fabrication process very difficult. As such, it is important that not only the design DCF should have high negative dispersion and low confinement loss, the design must also be made simpler.

The principle of golden ratio may be used for designing such PCF. Considered to be pleasing to the human eye, golden ratio has been applied to many aspects of nature such as body proportions of living things, insects, the arrangement of leaves in the stem of a plant, and the model of the universe. Not only that, the golden ratio is responsible for the basis of many simple but yet strong structures and architectures around the world, namely the Pyramids of Giza and the Parthenon, all built

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many years ago and still standing strong today [13], 14]. The principle has not been applied in many PCFs generally, with the exceptions for references [15], albeit not specifically as dispersion compensating fibre. Because of this, the golden ratio is applied to the structure of the air holes in the proposed PCF-based DCF.

In this paper, a simple octagonal PCF structure, based on the golden ratio, with 5 air-hole rings based on silica material is presented. The fibre gives sufficiently high negative dispersion of –295.2 ps/(nm.km) and low confinement loss of less than 10^{-3} dB/km at 1550 nm wavelength. Effective area and non-linear coefficient of the fibre are also studied. Due to its design simplicity, it can be fabricated easily using current fabrication technique.

II. Geometry of the Proposed Design

Geometrical cross-section of the proposed 5-ring octagonal PCF is presented in Fig. 1, with $8n$ air holes on the n^{th} ring of the fibre, where n = 1 to 5. Its geometry is defined by air hole diameter, d, and pitches; with Λ and Λ_1 denoting pitches between adjacent air holes on the same ring and on different rings, respectively. Pitches Λ and Λ_1 are related by $\Lambda = 0.765\Lambda_1$. In order to strengthen the fibre structure, the golden ratio principle is followed in the design of the fibre. Denoting the golden ratio [16] by the Greek letter φ, with a mathematical value of 1.618, pitch to diameter ratio (Λ/d) of the fibre is fixed, such that:

$$\Lambda/d = 1.618 \tag{1}$$

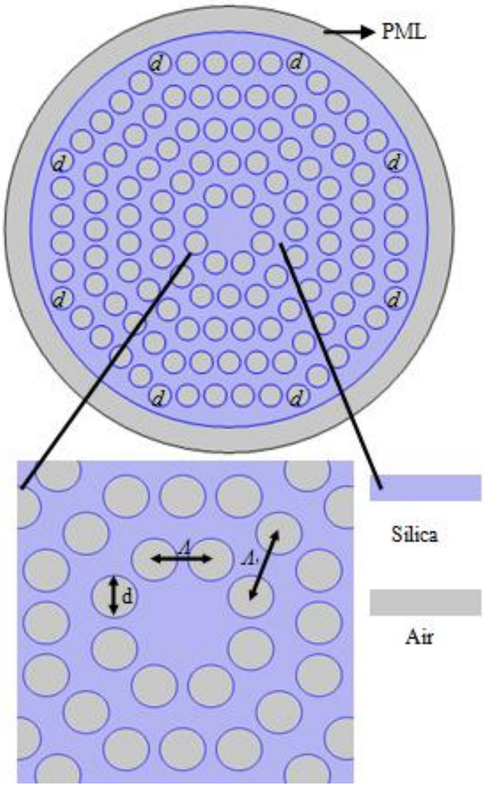

Fig. 1. Cross-sectional structure of the proposed PCF.

Silica is used as background material for the proposed fibre. Refractive indexes of the dielectric material and air are 1.45 and 1, respectively. A perfectly matched layer (PML) surrounds the PCF structure [17], absorbing lights which may pass from the core to the cladding and hence, suppressing any unwanted boundary reflection coming from the electromagnetic wave. A fine mesh type is used, which produces a total of 18900 elements, composed of 3124 edge elements, 488 vertex elements and 37738 triangular elements. Average element quality of 0.7943 is obtained from the mesh.

III. Analysis Method

Full vector finite element method (FEM) with PML boundary condition is used to simulate and analyse optical properties of the proposed PCF.

Effective refractive index, n_{eff} is calculated by using the three-terms Sellmeier equation [17], [18], given by

$$n_{\text{eff}} = \sqrt{1+\frac{B_1\lambda^2}{\lambda^2 - C_1}+\frac{B_2\lambda^2}{\lambda^2 - C_2}+\frac{B_3\lambda^2}{\lambda^2 - C_3}} \tag{2}$$

where λ is wavelength, and B_1, B_2 , B_3, C_1, C_2 and C_3, represent Sellmeier coefficients. For every wavelength, effective refractive index of Silica varies according to (2).

Effective refractive index is then used to calculate other optical properties of the proposed PCF such as chromatic dispersion D, confinement loss, L_c, effective area A_{eff} and nonlinearity coefficient γ [19]:

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2\ \text{Re}\left[n_{\text{eff}}\right]}{d\lambda^2} \tag{3}$$

$$L_c = 8.686\times k_0 \text{Im}[n_{\text{eff}}]\times 10^3 \tag{4}$$

$$A_{eff} = \frac{\left(\iint\left|\text{E}^2\right|dxdy\right)^2}{\iint|\text{E}|^4\ dxdy} \tag{5}$$

$$\gamma = \frac{2\pi}{\lambda}\frac{n_2}{A_{\text{eff}}}\times 10^3 \tag{6}$$

where Re[n_{eff}] and Im[n_{eff}] are real and imaginary parts of effective refractive index, n_{eff}, $k_0=2\pi/\lambda$ is the free space wave number, E is amplitude of the transverse electric field propagating inside the PCF and $n_2 = 3.0\times10^{-20}$ m^2/W is the non-linear refractive index of pure silica material [20], [21].

Relative dispersion slope, RDS and total residual dispersion, D_T are properties that are equally important to determine suitability of the proposed PCF to function as dispersion compensating fibre. These properties are calculated using [20], [22]:

$$\text{RDS} = \frac{S_{\text{SMF}}}{D_{\text{SMF}}} = \frac{S_{\text{DCF}}}{D_{\text{DCF}}} \tag{7}$$

$$D_T = D_{\text{SMF}}L_{\text{SMF}} + D_{\text{DCF}}L_{\text{DCF}} \tag{8}$$

where D_{SMF} and D_{DCF} are dispersion coefficients of single mode fibre and dispersion compensating fibre, respectively. D_{DCF} is derived for particular wavelength λ using (3). L_{SMF} and L_{DCF} are lengths of single mode fibre and dispersion compensating fibre, respectively. L_{SMF} is taken to be 40 km, standard length for analysis of dispersion compensating fibre whilst L_{DCF} is chosen such that total residual dispersion is zero at 1.55 μm wavelength.

S_{SMF} and S_{DCF} are the dispersion slopes of single mode fibre and dispersion compensating fibre, respectively, both of which can be calculated using [20], [22]:

$$S_{\mathrm{SMF}} \text{ or } S_{\mathrm{DCF}} = \frac{dD(\lambda)}{d(\lambda)} \tag{9}$$

IV. Simulation Results

A. Effective Refractive Index

Simulations are performed for the proposed PCF for four different values of pitch Λ=0.9 μm, Λ=1.0 μm, Λ=1.06 μm and Λ=1.1 μm, in order to investigate different optical properties of the proposed PCF. Effective refractive index of the proposed PCF is obtained for different values of Λ and wavelength, used as basis for analysis, given in Fig. 2. It can be seen that effective refractive index n_{eff}, decreases as wavelength increases, with low Λ giving lower effective refractive index. When pitch value is larger in that time amount of silica in the cladding region is higher that bring core and cladding effective refractive index difference larger. Therefore, effective refractive index value is higher in higher pitch value. On the other hand, core and cladding effective refractive index will be reduced in case of small pitch value because less amount of silica will be existed in the cladding region that bring core and cladding effective refractive index difference smaller. Thereby in smaller pitch value effective refractive index value is lower.

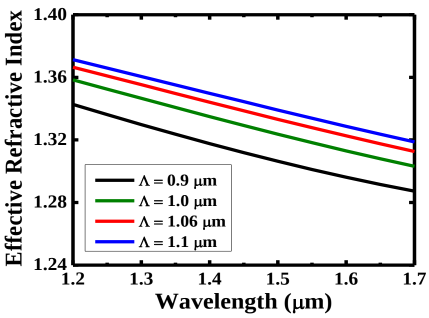

Fig. 2. Relationship between effective refractive index and wavelength, for different values of Λ.

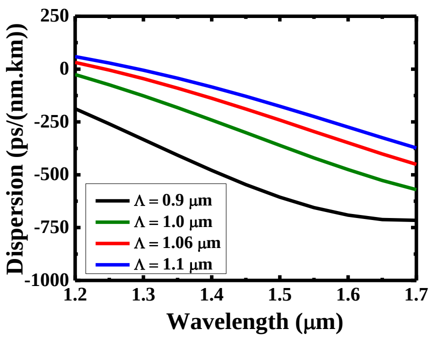

Fig. 3. Relationship between chromatic dispersion and wavelength, for different values of Λ.

B. Chromatic Dispersion

Effective refractive index n_{eff} is then used to determine other optical properties. Chromatic dispersion is an unavoidable phenomenon found in fibre optic communication, whereby light with a range of wavelength passing through the fibre travels at slightly different speeds, causing them to arrive at their destinations at slightly different times. This results in broadening of pulses, especially in long haul transmissions, where the information capacity of the fibre can be significantly reduced. Relationship between chromatic dispersion of the proposed PCF and wavelength, for different values of Λ is given in Fig. 3.

It can be seen that chromatic dispersion decreases with increasing wavelength, with lower Λ producing higher negative dispersion. Negative dispersion values of −420.3 ps/(nm.km), −295.2 ps/(nm·km) and −224.6 ps/(nm·km) are obtained with Λ at 1.0 μm 1.06 μm and 1.1 μm, respectively, at 1.55 μm wavelength. Similarly, it can be seen that the proposed PCF exhibits the highest negative dispersion at −655.1 ps/(nm·km) when Λ = 0.9 μm at 1.55 μm wavelength.

C. Confinement Loss

Fig. 4 gives the confinement loss of the proposed PCF for different wavelengths and Λ. The confinement loss represents the light loss due to the mode propagating outside the centre core of the fibre. Generally, the confinement loss increases with wavelength and Λ, as seen from the figure. Although Λ=0.9 μm gives the highest negative dispersion, the confinement loss is also particularly high for that value of Λ. Increasing Λ allows a reduction in the confinement loss. At 1.55 μm wavelength, the confinement loss for Λ at 0.9 μm is 0.872 dB/km, in contrast to losses of 0.04588 dB/km, 0.00755 dB/km and 0.00227 dB/km for Λ at 1.0 μm, 1.06 μm and 1.1 μm, respectively; which are in the order of less than 10^{-2} dB/km.

D. Effective Area and Nonlinear Coefficient

Effective area is used to measure non-linear properties of the fibre; with low effective area providing high density of power which in turn signifies nonlinear effect [23]. PCFs with high nonlinear coefficient are needed for soliton application, supercontinuum generation, optical code division multiple access and other nonlinear applications [12]. Additionally, PCFs with higher nonlinear coefficients are found to be more suitable for dispersion compensation [12].

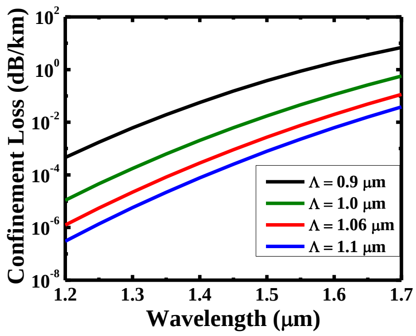

Fig. 4. Relationship between confinement loss and wavelength, for different values of Λ.

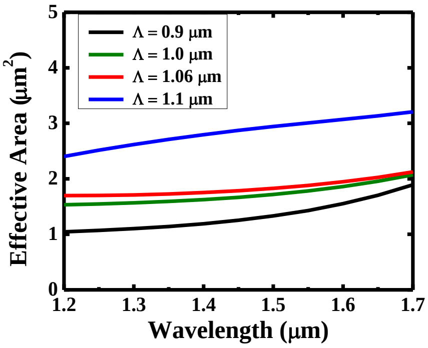

Fig. 5. Relationship between effective area and wavelength for different values of Λ.

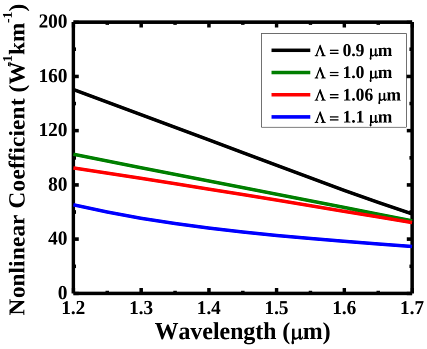

Fig. 6. Relationship between nonlinear coefficient and wavelength for different values of Λ.

Fig. 5 and Fig. 6 give the relationship between wavelength and effective area, and wavelength and nonlinear coefficient, respectively, for different values of Λ. Generally, effective area increases with wavelength and Λ. Conversely, nonlinear coefficient decreases with wavelength and Λ, with steeper relationship between nonlinear coefficient and wavelength, at low Λ. Lowest effective area, 1.43 μm^2, is obtained with Λ=0.9 μm at the 1.55 μm wavelength. Due to the inverse relationship between effective area and nonlinear coefficient, Λ=0.9 μm gives the highest nonlinear coefficient of 85.1 W^{-1}km^{-1}.

E. Relative Dispersion Slope

Dispersion slope S_{DCF} of the dispersion compensating fibre is essential in calculating the slope mismatch with single mode fibres (SMF). Taking relative dispersion slope, RDS of a SMF to be 0.0036 nm^{-1}, RDS of the DCF needs to be close to the assumed RDS value of the SMF at 1.55 μm wavelength, in order for the DCF to be applicable. RDS of the DCF at different values of Λ are tabulated in Table I. It can be seen that Λ=1.06 μm gives RDS of 0.0036 nm^{-1}, exact RDS of SMF, and as such Λ= 1.06 μm is used henceforth as the optimum Λ parameter. Fig. 7 shows the relationship between RDS of the proposed fibre and wavelength at Λ=1.06 μm; with RDS decreasing with increase in wavelength.

TABLE I. THE EFFECT OF CHANGING Λ VALUES ON THE RDS OF THE FIBRE AT 1.55 μM WAVELENGTH

Pitch, Λ (μm)	RDS (nm^{-1})
0.9	0.0013
1.0	0.0027
1.06	0.0036
1.1	0.0044

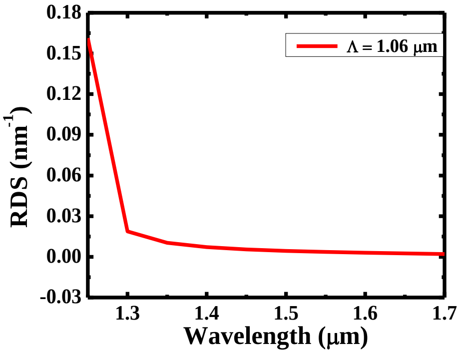

Fig. 7. Residual dispersion slope against wavelength, for Λ=1.06 μm.

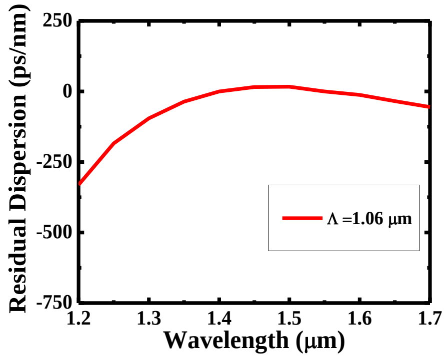

Fig. 8. Total residual dispersion D_T against wavelength, for Λ =1.06 μm.

F. Residual Dispersion

Negative dispersion property of dispersion compensating fibre is needed to compensate for the positive dispersion of single mode fibre, over wide range of wavelength. However, even after compensation, there still may be some left over dispersion, referred to as total residual dispersion, D_T, which needs to be kept as low as possible. Fig. 8 depicts D_T for different wavelengths at Λ=1.06 μm; with residual dispersion equal to zero at 1.55 μm wavelength and length of dispersion compensating fibre L_{DCF}=2.24 km for a single mode fibre L_{SMF}= 40 km.

V. CONCLUSION

A single mode octagonal PCF with 5 air-hole rings has been proposed; following golden ratio principle to strengthen its structure whilst still keeping the design simple. Full vectorial finite element method has been used to numerically analyse different optical properties of the proposed PCF, for different values of Λ. With Λ=0.9 μm, the proposed PCF exhibits the highest negative dispersion and nonlinear coefficient of –655.1 ps/(nm.km) and 85.1 W^{-1}km^{-1}, respectively, with the lowest effective area of 1.3 μm^2. However, minimum confinement loss of 0.00227 dB/km is obtained with Λ = 1.1 μm. As such, the study has shown that it is not possible to simultaneously obtain high negative dispersion with low confinement loss due to trade-off between these two properties.

It has been shown that RDS of the proposed PCF is identical to that of single mode fibre, at Λ = 1.06 μm and as such, the value has been adopted as the recommended pitch of the proposed PCF. With this pitch value, sufficiently high negative chromatic dispersion of –295.2 ps/(nm.km) and low confinement loss of 0.00755 dB/km are obtainable, at 1.55 μm wavelength. Effective area of

1.88 μm^2 and non-linear coefficient of 64.66 W^{-1}km^{-1} may also be obtained. Additionally, the proposed PCF is able to cover a wide range of bandwidth, notably the E+S+C+L+U, and the O band partially. This makes the fibre suitable for not only dispersion compensation, but also for non-linear applications. Moreover, design simplicity of the proposed PCF makes its fabrication feasible.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Fatin Nadhirah and Izaddeen Yakasai designed the model, carried out the simulation, analysed the data and performed the numerical calculations. Fatin Nadhirah and Izaddeen Yakasai wrote the manuscript with the help of Pg Emeroylariffion Abas, Saifullah Abu Bakar, and Feroza Begum. Pg Emeroylariffion Abas and Feroza Begum provided critical feedback and helped shape the research, analysis and manuscript. Feroza Begum conceived the original idea, contributed to the interpretation of the results and supervised the project. All authors discussed the results and contributed to the final version of the manuscript.

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Being a strong advocate of self-learning and research, her final year project involves the study of photonic crystal fibres at the Faculty of Integrated Technologies in UBD. Reading journals and papers were necessary to develop an in depth understanding of the said study, and being an avid reader has helped during the process.

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