Novel Design to Compensate Dispersion for Index-Guiding Photonic Crystal Fiber with Defected Core

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Abstract—**In this paper we present a novel dispersion compensating photonic crystal fiber with defected core. The small central defect of air hole can flexibly control the chromatic dispersion properties of this kind of photonic crystal fiber. The 2-D finite difference frequency domain method (FDFD) with perfectly matched layers (PML) is used to investigate dispersion properties. By varying the size of defected core, it is possible to obtain high negative dispersion coefficient. The proposed photonic crystal fiber is suitable for broadband dispersion compensation in wavelength division multiplexing (DWDM) optical communication systems.**

Keywords– Photonic crystal fiber, negative dispersion, dispersion compensation fiber.

I. INTRODUCTION

Photonic crystal fiber (PCF) technology has rapidly progressed in recent years and attracted much attention for fiber device applications because of its unusual optical properties. In particular, PCF can control the chromatic dispersion over a wide wavelength range and can be expected to provide a novel dispersion compensating fiber (DCF). DCF can be used for long distance high speed transmission in the dense wavelength division multiplexing (DWDM) optical communication systems based on the standard single mode fiber (SMF). Gerome et al. have reported the dispersion compensating fiber based on the equivalent dual-core structure of PCF. The negative chromatic dispersion coefficient of −2200 ps/(nm·km) was theoretically obtained with pure silica PCF[1]. The dual-core structures of PCF with large negative dispersion have been studied subsequently ([2],[3],[4]). Shen et al. have proposed the model by considering the micro-structured cladding with $1\mu m$ thick pitch. The chromatic dispersion coefficient up to −474.5 ps/(nm·km) was achieved in their PCF structure [5]. Yang et al. have reported a modified dual-core structure of PCF to realize the broadband large negative dispersion compensation. They theoretically designed and analyzed the dispersion compensating PCF, and realized the chromatic dispersion coefficient from −380 to −420 ps/(nm·km) in the C band[6]. Wu et al. have reported an index-guiding PCF with defected core. They theoretically and experimentally demonstrate this broadband DCF based on index guiding PCF with defected core. The chromatic dispersion properties of PCF with defected core were simulated by the vectorial finite element method (VFEM) theoretically[7,8]. The chromatic dispersion properties can be modified greatly by the central defect of air hole, and the chromatic dispersion coefficient varies from −440 to −480 ps/(nm·km) in the measured wavelength range of 1500 -1625 nm [9]. In this paper, we present a new design photonic crystal fiber with defected core and four ring air holes in cladding reigns for dispersion compensation over C+L wavelength bands. We can obtain high negative dispersion by varying the size of defected core. The dispersion coefficient varies from -466 to -460 ps/(nm.km) in the measured wavelength range of 1530-1625 nm. It has ultra-flattened negative dispersion that is suitable for broadband dispersion compensation in DWDM optical communication systems. This paper is organized as follows: In the next section, the theory of FDFD is described. In section III, it is focused on the PCF characteristics. In section IV, fiber geometry structure is described. Finally, numerical results are discussed in section V.

II. ANALYSIS METHOD

The finite difference frequency domain (FDFD) is popular and appealing for numerical electromagnetic simulation due to its many merits. It has been one of the major tools for the analysis and understanding of PCFs. The discretization scheme can be derived from the Helmholtz equations or Maxwell's equations directly. Now we use the direct discretization schemes first described for photonic crystal fibers by Zhu et al [10]. Now we use the direct discretization schemes described for photonic crystal fibers. Yee's two-dimensional mesh is illustrated in Fig. 1; note that the transverse fields are tangential to the unit cell boundaries, so the continuity conditions are automatically satisfied. After inserting the equivalent nonsplit-field anisotropic PML in the frequency domain, the curl Maxwell equations are expressed as:

$$jk_0 s\varepsilon_r E = \nabla \times H$$
$$-jk_0 s\mu_r H = \nabla \times E \tag{1}$$

$$s = \begin{bmatrix} s_y/s_x & 0 & 0 \\ 0 & s_x/s_y & 0 \\ 0 & 0 & s_x s_y \end{bmatrix} \tag{2}$$

where μ_r and ε_r are the relative permittivity and permeability of the medium considered, $k_0 = 2\pi/\lambda$ is the wave number in free space, $s_x = 1 - \sigma_x / j\omega\varepsilon_0$, $s_y = 1 - \sigma_y / j\omega\varepsilon_0$ and σ is the conductivity profile. Assuming that the PCFs are loss less and uniform and the propagation constant along the *z* direction is β. Thus, the field variation along the propagation direction *z* is of the form $\exp(-j\beta z)$. The *z*-derivatives, $\partial/\partial z$ can be replaced by $-j\beta$ in Maxwell's equations and thus three dimensional equations can be solved using only a two dimensional mesh. Using the central difference scheme and zero boundary conditions outside of the anisotropic PML layers, the curl equations (1) can be rewritten in a matrix form which includes six field components. Then eliminating the longitudinal magnetic and electric fields, the eigenvalue matrix equation in terms of transverse magnetic fields and transverse electric fields can be obtained as:

$$\begin{bmatrix} Q_{xx} & Q_{xy} \\ Q_{yx} & Q_{yy} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \end{bmatrix} = \beta^2 \begin{bmatrix} H_x \\ H_y \end{bmatrix} \tag{3}$$

$$\begin{bmatrix} P_{xx} & P_{xy} \\ P_{yx} & P_{yy} \end{bmatrix} \begin{bmatrix} E_x \\ E_y \end{bmatrix} = \beta^2 \begin{bmatrix} E_x \\ E_y \end{bmatrix} \tag{4}$$

Where the *Q* and *P* are highly sparse coefficient matrices. The order and the nonzero elements in them are reduced and effectively stored in sparse format, so the computation efficiency is improved greatly. The complex propagation constant β and the transversal magnetic or electric field distribution can be solved out quickly and accurately by a sparse matrix solver [11].

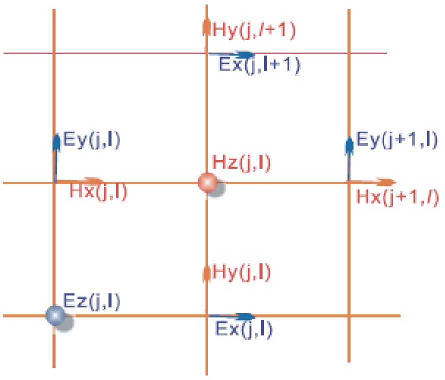

Figure 1. Unit cell in Yee's 2D-FDFD mesh

III. PHOTONIC CRYSTAL FIBER CHARACTERISTICS

A. *Chromatic Dispersion*

The chromatic dispersion *D* of a PCFs is easily calculated from the n_{eff} value vs. the wavelength using the following [12]:

$$D(\lambda) = -\frac{\lambda}{c} \frac{d^2 \operatorname{Re}[n_{eff}]}{d\lambda^2} \tag{5}$$

in (ps/(nm.km)), where Re(n_{eff}) is the real part of the refractive index, λ is the operating wavelength, and *c* is the velocity of light in a vacuum. The material dispersion can be obtained from the three-term sellmeier formula and is directly included in the calculation. In PCFs, the chromatic dispersion *D* is related to the additional design parameters like geometry of the air holes, pitch, and hole diameters. By optimizing these parameters, suitable guiding properties can be obtained.

B. *Confinement Loss*

Confinement loss is the light confinement ability within the core region. The increase of air hole rings help the confinement of light in the core region, which results in smaller losses than those with less air hole rings. The confinement loss L_c is then obtained from the imaginary part of n_{eff} as follows [13]:

$$L_c = \frac{(20\times10^6)}{\ln(10)} k_0 \operatorname{Im}[n_{eff}] \tag{6}$$

With the unit dB/m, where Im (n_{eff}) is the imaginary part of the refractive index, $k_0 = 2\pi/\lambda$ is the wave number in the free space.

IV. DESIGNED MODEL

The proposed PCF is made of pure silica and has a triangular array of air holes running along its length. The transverse cross-section of the PCF is shown in Fig. 2.

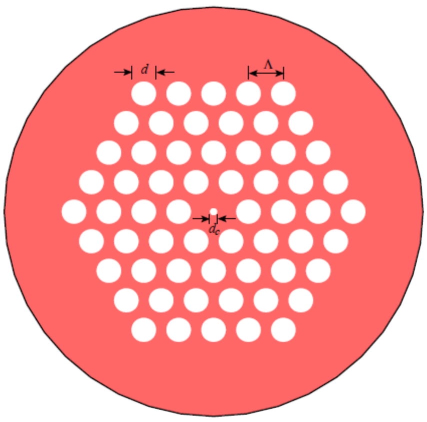

Figure. 2. Cross-section of the PCF with defected core

where Λ is the pitch of the lattice, d_c is the defected core diameter and d is the air-hole diameter in other rings.

The total number of air-hole rings was chosen to be four in order to simplify as much as possible the structural composition of the PCF. The chromatic dispersion can be controlled by the central hole of the defected core. Fig.3 and Fig.4 show the effective index profile over C to L wavelength bands and the mode field distribution of the PCF at wavelength of 1550nm. The physical mechanism of the proposed design procedure can be explained as follows: the continuous enlargement of the defected air-hole in the central silica-region reduces the portion of the material in the core and as a result, there is a compensation of the inherent dispersion of the silica. The existence of the defected air-hole in the core slightly reduces the effective core index and as a result the field lines penetrate the cladding more strongly in comparison with the non-defected core PCFs [14].

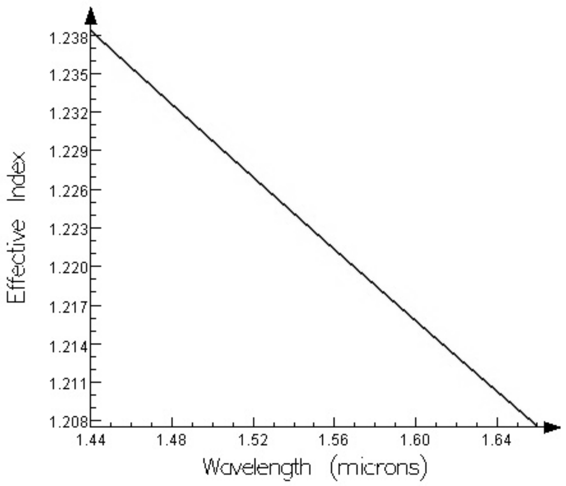

Figure.3: Effective index curve of the PCF as a function of wavelength. $d_c/\Lambda = 0.4\mu m$, $d = 1.35\mu m$ and $\Lambda = 1.37\mu m$

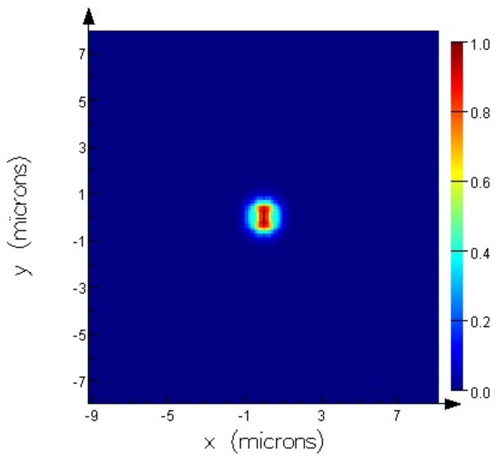

Figure. 4. Transversal field intensity distribution at a wavelength of $\lambda = 1550nm$ for the fundamental guiding mode. $d = 1.35\mu m$, $\Lambda = 1.37\mu m$ and $d_c/\Lambda = 0.4\mu m$

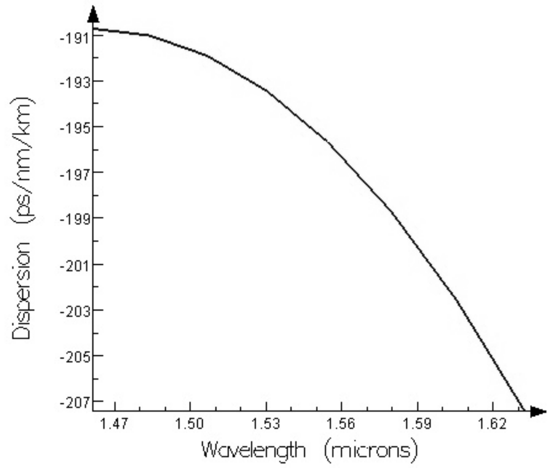

Figure .5. Dispersion curve of the PCF as a function of wavelength. $d = 1.35\mu m$, $d_c/\Lambda = 0.4\mu m$ and $\Lambda = 1.37\mu m$

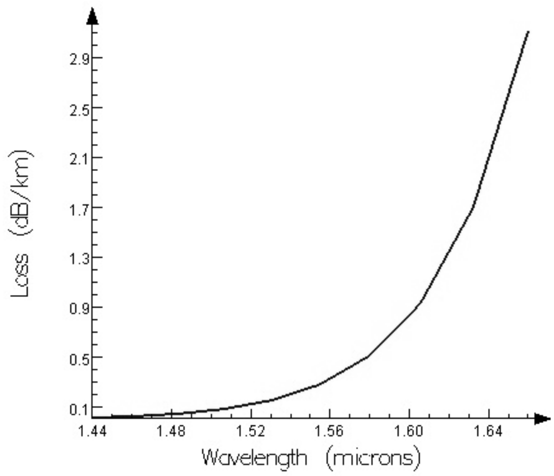

Figure. 6. Loss curve of the PCF as a function of wavelength. $d = 1.35\mu m$, $d_c/\Lambda = 0.4\mu m$ and $\Lambda = 1.37\mu m$

IV. NUMERICAL RESULT AND DISCUSSION

A small air hole is introduced in the center of PCF structure, and the diameter d_c of the defected core is smaller than the diameters of the cladding air holes. The compensating bandwidth is over the measured wavelength range of 1530−1625 nm. As shown in Fig 2, we choose one degree of freedom d_c in the design procedure. The influence of any other single outer ring is much more limited, therefore we set those rings to have the same air-hole diameter to reduce fabrication complexity. This parameter is d_c adjusted and its influence on the dispersion curve is investigated. The dispersion curve of the designed PCF with $d = 1.35\mu m$, $\Lambda = 1.37\mu m$ and $d_c/\Lambda = 0.4\mu m$ from C to L band is shown in Fig. 5. As it can be seen, the designed PCF has negative dispersion of -193.4 ~ -196.95 (ps/nm.km) over C-band. In addition , the PCF shows negative dispersion of –196.95~ -206.1(ps/nm.km), over L bands. In this designed PCF, with increasing of defected core diameter, dispersion is shifted to negative value. Table I, summarize the dispersion variation in the designed PCF with altering the hole diameters of the defected core. With respect to Tables I, the lowest negative dispersion variation is achieved in the C band for the PCF with the following parameters; $d = 1.35\mu m$, $d_c / \Lambda = 0.6\mu m$, and $\Lambda = 1.37\mu m$. It has ultra-flattened negative dispersion that can be used for dispersion compensation. The loss characteristics of the designed PCF with $d = 1.35\mu m$, $d_c / \Lambda = 0.4\mu m$ and $\Lambda = 1.37\mu m$, within the wavelength range of 1530-1625 nm is shown in Fig. 6. With respect of Fig. 6, the loss of the designed PCF is 0.25(dB/km) at a wavelength 1550nm. In addition, the PCF shows the losses of 0.25~ 0.42(dB/km) and 0.42~ 1.1(dB/km) over C, and L bands respectively. Tables II, summarize the losses of the PCF with altering the d_c / Λ , at wavelength of 1550nm. As shown in Fig 4, we can see the strong confinement of light in the core of PCF, and the mode field is mainly distributed in the silica core region. The light is guided in the silica core region, so this structural PCF is a modified index-guiding PCF.

V. CONCLUSION

We have theoretically investigated the novel design for index-guiding photonic crystal fiber with defected core based on pure silica. The results show that negative dispersion can be obtained. Our proposed PCF architecture is significantly simpler than other structures proposed so far for controlling the chromatic dispersion . Main advantage is that, compared with previously presented PCFs, with defected core, the design procedure for this proposed novel PCF structure could be more efficient and easier because relatively fewer geometrical parameters are need to be optimized. Thus, we can choose the appropriate geometric parameters to achieve the desirable dispersion compensation over different communication bands. Take all things to account; we believe that our proposed PCF will be useful in dispersion compensation ultra-broadband transmission application.

TABLE I.
DISPERSION OF THE DESIGNED PCF WITH DIFFERENT d_c / Λ OVER C+L-BAND, $d = 1.35\mu m$, , and $\Lambda = 1.37\mu m$

d_c / Λ (μm)	Dispersion (ps/nm.km) C-band	Dispersion (ps/nm.km) L-band
0	141.2~ 128.2	128.2~ 103.1
0.3	-52.8 ~ -59.76	-59.76 ~ -74.7
0.4	-193.4 ~ -196.95	-196.95~ -206.1
0.5	-334.4~ -334.1	-334.1~ -336.5
0.6	-466.41~ -460.6	-460.6~ -454.2

TABLE II.
LOSS OF THE DESIGNED PCF WITH DIFFERENT d_c / Λ AT A WAVELENGTH OF $\lambda = 1550nm$. $d = 1.35\mu m$ and $\Lambda = 1.36\mu m$

d_c / Λ (μm)	Loss (dB/km)
0	6.7×10^{-4}
0.3	2.76×10^{-2}
0.4	0.25
0.5	3.2
0.6	60.5

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