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Design and characterization of single mode circular photonic crystal fiber for broadband dispersion compensation

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ABSTRACT

In this paper, we present a single mode circular photonic crystal fiber (C-PCF) for broadband dispersion compensation covering 1400 to 1610 nm wavelength band over the telecommunication windows. Investigations of guiding properties are carried out using finite element method (FEM) with circular perfectly matched layer boundary condition. Numerical study reveals that a negative dispersion coefficient of about −386.57 to −971.44 ps/(nm km) is possible to obtain over the wavelength ranging from 1400 to 1610 nm with a relative dispersion slope (RDS) of about 0.0036 nm^{-1} at 1550 nm wavelength. In addition, the single mode behaviour of C-PCF is demonstrated by employing V parameter. According to simulation, it is found that the proposed C-PCF acts as a single mode fiber within 1340 to 1640 nm wavelength. Moreover, effective dispersion, relative dispersion slope, birefringence and confinement loss are also presented and discussed.

1. Introduction

Photonic crystal fiber (PCF) consists of microscopic array of air channels running down their length that make a low index cladding around the undoped silica core [1]. Such holey cladding is capable enough to control the optical properties including dispersion in PCFs in a way that is not possible using conventional optical fibers [2]. Thus, PCF offers great flexibility in tuning dispersion [3,4] which is significant in designing dispersion compensating fiber. Dispersion plays a vital role in optical communication which spreads optical pulses when transmitted through the fiber. As a result, it limits the maximum transmission distance and the bit rate [5]. Thus, the dispersion must be compensated in the long distance optical data transmission system to mitigate the effect of pulse broadening. Presently, dispersion compensating fiber (DCF) is widely used and commercially available for dispersion compensation which is designed to have large negative dispersion [6–10]. However, the large negative dispersion should span over a wide band of wavelength to compensate the accumulated dispersion of conventional optical fiber used in WMD transmission systems. Hence, compensation of accumulated dispersion and dispersion slope of conventional fibers are simultaneously required for broadband applications. To reduce the cost and minimize the confinement loss, the DCF should be as short as possible which calls for a large negative dispersion coefficient over a wide band. However, it is quite difficult to obtain high negative dispersion over a wide band of wavelength using conventional DCFs [11]. In addition, conventional DCFs have some limitations related to their structure, for instance, materials of different thermal expansion coefficients (i.e., germanium-doped core and silica cladding regions). Moreover, the DCF should ensure the single mode operation to avoid the multimode dispersion as it is responsible for signal degradation. So, the key issue is to design a DCF which simultaneously ensures large negative dispersion over a wide band and single mode operation. Therefore, in designing DCFs, it is also important to consider other properties like dispersion slope, RDS, confinement loss, effective area and birefringence [12]. The indication of incorporating PCF for broadband dispersion compensation was first proposed in [13]. However, the design experiences a small effective area and raises complexity in coupling light into the fiber. A dual core PCF with highly doped internal core is proposed in [14] for dispersion compensation which achieves a large dispersion peak of about −59,000 ps/(nm km) and hence the available bandwidth for dispersion compensation becomes narrow. In addition, doping the internal core increases confinement loss and makes the fabrication process more difficult. M-OPCF designed with six air hole rings is proposed in [15] which obtains a negative dispersion of −239.5 ps/(nm km) at 1550 nm but the RDS does not match accurately with the RDS of single mode fiber. In recent times, several PCF designs are proposed for addressing the issue of broadband dispersion compensation and sensing simultaneously. For example, square lattice photonic crystal fiber is proposed in [16] which provides unmatched RDS of 0.0034 nm^{-1} and insufficient negative dispersion of only −204.4 ps/(nm km) requiring longer fiber to compensate the accumulated dispersion. Selim Habib

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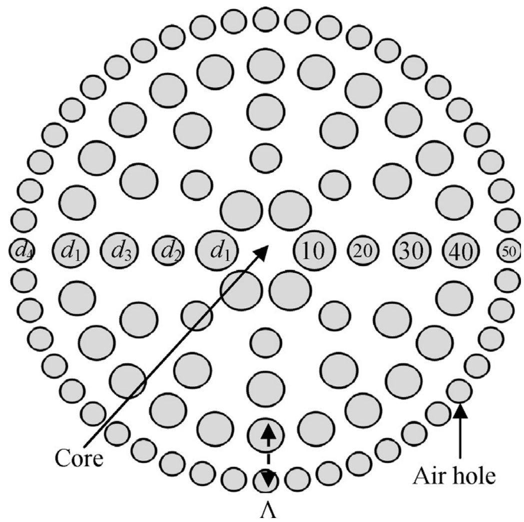

Fig. 1. Illustration of the proposed single mode broadband dispersion compensating C-PCF.

et al. [17] proposed a polarization maintaining holey fibers for residual dispersion compensation over S + C + L wavelength bands that possesses a better negative dispersion coefficient of −470 to −850 ps/(nm km) over S to L-bands with perfect slope matching. Furthermore, a spiral microstructure optical fiber is proposed in [18] which successfully achieves negative dispersion coefficient of about −327 ps/(nm km) at 1550 nm wavelength with high birefringence of about 1.79×10^{-2}. However, no discussion is made about the modeness of their proposed designs, i.e. they support either single mode or multimode. So it is equally important for dispersion compensating photonic crystal fiber to ensure the single mode operation to avoid multimode dispersion together with high negative dispersion and high birefringence.

In this work, we propose a broadband dispersion compensating photonic crystal fiber based on circular structure with five air hole rings. Simulation results show that the proposed structure exhibits a high negative dispersion over a wide band of wavelength and particularly −790.12 ps/(nm km) at 1550 nm with RDS of 0.0036 nm^{-1} at the same wavelength. It is also found that proposed dispersion compensating PCF supports only single mode over the wavelength ranging from 1340 to 1640 nm. Furthermore, the proposed PCF structure has a birefringence of 7×10^{-4} which is also suitable for sensing applications. Hopefully, the proposed fiber will be greatly applicable in high speed optical communication systems for effective dispersion compensation.

2. Design approach

Fig. 1 represents geometries of the proposed single mode C-PCF with air hole distribution. The proposed C-PCF contains only circular air holes and a total of five air-hole rings. The material of the proposed structure is considered as silica. However, the air-holes on the first ring are rotated at an angle 60° while air-holes on the 2nd to 5th rings are rotated at an angle 45°, 30°, 15°, and 7.5°, respectively. In the following figure, circle 10 indicates the position of 1st air hole of 1st air hole ring whereas circle 20 indicates the position of 1st air hole of 2nd air hole ring and so on. The number of air-holes of the proposed structure for 1st, 2nd, 3rd, 4th, and 5th rings are respectively 6, 8, 12, 24 and 48. The air-hole diameter of 1st and 4th ring is d_1 while air-hole diameter of the 2nd, 3rd and 5th ring is selected as d_2, d_3 and d_4. The pitch which is the distance between the centres of neighbouring air holes is indicated as Λ.

3. Numerical method

The FEM with a circular perfectly matched layer boundary condition is used to carry out the numerical simulation for investigating the guiding properties of proposed design for dispersion compensation. Maxwell's vectorial equation [19] is solved using FEM to best approximate the value of modal effective refractive indexes n_{eff}. Once the modal effective indexes n_{eff} is obtained, chromatic dispersion $D(\lambda)$, effective dispersion D_e, confinement losses L_c, birefringence B and effective area, A_{eff} can be determined by the using the following Eqs. (1)–(5) formulated in [15,20]. On the other hand, effective V parameter V_{eff} for the PCF is calculated from Eq. (6) [3].

$$D(\lambda) = -\frac{\lambda}{c}\frac{d^2 Re[n_{\text{eff}}]}{d\lambda^2} \quad \text{ps/(nm km)} \tag{1}$$

$$D_e = \frac{D_m(\lambda)L_m + D_n(\lambda)L_n}{L_m + L_n} \quad \text{ps/(nm km)} \tag{2}$$

$$L_c = 8.686 \times \frac{2\pi}{\lambda} \times Im[n_{\text{eff}}] \quad \text{dB/m} \tag{3}$$

$$B = \left| n_x - n_y \right| \tag{4}$$

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

$$V_{\text{eff}} = k\Lambda F^{1/2}(n_{\text{eff}}^2 - n_a^2)^{1/2} \tag{6}$$

Eq. (1) represents the chromatic dispersion since material dispersion is directly included in the FEM calculation process where real part of effective refractive index is $Re[n_{\text{eff}}]$, λ is the wavelength, c is the velocity of light in vacuum. Eq. (2) is to determine the effective dispersion, D_e after compensating dispersion of single mode fiber used in WMD transmission systems. In Eq. (2) D_m and D_n are dispersion of single mode fiber and dispersion compensating fiber whereas L_m and L_n represent the length of single mode fiber and dispersion compensating fiber. Moreover, $\text{Im}[n_{\text{eff}}]$ is imaginary part of refractive index, n_x and n_y are effective refractive index of two orthogonal polarization modes and E is the electric field in Eqs. (3)–(5), respectively. Eq. (6) is to test the single mode behaviour of the proposed design where $k = 2\pi/\lambda$ represents the wave number in the vacuum, F is the air-filling fraction, Λ is the pitch, n_{eff} is the effective index and n_a is the refractive index of the air. However, the single-mode regime of the C-PCF is characterized by $V_{\text{eff}} < \pi(= 3.1416)$ [21]. Once the magnitude of V_{eff} is found less than 3.1416 over a band, a fiber will act as single mode over the specific band.

4. Simulation results and discussion

The fundamental optical field distribution of the proposed single mode C-PCF for both x and y polarization modes at operating wavelength of 1550 nm is presented in Fig. 2. Simulation result clearly demonstrates that the optical field is tightly confined into the core region. We then investigate the single mode behaviour with the help of V parameter over the wavelength ranging from 1340 to 1640 nm. The effective V parameter of the proposed C-PCF for optimum design parameters ($\Lambda = 1.0$, $d_1/\Lambda = 0.95$, $d_2/\Lambda = 0.81$, $d_3/\Lambda = 0.98$, $d_4/\Lambda = 0.60$) is shown in Fig. 3. According to simulation, the proposed C-PCF supports only single mode over the wavelength range 1340–1640 nm as the magnitude of V_{eff} does not exceed 3.1416 over the band. In particular, the value of V_{eff} is 1.85 at operating wavelength of 1550 nm. Now, we explore the effect of chromatic dispersion on wavelength for optimum design parameters. It is theoretically found that the chromatic dispersion coefficient increases monotonically with increase in wavelength as shown in Fig. 4.