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A single mode ultra flat high negative residual dispersion compensating photonic crystal fiber

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ABSTRACT

In this paper, a single mode photonic crystal fiber based on hexagonal architecture is numerically demonstrated for the purpose of residual dispersion compensation in the wavelength range of 980–1580 nm. The designed fiber offers ultraflattened negative dispersion in the near-infrared to most widely used S to L wavelength bands and average dispersion of about −138 ps/(nm km) with an absolute dispersion variation of 12 ps/(nm km). Besides, the proposed fiber successfully operates as a single mode in the entire band of interest. Moreover, to check the dispersion accuracy, sensitivity of the fiber dispersion properties to a ±1–5% variation in the optimum parameters is studied for practical conditions.

1. Introduction

Recently, index guiding photonic crystal fibers (IG-PCFs) [1] have been intensively studied due to their novel optical properties in different areas of optical system which is unachievable in conventional single mode fibers (SMFs). In PCFs, air-holes are arrangement in periodic fashion along the entire fiber length in such a way that makes a low index cladding around the pure silica core [2]. Inclusions of air-holes in the PCF offer a variable index-contrast between the core and the cladding which is achieved by changing dimensions of holes and cladding geometry. In comparison to SMF, the PCF offers more design freedom, which leads to flexible tailoring of various guiding properties such as birefringence [3], nonlinearity [4,5], and chromatic dispersion [6,7] in smart way.

To avoid nonlinear interaction, long distance transmission system requires non zero dispersion fiber [8]. In long haul transmission systems, one of the main issue worthy consideration is dispersion in the optical links because it broadens the optical pulse and limits the bandwidth of the system. To avoid pulse broadening, the dispersion must be compensated. It is well known that, a standard single-mode optical fiber have positive dispersion of ∼10 to 20 ps/(nm km). To successfully compensate the positive dispersion of SMF over a long distance, dispersion management technique should be used. One of the practical way to reduce the effect of dispersion is to use short piece of a dispersion compensating fibers (DCFs) having large dispersion of opposite sign [9] in the entire band. In dense wavelength division multiplexing (DWDM), to effectively compensate the dispersion at all the frequencies, the DCF should cover wide spectrum, and provide simultaneous dispersion and dispersion slope compensation [10].

So far, dispersion management using different PCFs structures have been reported by many research groups. Varshney et al. [11] proposed a PCF that exhibits a flat negative dispersion having average dispersion of about −98.3 ps/(nm km) with absolute dispersion variation of about 1.1 ps/(nm km) over S + C + L wavelength bands. The fiber designed by [12] exhibits ultraflattened negative dispersion over S + C + L + U wavelength bands and average dispersion of about −179 ps/(nm km) with an absolute dispersion variation of 2.1 ps/(nm km) covering only 195 nm flat band. A Ge-doped core PCF by using genetic algorithm proposed by [13] shows a high negative dispersion of −212 ps/(nm km) with an absolute dispersion variation of 11 ps/(nm km) over S + C + L + U wavelength bands. The fibers mentioned above have limited wavelength bands and the doped core in [13] will leads to fabrication difficulties. Apart from hexagonal structure, an equiangular spiral PCF was designed to have average dispersion of −212 ps/(nm km) with high birefringence of 0.0221 [14]. Although the PCF in [14] shows attractive negative dispersion and birefringence properties, the spiral PCF is difficult to fabricate using the conventional stack-and-draw method which limits its practical realization. More recently, photonic crystal fiber in photonic crystal fiber proposed in [8] exhibits highest negative flat dispersion covering all telecommunication bands. The main penalty of [8] is the inner PCF with very small air-holes which increases the splice loss and no attempt was made to check the mode properties of the fiber which is

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necessary. In the previous works mentioned above, flat negative dispersion ranges from commonly used E to L bands, but no effort has been done to flat the dispersion in the near-infrared region.

In this study, we explore the possibility of designing a simple hexagonal residual dispersion compensating fiber (H-RDCF) in the near-infrared to most widely used S to L wavelength bands. The main advantage of our proposed structure is the design simplicity along with simultaneous wideband high negative dispersion with large nonlinear coefficient which is very crucial in high-bit-rate transmission network, and nonlinear optics applications. According to simulation it is seen that, the designed PCF operates as a single mode fiber in all telecom bands, high negative dispersion of −138 ps/(nm km) over wavelength bands much higher than reported earlier in [8,11–14], large nonlinearity of 33.6 W^{-1} $K m^{-1}$ at the operating wavelength 1550 nm.

2. Design methodology

The proposed residual dispersion compensating fiber design is based on the hexagonal structure. Fig. 1 shows the air-hole distribution of the proposed PCF. The lattice of the H-RDCF fiber cladding region is defined by the distance between consecutive air-holes, Λ and the air-hole diameter, d. The designed fiber have five rings with two optimized parameters as d_c and Λ_c. The diameter of the third ring is assinged as d_3, first ring air-hole diameter is assinged as d_c while the rest of the rings are assinged as d. The hot material used in our proposed structure is silica and air-holes are arranged in hexagonal rotational symmetry with vertax angle 60° in the fiber cladding with a common pitch Λ. The air-holes of first ring are subdivided into small five air-holes that will control the flat range of the PCF.

3. Simulation results and discussions

An efficient finite element method (FEM) with circular perfectly matched layer (PML) boundary condition is used to investigate the modal properties of H-RDCF structure. A full-vector finite-element software (COMSOL) with first-order of about 17,954 triangular vector edge elements with mesh area 152.2 μm^2 was used to calculate the modal properties of the fiber. To model the leakage and no reflection at the boundary, an efficient boundary condition has to be used. It is already known that PMLs are the most efficient absorption boundary conditions for this purpose [2]. A Sellmeier equation was used to evaluate the silica refractive index. The wavelength-dependent refractive index of the silica was included in the simulation from Sellmeier equation. The dispersion D, effective area A_{eff}, nonlinear coefficient, γ and V-parameter of the H-RDCF was evaluated using [2,15]. The three term Sellmeier equation is given by

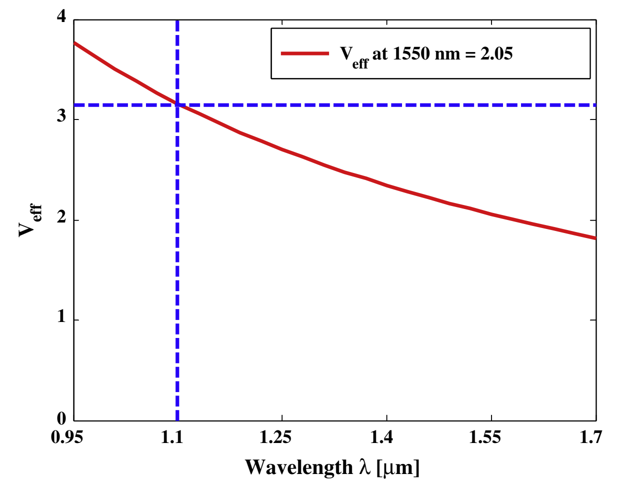

Fig. 2. V-parameter versus wavelength of the structure for optimum design parameters.

$$n(\lambda) = \sqrt{1 + \frac{B_1\lambda^2}{\lambda^2 - C_1} + \frac{B_2\lambda^2}{\lambda^2 - C_2} + \frac{B_3\lambda^2}{\lambda^2 - C_3}} \quad (1)$$

where n is the refractive index, λ is the wavelength, B_1, B_2, B_3, C_1, C_2 and C_3 are Sellmeier coefficient. The proposed PCF is a ture single-mode fiber in all telecommunication wavelength bands because the high confinement losses of higher order modes [12]. It is found that in shorter wavelengths this fibre supports a second-order mode. But confinement loss of the second-order mode at 1550 nm wavelength is more than 7 dB/km. Therefore, this fibre will effectively operate as a singlemode fibre in the entire band of interest. Besides, single modeness of the fiber is verified with the help of effective V-parameter of the PCF [15].

It is already known that the condition for high order mode cut-off can be associated with a value of effective V-parameter, $V_{eff} \leqslant \pi$. From Fig. 2 it is seen that V_{eff} is less than π which satisfies the single modeness of the PCF in the entire band of interest. Fig. 3 shows fundamental optical field profile for two polarized modes (both x and y polarization) at 1550 nm wavelength. It can be noticed that the fundamental modes are strongly confined around the centre core region of the PCF due to the relatively higher

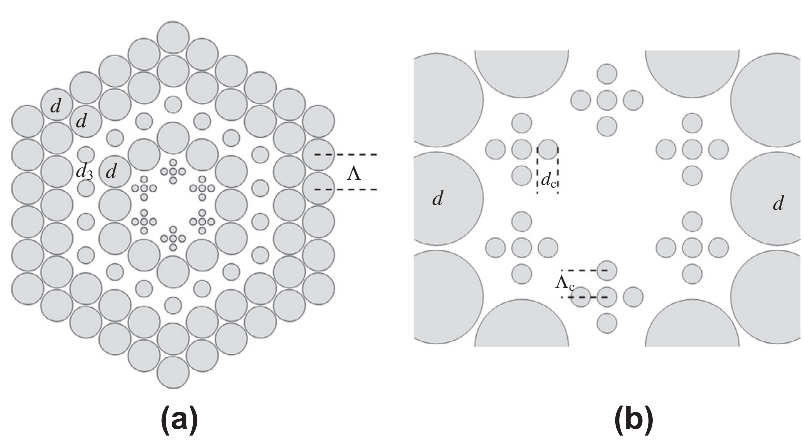

Fig. 1. Geometry structure and air-hole arrangement of the proposed H-RDCF. (a) Proposed H-RDCF with a central air-hole arrangement. (b) Detail of the core region.