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Maintaining single polarization and dispersion compensation with modified rectangular microstructure optical fiber

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ABSTRACT

In this paper, we propose and numerically demonstrate a highly birefringent microstructure optical fiber which shows negative dispersion coefficient of about −288 to −550 ps/(nm km) covering S to L wavelength bands and −425 ps/(nm km) at the excitation wavelength 1550 nm. This proposed design successfully compensate the dispersion covering S to L communication bands ranging from 1460 to 1625 nm along with relative dispersion slope (RDS) perfectly matched to that of single mode fiber of about 0.0036 nm^{-1}. Apart from dispersion compensation, the designed MOF offers high birefringence of 2.94×10^{-2} at 1550 nm and better compensation ratio with design simplicity due to circular air-holes in the fiber cladding.

1. Introduction

Microstructure optical fibers (MOFs) or Photonic crystal fibers (PCFs) [1] have gained significant interest in recent years due to its novel optical properties, such as endlessly single mode operation, tailorable dispersion, high nonlinearity, large negative dispersion, ultrahigh birefringence and so on. MOFs have a microscopic array of air channels running down their length that make a low index cladding around the silica core. Due to design freedom of MOFs, chromatic dispersion, dispersion slope and confinement losses can be easily controlled in smart way which is not possible in conventional optical fibers [2]. MOFs offer flexibility in tuning dispersion which is crucial in designing dispersion compensating fiber (DCF) [3,4].

The dispersion must be compensated in the long-distance optical data transmission system to suppress the broadening of pulse. If MOF has the appropriate dispersion slope and large negative dispersion coefficient, it will successfully compensate a single mode fiber (SMF) over a certain range of operating wavelengths. These characteristics make MOF promising devices for broadband compensating fiber. On the other hand, highly birefringent microstructure optical fibers (HB-MOFs) are suitable for optical device and sensing applications. High birefringent can be made by making fiber core asymmetrical or artificial defects in the center core. In many applications, high birefringence with high negative dispersion coefficient is necessary.

Several designs of MOFs have been proposed to date to achieve high negative dispersion coefficient with high birefringence. The idea of using PCF for dispersion compensation was first proposed by Birks et al. [5]. However the design in [5] suffers from its small effective area. In addition, several attempts have been made by other groups with the aim of achieving a high negative dispersion as well as dispersion compensation. Fujisawa et al. [6] employed a genetic algorithm procedure in a PCF for DC design to cover the entire S-band. The designed PCF in [6] offers peak dispersion of about −500 ps/(nm km) but major drawback is this PCF structure has 14 air-hole rings, which limits its practical realization. A double cladding PCF structure by [7] is capable of dispersion compensation in all three telecommunication bands. The main problem of this design is low dispersion peak, only −100 ps/(nm km), which requires long fiber to compensate the dispersion, and hence increases the cost of DCF. Yang et al. proposed a honeycomb structure with a Ge-doped central core for a wide compensation bandwidth and a large dispersion coefficient which can reach −1350 ps/(nm km) [8], but the doped core will lead to fabrication difficulties. More recently, the proposed PCF in [9], although have excellent negative dispersion and birefringence properties but inclusion of elliptical air-holes in the first ring impose fabrication challenges. On the other hand, hexagonal PCFs reported by Selim et al. exhibits negative dispersion of −300 ps/(nm km) but polarization is not considered here, hence not promising for sensing applications [12]. A dual core PCF with a highly doped internal core was proposed by Huttunen et al. [13], where negative dispersion peak of −59,000 ps/(nm km) and a modal effective area of 10 μm^2 but this design exhibits high confinement losses, and doped core in this design leads fabrication difficulties too. Besides, in [13], no

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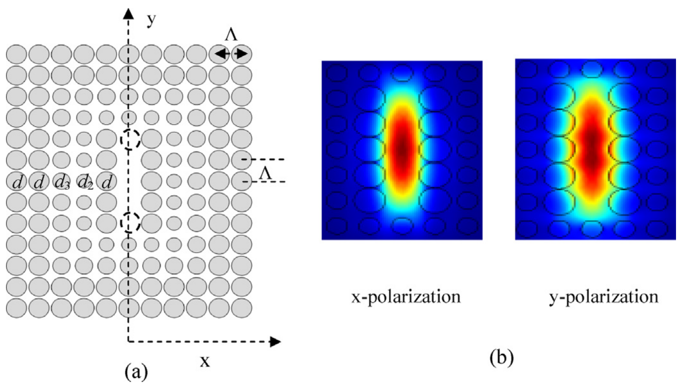

Fig. 1. (a) Air-hole distribution of the proposed five rings MR-MOF with 13 × 11 rectangular array. (b) Optical field distribution of fundamental modes for x and y polarization at 1550 nm.

attempt was made to match RDS to that SMF which is necessary. Earlier, the fiber in [18] shows birefringence of the order 10^{-2} using all elliptical air-holes of different size in the cladding region, but the shape of elliptical holes is not easy to be controlled in the fabrication process, hence not attractive for practical application.

In this paper, we propose a modified rectangular microstructure optical fiber (MR-MOF) with defected core, which provides high negative dispersion coefficient of about −425 ps/(nm km) and high birefringence of about 2.94×10^{-2} at 1550 nm wavelength respectively. In addition to this, the proposed fiber is very simple in design and circular air-holes are used in the cladding which simplifies the fabrication process and can be fabricated using conventional stack and draw method without any major complications [19]. Due to dual characteristics of the proposed MOF, it can be efficiently used in high-bit rate transmission network and sensing applications.

2. Geometry of the proposed MOF

Fig. 1 shows the air-hole distribution of the proposed MOF. The cross section of the MOF is shown in Fig. 1(a), where Λ is the pitch of the lattice, d_2 is the air-hole diameter of the second ring, d_3 is the air-hole diameter of the third ring and d is the air-hole diameter of the first and outer two rings. We set the diameter of the outer two rings high to reduce the confinement loss and tight confinement in the center core. The hot material used in our design is silica and air-holes are arranged in rectangular symmetry. The total number of rings is chosen to be five in order to simplify the structural composition of the MOF with 13 × 11 rectangular array. In order to achieve large negative dispersion air-holes near the fiber core is chosen higher because it affects the dispersion characteristics [9]. An artificial defect is created by omitting two air holes along the y-axis from the first ring which is shown in Fig. 1(a). This attempt will increase the birefringence of the proposed design. There are two regulating parameters namely d_3 and Λ for controlling the RDS and dispersion nature.

3. Numerical method

In our simulation, COMSOL software 4.2 version is used as the simulator for this study and an efficient finite element method (FEM) with circular perfectly matched layers (PML) is used to simulate modal properties of the proposed MOF. Using the PML, from Maxwell's curl equations we can obtain the following vectorial equation [10]

$$\nabla \times [s]^{-1}\nabla \times \mathrm{E}) - k_0^2 n_{\mathrm{eff}}^2 [s]\mathrm{E} = 0 \tag{1}$$

where E is the electric field vector, n_{eff} is the refractive index, λ is the operating wavelength, k_0 is the wave number in the vacuum and $[s]^{-1}$ is an inverse matrix of $[s]$. The effective refractive index is given as $n_{\mathrm{eff}} = \beta/k_0$, where β is the propagation constant, $k_0 = 2\pi/\lambda$ is the free space wave number. Once the modal effective indexes n_{eff} are solved, the dispersion D, and birefringence B can be given by the following equations [11]

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

$$B = |n_x - n_y| \tag{3}$$

where $\mathrm{Re}[n_{\mathrm{eff}}]$ is the real part of the effective refractive index n_{eff}, λ is the wavelength, c is the velocity of light in vacuum, k_0 is the free space wave number. D in (2) corresponds to the total dispersion of the PCF since material dispersion given by Sellmeir formula is directly included in the calculation. In Eq. (3), n_x and n_y are the effective refractive indices of the two orthogonal polarization fundamental modes.

4. Condition for dispersion compensation

Dispersion compensating fiber is a fiber that has the opposite dispersion of the fiber being used in the transmission system. The terms of broadband dispersion compensation [12]

$$D_{\mathrm{SMF}} \cdot L_{\mathrm{SMF}} + D_{\mathrm{DCF}} \cdot L_{\mathrm{DCF}} = D_{\mathrm{T}} \tag{4}$$

where D_{SMF}, D_{DCF}, L_{SMF} and L_{DCF} are the dispersion coefficients and the lengths of the single mode fibers and the dispersion compensating fibers, respectively. If the total compensation is required, L_{DCF} is chosen so that $D_{\mathrm{T}} = 0$. Besides the dispersion, it is also necessary to compensate for the dispersion slope. The total dispersion slope is

$$S_{\mathrm{slope}} = S_{\mathrm{SMF}} \cdot L_{\mathrm{SMF}} + S_{\mathrm{DCF}} \cdot L_{\mathrm{DCF}} \tag{5}$$

where S_{SMF}, S_{DCF} are the dispersion slopes of the single mode fibers and the dispersion compensating fibers, respectively. As there stays a positive dispersion and dispersion slope at the SMF, the elementary need of a DCF for WDM operation is the negative dispersion as large as possible to reduce the length of DCF which leads to a reduced cost. To compensate the dispersion of the SMF over a particular range of the wavelengths, the mentioned expression must be satisfied [9]

$$\mathrm{RDS} = \frac{S_{\mathrm{SMF}}(\lambda)}{D_{\mathrm{SMF}}(\lambda)} = \frac{S_{\mathrm{DCF}}(\lambda)}{D_{\mathrm{DCF}}(\lambda)} \tag{6}$$

where $S_{\mathrm{SMF}}(\lambda)$ and $S_{\mathrm{DMF}}(\lambda)$ are the dispersion slope of the SMF and DCF, respectively. The relative dispersion slope RDS of SMF is 0.0036 nm^{-1}. The design of the DCF can be corroborated when RDS of the proposed DCF is exactly equal or very close to that of SMF.

5. Simulation results and discussion

Inset Fig. 2 shows the effective refractive index curve of the proposed MOFs for optimum design parameters with $d_1/\Lambda = d_4/\Lambda = d_5/\Lambda = 0.975$, $d_2/\Lambda = 0.65$, $d/\Lambda = 0.775$ and pitch $\Lambda = 0.80$ μm. It can be seen from Fig. 2 that, in our proposed design y-polarized fundamental mode has the highest refractive index (slow axis) than x polarized fundamental mode (first axis).

The differences between effective refractive index of x and y polarization is known as birefringence which is shown in Fig. 2. From Fig. 2 it is clear that this proposed design provides high birefringence of 2.94×10^{-2} at 1550 nm due to structural asymmetry in the fiber core. The asymmetrical core design increases birefringence properties, which is suitable for polarization maintaining (PM) applications. However, conventional PM fibers show a modal