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Polarization maintaining large nonlinear coefficient photonic crystal fibers using rotational hybrid cladding

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ABSTRACT

In this paper, we present and explore a new hybrid cladding design for improved birefringence and highly nonlinear photonic crystal fibers (PCFs) in a broad range of wavelength bands. The birefringence of the fundamental mode in such a PCF is numerically analyzed using the finite element method (FEM). It is demonstrated that it is possible to design a simple highly nonlinear hybrid PCF (HyPCF) with a nonlinear coefficient of the about $46\,W^{-1}\,km^{-1}$ at a $1.55\,\mu m$ wavelength. According to simulation, the highest modal birefringence and lowest confinement loss of our proposed structure at the excitation wavelength of $\lambda = 1.55\,\mu m$ can be achieved at a magnitude of 1.77×10^{-2} and of the order less than 10^2 dB/km with only five rings of air-holes in the fiber cladding.

1. Introduction

Index-guiding photonic crystal fibers (IG-PCFs) or holey fibers or microstructured optical fibers have a periodic arrangement of microscopic air-holes in the whole silica background that offer feasibility of tuning birefringence and nonlinear coefficient in smart way [1]. Over the last few years, PCFs have drawn significant interest and attention in different areas of optical system due to their unique optical properties such as endlessly single-mode operation, high birefringence, high nonlinearity and tailorable chromatic dispersion [2–4], Due to extra degrees of freedom in tailoring guiding properties, various laudable properties such as high nonlinearity, flat dispersion, large negative dispersion, and large effective mode area, etc. [5,6], have been demonstrated by many researchers with PCFs. In addition, high modal birefringence can be achieved with specially designed PCFs to realize polarization maintaining fibers (PMF) or single polarization fibers [3,7].On the other hand, highly nonlinear PCFs are promising candidate for various novel applications including supercontinuum generation (SCG), wavelength conversion and optical parametric amplification [6].

Highly birefringent PCFs focuses potential application in the field of fiber-optic sensing and high bit rate transmission system. It is well known that PCFs with single polarization can be realized based on the higher index contrast and the asymmetric microstructure in either the cladding or the core region of PCFs. So far, various high birefringent PCFs with the modal birefringence on the order of 10^{-3} have been reported [3,7], and birefringence as high as 0.0076 has been experimentally demonstrated in PCF [8]. Furthermore, numerical simulations have indicated that inclusion of elliptical air-holes either in the cladding [9] or in the core region [10] significantly enhances the birefringence of PCFs. PCFs with elliptical holes in the cladding [9] could suffer from poor power confinement and higher propagation loss [10],and at the same time guiding the light partly in the cladding region.However, currently, highly nonlinear birefringent PCFs have gained momentous interest in SCG and high bit rate transmission system.

With this in mind in this paper, we present a relatively simple new hybrid cladding structure with high birefringence of the order 1.77×10^{-2} and large nonlinear coefficient of $46\,W^{-1}\,km^{-1}$ using FEM. We explore the possibility of designing a highly nonlinear PCF with improve birefringence using the HyPCF by modulating only dimension of the first two rings. The ultrahigh birefringence and large nonlinear coefficient of our structure is a result of the rotational effect of inner two rings and geometrical asymmetry. For current PCFs with elliptical holes, typically there is considerable variation in precise hole-size and shape [11]. In additions, PCFs with elliptical holes were experimentally realized in 2004 [12]. With the significant development of fabrication process, namely drilling, sol gel casting, tapering, and lithography [12,13] it is possible to draw our PCF structure without any major complication.

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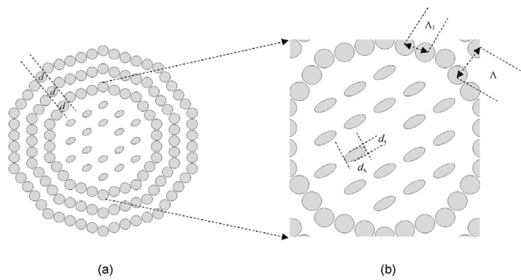

Fig. 1. Geometry model of the proposed HyPCF. (a) Proposed PCF with a central air-hole arrangement and (b) details of the core region.

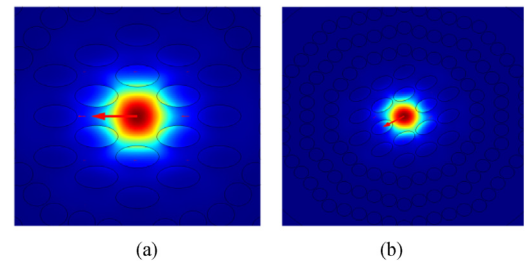

Fig. 2. Fundamental mode field pattern for $\Lambda = 1.1\,\mu$m, $d/\Lambda = 0.57$, $r_x = 0.5$, $r_y = 0.3$, $N_r = 5$, $\eta = 1.67$ and rotated by angles of (a) $\theta = 0^\circ$ and (b) $\theta = 30^\circ$ at operating wavelength $\lambda = 1.55\,\mu$m.

2. Design methodology

Fig. 1 shows the geometry of the proposed polarization maintaining highly nonlinear fiber with elliptical air-hole in first two rings having elliptical ratio $\eta(r_x/r_y) = 5$, circular air-hole in outer three rings having diameter d and a common pitch Λ. The inner two rings resemble a hexagonal cladding structure with regular triangular lattices, whereas the outer three rings are in decagonal symmetry.

The spacing between air-holes on the same ring of the decagonal structure is Λ_1, which is related Λ to by $\Lambda_1 = 0.618\Lambda$. In contrast to hexagonal PCFs, the decagonal structure has isosceles triangular unit lattices with vertex angle of 36°. Owing to isosceles triangular unit lattices, it contains more air-holes in the cladding region for the same number of rings compared to conventional PCFs. The numbers of air-holes of the decagonal structure for rings 1, 2, 3, 4 are respectively, 10, 30, 60, 100, whereas in a regular triangular lattice, the number of air-holes are 6, 18, 36, and 60, respectively. This results in a higher air-filling ratio and a lower effective refractive index around the core, thereby providing strong confinement ability. The refractive index of background silica is set to be $n_s = 1.45$ at 1.55 μm and that of the air-holes is set to be $n_a = 1$ in our simulation. The elliptical air-holes in the first two rings are rotated by an angle of θ in order to improve the birefringence and decagonal structure of the outer cladding ensures tight optical field confinement in the core. Due to hybrid cladding structure, there is an asymmetry between axes which induces extra birefringence in a wide range of wavelength bands.

3. Simulation methodology and equation

The numerical method used in this study is FEM which is adequate for the analysis of general dielectric waveguide geometries. A full-vector finite-element software (COMSOL) with first-order of about 60402 triangular vector edge elements with mesh area 254.3 μm^2 was used to calculate the modal properties of the fiber. The FEM with circular perfectly matched layer (PML) boundary is used to simulate the properties of PCF. In order to evaluate confinement loss of the fundamental mode and no reflection at the boundary, an anisotropic PML [14] is employed as a boundary condition at computational domain edges.

The effective refractive index of the base mode is given as $n_{eff} = \beta/k_0$, 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, birefringence B, confinement loss, Lc and nonlinear coefficient, γ can be given by the following equations [15,16]

$$B = |n_x - n_y| \tag{1}$$

$$Lc = 8.686 \times k_0\, Im[n_{\mathrm{eff}}] \times 10^3\ \mathrm{dB/km} \tag{2}$$

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{\mathrm{eff}}}\right) \times 10^3\ \mathrm{W^{-1}\,km^{-1}} \tag{3}$$

Where λ is the wavelength, c is the velocity of light in vacuum, Im[n_{eff}] is the imaginary part of n_{eff}, and k_0 is the free space wave number. Where λ is the wavelength, c is the velocity of light in vacuum, Im[n_{eff}] is the imaginary part of n_{eff}, and k_0 is the free space wave number. In Eq. (1) n_x and n_y are the effective refractive indices of each fundamental mode. n_2 in Eq. (3) is the nonlinear index coefficient in the nonlinear part of the refractive index and A_{eff} is the effective area.

4. Simulation results and discussion

In order to illustrate the optical field pattern of our proposed PCFs, the fundamental mode of the designed fiber with various parameters, such as η $(r_x/r_y) = 1.67$, $\Lambda = 1.1\,\mu$m, $r_x = 0.5$, $r_y = 0.3$, $N_r = 5$ and rotational angle θ at the excitation wavelength $\lambda = 1.55\,\mu$m are shown in Fig. 2, representing the confinement of light in the PCFs. According to simulation, it is seen that x- and y-polarized modes are strongly bounded in the high-index core region, giving the birefringence, $B = |n_x - n_y| = 8.3 \times 10^{-3}$ for the rotational angle $\theta = 0^\circ$ and the birefringence $B = |n_x - n_y| = 10^{-2}$ for the rotational angle θ=30°, which is much higher than those obtained from a conventional step index fiber [17] (10^{-4}), circular air-holes [6] (10^{-3}) and elliptical hollow PCFs [2] (10^{-3}). Simulation result shows that the rotational effect of the elliptical air-holes in the first two rings significantly enhances birefringence and another significant result from Fig. 2 is that the asymmetric core shape affects the polarization mode in PCFs.

4.1. Effect of the elliptical air-holes in the core on birefringence

(1) Case 1 [Circular-hole PCF]: Air-holes in every ring are constructed by circular air-holes. The diameters of air-holes in the inner two rings are denoted by d, respectively, whereas for the air-holes in outer three rings, same diameter value d is assigned as seen from fig. 1. The pitch between air-holes on the same ring for the decagonal cladding is Λ_1, which is related to the common pitch Λ by the relation $\Lambda_1 = 0.618\Lambda$.
(2) Case 2 [Elliptic-hole PCF (first ring)]: The circular air-holes of first ring are replaced by elliptical ones with $\eta = 1.67$ keeping air-holes in outer three rings diameter d.
(3) Case 3 [Elliptic-hole PCF (inner two rings)]: The circular holes of first two rings are replaced by elliptical ones with $\eta = 1.67$ keeping air-holes in outer three rings diameter d.

Fig. 3 shows the birefringence as a function of wavelengths for the three cases of the PCFs mentioned above. Simulation result reveals that, the structures with elliptical air-holes distributed on the inner two rings (case 3) have higher birefringence than that of circular-hole ones and elliptical air-holes distributed on the first