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Highly nonlinear polarization maintaining two zero dispersion spiral photonic crystal fiber using artificial defects

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ABSTRACT

This paper presents a soft glass spiral photonic crystal fiber (S-PCF) for tailoring two zero dispersion wavelengths (ZDWs) in the visible and near infrared region. A full-vector finite-element method with perfectly matched boundary layer is used to characterize the properties of the S-PCF. The designed fiber has two ZDWs at 700 nm and 1050 nm along with a very high nonlinearity of 7326 W^{-1} K m^{-1} at 700 nm and 3919 W^{-1} K m^{-1} at 1050 nm. Optimizing the cladding parameters the proposed S-PCF offers high birefringence of 0.09 at the excitation wavelength at $\lambda = 1550$ nm. Moreover, the proposed S-PCF has identical circular air-holes in the cladding that simplify the fabrication process.

1. Introduction

Index-guiding photonic crystal fibers (PCFs) or holey fibers (HFs) or microstructured optical fibers (MOFs) are a single material optical fiber consisting of a microscopic array of air channels running down the entire fiber length that provides the confinement and guidance of light in the center core [1]. Over the past decade, the PCF has acquired increased attention in optical fiber communications due to its unique properties [2]. Air-hole arrangement in the cladding can be tailored to get anomalous dispersion at wavelengths shorter than the zero material dispersion wavelengths. In such PCFs, more circular tightly confined optical field can be obtained with small effective area and high nonlinearity which coupled with flat, anomalous dispersion has led to successful broadband supercontinuum generation (SCG) [3]. In comparison to conventional single mode fiber (SMF), the PCF provides more design freedom, which leads to flexible tailoring of various guiding properties such as birefringence [4], nonlinearity [5,6], and chromatic dispersion [7,8] in smart way. Highly-birefringent PCFs focuses potential application in the field of optical communications, optical devices as fiber-optic sensors. High modal birefringence can be realized by creating asymmetry in the core region of PCFs. High birefringence can be obtained in various ways such as the fiber core can be designed to be asymmetrical, the air-holes in the cladding can be elliptical instead of circular one [9,10]. Inclusion of elliptical air-holes in the fiber cladding induces birefringence up to 10^{-2}, but the main issue in this case is the fabrication challenge. Besides, improved nonlinearity can be easily accomplished by the use of different materials, different sizes and structure of PCFs. In contrast to pure silica [11], glasses with different compositions are potential candidate for SCG and also offer an additional advantage of low softening temperatures. Moreover, SCG in PCFs has gained increased attention in current research [3]. Tailoring the dispersion to obtain flat, anomalous dispersion with small slope and pumping at near zero wavelengths is an important aspect in SCG [12]. At a ZDW pumping with higher nonlinearity reduces its power requirement along with generated broad supercontinuum power spectra. Therefore, various index-guiding PCFs with highly nonlinear dispersion flattened PCF has been reported using hexagonal, octagonal and irregular design structures [13].

In this work, we have proposed a S-PCF having identical circular air-holes in the fiber cladding with artificial defects in the inner ring. The main elegance of our proposed structure is the design freedom along with simultaneous wideband high birefringence, large nonlinearity, and two ZDWs, which is very crucial in SCG and highly efficient wideband signal processing applications. Besides, it is also desired to decrease the complexity of the structure; hence, circular air-holes with artificial defects in the inner ring offer ultrahigh birefringence at the operating wavelength of 1550 nm.

According to simulation it is seen that, the designed S-PCF exhibits ultra high birefringence of 0.09 at 1550 nm which is much higher than reported in [16,20], two ZDWs at 700 and 1050 nm in the visible and near infrared region along with high nonlinearity of 7326 W^{-1} K m^{-1} at 700 nm and 3919 W^{-1} K m^{-1} at 1050 nm. So, the proposed S-PCF may be a excellent candidate for SCG in visible and near infrared region.

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2. Design methodology

Fig. 1 shows the air-hole arrangement of the proposed S-PCF. The cladding material of the S-PCF is soft glass (SF57) surrounding with circular air-holes in the fiber cladding. The air-hole distribution in the fiber cladding is composed of six circular rings with eight spiral arms and each spiral arm contains six air-holes with radious r_a. Each air-hole of the first ring is the starting point of a spiral arm. The first air-hole in each spiral arm is placed at a distance r_0. The distance of the second air-hole of each arm from the center is $r_1 = r_0 + 0.8(2 \times r_a)$ with an angular displacement of $\theta_1 = 360°/(2 \times N_a)$, where N_a is the number of arms. The nth air-hole in each spiral arm is at a distance of $r_n = r_{n-1} + 0.8 \times (2 \times r_a)$ with an angular displacement of $\theta_n = (n \times 360°)/(2 \times N_a)$ from the first one [14]. In order to produce high birefringence, an artificial defects S-PCF is considered, i.e. an artificial defects in the inner ring is formed at the center instead of the regular circular core region that was proposed in the previous equiangular structure [15,16].

3. Numerical method and equation

In this work, an efficient finite element method (FEM) has been used to characterize the performance of the S-PCF. The simulation tool used for this study is COMSOL software of version 4.2. The PCF cross sections, with a fixed number of air-holes are divided into homogeneous subspaces where Maxwell's equations are solved by accounting for the adjacent subspaces. These subspaces are triangles that permit a good approximation of the PCF structures. From Maxwell's curl equations we can obtain the following vectorial equation [17]:

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

where E is the electric field vector, k_0 is wave number in the vacuum, n_{eff} is the effective refractive index, $[s]^{-1}$ is an inverse matrix of $[s]$ and λ is the operating wavelength. The effective refractive index 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. The FEM with circular perfectly matched layer (PML) boundary is used to simulate the properties of PCF. The FEM directly solves the Maxwell equations to best approximate the value of the effective refractive index. Once the modal effective indexes, n_{eff} are solved, the dispersion D, birefringence B, nonlinear coefficient, γ and confinement loss Lc can be given by the following equations [4,18]:

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

$$B = |n_x - n_y| \quad (3)$$

$$\gamma = \left(\frac{2\pi}{\lambda}\right)\left(\frac{n_2}{A_{eff}}\right) \times 10^3\ \mathrm{W^{-1}\,K\,m^{-1}} \quad (4)$$

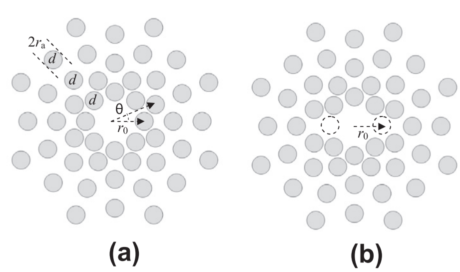

Fig. 1. Air-hole arrangement of the proposed S-PCF. (a) Proposed S-PCF with a central air-hole arrangement with diameter d and (b) artificial defects in the center core region by removing two air-holes.

$$Lc = 8.686 \times k_0 \mathrm{Im}[n_{eff}] \times 10^3\ \mathrm{dB/km} \quad (5)$$

where $\mathrm{Re}[n_{eff}]$ is the real part of effective refractive index n_{eff}, λ is the wavelength, c is the velocity of light in vacuum, $\mathrm{Im}[n_{eff}]$ is the imaginary part of n_{eff}, and k_0 is the free apace wave number. D in (2) corresponds to the chromatic dispersion of the PCF since material dispersion given by Sellmeier formula is directly included in the calculation. In Eq. (3) n_x and n_y are the effective refractive indices of each fundamental mode. n_2 in Eq. (4) is the nonlinear index coefficient in the nonlinear part of the refractive index and A_{eff} is the effective area. The nonlinear refractive index of SF57 is $n_2 = 4.1 \times 10^{-19}\ \mathrm{m^2\,w^{-1}}$ [15].

4. Simulation results and discussion

The fundamental optical field distribution for x and y polarization modes at the operating wavelength of 1550 nm is shown in Fig. 2. According to simulation, it is seen that x and y polarization modes are strongly bounded in the high-index center core region.

In contrast to the conventional SMF, the spiral PCF provides increased design flexibility in tailoring birefringence, nonlinearity, and chromatic dispersion. In this work, we first investigate the dependence of birefringence on the radius of circular air-holes at 1550 nm. The dependence of birefringence on the radius of all circular air-holes is shown in Fig. 3. Simulation result reveals that the birefringence increases with the increase in the radius of all circular air-holes. The relationship between the birefringence and the radius of circular air-holes is almost linear. Field distributions of fundamental modes for x and y polarization for $r_0 = 0.54\ \mu m$, $r_a = 0.2\ \mu m$ is also included in Fig. 3.

Simulation result depicts that the birefringence is sensitive to variation of radius of air-hole and significantly enhances as radius

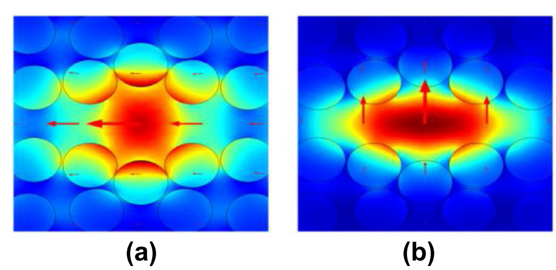

Fig. 2. Field distributions of fundamental modes for x and y polarization at 1550 nm.

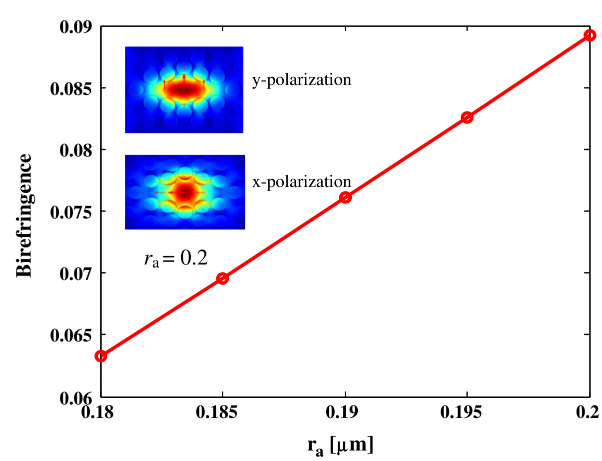

Fig. 3. Wavelength dependence of birefringence with variation of radius of air-hole.

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