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Dual-cladding high-birefringence and high-nonlinearity photonic crystal fiber with As_2S_3 core

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ABSTRACT

A novel dual-cladding photonic crystal fiber (PCF) with elliptical As_2S_3 core has been proposed to obtain high-birefringence and high-nonlinearity in PCFs. As_2S_3 has a high refractive index and a high nonlinear refractive index, as a result, it has a desired application on strengthening birefringence and nonlinearity. Then outer cladding of the PCF contains a hexagonal array of circular air holes. A circular array of circular air holes is introduced near the core as the inner cladding. We find that inner cladding could heighten birefringence and nonlinearity obviously. The simulation results show that the birefringence is as high as 0.307 at a wavelength of 1550 nm, and the nonlinearities of X- and Y-polarized reach 28660 km^{-1} W^{-1} and 38080 km^{-1} W^{-1} at the same wavelength, respectively.

1. Introduction

Photonic crystal fibers (PCFs) were first proposed by Russell et al. in 1992 [1–5]. Since then, they have been intensively studied owing to their unusual optical properties, such as their tailorable chromatic dispersion [6], high birefringence [7–9], high nonlinearity [10], and endlessly single-mode operation [11], which are not found in conventional optical fibers. Among the optical properties, the high birefringence – which has a wide range of applications in fiber-optic sensors, high-speed optical communication systems, and precision optical instruments [12] – is one of the most attractive features. In addition, PCFs with high nonlinearity have tremendous potential for applications such as self-phase modulation (SPM) [13] and four-wave mixing (FWM) [14], which is why high-nonlinearity PCFs have attracted increasing attention in recent years [15–18].

At the wavelength of 1550 nm, the loss of optical fiber is lower and it is widely used for erbium-doped optical fiber amplifiers at this wavelength [19]. Otherwise, the range 1.5–2.0 μm in fiber lasers operating calls eye-safe wavelengths, and in telecommunications, the range 1.5–1.6 μm is particularly important [20]. This is increasing interest in erbium–ytterbium co-doped fiber (EYDF) to operate efficient high-power at 1550 nm [21,22]. Then there are many other researchers that discuss the birefringence and the nonlinearity of PCFs at 1550 nm. Lee et al. designed a PCF, which got a high birefringence of 1.92×10^{-2} at 1550 nm [23]. Amin et al. introduced a high birefringence of ∼0.58 at 1550 nm [16]. Liao et al. acquired ultrahigh nonlinear coefficient up to 3.5739×10^4 W^{-1} km^{-1} at the wavelength of 1550 nm [24]. Kim et al. proposed a PCF with a birefringence of 1.94×10^{-2} at 1550 nm [25].

Birefringence in PCFs can be obtained by reducing the rotational symmetry of the fiber structure. The structural symmetry of PCFs can easily be destroyed, e.g., by the introduction of elliptical holes in the cladding hole or the introduction of an elliptical core. For example, Liang et al. [26] introduced two small circles at the core and a row of elliptical air holes along the X direction. The structure exhibited a birefringence of 2.18×10^{-3}, but its birefringence and nonlinear coefficients require further improvement. Hossain et al. [27] obtained a nonlinearity factor as high as 83 W^{-1} km^{-1} by introducing an elliptical air hole at the core and reducing the size of the inner-cavity air hole. PCFs with a high nonlinear effect are very important in nonlinear optics, but the birefringence of the PCF reported by M. A. Hossain et al. was only 2.82×10^{-4}; Wang et al. [28] proposed an octagonal structure with two elliptical air holes in the symmetrical position of the inner cladding. The nonlinear coefficient reached 10^{-2} m^{-1} W^{-1}, and two zero dispersion points were obtained between 0.8 and 2 μm, but the birefringence was only on the order of 10^{-3}. Kim et al. [25] designed a nanocomposite

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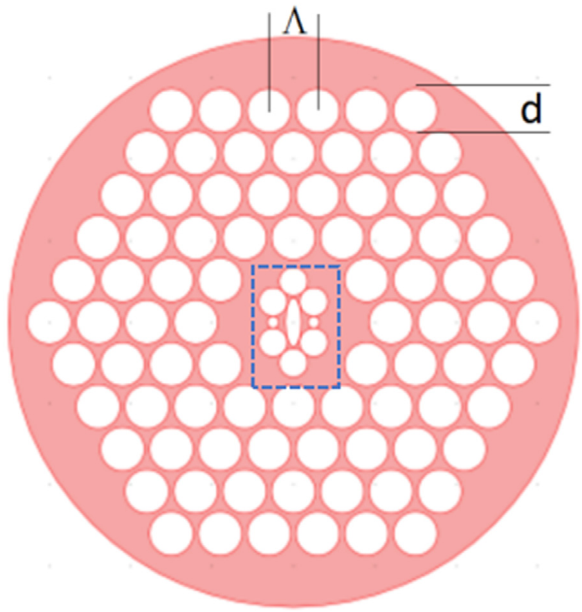

Fig. 1. Cross section of the proposed PCF.

cladding with a high birefringence of 1.94×10^{-2} and a flat dispersion characteristic, but the fiber had no zero-dispersion wavelength, which limits its application in the optimized super-continuum. The foregoing analysis indicates that to improve the birefringence, elliptical holes are often introduced in the cladding or core.

Besides the structure, the material is also a decisive factor to improve the birefringence and nonlinearity. Chalcogenide glass is a common material to manufacture PCF. For example, S. Vyas, et al. designed a $Ge_{11.5}As_{24}Se_{64.5}$ photonic crystal fiber to obtain ultraflat broadband supercontinuum [29]. As_2S_3 is a kind of chalcogenide glass. Compare to silica, it has a higher refractive index (n = 2.437 at 1550 nm), and a higher nonlinear refractive index (two or three orders of magnitude larger than that of silica) [30] that has a desirable application in limiting the role of light field, which is important for devices of nonlinear optics. Furthermore, the transmission window of As_2S_3 is 0.62–9.5 μm [31].

Herein, we propose a novel design of a high-birefringence and high-nonlinearity PCF with dual-cladding and an elliptical As_2S_3 core (see Figs. 1 and 2). As_2S_3 has a high refractive index, and a high birefringence can be achieved easily owing to the high refractive-index contrast between the core and cladding of the PCF. Furthermore, a circular array of air holes is introduced around the elliptical core as an inner cladding. Light is better constrained in the core area after the introduction of this circular array of air holes, increasing the nonlinearity of the fiber. We simulated the proposed PCF using the full-vector finite-element method (FV-FEM) [32,33] with anisotropic perfectly matched layers (PMLs) [34].

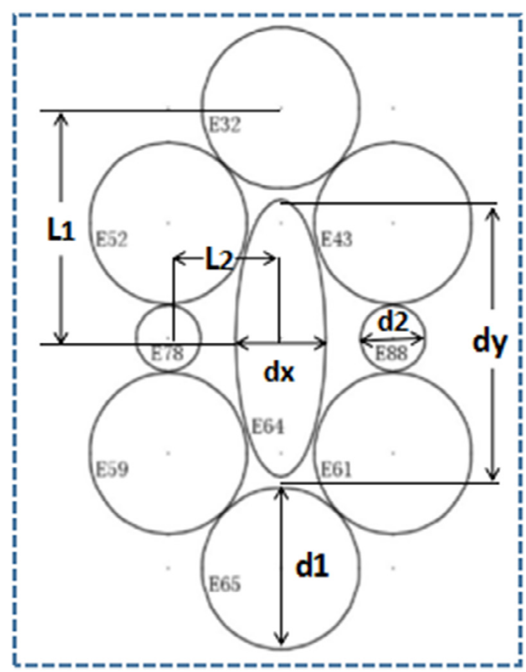

Fig. 2. Core structure of the PCF.

2. Fiber design and numerical theory

The cross section of the proposed PCF is shown in Fig. 1, and the core structure is shown in Fig. 2. To facilitate the description of the structure, we labeled the circular air holes. The basic material of the PCF is SiO_2. The cladding comprises circular air holes, and a dual-cladding structure is employed. A hexagonal array of circular holes form the outer cladding. The elliptical core is introduced in center of the PCF and is filled with As_2S_3. The fiber structure exhibits second-order symmetry, and the two orthogonal polarization modes are in the degenerate state, resulting in a high birefringence effect. The center-to-center distance between the air holes of the outer cladding is Λ, and the diameter of the air holes is d. In order to study how birefringence and nonlinearity change with varying structure of inner cladding, we designed a special structure. Six relatively large air holes with two small air holes form the inner cladding. The two large air holes above and below are on the Y-axis with a distance L_1 from the center, while two small holes are on the X-axis with a distance L_2 from the origin. The diameter of large holes is d_1, while the diameter of small ones is d_2. The structure is designed so that the edges of the individual circles do not come into contact. The short axis of the elliptical core is d_x = 0.4 μm, and the ellipticity is $\eta = d_y/d_x$.

To demonstrate the feasibility of our design, that is, As_2S_3 can be used in combination with silicon, we illustrate several fabrication methods. The common method to fabricate PCF is stack and draw [1], however, the PCFs fabricated by this method often suffer