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Dispersion properties of a photonic quasi-crystal fiber with double cladding air holes

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ABSTRACT

We propose a novel photonic quasi-crystal fiber (PQF) with a near-zero flattened dispersion in the 1450–1650 nm optical telecommunication window. A 10-fold quasi-crystal lattice of holes is used to constitute the double clads. Using a full-vectorial finite element method, we analyze the relationship between the dispersion properties of the optical fiber and the structure parameters of cross section. According to the numerical simulation results, in 1450–1650 nm optical telecommunication window, the dispersion of the PQF can be kept within (-0.25 ± 0.31) ps/(nm km) and there are dual zero dispersion wavelengths, while the confinement loss is limited to less than 0.04 dB/km. Meanwhile, in this work it is demonstrated numerically that little variation in the fabricated affects moderately the figure of merits such as dispersion or confinement loss. Our structure and optical properties predictions are expected to provide valuable reference and basic data to aid in relative experiments and fabrication.

1. Introduction

In 1984, Shechtman et al. [1] found an alloy phase with an icosahedron point group symmetry, including a 5-fold rotation axis, when they detected an Al–Mn alloy after rapid cooling solidification. This opened the door to research into quasi-crystals. A permutation of this symmetric alloy phase has a long-range ordered structure, with the units of the quasi-crystal consisting of adjacent triangle lattices and square lattices. This alloy phase was quickly applied to the optical field. In 1998, the quasi-crystal structure was applied to two-dimensional photonic crystals by Chan et al. [2], who proposed the concept of a two-dimensional photonic quasi-crystal (2D PQC). This type of special structure photonic quasi-crystal, which has a long range order, self-similar structure, and rotational symmetry without translational symmetry, has good application prospects.

Since 1996, when Knight et al. [3] first fabricated a photonic crystal fiber (PCF) in the laboratory, the superior performance of PCFs has been of particular interest, and various new types of PCF [4] and new applications [5–8] have been put forward. With the development of the PCF, the concept of the photonic quasi-crystal was applied to optical fibers, leading to the proposed photonic quasi-crystal fiber (PQF) [9]. PQFs are a novel micro-structured fiber with a quasi-periodic structure, in which there is a long-range order but no periodicity. Although the study of PQFs is quite new, the existing research shows that PQFs have excellent transmission properties which ordinary fibers and traditional PCFs do not have. For example, PQFs have a large aperture ratio for single mode operation [9], near-zero flattened dispersion [10–12], two low-confinement-loss waveguide photonic band gaps [13], high negative dispersion [14–16], and a large effective mode field area [17].

There is currently even less research into the dispersion properties of photonic quasi-crystal fibers. In 2014, Su et al. [18] proposed a photonic quasi-crystal fiber with a near-zero flattened dispersion. The dispersion was confined to within (0 ± 3.4) ps/(km nm) between 1373 nm and 1627 nm. A year later, in 2015, Barrientos-García [19] designed a PCF based on gradient air holes, which can achieve a near-zero flattened dispersion of (-0.34 ± 0.66) ps/(km nm). Researchers are currently generally filling the air holes with other materials [20] or bringing in the gradient air holes structure [21,22] to design new PCFs. However, the complicated structure of the fiber requires more structure parameters, increases the difficulty of the fabrication process, and greatly

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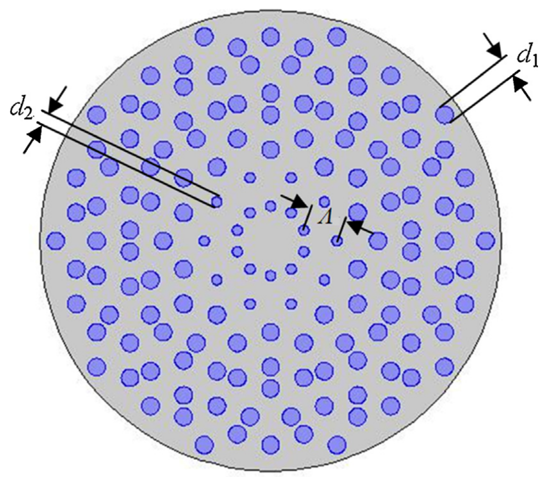

Fig. 1. Cross-sectional diagram of the PQF.

reduces the practicability, even though we get excellent near-zero flattened dispersion properties.

In this paper, we use a 10-fold Penrose photonic quasi-crystal structure. Compared with 12-fold Stampfli structure, 10-fold structure is rarely seen in the current PQF research, and compared with 8-fold or less figure of fold, 10-fold structure has enough air holes to ensure lower confinement loss of the PQF. From the perspective of reducing the number of parameters, we use double cladding air holes structure to keep that there are only three structure parameters (diameters of the large and small air holes, lattice constant) of the fiber cross section and adopt only silica as the background material. After the precise adjustments of the structure of PQF using different combinations of parameters, the optimum structure parameters can be obtained for the proposed PQF which has near-zero flattened dispersion, dual zero dispersion wavelengths (ZDWs) and low confinement loss within optical telecommunication window. Finally, considering the variation in the fabricated process, we discuss the effects of small deviations of structure parameters on the figure of dispersion, confinement loss and effective area of the PQF and conclude that it is demonstrated numerically that little variation in the fabricated affects moderately the figure of fiber properties.

2. Structures and methods

The cross-sectional structure of the PQF we propose, which is composed of a pure silica background, is shown in Fig. 1. For the purposes of practical fabrication, two sizes of air holes are adopted in the proposed PQF. The smaller air holes, with a diameter of d_2, are arranged in the first and second rings to form a dual concentric core structure which can adjust the dispersion properties and thus flatten the dispersion curve. The larger air holes, with a diameter of d_1, constitute the external cladding. Λ is the lattice constant.

We can study the dispersion properties of the PQF by changing the diameter of the air holes and the lattice constant. The dispersion of the fiber is a combination of the material dispersion and the waveguide dispersion. The total dispersion formula can be written as:

$$D = D_m + D_w \quad (1)$$

here D_m is the material dispersion, which is a function of the refractive index of the material of the fiber:

$$D_m = -\frac{\lambda}{c}\frac{\partial^2 n(\lambda)}{\partial \lambda^2} \quad (2)$$

The refractive index can be obtained from the Sellmeier equation for silica:

$$n^2 = 1 + \frac{B_1\lambda^2}{\lambda^2 - C_1^2} + \frac{B_2\lambda^2}{\lambda^2 - C_2^2} + \frac{B_3\lambda^2}{\lambda^2 - C_3^2} \quad (3)$$

where B_1, B_2, B_3, C_1, C_2 and C_3 are the coefficients related to the material and temperature. For the silica at normal temperature, the figure of the coefficients are:

$B_1 = 6.96166300 \times 10^{-1}$ $\quad C_1 = 4.67914826 \times 10^{-3}\ \mu\text{m}^2$

$B_2 = 4.07942600 \times 10^{-1}$ $\quad C_2 = 1.35120631 \times 10^{-1}\ \mu\text{m}^2$

$B_3 = 8.97479400 \times 10^{-1}$ $\quad C_3 = 9.79340025 \times 10^{1}\ \mu\text{m}^2$

By using MATLAB we can get the waveguide dispersion D_w:

$$D_w = -\frac{\lambda}{c}\frac{\partial^2 [Re(n_{eff})]}{\partial \lambda^2} \quad (4)$$

$Re\,(n_{\text{eff}})$ is the real part of the effective refractive index. The effective refractive index of the fundamental mode $Re\,(n_{\text{eff}})$ can be obtained using simulations.

The confinement loss is set by the ability of the fiber to restrict light to the core region and can be calculated by:

$$\alpha = \frac{20}{\ln 10} k_0 Im(n_{\text{eff}}) \times 10^{12} \quad (5)$$

where Im (n_{eff}) is the imaginary part of the refractive index and $k_0 = 2\pi/\lambda$ is the wavenumber in a vacuum.

The effective area [23,24] of the PQF can be expressed as:

$$A_{\text{eff}} = \frac{\left(\iint |E|^2 \text{d}x\text{d}y\right)^2}{\iint |E|^4 \text{d}x\text{d}y} \quad (6)$$

where E is the electric field amplitude.

The nonlinear coefficient can be defined by:

$$\gamma(\lambda) = \frac{2\pi n_2}{\lambda A_{\text{eff}}} \quad (7)$$

where $n_2 = 2.6 \times 10^{-20}\ \text{m}^2/\text{W}$ is the nonlinear refractive index of pure silica and represents the degree of the nonlinear effects [25], and λ is the wavelength in a vacuum.

This paper adopts a full-vector finite element method to study the PQF, which has the advantages of a high calculation precision and a strong adaptability to various kinds of fibers, meaning that it can be applied in any conditions, such as to fibers with irregular shapes and any combination of material refractive indexes. It has been widely used to analyze the properties of PCFs [26]. In this paper, we adopt COMSOL Multiphysics modeling software [27] which uses full-vector finite element method to simulate mode field of the PQF and calculate the effective refractive index under different wavelengths and structure parameters.

3. Results and discussion

Changes in the structure parameters, such as the diameter of the large air holes, small air holes, or lattice constant, will have an effect on the dispersion properties of the PQF. In order to obtain a PQF with an excellent, near-zero, flattened dispersion and maintain single mode transmission, the dispersions and properties of the PQF with different structural parameters have been investigated and presented below. The field distributions of the fundamental modes of the PQF at 1550 nm are shown in Fig. 2. The mode field is well restricted at the core of the PQF. The dispersion curves shown in Fig. 3 are obtained by changing the ratio d_2/Λ from 0.29 to