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Birefringence, dispersion and loss properties for PCFs with rectangular air-holes

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HIGHLIGHTS

- Solid-core square-lattice PCFs with rectangular air holes are investigated theoretically.
- Square-lattice silica photonic crystals with rectangular shaped air-holes have been investigated theoretically.
- The characteristics of these PCFs have been compared with those of square ones.
- Birefringence, dispersion, numerical aperture and confinement loss of the fundamental modes of PCF are analyzed.

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ABSTRACT

In this paper, the solid-core fiber designs constructed by omitting one air-hole at the center of square-lattice silica photonic crystals with rectangular shaped air-holes have been investigated theoretically and their characteristics have been compared with those of square ones. Using commercial simulation software, birefringence, dispersion, numerical aperture and confinement loss of the fundamental modes are analyzed.

1. Introduction

Photonic crystal fibers (PCFs) are single material optical fibers with regular array of air-holes running along the fiber which act as cladding, and guide the light via one of the two mechanisms [1–8]: effective index-guidance (EIG) and photonic band-gap guidance (PBG). In the EIG mechanism a solid-core is created by filling the central air-hole with glass to guide to light by total internal reflection (TIR). So these index-guiding PCFs are also called TIR-PCFs. In the PBG mechanism, PCFs use a perfectly periodic structure exhibiting a photonic band-gap effect at the operating wavelength to guide light in a low-index core-region.

Their design parameters are the air-hole width (d), the hole-to-hole spacing (Λ) so-called pitch length and the number of layers of air holes. The photonic crystal structure is usually described by the air-filling fraction or the ratio d/Λ. This ratio ranges from a few percent up to 90%, whereas the pitch length values are typically from 1.0 to 20 μm. By manipulating them, one can easily change the propagation constant of the guided mode and, consequently, tailor the fiber modal, dispersion and nonlinear properties. Therefore, these parameters should be designed in accordance to the desired application. These design possibilities provided by PCFs mean that these new fiber types could emerge as one of the biggest candidates for next generation submarine and terrestrial transmission fiber development.

The guiding and dispersion properties of PCFs with a silica-core and square-lattice (SL) of circular air-holes are investigated for the first time in Ref. [9]. In that work, a comparative study between the square-lattice and triangular PCFs is performed and it is concluded that the SL-PCFs can be used as dispersion compensating fibers in a wide wavelength range around 1550 nm and could be useful if applied as pig-tail fibers of integrated optical devices with a rectangular or square transverse section, due to their field shape.

F. Poli et al. [10] investigated the single-mode regime of square-lattice circular-hole PCFs by applying a method that involves the second-order-mode complex propagation constant

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and demonstrated that the single-mode operation region of SL-PCFs is wider than that of triangular ones, and that normalized cut-off frequency V^* is lower than π, which is the value obtained for triangular lattices. Tan et al. [11] proposed a SL-PCF with two different air-hole diameters in cladding region and found that the PCF proposed gives an ultraflatenned dispersion, which more flat than that of triangular PCF, and the confinement loss as low as about 0.01 dB/km at wavelength of 1.55 μm. B. Dabas and R.K. Sinha [12] investigated the dispersion characteristic and the effective area of hexagonal and square lattice chalcogenide As_2Se_3 glass PCF and observed that only negative dispersion is obtained in wavelength range 1.2–2.5 μm while zero dispersion points are observed in wavelength range 2.5–5 μm for hole-to-hole spacing $\Lambda \geqslant 2.0$ μm for both of the lattices of PCF. Furthermore, they obtained a maximum effective area of about 23 μm^2 for hexagonal and of about 26 μm^2 for square lattice PCF at the wavelength 5 μm using the fiber parameters $d/\Lambda = 0.9$ and $\Lambda = 6$ μm. The difference between the values of effective area for the two structures is lowering with decreasing pitch Λ. Md. O. Faruk et al. [13] investigated the mode profile in square and triangular lattice PCFs at THz regime ($\lambda = 0.55$ μm) and obtained a good optical confinement with increasing air filling fraction d/Λ. F. Begum et al. [14] proposed a simple index-guiding square PCF design where the core is surrounded by air holes with two different diameters and obtained that a nearly zero ultra-flattened dispersion in a wavelength range of 1.38 μm to 1.89 μm, a low confinement loss of less than 10^{-7} dB/km in a wavelength range 1.3 μm to 2.0 μm and wide super-continuum spectrum (FWHM = 450 nm) by using picosecond lasers at a center wavelength of 1.55 μm.

All of the works referred above used circular air-holes in their PC structures. M.A. Rahman and et al. [15] used first time square and rectangular air-holes in their study. They showed that a PCF with square holes would have degenerate modes. However, when the hole shapes are not square, but rectangular in shape, the propagation constants for the quasi-TE and TM modes would be different and waveguide have a finite form birefringence. Furthermore, they noted that the variations of group velocity dispersion (GVD) with the wavelength are most similar for the both cases, since they had exactly the same cross-sectional areas and the slight difference observed is probably due to their shapes, which are different. They also observed that as the operating wavelength is increased, the waveguide dimensions are reduced compared to the operating wavelength and spot-size also increases since mode approaches its cut-off condition and so expands.

The ideal beam delivery system for an industrial processing tool should supply laser light with the desired shape and intensity profile. In many of these applications, multi-mode beams becomes with "top-hat" intensity profiles represent the processing beam of choice. Commercially available large-core fibers, created by cladding pure silica with a low index glass or polymer, are capable of meeting these require restricted in application by the limited range of achievable numerical apertures [16].

Among the features of PCFs, birefringence is one of the most interesting characteristics. Birefringence is usually an undesirable property of fiber optics, but highly birefringent fibers are usually required. High birefringence fibers have been widely used for polarization control in fiber optic sensors, precision optical instruments and optical communications systems [17–19].

In this study, the solid-core square-lattice photonic crystal fibers are investigated numerically for rectangular air-holes in the photonic crystal cladding, to see the impact of the deviation from square shape of holes on the fiber parameters, such as birefringence, dispersion, numerical aperture and confinement loss. The proposed PCF is obtained in the way that the core is formed by one missing hole at the center of the photonic crystal structure with a square lattice of rectangular shaped air-holes.

2. Optical and geometrical parameters of the fiber

We have considered solid-core PCFs with rectangular air-holes structures of square lattice as shown in Fig. 1 and we have compared their characteristics with those of square ones [20], where d is the width of square air-holes, Λ is the pitch of the air-hole array that is, the distance between hole centers, $d_x(= d)$ and d_y are widths of rectangular air-hole in x- and y-direction, respectively. Now, we define an anisotropy the parameter as $s = d_x/d_y$. We use 0.75, 1.25 and 1.50 for s in this work. The pitch length is chosen as $\Lambda = 4.2$ μm for the purpose of the comparison to our earlier works on PCFs using square holes ($s = 1$) in the cladding with the same pitch length Λ [20]. Since the refractive index variation of silica, which forms the photonic crystal background and solid-core, over the transparent wavelength region is of the order of a few percent, we used a fixed value of $n_{co} = 1.45$. The investigation covers relative air-hole sizes $d/\Lambda = 0.3$ and 0.5, and the wavelength ranges from 0.8 to 2.0 μm. Four air-hole rings are used in the calculations.

2.1. Birefringence

In general, optical fibers possess two orthogonal polarization modes. In an ideal single-mode fiber with a perfectly rotational symmetry, these modes are degenerate and their propagation constants are equal. However, an actual single-mode fiber is rotationally asymmetrical due to their geometrical asymmetries and external influences such as stress and temperature variation which lift the degeneracy. The birefringence is calculated by the following equation [21]:

$$B = |n_{eff}^x - n_{eff}^y| \tag{1}$$

where n_{eff}^x and n_{eff}^y are the effective indices of the x and y-polarized fundamental modes, respectively.

2.2. Dispersion

Chromatic dispersion $D(\lambda)$ in single-mode optical fibers causes optical pulses to broaden an so higher $D(\lambda)$ requires a dispersion compensation. $D(\lambda)$ of the PCFs studied in this work is calculated

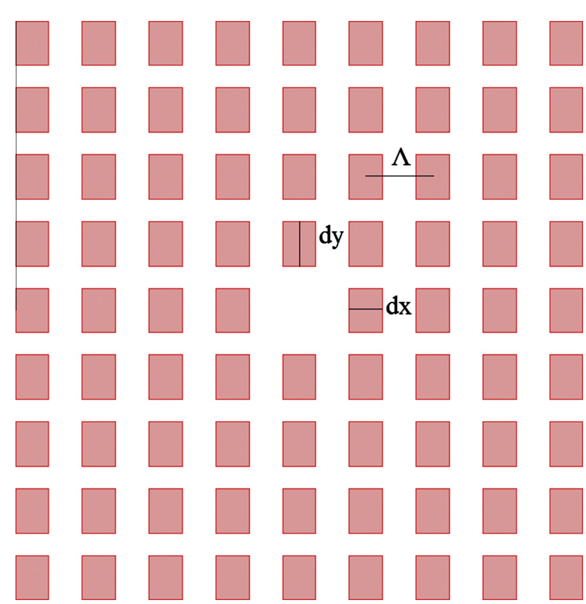

Fig. 1. Cross-sections of the solid-core PCFs with rectangular air-holes.