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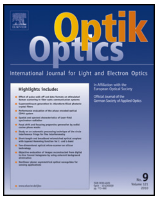

Original research article

Bending resistive improved effective mode area fluorine doped quadrilateral shaped core photonic crystal fiber for high power fiber lasers

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ABSTRACT

In this paper we propose a new design of a low loss large mode area (LMA) quadrilateral core photonic crystal fiber (QC-PCF). Removal of air holes from the rings adjacent to core and insertion of lower index rod near core region enables the fiber to enhance effective mode area even in bent condition. Finite element method (FEM) based software is used to simulate and analyze the guiding properties. According to simulation effective mode area of 1798 μm^2 is achieved at an operating wavelength of 1.064 μm when no lower index rod is used. At the same time, the fiber provides ultra-low confinement loss of 9.38×10^{-13} dB/m. The area of our PCF reduces to 989 μm^2 when it is bent at a radius of 30 cm with low bending loss of order 1.95×10^{-5} dB/m. On the other hand, the shrinkage of mode area due to bending is reduced from 45% to 36% by employing low index fluorine doped rods around the core. Moreover, both confinement loss and bending loss reduce significantly to 3.05×10^{-16} dB/m and 1×10^{-6} dB/m respectively. However, our proposed quadrilateral shaped core PCF can be a consistent competitor in realm of high power lasers.

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1. Introduction

Photonic crystal fibers (PCFs) [1,2] have drawn our attention in many commercial realms including telecommunication applications [3], high power signal transmission, sensing, high power fiber lasers [4–6] and amplifiers [5,6], fiber-to-the-home (FTTH) applications [7], super continuum generation [8], terahertz applications [9] etc. due to being endowed with some unique and novel properties that are not imaginable in conventional step index optical fibers. With the unlimited design flexibilities and high index contrast PCFs are blessed with endlessly single-mode features [10], large effective mode area, management of chromatic dispersion, high nonlinearity, and high birefringence.

However, in applications like fiber lasers and amplifiers, high power signal transmission systems maintaining large effective mode area is a key factor. In these applications high power beam has to be delivered with reduced nonlinearity. It is large effective mode area that tends to alleviate the nonlinear effects such as stimulated Brillouin scattering, self-phase modulation and stimulated Raman scattering [11,12]. These nonlinear effects weaken the power density over core area of fiber. Therefore, to maintain high beam quality large effective mode area is a must.

Recently, to ensure large effective mode area has become a topic of interest of many published papers. Increasing hole to hole spacing to enhance the effective mode area [13] is the most common technique. Moreover, removal of air holes around

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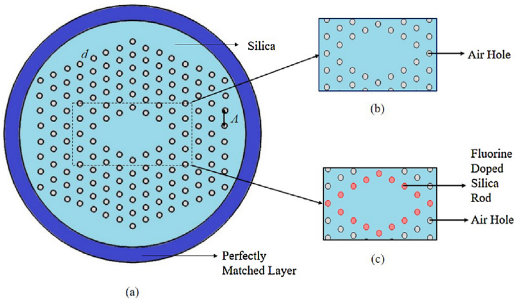

Fig. 1. Cross section of the proposed fluorine doped quadrilateral shaped core large mode area photonic crystal fiber.

the core is another technique to achieve large core size. In this regard, a large hexagonal lattice solid core PCFs with seven missing air holes has been presented by Demir *et al.* [14]. With seven missing air holes they found 500 μm^2 of effective mode area with an air filling fraction of 0.1. Furthermore, in Limpert et al. [15], ytterbium-doped 4 ring PCF with 19 missing air holes has been experimentally investigated. Their proposed PCF presents effective mode area of 2000 μm^2. Also, a square lattice PCF with nine omitted air hole [16], they found $A_{eff} = 630$ μm^2. Likewise, a PCF with circular lattice is reported in Medjouri *et al.* [17]. They claim that their six ring PCF with one omitted air hole in the center offers 1072.6 μm^2 with an air filling fraction, $d/\Lambda = 0.16$. In Ref. [18], same technique is applied for enlarge effective mode area and according to this paper by removing a group of air holes they found a PCF whose effective mode area is approximately 3000 μm^2.

Another technique of extending effective area demonstrated by Chen *et al.* [19] is to use doped silica. They theoretically show that by up doping and down doping silica in the PCF core effective mode area can be enlarged notably. In Ref. [20], a triangular core with three missing air holes and low index fluorine doped silica rod around the core is used. As a result, large effective mode area of 1500 μm^2 has been achieved.

One more technique is used by Wang *et al.* [21] have shown that by using different doping levels in the core with seven missing air holes effective mode area can be increased significantly. Also, in Ref. [22], same method is used and by increasing the doping level gradually through outside the core of the PCF large effective mode area is found.

In this article, a new design of large mode area PCF is introduced. This six ring PCF with eight missing hole give the core a quadrilateral shape. Both the missing air holes and insertion of fluorine doped silica rods around the core makes the PCF able to ensure enhanced effective mode area. In addition, the reduction of effective mode area due to bending is minimized due to use of this low index rod in the vicinity of the core. Moreover, this structure also provides ultra-low confinement loss. To optimize geometrical parameters and investigate the guiding properties finite element method (FEM) with circular perfectly matched layer (PML) is used.

This paper is organized as follows. Firstly, Section 2 introduces the methods and materials that are used for the simulation of the model. Then, Section 3 explains the basic theories on the guiding properties of the fiber and simulation method. Later in Section 4, the results of the proposed PCF are reported and discussed elaborately. Finally, the conclusion is described in Section 5.

2. Methods and materials

The quadrilateral core LMA PCF design is based on symmetrical hexagonal structure. Fig. 1(a) shows the air-hole distribution of the PCF where six missing air holes in the 1st ring and two missing air holes in the 2nd ring make the quadrilateral core. In Fig. 1, d represents the diameter of air holes of each ring. The material of the cladding is silica with a refractive index of 1.45. The air-holes are arranged in hexagonal rotation with a symmetry in the fiber cladding and a common pitch Λ.

The air-holes of first ring shown in Fig. 1(b) are replaced by low index fluorine doped rods having refractive index of 1.442 shown in Fig. 1(c) to prevent the reduction of effective mode area due to bending.

3. Theory and simulation method

As a simulation tool, commercially available COMSOL Multiphysics software is employed. This software uses Finite Element Method (FEM) [23,24] to solve for the electromagnetic fields within the modeling domains. By assuming the fields vary sinusoidally in time and the properties of materials are linear with respect to field strength, the governing Maxwells curl equation reduces to:

$$\Delta \times (\mu_r^{-1} \Delta \times E) - k_0^2 \epsilon_r E = 0 \tag{1}$$

where E is the electric field vector, $k_0 = \frac{2\pi}{\lambda}$ is the wave-number in the vacuum, ϵ_r and μ_r is the relative permittivity and the relative permeability, respectively. Moreover, circular perfectly matched layer (PML) boundary condition [25] is imposed to calculate the leakage loss appropriately.

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