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Silicon nano crystal filled photonic crystal fiber for high nonlinearity

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A B S T R A C T

A novel design of circular hybrid photonic crystal fiber (CH-PCF) with high nonlinearity and high numerical aperture (NA) is introduced in this paper. The numerical simulation results are obtained by using finite element method (FEM) and selecting finer mesh. Some fundamental optical parameters such as nonlinearity, effective area, scattering loss, power fraction and NA for the two orthogonal polarized modes are rigorously evaluated. Significant improvement of PCFs in terms of the non-linearity and NA are demonstrated by carefully investigating of the geometrical parameters of structure. The reported design undoubtedly confirms high nonlinearity of 128873.1183 $W^{-1}km^{-1}$ for x-polarization and 152134.1052 $W^{-1} km^{-1}$ for y-polarization respectively at the optical wavelength of 0.5 µm. Simultaneously, outmost NA of 0.57 and 0.59 are found at optical wavelength $\lambda = 2.5$ µm. So, the obtained outcomes make the proposed PCF a prominent candidate in super continuum generation as well as all optical signal processing applications.

1. Introduction

Photonic crystal fiber is new types of optical fiber where cylindrical shape air holes run through the total fiber. Low-loss periodic dielectric medium based photonic crystal fiber is built by utilizing a periodic array of tiny air holes which is run along the whole fiber length. For showing broadened optical properties, PCFs or microstructure holey fibers are best fitted with some new applications, for example, fiber sensors and capacity to maintain high polarization, super continuum generation, broadband dispersion controlling four wave mixing, all optical signal processing and so on. In PCFs, nonlinearity is one of the most fundamental possessions for some applications including optical switching, optical parameter amplification, optical regeneration, super continuum generation, and optical wavelength conversion [1,2]. Besides microstructures PCFs are also found in some wonderful applications such as all optical logic gates [3], optical demultiplexer [4], optical switch [5] and many more. PCFs have numerous tunable properties, for instance; air hole distance diameter, pitch, cladding, background material, doped core and so on. These adaptabilities give better control over nonlinearity, confinement loss, NA, effective mode area. These are achievable in PCF but unachievable in single mode fibers (SMFs). PCFs are mainly characterized into two concentrations, one is index guiding (IG) and the others is photonic band gap (PBG) PCFs. In these PCFs, in the middle of core and cladding high refractive index contrast is strictly maintained for optical guidance.

To accomplish proficient nonlinear procedures, PCFs are very well known, for example, all optical wavelength transformation, optical parametric amplification and super continuum generation [6,7] etc. are the most attracted incredible interests [8,9].

To accomplish high nonlinearity, researchers have considered the conduct of PCFs by utilizing nanostructure core with high refractive index. Pure silica core of a PCF make nonlinear coefficient is very low just around 100 $W^{-1}km^{-1}$. The scenario of the matter is that the nonlinear refractive index of silica is soft, nominally 29.6×10^{-21} $W^{-1}m^2$. To enhance high nonlinearity, higher nonlinear refractive index based materials are embedded inside the core region. Recently, Liao et al. [10] proposed a PCF of high nonlinearity utilizing nano scale slot core. The PCF displays a high nonlinearity up to 3.5739×10^4 $W^{-1} km^{-1}$ at the optical wavelength $\lambda = 1.55$ µm. Huang et al. proposed a slot coiled silicon PCF having a high nonlinear coefficient up to 1068 $W^{-1} km^{-1}$ [11]. In both articles, the structure leads to the fabrication complication due to the use of slot inside the

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core region. Li and Zhao utilized nano wires of gold in center and it supports polarization dependent coupling and transmission [12]. Liao et al. [13] recommended a winding PCF of high nonlinearity showing nonlinear coefficient of 226 $W^{-1} km^{-1}$ at the communication band. In the year 2016, Amin et al. [14] proposed a spiral shape photonic crystal fiber employing GaP strips inside the core for high nonlinear purpose. It demonstrates a high nonlinearity order of 10^4 $W^{-1} km^{-1}$ through the investigational electromagnetic spectrum. In any case, fiber shows confinement loss of 10^3 dB/km and 10^{-10} dB/km for x and y polarization modes, individually at 1550 nm wavelength. To create strands having huge nonlinearity with nanoscale slot core, recently article [15] is published. Slot bismuth PCFs are proposed by K. Saitoh et al. [16]. It also certified the high nonlinear coefficient of 11 $W^{-1} m^{-1}$ at the electromagnetic wavelength λ = 1.55 μm. Very recently in 2018, another nanoscale GaP strips based silicon PCF is introduced in the article [17] and it achieves ultrahigh nonlinear coefficient of 63435.74 $W^{-1} km^{-1}$ at the controlling wavelength λ = 1.00 μm.

In the presented article, CH-PCF is proposed for high nonlinear applications. The geometric structure of the proposed PCF is very simple. Moreover the air cavities of the PCF are perfectly circular. To best of our knowledge this types of PCF has not been previously published for such type of applications. The suggested PCF demonstrated a high nonlinear coefficient up to 128873.1183 $W^{-1} km^{-1}$ and 152134.1052 $W^{-1} km^{-1}$ at the optical wavelength λ = 0.5 μm for the fundamental x-polarization and for y-polarization, respectively. As far as anyone is concerned, this is the most beneficial outcome contrasted with recently published articles. In this manner, proposed fiber can be helpful for super continuum generation, optical parameter amplification and all optical signal processing applications.

2. Fiber design and theory

The geometric perspective of the proposed CH-PCF with amplified sight of slot core is exhibited in Fig. 1(a) cladding region and (b) core region embedded with silicon nano crystal. The outline is kept as basic as it could reasonably be expected. The cladding region is engineered with perfectly circular shape air holes. The first three layers of the cladding air holes rings are organized in hexagonal manner and rest of two layer rings are positioned in circular manner. It means. The air gap distance across in cladding distance, d = 1.40 μm and 1.50 μm with the pitch estimation of Λ = 1.60 μm. Air filling portion in the cladding

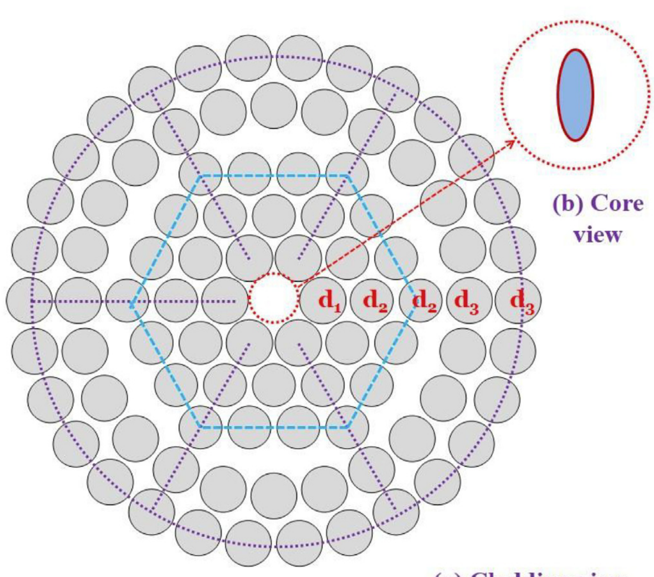

Fig. 1. The end faces cross sectional view of microstructure PCF; (a) cladding region and (b) core region embedded with silicon nano crystal.

region is formatted by d/Λ. Adapting with the manufacturing possibility the air filling fractions (AFF) are strictly preserved. In this work, a reasonable AFF of < 0.93 is regarded. Because high value AFF of any PCF is a key factor which directly leads fabrication hindrance. The foundation material is silica which is commercially available. Besides silica has some extraordinary optical behaviors such as high optical transitivity, low loss, inert with water or chemicals (i. e. acid, base etc). The inner region of the proposed PCF is embedded with optical material of silicon nano crystal. Nonetheless an absorption boundary PML with depth 10% of cladding diameter has been employed. PML boundary plays a significant role by diminishing undesirable nonphysical electromagnetic radiations. The mode field distributions of the proposed structure are exhibited in Fig. 2 (a) x-polarization and (b) y-polarization at λ = 1.55 μm. It is nicely comprehended the small effective mode area for both orthogonal polarizations. This small zone of the compelling mode gives ascent of huge nonlinearity.

3. Numerical methods and results analysis

Numerical investigation is a vital portion for characterization designed model. In this work, the state and art of the PCF has been done by FEM based commercially accessible software package COMSOL Multiphysics version 4.2. Moreover it takes less computer memory and computational time for electromagnetic investigation. Number of degrees-of-freedom (DOF) is fixed here and 48,547 are found from the indicated model. FEM provides the propagation constant spontaneously having more accurate result by solving the matrix eigenvalue problem even the structural mensuration is more complex. The base material is pure silica. The refractive index of silica is dependent on electromagnetic wave. There is also established an imperial relationship for the determination of the refractive index. In the year of 1871, Wilhelm Sellmeier developed an equation as follows

$$n^2(\lambda) = 1 + \sum_{i}^{3} \frac{B_i \lambda^2}{\lambda^2 - C_i} \tag{1}$$

Where, B_i and C_i are the sellmeier coefficients of silica and λ is the controlling wavelength in μm unit.

Optical power flows through the fiber core for propagation mode. Power flow distribution is not same for core, cladding and material. So core, cladding and material paper fraction has been investigated for better realization using the imperial relation. Besides, there are found two fundamental modes like X-polarization and Y-polarization for propagation constant β. Very small variation exists in refractive index for these two orthogonal polarizations. The power fraction (in %) can be calculated by the following relationship.

$$Power\ Frtaction\ (\eta') = \frac{\int_X S_z dA}{\int_{All} S_z dA} \tag{2}$$

Where, x is the area of interest (i. e. core, cladding and material) and all means cross sectional entire area of that PCF. Estimation of the effective mode area is very much substantive. Effective mode area or effective area (EMA) is the prerequisite for resolving nonlinearity as well NA. The nonlinearity and the NA can be calculated by the following equation as follows.

$$A_{eff} = \frac{(\iint |E(x, y)|^2 dxdy)^2}{\iint |E(x, y)|^4 dxdy} \tag{3}$$

Where, E(x,y) is the modal field distribution. Now nonlinearity and NA can be computed by the following mathematical expressions

$$Nonlinearity\ (\gamma) = \frac{2\pi}{\lambda} \times \frac{n_2}{A_{eff}} \tag{4}$$

Here, n_2 represented nonlinear coefficient of equation (4), of the optical material embedded inside the core region. From the small size core area with comparative larger size air hole in the outer boundary of