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A systematic study of linear and nonlinear properties of photonic crystal fibers

Hamed Saghaei [a,*], Vahid Heidari [b], Majid Ebnali-Heidari [c], Mohammad Rouhollah Yazdani [b]

[a] Department of Electrical Engineering, Shahrekord Branch, Islamic Azad University, Shahrekord, Iran
[b] Department of Electrical Engineering, Isfahan (Khorasgan) Branch, Islamic Azad University, Isfahan, Iran
[c] Faculty of Engineering, Shahrekord University, Shahrekord, Iran

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ABSTRACT

In this paper, linear and nonlinear properties of photonic crystal fiber (PCF) are studied in terms of wavelength for triangular and square lattices to investigate the effects of changing the fiber dimensions including air-hole diameter, pitch size and the number of air-hole rings on the dispersion profile and its nonlinear parameter. A chalcogenide based PCF is proposed in this paper and modeled in TCAD environment of Mode Solution software related to Lumerical package. The finite difference eigenmode solver numerical method is utilized in the modeling and anisotropic perfectly matched layers (PML) are assumed as absorbing boundaries to be positioned outside the outer-most ring of the air-holes. Accordingly, the effects of changing each of aforementioned parameters on the value and slope of dispersion and loss profiles as well as on its nonlinear parameter are systematically determined. For instance, numerical results achieved by the simulation results show that both the value and slope of dispersion profile are reduced by considering the diameter of air holes with a constant value and increasing the pitch size of the fiber. Moreover, considering a fixed value for the pitch size and increasing the air hole diameters lead to an increase of dispersion profile in terms of wavelength. Additionally, the numerical results show that an increase in the diameter of the air holes results in an increase in the nonlinear parameter. Further, the input source's wavelength increase will result in the reduction of the nonlinear parameter.

1. Introduction

Photonic crystal fiber (PCF) is a novel type of optical waveguides with its core surrounded by air holes in a variety of square and hexagonal lattices. These structures have various features that have been recently studied extensively by researchers [1,2]. One of the unique properties of PCFs compared with conventional optical fiber is their controllable dispersion profile. The presence of the air-holes in the cladding of a solid core PCF, whose core is basically made of the same material, makes the cladding effective refractive index smaller than that of the core. Therefore, the guiding mechanism is provided by the total internal reflection (TIR) along the solid core PCFs [3].

* Corresponding author.
E-mail addresses: h.saghaei@iaushk.ac.ir, h.saghaei@gmail.com (H. Saghaei).

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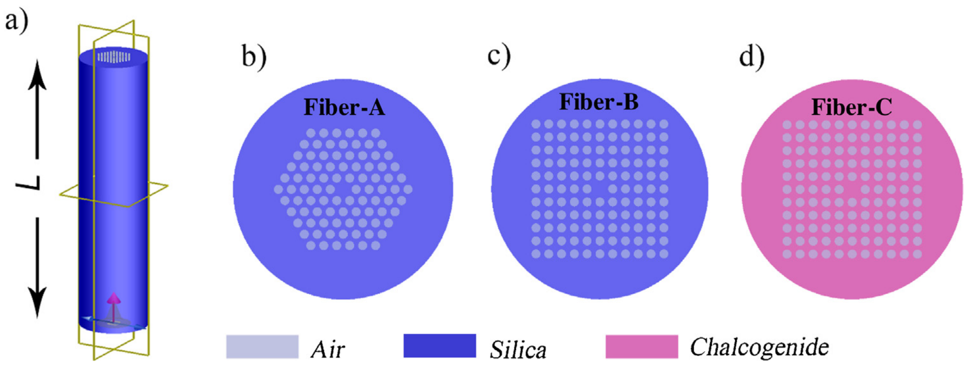

Fig. 1. a) Perspective view of PCF b), c) and d) are cross-sectional views of silica-based PCF with triangular (Fiber-A) and square (Fiber-B) lattices and chalcogenide (As2S3) PCF with square lattice (Fiber-C), respectively, with five rings of air holes.

Stack and draw technique is used for PCF fabrication, which relies on the manual assembly of glass capillaries and rods into an appropriate preform stack whose structure corresponds approximately to the desired fiber structure. After inserting the preform stack into a glass tube and fusing during the drawing process, one obtains a microstructured preform or "cane". The final step in PCF fabrication involves drawing the cane into the fiber with the desired dimensions, such as cladding-lattice pitch and the outer fiber diameter [3,4]. By tuning process parameters such as temperature, preform feed rate and drawing speed, as well as the pressure inside the preform, the size of the air-holes and their regularity can be controlled. As for standard fibers, the fabricated PCF is coated with a polymer jacket for improved mechanical strength [5].

Changing the physical dimensions of the PCF leads to changes in the effective cross-sectional area and eventually results in dispersion profile and nonlinear parameter control [6]. Due to their smaller effective area compared to their conventional counterparts, these types of the fibers not only preserve single-mode property but also act as the medium for the appearance of non-linear phenomena with the smaller threshold of peak power, making supercontinuum generation possible via them [7]. It has many applications in different fields such as optical communication based on dense wavelength division multiplexing [8–13], fluorescence microscopy [14], designing tunable ultrafast femtosecond laser sources [15], precise measurement of optical frequencies [16], mid-infrared SCG for spectroscopy [17,18], and non-invasive imaging of sensitive surfaces based on optical coherence tomography (OCT) [19]. Depending on the mentioned applications, a PCF should be selected that has a minimum dispersion in the range of interest.

In this study, the linear and nonlinear parameters of a silica and chalcogenide based PCFs are analyzed in terms of wavelength in triangular and square lattices. Our goal is to study the effect of changing the fiber structure including the air-hole diameter, pitch size, and the number of rings of air holes on the profile of the dispersion and its nonlinear parameter. Thus, the effects of changing any of the aforementioned items on the value and slope of dispersion profile as well as on its nonlinear parameter are presented.

2. Fiber structures and parameters

The perspective and cross-sectional views of PCFs used in this study are illustrated in Fig. 1. Fig. 1(b) and (c) shows the cross-sectional views of silica-based PCF with triangular and square lattices, respectively and Fig. 1(d) demonstrates cross-sectional view of chalcogenide-based PCF with square lattice. In the following, Fig. 1(b)–(d) are called Fiber-A, Fiber-B and Fiber-C, respectively. In these structures, there are five rings of air holes around the PCF core with air-holes' diameter of 1.4 μm, pitch size of 2 μm, pitch size is the center to center distance of adjacent air holes, and thus, the fiber center core diameter of 2.6 μm. The length of the fiber is also considered to be 200 mm.

3. Numerical computation of the structure

In this section, numerical calculations of the proposed PCFs used in this study will be described. The refractive index as a function of wavelength is given by four-term Sellmeier equation as

$$n(\lambda) = \left\{1 + B_1\lambda^2\left(\lambda^2 - C_1\right)^{-1} + B_2\lambda^2\left(\lambda^2 - C_2\right)^{-1} + B_3\lambda^2\left(\lambda^2 - C_3\right)^{-1}\right\}^{0.5} \quad (1)$$

As stated earlier, the background material of Fiber-A and Fiber-B is silica (SiO_2) manufactured by Corning Co. [20] and for Fiber-C is chalcogenide (As_2S_3) in which the Sellmeier constants of Eq. (1) for Silica and chalcogenide are presented in Table 1.

There are various software packages to calculate the effective refractive index, n_{eff}, numerically for the proposed structures; some of these packages are based on finite element numerical method similar to Comsol and the others are based on finite difference time domain (FDTD) similar to Rsoft and Lumerical. In this study, the proposed PCF is depicted in TCAD