Transmission Properties of THz Silicon Photonic Crystal Fiber

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Abstract— In this paper, using finite element method, we design a novel photonic crystal fiber which acts as a terahertz (THz) silicon waveguide. We study the important transmission properties, namely, group velocity dispersion (GVD), absorption coefficient, effective mode area and effective nonlinearity by varying the core diameter and distance between two consecutive air-holes for a wide range of frequency from 0.5 to 10 THz. The proposed THz silicon PCF exhibits three zero dispersions at 1.75, 4.8 and 7.8 THz frequencies. Further, we report a low absorption coefficient of $10^{-4}\,\mathrm{cm}^{-1}$ in a broad frequency region (2.5 to 10 THz). We obtain a large mode area of $325\,\mathrm{mm}^2$ at 0.5 THz frequency for the core diameter of 0.9 mm and the pitch of 3 mm. These results show that the proposed THz silicon PCF (THz-SPCF) would turn out to be a good candidate for THz waveguide compared to other plastic THz waveguides.

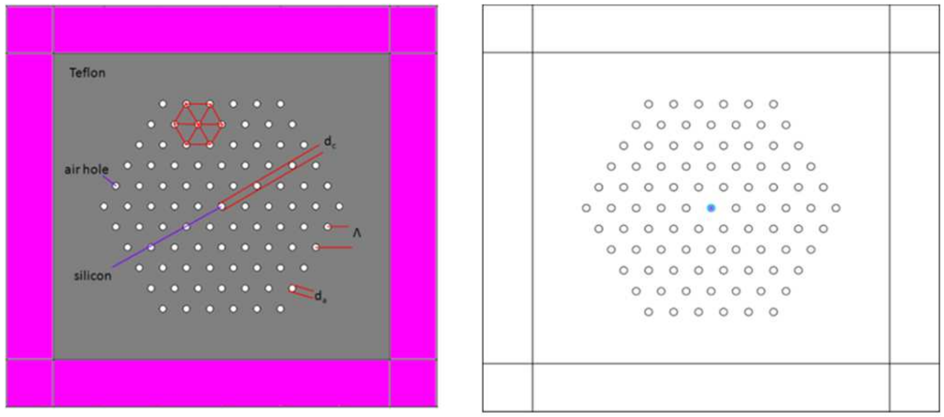
1. INTRODUCTION

THz radiation lies between electronic and optical region in the electromagnetic spectrum with frequencies ranging from 300 GHz to 10 THz. In recent years, THz regime has gained impetus as it finds applications in various important fields such as imaging, astronomy, communications, pharmaceutical quality control, etc. [1–3]. For the successful implementation of THz systems, low loss and commercially viable waveguides are essential. To date, most of the THz systems rely on free space propagation due to the virtual absence of low-loss waveguides at THz frequencies. In general, plastic, metallic ribbon waveguides and polymer PCFs have demonstrated THz guidance and they are fabricated using the drill and draw, stack and fuse technology [4–8]. Very recently, there have been reports of using plastic PCFs as THz waveguides [9, 10]. PCFs consisting of a waveguiding core and a cladding layer with spatially periodic air holes are currently another subject of intensive research, because a number of unusual properties, such as endlessly single mode, tailorable dispersion, and controllable mode area, have been demonstrated with such fibers [11–13]. The reported PCFs for THz frequencies were based on high-density polyethylene or polytetrafluorethylene (Teflon) both of which have low loss in the THz regime [6, 9, 10]. Thus, reasonably long and low-loss terahertz photonic crystal fibers (TPCFs) have been realized. In view of the rapid progress in both the THz and the PCF fields, TPCFs with better-controlled properties can be envisaged.

In this paper, we analyze the transmission properties using a new kind of silicon triangular PCF with low loss teflon. Compared to the conventional optical fibers, our newly designed silicon triangular PCF has many advantages, namely, less absorption loss, larger nonlinear refractive index than that of silica and stronger light confinement. The paper is laid out as follows. In Section 2, we discuss the design of a THz-SPCF using a fully-vectorial finite element method. We study the transmission properties of THz-SPCF including GVD, absorption loss, effective mode area and nonlinearity by varying the core diameter and lattice constant between the two consecutive air-holes for a wide range of frequencies in Section 3. Finally, we summarize the findings in Section 4.

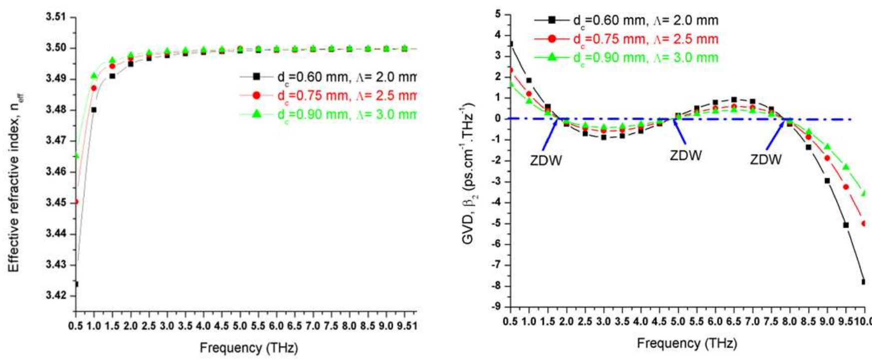
2. DESIGN OF THE PROPOSED THZ-SPCF

Figure 1(a) shows the geometrical cross-section of the proposed THz-SPCF. The PCF is an index guided one wherein the core material is of silicon with air holes distributed in the cladding. The core region can have a higher effective index than the cladding region, and by a modified total internal reflection principle, THz waves can be effectively confined in the core region as guiding modes. In this structure, the cladding of the PCF consists of five rings of air holes distributed in a triangular pattern around the core region. In general, the number of air hole rings in the cladding decides the confinement loss and in this work, we optimize the number of rings to five for ensuring better light confinement. In this design, as the air-filling fraction (d/Λ) is kept as 0.3. Here, we



(a) (b)

Figure 1: (a) Geometrical structure of the proposed fiber and (b) mode field distribution at 3 THz frequency for $d_c = 0.6$ mm and $\Lambda = 3$ mm.



(a) (b)

Figure 2: (a) Variations of effective refractive index and (b) GVD of the proposed THz-SPCF for different core diameters and air-hole distances.

study the transmission properties for the various air-hole diameters (0.6, 0.75 and 0.9 mm) with various pitch (2, 2.5 and 3 mm) for a wide range of frequency from 0.5 to 10 THz. A full-wave finite element method is used to systematically analyze the transmission properties of the THz-SPCF. In the calculation, perfectly matched layers are used as the absorbing boundary. The refractive indices of the dielectric material, core material and the air holes are 1.5, 3.5 and 1, respectively. To simplify the analysis, material dispersion is neglected. Figure 1(b) illustrates the mode field distribution in contour view at 3 THz frequency when the core diameter is 0.6 μm. In order to determine the dispersion of THz-SPCF, it is necessary to compute the effective refractive index of the fundamental mode.

In Figure 2(a), we plot the effective index as a function of frequency for various core diameters and pitch. The effective index is calculated for a range of frequencies from 0.5 to 10 THz. From the Figure 2(a), as the frequency increases, the effective index of the fundamental mode increases slowly up to 3 THz due to small amount of light spreading towards the silicon core boundary. It may be noted here that the effective index of the fundamental mode is less than the silicon effective index. Further, with the increment in frequency, the effective index of the fundamental mode is almost equal to silicon refractive index due to tight confinement of light within the core. However, as the frequency is increased further, the modal field is tightly bounded within the center of the silicon core. So, the effective index becomes constant for a broad range of frequencies from 3 to 10 THz.

3. TRANSMISSION PROPERTIES OF THZ-SPCF

In general, the dispersion is the main reason for pulse broadening which restricts the transmission speed in communication systems. As mentioned above, the material used here has a negligible material dispersion, so a near-zero waveguide dispersion becomes essential. The waveguide dispersion depends on the geometry of the fiber, specifically the air hole pitch, Λ and the diameter of the core,

d_c. The GVD, β_2 (ps/THz.cm), is determined from the second derivative of the effective mode index as a function of the frequency. We use the following equation for determining the GVD [14],

$$\beta_2 = \frac{1}{c}\left[2\frac{dn_{eff}}{d\omega} + \omega\frac{d^2 n_{eff}}{d\omega^2}\right], \tag{1}$$

where $\omega = 2\pi f$ and $n_{eff} = \mathrm{Re}(\beta)c/\omega$ denotes the real part of the effective refractive index of the mode and c is the velocity of light in vacuum. Figure 2(b) shows the variations of dispersion parameter β_2 with frequency for different values of pitch, Λ by keeping d_c and the filling factor, d/Λ as constant. The proposed fiber exhibits three zero dispersion frequencies (ZDFs) and they are 1.75, 4.8 and 7.8 THz for different values of Λ. The loss is an important parameter due to the large size (mm) of the THz-SPCF. Since the propagation loss is the main reason for the power dissipation of the guided THz waves due to the material absorption. The confinement loss is very low compared to the material absorption. So, we ignore the confinement loss in this paper. According to perturbation theory, relative absorption loss for the fundamental modes of the proposed THz-SPCF can be expressed by [15],

$$L_{abs} = \frac{\alpha_{mod}}{\alpha_{mat}} = \sqrt{\frac{\epsilon_0}{\mu_0}}\frac{\int_{background} n_b|E|^2 dA}{\left|\int_{all} S_z dA\right|}, \tag{2}$$

where n_b is the refractive index of the background dielectric material, α_{mod} is the absorption coefficient for the fundamental polarization modes, and α_{mat} is the bulk material absorption coefficient

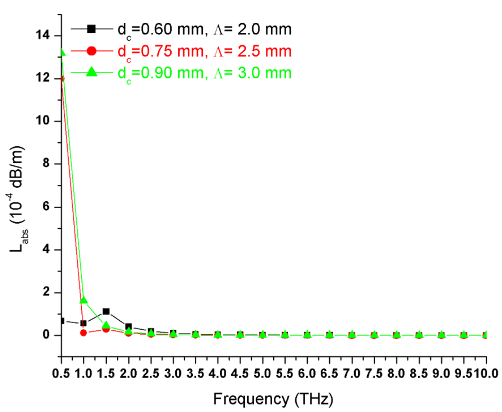


Figure 3: Variations of absorption loss of the proposed THz-SPCF for different core diameters and air-hole distances.

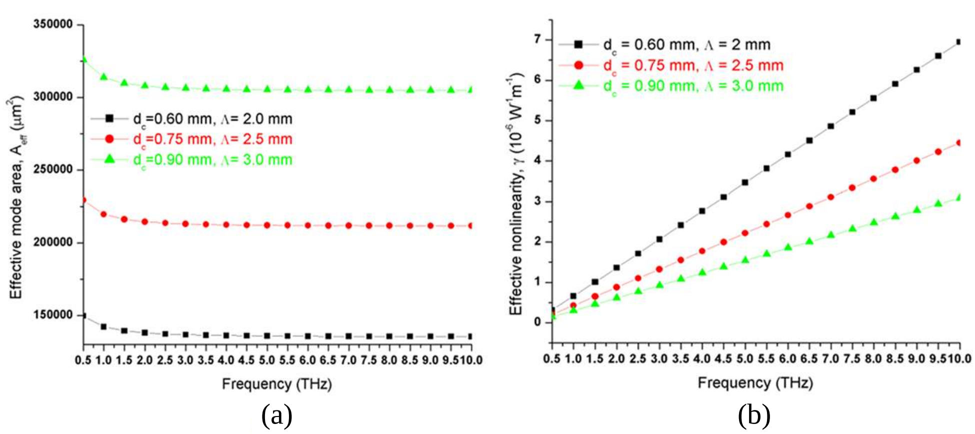


Figure 4: (a) Variations of effective mode area and (b) variations of effective nonlinearity for various core diameters and air-hole distances.

of the dielectric material. Although α_{mat} is related to the frequency dependent on the dielectric material, the relative absorption loss $\alpha_{mod}/\alpha_{mat}$ is dependent on the parameters of the fiber only. The variation of absorption loss for various fiber parameters is shown in Figure 3. The absorption loss is very high for lower frequency due to the fundamental mode residing mostly in the solid silicon core. The absorption loss is almost constant for various fiber diameters for a wider range of frequencies from 2 to 10 THz which is evident in Figure 3.

The nonlinear coefficient of a THz-SPCF can be calculated as follows:

$$\gamma = \frac{\omega n_2}{c A_{eff}} \tag{3}$$

where n_2 is the nonlinear index coefficient and the value of n_2 is $4 \times 10^{-18}\,\mathrm{m^2/W}$, c is the speed of light in vacuum, and A_{eff} is the effective mode area of the proposed fiber. As the air-hole diameter becomes larger, although more energy of the THz-wave could be confined in the core areas of this PCF, A_{eff} is larger, which leads to a low nonlinearity as shown in Figures 4(a) and (b).

4. CONCLUSION

In this paper, we have proposed a novel air-clad silicon photonic crystal fiber and studied the transmission properties for different core diameters using fully-vectorial finite element method. We have been able to achieve three zero dispersions at 1.75, 4.8 and 7.8 THz frequencies and also report a low absorption coefficient of $10^{-4}\,\mathrm{cm^{-1}}$ in a broad frequency region (2.5 to 10 THz). We expect that these desired optical properties that have been investigated would be useful in photonic device applications.

ACKNOWLEDGMENT

KSN wishes to thank CSIR [No. 03(1264)/12/EMR-II] and DST [No. SR/FTP/PS-66/2009], Government of India, for the financial support through the sponsored projects. SS wishes to thank DST [No. SR/S2/LOP-0014/2012], Government of India, for the financial support through the sponsored project.

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