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Single-mode Condition and Dispersion of Terahertz Photonic Crystal Fiber

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We have investigated properties of a plastic photonic crystal fiber guiding terahertz radiations, THz photonic crystal fiber. The single-mode condition and dispersion of a plastic triangular THz photonic crystal fiber are investigated by using the plane wave expansion method and the beam propagation method. The THz photonic crystal fiber can perform as a single-mode fiber below 2.5 THz when the ratio of diameter (d) and period (Λ) of air holes is less than 0.475. The THz photonic crystal fiber with Λ = 500 μm and d/Λ = 0.4 shows almost zero flattened dispersion behavior, -0.03±0.02 ps/THz·cm, in the THz frequency range from 0.8 to 2.0 THz.

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I. INTRODUCTION

The terahertz (THz) frequency ranges from 0.1 to 10 THz, which lies between the electronic and the optical region in the electromagnetic spectrum. Recently much interest has been shown in THz sources and detector technology, and significant advances have produced a number of potential applications such as space-based communication, THz sensing and image for the military, security, and biology [1-2]. THz spectroscopic techniques use mainly free space propagation but guiding THz waves still remains a challenge. Although several THz waveguides such as metal tubes, microstrips, coplanar striplines, and coplanar waveguides are reported, it is still a hard task to guide THz radiation over a long distance with low loss [3-5].

Photonic crystal fibers (PCFs) are very attractive from the scientific and technological point of view due to the many unusual properties such as an endless single mode operation, flexible controlled dispersion properties, and high nonlinearity [6-9]. Silica materials are used to fabricate the PCF, but its loss is quite high at THz frequencies. Alternatively, many plastic materials, such as polyethylene and polytetrafluorethylene (Teflon), have been found to be transparent in the THz range. Han *et al.* and Masahiro *et al.* have recently proposed plastic PCFs with a triangular lattice [10-11]. They have investigated experimentally the fabrication methods of plastic PCFs and THz pulse propagation in the PCFs. The propagation loss of the plastic THz PCF depends on the field confinement and the material absorption. Han *et al.* reported that the main contribution of the propagation loss is the material absorption loss. [10] However, so far, there has been no reports about the theoretical analysis of the optical properties, such as a single-mode operation and chromatic dispersion, for plastic THz PCFs.

In this paper, we theoretically investigated a cutoff value for the single-mode operation and chromatic dispersion properties of THz PCF by using the plane wave expansion method and the beam propagation method [12-13]. The THz PCF can perform as a single-mode fiber below 2.5 THz when the ratio of diameter (d) and period (Λ) of air holes is less than 0.475, and can exhibit the flattened dispersion behavior when d/Λ is small.

II. RESULTS AND DISCUSSION

The cross section of a triangular THz PCF is shown in Fig. 1. Black circles denote air holes and the grey region denotes the background material, polyethylene of which the refractive index of 1.528 in THz frequency region. The period and the diameter of holes are represented by Λ and d, respectively. The air holes decrease the average refractive index in the cladding region and confine lights in the plastic core. Thus, the light guidance in the plastic PCF can be explained by the total internal reflection, like the guiding mechanism

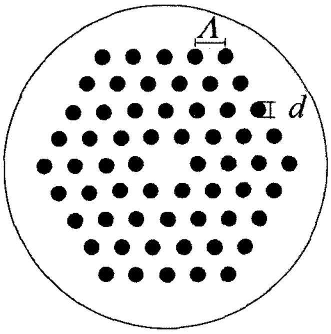


FIG. 1. Schematic of triangular THz photonic crystal fiber. Black circles denote air holes and the grey region denotes the background material.

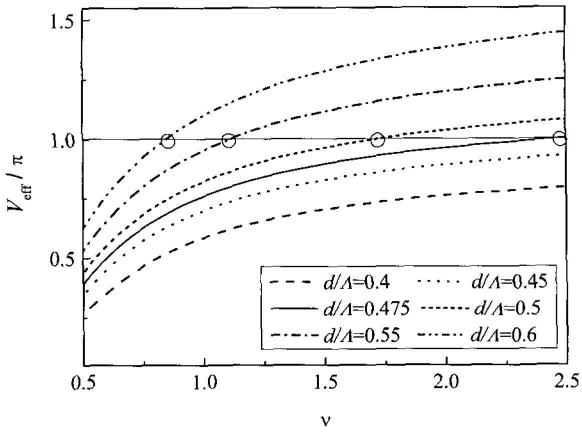


FIG. 2. V parameters of the THz PCF for various d/Λ.

of lights in silica PCFs with silica cores. It has been demonstrated that the PCFs can support an endlessly single-mode and that the fundamental mode can propagate in the silica core for all wavelengths. Plastic THz PCFs are also expected to support an endlessly single-mode, like silica PCFs.

In general, to verify the endlessly single-mode operation of a PCF, we need to parameterize the optical properties of a PCF in terms of V parameter that is characterized by the core radius r, the core index n_c, and the cladding index n_{cl}. The V parameter in the step index fiber is given by $V(\nu)=(2\pi\nu/c)r\sqrt{n_c^2-n_{cl}^2}$. However, the equation is not valid for a PCF because r, n_c, and n_{cl} are not clearly defined in a PCF. This problem can be solved by introducing a modified V parameter given by $V_{PCF}(\nu)=(2\pi\nu/c)\Lambda\sqrt{n_{eff.c}^2(\nu)-n_{eff.cl}^2(\nu)}$, where $n_{eff.c}$ (ν) is the effective index of the fundamental mode confined in the plastic core, and $n_{eff.cl}$ (ν) is the effective index of the mode which distributes over the cladding with a periodic array of air holes [13]. The V parameter of a PCF can be simply written as

$$V_{PCF}(\nu)=k\Lambda\sqrt{n_{eff.c}^2(\nu)-n_{eff.cl}^2(\nu)}=k\Lambda\sin\theta=k_{\perp}\Lambda, \quad (1)$$

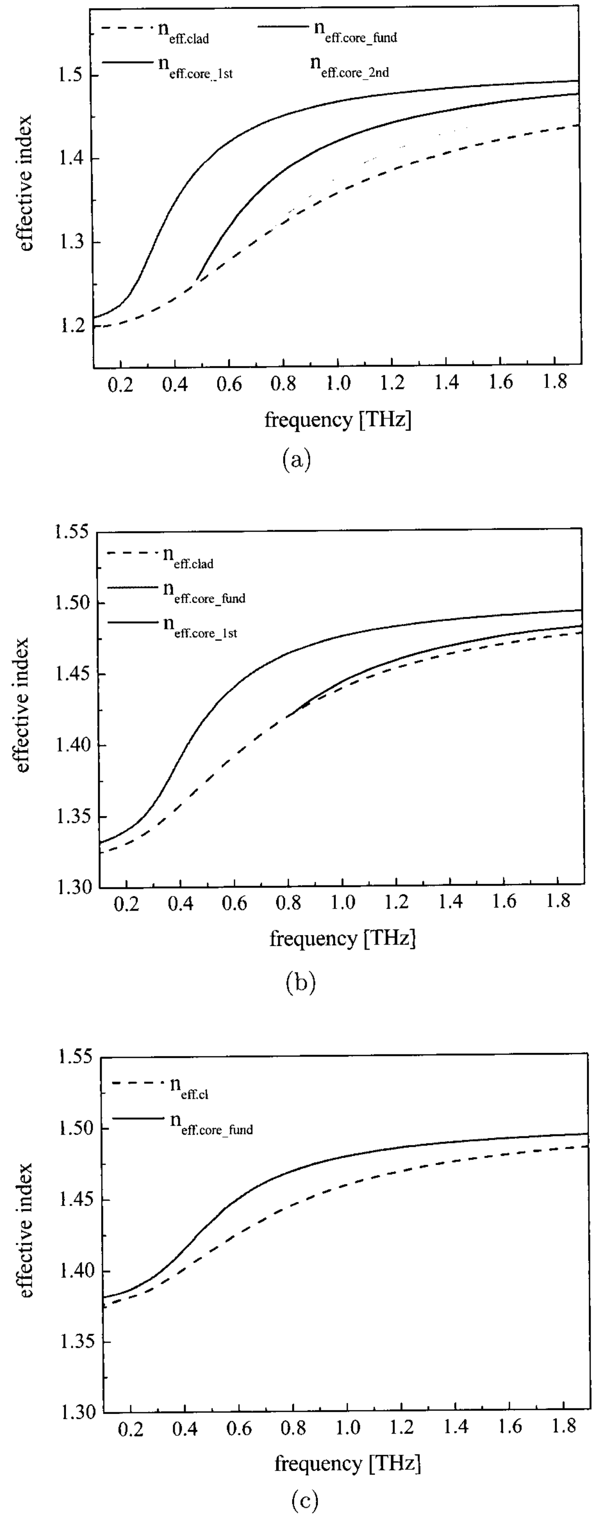
where k is the free space wave number, $k=2\pi\nu/c$. The relation, $\sqrt{n_{eff.c}^2(\nu)-n_{eff.cl}^2(\nu)}=\sin\theta$, is derived by using Snell's law for the incidence of critical angle at the interface between the core and the cladding regions, and $k_{\perp}$ is the transverse component of free space wave number. The simplified V parameter is useful in finding the cutoff frequency of the second order mode. The second-order mode should have one node and fit into the core region. Thus, the transverse wavelength of the lowest second-order mode, i.e. the cutoff wavelength, λ_{cutoff} is estimated to be 2Λ because the core diameter is about 2Λ. Therefore, ν_{cutoff} is estimated to be $c/2\Lambda$. The value of V parameter for the lowest second-order mode is given by,

$$V_{PCF}(\nu_{cutoff})=k_{\perp}\Lambda=\frac{2\pi\nu_{cutoff}}{c}\Lambda\approx\frac{2\pi}{c}\frac{c}{2\Lambda}\Lambda=\pi. \quad (2)$$

From the value, the single-mode condition is found to be V_{PCF} (ν) < π.

Figure 2 shows the numerical results of $V_{THz\text{-}PCF}$ (ν) for various d/Λ when Λ = 500 μm. The inset shows the values of d/Λ. $V_{THz\text{-}PCF}$ (ν) is normalized to π. We employed the plane wave expansion method to calculate $n_{eff.c}$ (ν) and $n_{eff.cl}$ (ν) for various d/Λ. The dashed line denotes the cutoff value below which a single-mode is allowed and circles denotes the cutoff frequency of the second-order mode. One can see that a single-mode is allowed for the THz frequency range from 0 to 2.5 THz when d/Λ is less than 0.475. To investigate the dependence of the number of guided modes on d/Λ, we plotted the effective mode indices for each value of d/Λ, 0.8 (a), 0.6 (b), and 0.4 (c) in the range of frequency from 0 to 2.0 THz as shown in Figure 3. The number of guiding modes decreases as d/Λ decreases. For example, the number of guiding modes at 1.0 THz are three, two, and one when d/Λ = 0.8, 0.6 and 0.4, respectively, and thus the THz PCF with d/Λ of 0.4 only supports a single-mode at 1 THz.

One of important properties of an optical fiber is dispersion. A variation in structure parameters affects the dispersion properties of the THz PCF. Figure 4 shows the dispersion of the fundamental mode of the THz PCF for various d/Λ with Λ = 500 μm. The positive peak grows up and becomes narrow as d/Λ increases and the dispersion profile tends to be flattened as d/Λ decreases. Figure 5 shows the flattened dispersion behavior of the THz PCF in the THz frequency range from 0.8 to 2.0 THz, -0.03±0.02 ps/



(a)

(b)

(c)

FIG. 3. The effective mode indices as a function of frequency when $d/\Lambda = 0.8$ (a), 0.6 (b), and 0.4 (c).

THz·cm, when Λ = 500 μm and $d/\Lambda = 0.4$. The proposed single-mode THz PCF can deliver well THz pulses in the frequency range.

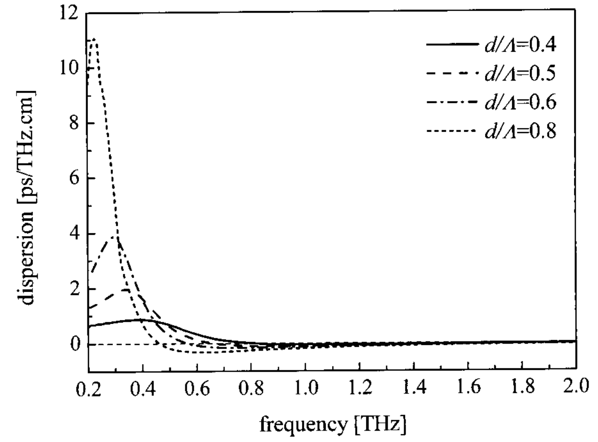


FIG. 4. Dispersion as a function of frequency for various d/Λ.

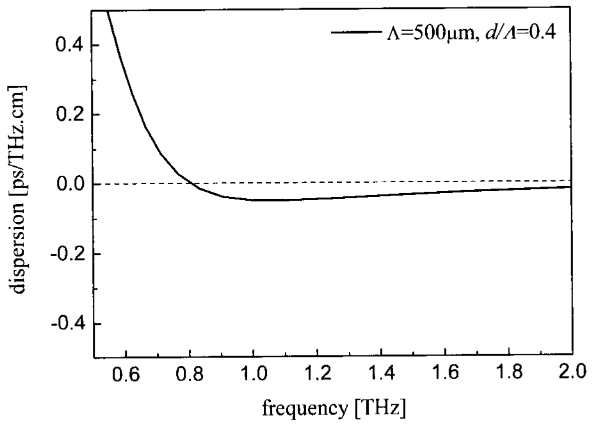


FIG. 5. Dispersion profile for the THz PCF with Λ = 500 μm and $d/\Lambda = 0.4$.

III. CONCLUSIONS

In summary, we investigated the dependence of the single-mode condition and dispersion property for the plastic triangular THz PCF on the structure parameter d/Λ. When d/Λ is less than 0.475, the THz PCF supports a single-mode below 2.5 THz. The dispersion profile becomes flattened as d/Λ decreases. The dispersion coefficient is -0.03±0.02 ps/THz·cm in the THz frequency range from 0.5 to 2.0 THz when Λ = 500 μm and $d/\Lambda = 0.4$. The single-mode THz PCF can be used in the construction of compact THz devices and measurement systems.

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