Investigation on terahertz wave transmission in polyethylene photonic crystal fibers with triangle core

Lei Jingli[1], Hou Shanglin[1], Yuan Peng[1], Wang Daobin[1], Li Xiaoxiao[1], Wang Huiqin[2], Cao Minghua[2]

(1. School of Science, Lanzhou University of Technology, Lanzhou 730050, China;
2. School of Computer and Communication, Lanzhou University of Technology, Lanzhou 730050, China)

Abstract: The cutoff frequency of single mode, dispersion and loss of a novel terahertz polyethylene photonic crystal fiber with triangle core were investigated by using the full-vector finite element method (FEM). The results show that the terahertz frequency range of the single-mode is tailored by the cladding pitch, cladding air hole and core air hole diameters. 0.1-5 THz broadband single-mode transmission is obtained and waveguide dispersion is limited in ±0.5 ps/(nm·km) for wavelength of 60-450 μm, and the transmission loss is 2.67 dB/m at 2.8 THz.

Key words: terahertz; photonic crystal fiber; single-mode
CLC number: TN929.11 **Document code:** A **DOI**: 10.3788/IRLA201847.S120004

聚乙烯三角芯光子晶体光纤的太赫兹波传输研究

雷景丽[1],侯尚林[1],袁 鹏[1],王道斌[1],李晓晓[1],王惠琴[2],曹明华[2]

(1. 兰州理工大学 理学院,甘肃 兰州 730050;
2. 兰州理工大学 计算机与通信学院,甘肃 兰州 730070)

摘 要: 利用全矢量有限元法，研究了一种新型三角芯聚乙烯太赫兹光子晶体光纤，对单模截止频率,色散和损耗进行了数值模拟。结果表明单模传输太赫兹频率范围可通过包层节距、包层空气孔直径和纤芯空气孔直径调节。在波长 60~450 μm 范围内,可以获得 0.1~5 THz 的宽频带单模传输,波导色散值可以控制在±0.5 ps/(nm·km)。在 2.8 THz 频率处传输损耗可以低至 2.67 dB/m。

关键词: 太赫兹; 光子晶体光纤; 单模

收稿日期: 2018-03-12; **修订日期:** 2018-05-11

基金项目: 国家自然科学基金(61665005);甘肃省自然科学基金(17JR5RA132)

作者简介: 雷景丽(1977-),女,讲师,硕士,主要从事新型光纤与光传感技术、光子晶体光纤技术方面的研究。Email:leijingli@lut.cn

0 Introduction

Terahertz (THz) radiation with frequencies from 0.1 to 10 THz has potential applications, such as short distance communication network, ultra broadband terahertz radar and secure communication[1-2]. A new research topic, microwave photonics, therefore, has been emerging rapidly under this background in recent years. With rapid development of the research on the THz radiation sources and detectors, there is also a high demand for developing relevant THz transmission-based optic components[3-4]. More recently, photonic crystal fibers (PCFs) have attracted much attention of researchers due to its large effective area, anomalous dispersion, high-birefringence and endless single mode[5-6]. So far most silica PCFs have been fabricated due to their applications in optical domain. However, the material loss of silica is prohibitively high at THz frequencies. Thus, for THz applications, low loss materials such as plastics need to be used[7-10].

In recent years, THz wave transmission characteristics of PCF have been extensively studied. In 2002, Han et al[11] demonstrated the efficient guided-wave propagation of THz pulses within the bandwidth of 0.1-3 THz and the loss and GVD were measured to be less than 0.5 cm^{-1} and -0.3 ps/THz·cm at 0.6 THz, respectively. Daniel et al[12] reported a 2-D photonic crystal waveguide with strong pass bands in the THz frequency range and the measured dispersion characteristics of the waveguide were discussed. K. Nielsen et al[13] designed and produced the photonic crystal waveguide with zero dispersion at the vicinity of 0.6 THz. In 2012, Arti Afrawak et al[14] proposed a equiangular spiral structure with low bending loss of 10 dB/cm. With the development of THz technology, it is important to design the terahertz photonic crystal fibers (THz-PCFs) which can be not only the single-mode transmission, but also with low loss and low dispersion.

Compared to the conventional photonic crystal fibers, Triangle Core PCFs possess many unique properties such as unprecedented dispersion control, lower loss and high nonlinearity[15]. In this paper, a THz-PCF with three small air holes equilateral triangle core is proposed. Not only the light has better confined in the structure, but also it has more tailorable parameters to achieve single-mode transmission, and wide band single-mode transmission, ultra low loss and waveguide dispersion can be obtained in the THz waveband. The work may be helpful for broadband application and the next generation communication technology of terahertz wave.

1 Structure and theory

The cross-section of the proposed THz-PCF is shown in Fig.1. The cladding is made of a hexagon lattice structure. The core region is introduced into three small air holes forming an equilateral triangle. The diameter of air holes in the cladding is d_1, the diameter of small air holes in the core is d_2, and the distance a between the air holes in triangle core is 500 μm. The pitch of the PCF is Λ. The matrix materials of PCF is polyethylene.

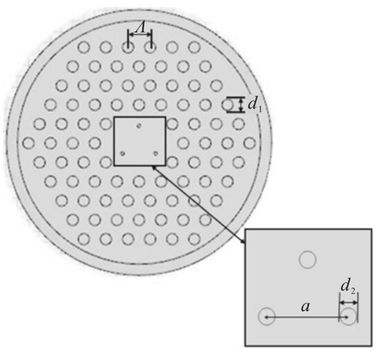


Fig.1 Cross-section of the designed terahertz photonic crystal fiber with triangle core

According to effective index method, the normalized frequency can be expressed as[16]

$$V=(2\pi\alpha/\lambda)(n_{core}^2-n_{clad}^2)^{1/2} \tag{1}$$

where α is the radius of the core, n_{core} is the refractive index of the core, n_{clad} is the refractive index of the cladding. $V\approx2.405$ is the first zero of Bessel function in traditional step-index fiber, only when $V<2.405$ optical fibers can operate in single-mode. In the PCF the core index is greater than the average index of the cladding because of the air holes in cladding, and single mode transmission must satisfy the condition[17-20]:

$$kn_0>\beta>\beta_{FSM} \quad (2)$$

where $k=2\pi/\lambda$, n_0 is the index of polyethylene, and β_{FSM} is the propagation constant of the fundamental space-filling mode (FSM). The FSM is the fundamental mode of the infinite photonic crystal cladding if the core is absent. If the value of β is less than β_{FSM}, light is radiated, thus β_{FSM} is the maximum β allowed in the cladding. So an effective normalized frequency V_{eff} can be defined for the PCF:

$$V_{eff}=(2\pi\rho/\lambda)(n_0^2-n_{eff}^2)^{1/2} \quad (3)$$

where ρ is the equivalent radius of the core, n_{eff} is the equivalent index of the cladding which identify the cladding the maximum fill rates ($n_{eff}=\beta_{FSM}/k$).

The total dispersion of the fiber is the sum of material dispersion and waveguide dispersion. But the material dispersion of polyethylene is near zero and can be neglected, so only waveguide dispersion is taken into account. Waveguide dispersion of single mode optical fiber can be expressed as[21]:

$$D=-\frac{\lambda}{c}\frac{\partial^2|\mathrm{Re}(n_{eff})|}{\partial\lambda^2} \quad (4)$$

where c represents the speed of light in a vacuum, $\mathrm{Re}(n_{eff})$ is real part of the effective index.

For the conventional optical fiber, the propagation loss indicates the degree of attenuation of light waves in optical fiber which can be expressed as[22]:

$$L_{tot}=L_{abs}+L_{con} \quad (5)$$

where L_{tot} is the total transmission losses, L_{abs} and L_{con} are the absorption loss and confinement loss. The loss can be expressed as

$$L=\frac{20}{\ln 10}\frac{2\pi}{\lambda}\mathrm{Im}(n_{eff}) \quad (6)$$

where λ is transmitted wavelength. $\mathrm{Im}(n_{eff})$ is imaginary part of the effective index. The plural propagation constant can be calculated by setting a PML boundary condition, then the confinement loss can be achieved. The absorption loss can be achieved by setting zero boundary condition[23-24].

2 Results and discussions

2.1 Single-mode cutoff frequency

THz wave frequency range is between 0.1 THz to 10 THz, in order to achieve the single-mode transmission in terahertz band, the structure parameters can be optimized by adjusting the cladding pitch, cladding air hole and core air hole diameters to make single-mode transmission range as large as possible.

Setting Λ is 400 μm, d_2 is 60 μm, and d_1 is 100, 200 and 300 μm separately, the relationship between V_{eff} and frequency is shown in Fig.2(a). It can be seen that the cut-off frequency increases as the diameter of cladding air holes decreases. Due to the increase of d_1, d_1/Λ increases as well, the corresponding effective refractive index of cladding decreases as the normalized frequency increases, the range of single mode cutoff frequency decreases. Setting Λ is 400 μm, d_1 is 200 μm and d_2 is 40, 120 and 200 μm separately, the curves of V_{eff} and frequency is shown in Fig.2(b). As can be seen from Fig.2(b), the cut-off frequency of terahertz photonic crystal fiber increases as the diameter of core air hole decreases.

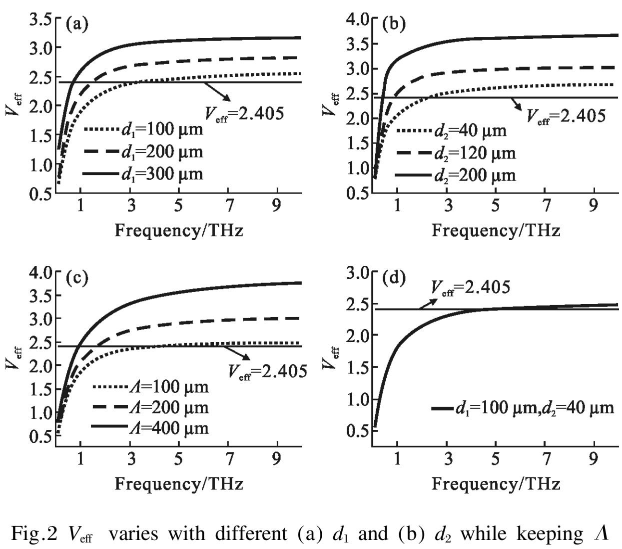


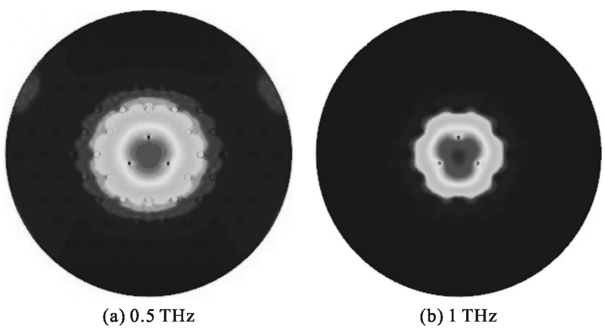
Fig.2 V_{eff} varies with different (a) d_1 and (b) d_2 while keeping Λ as constant, (c) Λ while keeping d_1 and d_2 as constant and (d) Λ of 400 μm, d_1 of 100 μm, d_2 of 40 μm

Setting d_1 is 100 μm, d_2 is 60 μm, Λ is 100, 200 and 400 μm separately, the relationship between V_{eff} and frequency is shown in Fig.2(c). It can be seen that normalized frequency decreases with the pitch increase, due to the pitch increases so as to d_1/Λ decrease, and the corresponding cladding effective refractive index increases, the normalized frequency decreases, at last the cutoff frequency shifts to high frequency band and single mode cutoff frequency range is larger. In order to achieve ultra low loss and dispersion, we set d_1 is 100 μm, d_2 is 40 μm and Λ is 400 μm. From Fig.2(d), it is clear that THz-PCF can transmit single-mode in the frequency range from 0.1 to 5 THz.

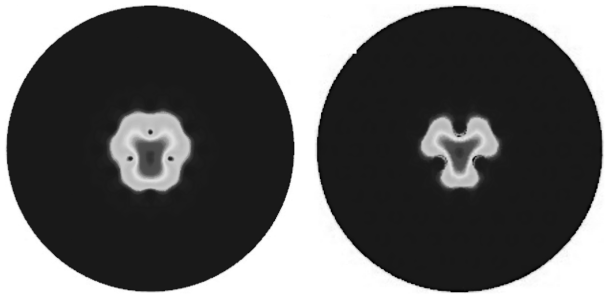
From above analysis, we can conclude that the cut-off frequency is optimized by decreasing d_1, decreasing d_2, and increasing Λ. Thus, through optimizing these parameters properly, wide band single-mode transmission can be achieved. Moreover, ultra low loss and waveguide dispersion also can be achieved in the single mode transmission range as discussed in the following sections.

2.2 Mode field distribution of fundamental mode

Only fundamental mode can be transmitted in single-mode fibers, so the mode field distribution of the fundamental mode and its magnitude of effective mode area could demonstrate the properties of the THz-PCF. Figure 3 shows the mode field distribution of fundamental mode in single-mode transmission range. In this figure, Λ is 400 μm, d_1 is 100 μm, d_2 is 40 μm, and the frequencies are 0.5, 1, 3, 5 THz separately. It can be seen from Fig.3, the effective mode area of fundamental mode decreases as the frequency increases,



(a) 0.5 THz (b) 1 THz



(c) 3 THz (d) 5 THz

Fig.3 Mode field distribution of fundamental mode at (a) 0.5 THz, (b) 1 THz, (c) 3 THz and (d) 5 THz for the THz-PCF

and the mode field is confined to the triangle fiber core in single-mode transmission frequency range. Moreover, with the increase of frequency, the wave energy is more obviously confined in the core region of the three small air holes.

2.3 Waveguide dispersion and loss

Figure 4 and Fig.5 show the confinement loss and absorption loss with the frequency variation. In Fig.4, the curve depicts that the confinement loss decreases as the frequency increasing. In Fig.5, the curve indicates that the absorption loss gradually increase and then smoothly tend to a constant as the frequency increasing. In order to illustrate the confinement loss and absorption loss for waveguide transmission loss of the dominant, the total transmission loss curve is plotted in Fig.6. As can be seen from Fig.6, the total loss decreases gradually when the frequency is less than 2.8 THz, and the transmission loss is mainly affected by the confinement loss; When the frequency is greater than 2.8 THz, the total loss increases quickly, and the transmission loss is mainly affected by the absorption loss. For low frequency, the modal field mostly spreads in the fiber cladding area. Due to the cladding air holes absorption, loss is quite low in the THz waveband, so confinement loss is more than absorption loss. For high frequency, the model field is more confined in the core region. The polyethylene absorption loss increases gradually and more than confinement loss. Moreover, the total loss is merely 2.67 dB/m at 2.8 THz. The result is reasonable and which have much wider low loss single-mode bandwidth[25-26].

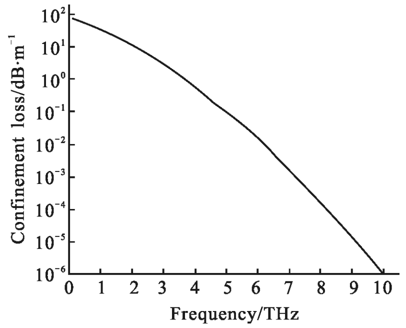


Fig.4 Confinement loss varies with frequency

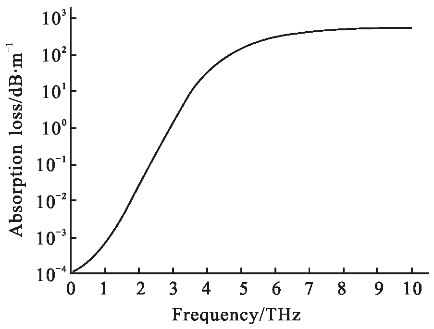


Fig.5 Absorption loss varies with frequency

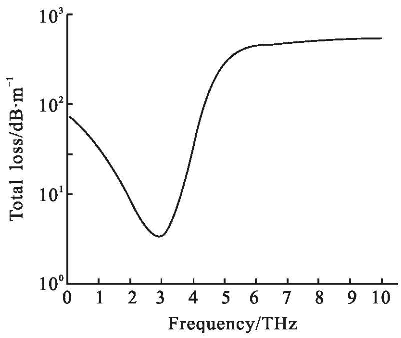


Fig.6 Total loss varies with frequency

Figure 7 describes the waveguide dispersion of the

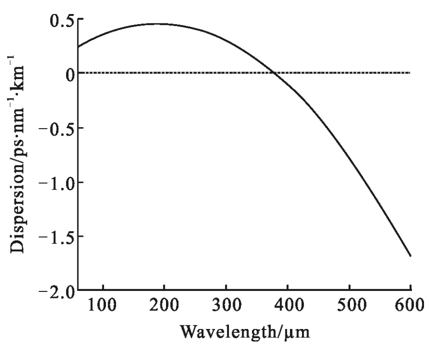


Fig.7 Dispersion varies with different wavelength

wavelength from 60 to 600 μm when Λ is 400 μm, d_1 is 100 μm, d_2 is 40 μm separately. As can be seen, the dispersion increases gradually in short wavelength and it reaches the peak value of 0.5 ps/(nm·km) at wavelength of 200 μm. Then the dispersion decreases at long wavelength and is limited in ±0.5 ps/(nm·km) at wavelength of 60 to 450 μm.

3 Conclusion

In conclusion, a triangle core THz-PCF is proposed by introducing an equilateral triangle array of small air holes in the core region. The transmission properties such as the single-mode cutoff frequency, waveguide dispersion and transmission loss are studied by the full-vector finite element method. Results indicate that through optimizing the cladding the pitch, cladding air hole and core air hole diameters, single-mode transmission, ultra low loss and dispersion can be achieved in the THz broadband. Moreover, the waveguide dispersion can be limited in ±0.5 ps/(nm·km) for wavelength 60 to 450 μm, and the transmission loss is merely 2.67 dB/m at 2.8 THz. Meanwhile it has more tailorable parameters to achieve single-mode transmission and has a great significance in the further research of high-speed wireless communication technology of the next generation of terahertz wave.

References:

[1] Peter H Siegel. Terahertz technology[J]. ***IEEE Trans Microw Theory Tech***, 2002, 50(3): 910.

[2] Masayoshi Tonouchi. Cutting-edge terahertz technology [J]. ***Nature Photonics***, 2007, 1: 97-105.

[3] Fu Xiaoxia, Chen Mingyang. Terahertz transmission optical fiber with low absorption loss and high birefringence [J]. ***Acta Phys Sin***, 2011, 60(7): 074222.

[4] Zhou Ping, Fan Dianyuan. Terahertz-wave generation by surface-emitted four-wave mixing in optical fiber [J]. ***Chin Opt Lett***, 2011, 9(5): 051902.

[5] Hassani A, Dupuis A, Skorobogatiy M. Porous polymer fibers for low-loss terahertz guiding [J]. ***Opt Express***, 2008, 16(9): 6340-6351.

[6] Hou Shanglin, Zhang Shujun, Li Suoping, et al. Investigation

on transmission characteristics of doubly cladding fiber with an inner cladding made of negative refractive index material [J]. ***Acta Opt Sin***, 2011, 31(5): 0506004.

[7] Chen Haibin, Wang Hui, Hou Honglu, et al. A terahertz single-polarization single-mode photonic crystal fiber with a rectangular array of micro-holes in the core region [J]. ***Opt Commus***, 2012, 285: 3726–3729.

[8] Atakaramians S, Afshar V S, Fischer B M, et al. Low loss, low dispersion and highly birefringent terahertz porous fibers [J]. ***Opt Commus***, 2009, 282(1): 36–38.

[9] Hou Shanglin, Xue Lemei, Li Suoping, et al. Study on characteristics of acoustic modes via stimulated Brillouin scattering in photonic crystal fiber [J]. ***Acta Phys Sin***, 2012, 61(13): 134203.

[10] Amit Hochman, Yehuda Leviatan. Calculation of confinement losses in photonic crystal fibers by use of a source-model technique[J]. ***JOSA B***, 2005, 22(2): 474–480.

[11] Han H, Park H, Cho M, et al. Terahertz pulse propagation in a plastic photonic crystal fiber [J]. ***Appl Phys Lett***, 2002, 80(10): 2634.

[12] Daniel R Grischkowsky. Terahertz 2–D photonic crystal waveguides [J]. ***IEEE Microw Wireless Compon Lett***, 2008, 18(7): 428.

[13] Kristian Nielsen, Rasmussen Henrik, Adam Aurèle J L, et al. Bendable, low-loss Topas fibers for the terahertz frequency range[J]. ***Opt Express***, 2009, 17(10): 8592–8601.

[14] Arti Agrawal, Kejalakshmy N, Uthman M, et al. Ultra low bending loss equiangular spiral photonic crystal fibers in the terahertz regime[J]. ***AIP Advances***, 2012, 2: 022140.

[15] Hansen K P. Dispersion flattened hybrid-core nonlinear photonic crystal fiber[J]. ***Opt Express***, 2003, 11(13): 1503–1059.

[16] Masanori Koshiba. Full-vector analysis of photonic crystal fibers using the finite element method [J]. ***IEICE Trans Electron***, 2002, E85(4): 881.

[17] Birks T A, Knight J C. Endlessly single-mode photonic crystal fiber[J]. ***Opt Lett***, 1997, 22(13): 961–963.

[18] Martin D Mortensen, Jacob Riis Folkenberg. Modal cut-off and the V–parameter in photonic crystal fibers [J]. ***Opt Lett***, 2003, 28: 1879–1881.

[19] Soan Kim, Chul-Sik Kee, Jongmin Lee. Novel optical properties of six-fold symmetric photonic quasicrystal fibers [J]. ***Opt Express***, 2007, 15(20): 13221–13226.

[20] Kunimasa Saitoh, Yukihiro Tsuchida, Masanori koshiba. Endlessly single-mode holey fibers: the influence of core design[J]. ***Opt Soc Am***, 2005, 13(26): 10833.

[21] Li Yuquan, Cui Ming. Optical Waveguide Theory and Technology [M]. Beijing: Posts & Telecommunications Press, 2002.

[22] Bora Ung, Anna Mazhorova, Alexandre Dupuis, et al. Polymer microstructured optical fiber for terahertz wave guiding[J]. ***Opt Exp***, 2011, 19(26): B848–B861.

[23] Geng Youfu, Tan Xiaoling, Zhong Kai, et al. Low loss plastic terahertz photonic band-gap fibres[J]. ***Chin Phys Lett***, 2008, 25(11): 3961.

[24] Ren Guobin, Wang Zhi, Lou Shuqin, et al. Full-vectorial analysis of complex refractive-index photonic crystal fiber[J]. ***Opt Express***, 2004, 12: 1226.

[25] Geng Y F, Tan X L, Wang P. Transmission loss and dispersion in plastic terahertz photonic band-gap fibers [J]. ***Appl Phys B***, 2008, 91(2): 333.

[26] Lu Jayu, Yu Chinping, Chang Hungchung, et al. Terzhertz air-core microstructure fiber [J]. ***Appl Phys Lett***, 2008, 92: 064105.