High birefringence, low loss terahertz photonic crystal fibres with zero dispersion at 0.3 THz*

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(Received 4 January 2011; revised manuscript received 12 May 2011)

A terahertz photonic crystal fibre (THz-PCF) is designed for terahertz wave propagation. The dispersion property and model birefringence are studied by employing the finite element method. The simulation result reveals the changing patten of dispersion parameter versus the geometry. The influence of the large frequency band of terahertz on birefringence is also discussed. The design of low loss, high birefringence THz-PCFs with zero dispersion frequency at 0.3 THz is presented.

Keywords: terahertz, zero dispersion, birefringence, photonic crystal fibres

PACS: 07.57.–c, 42.81.Qb, 41.20.Jb **DOI:** 10.1088/1674-1056/20/9/090701

1. Introduction

The radiation in a frequency range from 100 GHz to 30 THz, which is known as terahertz (THz) radiation, has attracted the attention of researchers from a variety of fields, not only because THz is the last unexplored radiation spectrum between microwaves and infrared, but also because the application domain has been expanding from traditional fields such as astronomy to new fields such as biology,[1] wireless communication,[2] non-destructive evaluation,[3] homeland security[4] and sensors.[5] The fast development of information technology offers great convenience to modern society but it also has brought about an information flow that requires higher and higher transmission speeds. Optical communication based on optical fibres is still growing rapidly, which makes it possible that the data rate will exceed a terabyte per second; while wireless communication needs to shift towards higher carrier frequencies, which makes THz communication technology a significant option. Therefore, low loss, low dispersion THz wave guides have become essential elements for THz communication.

Many approaches have addressed THz field propagation, including metal wires,[6,7] plastic fibres,[8] porous polymer fibres[9,10] and photonic crystal fibres (PCFs).[11–13] PCFs with high-birefringence, a large mode area and anomalous dispersion have already been demonstrated in optical fields. However, the background material used in optical fibres is silicon-based and is not suitable for THz wave transmission. Therefore, the material used for THz-PCFs is a kind of cyclic olefin copolymer named Topas. It has a constant refractive index value $n = 1.5258 \pm 2 \times 10^{-4}$ in the 0.1–1.5 THz range.[14] Experiment[2] of a 0.3-THz transmission system has been successfully introduced and the atmospheric attenuation at 0.3 THz is relatively low, making it a potential communication window for the next generation of wireless communication spectrum.[15] Based on that, the constant refractive index of the host material has made the material dispersion negligible and waveguide dispersion, which strongly depends on the geometry of the cross-section, can be flexibly designed. Furthermore, THz-PCFs are composed of airholes periodically arranged around the core region and the airholes near the core can be tuned individually to introduce high birefringence.[16,17] This kind of PCF has a great potential in sensing and communications as the THz wave suffers from lower signal

*Project supported by the National Natural Science Foundation of China (Grant No. 10874145), the Specialized Research Fund for the Doctoral Program of Higher Education of China (Grant No. 20091333110010), the Natural Science Foundation of Hebei Province of China (Grant No. F2009000481), and the Postdoctoral Science Foundation of China (Grant Nos. 20080440014 and 200902046).

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distortion due to zero dispersion and high birefringence in long-distance propagation.

2. Simulation and discussion

Typical PCFs have airholes arranged in a triangular latitude. To effectively analyse the model, the finite element method (FEM) is employed. Through the numerical calculation, the propagation constant β and the effective mode index $n_{\rm eff}$ are acquired. Because of the six-fold symmetry, a typical PCF has a pair of degenerate fundamental modes with the equal propagation constant $\beta = \beta_x = \beta_y$, which also indicates the same effective mode index $n_{\rm eff} = n_{{\rm eff}_x} = n_{{\rm eff}_y}$. Then the dispersion parameter β_2 can be written as[18]

$$\beta_2 = \frac{1}{c}\left(2\frac{{\rm d}n_{\rm eff}}{{\rm d}\omega} + \omega\frac{{\rm d}^2 n_{\rm eff}}{{\rm d}\omega^2}\right), \tag{1}$$

where c and ω are the speed of light and the angular frequency of the propagation wave, respectively. The birefringence B is

$$B = \left|n_{{\rm eff}_x} - n_{{\rm eff}_y}\right|, \tag{2}$$

when the six-fold symmetry is destroyed.

2.1. Dispersion property of a THz-PCF

Chromatic 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 fibre, specifically the airhole pitch Λ and the airhole diameter d. The ratio of d/Λ is also known as the filling factor f. Figure 1 shows the variations of dispersion parameter β_2 with frequency for different values of pitch Λ while the filling factor f keeps constant, i.e., $f = 0.6$. For different values of Λ, i.e., $\Lambda = 1.0$, 1.5 and 2.0 mm, the zero dispersion frequencies (ZDFs) are 0.25, 0.165 and 0.125 THz, respectively. It is clear that as Λ increases from 1.0 mm to 2.0 mm, the ZDF decreases from 0.25 THz to 0.125 THz.

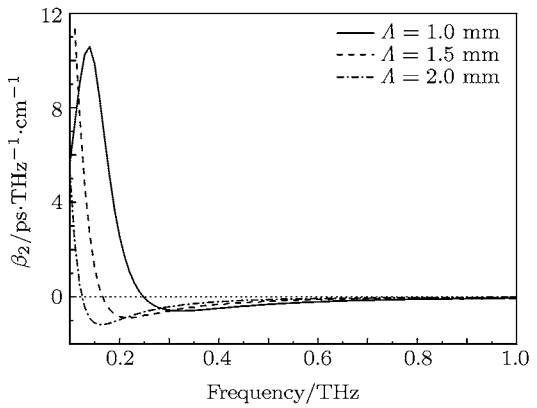


Fig. 1. Curves for dispersion parameter β_2 versus frequency from 0.1 THz to 1.0 THz when the airhole pitch $\Lambda = 1.0$ mm (solid line), 1.5 mm (dashed line) and 2.0 mm (dash-dotted line), respectively, with filling factor keeping constant ($f = 0.6$).

Figure 2 shows a comparison among the effects of different values of filling factor f with the same airhole pitch $\Lambda = 2.0$ mm. The ZDFs are 0.17, 0.125 and 0.115 THz for $f = 0.4$, 0.6 and 0.8, respectively. It is shown that the increase of f from 0.4 to 0.8 leads to a decrease of ZDF from 0.17 THz to 0.115 THz.

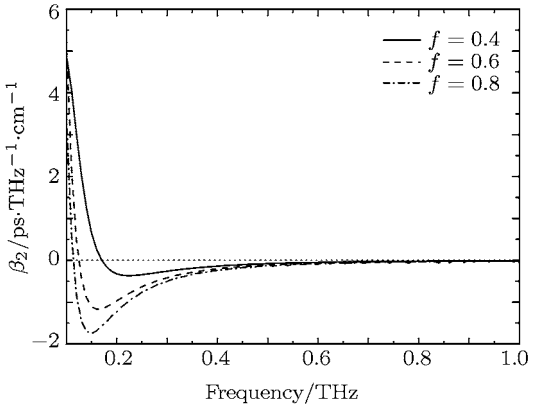


Fig. 2. Curves of dispersion parameter β_2 versus frequency from 0.1 THz to 1.0 THz when the filling factor $f = 0.4$ (solid line), 0.6 (dashed line) and 0.8 (dash-dotted line), respectively, with the airhole pitch keeping constant ($\Lambda = 2.0$ mm).

From the two figures, it is clear that the increases of pitch Λ and filling factor f shift the ZDF toward low frequencies. Moreover, each figure shows a flat-dispersion property in the high frequency region above the ZDF, which keeps β_2 negative and close to zero as frequency increases, indicating anomalous dispersion. For a frequency below the ZDF, β_2 increases sharply as frequency decreases. This changing trend ensures a possibility of a ZDF at 0.3 THz.

2.2. THz-PCFs with high birefringence and zero dispersion

Besides tuneable dispersion, the flexibility of the THz-PCF structure also enables us to introduce birefringence by tuning the airholes individually. To break the six-fold symmetry of THz-PCFs, the filling factor f of airholes close to the core in two perpendicular directions is optimized. Also the pitch Λ is tuned to shift

the ZDF to 0.3 THz. The filling factor f_x of airholes that are close to the core in the x-polarized direction is 0.4 while in the y-polarized direction $f_y = 0.95$; for other airholes $f = 0.6$, as they have less influence on the birefringence and dispersion; the pitch $\Lambda = 0.91$. As shown in Fig. 3, when the frequency decreases, the confinement of the fibre becomes weaker and weaker and behaves similarly to porous fibres, which have most energy confined in the airholes and the solid core stays in low field distribution. The simulation also demonstrates that THz-PCFs have lower loss than porous fibre for THz wave propagation.

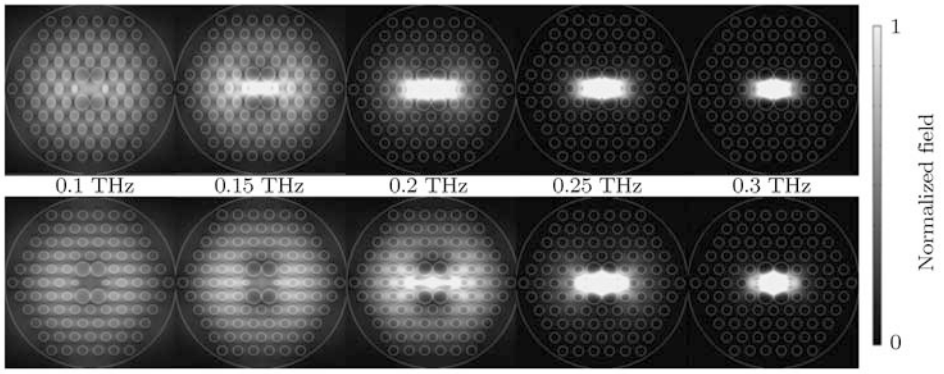


Fig. 3. Simulated modal pattens of the electric field of the proposed THz-PCF at different frequencies in two perpendicular polarized directions.

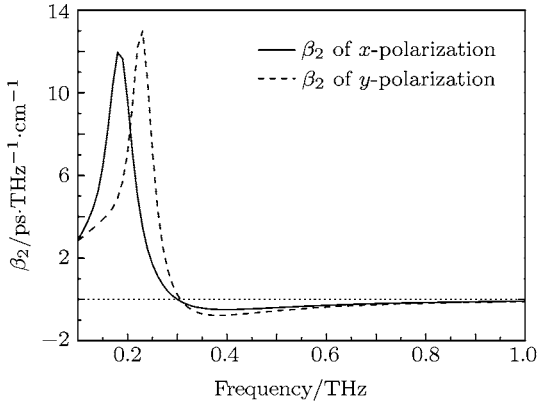


Fig. 4. Variations of dispersion parameter β_2 of two polarized modes with frequency in a range from 0.1 to 1.0 THz, with β_2 values being both close to zero.

In order to illustrate the THz-PCF design, the final dispersion and birefringence curves are plotted in Figs. 4 and 5. In Fig. 4, the dispersion parameters of the two polarized modes are close to zero, $\beta_{2x} = 0.0015$ ps·THz^{-1}·cm^{-1} and $\beta_{2y} = 0.2206$ ps·THz^{-1}·cm^{-1}. Birefringence $B = 0.012$ at 0.3 THz, then peaks at 0.24 THz and decreases as the frequency decreases. This is because the decline of n_{eff_x} is much faster than that of n_{eff_y} because f_x is much smaller than f_y. Therefore, the fibres have different confinement declines in speed in two polarized directions. The confinement loss can be written as

$$l = 20 \lg e \cdot k_0 \cdot \mathrm{Im}(n_{\mathrm{eff}}), \tag{3}$$

where $\mathrm{Im}(n_{\mathrm{eff}})$ is the imaginary part of the effective mode index and k_0 is the wave number of the THz wave. Then the confinement losses of the x- and the y-directions are 3.1376×10^{-8} dB/m and 4.5451×10^{-7} dB/m, respectively, which are much lower than the material loss.[14]

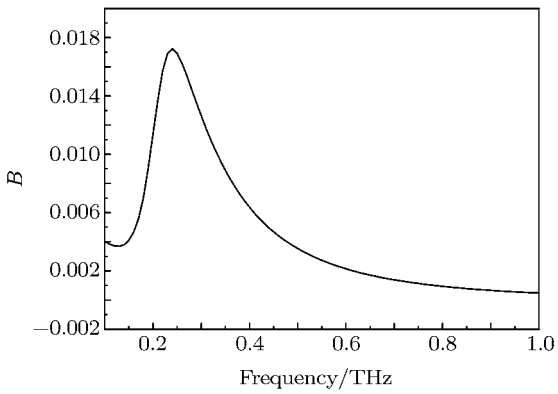


Fig. 5. Birefringence versus frequency in a range from 0.1 to 1.0 THz, with peak $B = 0.017$ at 0.24 THz and $B = 0.012$ at 0.3 THz, which is still higher than that of traditional birefringence fibre.

3. Conclusion

We present a THz-PCF design with high birefringence, low loss and zero dispersion at 0.3 THz. Numerical simulation shows that the ZDF decreases as pitch Λ or filling factor f increases; verifying that the diameter of airholes that are close to the core in two

perpendicular directions can introduce high birefringence and that the large frequency band in THz region can lead to a peak value of birefringence because the effective mode indexes have different declines in speed due to different filling factors in the x- and the y-directions. It is also noteworthy that the effect of a large frequency band of THz should be considered carefully in THz-PCF design. The proposed THz-PCFs can be beneficial for 0.3 THz wave transmission and they have great potential applications in the next generation of high speed wireless communication.

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