Vol 17 No 10, October 2008
1674-1056/2008/17(10)/3779-06

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Analysis of the special hollow-core photonic crystal fibre by finite element method*

Meng Jia(孟 佳)†, Hou Lan-Tian(侯蓝田), Zhou Gui-Yao(周桂耀), Gao Fei(高 飞), Yuan Jin-Hui(苑金辉), and Wei Dong-Bin(魏东宾)

College of Information Science and Engineering, Institute of Infrared Optical Fibers and Sensors, Yanshan University, Qinhuangdao 066004, China

(Received 24 September 2007; revised manuscript received 4 February 2008)

Two kinds of fabricated hollow-core photonic crystal fibres (HC-PCFs) are studied using finite element method (FEM) because the structures of the fibres are special. Normalized transmission spectra and transverse intensity distribution of the modes are calculated and measured. And the dispersion characteristics of these two kinds of HC-PCFs were analysed from 400 nm to 800 nm. Simulated and measured results show that the special structure could affect the properties of HC-PCFs. By comparing the simulated values with the measured results, it can be clarified that FEM is feasible and accurate for analysing photonic crystal fibres whose structures are irregular and complex.

Keywords: hollow-core photonic crystal fibre, normalized transmission spectrum, dispersion, finite element method

PACC: 4280L, 4281D, 8120J

1. Introduction

Photonic crystal fibre (PCF) can be classified as total internal reflection (TIR) PCF and photonic band gap (PBG) PCF. Solid core PCF is one of the total internal reflection PCFs. In this fibre, the energy is limited in silica and effectively propagates in the form of guided mode in the axial direction of the fibre. Because refractive index of solid core is still higher than cladding effective index, the transmission mechanism of this kind of PCF could be simply explained by the principle of total internal reflection, similar to conventional fibres. HC-PCF is a kind of typical PBG fibre. The conception of HC-PCF has been first put forward by Russell in 1991.[1] Later, Birks *et al* demonstrated this theoretically in 1995.[2] Bandgap photonic crystal fibre was made by Knight *et al* for the first time in 1998.[3] On the basis of these work, the first HC-PCF was designed and made by Cregan *et al* in 1999.[4] Different from the solid core fibre, the core of HC-PCF is a larger air hole, so the refractive index of the core is lower than cladding effective refractive index, and its guided mechanism should be explained by the photonic bandgap effect. The air holes in the cladding of HC-PCF must be in strict periodicity and the core is formed by destroying periodic structure of the cladding. According to the theory of PBG, only the wavelengths of specific frequency could be localized in the core, and the other frequencies will rapidly attenuate in the form of surface mode and leaky mode, which cannot propagates in axial direction of the fibre. The light propagating in the air core can greatly reduces losses, dispersion and nonlinear effect,[5] which is of great advantage to the practical application of HC-PCF. The fabrication of HC-PCF is much more difficult than that of solid core PCF, because any subtle changes in the fabrication course will cause distortion in fibre structure, which will directly affect the characteristics of HC-PCF. In this article, the normalized transmission spectrum, transverse intensity distribution of the mode and dispersion characteristic of the two kinds of fabricated HC-PCFs are studied using FEM. The specializations of these fibres lie in two aspects: first, there are triangular air holes in the node areas of both kinds of HC-PCFs; second, the first ring around the core is deformed because of the air core expanding. To ascertain the position of photonic band gap of the fibre, the transmission spectrum is measured and calculated. After finding the position of photonic band gap, the dispersion

*Project supported by the State Key Development Program for Basic Research of China (Grant No 2003CB314905) and the National High Technology Development Program of China (Grant No 2003AA311010).

†E-mail: bingyananying@sina.com

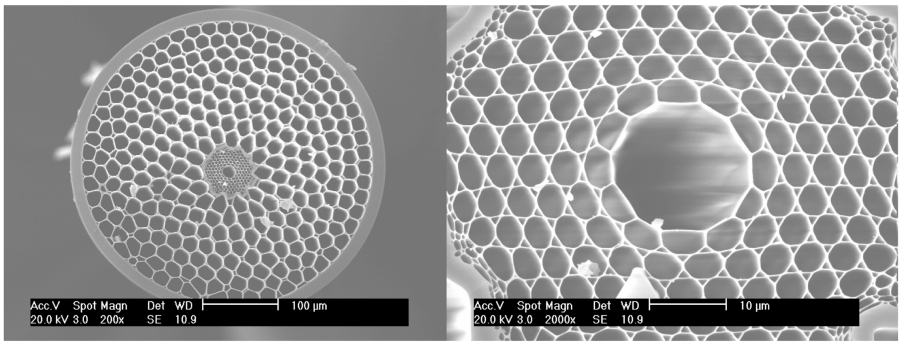
parameters of fundamental mode of the two kinds of HC-PCFs are completed according to the effective refractive index and transverse intensity distribution of the modes calculated by FEM. The characteristics of special-structured HC-PCF and the analytical method in this article can be used as references for analysis and fabrication of HC-PCF in the future.

2. Theoretic fundamentals

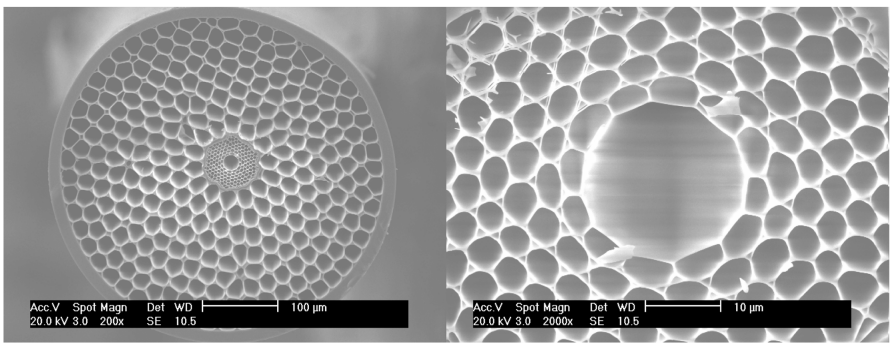
2.1. Choice of simulation method

There are many numerical methods used in PCF analysis.[6−8] Scalar methods are feasible to TIR, but not applicable to HC-PCF guiding light by photonic bandgap effect. Plane-wave method and finite difference method are difficult to accurately simulate HC-PCFs whose cladding is irregular. (see Fig.1.)

Figure 1 shows the special-structured HC-PCFs fabricated by twice-fabrication method. It could be seen from cross sections that there are distinct triangular air holes in the node areas of the fibres and the first rings around the hollow cores deformed obviously, which increase the diameters of the hollow cores. These changes of the structures make air filling fraction in HC-PCFs increased. Because conventional method of simulation is difficult to correctly show the effects caused by the changes in fibre structure, FEM is used to analyse these special-structured HC-PCFs.



(a)



(b)

Fig.1. The total and partial cross sections of two kinds of fabricated HC-PCF, (a) Λ=4.2 μm, d=3.7 μm, (b) Λ=4.8 μm, d=4.0 μm.

2.2. Finite element method

2.2.1. The model establishment of cross section of HC-PCF and the triangular net division

To analyse the special structure of HC-PCFs, firstly, the proper cross-section model of the fibre should be established to show the triangular air holes in the node areas and the deformation of the first rings around the core caused by hollow core expansion. After establishing the model, self-adapting triangular nets are used to divide the cross section. The information of divided cross-section can be extracted as the data for later computation. If we want to obtain a much more accurate solution, we could make the nets multiplicated by increasing divisions. The number of rings is taken to be five for the simulations.

2.2.2. Establishment and computation of eigenvalue equation

There are many methods to deduce the eigenvalue equation from Maxwell equation and the deduction course is very complicated. Here only a brief introduction is given. The vector wave equation is expressed as follows:

$$\nabla \times \left[\frac{1}{\varepsilon(\boldsymbol{r})}\nabla \times H(\boldsymbol{r})\right] - k_0^2 \mu(\boldsymbol{r}) H(\boldsymbol{r}) = 0, \quad (1)$$

where $H(\boldsymbol{r})$ is magnetic field, $\mu(\boldsymbol{r})$ and $\varepsilon(\boldsymbol{r})$ are relative permeability and relative permittivity, respectively; $k_0 = 2\pi/\lambda$ is wave number in vacuum, and λ is wavelength. Because the refractive index is different in the air holes and silicon, the vector wave equation in the element could be expressed as

$$\left(\nabla_i^2 + k_0^2 n_i^2 - \beta^2\right) H = 0, \quad (2)$$

where subscript i is the number of elements, n_i is the index in this area, β is propagation constant, $k_0 = 2\pi/\lambda$ is wave number in vacuum, and λ is wavelength. Through the GALERKIN algorithm, we can obtain eigenvalue equation after a series of complicated deductions,

$$\left([A] - n_{\text{eff}}^2 [B]\right)\{h\} = 0, \quad (3)$$

where $[A]$ and $[B]$ are sparse matrix related to the structure of cross section, n_{eff}^2 and $\{h\}$ are eigenvalue and eigenvector respectively, corresponding to effective refractive index and transverse intensity distribution of the mode. Through effective refractive index, the dispersion parameter $D(\lambda)$ of HC-PCF could be obtained through the following equation,

$$D(\lambda) = -\frac{\lambda}{c}\frac{\mathrm{d}^2 n_{\text{eff}}^r(\lambda)}{\mathrm{d}\lambda^2}, \quad (4)$$

where λ is wavelength, n_{eff}^r is the real part of n_{eff}. From the imaginary part of n_{eff}, the normalized transmission spectrum of HC-PCF in unit length could be calculated by the following equation,

$$\frac{P_{\text{o}}}{P_i} = \exp\left(-2k_0 n_{\text{eff}}^i\right), \quad (5)$$

Here P_{o} is the input power, P_i is the output power, n_{eff}^i is the imaginary part of n_{eff}, $k_0 = 2\pi/\lambda$ is the wave number in vacuum, and λ is wavelength. According to the normalized transmission spectrum, the position of HC-PCF bandgap could be clarified.

3. Results and analysis

3.1. Computation and measurement of normalized transmission spectrum

Because HC-PCF could only guide light whose wavelength is within photonic band gap, in order to ascertain the position of HC-PCF band gap, the transmission spectra of the fibres should be computed and measured. In actual measurement, bromine tungsten-arc lamp is used as light source. The transmission spectra are normalized in a logarithmic scale to show the results clearly. In order to indicate the loss of these fibres indirectly, the length of HC-PCF is taken to be 1km for simulation. And for the convenience of comparison, the measured values are normalized to 1 km and the unit of ordinate is dB. The results are shown in Fig.2.

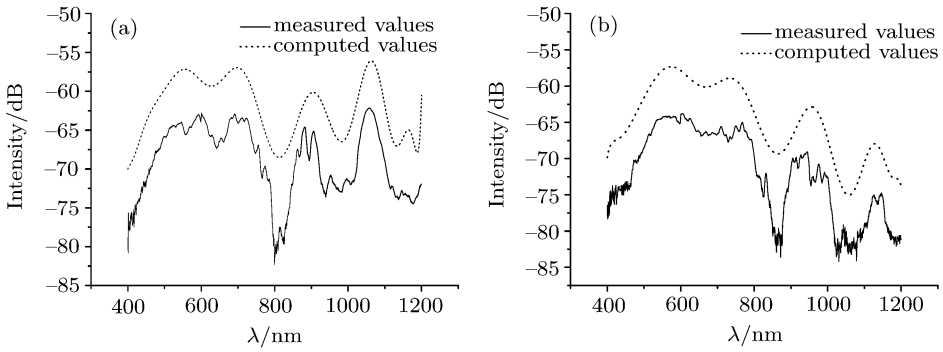
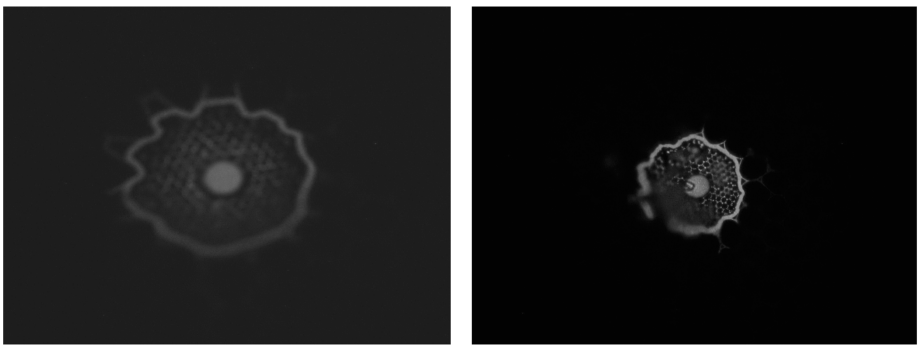


Fig.2. Normalized transmission spectra of two kinds of special-structured HC-PCFs, (a) Λ=4.2 μm, d=3.7 μm, (b) Λ=4.8 μm, d=4.0 μm.

It could be seen in the above figure that the computed normalized powers of these two kinds of HC-PCFs are bigger than measured values, and the shape of curves are not in full accord. The reason is as follows: only the effect of confinement loss on output power has been considered for computation, however, the absorption and scattering of light caused by impurities in fibres will weaken the output power to a degree. As we expect, although the computed and measured values do not agree very well, the position of the photonic bandgaps could be clearly seen from normalized transmission spectra, so the wavelengths in the bandgaps could be found. In Fig.2, it can be seen that the measured positions of HC-PCF bandgaps are in accordance with calculated results, which shows the feasibility and accuracy of FEM. From the normalized transmission spectra, it can be found that the photonic bandgaps of these two kinds of HC-PCFs cover the whole visible wavelengths, which is seldom to HC-PCFs. This is because the triangular air holes in node areas of both kinds of HC-PCFs greatly increase the air filling fraction. It makes photonic band gap move to short wavelengths and cover the visible region. In the past research, the band gap of HC-PCF generally centralizes in infrared wavelengths. Moving the bandgap of HC-PCF to visible wavelength range is not only of advantage to observation and measurement but also of benefit to the development of communication in these wavelengths because this kind of HC-PCFs is fit for the transmission of ultra-short optical pulse. After finding the position of the bandgaps, transverse intensity of the fundamental mode and the dispersion characteristics of the fibres will be studied in the wavelengths ranging from 400 to 800 nm.

3.2. Computation and measurement of HC-PCF mode

The near-field patterns of the fundamental modes (see Fig.3) also can be observed when the transmission spectra of these two kinds of HC-PCFs are measured.



(a) (b)

Fig.3. Near-field patterns of the fundamental mode of the two kinds of special-structured HC-PCFs, (a) Λ=4.2 μm, d=3.7 μm, (b) Λ=4.8 μm, d=4.0 μm.

The length of the measured fibre is about 60 cm and the light source is bromine tungsten-arc lamp. In the transmission spectrum, there is a small peak in the 500–600 nm wavelength range. To show the results computed by FEM, 532 nm is chosen as the input wavelength, in the meantime the effective index and transverse intensity distribution of the guided mode are computed in this wavelength, which correspond to eigenvalue and eigenvector of eigenvalue equation, respectively. The results are shown in Fig.4.

As shown in Fig.4, the patterns of the guided mode are computed at 532nm. The eigenvalues corresponding to the modes are marked in these figures. To clearly see the cross section of the HC-PCF, the contours of the modes are also drawn. The units of both abscissa and ordinate are both micron in order to show the structure of HC-PCF. Because the dispersion parameter only depends on the real part of the effective index, the eigenvalue $N(i)$ marked in drawings is the square of the real part of effective index n_{eff}^{r}, and i is the sequence number of this eigenvalue in all the computed eigenvalues. When using FEM for calculation, eigenvalues and eigenvectors of eigenvalue equation are not unique, and they could reflect all the modes which could exist in fibres, including high-order mode. The purpose of obtaining the patterns of the

fundamental mode is that the effect on the localization can be seen from the patterns. From Fig.4, it can be found that the fundamental mode is localized in the air core of HC-PCF even if the number of rings is less than three at 532 nm wavelength. It is also a property of these special-structured HC-PCFs. However, in order to make the calculated results much more accurate, the number of rings is taken to be five for all the simulations except for drawing Fig.4. The other advantage of this pattern is that the eigenvalue corresponding to the fundamental mode can be accurately found out by observing the transverse intensity distribution of the mode if the eigenvalue corresponding to high-order mode is very close to the one corresponding to the fundamental mode at some wavelengths.

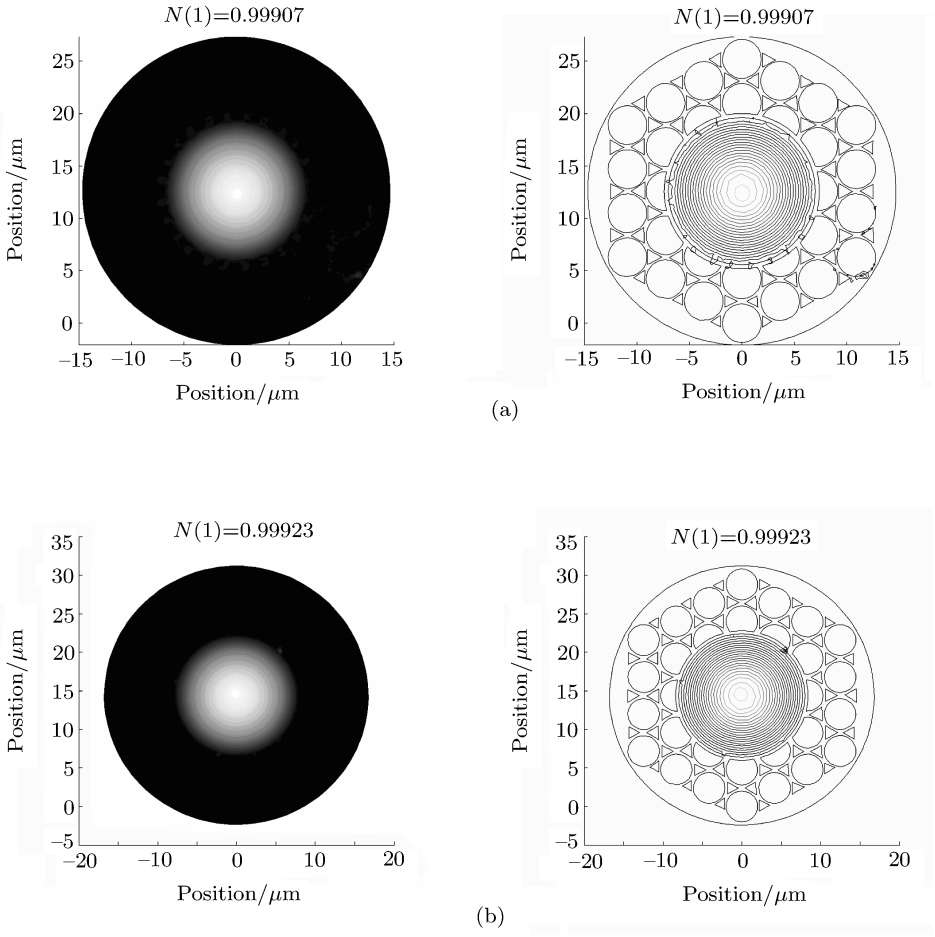


Fig.4. The contour patterns of the fundamental modes and corresponding effective refractive index of the two kinds of special HC-PCFs calculated by FEM, (a) Λ=4.2 μm, d=3.7 μm, (b) Λ=4.8 μm, d=4.0 μm.

3.3. Dispersions of special-structured HC-PCFs

Compared with fundamental mode, the leakage of higher order modes is much more serious, and it could be considered as a single mode operation when the length of fibre is more than 1m. So the dispersion parameter mainly depends on the fundamental mode.

The dispersion parameters of the fundamental mode in the range of 400–800 nm are calculated by Eq.(4). After that, the results are fitted by least square method and the dispersion curves of the fundamental mode are shown in Fig.5.

The solid curves in Fig.5(a) and 5(b) are the dispersion curves of the two kinds of special-structured HC-PCFs. It could be found that in 400–800 nm wavelength range, the dispersion parameters of the two kinds of HC-PCFs is less than 12 ps/nm/km, which is much smaller than the values reported in Refs.[9–12]. It is because the total dispersion of fibres mainly depends on the material dispersion and the waveguide dispersion. For solid-core fibres, material dispersion

is dominating; however, for HC-PCFs, waveguide dispersion is predominant because the light is guided in the hollow core. Compared with HC-PCFs studied in Refs.[9–12], the hollow core diameters of this kind of special-structured HC-PCF are much larger, so the material dispersion is much weaker and the total dispersion is smaller, i.e. the total dispersion could be reduced greatly by increasing the diameter of the hollow core.

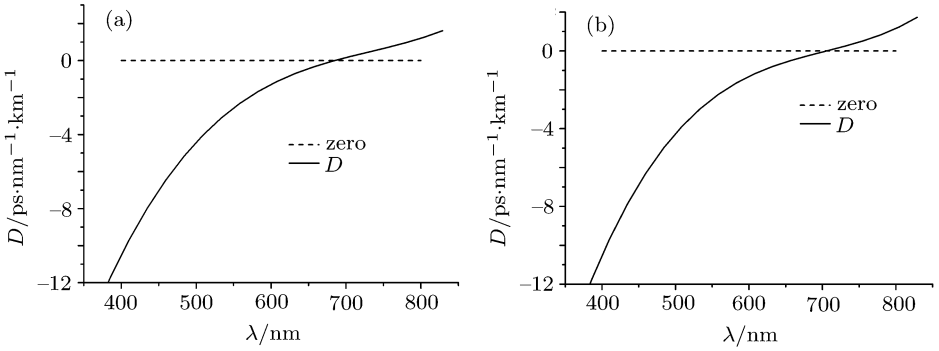


Fig.5. Dispersion curve of fundamental mode of special-structured HC-PCF, (a) Λ=4.2 μm, d=3.7 μm, (b) Λ=4.8 μm, d=4.0 μm.

4. Conclusions

From the simulated and experimentally measured results of normalized transmission spectra, it could be seen that the lowest loss of both kinds of HC-PCFs is about 56 dB/km, which can meet the requirement in practical applications. In the past researches, the bandgaps of HC-PCF generally centralize in infrared wavelength range; however, the bandgaps of these two kinds of HC-PCF nearly cover the whole visible region. This is because there are triangular air holes in node areas and the first ring around the hollow core is deformed. These changes of structure greatly increase air filling fraction, which makes photonic bandgaps move to the short wavelengths. This effect gives a reference to designing and fabricating HC-PCF which can guide light in visible wavelength region.

Because the core diameters of these special-structured HC-PCFs lie between from 10 and 20 micron, the total dispersion is hardly affected by material dispersion. So the dispersion parameters in wavelength range from 400 to 800 nm are smaller. These simulated results provide a basis for the application of large-core HC-PCF in the field of fibre communication.

FEM can be used to simulate the fibre with irregular and complex cross-section. The effective refractive indices and the transverse intensity distributions of fundamental mode and higher-order modes can be calculated. By comparing simulated values and measured results, it can be clarified that FEM is feasible and accurate for the study on special-structured HC-PCFs.

References

[1] Russell P St J 2003 *Science* **299** 358
[2] Birks T A, Roberts P J, Russell P St J, Atkin D M and Shepherd T J 1995 *Electron Lett.* **31** 1941
[3] Knight J C, Broeng J, Birks T A and Russell P St J 1998 *Science* **282** 1476
[4] Cregan R F, Mangan B J, Knight J C, Birks T A, Russell P St J, Roberts P J and Allan D C 1999 *Science* **285** 1537
[5] Galea A D, Couny F, Coupland S, Roberts P J, Sabert, Knight J C, Birks T A and Russell P St J 2005 *Opt. Lett.* **30** 717
[6] Knight J C 2003 *Nature* **424** 847
[7] Li S G, Liu X D and Hou L T 2004 *Acta Phys. Sin.* **53** 1873 (in Chinese)
[8] Li S G, Xing G L, Zhou G Y, Han Y, Hou L T, Hu M L, Li Y F and Wang Q Y 2006 *Chin. Phys.* **15** 437
[9] Bouwmans G, Luan F, Knight J C and Russell P St J 2003 *Opt. Express* **14** 1613
[10] Jasapara J, Tsing Hua Her, Bise R and Windeler R 2003 *J. Opt. Soc. Am.* B **8** 1611
[11] Lim H and Wise F W 2004 *Opt. Express* **10** 2231
[12] Zhao C J, Tang Z X and Ye Y X 2007 *Opt. Express* **11** 6629