Vol 18 No 3, March 2009
1674-1056/2009/18(03)/1109-07

Chinese Physics B

© 2009 Chin. Phys. Soc.
and IOP Publishing Ltd

Lateral stress-induced propagation characteristics in photonic crystal fibres*

Tian Hong-Da(田宏达), Yu Zhong-Yuan(俞重远),
Han Li-Hong(韩利红), and Liu Yu-Min(刘玉敏)

Institute of Optical Communication and Optoelectronics, Beijing University of Posts and Telecommunications, Beijing 100876, *China*

Key Laboratory of Optical Communication and Lightwave Technologies Ministry of Education (Beijing University of Posts and Telecommunications), Beijing 100876, *China*

(Received 3 June 2008; revised manuscript received 31 July 2008)

Using the finite element method, this paper investigates lateral stress-induced propagation characteristics in a photonic crystal fibre of hexagonal symmetry. The results of simulation show the strong stress dependence of effective index of the fundamental guided mode, phase modal birefringence and confinement loss. It also finds that the contribution of the geometrical effect that is related only to deformation of the photonic crystal fibre and the stress-related contribution to phase modal birefringence and confinement loss are entirely different. Furthermore, polarization-dependent stress sensitivity of confinement loss is proposed in this paper.

Keywords: propagation characteristics, photonic crystal fibre, lateral stress, stress-optical effect
PACC: 4281, 4281D, 4281F

1. Introduction

In recent years, photonic crystal fibres (PCFs) have attracted a great deal of interest due to their unique optical properties. It has already been demonstrated that PCFs can be used in numerous applications such as compensation for chromatic dispersion,[1] generation of supercontinuum,[2] and so on. The polarization properties of PCFs are so important that many investigations on them have been reported so far.[3−5] It is already well known that modal birefringence in PCFs can exceed 10^{-3},[6] which is one order of magnitude higher than the birefringence in conventional fibres. Furthermore, the fundamental propagation properties of high birefringence PCFs have also been investigated.[7] Thus PCFs can find multitudinous applications in optical interferometric systems, fibre-optic sensors, and telecommunication devices.

PCFs are usually fabricated from a single material (fused silica). In single-material PCFs, in contrast to the thermal-stress-based birefringent fibres such as bow-tie fibres, polarization-maintaining and absorption-reducing fibres, the birefringence of the PCFs is attributed mainly to geometric anisotropy.[8] First of all, high birefringence can be induced by asymmetrical cladding, in which one row of hexagonal cells has lower fill factor than the other cladding cells.[9] Another way of inducing birefringence in PCFs is to form the core with twofold plane symmetry, for example the core composed of two adjacent elementary cells completely filled with glass (double defect).[10] It was also demonstrated that the birefringence in hexagonal structure can be induced by elliptical shape of the cladding holes.[11] Geometric anisotropy is attributed to construction in these examples. In other words, researchers have devoted a lot of time to designing of birefringent PCFs in recent years.

As is known, external stress can lead to birefringence in the conventional single-mode fibres. There are about two reasons for this. First, the symmetry of core is changed due to the deformations of fibres. Thus the degeneracy of orthometric polarization modes does not exist now. The second reason is stress-optical effect (SOE). Stress induces anisotropic changes of refractive index within the fibres and thus creates birefringence. In practical terms, handling PCFs may also cause stress-induced birefringence. Hydrostatic pressure, axial force, twisting and elongation may cause birefringence respectively. However, there is another reason for the birefringence of PCFs submitted to external stress. The deformations of PCFs also include

*Project supported by the National Natural Science Foundation of China (Grant No 60644004), and the State Key Development Program for Basic Research of China (Grant No 2003CB314901).

the reductions in the hole pitch and the change in the shape of holes. Thus the symmetry of cladding has also been changed. As we have mentioned before, birefringence is also related to the symmetrical change of cladding in PCFs. Analysis of the impact of axial force and twisting on modal birefringence has been implemented in one article.[12] An influence of hydrostatic pressure on phase and group modal birefringence has been theoretically analysed in another article.[13] In these articles, the operated PCFs are highly birefringent fibres originally.

In this paper, we study lateral stress-induced propagation characteristics in PCFs using the finite element method (FEM). As the crucial parameters in PCFs, we have investigated the dependence of stress on effective index of the fundamental guided mode, birefringence and confinement loss. In our work, there is another difference from former investigations. In order to investigate the diversity of propagation characteristics in PCFs under lateral forces from different directions, we select a standard PCF of hexagonal symmetry. So there is no birefringence when no pressure is applied to the PCF. Furthermore, as a contrast, we analyse separately the contribution of the geometrical effect which is related only to deformation of the PCF and the stress-related contribution to effective index of the fundamental guided mode, birefringence and confinement loss.

2. Fibre structure and modelling method

Under external forces, PCFs are deformed and a series of stress distribution are formed in the PCFs. For convenience, the dependence of strain components on stress components can be set up by using a stiffness matrix, and then the strain and stress may be expressed as two column vectors.[14,15] If the applied force acts in the transverse plane and does not vary in the axial direction, then, under the plane strain approximation the stress can be readily obtained through FEM.[16] Researchers have also analysed SOE in PCFs in detail.[13] Thus the principal refractive indices are given in the most general case by the following equations:

$$\begin{aligned} n_x &= n + B_1\sigma_x + B_2(\sigma_y + \sigma_z), \\ n_y &= n + B_1\sigma_y + B_2(\sigma_x + \sigma_z), \\ n_z &= n + B_1\sigma_z + B_2(\sigma_x + \sigma_y), \end{aligned} \tag{1}$$

where B_1 and B_2 are stress-optic coefficients and σ_x, σ_y, and σ_z are the principal components of the lateral pressure-induced stress. One should note that in PCFs, owing to uniformity of the glass composition over entire cross section, axial stress component σ_z is equal to zero. Therefore σ_z can be disregarded in Eq.(1).

The cross section of our selected PCF is shown in Fig.1.

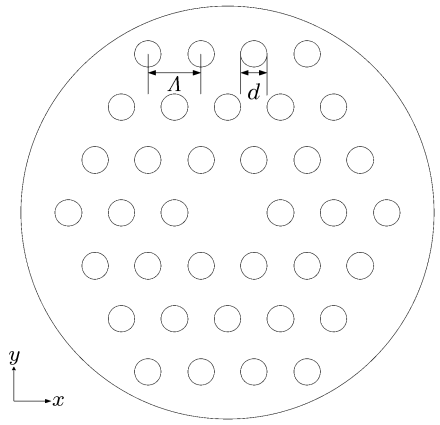


Fig.1. Schematic representation of the selected PCF.

The light-guiding mechanism of such a PCF is modified form of total internal reflection. Due to its high symmetry, the transverse structure of such a PCF is mainly determined by the following geometrical parameters: the hole pitch Λ and the hole diameter d. In this paper, we assume that Λ is equal to $2.2\,\mu$m, and d/Λ is 0.5. The finite element calculations are especially useful in processing complicated strain problems.[17−19] Thus FEM is also applied in the following simulation. Particular boundary condition is required to improve the accuracy of calculation. We adopt cylindrical perfectly matched layer (PML).[20] The refractive index of silica glass is obtained according to the Sellmeier equation in this model, which takes the material dispersion into account. In the calculations of stress components and structure deformations we use material constants which are adequate for silica glass:[21] elasticity modulus E=72.5 GPa, Poisson ratio ν=0.17, stress-optic coefficients $B_1 = -6.9\times10^{-13}\,\mathrm{m^2/N}$ and $B_2 = -4.2\times10^{-12}\,\mathrm{m^2/N}$. Because of a lack of reliable experimental data, we assume that stress-optic coefficients are wavelength independent. In order to express structure deformations vividly, we define degree of distortion (DOD) of the PCF. If r denotes the hole radius, and d' denotes the magnitude of deformation of the PCF in certain direction where force is applied, DOD is given

by DOD=d'/r. Thus DOD_x describes the degree of distortion of the PCF under force which is applied in x direction. We may comprehend DOD_y similarly. Finally, it should be noted that only the fundamental modes are considered in this paper.

3. Results and discussions

3.1. Effective index of the fundamental mode

If we only take the anamorphic effect (AE) into account, the dependence of wavelength on effective index of the fundamental mode is shown in Fig.2. It is found that effective index decreases with the increase of wavelength regardless of lateral force. When no pressure is applied to the PCF, there is no difference between the effective index of x-polarization and the one of y-polarization due to high symmetry of the PCF. With the increase of DOD, the effective index of x-polarization is separated from the one of y-polarization gradually. Furthermore, we can see that there is only a little difference between two effective indices in the shorter wave band when DOD_x or DOD_y has a certain value. But the difference is considerable in the longer wave band. If the wavelength is given, the effective index of y-polarization is larger than the one of x-polarization when DOD_x has a certain value. Inverse result is obtained for DOD_y.

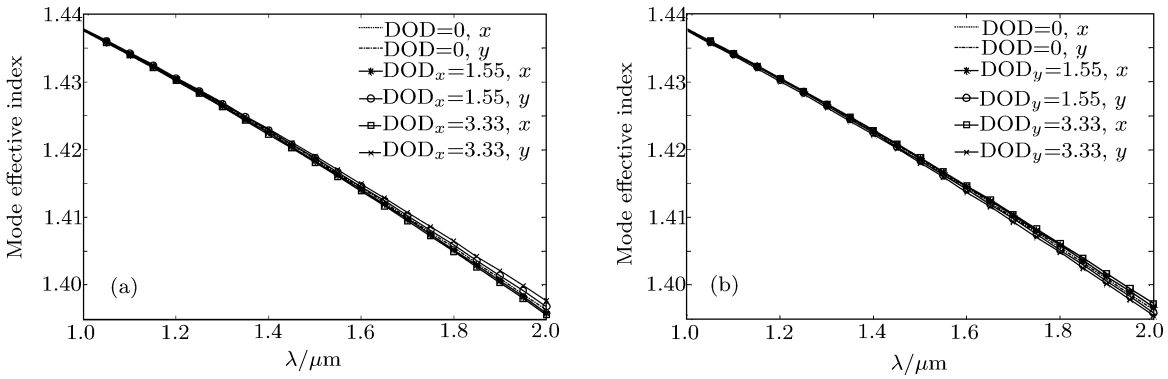


Fig.2. Effective index of the fundamental mode as a function of wavelength for different DOD and polarized components (x represents x-polarization, y represents y-polarization) without consideration of SOE.

Next, if SOE is also considered, we obtain the dependence of wavelength on effective index of the fundamental mode in Fig.3. Plenty of conclusions which are similar to the ones in the above case can be easily made. However, in contrast to the above case, there is a prominent difference between the effective index of x-polarization and the one of y-polarization when DOD_x or DOD_y has a certain value. This facilitates high birefringence in the PCF.

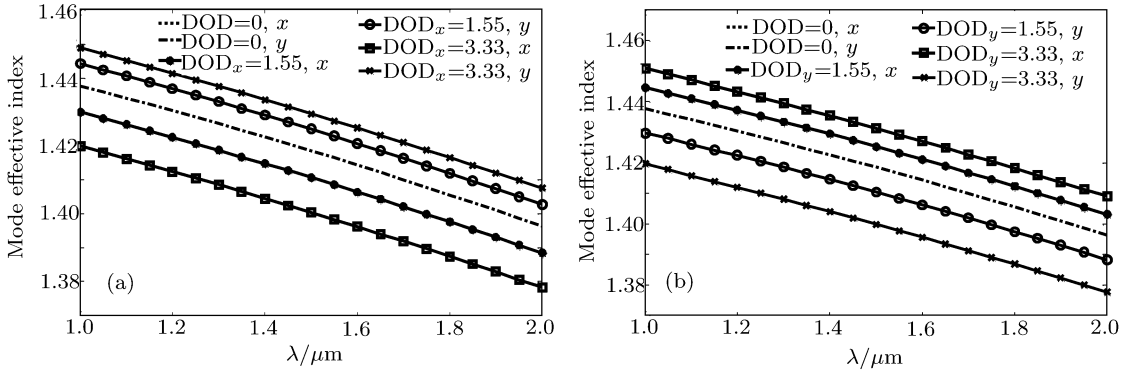


Fig.3. Effective index of the fundamental mode as a function of wavelength for different DOD and polarized components (x represents x-polarization, y represents y-polarization) with consideration of SOE.

3.2. Phase modal birefringence

On the basis of the foregoing investigations, we now study phase modal birefringence,[13] which is defined by

$$B = |n_{\text{eff}}^{x} - n_{\text{eff}}^{y}|\,, \tag{2}$$

where n_{eff}^{x} and n_{eff}^{y} are effective indices of the x- and y-polarized fundamental modes, respectively. It is noted that absolute value is adopted here to interpret results expediently.

The relationship between phase modal birefringence and DOD is shown in Fig.4. Here the operating wavelength is $1.55\,\mu$m. If we only take AE into account, we obtain the results in Fig.4(a). If SOE is also considered, the results are shown in Fig.4(b). Furthermore, because we apply pressure to the PCF in different directions, comparison between the results is also exhibited. From Fig.4, we find that birefringence increases with the increase of DOD. This can be easily understood from the standpoint of destructive symmetry. Due to hexagonal symmetry, we also find that the relationship between phase modal birefringence and DOD varies with the change of direction in which force is applied. When DOD has a small value and DOD_x is equal to DOD_y, we obtain equivalent birefringence. With the increase of DOD, the birefringence separates farther and farther. What is more, whether we consider that SOE has a great impact on the results.

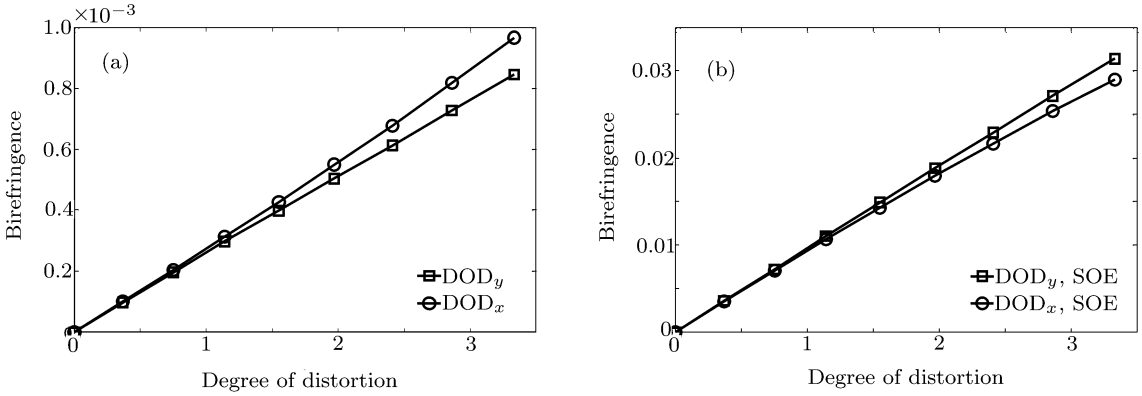


Fig.4. Phase modal birefringence as a function of DOD for different direction of force with (a) AE and (b) SOE considered, where the operating wavelength is $1.55\,\mu$m.

The dependence of wavelength on phase modal birefringence is shown in Fig.5. If we only take AE into account, we find that birefringence increases with the increase of wavelength, which is shown in Fig.5(a). When DOD_x is equal to DOD_y, the difference of birefringence induced by force which is applied in x and y direction respectively is enlarged with the increase of wavelength. We also find that this difference is more remarkable when DOD has a larger value. As we can see in Fig.5(b), when SOE is also considered, birefringence is almost invariable with the increase of wavelength. Thus when DOD_x is equal to DOD_y, the difference of birefringence induced by force which is applied in x and y direction respectively is also invariable with the increase of wavelength. Similarly, this difference is more remarkable when DOD has a larger value. Thus the dependence of wavelength on phase modal birefringence is significantly decreased when SOE is considered. Actually, this phenomenon can be readily understood from the dependence of wavelength on effective index of the fundamental mode. As we can see in Fig.2, when DOD is not equal to zero, the dependence of wavelength on effective index without consideration of SOE appears to present nonlinear change relative to the one when DOD is equal to zero. But in Fig.3, when DOD is not equal to zero, the dependence of wavelength on effective index with consideration of SOE seems to have a parallel move relative to the one when DOD is equal to zero. Furthermore, the birefringence which is calculated with consideration of SOE is at least one order of magnitude higher than that calculated with consideration of AE merely. We may conclude that, in terms of phase modal birefringence, the contribution of SOE is larger than that of AE.

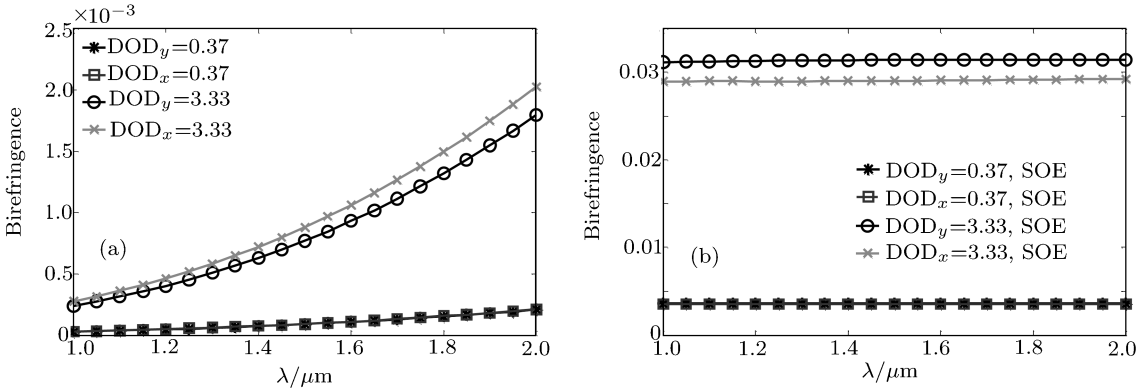


Fig.5. Phase modal birefringence as a function of wavelength for different DOD with consideration of (a) AE and (b) SOE.

3.3. Confinement loss

Confinement loss[22] in PCFs is defined in the following way

$$L_c = -\frac{20}{\ln 10}\mathrm{Im}\beta[\mathrm{dB/m}], \tag{3}$$

where β is propagation constant of the fundamental mode.

There are a few papers published so far reporting on polarization-dependent confinement loss in PCFs.[23] But to our knowledge, confinement loss in PCFs under lateral stress has not been explored. We analyse the case without consideration of SOE first. Figure 6 shows us the dependence of wavelength on confinement loss for different DOD and polarized components. It is found that confinement loss will experience a steady increase with the increase of wavelength regardless of lateral force. When no pressure is applied to the PCF, there is a little difference between the confinement loss of x-polarization and the one of y-polarization. As we can see in Fig.6(a), if the wavelength is given, the confinement loss of y-polarization is larger than the one of x-polarization when DOD_x has a certain value. Furthermore, this difference is more notable when DOD_x has a larger value. We obtain similar results for different DOD_y and polarized components in Fig.6(b). In contrast to Fig.6(a), if the wavelength is given, the confinement loss of x-polarization is larger than the one of y-polarization when DOD_y has a certain value.

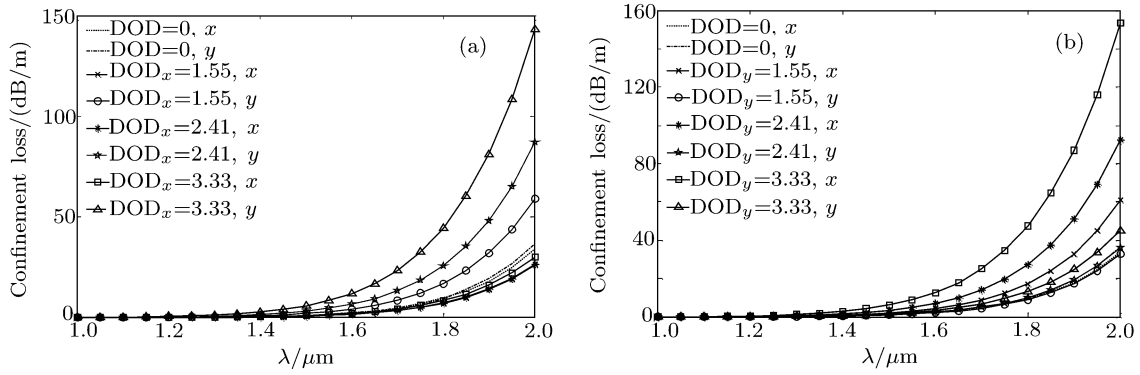


Fig.6. Confinement loss as a function of wavelength for different DOD and polarized components (x represents x-polarization, y represents y-polarization) without consideration of SOE.

Next, after taking SOE into account, we study the same topic. Analogous results have been found when DOD has a smaller value, which are not included in this paper. If DOD has a value large enough, the confinement loss of one polarized component still increases with the increase of wavelength steadily, but the other one does not. As we can see in Fig.7, if DOD_x has a value large enough, the confinement loss of y-polarization still experiences a steady increase with the increase of wavelength. However, fantas-

tic phenomena have been found in the shorter wave band for the confinement loss of x-polarization. We find that there is a minimum confinement loss in the wave band which we investigate. Furthermore, fantastic phenomena only occur in the shorter wave band when DOD_x has a smaller value. If DOD_x is increased, there is such a tendency that fantastic phenomena will extend to the longer wave band. We also find that if DOD_y has a value large enough, there are fantastic phenomena in the shorter wave band for the confinement loss of y-polarization, which is shown in Fig.8. Now we can make a conclusion that stress sensitivity of confinement loss is incarnated in the shorter wave band first. What is more, this stress sensitivity is polarization-dependent.

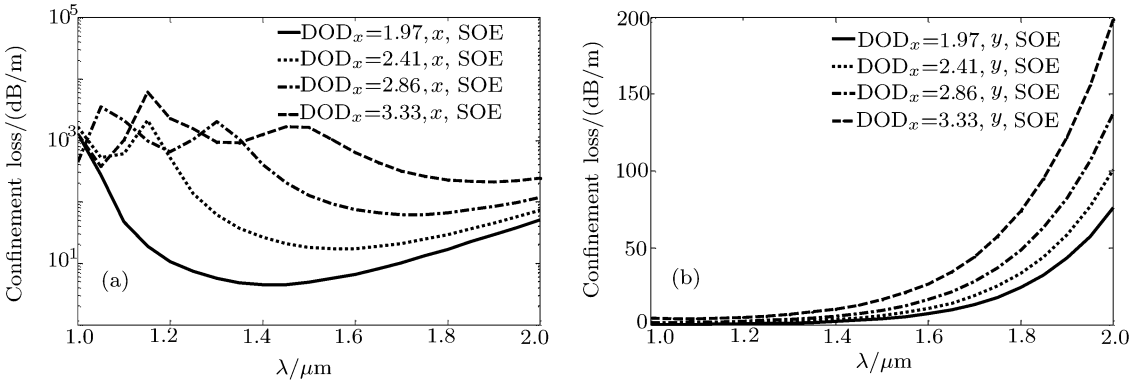


Fig.7. Confinement losses of (a) x-polarization (x represents x-polarization) and (b) y-polarization (y represents y-polarization) as a function of wavelength for different DOD_x with consideration of SOE.

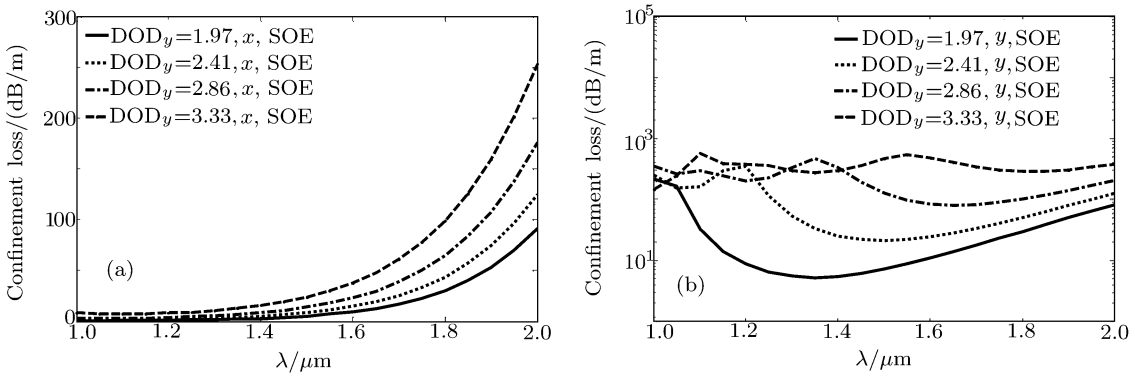


Fig.8. Confinement losses of (a) x-polarization (x represents x-polarization) and (b) y-polarization (y represents y-polarization) as a function of wavelength for different DOD_y with consideration of SOE.

It should be noted that the PCF is deformed regardless of considering SOE. In other words, once SOE is considered, AE is included automatically. In order to investigate what kind of effects has a greater impact on confinement loss, we make a contrast. Here AE has the same meaning as before. However, once SOE is considered, AE is not included now. From Fig.9, we find that the contribution of AE to the confinement loss is larger than the one of SOE. Furthermore, the difference between them will decrease with the increase of DOD. Figure 9 just shows us the confinement loss of x-polarization for different DOD_x. Actually, the results for different polarized components or DOD_y agree with Fig.9 very well, which are not included in this paper. Of course, the magnitude of DOD may not exceed a certain range.

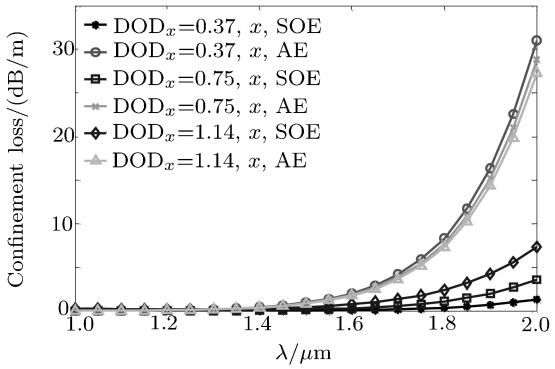


Fig.9. Confinement loss of x-polarization (x represents x-polarization) as a function of wavelength for different DOD$_x$ with consideration of different effects.

4. Conclusions

We have numerically shown the effective index of the fundamental mode, phase modal birefringence and confinement loss properties in a standard PCF of hexagonal symmetry under lateral stress. It is found that all of these important parameters in PCFs have strong stress dependence. In terms of phase modal birefringence, the contribution of SOE is larger than that of AE. However, the contribution of anamorphic effect to the confinement loss is larger than the one of SOE. We also find that there is polarization-dependent stress sensitivity for confinement loss.

In general, PCFs are achieved through introducing air holes into a single material. Thus PCFs are not as good as conventional single-mode fibres in pressure resistance. Introducing stress into PCFs will destroy the fibres easily. The fantastic phenomena of confinement loss may be a proof in this paper. Although large deformations can lead to high birefringence, fantastic phenomena of confinement loss also appear in such a case. As we all know, there is great flexibility in the design of PCFs. Various birefringent effects can be achieved through designing the symmetry of transverse structure. Thus our analysis suggests that, in order to obtain higher birefringence, which may exceed 10^{-2}, researchers still have to commit themselves to the design of the transverse structure of PCFs.

References

[1] Matsui T, Nakajima K and Sankawa I 2007 *J. Lightwave Technol.* **25** 757
[2] Xu Y, Ren X, Wang Z, Zhang X and Huang Y 2007 *Electron. Lett.* **43** 87
[3] Liu X Y, Zhang F D, Zhang M and Ye P D 2007 *Chin. Phys.* **16** 1710
[4] Zhang X J, Zhao J L and Hou J P 2007 *Acta Phys. Sin.* **56** 4668 (in Chinese)
[5] Zhang Y N, Miao R C, Ren L Y, Wang H Y, Wang L L and Zhao W 2007 *Chin. Phys.* **16** 1719
[6] Yue Y, Kai G Y, Wang Z, Lu Y F, Zhang C S, Sun T T, Li Y, Jin L, Liu J G, Liu Y G, Yuan S Z and Dong X Y 2006 *IEEE Photon. Technol. Lett.* **18** 2638
[7] Lou S Q, Wang Z, Ren G B and Jian S S 2004 *Chin. Phys.* **13** 1493
[8] Szpulak M, Urbanczyk W, Martynkien T, Wojcik J and Bock W J 2003 *SPIE* **5028** 108
[9] Ortigosa-Blanch A, Knight J C, Wadsworth W J, Arriaga J, Mangan B J, Birks T A and Russell P St J 2000 *Opt. Lett.* **25** 1325
[10] Hansen T P, Broeng J, Libori S E B, Knudsen E, Bjarklev A, Jensen J R and Simonsen H 2001 *IEEE Photon. Technol. Lett.* **13** 588
[11] Steel M J and Osgood Jr R M 2001 *J. Lightwave Technol.* **19** 495
[12] Zhu Z and Brown T G 2003 *Opt. Lett.* **28** 2306
[13] Szpulak M, Martynkien T and Urbanczyk W 2004 *Appl. Opt.* **43** 4739
[14] Liu Y M, Yu Z Y and Huang Y Z 2006 *Acta Phys. Sin.* **55** 5023 (in Chinese)
[15] Liu Y M, Yu Z Y, Ren X M and Xu Z H 2008 *Chin. Phys.* B **17** 3471
[16] Okamoto K, Hosaka T and Edahiro T 1981 *IEEE J. Quantum Electron.* **QE-17** 2123
[17] Liu Y M, Yu Z Y and Huang Y Z 2006 *Int. J. Mod. Phys.* B **20** 4899
[18] Liu Y M, Yu Z Y and Huang Y Z 2007 *J. University Sci. Technol. Beijing* **14** 477
[19] Liu Y M, Yu Z Y and Ren X M 2008 *Chin. Phys. Lett.* **25** 1850
[20] Huang W P, Xu C L, Liu W and Yokoyama K 1996 *IEEE Photon. Technol. Lett.* **8** 652
[21] Urbanczyk W, Martynkien T and Bock W J 2001 *Appl. Opt.* **40** 1911
[22] Saitoh K and Koshiba M 2005 *J. Lightwave Technol.* **23** 3580
[23] Koshiba M and Saitoh K 2003 *IEEE Photon. Technol. Lett.* **15** 691