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# Effect of structure random disturbances on characterizations of microstructured optical fibres*

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A method is presented to analyse the effect of structure random disturbances on the confinement loss and the chromatic dispersion characterizations of microstructured optical fibres, which combines multipole methods with the random statistics process. Some useful results to the fabrication of microstructured optical fibres have been obtained.

**Keywords:** microstructured optical fibres (MOFs), dispersion, loss, multipole methods
**PACC:** 4270Q 4280M

## 1. Introduction

Recently, much effort has been devoted to the research of microstructured optical fibres (MOFs) which usually consist of a hexagonal arrangement of microscopic holes (mostly air) running through the entire length of the fibres surrounding a central core of solid silica or, in some cases, air, in the insulating environment. These fibres are of great interest due to a unique combination of dispersion, polarization, and nonlinear properties such as a wide range of single mode operation, the adjustable dispersion, supercontinuum generation and easily controllable effective modes areas. MOFs are ready to lend themselves for applications such as dispersion compensation, soliton formation and visible continuum generation.[1−17] By varying the size of the holes and their number and position, people can also design MOFs with carefully controlled the dispersion, loss, modal, birefringent and other properties.[18−20] But the actual properties of the MOFs which is fabricated by drawing a macroscopic perform down into a fibre using a conventional fibre-drawing tower are often different from what we anticipate, because of the disturbance errors in fibres' producing. In this work we combine random statistics with a high-accuracy calculation of the full complex propagation constant of MOFs introduced by White,[21,22] and multipole methods showing the effect of disturbance error in fibres' fabrication on the MOFs' properties such as the confinement loss and the chromatic dispersion. Through the calculation, some useful results have been obtained.

## 2. Multipole methods and random statistics

Many modelling techniques have been applied in analysing MOFs, including approximate effective index models,[1] plane-wave expansion method,[23] localized-function methods,[24] finite element methods,[25] eigen matrix method,[26] finite difference time domain (FDTD) methods,[27] and multipole methods.[21,22] In this paper, we use multipole methods to analyse the modal properties of MOFs. By using multipole methods, the confinement loss and the chromatic dispersion can be obtained at the same time. We use a full vector multipole formulation in which the mode has generally complex propagation constants. In the calculation, we choose 7-order modified Bessel functions of the first and second kind, and a method of scanning the real and imaginary part of index is used to solve the eigenvalue problem.

To describe the disorder of MOFs' cross structure, which is caused by the disturbance in the fibres' fabrication, a random disturbance model is adopted. The

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model includes the random positional disturbance and the random diametrical disturbance. The positional disturbance presents the air holes' position error to show the difference between the designed and the produced ones. In polar coordinates $(r, \theta)$, the position error includes two dimensions. The diametrical disturbance presents the air holes' diameters $(d)$ error. All the disturbances may be positive or negative and the extent of disturbance is denoted in percent. For the $r$ in polar coordinates and the $d$, air holes' diameter, the extent percent shows the range between the positive peak and negative peak compared with the designed ones. As an example,10% of disturbance means that the error between designed and actual ones may be positive or negative 0–5%. For the $\theta$, angle in polar coordinates, the extent percent shows the range between the positive peak and negative peak compared with $\pi/3$, so 10% of disturbance means that the angle departure between designed and actual ones may be from $-\pi/60$ to $\pi/60$. This research is different from that of those authors,[18,19] who study the situation by changing $d$ or $d/\Lambda$. They usually investigate the MOFs' characteristic by varying $d$ and $d/\Lambda$ in large range, but all holes of MOFs have one $d$ and $d/\Lambda$. This work shows the difference between a certainly designed structure and a produced one. In the former case, all holes also have same $d$ and $d/\Lambda$ in a regular crystal lattice, but in the latter case, which we mainly consider, all holes have its own $d$ (only a little error of the former's $d$) in a crystal lattice with random disturbance. In the following, by using this random disturbance model the effect of the structure error on MOFs' properties will be presented. Since the situation of structure error in MOFs' producing is complex and unexpected, the random model is more reasonable to instruct MOFs' designing and producing.

# 3. Results and discussion

## 3.1. The confinement loss

The work done by White[18,21,22] means that we know how to choose proper cross section parameters such as the ring number, the diameter of air holes, $d$, the hole spacing, $\Lambda$, and their diameter to spacing ratio, $d/\Lambda$, for the sake of designing a low confinement loss fibre. However, because of the reason mentioned above, the actual fibre's loss is different from that of the designed one. A three-ring hexagonal MOF with solid core region is chosen to study the difference. Figure 1 illustrates the transverse geometry structure of this MOF. We calculate the confinement loss of the fundamental mode for a 36-holed MOF with cladding refractive index $n_e$=1.44402, a hole spacing of $\Lambda$=4$\mu$m, wavelength $\lambda$=1550nm and diameter to spacing ratio $d/\Lambda$=0.6. When there is no disturbance, its confinement loss is about 0.03dB/km ($\mathrm{Re}(n_{\mathrm{eff}}) = 1.432864441 \pm 10^{-9}$ $\mathrm{Im}(n_{\mathrm{eff}})=(8.430\pm0.001)10^{-13}$).

Then the loss of the MOFs with different extents of disturbance is calculated by multipole methods[14,17] and some useful results that conduce to the fabrication of MOFs can be obtained.

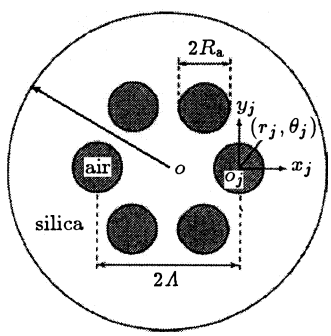



**Fig.1.** Transverse geometry of MOFs.

After calculating the MOFs' confinement loss for dozens of times at each extent of structure disturbance, we obtained the six curves of Fig.2(a). We set disorder range (%) as $X$ axis and the MOFs' confinement loss (dB) as $Y$ axis. So each spot with coordinates $(x, y)$ means a specific extent of structure disturbance which is diametric disturbance or positional disturbance. Five hundred loss values at the same disturbance extent is calculated. The statistic histogram of the 500 spots with 5% diametric disorder is shown in Fig.2(b). We accounted the number of the spots by confinement loss from 0.024 to 0.038dB/km with a step 0.0005 dB/km. The confinement loss is set as $X$ axis and the statistic number as $Y$ axis and the sum of all rectangle numbers is 500. The result in Fig.2(b) shows that the spots are about normal distribution. The spots with different disturbance extents constitute some areas with two conspicuous borders. In Fig.2(a) curve $c$ and curve $d$ are the borders of the area constituted by diametric disturbance spots, curve $e$ and curve $f$ are the borders of the area constituted by positional disturbance spots. Curve $a$ and curve $b$ are obtained by different method which is described in the following.

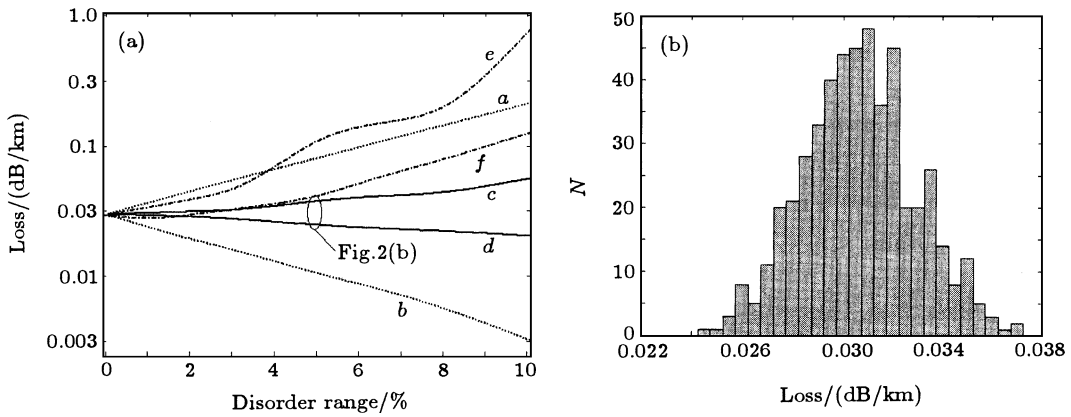



**Fig.2.** The confinement losses of MOFs as a function of the disorder of the holes' diameters and positions, with $\Lambda$=4$\mu$m, $n_e$=1.44402, $\lambda$=1550nm and 3 rings of holes. In Fig.2(a), curve a is the upper limit of the confinement losses in theory only with the disorder of the holes' diameters, curve $b$ is the lower limit in that condition. Curve $c$ and curve $d$ are the upper and the lower limits of the confinement losses simulated by multipole method only with the random disturbances of the holes' diameters. Curve $e$ and curve $f$ are the upper and the lower limits of the confinement losses simulated by multipole method only with the random disturbances of the holes' positions. Figure 2(b) is a statistic histogram of the spot between curve $c$ and curve $d$ at 5% disorder.

In Fig.2(a), three groups of curves show the following results. The confinement loss is in inverse proportion to air spacing average ratio. If the effect of diametrical disturbance makes air spacing average ratio enlarged, the MOFs' confinement loss will decrease. On the contrary, it will increase. Basing on this rule, we can obtain curve $a$ and curve $b$ as the upper and the lower limit of the confinement loss in theory only with the disorder of the holes' diameter.

It is obvious that the deviation of loss (the range between curve $c$ and curve $d$) is much less than the theoretical one (the range between curve $a$ and curve $b$). The reason is that, by introducing random disturbance, the probability of reaching the limit of disturbance is very small (for MOFs with three rings, the probability is less than $10^{-36}$, of all holes diametrical variation larger than 95% of the max limit or all less than 95% of the min limit). Generally, the increscent will counteract the contractive. So, besides actual loss curves must lie between curve $a$ and curve $b$. Curve $c$ and curve $d$ show the random disturbance of the holes' diameter. The probability of an actual MOF's loss between curve $c$ and curve $d$ is larger than 99.99%. So we regard the two curves as the most upper and the lower limits of the actual confinement loss.

Another aspect, the loss deviation only with the disorder of the holes' positions is much larger than the diametrical simulated one, also the diametrical theoretical one. Curve $e$ and curve $f$ show that the positional disturbances only increase MOFs' confinement loss, and the extent of increment is much more than the one caused by diametrical disturbances. When the degree of disturbances is over 3%, as shown in curve $f$, the lower limits of the confinement loss simulated by multipole methods only with the disorder of the holes' positions will exceed the diametrical simulated upper limit (curve $c$). When the degree of disturbances is larger than 4% (curve $e$), the upper limits of the confinement loss with positional disorders, will exceed the diametrical random disturbance theoretical upper limit (curve $a$), and increase more and more rapidly. As an example of concrete data, the no-disturbance loss is 0.0297dB/km. When the extent of disturbance is 5%, the max loss in diametrical disturbance simulation is 0.0375dB/km and the max loss of theoretical calculation is 0.0805dB/km, but the max loss in positional disturbance simulation reaches 0.116dB/km.

Figure 2(a) shows that diametrical disturbances make the confinement loss increase or decrease. However, positional disturbances make it increase and the effect is more prominent than the diametrical ones. As a result, in order to get the MOFs with the designed confinement loss properties, we should pay more attention to holes positional accuracy than to their diametrical accuracy.

### 3.2. The chromatic dispersion

As we know that once the modal effective index is solved, the dispersion properties can be readily obtained by[28]

$$D = -\frac{\lambda}{c}\frac{\mathrm{d}^2\Re(n_{\mathrm{eff}})}{\mathrm{d}\lambda^2}, \qquad (1)$$

where $c$ is the velocity of the light in a vacuum and $\lambda$ is the operating wavelength. To validate the fundamental mode solver, the dispersion properties of a MOF with $\Lambda$=2.3$\mu$m, $d/\Lambda$=0.6 and silica cladding are calculated. The silica refractive index follows from the Sellmeier equation. By varying the wavelength $\lambda$ with the step 5nm, we obtained the corresponding effective index $n_{\mathrm{eff}}$ was obtained. The dispersion curve can be worked out by Eq.(1).

A full dispersion curve of MOFs with three rings of holes is shown in Fig.3. Compared with the dispersion curve with the same structure as that calculated by White, there is a good agreement. The material dispersion can be obtained directly from the three-term Sellmeier formula.

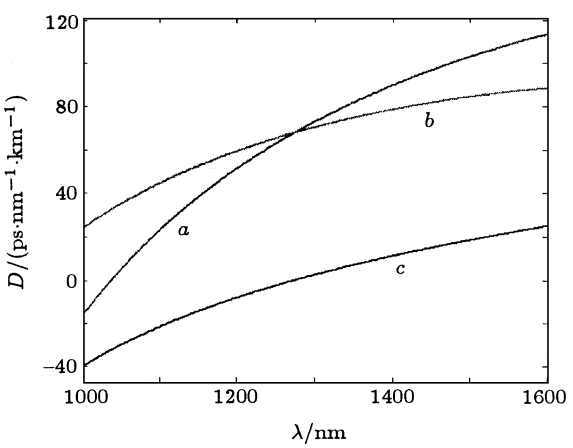



**Fig.3.** The chromatic dispersion of the MOF with $\Lambda$=2.3$\mu$m, $d/\Lambda$=0.6, and three rings of holes. Curve $a$ is the sum of cure $b$ and curve $c$. Curve $b$ is material dispersion from the Sellmeier model for silica, and curve $c$ is the waveguide dispersion of MOFs.

The dispersion curve with three rings of holes has been closed to convergent, so a 3-ring MOF is selected and other structure parameters are given by $\Lambda$=4$\mu$m, $n_{\mathrm{e}}$=1.44402, $\lambda$=1550nm and $d/\Lambda$=0.6. The extent of disturbance is 1%, 2%, 5% and both positional and diametrical will be considered.

The curves in Fig.4 except curve a are obtained by the same method as that of curve $c$ and curve $d$ in Fig.2(a). 300 dispersion curves with 1%, 2% and 5% random diametric disturbance constitute strips whose boarders are curve $b$ to curve $g$. As shown in the Fig.4(a), the shapes of the dispersion curves only with diametric disorder are similar to the one without disorder. As the extent of increasing disorder, the difference between the upper limit and the lower limit becomes larger. In Fig.4(a), at $\lambda$=1550nm, the dispersion without disorder is 57.20ps/(nm·km) (calculated from Eq.(1), the upper and lower limits dispersion with 1% diametric disorder are 57.21 and 56.97 ps/(nm·km). The upper and lower limits dispersion with 2% diametric disorder are 57.22 and 56.87 ps/(nm·km). The upper and lower limits dispersion with 5% diametric disorder are 57.27 and 56.80ps/(nm·km) and Fig.4.(c) is the statistic histogram of this dispersion area. Figure 4(c) show that most of dispersion values are about 57.15ps/(nm·km) and the distributing is about normal distribution.

We also calculate dozens of dispersion curves with 5% random positional disturbance, but as these curve is more different from the one without disorder, a typical one (curve $d$) is selected in Fig.5(a).

As shown in Fig.5(a), it is obvious that the deviation of the dispersion curve $d$ caused by positional disturbance is much greater than the one caused by diametrical disturbance. There is little difference between curves $a$, $c$ and $b$, but an obvious difference between curve $d$ and curve $b$. So it can be seen that MOFs' dispersion is more sensitive to positions of their holes than to the diameters. The dispersion curves with different disorder extents(1%, 2% and 5%) are given in Fig.5.(b). Their shapes are alike but quite different from the one without disorder. As increasing positional disorder the dispersion curves distort more seriously. In order to get a MOF with designed dispersion properties, we should also pay more attention to holes positional accuracy.

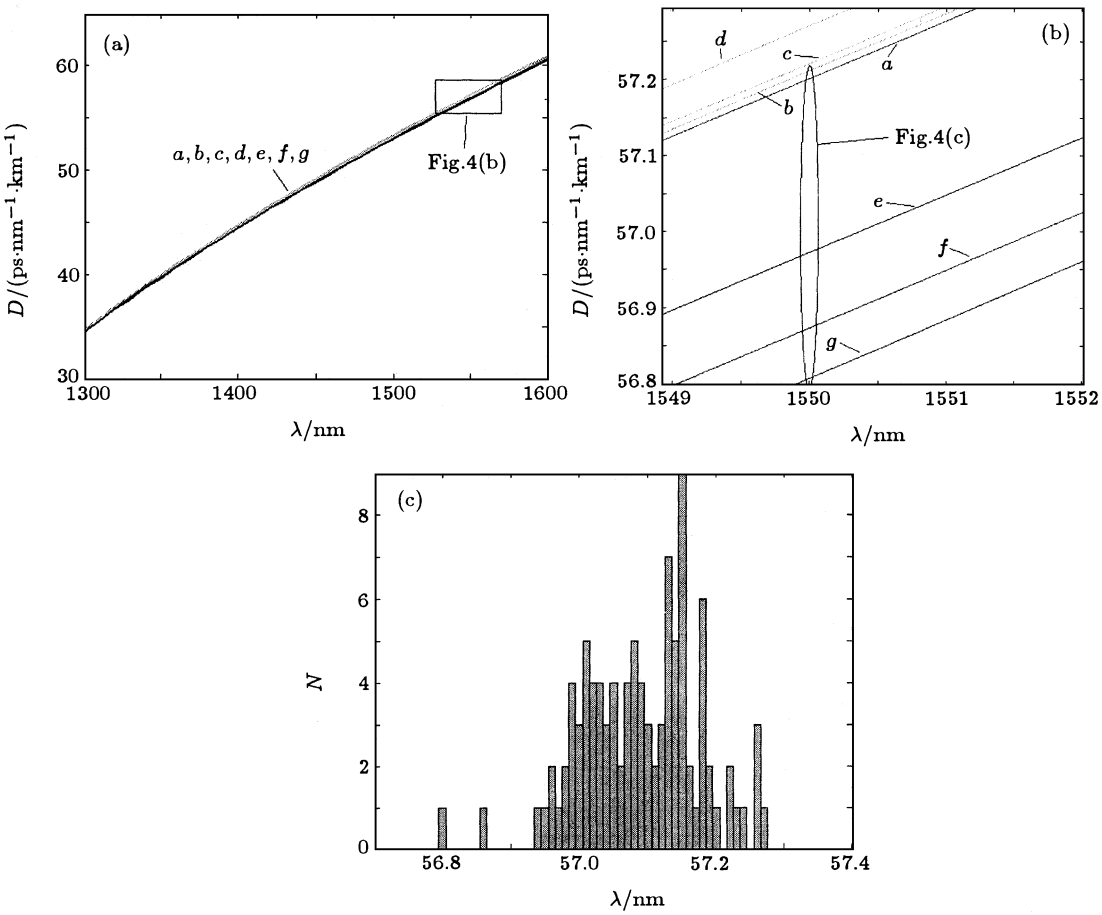



**Fig.4.** The chromatic dispersion of MOFs by multipole methods only with the disorder of the holes' diameters under different conditions. Curve $a$ is the chromatic dispersion without disorder. Curve $b$ and curve $e$ are the upper and the lower limits of the chromatic dispersion under the condition of 1% random diametric disturbance. Curve $c$ and curve $f$ are the upper and the lower limits of the chromatic dispersion under the condition of 2% random diametric disturbance. Curve $d$ and curve $g$ are the upper and the lower limits of the chromatic dispersion under the condition of 5% random diametric disturbance. Figure 4(b) is the details of Fig.4(a). Figure 4(c) is the statistic histogram of the dispersion result after simulating 100 times at 1550nm with 5% diametric disorder.

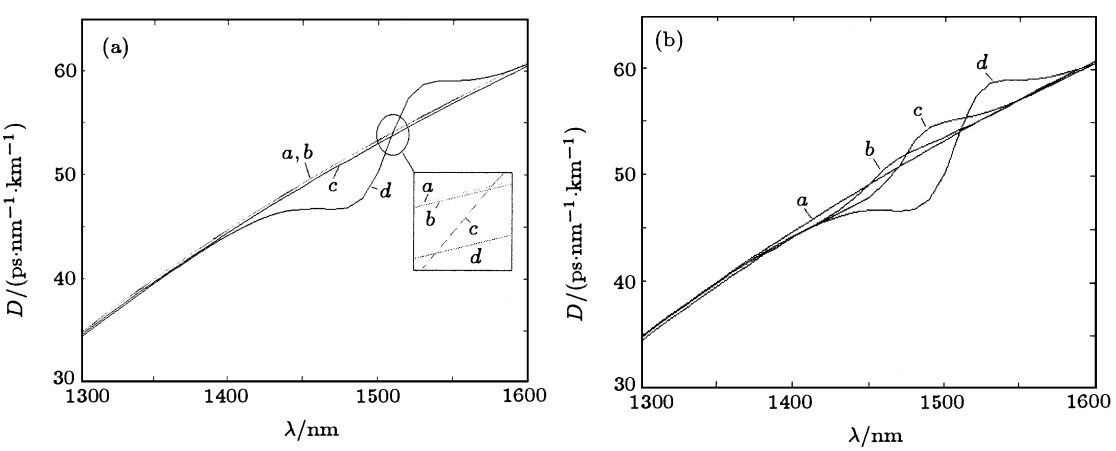



**Fig.5.** The chromatic dispersion of MOFs under different conditions. Curve $a$ and curve $c$ in Fig.5(a) are the upper and the lower limits of the chromatic dispersion by multipole methods only with the disorder of the holes' diameters. Curve $b$ in Fig.5(a) and Curve $a$ in Fig.5(b) are the chromatic dispersion without disorder. Curve $d$ in Fig.5(a) and Fig.5(b) are the representative of the dispersion curves only with 5% disorder of the holes' positions. Curve $b$ and curve $c$ in Fig.5(b) are the representative of the dispersion curves only with 1% and 2% disorder of the holes' positions.

## 4. Conclusion

This work combines multipole methods with random statistics to show the effect of random disturbance error of fibres' fabrication on the MOFs' loss and the chromatic dispersion. As a result, positional accuracy is more important in fabrication of MOFs. In order to obtain a MOF with the designed loss and dispersion properties, more attention should be paid to holes' positions than to their diameters.

## References


[1] Birks T A, Knight J C and Russell P St J 1997 *Opt. Lett.* **30** 961

[2] Birks T A, Mogilevtsev D, Knight J C and Russell P St J 1999 *IEEE Photon. Technol. Lett.* **11** 674

[3] Ranka J K, Windeler R S and Stentz A J 2000 *Opt. Lett.* **25** 796

[4] Ortigosa-Blanch A, Knight J C, Wadsworth W J, Arriaga J, Mangan B J, Birks T A and Russell P S J 2000 *Opt. Lett.* **25** 1325

[5] Knight J C, Arriaga J, Birks T A, Ortigosa-Blanch A, Wadsworth W J and Russell P St J 2000 *IEEE Photon. Technol. Lett.* **12** 807

[6] Wadsworth W J, Knight J C, Ortigosa-Blanch A, Arriaga J, Silvestre E and Russell P St J 2000 *Electron. Lett.* **36** 53

[7] Ferrando A and Miret J J 2001 *Appl. Phys. Lett.* **78** 3184

[8] Liu X, Xu C, Knox W H, Chandalia J K, Eggleton B J, Kosinski S G and Windeler R S 2001 *Opt. Lett.* **26** 358

[9] MoInro T M, Belardi W, Furusawa K, Baggett J C, Broderick N G R and Richardson D J 2001 *Meas. Sci. Technol.* **12** 854

[10] Li S G, Ji Y L, Zhou G Y,Liu X D and Hou L T 2004 *Acta Phys. Sin.* **53** 478 (in Chinese)

[11] Hu M L, Wang Q Y, Li Y F *et al* 2004 *Acta Phys. Sin.* **53** 4243 (in Chinese)

[12] Belov A V and Dianov E M 2002 *Quantum Electron.* **32** 641

[13] Kerbage C and Eggleton B J 2002 *Opt. Photonics News* **13** 38

[14] Omenetto F G, Efimov A, Taylor A J, Knight J C, Wadsworth W J and Russell P S J 2003 *Opt. Express* **11** 61

[15] Kuhlmey B, Renversez J and Maystre D 2003 *Appl. Opt.* **42** 634

[16] Liu X D, Xu X S, Wang Y Q, Zhang D Z and Cheng B Y 2003 *Chin. Phys.* **12** 992

[17] Ren G B, Wang Z, Lou S Q and Jian S S 2004 *Acta Phys. Sin.* **53** 2600 (in Chinese)

[18] White T P, McPhedran R C, Sterke C M and Steel M J 2001 *Opt. Lett.* **26** 1660

[19] Zhu Z M and Thomas G B 2002 *Opt. Commun.* **206** 333

[20] Ren G B, Wang Z, Lou S Q and Jian S S 2004 *Acta Phys. Sin.* **53** 1862 (in Chinese)

[21] Kuhlmey B T, White T P, McPhedran R C, Maystre D, Renversez G, Sterke C M and Botten L C 2002 *J. Opt. Soc. Am.* B **19** 2331

[22] White T P, Kuhlmey B T, McPhedran R C *et al* 2002 *J. Opt. Soc. Am.* B **19** 2322

[23] Ferrando A, Silvestre E, Miret J J, Andr'es P and Andr'es M V 2000 *J. Opt. Soc. Am.* B **17** 1333

[24] Ren G B, Wang Z, Lou S Q and Jian S S 2004 *Acta Phys. Sin.* **53** 484 (in Chinese)

[25] Koshiba M and Saitoh K 2001 *IEEE Photon Technol. Lett.* **13** 1313

[26] Wang H and Li Y P 2001 *Acta Phys. Sin.* **50** 2172 (in Chinese)

[27] Yang S G, Zhang Y j, Peng X Z *et al* 2004 *SPIE* **5623** 105

[28] Agrawal G 1995 *Nonlinear Fiber Optics* (New York: Academic)