Research on the stability of nearly zero flattened dispersion of photonic crystal fibers

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To analyze the stability of nearly zero flattened dispersion, the dispersion deviations for three kinds of PCFs are calculated when the hole diameters deviate from their designed values. Numerical results show that around the wavelength of 1.55 μm, the dispersion deviations of both the PCF with three-fold symmetry core and the PCF with hexagonal lattice are much less than that of the PCF with different hole diameters in different rings. Therefore, the stabilities of nearly zero flattened dispersion of the first two kinds of PCFs are much better than that of the last one. Considering the confinement loss, the PCF with three-fold symmetry core is preferable to practical use.

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Photonic crystal fibers (PCFs) possess the property to tailor the dispersion curves flexibly. By varying the hole diameters and the pitch, it is possible to change zero-dispersion wavelength[1] or engineer the dispersion curve to be flattened[2]. The PCFs with nearly zero flattened dispersion are so meaningful to improve the capabilities of optical fiber communication systems that many attentions have been drawn[3-7].

So far, the nearly zero flattened dispersion PCFs with different structures have been designed. The hexagonal PCF is first designed by Ferrando et al[3]. To obtain low confinement loss, more than twenty air-hole rings are necessary, which is difficult to be manufactured. So, a PCF with less rings has been presented by Hasen[4]. The PCF is not only the nearly zero flattened dispersion but also highly nonlinear. Recently, the PCFs with only four or five rings have been successfully designed[5-7]. The low confinement loss in the PCFs is realized by increasing hole diameters from inner to outer rings.

For the PCFs designed in Ref.[3~7], dispersion parameter between ± 0.5 ps·km^{-1}·nm^{-1} in the wavelength range of at least 200 nm is realized around 1.55 μm. But the PCF structures usually deviate from their designed ones during the fabrication, which have an impact on the dispersion properties. Then, the stabilities of nearly zero flattened dispersion have to be considered. It is important and necessary to compare and judge which PCF has more stable dispersion when hole diameters deviate from their designed values.

In this paper, the stabilities of nearly zero flattened dispersion are studied for the first time, to our knowledge. The dispersion deviation is calculated by using the full-vector finite element method (FEM)[8-10] and the error theory. And the PCF which is preferable to practical use is selected in consideration of the confinement loss.

The dispersion parameter could be calculated by

$$D = -\frac{\lambda}{c}\frac{d^2 n_{\text{eff}}}{d\lambda^2} \tag{1}$$

where n_{eff} is the effective index of the fundamental mode, λ is the operating wavelength and c is the velocity of light in vacuum.

The dispersion deviation is related to the hole diameters and the pitch. At present, the percentage of variation in pitch can be controlled under 2% during the fabrication[4]. Under the amount, the dispersion has been proved to be robust[11]. So, only the deviation of the hole diameters can be taken into account when the dispersion deviation is calculated.

If the standard deviation of the i-th hole diameter, S_{d_i}, is given, the standard deviation of dispersion, S_D, can be calculated by:

$$S_D = \sqrt{\sum_{i=1}^{n}\left(\frac{\partial D}{\partial d_i} S_{d_i}\right)^2} \tag{2}$$

where d_i is the i-th hole diameter, n is the total number of the cladding holes. $\partial D/\partial d_i$ is the derivative of dispersion parameter with respect to the i-th hole diameter and represents the effect of the i-th hole on dispersion. According to formula (2),

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the effects of deviations of the hole diameters on dispersion are able to be evaluated.

The PCF with four hole rings[5] is typical of the nearly zero flattened dispersion fiber with different air-hole diameters in different rings. The cross section of the PCF is shown in Fig.1, where the pitch Λ is 0.9 μm and the ratio of the air-hole diameter to the pitch is 0.42, 0.86, 0.93 and 0.70 from the first to the fourth ring, respectively.

At first, the effects of the air holes in the first ring on dispersion are analyzed. To compute $\partial D/\partial d_1$, D is calculated when the d_1 is increased and decreased 5% and 10% of its designed value, respectively, while all the other hole diameters are kept constant. The slope of the fitted curve of D with respect to d_1 gives the value of $\partial D/\partial d_1$. $\partial D/\partial d_2$ can be obtained in the same way. At the wavelength of 1.50, 1.55 and 1.60 μm, $\partial D/\partial d_1$ and $\partial D/\partial d_2$ for the x-polarized and y-polarized fundamental mode, respectively, are listed in line 2 to 5 of Tab. 1. Due to the symmetry of the structure, $\partial D/\partial d_3=\partial D/\partial d_4=\partial D/\partial d_6=\partial D/\partial d_1$ and $\partial D/\partial d_5=\partial D/\partial d_2$[8].

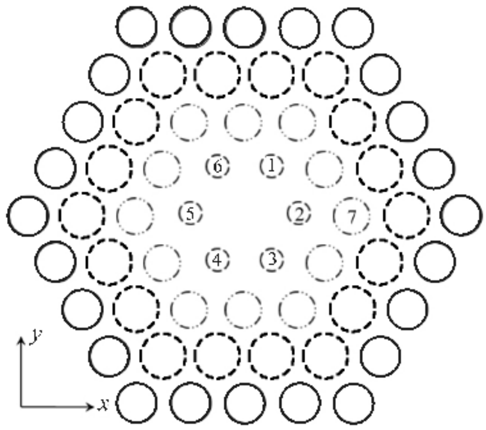

Fig.1 Cross section of the PCF with different air-hole diameters for different rings[5]

Tab.1 Numerical results when the hole diameters deviate from the designed values [5]

Wavelength λ/μm	1.50	1.55	1.60
$\partial D/\partial d_1$ (x-polarization)	-109.83	-115.56	-120.20
$\partial D/\partial d_1$ (y-polarization)	-135.06	-142.04	-147.97
$\partial D/\partial d_2$ (x-polarization)	-135.10	-142.18	-149.86
$\partial D/\partial d_2$ (y-polarization)	-107.36	-113.09	-117.82
S_D/S_d (x-polarization)	291.1	306.3	320.5
S_D/S_d (y-polarization)	309.9	326.0	339.6
Dispersion deviation ΔD (ps·km^{-1}·nm^{-1})(x-polarization)	± 5.50	± 5.79	± 6.06
Dispersion deviation ΔD (ps·km^{-1}·nm^{-1})(y-polarization)	± 5.86	± 6.16	± 6.42

Then the effects of the holes in other three rings on dispersion are analyzed. Because the holes in the second ring are farther from the core, the effects on dispersion should be less than that of the holes in the first ring. It is proved by numerical results. For example, for hole 7, $\partial D/\partial d_7$=10.28 and 13.45 at 1.55 μm for the x-polarized and y-polarized fundamental mode, respectively. $\partial D/\partial d_7$ is 10 times lower than the absolute value of $\partial D/\partial d_1$ and $\partial D/\partial d_2$. So, the effects of hole 7 on dispersion can be neglected. other holes in the second ring are similar to hole 7. When diameters other holes in the third and fourth rings deviate from their designed values, the dispersion deviations are shown to be even less. Therefore, $\partial D/\partial d_i$ (i=7, 8,⋯, n) can be neglected.

If $S_{d_1}=S_{d_2}=\cdots=S_{d_6}=S_d$, applying eg.(2), S_D/S_d can be calculated for the two polarized fundamental modes around 1.55 μm, and are listed in line 6 and 7 of Tab.1. When the ratio of the standard deviation of the hole diameter to its designed value is 5%, i.e. S_d/d_1=0.05, the dispersion deviation, ΔD, can be calculated and are listed in the last two lines of Tab.1.

The hexagonal PCF[3] and the PCF with the three-fold symmetry core[4] are two typical of the nearly zero flattened dispersion PCFs with same air-hole diameters. Both PCFs will be researched in the following.

The cross section of the PCF with three-fold symmetry core is shown in Fig.2. For simplicity, the PCF made of pure silica is studied in this paper. A nearly zero flattened dispersion PCF is designed, and then the effects of the air holes on dispersion are analyzed.

Numerical results show that when Λ is about 1.6 μm and d/Λ is about 0.3, the dispersion tends to be zero and to be flattened around 1.55 μm. Three dispersion curves are shown in Fig.3. At 1.55 μm, the dispersion is 2.7 and -1.4 ps·km^{-1}·nm^{-1}for the structure with Λ = 1.63 μm and d=0.49 μm, and the structure with Λ = 1.60 μm and d=0.46 μm, respectively. In addition, for the structure with Λ=1.64 μm and d=0.46 μm, the dispersion is between ±0.5 ps·km^{-1}·nm^{-1} in the wavelength range of 1.47-1.63 μm. So, the PCF with the third structure has nearly zero flattened dispersion property. The following is the analysis about the third structure.

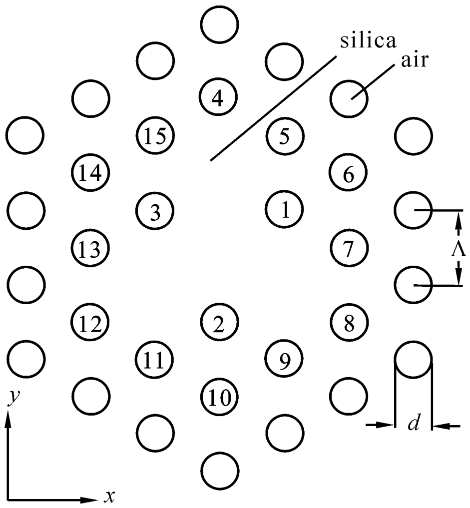

Fig.2 Cross section of the PCF with three-fold symmetry core

At first, the effects of hole 1, 2 and 3 on dispersion are analyzed. Due to the symmetry of the structure, the effects of hole 1 and 3 on dispersion are the same, i.e. $\partial D/\partial d_3=\partial D/\partial d_1$

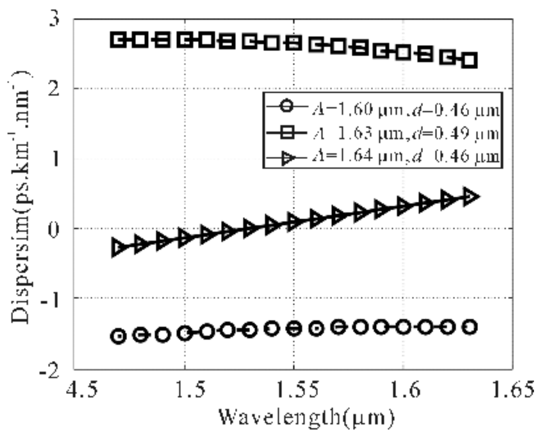

Fig.3 Dispersion curves of the PCF with three-fold symmetry core

, so it is enough to calculate $\partial D/\partial d_1$ and $\partial D/\partial d_2$. At the wavelength of 1.50, 1.55 and 1.60 μm, $\partial D/\partial d_1$ and $\partial D/\partial d_2$ for the x-polarized and y-polarized fundamental mode are calculated and listed in line 2 to 5 of Tab.2.

Then, the effects of the holes except hole 1, 2 and 3 on dispersion are analyzed. Numerical results show that $\partial D/\partial d_i$ (i=4, 5, ⋯, n) is at least 10 times lower than the absolute values of $\partial D/\partial d_1$ and $\partial D/\partial d_2$, and can be neglected. For example, at 1.55 μm, for the x-polarized and y-polarized mode, $\partial D/\partial d_4$= 2.2, 3.0, $\partial D/\partial d_7$= 1.3, 3.5.

Tab.2 Numerical results when the hole diameters deviate from the designed values of the PCF with three-fold symmetry core

Wavelength λ/μm	1.50	1.55	1.60
$\partial D/\partial d_1$ (x-polarization)	-25.818	-29.695	-33.351
$\partial D/\partial d_1$ (y-polarization)	-25.333	-29.173	-32.818
$\partial D/\partial d_2$ (x-polarization)	-25.620	-29.219	-34.139
$\partial D/\partial d_2$ (y-polarization)	-26.429	-30.342	-32.925
S_D/S_d (x-polarization)	44.60	51.16	59.12
S_D/S_d (y-polarization)	44.56	51.21	57.24
Dispersion deviation ΔD (ps·km^{-1}·nm^{-1})(x-polarization)	± 1.02	± 1.18	± 1.36
Dispersion deviation ΔD (ps·km^{-1}·nm^{-1})(y-polarization)	± 1.02	± 1.18	± 1.32

If $S_{d_1}=S_{d_2}=S_{d_3}=S_d$, applying eg.(2), S_D/S_d can be calculated for the two polarized fundamental modes around 1.55 μm, and are listed in line 6 and 7 of Tab.2. When S_d/d_1=0.05, ΔD for x-polarization and y-polarization can be calculated and are listed in the last two lines of Tab.2.

The structure parameters of the hexagonal PCF are: the pitch Λ = 2.62 μm and the hole diameter d=0.64 μm[3]. In the same way, the effects of the air holes on dispersion can be analyzed. And the results, S_D/S_d and ΔD for the two polarized modes, are listed in Tab.3.

Tab.3 Numerical results when the hole diameters deviate from the designed values of the hexagonal PCF[3]

Wavelength λ/μm	1.50	1.55	1.60
S_D/S_d (x-polarization)	7.469	12.78	18.55
S_D/S_d (y-polarization)	11.78	17.10	22.70
Dispersion deviation ΔD (ps·km^{-1}·nm^{-1})(x-polarization)	± 0.235	± 0.403	± 0.584
Dispersion deviation ΔD (ps·km^{-1}·nm^{-1})(y-polarization)	± 0.371	± 0.539	± 0.715

In the above research, the effects of the holes on dispersion for three kinds of PCFs have been analyzed. Numerical results show that from 1.50 to 1.60 μm, the dispersion deviation for the fundamental mode is between ±1.4 and ±0.72 ps·km^{-1}·nm^{-1} for the PCF with three-fold symmetry core and the hexagonal PCF, respectively, while the dispersion deviation is between ± 6.4 ps·km^{-1}·nm^{-1} for the PCF with different air-hole diameters in different rings. Therefore, the stability of nearly zero flattened dispersion of the PCF with the same air-hole diameters is much better than that of the PCF with different air-hole diameters in different rings.

In fact, the fabrication difficulties have to be considered besides the stability of nearly zero flattened dispersion. Although the stability of nearly zero flattened dispersion of the hexagonal PCF is the best, more than twenty hole rings are necessary to make the confinement loss be the same as the loss of conventional fiber. The holes are so many that they usually collapse during the drawing. The collapsed holes will cause the increase of the confinement loss. However, the PCF with three-fold symmetry core has better stability of nearly zero flattened dispersion, and the holes are less than half of those of the hexagonal PCF in particular. With such less holes, the hole collapse can be avoided greatly. So, the PCF with three-fold symmetry core is preferable.

In conclusion, the effects of the air hole diameters on nearly zero flattened dispersion of three kinds of PCFs are studied in this paper. The stability of nearly zero flattened dispersion of the hexagonal PCF is the best, that of the PCF with three-fold symmetry core is better, and that of the PCF with different hole diameters in different rings is the worst of all the three. Because the hexagonal PCF with low confinement loss is difficult to fabricate, the PCF with three-fold symmetry core is preferable to practical use.

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