The study of a kind of photonic crystal fiber grating based on structural change

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Abstract. A kind of novel photonic crystal fiber grating based on structural change was studied, the effective refractive index induced by structural change was computed using Multipole Method, the relationship between the effective refractive index and the shrinkage of air-holes was got. Moreover, the fabrication principle was proved in the mathematics way. A model of photonic crystal fiber grating based on structural change was built, the transmission characteristics were analysed with Coupled Mode Theory. The emphasis of this study was the impacts of the rings of air-holes in the cladding, the rings of air-holes shrinkage and the degree of air-holes shrinkage on the transmission characteristics. The research results indicate that the periodic air-holes shrinkage can form grating, not only the degree of air-holes shrinkage, but also the shrinkage envelope has important effect on the magnitude and the distribution of the effective refractive index; the resonance wavelength, the resonance bandwidth and the intensity have relations to the rings of air-holes in the cladding, the rings of air-holes shrinkage, and the degree of air-holes shrinkage.

1. Introduction
Fiber grating (FG), as a kind of important passive optical device, has many advantages, such as compact size, light weight, low loss and easy to be integrated with the fiber system, so it is widely used in the fields of tunable lasers, optical add-drop multiplexers, fiber sensors, dispersion compensation [1-4]. The conventional fiber grating is written with the UV exposure method. Using the phase mask, the photosensitive fiber or the single mode fiber loaded hydrogen is written into the gratings. At present, the UV exposure method is a mature technology and easy to be operated, but the disadvantages of the fiber grating made by this method are obvious. For example, the gratings will undergo degeneration in the condition of long-term working and high temperature environment [5]. The instability of performance impedes the applications of fiber grating in many fields.

The invention and rapid improvement of photonic crystal fiber (PCF) present a new solution. After analyzing the advantages and disadvantages of the conventional fiber grating, this paper studied a kind of novel fiber grating, namely, photonic crystal fiber grating (PCFG). It need neither doping B/Ge in the core of PCF during the fiber producing process nor loading hydrogen before the fabrication of PCFG, it can be engendered by changing the structure of PCF. Thereby, this kind of PCFG based on structural change can overcome the shortcomings of long-term instability and thermal instability of the conventional fiber grating, it will have many potential applications in the long-term health estimation system or the special safety monitoring system of the big structure [6], such as the bridges, the dams and the oil storages.
2. The fabrication technique and principle analysis

2.1. The fabrication technique of PCFG based on structural change

PCF, generally called microstructured optical fiber (MOF) or holey fiber (HF) [7], is constructed by the homogeneous medium (pure SiO$_2$ or polymerized substance) and the air-holes orderly arranged or out-of-orderly arranged. In the core of PCF, there is a defect center (solid core or hollow core). According to the different principle of transmitting light, PCF is divided into two types, the total internal reflective PCF (TIR-PCF) and the photonic bandgap PCF. The transmission performance of PCF is determined by the size and arrangement of the air-holes in the cladding, the space between the air-holes and the type of the fiber core.

In 2003, Yinian Zhu of Nanyang Technological University of Singapore proposed the grating fabrication in PCF using CO$_2$ laser beam [8]. When a focused CO$_2$ laser beam notched periodically on the surface of PCF, the effective refractive index of the cladding would become periodic change, it was the reason of forming grating. The principle of this method was similar to the UV exposure method, which introduced the refractive index perturbation into the core of the fiber. In 2004, Lim J. H. presented the grating fabrication method in PCF using mechanical pressure. The equipment was composed of two plates, either of them had parallel plow grooves. The PCF was fixed between the two plates, using elastic-optic effect, the perturbation of refractive index was got at the pressure point, which could cause to form grating in the PCF.

As for the research of PCFG based on structural change, the present references just gave the description about the technique, and did not prove the principle from the standpoint of the mathematics [9]. Using Multipole Method and Coupled Mode Theory, with focus on the change of the effective refractive index brought by air-holes shrinkage, this paper analyzed the forming grating principle from the mathematic way.

2.2. The fabrication principle of PCFG based on structural change

When a CO$_2$ laser light beam heated a PCF with the properly designed period, spot, power and duration, the PCF would collapse with the certain period, depth of concavity and envelope profile. The deformation of the collapsed PCF in the longitudinal direction was such as the figure 1. $L$ was the length of PCFG. $\Lambda$ was the period of the air-holes shrinkage, it was also the period of PCFG. $w$ was the width of the collapse segment, which was determined by the size of the laser spot. $m$ was the collapse depth, which was determined by the power and duration of the CO$_2$ laser beam. The collapsed envelope profile was depended on the shape of the laser spot.

![Figure 1. The PCF with the shrunken air-holes.](image)

Using Multipole Method [10,11], this paper computed and compared the change of the effective refractive index induced by structural change in the collapse rules of sine curve and rectangular curve, and got the data of the effective refractive index. The figure 2 showed the relationship curves of the effective refractive index vs. the diameter of the shrunken air-holes. In the figure 2, the abscissa represented the diameter of the shrunken air-holes. The smaller the value was, the more seriously the air-holes shrunk. From left to right, the degree of the air-holes shrinkage decreased gradually, the effective refractive index showed a downtrend. Compared with the instance of the rectangular curve envelope function, the effective refractive index of sine curve envelope function descended smoothly and slowly. However, in the rule of rectangular curve, the effective refractive index sloped gently when the degree of air-holes shrinkage was serious, then it showed a rapid downtrend till the two $n_{eff}$
curves overlapped. The results of this study indicate that the more seriously the air-holes shrink, the bigger the effective refractive index is. Not only the degree of air-holes shrinkage, but also the shrinkage envelope has effect on the magnitude and the distribution of the effective refractive index.

Figure 2. The curves of the effective refractive index vs. the diameter of the shrunken air-holes.

Using the data in the figure 2, the distribution function of the effective refractive index in the collapse segment could be obtained. Taking the typical sine curve envelope function as an example, this paper accomplished curve fitting with 5 orders for the effective refractive index, the distribution function expression along the longitudinal direction was

\[ f(z) = \sum_{k=0}^{5} a_k e^{iz} \quad \frac{W}{2} \leq z \leq \frac{W}{2} \]  

(1)

Here \( a_k \), the coefficient of the series expansion, was determined by the following Matrix \( A \).

\[ A = \begin{bmatrix} 1.138e+007, 5.581e+007, 1.636e+008, -3.187e+008, 4.331e+008, -4.189e+008 \end{bmatrix} \]  

(2)

If the effective refractive index of PCF was uniform distribution along the radial direction, the distribution model of sine curve envelope function was built such as the figure 3.

Figure 3. The distribution model of the effective refractive index in PCFG.

In the figure 3, \( n_0 \) was the effective refractive index of PCF. \( \Delta n_{\text{eff}} \) was the maximum of the effective refractive index in the collapse segment of PCFG, which was the modulation amplitude. Then \( n(z) \) could be written as

\[ n(z) = \begin{cases} n_0 + f(z) & kA - \frac{W}{2} \leq z \leq kA + \frac{W}{2} \\ n_0 & kA - \frac{W}{2} > z, z > kA + \frac{W}{2} \end{cases} \]  

(3)

Here, \( k \) was an integer. After putting the equation (1) into the equation (3) and doing Fourier series expansion, the expression including the top 5 orders was

\[ n(z) = n_0 + \sum_{k=0}^{5} b_k \cos \left( \frac{2\pi}{A}z \right) \]  

(4)
In the expression, $b_k$, the coefficient of the Fourier series expansion, was determined by the following Matrix $B$.

$$ B = \begin{bmatrix} 1.435, & -0.008822, & -0.0002008, & -0.1478305, & -0.0001246, & -0.0004898 \end{bmatrix} $$

(5)

According to Coupled Mode Theory, the coupled coefficient $C_q$ [12] between the $q$ order mode and the fundamental mode was

$$ C_q = \zeta_q(z) + 2k_q(z) \sum_{k=0}^{\infty} c_k \cos \left( k \frac{2\pi}{A} z \right) $$

(6)

In the equation (6), $\zeta_q(z)$ and $k_q(z)$ were defined as the self-coupling coefficient and the mutual-coupling coefficient respectively. They were determined by the following equations [12].

$$ \begin{align*}
\zeta_q(z) &= \frac{\Delta n_{eff}}{2} \int \int_{\Omega} e_q(x,y) \cdot e_{core}(x,y) \, dx \, dy \\
\frac{k_q(z)}{2} &= \zeta_q(z) 
\end{align*} $$

(7)

Here, $e_q(x,y)$ was electric field distribution of the $q$ order mode in the cladding, $e_{core}(x,y)$ was electric field distribution of the fundamental mode. $\Omega$ was the overlap area of the both electric field, $s$ was the visibility of grating fringe, this paper let $s = 0.6$. Putting the equation (6) and (7) into the coupled mode equations and solving them, the normalized amplitude and reflectivity could be obtained, the expression of the resonance wavelength [13] was

$$ \lambda_{clad, q} = \left( n_{core} + n_{clad, q} \right) P_{FBG} $$

(8)

In the equation (8), $n_{clad, q}$ was the effective refractive index of the $q$ order mode in the cladding, $n_{core}$ was the effective refractive index of the fundamental mode, $P_{FBG}$ was the period of Bragg fiber grating.

3. Numerical calculate and simulation results analysis

3.1. The model of PCFG based on structural change

Using the above analysis method, a model of $C_{6v}$ TIR-PCFG was built and simulated. The PCFG model with 7 rings air-holes, it’s cross-section and longitudinal structure were (a) and (b) in the figure 4.

![Figure 4. The cross-section and longitudinal structure of PCFG.](image)

From within to outside of PCFG, the rings number of air-holes was 1, 2, ⋯⋯, 7. The diameter of the air-holes was $d = 2.16 \mu m$, the space between the air-holes was $p = 7.2 \mu m$, the outside diameter of PCFG was $D = 125 \mu m$, the length of the fiber grating was $L = 20 \text{mm}$, the diameter of the fiber core was $d_{core} = 2p - d = 12.24 \mu m$, the period of the fiber grating $A = 600 \text{nm}$. The fiber material was SiO$_2$, it’s effective refractive index was $n_{SiO_2} = 1.4466$. The maximum of the collapse depth of the outside diameter was $m = 4.5 \mu m$. The collapse degree of air-holes was closely related to their position...
in PCFG. From the outermost ring to the innermost ring, the collapse depth was from 1.96µm to 0.26µm, the collapse period was grating period. With the above parameters, the reflectance spectrum of PCFG showed an obvious grating effect, the resonance wavelength was about 1.55µm, the resonance bandwidth was over 100nm, and the intensity of the peak was about 0.96.

3.2. The impact of the rings of air-holes on the performance of PCFG

The structure of PCF, especially the rings of air-holes, had an important impact on the transmission characteristics of PCFG. The table 1 was the data of the resonance wavelength and the resonance bandwidth varying with the rings of air-holes, whose curves were described in the figure 5.

| The rings of air-holes | Resonance wavelength (µm) | Resonance bandwidth (nm) |
|------------------------|---------------------------|--------------------------|
| 1                      | 1.5512                    | 0.8                      |
| 2                      | 1.5511                    | 1.6                      |
| 3                      | 1.5510                    | 3.2                      |
| 4                      | 1.5506                    | 8.0                      |
| 5                      | 1.5499                    | 20.6                     |
| 6                      | 1.5479                    | 61.8                     |
| 7                      | 1.5490                    | 134.4                    |

**Figure 5.** The curves of the resonance wavelength and the resonance bandwidth vs. the rings of air-holes.

From the Table 1 and the figure 5, as the rings of air-holes rose, the resonance wavelength showed blue-shift, the grating had a wider bandwidth. According to the equation (8), the resonance wavelength was determined by the sum of the effective refractive indexes of the core and the cladding. When the rings of air-holes in the cladding increased, the effective refractive index of the cladding would diminish, this led to the sum of the effective refractive index of the core and the cladding reducing, so the resonance wavelength shifted right. At the same time, because the effective refractive index of the cladding diminished, the energy was concentrated in the core, the fiber core could support more high-order modes, this was the reason of the bandwidth increasing.

3.3. The impact of the duty ratio of air-holes on the performance of PCFG

The duty ratio of air-holes (d/p) had an obvious impact on the performance of PCFG. The figure 6 disclosed the changing trends of the resonance wavelength and the resonance bandwidth vs. d/p. Furthermore, it was found that d/p increased from 0.3 to 0.5, the resonance wavelength and the resonance bandwidth showed a downtrend on the whole, that was because the effective refractive index of the cladding reduced with d/p increasing. According to the equation (8), the resonance wavelength would shift left. But in the simulation, it was supposed that the functional relation among
the diameter of the fiber core, the space between the air-holes and the diameter of air-holes was $d_o = 2p - d$. In this expression, if $d$ held the current value all through, it could be deduced that $d_o$ would diminish with $d/p$ reducing; just the same, if $p$ kept unchangingly, it could also be inferred that $d_o$ would diminish with $d/p$ increasing. These could cause the coupled area of the fundamental mode and the high-order modes to reduce, and the modes satisfied with the phase match condition would be cut down in quantity, so the reflectance spectrum had a narrower bandwidth. In the figure 6(b), while $d/p$ was equal to 0.32, the bandwidth arrived at the peak value, it was about 140nm.

![Figure 6. The curves of the resonance wavelength and the resonance bandwidth vs. $d/p$.](image)

3.4. The impact of the rings and degree of air-holes shrinkage on the performance of PCFG

Not only the rings and the duty ratio of air-holes had the impact on the performance of PCFG, but also the rings and degree of air-holes shrinkage had the obvious effect on the transmission characteristics. In the simulation, it was assumed that the air-holes shrinkage was periodic and the rings of shrunken air-holes increased gradually. In addition, when the numbers of shrunken rings were same, the degree of air-holes shrinkage was divided into two grades.

The figure 7 was the changing curves of the effective refractive index varying with the rings of the shrunken air-holes. The real line showed the effective refractive index with the outer two rings air-holes shrinkage, the broken line showed the effective refractive index with the outer four rings air-holes shrinkage. From the figure 7, it could be drawn a conclusion that the effective refractive index went a downtrend with the wavelength increasing. Moreover, the more rings of shrunken air-holes were and the more seriously the air-holes shrunk, the bigger the effective refractive index of the cladding was. The figure 8 showed the curves of the resonance wavelength and the resonance bandwidth varying with the air-holes shrinkage. When the rings of shrunken air-hole increased, the effective refractive index rose. As the degree of air-holes shrinkage enhanced, the resonance wavelength showed red-shift and the grating had a narrower bandwidth. This coincided with the equation (8). Furthermore, because the effective refractive index of the cladding increased, it had the weak ability to confine the energy in the fiber core, the fiber could only support a few high-order modes, this led to the bandwidth reducing.

However, in the figure 8, when the rings numbers of air-holes shrinkage were same, it could be found that the resonance wavelength was unresponsive to the degree of air-holes shrinkage, the effective refractive index had not an obvious change in the condition of the same rings of shrunken air-holes. It was because of a small diameter of air-holes supposed in the simulation. If the diameter of the air-holes was bigger, the resonance wavelength would have a remarkable change.
Figure 7. The $n_{\text{eff}}$ vs. with the shrunken air-holes in the rings of 6th, 7th and the rings of 4th, 5th, 6th, 7th.

Figure 8. The curves of the resonance wavelength and the resonance bandwidth vs. the shrinkage degree of air-holes.

4. Conclusion
A kind of novel PCFG based on structural change was studied. It was the new progress that the fabrication principle was proved in the mathematics way. The relations between PCFG’s performance and some important PCF’s structure parameters were also discussed. The results of this study indicate that the periodic air-holes shrinkage can form grating, not only the degree of air-holes shrinkage, but also the shrinkage envelope has the very close relationships with the magnitude and the distribution of the effective refractive index; the structure parameters of PCF, such as the rings of air-holes in the cladding, the duty radio of air-holes, the rings and the degree of air-holes shrinkage, have the important impacts on the resonance wavelength, the resonance bandwidth and the intensity of resonance peak. Compared the PCFG based on structural change with one based on the UV exposure method, the former has a preferable stability in the high temperature environment or the longtime working system, it will have many potential applications in the field of optical fiber sensors.

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