Design of a Large Mode Area Photonic Crystal Fiber with Flattened Dispersion and Low Confinement Loss

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Abstract: In this paper, a novel structure of photonic crystal fiber (PCF) with large mode area, low confinement loss and flattened dispersion at C telecommunication band is presented. The numerical results revealed that these significant characteristics have been obtained by removing the first six surrounding air-holes in the transverse section. The perfectly matched layer (PML) for the boundary treatment and an efficient compact two dimensional finite-difference frequency-domain (2-D FDFD) method were combined to model photonic crystal fibers. Macro-bending loss performance of the designed PCF is also studied and it is found that the fiber shows low bending losses for the smallest feasible bending radius of 5 mm.

Keywords: Bending loss, Finite difference frequency domain, Dispersion, Large mode area, Photonic crystal fiber.

1. Introduction

Photonic crystals have attracted a great deal of attention in the optics community in recent years. One of the most promising applications of photonic crystals is the possibility of creating compact integrated optical devices with photons as the carriers of information, and then the speed and bandwidth of advanced communication systems can be increased dramatically [1-2]. Photonic crystal fibers (PCFs), a kind of two dimension photonic crystals, consisting of a central defect region surrounded by multiple air-holes that run along the fiber length are attracting much attention in recent years because of unique properties which are not realized in conventional optical fibers. PCFs are divided into two different kinds of fibers. The first one is index-guiding PCF, guiding light by total internal reflection between a solid core and a cladding region with multiple air-holes. The second one uses a perfectly periodic structure exhibiting a photonic band-gap (PBG) effect at the operating wavelength to guide light in a low index core-region. Index-guiding PCFs, also called holey fibers or microstructure optical fibers, possess especially attractive property of great controllability in chromatic dispersion by varying the hole-diameter and hole-to-hole spacing or hole-pitch [3-5]. Here, we proposed PCFs, with large effective mode area that simultaneously exhibit low confinement losses and ultra-flattened dispersion at C communication band.

This paper is organized as follows: In the next section, the theory of FDFD is described. In section 3, it is focused on fiber geometry structures and then the numerical results are discussed.

2. 2D-FDFD Method

The finite difference frequency domain (FDFD) is popular and appealing for numerical electromagnetic simulation due to its many merits. The discretization scheme can be derived from the Helmholtz equations or Maxwell’s equations directly. Now we use the direct discretization schemes first described for photonic crystal fibers by Zhu et al. Yee’s two-dimensional mesh is illustrated in Fig. 1; note that the transverse fields are tangential to the unit cell boundaries, so the continuity conditions are automatically satisfied. After inserting the equivalent nonsplit-field anisotropic PML in the frequency domain, the curl Maxwell equations are expressed as

\[ jk_0 s_x E = \nabla \times H \]
\[ -jk_0 s_y H = \nabla \times E \]  

(1)

\[ s = \begin{bmatrix} s_x/s_x \\ s_x/s_y \\ s_y/s_y \end{bmatrix} \]  

(2)

where \( s_x = 1 - \sigma_x/j\omega\epsilon_0 \), \( s_y = 1 - \sigma_y/j\omega\epsilon_0 \) and \( \sigma \) is the conductivity profile. Assuming that the PCFs are lossless and uniform and the propagation constant along the \( z \) direction is \( \beta \), the propagation direction derivative can be replaced by \( -j\beta \). Using the central difference scheme and zero boundary conditions outside of the anisotropic PML layers, the curl equations (1) can be rewritten in a matrix form which includes six field components. Then eliminating the longitudinal magnetic and electric fields, the eigenvalue matrix equation in terms of transverse
magnetic fields and transverse electric fields can be obtained as

\[
\begin{bmatrix}
Q_{xx} & Q_{xy} \\
Q_{yx} & Q_{yy}
\end{bmatrix}
\begin{bmatrix}
H_x \\
H_y
\end{bmatrix} = \beta^2
\begin{bmatrix}
H_x \\
H_y
\end{bmatrix}
\]

(3)

\[
\begin{bmatrix}
P_{xx} & P_{xy} \\
P_{yx} & P_{yy}
\end{bmatrix}
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix} = \beta^2
\begin{bmatrix}
E_x \\
E_y
\end{bmatrix}
\]

(4)

where the \( Q \) and \( P \) are highly sparse coefficient matrices [6-8]. The order and the nonzero elements in them are reduced and effectively stored in sparse format, so the computation efficiency is improved greatly. The complex propagation constant \( \beta \) and the transversal magnetic or electric field distribution can be solved out quickly and accurately by a sparse matrix solver.

3. Fiber Geometry Structure and Numerical Results

In this section, we will address the modified confinement loss and dispersion curves when the first six surrounding air-holes are removed and the PCFs’ structure parameters are altered. Fig. 2(a) shows the structure of the proposed PCF. All the air-holes in the section of PCFs are arrayed according to triangle regularity with identical pitch \( \Lambda \), spacing of the neighboring air-holes. The scale of the air-holes is denoted by \( d \) of its diameter. The material dispersion using Sellmeier equation is directly considered in the perturbation formulations [9].

Combining perfectly matched layer (PML) for the boundary treatment, and the finite difference frequency domain (FDFD) method is applied to analyze the dispersion property of the triangular PCF and it has been one of the major tools for the analysis and understanding of PCFs. Because the effective refractive index of the core region is higher than the cladding region, total internal reflective (TIR) can occur in the interface between the core and cladding.

In the following, we will investigate the loss and dispersion characteristics of the designed PCFs. There are two degrees of freedom; the ratio of air-hole diameter to air-hole pitch; \( d/\Lambda \) and the number of hole-rings; \( N \), for controlling the confinement loss and dispersion behaviors. In the numerical calculation, the pitch is \( \Lambda = 1.8 \mu m \) in whole section of PCFs.

3.1 Guided Modes in PCFs

In an index-guiding PCF, the core index is greater than the average index of the cladding because of the presence of air-holes, and the fiber can guide the light by total internal reflection as a standard fiber does. That is, the guided light has an effective index \( n_{\text{eff}} \) that satisfies the condition

\[
n_{co} > n_{\text{eff}} = \frac{\beta}{k_0} > n_{FSM}
\]

(5)

where \( \beta \) is the propagation constant along the fiber axis, \( n_{co} \) is the core index, and \( n_{FSM} \) is the cladding effective index of the FSM. In the case of a PCF made from pure silica, \( n_{co} \) is reduced to the index of silica [10].

In the operating wavelength \( \lambda = 1.55 \mu m \), the transversal field intensity distribution for the fundamental guiding mode of PCF is shown in Fig. 2(b).

3.2 Chromatic Dispersion

PCFs possess the attractive property of great controllability in chromatic dispersion. The chromatic dispersion profile can be easily controlled by varying the hole-diameter and the hole-pitch. Controllability of chromatic dispersion in PCFs is a very important problem for practical applications to optical communication systems, dispersion compensation, and nonlinear optics. So far, various PCFs with remarkable dispersion properties have been investigated numerically.
The chromatic dispersion $D$ of a PCF is easily calculated from the effective index of the fundamental mode $n_{\text{eff}}$ versus the wavelength using

$$D = \frac{\lambda^2}{c} \frac{d^2 n_{\text{eff}}}{d\lambda^2}$$  \hspace{1cm} (6)$$

where $c$ is the velocity of light in a vacuum. When the hole-diameter to pitch ratio is very small and the hole-pitch is large, the dispersion curve is close to the material dispersion of pure silica. As the air-hole diameter is increased, the influence of waveguide dispersion becomes stronger [10-11].

As mentioned above, the dispersion coefficient $D$ is proportional to the second derivative of the modal effective index with respect to the wavelength $\lambda$. For this reason, we have to calculate the dependence of modal effective index $n_{\text{eff}}$ with respect to the wavelength $\lambda$ first. By fixing $\Lambda=1.8\mu$m and changing $\lambda$ in the range of $1.53\mu$m~$1.57\mu$m (C communication band), the characteristics of dispersion are shown in Fig. 3 at $N=8$ for different ratio of air-hole diameter to air-hole pitch PCF1: $d/\Lambda = 0.4$, PCF2: $d/\Lambda =0.45$, PCF3: $d/\Lambda =0.5$, PCF4: $d/\Lambda =0.55$, PCF5: $d/\Lambda =0.6$.

As it can be seen, the chromatic dispersion increases when the ratio of air-hole diameter to air-hole pitch $d/\Lambda$ increases, and in the best case, it reaches to 38.4ps/km/nm at the wavelength of $1.55\mu$m for the PCF with $d/\Lambda=0.4$ and $N=8$. Also the dispersion slop is 0.067(ps/km/nm$^2$) in the wavelength range of $1.53\mu$m~$1.57\mu$m.

Then, we change the geometrical parameters such as the number of hole-rings ($N=10$) along with the air-holes diameter. Fig. 4 shows the results for 5 values of these parameters. As it can be seen both dispersion and dispersion slope are increased with the increasing of the $d/\Lambda$.

### 3.3 Confinement Loss

The losses in PCFs occur for a number of reasons, such as intrinsic material absorption loss, structural imperfection loss, Rayleigh scattering loss, confinement loss, and so on. Fabrication-related losses can be reduced by carefully optimizing the fabrication process. Confinement loss is an additional form of loss that occurs in single-material fibers [12-13].

PCFs are usually made from pure silica, and so the guided modes are inherently leaky because the core index is the same as the index of the outer cladding without air-holes. This confinement loss can be reduced exponentially by increasing the number of rings of air-holes that surround the solid core, and is determined by the geometry of the structure. It is important to know how many numbers of rings of air-holes are required to reduce the confinement loss under the Rayleigh scattering limit for practical fabrication process.

Fig. 5 shows the Confinement loss characteristics as a function of the wavelength for different photonic crystal fibers for $d/\Lambda$ varying from 0.4 to 0.6 with the fixed number of hole-rings of 8. Because the confinement loss is less than 0.005dB/km for the PCFs with the ratio of air-hole diameter to air-hole pitch ($d/\Lambda$) of 0.5 or higher, they are positioned on the $L\cong0$ in this scale.
In the next step, we change the geometrical parameters such as the number of hole-rings (N=10) along with the air-holes diameter. Fig. 6 shows the confinement loss characteristics of the fundamental mode in PCFs as a function of the wavelength when ratio of air-hole diameter to air-hole pitch \(d/\Lambda\) varies from 0.4 to 0.6 and the number of rings of air-holes is fixed to 10. Again, because the confinement loss is higher than 10dB/km for PCF with \(d/\Lambda=0.4\), so its loss curve is out of the graph range. On the other hand, since the confinement loss is less than 0.005dB/km for the PCFs with the ratio of air-hole diameter to air-hole pitch \(d/\Lambda\) of 0.5 or higher, they are positioned on the L\(\cong0\) in this scale.

![Fig. 6. The confinement loss characteristics as a function of the wavelength for different photonic crystal fibers with the following parameters; \(\Lambda=1.8\mu m\), N=10, PCF1: d/\Lambda = 0.4, PCF2: d/\Lambda =0.45, PCF3: d/\Lambda =0.5, PCF4: d/\Lambda =0.55, PCF5: d/\Lambda =0.6. The loss curves are positioned on the L\(\cong0\) for d/\Lambda\geq0.5 and it is out of the graph for d/\Lambda=0.4 because of its high value.](image)

Therefore the confinement loss is not only reduced exponentially by increasing the number of rings of air-holes that surround the solid core, but also by increasing the air-hole diameter.

### 3.4 Effective Mode Area in PCFs

The effective area of the fiber core \(A_{eff}\) is defined as

\[
A_{eff} = \frac{\iint |E|^2 \, dx\,dy}{\iint |E|^2 \, dx\,dy} \tag{7}
\]

where \(E\) is the transverse electric field vector and \(S\) denotes the whole fiber cross section [10]. As expected, increasing the air-hole size, the mode becomes more confined, and thus the effective area and the confinement loss are both reduced. Also, increasing the number of rings of air-holes, the confinement loss is significantly reduced. On the other hand, the effective area is almost independent of the number of hole-rings. We can see that the confinement loss contributes significantly to the loss of PCFs when the hole-pitch \(\Lambda\) is small.

Table I shows the effective mode area for the different PCFs at operating wavelength of 1.55\(\mu m\). As mentioned before, the feasible dispersion characteristics of the fundamental mode is for the PCF with the following parameters; \(\Lambda=1.8\mu m\), N=8 and d/\(\Lambda=0.4\). The calculated effective mode area of this fiber is 20.0535\(\mu m^2\) that is greater than the other PCFs with N=8. When the number of hole-rings increases to 10, the effective mode area will be increased, but their fundamental modes are not in the core centre and also their dispersion characteristics are not feasible.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Effective Mode Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>d/\Lambda</td>
</tr>
<tr>
<td>8</td>
<td>0.4</td>
</tr>
<tr>
<td>8</td>
<td>0.45</td>
</tr>
<tr>
<td>8</td>
<td>0.5</td>
</tr>
<tr>
<td>8</td>
<td>0.55</td>
</tr>
<tr>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>10</td>
<td>0.45</td>
</tr>
<tr>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>10</td>
<td>0.55</td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
</tr>
</tbody>
</table>

### 3.5 Bending loss

In the following step of analyzing the PCFs characteristics, we examine how the total loss in a 90° bend varies as a function of the radius of curvature. Compared with conventional fibers, PCFs with several air-holes arranged in the cladding are more robust towards bending; hence they have an advantage in realizing large-mode areas.

The total optical loss as a function of the bend radius of curvature for PCF with \(d/\Lambda=0.4\), \(\Lambda=1.8\mu m\) and N=8 at operating wavelength of 1.55\(\mu m\) is depicted in Fig. 7. As it can be seen, the total loss is decreased by increasing the bend radius of curvature.

![Fig. 7. The total optical loss as a function of the bend radius of curvature for PCF with d/\Lambda = 0.4, \Lambda =1.8\mu m and N=8 at 1.55\(\mu m\) wavelength.](image)
4. Conclusion

In this article, a novel structure of photonic crystal fiber (PCF) with large mode area, low confinement loss and flattened dispersion at C telecommunication band is proposed. The computations based on the FDFD method revealed that the significant characteristics have been obtained by removing the first six surrounding air-holes in the transverse section and increasing the number of hole-rings. So, a PCF with the following characteristics is designed: $d/\Lambda =0.4$, $\Lambda=1.8\mu$m, $N=8$, $L=0.01464\text{dB/km}$, $D=38.4\text{ps/km/}n\mu$m, $A_{\text{eff}}=20.0535\mu\text{m}^2$ at the wavelength of $1.55\mu$m, $S=0.067(\text{ps/km/}n\mu\text{m}^2)$ in the C band. Taking all things into account; it is believed that the proposed PCF will have promising future in ultra-broadband transmission applications.

References