Effects of air holes in the cladding of photonic crystal fibers on dispersion and confinement loss of orbital angular momentum modes

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Received: 10 November 2021 / Accepted: 15 April 2022 / Published online: 12 May 2022
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Abstract
In the development of orbital angular momentum (OAM) mode division multiplexing, the capacity of optical fiber communication must be improved. However, owing to dispersion and confinement loss, many OAM modes do not propagate stably over a long distance in optical fibers. In this work, the effects of the size, number, shape, number of layers, and layer spacing of air holes in the cladding of the fiber on the dispersion and confinement loss are analyzed based on a simple structure. The trends are studied and summarized to facilitate the design of optical fibers to achieve stable transmission of OAM modes over a long distance.

Keywords Orbital angular momentum · Confinement loss · Dispersion · Optical fiber communication

1 Introduction
Future internet technology requires higher capacity, speed, and stability (Richardson et al. 2013) and optical fiber communication based on total reflection of light has become a pillar in the field of optical communication (Ryf et al. 2011). In order to increase the capacity, stability, and security of optical fiber communication, mode division multiplexing (MDM) (Bozinovic et al. 2013) based on the orbital angular momentum (OAM) has become a hot research topic (Parmigiani et al. 2017). Since OAM modes are prone to atmospheric
interference, serious OAM degradation occurs when the number of OAM modes in free space is large. Therefore, it is very important to design the suitable medium to transmit OAM modes.

Photonic crystal fibers (PCFs) (Liu et al. 2019a, b; Li et al. 2019) have strong anti-interference ability and flexible structures suitable for OAM modes. To ensure stable transmission of OAM modes in PCFs, the effective index difference between the HE and EH modes for synthesis of the same order OAM should be greater than $1 \times 10^{-4}$, so that the OAM modes do not degenerate into the linear polarization (LP) modes (Wang et al. 2016). Moreover, in order for OAM modes to propagate over a long distance in the PCF with as little distortion as possible, dispersion (Issa et al. 2004) and confinement loss (Maji and Chaudhuri 2013) must be considered. In this respect, the size, number, shape, and other structural parameters of the air holes in the cladding of the PCF affect the communication performance and must be optimized.

Optical fibers have been proposed for transmission of OAM modes (Yue et al. 2012; Lixia and Wei 2016; Bai et al. 2020a; Yu et al. 2018; Zhang et al. 2018). For example, Huang et al. proposed a PCF for transmission of 30 OAM modes with mode dispersion between 50 ps/(km-nm) and 100 ps/(km-nm) (Wei et al. 2020). Ma et al. designed a PCF for propagation of 180 OAM modes from 1.50 to 1.70 μm with a minimum confinement loss of $10^{-12}$ dB/m (Ma et al. 2021). Although a large number of studies on OAM mode transmission in PCF have been proposed, the effects of air holes in the cladding on the dispersion and confinement loss have been clearly understood. Dispersion and confinement loss are two important physical quantities affecting optical fiber communication. They will change with the variation of fiber structure. It should be noted that the shape, size, number, spacing of air hole layer, and so on in the cladding will have a great impact on these two properties. In fact, the fiber dimensions are usually determined by trial-and-error with low efficiency. The purpose of this work is to calculate and summarize the influence law of cladding air hole arrangement on dispersion and confinement loss by means of simulation, which can be utilized as a theoretical reference when designing and optimizing the structure of communication fiber in the future, so as to improve the efficiency of optical fiber communication.

Herein, a simple PCF is designed for transmission of OAM modes and by varying the structural parameters such as size, number, layer spacing, and shape of the air holes in the cladding, the dispersion and confinement loss of OAM modes are analyzed numerically by the finite element method (FEM). The trends are studied and summarized to facilitate the design and optimization of PCFs for stable transmission of OAM modes over a long distance.

## 2 OAM theory and PCF design

As a new optical communication technique, OAM is a phenomenon related to quantum physics which exists mainly in the vortex light with the helical phase factor. In optical communication, the transmitted information through optical fibers can be loaded into OAM after modulation and converted into optical signal at the input end. When the signal reaches the receiving end, the information can be obtained by demodulation. In other words, OAM modes carry the information to be transmitted, and the performance of OAM modes represent the quality and efficiency of optical fiber communication. In addition, OAM mode is easier to be identified and has important application value.
in signal conversion and demodulation. Consequently, various performances of OAM mode need to be analyzed in detail. The transverse electric field distribution of eigen-vector mode in optical fiber follows formula (1) in polar coordinate system:

\[
\begin{align*}
HE_{l+1,m}^{even} &= F_{l,m}(r) \cdot (\hat{x} \cos(l\theta) - \hat{y} \sin(l\theta)) \\
HE_{l+1,m}^{odd} &= F_{l,m}(r) \cdot (\hat{x} \sin(l\theta) + \hat{y} \cos(l\theta)) \\
EH_{l-1,m}^{even} &= F_{l,m}(r) \cdot (\hat{x} \cos(l\theta) + \hat{y} \sin(l\theta)) \\
EH_{l-1,m}^{odd} &= F_{l,m}(r) \cdot (\hat{x} \sin(l\theta) - \hat{y} \cos(l\theta))
\end{align*}
\]

where \(F_{l,m}(r)\) is the radial field distribution of scalar LP mode and \(\theta\) is the azimuth coordinate. Since the odd mode solution and even mode solution of eigenmodes are completely degenerate, they can be expressed as a linear combination shown in Eq. (2), which can form OAM modes with a topological charge of \(l\).

\[
\begin{align*}
\{\hat{e}_{l,m}\} &= HE_{l+1,m}^{even} \pm iHE_{l+1,m}^{odd} = F_{l,m}(r)\hat{\sigma} \pm \exp(\pm il\theta) \\
\{\hat{e}_{l,m}\} &= EH_{l-1,m}^{even} \pm iEH_{l-1,m}^{odd} = F_{l,m}(r)\hat{\sigma} \mp \exp(\pm il\theta)
\end{align*}
\]

Consequently, OAM modes are mainly composed of odd and even components of the HE and EH modes as shown in Eq. (3) (Liu et al. 2019c):

\[
\begin{align*}
\text{OAM}_{\pm}^{l,m} &= HE_{l+1,m}^{even} \pm iHE_{l+1,m}^{odd} \\
\text{OAM}_{\mp}^{l,m} &= EH_{l-1,m}^{even} \pm iEH_{l-1,m}^{odd}
\end{align*}
\]

where \(l\) is the topological charge number and \(m\) is the radial order which is usually 1 for easy de-multiplexing. “\(\pm\)” and “\(\mp\)” in the upper right corner of the OAM represent the direction of circular polarization and “+” is the right-hand circle polarization and “−” is the left-hand. When \(l=1\), the polarization direction and rotation direction of the OAM mode are the same and can only exist as two channels. When \(l\geq2\), they are opposite and can exist as four channels. Therefore, the number of OAM modes that can propagate in the PCF is \(4l+2\).

The reason why PCF can transmit an infinite number of OAM modes in theory is that the OAM beams with different topological charges are orthogonal to each other and \(l\) can be any integer. However, in reality, the number of OAM modes that can propagate stably over a long distance transmission is finite due to dispersion and confinement loss. The pulse broadening phenomenon caused by different frequency components or different mode components of optical signals propagating at different speeds and reaching a certain distance is called fiber dispersion. Because excessive dispersion produces signal distortion, dispersion of OAM modes should be minimized when designing optical fibers. In addition, loss is one of the critical characteristics of optical fibers. Because of the large number of air holes in the cladding, light in the PCF can leak into the cladding air holes during propagation resulting in confinement loss (Qin et al. 2019). Consequently, OAM modes cannot propagate stably over a long distance in the PCF when the confinement loss is high and therefore, the confinement loss must be reduced by tailoring the air holes in the cladding.

In this work, the changes in the dispersion and confinement loss stemming from the cladding air holes are investigated using the finite element software COMSOL based on the simple PCF structure shown in Fig. 1. The core of the structure is a large air hole.
with a radius of $R_0$. The blue area is the cladding in the optical fiber and the thickness of the annular area with the main concentration of photon energy is $l + d$. The cladding is made of SiO$_2$ and its refractive index is determined by Sellmeier equation (Wang et al. 2021):

$$n^2(\lambda) = 1 + \frac{A_1 \lambda^2}{\lambda^2 - B_1} + \frac{A_2 \lambda^2}{\lambda^2 - B_2} + \frac{A_3 \lambda^2}{\lambda^2 - B_3}$$  \hspace{1cm} (4)

where $A_1 = 0.6961663$, $A_2 = 0.4079426$, $A_3 = 0.897479$, $B_1 = 0.0684043$, $B_2 = 0.1162414$, and $B_3 = 9.896161$. There are two layers of circular air holes with radii of $r_1$ and $r_2$, respectively, in the cladding. The number of air holes, layer spacing ($\Lambda$), shape, size of the two air-hole layers, and number of air holes in the first layer are varied to study their effects on the dispersion and confinement loss. In Fig. 1, the green area represents the perfect matching layer (PML) that has no effect on the performance of the fiber and is mainly used to establish the boundary conditions. In order to study the influence of the cladding air holes on dispersion and confinement loss, each parameter is varied while the other parameters are the same. In order to determine the relevant trends, we set $R_0 = 5.5$ $\mu$m, $l = 2.5$ $\mu$m, $d = 0.2$ $\mu$m and the number of air holes in the cladding are varied in the calculation. And $r_1$, $r_2$ and $\Lambda$ are the radius of inner and outer air holes and the layer spacing between two layers of air holes respectively, and the initial value is $r_1 = r_2 = 0.8$ $\mu$m, $\Lambda = 0.2$ $\mu$m which will change in the discussion of Chapter 3. At the same time, we discuss that the radius of cladding $R_1$ is in the range of 11 $\mu$m to 13 $\mu$m. When $R_1 = 11.8$ $\mu$m, the second-order radial mode will not be excited, so we set $R_1 = 11.8$ $\mu$m. The cross-section of the proposed fiber is shown in Fig. 1.

Besides, the reason why we design this structure is that the radius of central air-hole and the thickness of annular region are fixed, and the only factor affecting dispersion and confinement loss is the arrangement of the pores in cladding. Firstly, the design of two-layer air holes is conducive to the study of layer spacing. Secondly, the air hole size is smaller than that of the cladding in order to accommodate more air holes. Finally, the shape of the initial air-hole is designed as a circle, which can be compared with other shapes more intuitively. This structure is mainly used in the field of optical fiber communication, and has great application value for the design of optical fiber and the optimization of communication performance.
In addition, the proposed structure can be produced by sol–gel method (Fu et al. 2021). Under the action of a specific catalyst, the material will form sol after hydrolysis condensation reaction, and then form a gel through cooling. The silicon dioxide powder is made into a fiber preform under heat treatment of the gel, and finally the fiber is made through a drawing tower. Because this method can freely adjust the shape, size, number and other parameters of the air holes, it is very suitable for this study.

3 Results and discussion

Dispersion can be divided into materials and waveguide dispersion. Materials dispersion depends on the properties of the optical fiber and is governed by Sellmeier equation. Waveguide dispersion is mainly determined by the second derivative of the OAM mode refractive index to wavelength. Moreover, the dispersion of OAM mode in the communication band should not change greatly as much as possible, and the dispersion slope should be as low as possible, that is, flat dispersion should be pursued. This is because the smoother the dispersion is, the lower the probability of signal distortion is. The total dispersion can be obtained by Eq. (5) (Bai et al. 2018):

\[ D = D_m(\lambda) + D_w(\lambda) = -\frac{\lambda}{c} \frac{d^2 \text{Re}(n_{\text{eff}})}{d\lambda^2} \] (5)

where \( D_m(\lambda) \) is materials dispersion, \( D_w(\lambda) \) is waveguide dispersion, \( \lambda \) is the wavelength, \( c = 3 \times 10^8 \text{ m/s} \) is the speed of light, and \( \text{Re}(n_{\text{eff}}) \) is the real part of the effective refractive index. The confinement loss can be calculated by Eq. (6) (Liu et al. 2018):

\[ L = \frac{2\pi}{\lambda} \frac{20}{\ln(10)} 10^6 \text{Im}(n_{\text{eff}}) \] (6)

where \( \text{Im}(n_{\text{eff}}) \) is the imaginary part of the effective refractive index. In the following sections, the effects of the number of air hole layers, size and number of inner air holes, size of outer air holes, distance between the two air-hole layers, as well as shape of air holes on the dispersion and confinement loss at 1.55 \( \mu \text{m} \) will be discussed.

3.1 Transmission modes

According to the basic theory of OAM, OAM modes can be formed by superposition of HE and EH modes. Since the parameters that determine the number of OAM modes (size of the central air hole and annular area thickness) are fixed, the number of OAM modes will not change when the air holes in the cladding are varied. The HE and EH modules are obtained by COMSOL. Figure 2a–f display the light field distributions of the partial HE and EH modes in the z direction and Fig. 2g–i show the corresponding phase distributions at 1.55 \( \mu \text{m} \).

As shown in Fig. 2, the photon energy is mainly concentrated in the circular region. The field distributions of the HE modes are closer to the cladding and those of the EH are closer to the core thus making it possible to distinguish the HE modes from the EH modes. Figure 2g–i show the phase distributions and \( l \) can be easily differentiated in the phase diagram because OAM \( \pm l \) has a phase change of 2\( l\pi \). It is important to note that all modes are perfectly confined in the annular region and maintain a good single mode in the radial
direction. Moreover, the topological charge of the OAM module is equal to the number of red and blue region pairs. Since the maximum value of $l$ is 6, $4 \times 6 + 2 = 26$ OAM modes can be transmitted, including $\text{OAM}^\pm_{2l,1,1} \{\text{HE}_{2,1}\}$ and $\text{OAM}^\pm_{2l,1,1} \{\text{HE}_{l+1,1,1}, \text{EH}_{l-1,1,1}\} \ (l = 1 \sim 6)$. It is well known that the modulus in the optical fiber is directly proportional to the normalized frequency determined by Eq. (7) and is related to the ratio of the inner and outer radius of the circular region defined by formula (8) (Huang 2019)

$$V_{\text{eff}} = \frac{2\pi}{\lambda} a \sqrt{n_{\text{si}}^2 - n_{\text{cladding}}^2}$$

$$\rho = \frac{R_0}{R_0 + l}$$

where $a$ is the outer radius of the annular region, $n_{\text{si}}$ and $n_{\text{cladding}}$ are the refractive index of silica and cladding, $n_{\text{si}}$ and $n_{\text{cladding}}$ are determined by Eqs. 4 and 9 (Li et al. 2018), respectively:

$$n_{\text{cladding}} = 1.444(1 - f) + f$$

where $f$ is the air-filling fraction of the cladding, whose form can be written as Eq. 10 (Li et al. 2018):

$$f = \frac{((N_i - 0.5 + (N_o - N_i + 1))\Delta d)^2 - ((N_i - 0.5)\Delta d)^2}{6r_1^2(N_i + N_o)(N_o - N_i + 1)/2} = 3\left(\frac{r_1}{\Delta d}\right)^2$$

where $\Delta d$ is the core pitch, $r_1$ is the radius of the cladding air holes. Utilizing (7)–(10) to calculate the deigned optical fiber, we can obtain the relationship between the number of modes in the fiber and the normalized frequency described in Fig. 3. After calculation, the
The normalized frequency of the designed structure is 27.622 and can transmit about 26 modes, which is consistent with the previous analysis.

3.2 Effective index difference

If the effective index difference is less than $1 \times 10^{-4}$, the OAM modes degenerate into LP modes and inter-mode crosstalk increases. Table 1 shows the effective index difference of $\text{OAM}_{6,1}$ under different conditions at 1.55 $\mu$m.

The radius of the inner air holes is inversely proportional to the effective index difference, and the number of inner air holes and radius of outer air holes are directly

| Number of layers | 1  | 2  | 3  |
|------------------|----|----|----|
| $\Delta n_{\text{eff}}$ | $3.22 \times 10^{-4}$ | $3.21 \times 10^{-4}$ | $3.20 \times 10^{-4}$ |
| Shape of pores | Circular | Square | Oval |
| $\Delta n_{\text{eff}}$ | $2.81 \times 10^{-4}$ | $5.25 \times 10^{-4}$ | $3.71 \times 10^{-4}$ |
| Layer spacing$(\mu$m) | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 | 0.40 |
| $\Delta n_{\text{eff}}$ | $3.22 \times 10^{-4}$ | $3.23 \times 10^{-4}$ | $3.21 \times 10^{-4}$ | $3.21 \times 10^{-4}$ | $3.23 \times 10^{-4}$ | $3.22 \times 10^{-4}$ | $3.22 \times 10^{-4}$ |
| Radius of inner pores$(\mu$m) | 0.8 | 1.0 | 1.2 | 1.4 | 1.6 | 2.0 |
| $\Delta n_{\text{eff}}$ | $3.22 \times 10^{-4}$ | $2.98 \times 10^{-4}$ | $2.40 \times 10^{-4}$ | $2.37 \times 10^{-4}$ | $2.25 \times 10^{-4}$ | $1.79 \times 10^{-4}$ |
| Number of inner pores | 20 | 23 | 26 | 29 | 32 | 35 |
| $\Delta n_{\text{eff}}$ | $1.12 \times 10^{-4}$ | $1.44 \times 10^{-4}$ | $1.71 \times 10^{-4}$ | $2.29 \times 10^{-4}$ | $2.81 \times 10^{-4}$ | $3.23 \times 10^{-4}$ |
| Radius of outer pores$(\mu$m) | 0.80 | 0.96 | 1.12 | 1.28 | 1.44 | 1.60 |
| $\Delta n_{\text{eff}}$ | $3.23 \times 10^{-4}$ | $3.22 \times 10^{-4}$ | $3.29 \times 10^{-4}$ | $3.41 \times 10^{-4}$ | $3.55 \times 10^{-4}$ | $3.62 \times 10^{-4}$ |
proportional to the effective index difference. The number and spacing of the air holes have little effects on the effective index difference. Furthermore, regardless of the changes resulting from the cladding air holes, the effective refractive index difference is greater than $1 \times 10^{-4}$ when $l = 6$. With increasing topological charge, the effective index difference continues to decrease at the same wavelength (Bai et al. 2020b). Therefore, when the topological charge is $l$ ($l = 1 \sim 5$), the effective index difference is larger than $1 \times 10^{-4}$ and consequently, all the OAM modes can be transmitted in the PCF.

### 3.3 Number of air-hole layers

The number of air-hole layers in the cladding is critical when designing and optimizing the optical fiber structure because different layer numbers alter the optical fiber characteristics. In our numerical calculation, regardless of the number of air-hole layers, the number of each layer is 35. Figure 4a and b present the effects of air holes with different layers on the dispersion and confinement loss, respectively. With regard to dispersion, the red and blue curves almost overlap indicating that the number of air-hole layers hardly affects dispersion. On the contrary, the number of air-hole layers has a great impact on the confinement loss. As the number of air-hole layers goes up, the confinement loss decreases by thousands of times and therefore, more air-hole layers can reduce the confinement loss.

### 3.4 Layer spacing of air holes

The distance between air-hole layers is small compared to the size of the air holes leading to insufficient optimization of the layer spacing. In this section, the influence of the layer spacing ($\Lambda$) on the dispersion and confinement loss is investigated while the size and number of air holes are the same. As shown in Fig. 5, with increasing layer spacing, the variation of dispersion is on the order of $10^{-2}$, which is almost negligible. However, the confinement loss changes when the layer spacing increases. Although the higher order modes are greatly reduced, the confinement loss is still high mainly due to the low restriction ability of the annular region to the high-order modes and subsequent leakage into the cladding.

### 3.5 Size and number of air holes in the first layer

The reason why the first air-hole layer is the most important in the cladding is that it is closest to the annular region. In determining the radius range, we ensure that there are as many pores as possible in the same layer while the adjacent air holes do not intersect. The relationship between the dispersion and confinement loss with the radii of the first air-hole layer is displayed in Fig. 6a and b.

As the air hole radii increase, dispersion decreases gradually, especially the higher order modes. However, the variation in the dispersion is still small compared to the absolute value. When the pore radius is between 0.8 and 1.1 μm, the confinement loss decreases rapidly. When the radius is greater than 1.3 μm, the confinement loss decreases by thousands of times thus boding well for long-distance transmission of OAM modes. The effects of the number of air holes in the first layer on the dispersion and confinement loss are shown in Fig. 7a and b. Because the number of air holes in the first layer is directly proportional to the dispersion and inversely proportional to the confinement loss, the influence of the other parameters should be considered in the design and optimization of the fiber.
When the number is less than 29, the confinement loss decreases greatly and when the number is more than 29, the confinement loss decreases by $10^4$ times, which is beneficial to stable propagation of OAM modes in the fiber.

Fig. 4 Effects of different air-hole layers on \(a\) dispersion and \(b\) confinement loss
To investigate the effects of the air-hole size in the second layer on the dispersion and confinement loss, the radius and number of the air holes in the first layer are 0.8 μm and 35, respectively, and the layer spacing is 0.2 μm. As shown in Fig. 8, changing the radius of the air holes in the second layer has little effects on dispersion but decreases the confinement loss significantly. When the radius is less than 1.12 μm, confinement loss is between $10^{-5}$.
and $10^{-6}$ dB/m, when the radius is greater than 1.12 μm, the confinement loss decreases by hundreds of times. For example, the confinement loss decreases to $10^{-9}$ dB/m when the radius is larger than 1.3 μm.

**Fig. 6** a Dispersion and b confinement loss as a function of the air-hole radius in the first layer
3.7 Shape of air holes

The shape of the air holes in the cladding is another important parameter and in this section, the effects of circular, square, and elliptical air holes on the dispersion and confinement...
Fig. 8  a Dispersion and b Confinement loss as a function of the air-hole size in the second layer
loss are described. The number of air holes in both layers in the cladding is 32, whereas the
diameter of the round pores, side length of the square pores, and long axis of the oval pores
are equal, which has been shown in Fig. 9. With more topological charge, dispersion rises
continuously because the higher order modes are more prone to signal distortion (Fig. 10).
Moreover, dispersion of the circular and oval air holes is about the same and the curves
almost overlap. On the other hand, dispersion of the square air holes is slightly larger. The
square and circular pores show very low confinement loss that is 5 to 6 orders of magnitude
different from that of the oval pores. Therefore, circular pores which are also easy to pro-
duce deliver the best performance.

4 Conclusion

The effects of different air-hole arrangements in the cladding on dispersion and confine-
ment loss are analyzed based on a simple structure. Our results indicate that the confine-
ment loss can decrease by thousands of times by optimizing the size, shape, number, and
layer spacing of the air holes. The size and number of air holes in the first layer also have
a large impact the dispersion. The general trends are derived to facilitate the design and
optimization of optical fibers.

Fig. 9 Size of a circular, b square and c oval air holes
Fig. 10  a Dispersion and b Confinement loss for different air-hole shape
Funding This work was jointly supported by the Local Universities Reformation and Development Personnel Training Supporting Project from Central Authorities [140119001], City University of Hong Kong Strategic Research Grant (SRG) [Grant Number 7005505], and Scientific Research Fund of Sichuan Province Science and Technology Department [2020YJ0137].

Declarations

Conflict of interest The authors declare no conflicts of interest.

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