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Band structure of photonic crystal fibers with silica rings in triangular lattice

Qin-Ling Zhou [a,*], Xing-Qiang Lu [b], Dan-Ping Chen [a], Cong-Shan Zhu [a], Jian-Rong Qiu [a]

[a] *Photon Craft Project, Shanghai Institute of Optics and Fine Mechanics, Chinese Academic of Sciences, Shanghai 201800, China*
[b] *National Laboratory on High Power Laser and Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China*

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Abstract

The characteristics of the cladding band structure of air-core photonic crystal fibers with silica rings in triangular lattice are investigated by using a standard plane wave method. The numerical results show that light can be localized in the air core by the photonic band gaps of the fiber. By increasing the air-filling fraction, the band gap edges of the low frequency photonic band gaps shift to shorter wavelength, whereas the band gap width decreases linearly. In order to make a specified light fall in the low frequency band gaps of the fiber, the interplay of the silica ring spacing and the air-filling fraction is also analyzed. It shows that the silica ring spacing increases monotonously when the air-filling fraction is increased, and the spacing range increases exponentially. This type fiber might have potential in infrared light transmission.

Keywords: Photonic crystal fiber; Photonic band structure; Silica ring

Photonic crystal fibers (PCFs) attracted a lot of attention in the last few years because of their unique structures and novel properties [1–6]. PCF generally consists of an array of air holes in the cladding extending the whole length of the fiber. According to light guiding mechanism, PCFs can be classified into two families. One is index-guiding PCF and the other is photonic band gap (PBG) PCF. For index-guiding PCFs, light is guided in the core by the modified total internal reflection owing to the core index being larger than the effective index of the cladding. For PBG PCFs, light is guided in the core by the PBGs of the cladding. Therefore, their core index is not necessarily larger than the effective index of the cladding. Owing to this unconventional guiding mechanism and particular geometrical structure, intriguing properties and promising applications have been aroused in PBG PCFs [4–6]. However, the overall progress made in PBG PCFs has got behind compared with that of index-guiding PCFs. This is not only caused by the technique difficulties, but also caused by a few structures having been proposed and numerically tested [7–10].

In this paper, we report the properties of the cladding band structure of air core PCFs with silica rings in triangular lattice. The cross section of the fiber is shown in Fig. 1. In this fiber, seven central silica capillaries are removed to form the core. Silica ring spacing (the distance between consecutive silica rings) Λ, inner radius r and outer radius R ($R = \Lambda/2.0$) of the silica rings, are used to define the structure.

In the following, we first introduce the theoretical basis, and then give the out-of-plane photonic band structure the fiber. Later, we present the dependence of the low frequency PBGs on structure parameters, silica ring spacing and air-filling fraction. Finally, to make a specified light fall in the low frequency band gaps of the fiber, the interplay of the silica ring spacing and the air-filling fraction is analyzed.

* Corresponding author.
E-mail address: kerryqling@hotmail.com (Q.-L. Zhou).

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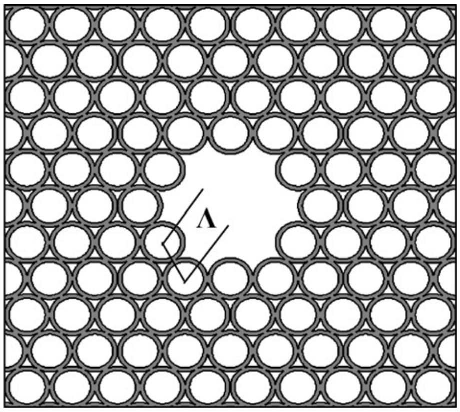

Fig. 1. The cross section of air-core photonic crystal fibers with silica rings in triangular lattice. The dark region is silica glass, the white region is air. The large air hole serves as the core. Parameters of the spacing Λ (the distance between two nearest silica rings), inner radius r and outer radius R of the silica rings are used to characterize the structure.

In order to model the cladding band structure of the fiber, a standard plane-wave method based on the full-vector nature of electromagnetic fields is employed [11]. Because in the periodic plane, the dielectric constant $\varepsilon(r)$ is position dependent, Maxwell's equations for electromagnetic fields can be simplified to:

$$\nabla \times \left[\frac{1}{\varepsilon(r)} \nabla \times H(r)\right] = \left(\frac{\omega}{c}\right)^2 H(r) \tag{1}$$

According to Bloch's theorem, magnetic field $H(r)$ can be expanded in plane waves, and the following matrix equations are obtained:

$$\sum_{G',\lambda'} H_{G,G'}^{\lambda,\lambda'} h_{G',\lambda'} = (\omega^2/c^2) h_{G,\lambda} \tag{2}$$

where

$$H_{G,G'}^{\lambda,\lambda'} = \eta(G - G')[(K + G) \times \bar{e}_\lambda] \cdot [(K + G') \times \bar{e}_{\lambda'}] \tag{3}$$

and G is a reciprocal-space vector, K is a wave vector in the Brillouin zone of the lattice, $\bar{e}_\lambda$, $\bar{e}_{\lambda'}$ are unit vectors perpendicular to $K + G$ because of the transverse nature of H (i.e., $\nabla \cdot H = 0$). $\eta(G - G')$ is the Fourier transform of $1/\varepsilon(r)$.

In this fiber, the unit cell of the periodic structure can be regarded as a silica ring in air background. Hence, $\eta(G)$ can be given:

$$\eta(G) = \begin{cases} \frac{1}{\varepsilon_a} + \left(\frac{1}{\varepsilon_b} - \frac{1}{\varepsilon_a}\right)(p_f - p_{f1}) & G = 0 \\ 2\left(\frac{1}{\varepsilon_b} - \frac{1}{\varepsilon_a}\right)\left[p_f \frac{J_1(G \cdot R)}{G \cdot R} - p_{f1} \frac{J_1(G \cdot r)}{G \cdot r}\right] & G \neq 0 \end{cases} \tag{4}$$

where $\varepsilon_a = 1.0$, $\varepsilon_b(\lambda) = n(\lambda)^* n(\lambda)$ through Sellmeier equation [12]. $p_f = \frac{\pi \cdot R^2}{2\sqrt{3}R^2}$, $p_{f1} = \frac{\pi \cdot r^2}{2\sqrt{3}R^2}$. As a result, air-filling fraction of the cladding is $1.0 - p_f + p_{f1}$.

By solving Eq. (2), the low frequency photonic band structure of the fiber can be obtained. The numerical results show that there are no photonic band gaps for the propagation in the periodic plane. This is ascribed to the small index contrast between silica glass and air. However, full photonic band gaps would open up when the out-of-plane wave vector which corresponds to the propagation constant along the fiber axis in the core is involved (see Fig. 2). Furthermore, it shows that a photonic band gap covers the "air-line" ($\beta/k = 1$). According to Refs. [5,6], "air-line" across the photonic band gap is an indispensable condition for air core PBG guidance. Therefore, we may conclude that this type fiber could be used to guide light in the air core.

By varying the propagation constant, several low frequency photonic band gaps across air-line emerge. Fig. 3 shows the band gaps as a function of in-plane wave vector along the usual principal directions in the Brillouin zone from Γ point to M point, and then to X point, finally back to Γ point. Because the fundamental band gap is quite narrow, we take the third lowest one (marked with T in Fig. 3)

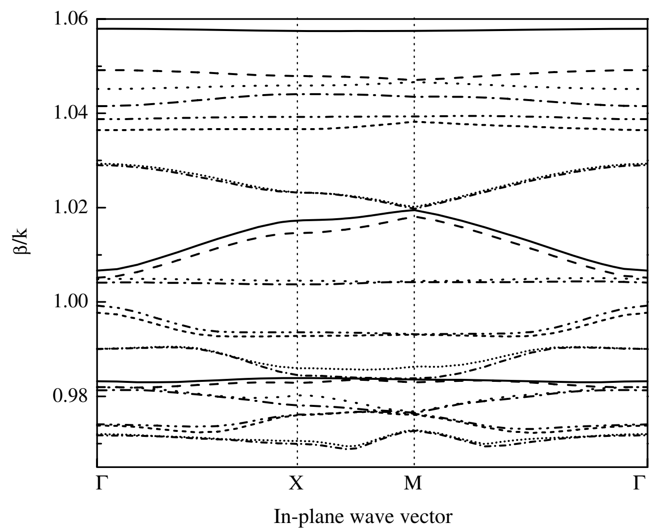

Fig. 2. Plot of the out-of-plane photonic band structure of the fiber. The air-filling fraction is 93%, spacing is 4.9 μm, and wavelength is 0.79 μm.

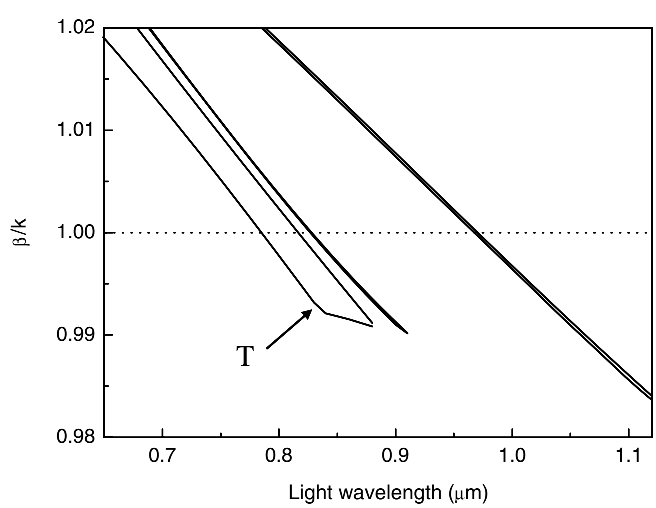

Fig. 3. Plot of β/k versus light wavelength λ. The solid curves describe the band gap edges and the dashed line is "air line" which across several band gaps. Air-filling fraction is 93%, spacing is 4.9 μm.

as an example to demonstrate the properties of the PBG of the fiber.

Fig. 4 shows the band gap edges as a function of air-filling fraction for different silica ring spacing. Here, for structure A Λ is 4.9μm and for structure B Λ is 5.5 μm. Fig. 5 shows the PBG width as a function of air-filling fraction. It is noticed that the band gap edges shift to shorter wavelength when the air-filling fraction is increased, and the band gap width decreases linearly. It is also indicated that the band gap width normalized with the spacing keeps constant for a fixed air-filling fraction. From these results, we may conclude that the center wavelength and the width of the photonic band gap are determined on both the air-filling fraction and the spacing.

To make a specified light fall in the low frequency band gaps of the fiber, the interplay of the silica ring spacing and the air-filling fraction is also investigated. Fig. 6 shows the spacing as a function of the air-filling fraction. It is found that the spacing edges increase monotonously with the increase of the air-filling fraction, and at the same time the spacing range increases exponentially (see Fig. 7). This result implies that a larger air-filling fraction allows a larger spacing deviation in fiber fabrication.

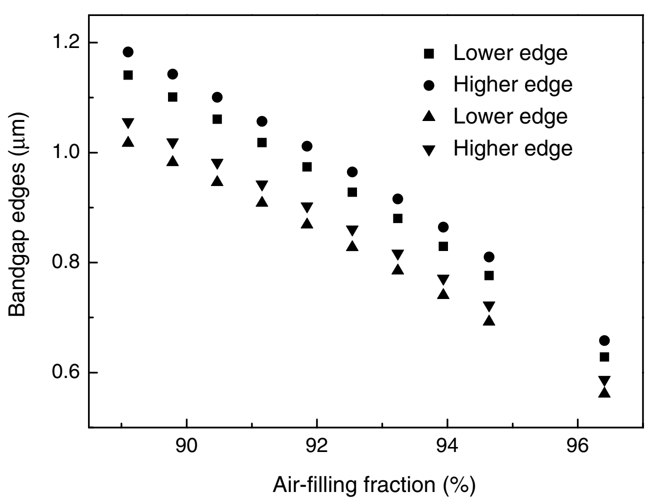

Fig. 4. The band gap edges versus air-filling fraction. The solid triangles correspond to structure A with $\Lambda = 4.9$ μm, the solid circles and squares denote structure B with $\Lambda = 5.5$ μm. Light wavelength is 0.79 μm.

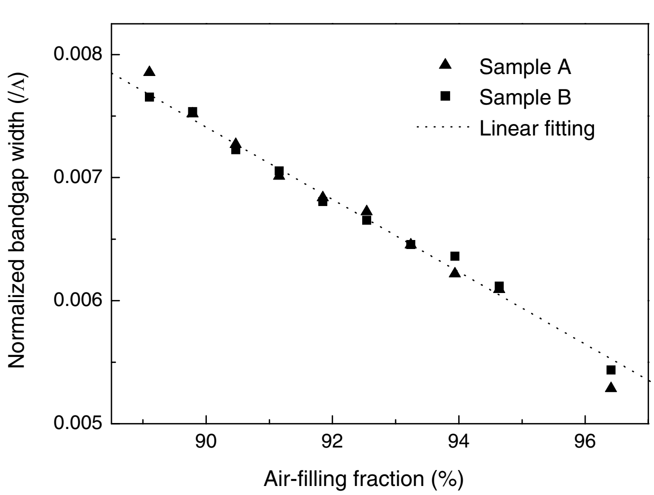

Fig. 5. The band gap width versus air-filling fraction.

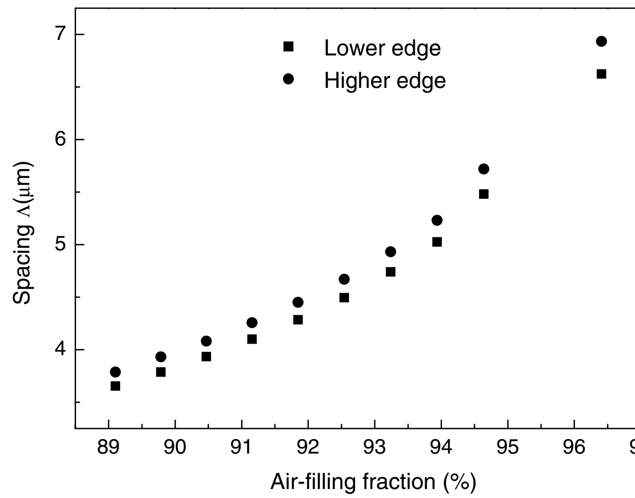

Fig. 6. Plot of the spacing as a function of air-filling fraction. Wavelength λ is 0.79 μm.

In the calculations, we also realize that there are some difficulties when this type fiber is used to guide the light within the wavelength range from visible to near infrared. This is because a much high air-filling fraction (larger than 80%) is required. But if it is used in infrared light (e.g. $\lambda = 2.7$ μm) transmission, the requirement of a high air-filling fraction is not necessary.

The transmission bands around 0.5 μm, 0.6 μm, and 0.7 μm of the first air-core PBG PCF [13] can also be explained using the theoretical model proposed above. But the transmission band around 0.8 μm of the fiber is difficult to explain. This reason needs further investigation.

Summary, the cladding band structure of air core PCFs with silica rings in triangular lattice are reported. The numerical results show that there exist complete photonic band gaps for the propagation out of the periodic plane. By increasing the air-filling fraction, the band gap edges

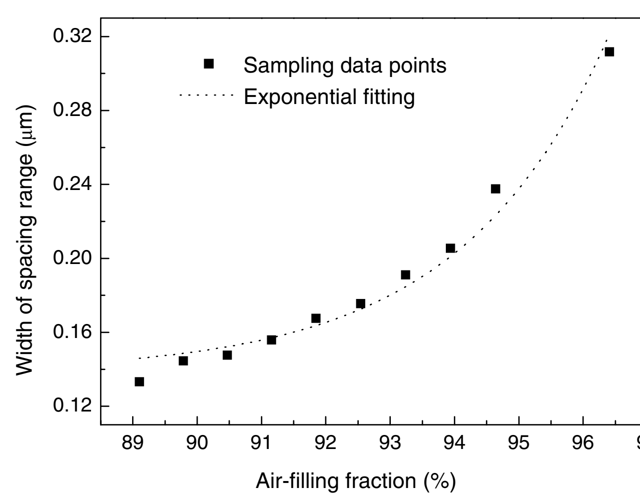

Fig. 7. The spacing range increases as a function of air-filling fraction.

of the low frequency photonic band gaps shift to shorter wavelength, and the band gap width decreases linearly. To make a specified light fall in the low frequency band gaps of the fiber, the interplay of the silica ring spacing and the air-filling fraction is also investigated. This type fiber might have advantages in infrared light transmission.

Acknowledgements

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