A dark hollow beam from a selectively liquid-filled photonic crystal fibre*

Zhang Mei-Yan(张美艳), Li Shu-Guang(李曙光)†, Yao Yan-Yan(姚艳艳), Fu Bo(付 博), and Zhang Lei(张 磊)

Key Laboratory of Metastable Materials Science and Technology, College of Science, Yanshan University, Qinhuangdao 066004, *China*

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This paper reports that, based on the electromagnetic scattering theory of the multipole method, a high-quality hollow beam is produced through a selectively liquid-filled photonic crystal fibre. Instead of a doughnut shape, a typical hollow beam is produced by other methods; the mode-field images of the hollow-beam photonic crystal fibre satisfy sixth-order rotation symmetry, according to the symmetry of the photonic crystal fibre (PCF) structure. A dark spot size of the liquid-filled photonic crystal fibre-generated hollow beam can be tuned by inserting liquid into the cladding region and varying the photonic crystal fibre structure parameters. The liquid-filled PCF makes a convenient and flexible tool for the guiding and trapping of atoms and the creation of all-fibre optical tweezers.

Keywords: liquid-filled photonic crystal fibre, fundamental mode, dark hollow beam

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1. Introduction

Optical beams with zero central intensity (also called dark-hollow beams (DHBs)) have attracted more and more attention because of their wide application in modern optics.[1] Such beams are used to guide and trap cold atoms,[2] confine Bose–Einstein condensates,[3] and create optical traps[4] and tweezers[5] for the manipulation of micro-objects, including biological species. DHBs with appropriate polarization patterns also generate optical vortices.[6] Several theoretical models have been proposed to describe DHBs, such as the TEM_{01} beam, some higher-order Bessel beams, and the hollow Gaussian beam, etc.[1,7,8]

Photonic crystal fibre (PCF) has recently gained a broad application in optical technologies. Many research efforts have been devoted to studying PCF structures for their amazing propagation characteristics, such as the endless single-mode operation,[9] tailorable dispersion,[10] high birefringence,[11] and large nonlinearity.[12] All these properties are primarily determined by the size and arrangement of the air holes in the cladding region.[13,14] Nevertheless, once a PCF is fabricated, it is hard to modulate its optical properties to function as a tunable optical device.

To introduce tunable optical properties into the PCF structures, one can infiltrate high-index liquids (or liquid crystals) into the air holes of the PCF to form the liquid-filled PCF.[15] The refractive index of the infused liquid can be varied by the operation temperature[16] or external electric field[17] to modulate the performance of the liquid-filled PCF. These tunable PCF structures can be utilized in dispersion-related devices,[18] switches,[19] filters,[20] laser sources,[21] and waveguide sensors.[22]

In this paper, we demonstrate that DHBs can be efficiently generated in a liquid-filled PCF by selectively filling the liquid into the PCF to maintain the tunability properties.

2. PCF structure and the numerical method

The core-cladding geometry of our fibre (Fig. 1) is typical of an index-guiding PCF.[23] The pitch of the PCF Λ is 1.5 μm, and the diameter D_1 of air holes in

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†Corresponding author. E-mail: shuguangli@ysu.edu.cn

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the fibre cladding is 1.0 μm. However, in addition to the standard structure of PCF, the core of our PCF features a hexagonal array of six additional air holes with a diameter D_2 of 0.4 μm running along the fibre axis. The DHBs can be generated by inserting liquid in the core and cladding region.

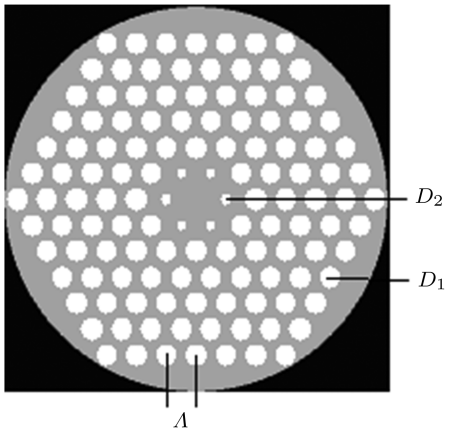


Fig. 1. Image of the photonic crystal fibre.

To manufacture these selectively liquid-filled PCFs, one must first selectively block specified air holes and infuse the liquid into the unblocked holes. One possible way is to employ the fusion splicing technique with tailored electric arc energies and fusion times.[24] The cladding region of the PCF can then be selectively fused, and the air holes are collapsed from the outer layers to the inner layers.[24] Another way to selectively plug specified air hole layers in the PCF is using microscopical position tips with glue.[25] Not only air-hole layers but a single air hole can be easily blocked by using this technique. In spite of the above methods, one can also selectively infiltrate the liquid into specified air-hole layers from a macroscopic fibre performance to a connected microstructure PCF by using an applied pressure.[26]

To analyse the properties of modes supported by such a waveguide structure, we employed the electromagnetic scattering theory of the multipole method.[27,28] The method was first used by T.P. White and B.T. Kuhlmey of the University of Sydney, Australia in the simulation of PCFs. The multipole method expresses the electric field and magnetic field component in the cylindrical coordinates system as a Bessel function, using boundary conditions to solve the Helmholtz equation. It is suitable for analysing the PCFs with a circular hole. The method uses symmetry to simplify the calculation and possesses a high degree of accuracy, fast and sufficient convergence to handle a variety of traits of optical geometric parameters. Another advantage of the multipole method is that the output propagation constant is a function of input angular frequency, and can easily take into account the material dispersion.

The multipole method can expand the mode field into the form of a Bessel function,[24] and in the interior of air holes of section l, the longitudinal electric field in polar coordinates can be expanded as

$$E_z = \sum_{m=-\infty}^{\infty} a_m^{(l)} J_m\left(k_\perp^i r_l\right) \exp(\mathrm{i}m\phi_l) \exp(\mathrm{i}\beta z). \quad (1)$$

In the adjacent medium of the air holes of section l, the longitudinal electric field can be expressed as

$$E_z = \sum_{m=-\infty}^{\infty} \left[b_m^{(l)} J_m\left(k_\perp^e r_l\right) + c_m^{(l)} H_m^1\left(k_\perp^e r_l\right)\right] \times \exp(\mathrm{i}m\phi_l) \exp(\mathrm{i}\beta z), \quad (2)$$

where $k_\perp^i = (k_0^2 n_i^2 - \beta^2)^{1/2}$, $k_\perp^e = (k_0^2 n_e^2 - \beta^2)^{1/2}$, the refractive index of air $n_i = 1$, n_e is the refractive index of quartz, $k_0 = 2\pi/\lambda$ is the wave number of free space, β is the propagation constant of the corresponding mode. The magnetic field component H_z is similar to the expression. Using the electromagnetic field boundary conditions in the interface of the air hole, we can obtain the expression of $a_m^{(l)}$, $b_m^{(l)}$ and $c_m^{(l)}$, and further obtain the effective refractive index n_{eff} of the mode through $\beta = n_{\mathrm{eff}} k_0$.

3. Results and discussion

We first consider fundamental modes based on the PCF without liquid-filling. By utilizing the electromagnetic scattering theory of the multipole method, we can obtain the energy flux distribution of the fundamental mode at various wavelengths. Figure 2 shows the energy flux distribution of the fundamental mode in the PCF without liquid-filling for $\lambda = 1.55$ μm. As can be seen from these calculations, the energy flux in the fundamental modes of the PCF is confined within the centre bounded by the hexagonal array of air holes.

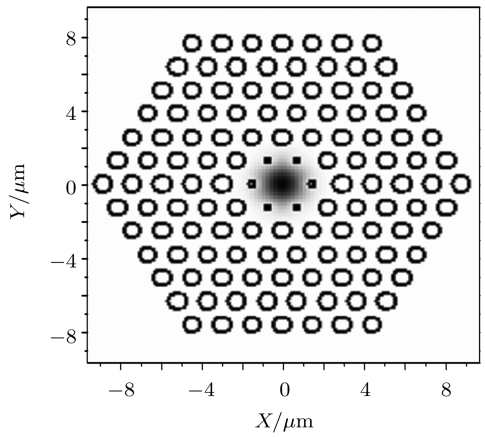


Fig. 2. Energy flux distribution for the fundamental mode in the PCF without liquid-filling for $\Lambda = 1.55$ μm.

We consider the same PCF with liquid-filling, and the refractive index of the liquid n_q is 1.33. First, we theoretically investigate the PCF with liquid-filling in the first air-hole layer. Figure 3 shows the energy flux distribution for the fundamental mode in the PCF with liquid-filling in the first air-hole layer at a wavelength of 1.55 μm. From the simulation result, it can be seen that the DHBs can be generated in the PCF with liquid-filling in the first air-hole layer. Although the structure of PCF satisfies sixth-order rotation symmetry, the mode-field image of the hollow-beam does not satisfy sixth-order rotation symmetry.

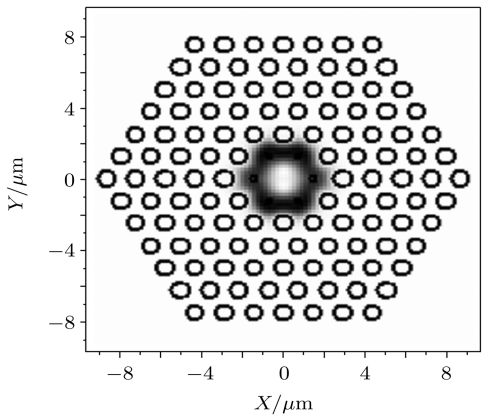


Fig. 3. Energy flux distribution for the fundamental mode in the PCF with liquid-filling in the first air-hole layer at a wavelength of 1.55 μm.

Second, we consider the second layer of air holes filled with liquid; figure 4 shows the energy flux distribution of the fundamental guided mode at wavelengths of 1.55 μm. The mode-field image of the hollow-beam also does not satisfy sixth-order rotation symmetry, and the energy flux distribution spreads out to the second layer of air holes filled with liquid.

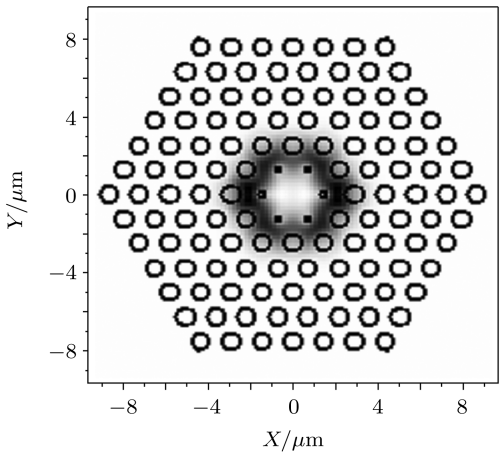


Fig. 4. Energy flux distribution for the fundamental mode in the PCF with liquid-filling in the second air-hole layer at a wavelength of 1.55 μm.

Third, considering the first and second layers of air holes filled with liquid, we can obtain the energy flux distribution of the fundamental guided mode at a wavelength of 1.55 μm. As shown in Fig. 5, a cleaner DHB is obtained in the liquid-filled PCF, and the dark spot of DHBs is almost the same size as the fibre core.

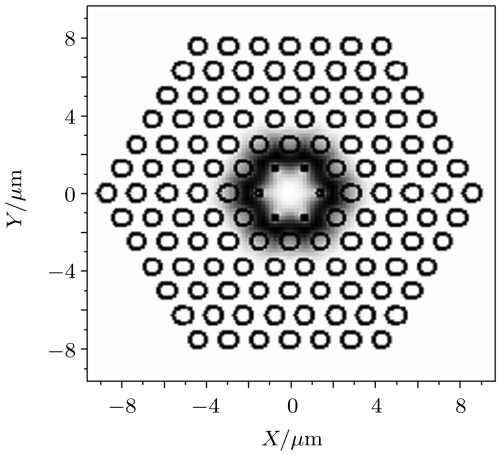


Fig. 5. Energy flux distribution for the fundamental modes of the PCF with liquid-filling in the first and second air-hole layers for $\lambda = 1.55$ μm.

Then we consider that the third layer of air holes is filled with liquid, and the third layer filled with liquid forms the outer core in the PCF. We can obtain the energy flux distribution of the fundamental mode as shown in Fig. 6. Power is well confined in the outer core region at different wavelengths, and DHBs can be efficiently generated in the outer liquid-filled air-hole layer. The size of the dark spot depends on the outer liquid-filled air-hole layer. So we can adjust the size of the dark spot by filling with liquid in the different air-hole layers of the outer core.

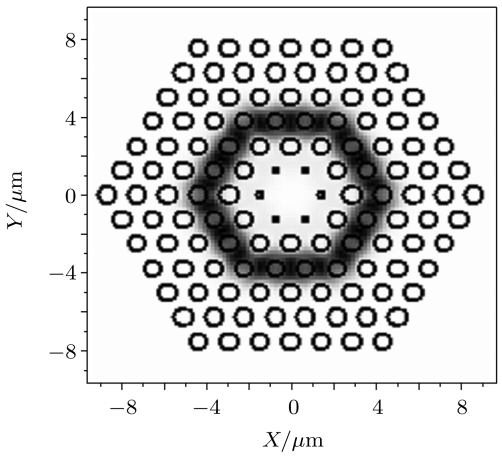


Fig. 6. Energy flux distribution for the fundamental mode of PCF with liquid-filling in the third air-hole layer for $\lambda = 1.55$ μm.

Then, we consider that the first and third layers of air holes in the PCF are filled with liquid, and the third layer forms the outer core in the PCF. As shown in Fig. 7, a double-circle beam has been formed at a wavelength of 1.55 μm. The power of the outer circle is larger than the inner circle in the PCF with liquid-filling in the first and third air-hole layers.

Figure 8 shows the wavelength range of DHBs which are generated by the liquid-filled PCF. Figure 8(a) shows the modal effective indices of fundamental guided modes for the liquid-filled PCF with the first air-hole layer, the third air-hole layer and the second air-hole layer, respectively. The wavelength range of PCF with liquid-filling in the third layer is smaller, and DHBs start from 1.30 μm.

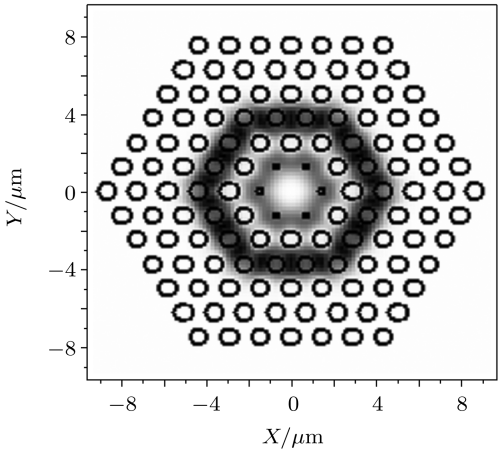


Fig. 7. Energy flux distribution for the fundamental mode of the PCF with liquid-filling in the first and third air-hole layers for $\lambda = 1.55$ μm.

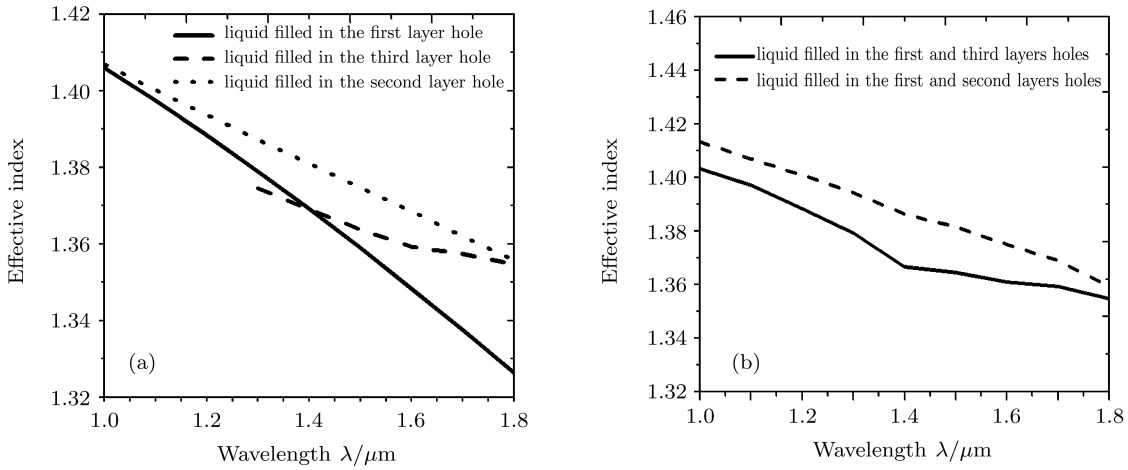


Fig. 8. The effective indices of fundamental guided modes (a) the liquid-filled PCF with only one air-hole layer; (b) the liquid-filled PCF with two air-hole layers.

In Fig. 8(b), the solid lines represent the effective index of mode in the PCF with liquid-filling in the air-holes of the first and third layers, and the dashed lines represent the effective index of mode in the PCF with liquid-filling in the air-holes of the first and second layers. From Fig. 8(b), we can see that the effective index of mode in the PCF with liquid-filling in the air holes of the first and second layers is consecutive, but the effective index of mode in the PCF with liquid-filling in the air holes of the first and third layers has an inflexion. What characteristics do mode field distributions have in this case? The mode field distribution of the PCF with liquid-filling in the air holes of the first and third layers at wavelengths of 1.30 μm and 1.70 μm is shown in Figs. 9(a) and 9(b). At the wavelength of 1.30 μm, the mode field concentrates on the region of the first layer which is filled with liquid, while at the wavelength of 1.70 μm, the mode field concentrates on the region of the

third layer which is filled with liquid. That is to say, for a fibre with the same structure and liquid-filling, the mode field concentrates on the inner layers for short waveband, while the mode field distribution concentrates on the outer layers for L-band. According to the translational nature of the electromagnetic field in waveguide, the hollow beam at different liquid-filled layers can be achieved by scaling up or down the structure parameters of PCF. Thus, the diameter of the hollow beam for different bands can be adjusted flexibly.

Compared with the DHBs, which are generated in the liquid-filled PCF, we can obtain different dark spot sizes of the hollow beam by varying the PCF structure parameters and filling with liquid in the different air-hole layers. So the new method is used to manipulate and trap the special micro-objects. The proposed liquid-filled PCF offers an extensive prospect for the application of DHBs in atomic optics and other fields.

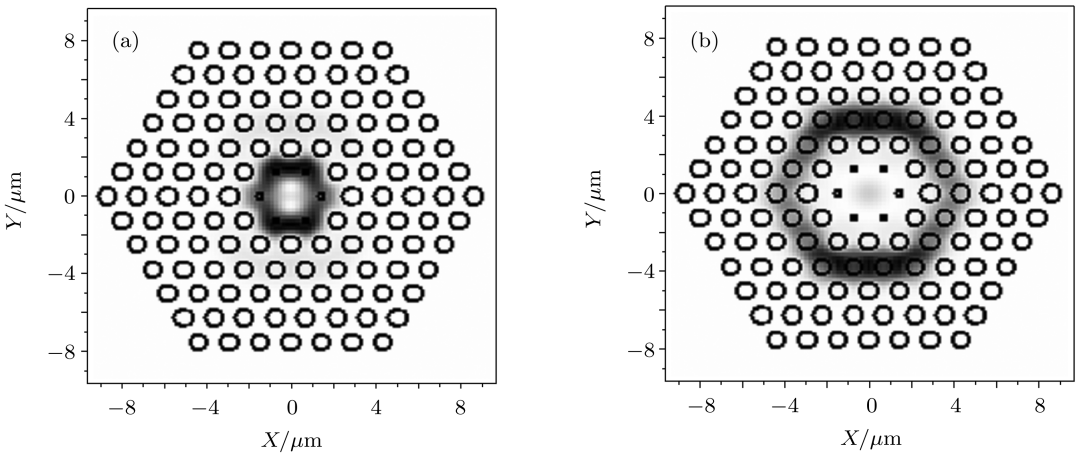


Fig. 9. Energy flux distribution for the fundamental mode of the PCF with liquid-filling in the first and third air-hole layers for $\lambda = 1.30$ μm (a) and 1.70 μm (b).

4. Conclusions

Using the electromagnetic scattering theory of the multipole method, we first compared the energy flux distributions of the fundamental mode based on a PCF without liquid-filling and a selectively liquid-filled PCF. It can be seen that our proposed selectively liquid-filled PCF can efficiently generate DHBs in different wavelength ranges. In order to manipulate different micro-sized particles, it is necessary to obtain different size dark spots. Thus, we considered inserting liquid in the cladding air-holes of different layers. We can not only change the size of the dark spot by inserting liquid in the cladding region and varying the PCF structure parameters, but also obtain DHBs within a wide wavelength region. This makes a liquid-filled PCF a convenient and flexible tool for guiding and trapping atoms and the creation of all-fibre optical tweezers.

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