A Novel Hollow-Core Holey Fibre with Random Hole Distributions in the Cladding *

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We provide a novel hollow-core holey fibre that owns a random distribution of air holes in the cladding. Our experiments demonstrate that many of the features previously attributed to photonic crystal fibres with perfect arrangement of air holes, in particular, photonic bandgap guidance, can also be obtained in the fibre. Additionally, this fibre exhibits a second guided mode with both the two-lobe patterns, and each pattern is in different colour.

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Photonic crystal fibres (PCFs) or holey fibres (HFs) have been revolutionizing fibre-optic design and performance for years.[1−4] A typical PCF structure is composed of glass or air core and glass–air cladding with periodic distribution of air holes. There are two kinds of photonic crystal fibres. One is the so-called index-guiding PCF,[5,6] in which air holes act to lower the effective refractive index in the cladding region, so light can be confined to the high-index solid core by the total internal reflection (TIR) mechanism. Another is the photonic band gap PCF,[7,8] in which the air core breaks the periodicity of the cladding, acting as a defect. The air core can guide light within the forbidden frequency windows of the cladding. This kind of fibres represents a radical departure from conventional optical fibres and theoretically exhibits many exclusive features, such as low loss optical transmission, delivery of solid particles, and gas sensing.[9−11] Previous research on photonic band gap PCFs mainly focused on near-perfect fibres, in which the air holes that define the cladding region were arranged on a periodic lattice. Reference [7] presented a photonic band gap PCF with a honeycomb array of air holes.

However, the guided modes reside mostly in glass in the core region, which appears to be a fundamental limitation of the honeycomb design. Reference [8] showed a new fibre in which the air holes were on simple triangular lattices. Only certain wavelength bands are confined and guided down the hollow core of the fibre, and the guided mode is a single transverse mode. These features make this kind of fibres most promising to guide ultrahigh-power laser, or deliver cold atoms. Currently, almost all works in the area (theoretical or experimental) have actually concerned on periodic structures. However, periodic conditions are not a prerequisite to photonic band gap effects.[12,13] In this letter, we experimentally demonstrated a photonic band gap guidance in a new kind of fibres with random distributed air holes in cladding.

The F2-type silicate glass (Schott type F3) was chosen for preparation of our fibre. This kind of glass has higher refractive index ($n = 1.6128$), which is important to the presence of photonic band gap. In the previous experiments, silicate glasses have also been used to design index-guiding photonic crystal fibres.[14] Tubes of F2 glass were pulled down to capillaries. These capillaries own different external diameters (from 1 mm to 1.2 mm) and internal diameters (from 0.5 to 0.8). The fibre preform was obtained by closely stacking together several-hundred capillaries into an approximate circular structure. Because the constructed capillaries are in different scales, the air holes are randomly dispersed. By introducing a large air hole in the centre of the preform, the fibre core can be formed. The air hole was created by replacing several capillaries in the centre of the preform with a thin-walled glass tube. This tube was made from low refractive index silicate glasses ($n = 1.5600$).

The whole structure was then fused together and pulled into fibres through a traditional fibre drawing tower. In the end, several hundred metres length of fibre with outer diameter of 200 μm was obtained. The final fibre cladding consists of a random array of air holes in F2 glass, with interstitial holes that result from the surface stress of stacking capillaries. The cross-section of the fibre is shown in Fig. 1. As can be seen, the fibre core is elliptic, which can be attributed to the different directional stresses originated from random arrangement of capillaries. The air holes in the cladding region have different shapes and scales.

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The length of the major axis of the core is 27 μm; the hole diameter d is from 1.5μm to 5μm, and the hole pitch Λ (centre-centre spacing of holes) from 4μm to 8μm.

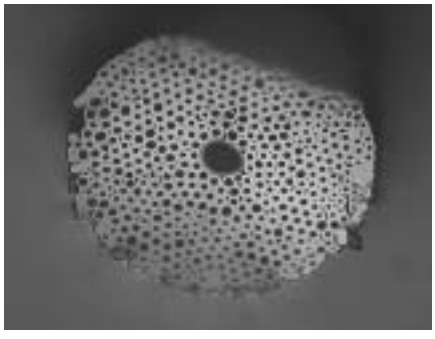


Fig. 1. Optical micrograph of the cleaved end-face of our typical hollow-core photonic crystal fibre.

By holding 4-cm-long fibres vertically on a side of slide, we illuminated them in the following with a white light source (tungsten halogen lamp) through an objective lens with a number aperture of 0.20. By carefully adjusting the angle of the fibre axis to objective lens axis, the light transmitted through the fibre core can be observed in an optical microscope, as shown in Fig. 2. The central air core is filled with coloured light. The coloured light region was divided into two parts along the major axis of the elliptic core, one is dominated by red light, and the other is filled with green light. Their mode transverse profile is smooth, with intensities peaked in the centre, and falling off at the boundary. In comparison with the mode trapped in the core, a significant amount of white light is present in the cladding, and it appears colourless.

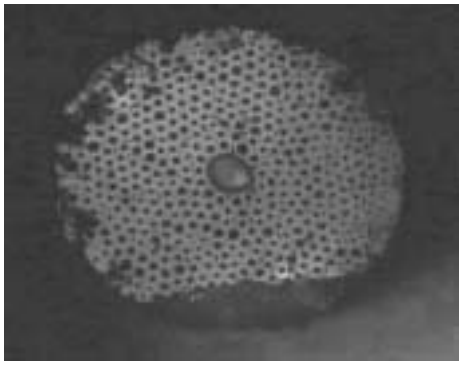


Fig. 2. Optical micrograph of the field intensity pattern at the output end of a 3-cm-long fibre, with white light input into the entrance face.

We examined the transmitted patterns by launching into the fibre with white light sources with different wavelength ranges. In any case, the colours of modes are red and green, indicating that guidance existed in restricted bands of wavelength, coinciding with the photonic band gap effect. Although there is a random distribution of air holes in the cladding, several photonic band gaps can exist in it, and the fibre core acts as a 'defect', capturing defect mode. That is, the red and green light can propagate along the defect. As can be seen from Fig. 2, the red and green are not unicolour, but a mixture of different colours and spanning a wide range of the spectrum, though the span can not be determined. Because the fibre core is elliptic, we investigated the dependence of guided modes on the direction of the major axis by rotating the fibre around the fibre core. We found that the two modes sometimes disappear. At some cases, the two patterns were still distributed along the major axis, though the relative colours, intensities and positions of modes altered slightly.

A direct coupling method was used to determine the transmission spectra. The white light was focused on cross section of the fibre by means of a confocal microscope system. The output light from the fibre was collected by an objective lens with a number aperture of 0.30, and then transmitted through a conventional multimode fibre to an optical spectrum analyser. By carefully adjusting the angle of the fibre axis to objective lens axis and repeatedly measuring the spectra, we obtained the intensity spectra of the light transmitted through the fibre. Among all the spectra, a spectrum was chosen as an approximate transmission spectrum, because there exist two transmission bands that are different from the spectrum of white light, as shown in Fig. 3. Between these transmission bands, there is a stop band. The intensity of the stop band is low, but far above zero, which may be a contribution from the white light in the cladding.

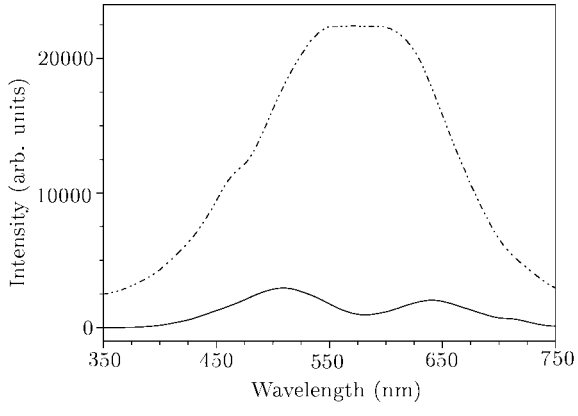


Fig. 3. Difference between the intensity spectrum of white light transmitted through the fibre (solid curve) and the spectrum of white light.

There is a special difference between our PCF and other kinds of photonic band gap PCFs. In the previous work about photonic band gap PCFs, the fibre core is always filled with one unicolour pattern, though the colour is a mixture of different colours. However, in our study, two patterns coexist with dif-

ferent colours. To clarify the mechanism, we launch into a 4-cm-long sample with a beam of focused He–Ne laser. The laser is just falling into the wave band of the transmitted mode. Thus, by this near-monochromatic light, we can determine the mode field distribution in the fibre core.

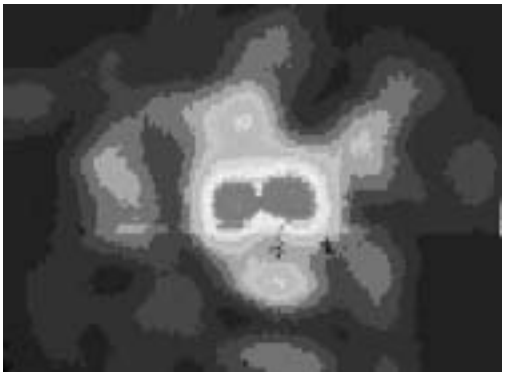


Fig. 4. Near-field pattern of the guided mode in the fibre at 632 nm.

We then used a beam diagnostics measurement system, BeamView Analyzer^{EM} (Coherent Inc.), to record the near-field patterns of the guided mode at the output end of the fibre. Figure 4 shows a contour map of the near-field pattern at 632 nm that we recorded by imaging the output end of the fibre onto the analyser. This plot clearly shows a second guided mode with two-lobe pattern. The intensity of one lobe seems to be higher than the other. Using this method, we also examined the near-field patterns of the guided mode at 532 nm, and the result is similar to that in Fig. 4. From the above demonstration, we confirm that this fibre is in the second-order mode. From the viewpoint of symmetry, the ellipticity of core is directly responsible for the asymmetric mode field distribution. We observed such confined modes in a variety of samples with similar cross sections to those in Fig. 1. However, there are many samples that were cut from different parts of the same fibre and cannot exhibit guidance, which was attributed to fluctuation of the fibre parameters, such as the core diameter and the hole pitch. The fibre cross-section and fibre parameters are dependent on the drawing conditions. Fluctuations in the fibre parameters can cause the photonic band gap close or open up. Due to this reason, we cannot systematically study the losses of the fibre. A qualitative study of the losses was demonstrated by coupling lasers with different wavelengths into the fibres. Almost 7% of the laser beam at 532 nm and 4% at 632 nm can be transmitted through a 4-cm-long fibre. We attribute the main reason for the loss to the input coupling efficiency. The random cladding PBG fibre presents higher losses in comparison with the periodic cladding PBG fibre. Besides the randomness of the cladding structure in our fibre, the higher loss may also be ascribed to the influence of drawing conditions and the contamination of perform by dust. The losses can be readily reduced by using high-quality glass tubes, precisely controlling the drawing conditions, and improving the grade of super-clean room.

We have fabricated a novel hollow core holey fibre that owns a random distribution of air holes in the cladding. By launching white light into the fibre core, and examining the output mode, we demonstrated that this fibre guided light in separated bands of wavelength, coinciding with photonic band gap effects. At the same time, this fibre exhibits a second guided mode, and each of lobes of pattern appears different colours.

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