Low-loss single-mode negatively curved square-core hollow fibers

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We introduce a novel design of anti-resonant fibres with negative-curvature square-cores to be employed in 1.55 and 2.94 µm transmission bands. The fibres have low-losses and single-mode operation via optimising the negative-curvature of the guiding walls. The first proposed fibre shows a broadband transmission window spanning from 0.9 to 1.7 µm, with losses of 0.025 and 0.056 dB/m at 1.064 and 1.55 µm, respectively. The second proposed fibre has approximately 0.023 dB/m guiding loss at 2.94 µm with a small cross-section area, useful for laser micromachining applications. © 2017

Microstructured hollow-core fibres (HCFs) have enabled a wide range of novel optical applications in both the linear and nonlinear regimes [1–6]. Silica solid-core fibres intrinsically possess a low-damage threshold and high absorption in the mid-infrared regime, hampering, for instance, the transmission of intense pulses with 2.94 µm central wavelength generated by Er:YAG lasers. HCFs have circumvented these problems by simply allowing free linear propagation away from any material loss. Moreover, by filling HCFs with gases or liquids the field of nonlinear fibre optics can be extended beyond the conventional solid media [4, 6].

Light is guided inside the low-index HCF via either the photonic bandgap (PBG) effect, or via anti-resonant effects. In the former category, the concept of forbidden bands in periodic solid crystals has been employed to prohibit the propagation of certain optical frequencies through the fibre cladding. In the latter category, anti-resonant Fabry-Perot modes have been harnessed in order to guide light in a thick low-index core surrounded by a thin high-index cladding [7–9]. These fibres are characterised by having a broad transmission band in comparison to the PBG fibres, however, with much higher losses. Many new interesting ideas in fibre-design have been proposed to dramatically suppress the attenuation coefficient of the anti-resonant (AR) HCFs, while maintaining its broad transmission window, for instance, by employing multi-capillary tubes [10], adding an extra optimised outer cladding [11], or exploiting suitable negatively curved cores [12–14].

A common main drawback of HCFs is the excitation of higher-order modes (HOM) with guiding losses comparable to the fundamental mode. For example, an omniguide fibre has shown an ultra low-loss of TE\textsubscript{01} mode at 1.55 µm together with a low-loss TE\textsubscript{02} mode [15]. This substantially limits the usefulness of the fibre for linear as well as many nonlinear applications due to the cross-coupling between different modes. Few recent works have been devoted towards inhibiting HOM excitations, for instance, by using multiple tubes arranged in a heptagonal symmetry [16], or few odd number of non-touching tubes [17], or elliptical capillaries [18]. Yu et al. have also designed a seven-capillary tube fibre with LP\textsubscript{11}-free, however, LP\textsubscript{21} mode shows guiding loss of 2 dB/m in the visible region [19]. Alternatively, by using phase-matched coupling between HOM and cladding modes in a chalcogenide negative-curvature fibre, a large loss ratio between HOM and the fundamental mode in the surrounding tube was obtained [20]. Also, a 6-capillary AR-HCF was demonstrated to perform robustly in single-mode condition with a 112 THz bandwidth, and a guiding loss of 0.18 dB/m at 1.6 µm [21]. The figure of merit of this fibre defined as FOM\textsubscript{lm} = α\textsubscript{lm} / α\textsubscript{01} - 1, where α\textsubscript{lm} is the loss of the LP\textsubscript{lm} core mode, reaches a value of almost 1000. All these fibres, with different extents, suffer from either the complexity of the design, relatively high fundamental mode loss, low FOM\textsubscript{lm}, or narrow operating bandwidth.

In this Letter, we propose a novel kind of anti-resonant fibre, where the hollow-core has a negatively-curved square shape. The fibre has a second surrounding tube that encompasses the core to form four eye-like hollow-cladding areas, see sketch of the fibre in Fig. 1 (a). The fibre design is similar to the one with non-touching core walls that has been recently suggested for large-birefringence applications [22]. The fibre walls are made of silica and have a thickness \( t \). The outer tube could be drawn from a thicker one. A negative curvature is applied to obtain a low confinement loss [12, 13] and to allow coupling between higher-order core modes and cladding modes. Also, the negative-curvature reduces the Fano-resonance related losses.
by moving the mode field as far as possible from the nodes located at the four corners. The radii of the core, surrounding tube, and negative curvature are denoted by \( r_{\text{core}}, r_{\text{tube}} \) and \( R_{NC} \), respectively, where \( r_{\text{tube}} = s/\sqrt{2} - \sqrt{R_{NC}^2 - s^2}/2 \) and \( s = r_{\text{core}} + R_{NC} + t \). An extra polymer jacket tube with a thickness multiple times \( t \) could be also added to lessen the fibre brittleness. Figure 1(b) illustrate the typical fundamental mode \( LP_{01} \) of the fibre core.

Precise positioning of six-hollow capillaries in a microstructured fibre cladding has been done by stacking the six capillaries at the apices of a glass tube with a hexagonal inner structure, and drawing it to a fibre in two steps [21]. Likewise, four capillaries at the corners of a glass tube with a hollow square structure (available e.g. from Ohara Corporation) could then be stacked and drawn to fibre while pressurizing the capillaries to blow them up until they touch each other and form a structure similar to Fig. 1 (a).

We present two fibres with the same design but different parameters for various applications. The first is a single-mode broadband fibre that covers wavelengths \( \lambda = 1.55 \mu m \) and 1.064 \( \mu m \), and is useful for nonlinear applications where broadband guidance is crucial to guide ultrashort pulses effectively. The second fibre is designed to operate at 2.94 \( \mu m \), beneficial for laser micromachining and CW applications. In comparison to the previous designs [19–21], (i) each fibre is capable of guiding light with very low losses \( < 0.1 \text{dB/m} \) over a wide transmission window; (ii) higher-order modes are also strongly suppressed by optimising the fibre geometrical parameters, allowing for single-mode operation; (iii) the used number of elements is significantly reduced; (iv) the fibre has a relatively-small core to increase the light intensity. All these advantages would definitely result in a better alternative microstructure fibre for multiple applications.

As explained in our previous work [24], transmission losses have a strong dependence on the surrounding tube thickness \( t \). Light will escape outside the core if the tube has an incorrect thickness, substantially deteriorating the fibre performance. The numerical simulations in this Letter are performed by COMSOL software, based on finite element method. Perfectly matched layer is properly laid outside the outer tube to calculate the fibre losses. Material absorption losses have not been included since they are not relevant for the wavelength used here, similar to what is done in recent studies [25].

We aim first to guide light at \( \lambda = 1.55 \mu m \) in a single-mode fibre over a broad range of optical frequencies with very low transmission losses. Litchinitser et al. have found that the bandwidth of the AR transmission windows decreases with the window order. Therefore, we have employed the zeroth-order AR window by choosing the wall thickness \( t = \lambda/4\sqrt{\pi} - 1 = 372 \text{nm} \) in order to obtain the widest possible transmission band, with \( n \) the refractive index. To achieve single-mode operation, higher-order \( LP_{11} \) modes that have the second lowest losses could be eliminated via phase-matched coupling between these modes and the fundamental mode of the hollow-claddings. This can be realised by changing the radius of negative curvature \( R_{NC} \). Figure 2 shows the dependence of the guiding loss of the fundamental mode \( LP_{01} \), and the FOM\(_{11} \) of the \( LP_{11} \) mode with the lowest loss within its family on the negative curvature \( R_{NC} \).

In the range from 38.9 \( \mu m \) to 39.4 \( \mu m \), the FOM\(_{11} \) is over 500, which shows a feasible fabrication tolerance for the optimum \( R_{NC} \).

With increasing \( R_{NC} \), \( a_{01} \) still shows very small values in the range of \( \approx 0.1 \text{dB/m} \), except few peaks that arise from coupling between the fundamental-core and cladding modes [13, 24].

Within the higher-order \( LP_{11} \) mode group, the two non-degenerate \( HE_{21} \) modes [26–28] have the lowest loss with a spatial transverse profile displayed in Fig. 3(a). The two modes are distinguished by their spatial distribution of the electric field that are opposite to each other inside the cladding areas. Using the method described in Ref. [21], the cladding mode has been computed as shown in Fig. 3(b). To explain the fibre single-mode performance, if \( R_{NC} \approx 39.13 \mu m \) is chosen, we plot the dependence of the effective indices, and losses of the two \( HE_{21} \) modes and the fundamental cladding mode on the negative curvature in Fig. 3(c,d). Around \( R_{NC} = 39.13 \mu m \), the two modes have very close anti-crossing refractive indices that allow strong coupling with the cladding mode, resulting in large FOM\(_{11} \). Moving away from this optimised value, only one of
The two modes can be coupled, since the refractive index of the cladding mode has an asymptotic-like behaviour as depicted in Fig. 3(c). Consequently, the fibre single-mode performance is deteriorated.

We have also investigated the effect of using other negative-curvature polygon-cores on the single-mode operation with \( r_{\text{core}} = 15 \, \mu m \). In case of a triangular-core, there is also an optimised value of \( R_{NC} \) that results in \( \text{FOM}_{11} = 160 \) and \( \alpha_{01} = 0.18 \, \text{dB/m} \). For polygon-cores with more than four sides, coupling between \( L_{l1} \) mode and cladding mode is not allowed, similar to recent microstructured fibres with more than seven capillary tubes [17]. Therefore, square-core fibres has attained the best performance.

Our fibre design for 1.55 \( \mu m \) is uniquely characterised by single-mode operation over a broadband transmission window. The wavelength dependence of the \( \alpha_{01} \) and \( \text{FOM}_{11} \) is portrayed in Fig. 4. Remarkably, the fibre transmission window with losses below 0.1 \( \text{dB/m} \) and \( \text{FOM}_{11} \) larger than 200 extends approximately from 0.9 to 1.7 \( \mu m \). Furthermore, the fibre loss at 1.064 \( \mu m \) is only 0.025 dB/m, very similar to the recent ‘pizza’-like fibre (0.022 dB/m) that has large number of geometrical elements [19]. This broadband transmission is obtained, because the thickness of the surrounding tube satisfies the zeroth-order AR. For instance, if we increase this thickness to 27\( \mu m \), we would maintain the single-mode and ultra-low loss operation. However, the bandwidth is dramatically suppressed to \( \approx 100 \, \text{nm} \). We also check the permissible tolerance of wall thickness \( t \) during fabrication. The effect of increasing (decreasing) \( t \) by 10% at \( \lambda = 1.55 \, \mu m \) is that \( \alpha_{01} \) remains almost unchanged, \( \text{FOM}_{11} \) drops to 830 (760), the bandwidth is shifted to 1.05 – 1.7 \( \mu m \) (0.8 – 1.65 \( \mu m \)), confirming a good robustness of the fiber design.

The parameters of the square-core AR-HCF can be modified for low-loss single-mode operation at \( \lambda = 2.94 \, \mu m \) generated by the powerful Er:YAG lasers. In comparison to the ‘pizza’ fibre [29, 30], we have designed our fibre with a smaller cross-section area \( (r_{\text{core}} = 30 \, \mu m) \) to enhance light intensity in the core, which is of course crucial for micromachining applications. We have explored the dependence of \( \alpha_{01} \) and \( \text{FOM}_{11} \) on the anti-resonant order \( l \) that equivalently represents the wall thickness \( t \). The optimal \( R_{NC} \) value for \( l = 0, 1, ..., 5 \) is first determined, as shown in Fig. 5(a). The corresponding \( \alpha_{01} \) and \( \text{FOM}_{11} \) are then computed, see Fig. 5(b). Very remarkably, the losses of the fundamental mode \( \alpha_{01} \) are approximately independent on \( l \) \( (\approx 0.023 \, \text{dB/m}) \) and \( \text{FOM}_{11} \) is greater than 1000 for the first five orders. This effect relaxes the fabrication constraints and provides a wider choice of the wall thickness.

In order to gain a better understanding of the coupling between the fundamental core mode and the higher order modes in the cladding, we transform the eye-like hollow-clad into a ring with the same area. The ring has a radius \( r_{\text{eff}} \) that depends on \( r_{\text{core}}, R_{NC}, l \), see Fig. 6 for a visual explanation of the equivalence. Figure 5(a) shows also the dependence of \( \alpha_{01} \) and \( \text{FOM}_{11} \) on the AR orders \( l \). Surprisingly, this ratio has very narrow range from 0.845 to 0.87. The same conclusion would be obtained if the modal distributions rather than the eye-like areas are transformed. Similarly, if we apply this process for the aforementioned fibre used to guide light at \( \lambda = 1.55 \, \mu m \) with \( l = 0 \), we get \( l = 0.845 \). This demonstrates that our proposed square-core AR-HCF has a universal geometrical ratio (0.845) that robustly enables low-loss single-mode operation at any arbitrary wavelength. This technique transforms our fibre to a conventional

![Fig. 3.](image-url) (Color online). (a,b) The transverse profiles of an \( HE_{21} \) and fundamental hollow-cladding modes with \( R_{NC} = 39.13 \, \mu m \). Dependence of (c) effective indices and (d) losses of the cladding (dotted red) and the two \( HE_{21} \) modes (solid blue). Other simulation parameters are the same as in Fig. 2.

![Fig. 4.](image-url) (Color online). Wavelength-dependence of \( \alpha_{01} \) (blue) and \( \text{FOM}_{11} \) (green) of the single-mode square-core AR-HCF. The simulation parameters are \( \lambda = 1.55 \, \mu m, r_{\text{core}} = 15 \, \mu m, t = 372 \, \text{nm} \), and \( R_{NC} = 39.13 \, \mu m \).

![Fig. 5.](image-url) (Color online). Dependence of (a) the optimal \( R_{NC} \) (blue circles) and \( \tau \) (green triangles), (b) \( \alpha_{01} \) (blue plus) and \( \text{FOM}_{11} \) (green cross), on the first six anti-resonant orders. The simulation parameters are \( \lambda = 2.94 \, \mu m \), and \( r_{\text{core}} = 30 \, \mu m \).
one with a hollow-core surrounded by four circular capillary tubes, similar to the six-capillary fibre with a universal ratio 0.68 \[21\]. In fact, this geometrical-area equivalence technique introduces a roadmap to explore other novel single-mode AR-HCFs with complicated cladding geometries.

In conclusion, we have introduced a novel design of anti-resonant fibre made of a hollow square core enclosed by a surrounding tube. The silica square-core side walls are negatively curved with an optimal radius of curvature in order to achieve single-mode low-loss operation via coupling higher-order core modes with the fundamental hollow-cladding mode. We have designed the fibre dimensions to operate in two different cases around 1.55 \(\mu\)m and at 2.94 \(\mu\)m wavelength range. Using the geometrical-area equivalence method, we have proven that the two fibres low-loss and single-mode performance have high robustness against the wall anti-resonant thicknesses, allowing for high-flexibility during fabrication. The first fibre has a broadband transmission window ranges from 0.9 to 1.7 \(\mu\)m, with propagation loss 0.025 and 0.056 dB/m at 1.064 and 1.55 \(\mu\)m, respectively. The second fibre has also low guiding loss approaching 0.023 dB/m at 2.94 \(\mu\)m and a small cross-section area for high field intensity applications. We believe that our design will potentially drive new experiments and pave the route for demonstrating a wide range of novel optical applications.

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REFERENCES

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