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Towards high-index-glass based monomode holey fibre with large-mode-area

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A high-index (n=1.80) glass based holey fibre was fabricated. The conventional capillary-stacking technique was used to make this fibre characterized by a complicated microstructured cladding. Monomode guidance was observed at 800nm in this fibre and the effective mode area A_{eff} was measured as ~ 40μm^2.

Introduction: The invention of the first silica holey fibre (HF) [1] has generated broad interest due to the novel applications offered by this new type of optical fibre [2]. The combination of wavelength-scale features of the microstructured cladding and the large-index contrast between the background material and the air, results in a broad range of optical properties in HFs. Moreover, high-index non-silica glass based HFs have also been developed [3, 4] and shows their unique advantages over silica HFs particularly in the applications of highly nonlinear optical fibre. Non-silica glasses offer higher refractive index and higher nonlinear refractive index than silica glass. The highest nonlinearity in optical fibres at 1.55μm, 640 W^{-1}km^{-1}, has been recently reported in an extruded HF based on high-index Schott SF57 glass [5].

Interestingly, almost all the non-silica glass holey fibres have relied on the extrusion technique to fabricate a microstructured fibre preform [4-7], while a conventional capillary-stacking technique, i.e., simply repeating stacking glass capillaries to obtain a fibre preform with periodical holey array, has been used for the fabrication of silica holey fibres [1]. Inherent to the extrusion technique [8], it is technically difficult to achieve very complicated microstructured cladding in the preform. As a result, the reported non-silica glass based HFs mainly have small-core, large air-filling fraction and less than 20 holes. Since the novel optical properties of holey fibres, such as bandgap effect, and endless single-mode guidance with large mode area [1, 2], arise from the complicated and periodically-arrayed holey cladding, it is undoubtedly important to find a simple fabrication technique to achieve the desired microstructured preform. Since the capillary-stacking technique [1,2] has shown its flexible ability to achieve this aim in silica HFs, it should also be suitable for fabricating non-silica HFs. Additionally, the procedure of capillary-stacking will permit fabricating HFs by the automated fabrication of HFs in the future.

In addition to the high nonlinearity of non-silica glasses, the high transparency in mid-IR region and the high solubility of rare-earth ions of non-silica glasses such as chalcogenide glasses [3] also motivate us to develop non-silica HFs for the applications in mid-IR region or active devices. However, the intensity-dependent nonlinear effect is particularly a large concern for non-silica glass based holey fibres with small mode-area (~2-5μm^2 [4]), due to the higher nonlinearity of non-silica glasses than that of silica glass. Monomode HF with large-mode-area (LMA) [9, 10] is a promising solution to prevent the nonlinear effect in high-index glass HFs. The typical mode area of commercial silica LMA HFs is between 28-530 μm^2 [11]. In this work, for the first time, we present a monomode holey fibre with the mode area of 40μm^2 at 800nm, based on a high-index non-silica glass (n=1.80). A novel design is constructed in the microstructured cladding by the conventional capillary-stacking technique.

Fabrication: A commercial optical glass, Schott SF6 glass (high lead silicate glass), was selected as the background material of this holey fibre. The SF6 glass has high refractive index of 1.80 at 589.3nm. The reported nonlinearity n_2 of this glass is 2.2 x 10^{-19} m^2/W at 1.06μm, which is almost one order of magnitude greater than that of silica glass [12]. Glass rods and tubes with the length of 100mm were drilled from the bulk glass by an ultrasonic-drilling machine and then elongated into capillaries with the uniform 250±10μm outer-diameter (OD). After the capillaries were stacked inside a jacket tube with 14mm OD, the preform was directly drawn into the fibre with uniform 230±10μm OD. In the resulting 20-meter-long fibre, no significant geometrical change was observed in the cross-sectional profile of the microstructured cladding. The cross-sectional microstructure of this HF is shown in Fig.1 (a) & (b), where a four-ring microstructured cladding is seen. In addition to the main holes having the inner-diameter (ID) of 2.7μm (d_1), six smaller holes with an inner diameter of 0.3μm (d_2) are periodically distributed in the second ring surrounding the solid core. In Fig.1 (c) the structural parameters of this HF are summarized. The fibre is shown to have an identical periodic spacing Λ (Λ=4.3±0.2μm) for the hexagonally arrayed holey cladding. For the holes near the solid core, i.e., the holes with the sizes of d_1 and d_2, the ratio of hole-diameter (d) to the hole-spacing (Λ) is d_1/Λ=0.63, and d_2/Λ=0.07, respectively. The 5.5μm holes are believed to have a comparatively minor influence on the optical guidance properties of this HF as they are placed far from the core.

Guidance properties: The fibre under characterization had a one-meter length and was excited by a tunable Ti:sapphire laser. Robust monomode optical guidance, between 700 to 800 nm was observed in this HF. The measured mode ($1/e^2$ intensity) at 800 nm is shown in Fig.2(a). An effective mode area (A_{eff}) [13] of 40±2 μm^2 was computed from the measured mode intensity profile. It is seen in Fig.2(b) that the measured mode is in good agreement with the fitted Gaussian function.

The mode area of 40μm^2 we have demonstrated is comparable to that of the commercial silica based large-mode-area HF (Type: LMA-8, with the mode-field area of 28μm^2, Crystal Fibre, Denmark [11]). Although the mode area of this LMA HF is still not large enough to avoid the intensity-dependent nonlinear effect in high-index glass based HF, it indicates that it is possible to fabricate a monomode high-index glass based HF with very large mode area (>>100μm^2) by this capillary-stacking technique.

Utilizing the concept of the HF sieve [2] (see Fig.3), we can understand how the monomode guidance can be achieved in this high-index glass holey fibre with A_{eff} of 40μm^2, while the typical value of A_{eff} for monomode high-index glass HF is only 1-2μm^2 [4]. The fundamental mode has a single-lobed pattern with the diameter of ~2Λ is confined within the core of PCF. It is unable to leak through the holey sieve as the bridge between the air-filled holes encircling the core is small and thus the travel length for the leaky light is sufficiently long with assistance from the ring structures. In the case of the higher-order modes having two or more lobed patterns with much smaller dimensions compared with the fundamental one, the lack of the tiny holes with $d_2 << d_1$ will lead to trapping of the higher-order modes in the core and if d/Λ is larger than a certain value, say 0.4 for silica HFs, and if the diameter of the core is larger than 4-5μm, the HF will operate in multimode [2]. The existence of the six tiny holes with d_2=0.3μm in the second ring effectively shortens the length of the supporting structure surrounding the core and widens the bridge width between the holes. Consequently, the confinement losses of the higher-order modes are largely increased. In other words, since HFs can only support leaky modes [4], through changing the parameters of the microstructured cladding to adjust the leakage losses for the fundamental mode and the higher-order modes, large-mode-area monomode operation can also be achieved in high-index glass HFs. We anticipate in the future modeling work could quantify this explanation.

Conclusion: We report the first stacked monomode high-index glass holey fibre with complicated holey cladding. Conventional capillary-stacking method was used for fabricating the fibre preform. By introducing defects, i.e., some much small holes in the second-ring on the holey cladding, only the fundamental mode can be observed in this high-index glass holey fibre. The measured effective mode area of 40μm^2 is comparable to the commercial silica LMA HFs. This type of HFs can be used for the applications of mode-filtering or high-power delivery [11]. And high-index glass based holey fibres with very large mode area (>>100μm^2) is anticipated to be fabricated using the same fabrication technique.

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Figure captions:

Fig. 1 SEM (Scanning Electron Microscope) photographs of SF6 glass holey fibre.

a Cross-section of holey fibre with 230μm OD

b Centre of microstructured region

c Structure parameters for holey cladding, where Λ=4.3±0.2μm Λ_1=4.5μm, Λ_2=4.1μm, Λ_3=4.3μm, and Λ_4=4.4μm), and d_1=2.7μm, d_2=0.3μm, d_3=5.5μm

Fig. 2 Mode profile of the HF observed at 800nm

a Contour plot of the HF with dB-spaced contour levels

b Gaussian fitting of the observed mode profile.

Fig. 3 Modal sieve of SF6 glass HF with a modified structured cladding

a The fundamental mode is confined within the small gap between the air-holes

b High-order modes leak away from the core due to a transverse effective wavelength than the gap between the air-holes with assistance from the small holes ($d_2 << d_1$) in the second ring ($d_1/\Lambda > 0.4$)

Figure 1

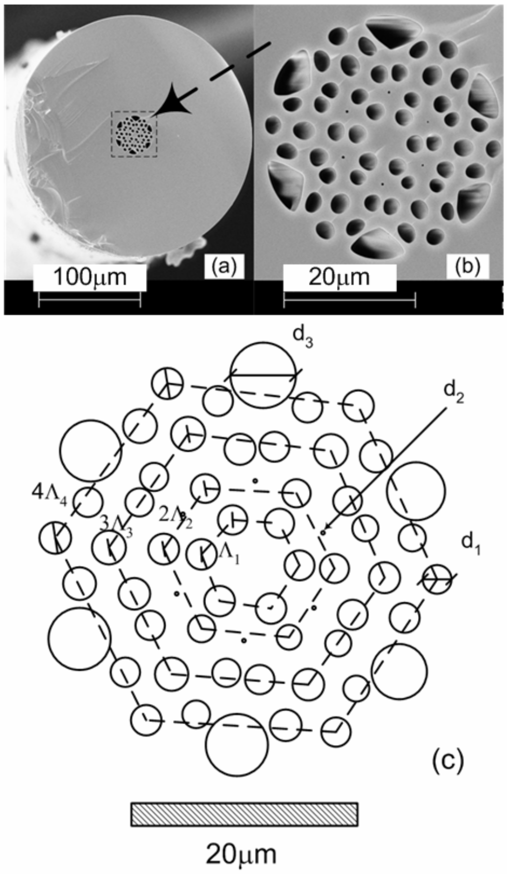


Figure 2

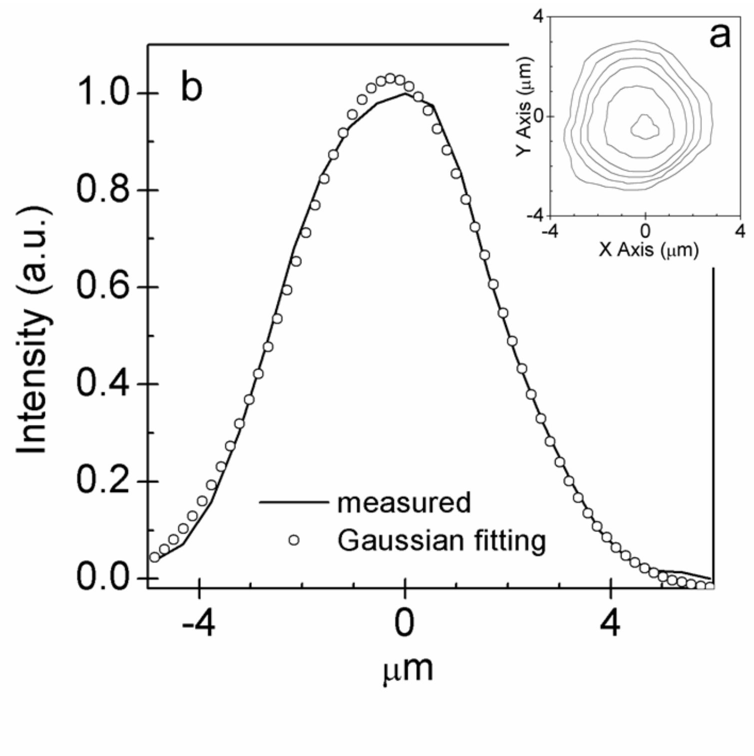
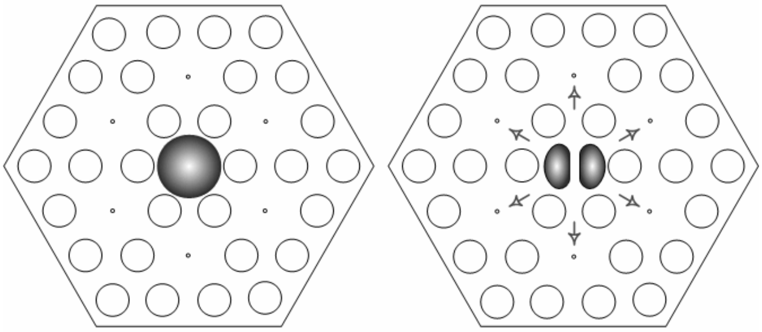

a
Y Axis (μm)
X Axis (μm)
4
0
-4
-4
0
4
b
Intensity (a.u.)
1.0
0.8
0.6
0.4
0.2
0.0
-4
0
4
μm
measured
Gaussian fitting

Figure 3



(a) (b)