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Developing holey fibers for evanescent field devices

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Abstract— **The overlap of the optical mode in a HF with the air holes is calculated for the first time. This is done using a vector modal decomposition approach. We show that a significant fraction of the modal power can be made to overlap with the holes, which suggests that these unusual fibers may be useful as evanescent field devices.**

Introduction: Holey optical fibres (HFs) have a cladding region comprised of air holes running along the full length of the fiber; see Fig. 1. HFs guide light due to the effective refractive index difference between the core (a missing hole) and the cladding. Altering the hole arrangement can radically change the properties of HF, and investigations to date have explored modal profiles, mode area and dispersion [1], [2], [3]. The unusual properties of HF arise from the strong wavelength dependence of the effective cladding index n_{cl}; at longer wavelengths the field extends further into the holes, reducing n_{cl}. As a consequence, some HFs can be single-moded regardless of the wavelength [1].

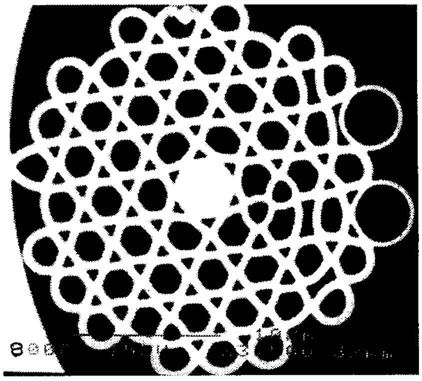

Fig. 1. SEM of a typical large air fill HF [$d/\Lambda \approx 0.6$, $\Lambda \approx 3.2\,\mu$m].

In Ref. [2] we developed a scalar orthogonal function method for HFs, which is valid when the holes are small. In Ref. [3] we extended this to the vector case, which enables us to explore the full range of HFs. This technique involves decomposing the modal field using localized functions. The central index defect and the air hole lattice are described independently using localized functions for the defect and periodic functions for the holes. This can be efficient and accurate because the quantities are described by functions chosen carefully to suit.

The holes in HF open up new opportunities for exploiting the interaction of light with gases and liquids via evanescent field effects. For example, the concentration of pollutants in a gas could be determined by measuring the absorption which occurs as light propagates through the gas for a range of wavelengths [4]. We show that the HF geometry can naturally provide extremely long optical path lengths.

Overlap with the holes: To assess the suitability of HFs for evanescent field devices, it is crucial to know the magnitude of the overlap of the modal field with the holes, and here we present what we believe to be the first such calculations. We define PF_{holes} to be the fraction of the fundamental mode's power which is located in the holes. First the mode profile for a given wavelength is calculated using the full vector model described in Ref. [3]. It is then straightforward to evaluate PF_{holes} at this wavelength numerically, and we have calculated PF_{holes} for a range of different HFs.

For the fiber in Fig. 1, PF_{holes} is surprisingly just 0.6% at $\lambda = 1.5\,\mu$m. Indeed, for the types of HFs fabricated thus far, which typically have hole spacings in the range $\Lambda = 2 \rightarrow 3.5\,\mu$m, we find that PF_{holes} is insignificant over the $\lambda = 0.5 \rightarrow 2\,\mu$m wavelength range. For example, see the lower set of curves in Fig. 2, which correspond to different HFs with $\Lambda = 3.2\,\mu$m, the hole spacing in Fig. 1.

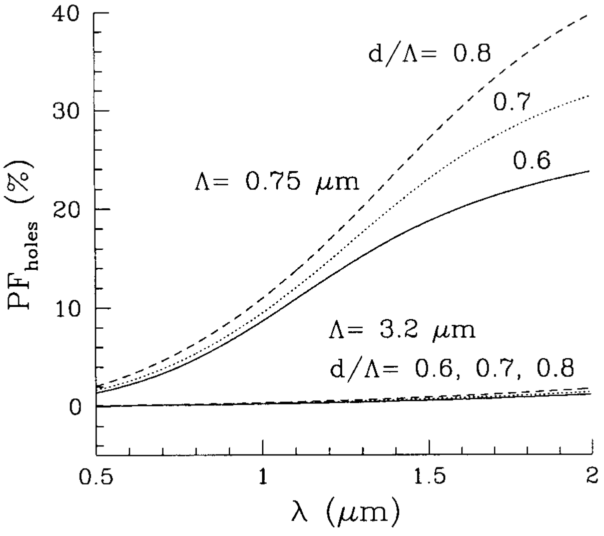

Fig. 2. $PF_{holes}(\lambda)$ for different HFs. The hole separations for each group of curves are $\Lambda = 0.75\,\mu$m and $\Lambda = 3.2\,\mu$m, and the solid, dotted and dashed lines are for relative hole diameters of $d/\Lambda = 0.6, 0.7$ and 0.8 respectively.

The field distribution depends strongly on the size of the features in the HF relative to λ, and so PF_{holes} can be tailored. To understand how this can be done, we consider a solid silica rod of diameter 1.25 Λ suspended in air, where Λ is the hole separation in HF. Although this suspended structure is clearly impractical, it is a good approximation for large air fill HFs, and we choose 1.25Λ because it gives good agreement in this step-index fiber analogy [5]. The modes of this simple structure can be found exactly [6]; we find that a significant fraction of the fundamental is outside the core when $V < 2$ (V is the fiber parameter).

This leads to the requirement $\lambda \gtrsim 2.2\ \Lambda$ in order for PF_{holes} to be significant. At telecommunications wavelengths, this condition is only satisfied for small Λ, which leads to very small mode areas ($\lesssim 1\,\mu\mathrm{m}^2$). Hence such fibres also have potential applications in nonlinear experiments.

The upper curves in Fig. 2 show PF_{holes} for a range of HFs with $\Lambda = 0.75\,\mu m$; we have used the condition $\lambda \gtrsim 2.2\ \Lambda$ from above to guide our choice of Λ. It is clear that PF_{holes} has been dramatically increased by using this smaller Λ. For example, $PF_{holes} \approx 30\%$ at 1.5 μm for a HF with hole separation $d/\Lambda = 0.8$ and $\Lambda = 0.75\,\mu$m. So far we have fabricated HFs with d/Λ as large as 0.7 [7], and so we expect that it should be practical to fabricate such fibers; it should not be more difficult to obtain small Λ. The high degree of overlap between the fundamental mode and the holes evident in Fig. 2 implies that HFs may be useful as evanescent field devices.

Discussion and Conclusions: To demonstrate the possibilities for using HFs in evanescent field devices, we consider the HF discussed above ($d/\Lambda = 0.8$). Using 1.67 μm light, it is possible to measure methane concentrations [8], and for this fibre, Fig. 2 predicts that $PF_{holes} \approx 35\%$ at this wavelength. Hence less than 3 m of this HF is required to obtain an equivalent free-space path length of 1 m. Hence by coiling the fibre, extremely long path lengths can be achieved compactly. Another advantage of this geometry is that only tiny gas volumes are required; 3 m of this HF be filled using only 30 nL of gas. Note however that if Λ is made too small, it becomes difficult to fill the holes with gas in a reasonable time.

Since fiber losses can be low, one could envisage HFs with extremely long equivalent free-space path lengths. Also, the combination of the confinement provided by the fiber and the endless single-moded operation which is possible in HF ensures good modal overlap between very different wavelengths over long distances. This is advantageous for sensing, because the absorption signatures of different pollutants can be at quite disparate wavelengths. Hence HFs have the potential to provide an ideal environment for evanescent field devices, and further optimisation of the HF geometry is likely to significantly enhance this potential.

Another type of air-clad fiber was proposed by Kaiser et al [9]. In this structure, the core is supported by a thin spoke-like membrane, and such a structure can be single-mode. Clearly this fiber is closely related to the suspended rod model described above. However, Kaiser et al. considered only structures where the membrane thickness $t \gg \lambda$, for which most of the light is located in the glass. By reducing the scale of this structure, which is analogous to reducing Λ in a HF, the overlap of the mode with the air could be increased. We propose that in this way, this alternative single-material fiber design could also be used to create compact evanescent field devices.

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