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Comparative study of large-mode holey and conventional fibers

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Little information exists regarding how large-mode holey fibers compare, in practical terms, with their conventional counterparts. We present what is to our knowledge the first experimental study of mode area and bend loss for a range of large-mode holey and conventional fibers. It is demonstrated here that large-mode holey fibers exhibit mode areas and bending losses that are comparable to those of conventional fibers at 1.55 μm. However, the novel wavelength dependence of the numerical aperture in a holey fiber offers a significant advantage for broadband and short-wavelength applications in which single-mode operation is required.

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Optical fibers with large mode areas are necessary for applications requiring high-power delivery, including laser welding and machining and fiber lasers and amplifiers. For many applications it is also essential for the fiber to be single mode. Recently, holey fiber (HF) technology emerged as an alternative route to large mode areas.[1] In a HF, light is guided by air holes that effectively lower the refractive index and so form the cladding. The air holes are typically arranged hexagonally, with hole-to-hole spacing Λ and diameter d. When the holes are on the same scale as the wavelength of light, the optical properties are particularly sensitive to the cladding geometry. The cladding parameters (d and Λ) and the hole arrangement give HFs extra degrees of design freedom relative to conventional fibers. As a result, HFs can possess a wide range of unique and potentially useful properties, including endlessly single-mode guidance, anomalous dispersion at short wavelengths, and mode areas ranging over 3 orders of magnitude.[1–3] Endlessly single-mode guidance offers obvious advantages for broadband applications and could also offer a simpler way of manufacturing single-mode fibers with large mode areas at visible and ultraviolet wavelengths. Despite these advantages, little is known about how large-mode HFs and conventional fibers compare in practical terms, such as bend loss and modal characteristics. Here we present the results from such a study.

In a conventional fiber, one creates large mode areas either by increasing the core size or by reducing the numerical aperture (NA). For any given core size and wavelength there exists a maximum NA that will result in single-mode guidance. Conventional techniques for reducing the NA rely on the ability to control dopant concentrations accurately, which ultimately limits the maximum mode size that can be created, especially for short-wavelength operation. In a HF, large mode areas can be engineered either by increasing the hole-to-hole spacing (Λ) or by decreasing the hole diameter (d). Increasing Λ is analogous to enlarging the core size, while decreasing d allows the field to penetrate farther into the cladding. This effect is particularly striking when d/Λ is small, resulting in dramatic increases in mode area for relatively small changes in hole size, as shown in Fig. 1. Note that in this figure we use the definition of effective area (A_{eff}) from Ref. 4

The largest mode size that can be tolerated in practice is determined by the macroscopic bending losses. Like conventional fibers, HFs exhibit a bend-loss edge at long wavelengths, as the mode's evanescent tail must travel a longer path length around the bend. The loss increases sharply when this evanescent tail reaches the speed of light in the cladding. HFs possess an additional bend-loss edge at short wavelengths as a

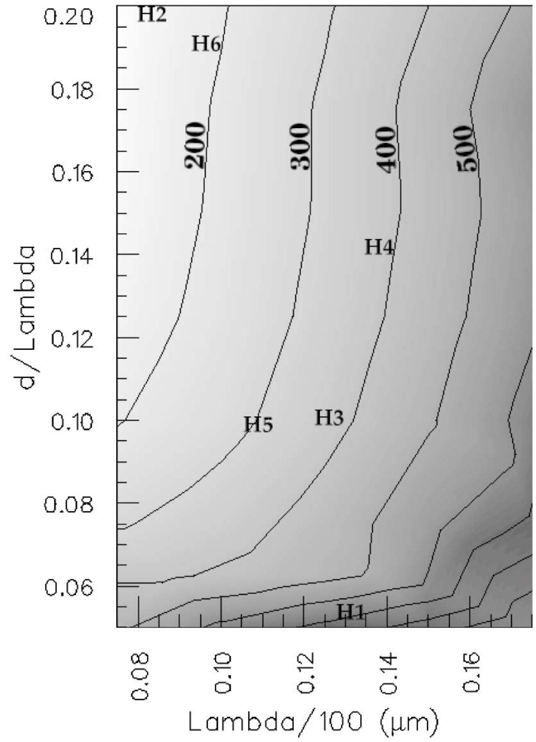

Fig. 1. Predicted fundamental mode area at 1.53 μm as a function of d and Λ for a hexagonal hole arrangement. The contours show the mode area in micrometers squared.

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direct consequence of the novel cladding structure.[2] If the hole-to-hole spacing is large compared with the wavelength, when the fiber is bent, the guided mode can escape via the solid silica bridges between neighboring holes. Here we consider the loss at 1.55 μm to present a comparative study.

Results for a selection of fibers are given in Figs. 1–3. Labels H1–H6 correspond to HFs with cladding parameters $7.5 \leq \Lambda \leq 15$ μm and $0.6 \leq d \leq 2.4$ μm. However, not all these fibers are considered in detail for brevity. Two conventional fibers are included for comparison: Fiber S1 is a large-mode fiber with a step-index profile, which has a ring of raised index surrounding the core to reduce the bend loss (NA, $\approx$0.06; core diameter, $\approx$18 μm),[5] and fiber S2 is a smaller-mode-area conventional step-index fiber with NA $\approx$0.10 and core diameter 8 μm.

The mode field diameter (MFD) of each fiber was extracted directly from divergence measurements made with a standard scanning knife-edge technique.[6] To extract the MFD by use of this approach, we assumed a Gaussian modal cross section. Although this is a simplification for the HFs considered here, which have somewhat hexagonal-shaped modes, direct measurement of the near-field mode profile shows this to be a reasonable approximation. For a circularly symmetric Gaussian modal field the effective area defined in Ref. 4 reduces to $A_{\text{eff}} = (\pi\ \text{MFD}^2)/4$, which is used here for all measured values. Including all sources of error, such as those arising from imperfect cleaves and alignment, in addition to that mentioned above, we estimate at most a 10% error in absolute MFD measurement. The bend loss was measured for one full loop of fiber, and care was taken to maintain minimal tension on the fiber and to ensure that the fiber lay flat along its length. The critical bend radius is defined as the curvature below which the transmitted power drops dramatically.

Figure 2 displays the effective area for a selection of HFs and conventional fibers. At 1.55 μm, mode areas ranging from 130 to 680 μm^2 were measured for the HFs; however, mode areas two or three times larger than this are not inconceivable. Note that, although H2 and S2 have similar mode areas at 1.55 μm, H2 has a much flatter wavelength dependence. This is also true for H4 and S1. This flattening reflects the wavelength dependence of the effective cladding index in the HFs. The inset in this figure shows the numerical predictions, calculated with the model in Ref. 7, and the experimental data for fiber H2, demonstrating that the wavelength dependence of optical properties within a HF can be accurately modeled by use of this approach.

Theoretical predictions of how A_{eff} depends on structural parameters d/Λ and Λ at 1.53 μm are shown in Fig. 1.[7] Notice that the same effective area can result from a range of structures. In structures with small holes relative to the wavelength, the light field is less influenced by each hole, and so the mode tends to be circularly symmetric. In contrast, large, closely spaced holes result in greater confinement and lead to filamentation of the mode as the field extends farther between the holes. In this way our numerical work indicates that modes can possess the same area but different optical properties, such as mode shape, bend loss, and dispersion.

Bend-loss measurements are shown in Fig. 3, which displays transmitted power as a function of bend radius at 1.55 μm. Unsurprisingly, one can see that bend losses increase for larger mode areas. In addition, we find that these conventional fibers and HFs with similar mode areas experience similar bend loss. However, it should be pointed out that fiber S1 was designed to have reduced bend loss,[5] which demonstrates that HFs are at least as bend resistant as conventional fiber types.

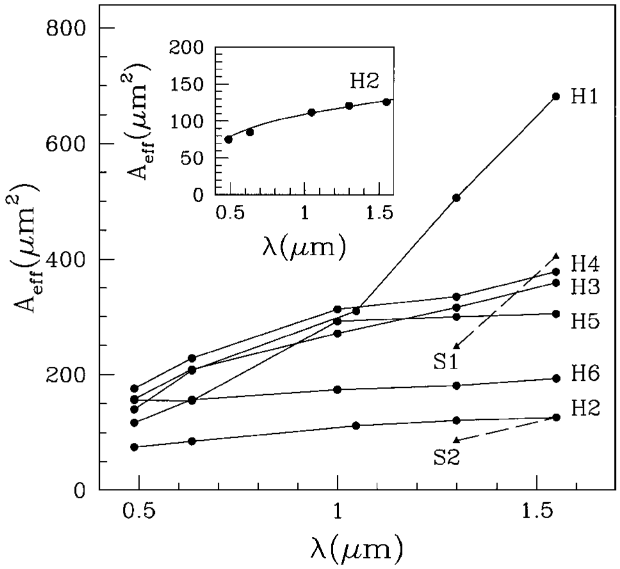

Fig. 2. Mode area versus wavelength for a selection of large-mode HFs and conventional fibers. Inset, predicted (curve) and experimental (filled circles) values for HF H2.

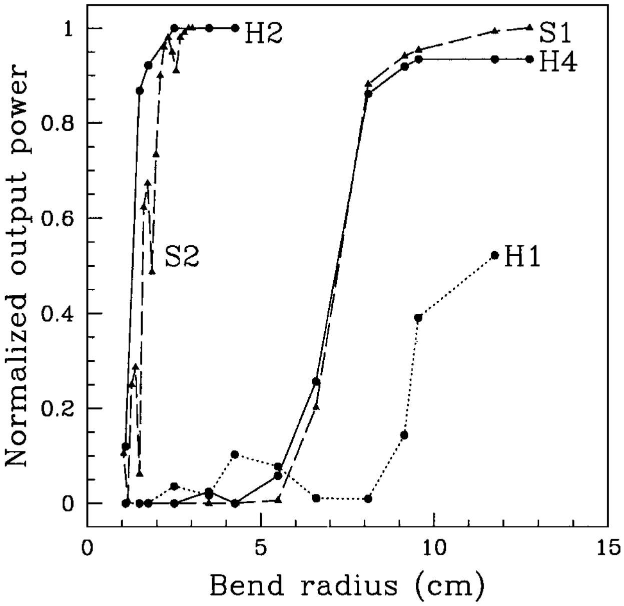

Fig. 3. Transmitted power as a function of bend radius for a selection of HFs and conventional fibers at 1.55 μm.

Table 1. Results for Fundamental Mode Area (A_{eff}) and Number of Modes (M) for a Selection of HFs (H) and Conventional (S) and Calculated (E) Step-Index Fibers

					A_{eff} (μm^2)		M	
Fiber	Λ (μm)	d/Λ	NA	a (μm)	1.55 μm	488 nm	1.55 μm	488 nm
H1	12.8	0.055	–	–	680	140	1	1
H2	8.2	0.197	–	–	126	75	1	few
H4	13.5	0.140	–	–	378	176	1	few
S1	–	–	0.060	9.0	405	140[a]	1	25[a]
S2	–	–	0.11	4.0	126	29[a]	1	17[a]
E1	–	–	0.026	7.0	No guidance	176[a]	No guidance	1[a]
E2	–	–	0.043	13.8	680[a]	140[a]	1[a]	30[a]

[a] Estimated from the NA and core diameter.[8]

We next examined the degree of modedness for our range of HFs. Previous studies predicted that HFs can be endlessly single mode when $d/\Lambda < 0.15$.[2] However, our far-field images of the guided mode indicate quantitatively that some fibers with d/Λ as small as 0.06 are not rigorously single mode at short wavelengths. In practice, our fibers had at most a few modes, and it was easy to eliminate these higher-order modes by introducing a bend.

Table 1 shows the number of modes supported by the selection of HFs and conventional fibers at various wavelengths. We have also included calculated values for two additional step-index fibers (E1 and E2) for comparison purposes. The differences between the fiber types are more apparent at short wavelengths. At 488 nm, for example, fibers H2 and H4 are few moded, whereas fibers S1 and S2 have ≈25 modes. To make a standard single-mode fiber with the same effective area as H4 at 488 nm (≈180 μm^2) would require a NA of 0.026 (example E1 in Table 1). Moreover, the useful operating wavelength range in which this fiber is both single mode and not leaky is extremely narrow. Also of interest is fiber H1, which has a mode area of ≈680 μm^2 at 1.55 μm and is also effectively single mode from 488 nm to 1.55 μm. A conventional fiber would require a NA of ≈0.043 for this mode area at 1.55 μm but would obviously be single mode in only a narrow region around this wavelength (E2 in Table 1). For example, at 488 nm, E2 would support ~30 modes. As examples E1 and E2 show, it is always possible to design single-mode conventional fibers with mode areas similar to these HFs for any given wavelength. However, the small NAs required in conventional fibers in the extreme short wavelength present fabrication difficulties. In addition, conventional fibers cannot remain single or few moded over a broad wavelength range.

Additional factors that need to be considered in assessing the practicality of large-mode HFs are the characteristics of bend loss at short wavelengths and the power-handling capabilities. Our preliminary bend-loss measurements at 488 nm show that for fibers such as H4 the critical bend radius occurs at ~8 cm, which is not prohibitive. Also, although it has yet to be demonstrated, we expect that HFs may offer advantages in terms of power handling, since they can be made entirely from pure silica. This is especially important in the visible and ultraviolet regions of the spectrum.

We have presented what is to our knowledge the first experimental comparison of bend loss and mode area for a range of large-mode holey and conventional fibers. Our study demonstrates that HFs can possess bend losses at 1.55 μm that are comparable to those of similarly sized conventional fibers. Although HFs and conventional fibers can exhibit similar mode areas and numbers of modes at any single wavelength, HFs have a distinct advantage for broadband applications because of their ability to be single or few moded over a large wavelength range. In addition, HFs may simplify the fabrication of large-mode-area single-mode fibers for use at short wavelengths.

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