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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, to their conventional counterparts. We present 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 comparable mode areas and bending losses to conventional fibers at long wavelengths. However, the novel wavelength dependence of the numerical aperture in a holey fiber offers a significant advantage for broad-band and short wavelength applications where single-moded operation is required. ©2001 Optical Society of America

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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-moded. Recently, holey fiber technology has emerged as an alternative route towards large mode areas [1]. In a holey fiber (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 holey fibers extra degrees of design freedom relative to conventional fibers. Hence, holey fibers can possess a wide range of unique and potentially useful properties, including endlessly single-moded guidance, anomalous dispersion at short wavelengths and mode areas ranging from 1 to 1000 μm^2 [1, 2, 3]. Endlessly single-moded 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 ultra-violet wavelengths. Despite these advantages, little is known about how large mode holey and conventional fibers compare in practical terms, such as bend-loss, and modal characteristics. Here we present the results from such a study.

Endlessly single-moded guidance arises from the fact that at short wavelengths, the field is more tightly confined to the core than at longer wavelengths, significantly reducing the numerical aperture (NA). If a is the core radius and λ is the wavelength of light, the fiber parameter $V = (2\pi \, a \, NA)/\lambda$, is a measure of the number of modes supported in a fiber. For example, a fiber is single moded when $V < 2.405$. In a conventional fiber, the numerical aperture depends only weakly on wavelength, resulting in increasing number of modes towards short wavelengths. In a holey fiber, however, the wavelength dependence of the numerical aperture allows V to remain nearly constant over a large wavelength range and single-moded guidance at all wavelengths can result if d/Λ is small enough.

In a conventional fiber, large mode areas are created either by increasing the core size or by reducing the numerical aperture. For any given core size and wavelength, there exists a maximum NA that will result in single-moded guidance. Conventional techniques for reducing the numerical aperture rely on the ability to accurately control dopant concentrations, which ultimately limits the maximum mode size that can be created, especially for short wavelength operation. In a holey fiber, large mode areas can be engineered in two ways, 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 further 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.

The largest mode size that can be tolerated in practice is determined by the macroscopic bending losses. Like conventional fibers, holey fibers exhibit a bend loss edge at long wavelengths. As the fiber is bent, the evanescent tail of the modal field must travel a longer path length around the bend. The loss increases sharply when the evanescent tail reaches the speed at which light can travel in the cladding. Holey fibers possess an additional bend loss edge at short wavelengths that is a direct consequence of the novel cladding structure [2]. If the hole-to-hole spacing is large compared to the wavelength, the guided mode can escape via the solid silica bridges between neighbouring holes as the fiber is bent. Here we consider the loss edge at long wavelengths in order to present a comparative study.

Results for a selection of fibers are given in Fig. 1, 2 and 3. Labels H1-6 correspond to holey fibers with cladding parameters ranging from $7.5 \leq \Lambda \leq 15$ μm and $0.6 \leq d \leq 2.4$ μm. Two conventional fibers are included for comparison: Fiber S1 is a large mode fiber with a ring of raised index surrounding the core to reduce the bend loss (NA $\approx$ 0.06 and core diameter $\approx 18\,\mu$m) [5] and fiber S2 is a smaller mode area conventional fiber with NA $\approx$ 0.10 and core diameter 8μm.

The mode field diameter of each fiber was extracted directly from divergence measurements made using a standard scanning knife-edge technique, and the effective mode area calculated using $A_{\mathrm{eff}} = (\pi\,\mathrm{MFD}^2)/4$. Our means of evaluating the MFD assumes a Gaussian cross-section, which although not strictly correct for the fibers investigated, we consider to be a reasonable approximation from direct measurment of the near field mode profile. 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, with care taken to maintain minimal tension on the fiber, and to ensure that the fiber lay flat along its entire length. The critical bend radius is then defined as the curvature below which the power transmitted through the fiber drops dramatically.

Figure 2 displays effective area for a selection of holey and conventional fibers. At 1.55 μm mode areas ranging from 130 $\mu\mathrm{m}^2$ to 680 $\mu\mathrm{m}^2$ were measured for the holey fibers, however mode areas two or three times larger than this are not inconceivable. Note that while 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 holey fibers. The inset in this figure shows the numerical predictions, calculated using the model in Ref. [6], and the experimental data for fiber H2, which demonstrates that the wavelength dependence of optical properties within a holey fiber can be accurately modeled using this approach.

Theoretical predictions for how A_{eff} depends on structural parameters d/Λ and Λ at 1.53 μm are shown in Figure 1. 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 hence lead to filamentation of the mode as the field extends further between the holes. In this way modes can possess the same area, but different optical properties, such as mode shape, bend loss and dispersion.

Some bend loss measurements are shown in Figure 3, which displays transmitted power as a function of bend radius at 1.55 μm. Unsurprisingly, we see that bend losses increase for larger mode areas. In addition, we find that these conventional and holey fibers 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], demonstrating that holey fibers are at least as bend resistant as conventional fiber types.

We next examined the degree of modedness for our range of holey fibers. Previous studies predict that holey fibers can be endlessly single-moded when $d/\Lambda < 0.15$ [2]. However, we observe that some fibers with d/Λ as small as 0.06 are not rigorously single-moded at short wavelengths. Although our fibers were at most few moded, this illustrates that the conditions for endlessly single-moded guidance require further investigation. However, from a practical perspective, 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 holey and conventional fibers at various wavelengths. The differences between the fiber types become more apparent at short wavelengths. At 488 nm, for example, fibers H2 and H4 are few-moded, whereas fibers S1 and S2 have $\approx$ 25 modes. In order to make a standard single-mode fiber with the same effective area as H4 at 488 nm ($\approx 180\mu\text{m}^2$) a numerical aperture of 0.026 would be required (example E1 in Table 1). Moreover, the useful operating wavelength range in which this fiber is both single-moded and not leaky is extremely narrow. Also of interest is fiber H1, which has a mode area $\approx 680\mu\text{m}^2$ at 1.55 μm and is also effectively single-moded from 488 nm - 1.55 μm. A conventional fiber would require NA $\approx$ 0.043 in order to achieve this mode area at 1.55 μm, but would obviously only be single-moded in a narrow region around this wavelength (E2 in Table 1). For example, at 488 nm, E2 would support about 30 modes. As examples E1 and E2 show, it always possible to design single-mode conventional fibers with similar mode areas to these holey fibers for any given wavelength. However, the small numerical apertures required in conventional fibers the short wavelength extreme present fabrication difficulties. In addition, conventional fibers cannot remain single or few-moded over a broad wavelength range.

Additional factors which need to be considered to assess the practicality of large mode holey fibers are the characteristics of the short wavelength bend loss edge 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 around 8cm, which is not prohibitive. Also, although it has yet to be demonstrated, we expect that holey fibers 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 ultra-violet regions of the spectrum.

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

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Fig. 1. Predicted mode area as a function of cladding parameters d and Λ for a hexagonal hole arrangement. Contour levels represent mode area in μm^2. Labels H1-6 represent some of our holey fibers.

Fig. 2. Mode area vs wavelength for a selection of large mode holey and conventional fibers. Inset shows predictions and experiment for holey fiber H2.

Fig. 3. Transmitted power as a function of bend radius for a selection of holey and conventional fibers.

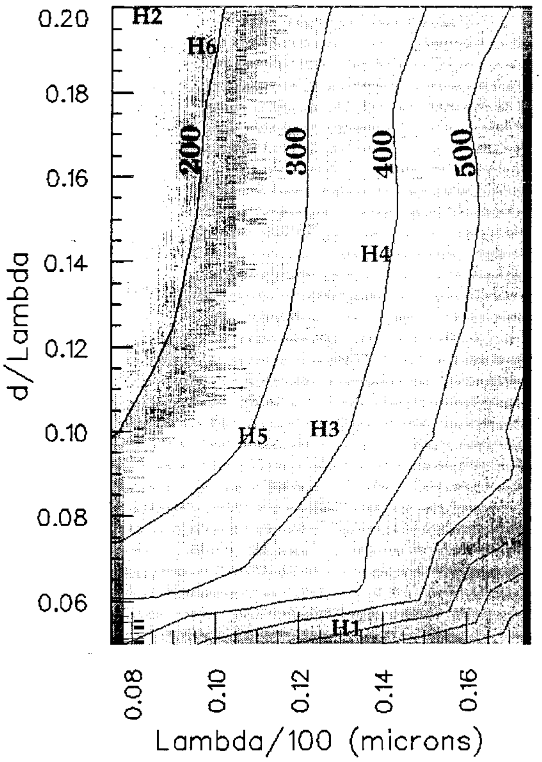

Figure 1 J.C. Baggett et al.

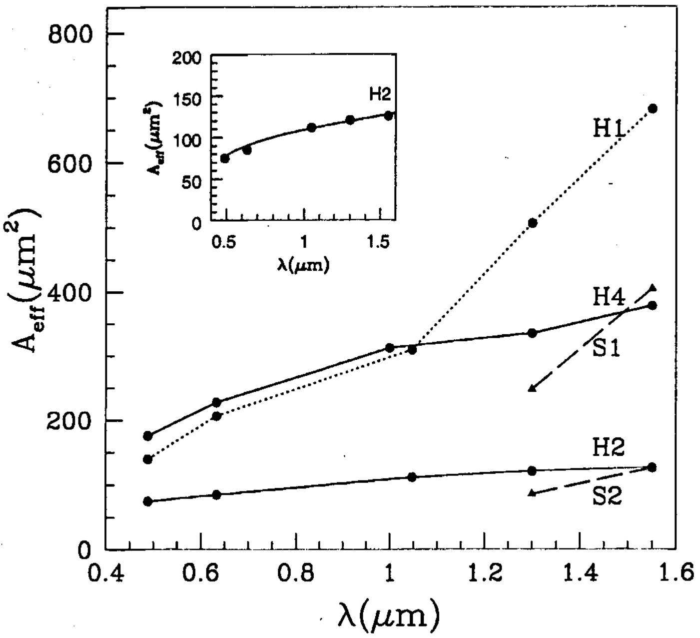

Figure 2 J.C. Baggett et al.

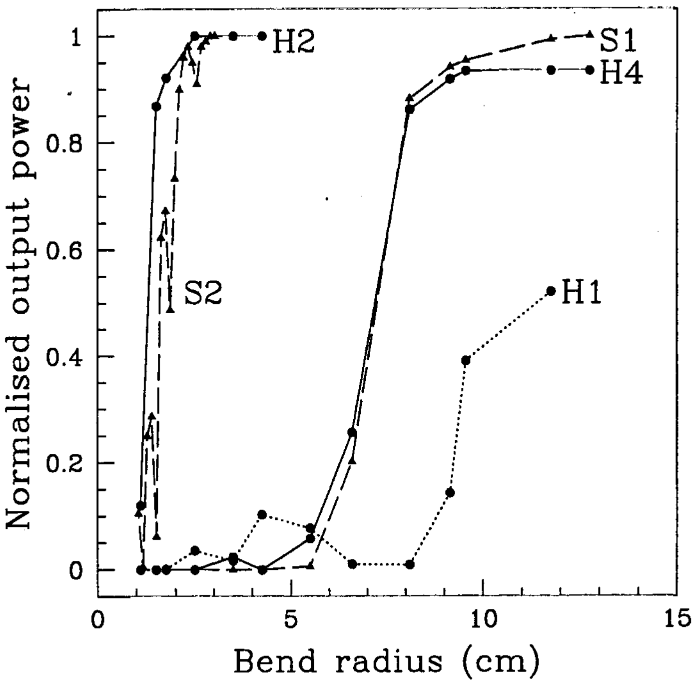

Figure 3 J.C. Baggett et al.

Table 1. Results for mode area (A_{eff}) and number of modes (M) for a selection of holey (H), conventional (C) and calculated (E) fibers. A_{eff} and M in plain text correspond to 1.55 μm, those in italics correspond to 488 nm. * represents calculated values.

	Λ [μm]	d/Λ	NA	a [μm]	A_{eff} [μm^2]	M
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**	1, *25**
S2	-	-	0.11	4.0	126, *29**	1, *17**
E1*	-	-	0.026*	7.0*	Leaky, *176**	Leaky, *1**
E2*	-	-	0.043*	13.8*	680*, *140**	1*, *30**