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# Mode Area Limits in Practical Single-mode Fibers

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**Abstract:** The upper limits imposed by bend loss on practical mode size in single-mode holey and step-index fibers are identified for a range of wavelengths. Using these results we quantify the advantages offered by holey fibers.

**OCIS codes:** (060.2400) Fiber properties; (060.2430) Fibers, single-mode.

## 1. Introduction

Fibers with low-nonlinearity, good spatial beam quality and high damage thresholds are essential for many high power applications. Although holey fiber (HF) technology has been shown to be an attractive route towards such fibers, offering endlessly single-mode guidance combined with large-mode-areas, the potential advantages over step-index designs are not well quantified. As with any fiber, the fundamental upper limit on mode area for practical applications is set by the bending losses. In order to determine what advantages holey fibers may offer relative to step-index designs, it is therefore essential to quantify the limitations imposed by bend loss in each fiber type. However, the novel waveguiding properties of HFs mean that a direct comparison is not trivial. In HFs, the bending losses increase towards both long and short wavelengths [1]. However, since the mid-point between the two loss edges is $\approx \Lambda/2$, where $\Lambda$ is the hole-to-hole spacing, only the short wavelength bend loss edge is apparent in large-mode-area (LMA) HFs which typically have $\Lambda > 4\ \mu$m [2, 5]. For this structure scale, the long wavelength bend loss edge is located beyond wavelengths transmitted in silica. In contrast to this, the bending losses of step-index fibers (SIFs) increase towards long wavelengths only. To date, studies have shown that the bending losses of a similarly sized single-mode HF and SIF can be comparable at a wavelength ($\lambda$) of 1550 nm for $\Lambda/\lambda \approx 5.3$ [3], and that the bandwidth of practicality, as determined by bend loss and modedness, can be wider in HFs than in similarly sized SIFs at visible wavelengths for $\Lambda/\lambda \approx 4.5 - 6.4$ [4]. However, the relative structure scale ($\Lambda/\lambda$) is similar in both of these studies and it is unclear if these results remain true for a larger range of $\Lambda/\lambda$. (Note that we find scale invariance to be a fair assumption for the fiber properties studied here).

The aims of the study presented here are twofold: (1) to determine the upper limits on mode size in single-mode HFs for a range of wavelengths, and (2), to benchmark the bend loss performance of HFs against step-index fibers.

## 2. Defining the range of practical structures

In order to predict the maximum practical mode size in a single-mode fiber it is necessary to understand the relationships between the refractive index profile and three key fiber properties: (1) effective mode area ($A_{eff}$), (2) bend loss and (3) the modedness of the fiber (i.e. single-mode or multi-mode guidance). The $A_{eff}$ and the bend loss of each HF considered here is calculated using the numerical techniques described in Ref [5]. In this model, an orthogonal function method is used together with a conformal transformation to obtain the distorted modal fields of the bent fiber. The bend loss is then extracted by estimating the fraction of the modal field lost to radiation. This bend loss model has very few restrictions on the refractive index profile that can be considered and has been experimentally validated for LMA HFs [5]. The third key property, the modedness of the fiber, is evaluated for HFs using the analytical expression in Ref [6]. For the SIFs considered here, the $A_{eff}$ and the single-mode cut-off is determined via exact solutions, and the bend loss is calculated using a well known formula for a step-index fiber with an infinite cladding [7]. A value of 1.45 is used for the refractive index of silica in all calculations. The calculated values for these three key fiber properties are plotted in Fig. 1 (a) for SIFs as a function of the relative core size ($a/\lambda$) and the refractive index contrast between core and cladding regions ($\Delta$n). Fig. 1 (b) shows these three key properties for the corresponding range of HFs, plotted as a function of $\Lambda/\lambda$ and the relative holey size ($d/\Lambda$). In each plot, the shaded contour lines represent values of $A_{eff}/\lambda^2$ and the solid black contour lines correspond to values of $R_c/\lambda$, where $R_c$ is the critical bend radius, defined as the radius at which the bend loss is equal to 3 dB per loop. The white line on each plot indicates the single-mode cut-off. Note that all values correspond to the fundamental mode only.

From Figs 1 (a) and (b) we see that in both fiber types, $A_{eff}/\lambda$ and $R_c/\lambda$ increase as the index contrast between core and cladding regions decreases (the effective $\Delta$n in a HF decreases with decreasing $d/\Lambda$). However, in other

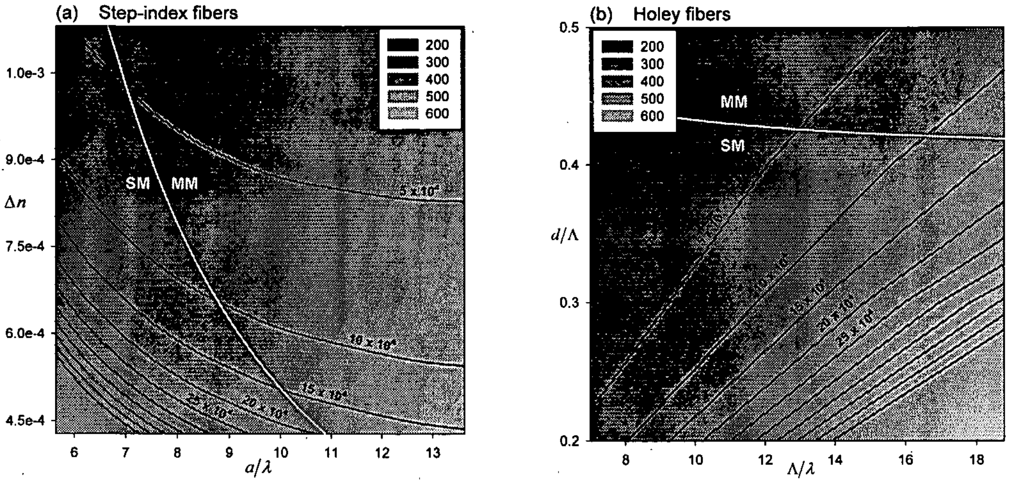

Fig. 1. (a) Fiber properties of SIFs with $5.6 < a/\lambda < 13.6$ and $4.27\times10^{-4} < \Delta n < 1.13\times10^{-3}$. (b) Fiber properties of HFs with $7.0 < \Lambda/\lambda < 18.8$ and $0.2 < d/\Lambda < 0.5$. Shaded contour lines represent values of $A_{eff}/\lambda^2$, the solid black contour lines correspond to values of $R_c/\lambda$ and the white line indicates the single-mode cut-off.

respects, Figs 1 (a) and (b) appear be rather different. For example, we see that while $R_c/\lambda$ decreases with increasing core size in a SIF, the reverse is true in a HF ($\Lambda$ defines the core size in a HF). This apparent difference arises from the fact that the effective $\Delta n$ in a HF is a strong function of both $d/\Lambda$ and also of $\Lambda/\lambda$ (a property which gives rise to endlessly single-mode guidance). If we instead focus on the behavior of each fiber type along the single-mode cut-off line (shown in white), we see that the both $A_{eff}/\lambda$ and $R_c/\lambda$ increase as the core size increases. Consequently, by comparing the wavelength dependence of $A_{eff}$ at cut-off for a fixed value of $R_c$, a fair comparison of bend loss can be drawn between the two fiber types. This is explored in more detail in the following section.

## 3. Comparing the performance of single-mode holey and step-index fibers

The maximum tolerable bend loss for a practical fiber is defined here as $R_c = 15$ cm. This value is based on our experimental observations in which fibers with $R_c > 15$ cm are found to exhibit rapidly fluctuating power levels in response to low level vibrations and air-currents in the laboratory environment. Of course, the definition of tolerable bend radius will differ greatly depending on the application and the way in which the fiber is packaged, but for many applications, critical bend radii <15 cm are considered to be practical.

In order to fairly compare the bending losses of HFs and SIFs we consider the maximum mode area that can be achieved for single-mode guidance with $R_c = 15$ cm. For the SIF case, the single-mode cut-off is given by $2\pi a(n_{core}^2 - n_{clad}^2)^{\frac{1}{2}}/\lambda = 2.405$. For the HF case, the condition for single-mode cut-off is taken to be $d/\Lambda = 0.40$ in order to encompass large values of $\Lambda/\lambda$ [6]. As shown in Fig. 2 (a), the maximum practical $A_{eff}$ is comparable for optimal HF (solid curve) and SIF (dashed curve) designs, with $A_{eff}^{max}$ ranging from $\approx 100\,\mu m^2$ at 400 nm to $\approx 700\,\mu m^2$ at 1600 nm. However, each of the SIF designs that lie on the dashed line in Fig. 2 (a) are only useful close to the design wavelength, becoming multi-mode at shorter wavelengths and prohibitively bend sensitive at longer wavelengths. In contrast, since bend loss increases towards short wavelengths only in HFs, each of the HFs represented by the solid curve in Fig. 2 (a) are also practical single-mode structures for all wavelengths greater than the design wavelength. The advantages of HFs thus lie with broadband or multiple wavelength applications.

To illustrate the advantages of HFs for broadband applications we consider the design of a fiber for high power single-mode transmission at and/or between the wavelengths of 532 and 1064 nm. In a HF, the limiting factor is the bend loss at the shortest design wavelength, and the largest practical mode size thus corresponds to a fiber with a maximum acceptable bend loss at 532 nm. Assuming the maximum tolerable $R_c$ is defined as 15 cm, the largest practical $A_{eff}$ of $180\,\mu m^2$ at 532 nm is obtained in a fiber with $\Lambda = 12.25\,\mu m$ and $d/\Lambda = 0.40$. In comparison, the limiting factors in a SIF are the bend loss at the longest design wavelength and the modedness of the fiber at the shortest design wavelength. In this case, the largest practical mode size corresponds to a fiber with $R_c = 15$ cm at 1064 nm and a cut-off wavelength of 532 nm, which can be achieved with $a = 2.488\,\mu m$ and $\Delta n = 2.316 \times 10^{-3}$ that results in $A_{eff} \approx 115\,\mu m^2$ at 1064 nm. The wavelength dependence of $R_c$ and $A_{eff}$ are plotted in Fig. 2 (b) and

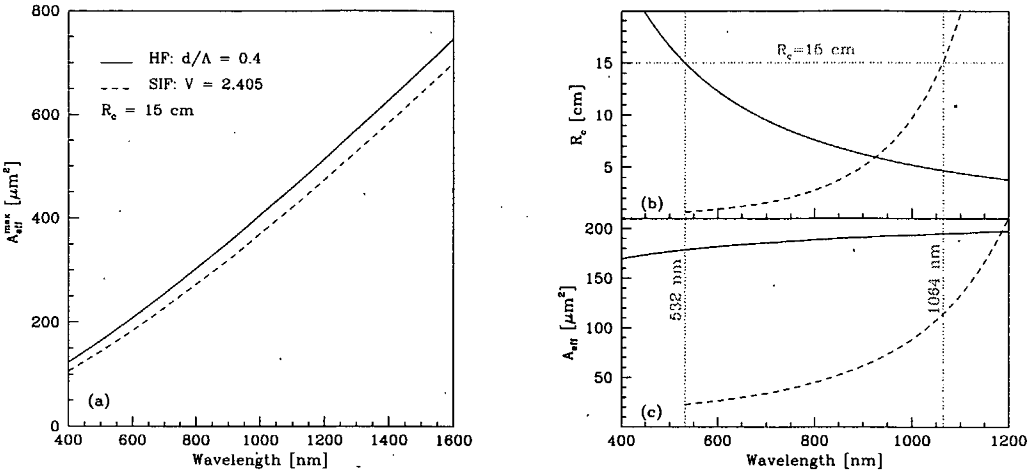

Fig. 2. (a) Maximum $A_{eff}$ for single-mode HFs (solid line) and SIFs (dashed line) with $R_C$ = 15 cm. (b) and (c) $R_C$ and $A_{eff}$ of the fundamental mode as a function of wavelength. In (b) and (c) solid lines correspond to a HF with $\Lambda$=12.25 $\mu$m and $d/\Lambda$=0.4 and dashed lines correspond to a SIF with $a$=2.488 $\mu$m and $\Delta$n=2.316$\times10^{-3}$.

(c) respectively, for both the HF (solid line) and SIF (dashed line) design. In addition to illustrating the difference between the wavelength dependence of bend loss in the HF and the SIF, Fig. 2 (b) shows that both fiber types can be designed to exhibit tolerable bend loss with single-mode guidance for 532 nm $< \lambda <$ 1064 nm. However, whilst the $A_{eff}$ of the HF remains relatively constant at $\approx$180 to 195 $\mu m^2$ in this wavelength range, as shown in Fig. 2 (c), the $A_{eff}$ of the optimal SIF design is almost half this value at 1064 nm and falls rapidly to $\approx$ 23 $\mu m^2$ at 532 nm. This demonstrates that while it is possible to design a SIF with broadband single-mode guidance and tolerable bend loss, it only possible to do so if the $A_{eff}$ is significantly reduced relative to a HF design.

## 4. Conclusion

Experimentally validated numerical techniques are applied to the problem of understanding the practical limits that bend loss imposes on large-mode-area holey fibers designed for single-mode operation. These properties are also evaluated for a range of step-index fibers using a well known bend loss formula in order to benchmark the potential offered by holey fiber technology for power delivery. We show that for single-mode guidance, the largest practical mode area that can be achieved in both fiber types is comparable and increases from $\approx$ 100 $\mu m^2$ at 400 nm, to $\approx$ 700 $\mu m^2$ at 1600 nm (assuming a maximum tolerable bend loss of 3 dB per loop for a bend radius of 15 cm). Furthermore, we show that although the limitations due to bend loss can be similar in both fiber types at any given wavelength, holey fibers possess a distinct advantage in terms of mode area and hence power handling for single-mode broadband and multiple-wavelength applications. These advantages are quantified for 532 nm $< \lambda <$ 1064 nm.

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