FUNDAMENTAL PROPERTIES OF SMALL CORE HOLEY FIBRES

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Abstract *We explore some of the fundamental limits in small core silica holey fibres that have a direct bearing on nonlinear device applications. In particular, we examine issues related to coupling and polarization in these fibres.*

Introduction

Since the first holey fibre (HF) was fabricated in 1996 [1], progress in this field has been explosive. HFs that combine wavelength-scale feature sizes with a large air-filling fraction confine light tightly within the core. Modest optical powers can then induce nonlinear effects in short lengths of these highly nonlinear HFs (HNLHFs). HNLHFs are thus a route towards efficient compact nonlinear devices. To date most such devices have made use of silica HFs, which can have effective nonlinearities as high as $\gamma \approx 60/(\mathrm{W.km})$, 60 times larger than standard fibre [2].

Fundamental limits in HNLHFs

Now that a range of devices have been demonstrated (see for example [2]-[4]), it is timely to assess the factors that impact the practical use of HNLHFs. One important consideration is the integration of HNLHFs with existing technologies. Although it is possible to splice HFs with solid fibres [5], the mode mismatch between HNLHFs and standard fibres makes this impractical. For laboratory demonstrations, free-space coupling has generally been used. The commercial development of HNLHF devices will require new techniques for ensuring low-loss interconnects to existing systems. In either case, it is vital to understand the limits on the efficiency with which light can be coupled into these extreme fibres.

To do this, we have used the multipole method [6] to calculate the modal properties at 1550nm for a range of small core high NA HFs with 4 rings of hexagonally arranged holes with hole-to-hole spacings (Λ) ranging from 0.8-2.8μm. The idealized HFs considered here have 2-fold degenerate fundamental modes (a pair of quasi-linearly polarized modes with the same propagation constant) [7], and any linear combination of these solutions is also a mode. In the following we choose the linear combination that results in a circular Poynting vector and transverse electric fields that are approximately linearly polarized along the *x*-axis and *y*-axis, labelled mode *(1)* and *(2)* respectively.

For some designs considered here, the core is sub-wavelength, and so the mode overlaps significantly with the holes. In Fig.1 (top left) the percentage of the field located in the holes (PF_{holes}) is plotted as a function of Λ for two air-filling fractions (d/Λ=0.6 and 0.9 where d is the hole diameter). For $\Lambda \leq 1.5\mu m$, the mode/air overlap increases dramatically.

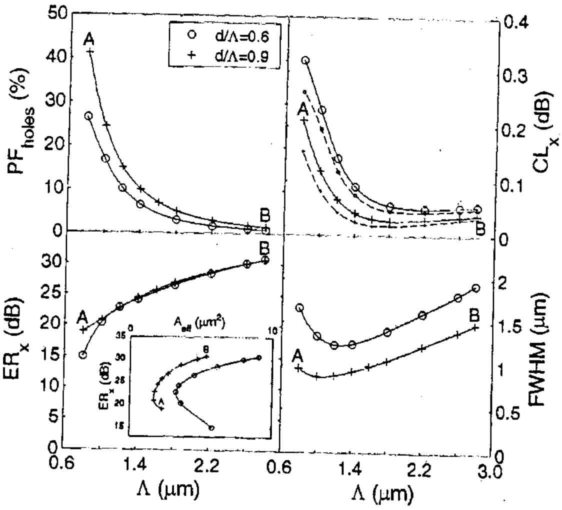

Fig.1 Top left: Percentage of the electric field in the holes Bottom Left: Polarization extinction ratio Top Right: Minimum coupling loss and Bottom Right: FWHM of the linearly polarized Gaussian that results in optimal coupling

For the smallest structures considered here, the silica bridges surrounding the core are sub-wavelength. Hence one might expect the mode shape to be less filamented for these fibres, and better coupling with a conventional fibre mode or a free space beam might be anticipated. To test this we calculated the coupling efficiency (C_x) between the HF mode $E=E^{(1)}(x,y)$ and a Gaussian field distribution $E_0(x,y)=exp(-(x^2+y^2)/w^2)$ linearly polarized along the x-axis using the definition:

$$C_x = \frac{\left|\iint E_x . E_0^* dxdy\right|^2}{\iint EE^* dxdy \iint E_0 E_0^* dxdy} \qquad \text{-(1)}$$

where E_x is the *x*-component of *E*. For any choice of *w*, C_x represents the power fraction of the linearly polarized Gaussian coupled into the HF mode. To determine the optimal coupling, *w* is chosen in order to maximize C_x. The minimum coupling loss (CL_x) is then determined via CL_x [dB]=-10 $\log_{10}(C_x)$.

Fig.1 shows the choice of Gaussian beam FWHM ($\sqrt{2\ln 2}\, w$) that results in optimum coupling for each fibre and the corresponding loss CL_x (solid lines). For fibres with core dimensions larger than the wavelength, reducing the core size indeed reduces the coupling loss slightly, reflecting a more Gaussian-like mode shape. However, for Λ<1.5μm, the coupling degrades. For Fibre A, which has an effective mode area of ≈2 μm^2, the minimum coupling loss is ≈0.2dB, where for the larger Fibre B (mode area ≈5 μm^2), the loss is reduced to ≈0.04dB. Notice that for the smallest structures, sub-wavelength Gaussian beams are required for optimal coupling, which is impractical. Hence in practice the coupling loss would degrade more at small structure scales than Fig.1 suggests, and so these predictions should be viewed as an upper bound on the coupling efficiency.

The dashed lines in Fig.1 show the coupling loss between mode *(1)* and a Gaussian beam, ignoring the contribution from the mode polarization. They thus describe the contribution to the coupling loss purely due to the mode shape. This contribution increases significantly for the smallest structures, and so the principal reason for the coupling degradation is the non-Gaussian mode shape that results when a significant fraction of the light is located in the holes.

The loss difference between solid and dashed lines in Fig.1 reflects the deviation from linearity of the holey fibre mode. The effect of the mode polarization on the coupling loss worsens for small-scale HFs, and to understand this trend, Fig.2 shows a close-up of the electric field for Fibres A and B. The bottom left corner of each box corresponds to the centre of the fibre. For each fibre, the field is essentially linearly polarized throughout the core region. For the largest fibre (B), the mode is effectively confined to the core. In contrast, in fibre (A), the field curvature becomes significant in the silica bridges between the holes. This deviation from linear polarization explains why the coupling from a linearly polarized Gaussian beam is poorer when the structure scale is decreased.

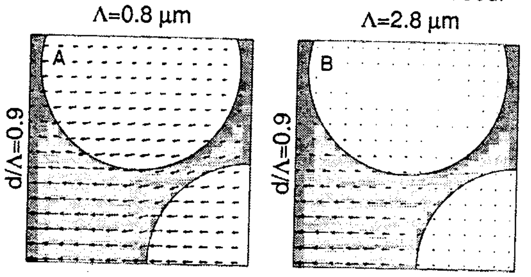

Fig.2 Vector plots of the transverse electric field for: (Left) Fibre A; (Right) Fibre B. Shading denotes silica regions.

We now further explore the implications of this field curvature for practical devices. Although it is known that HNLHFs are typically birefringent due to the effect of small asymmetries in the fibre profile, one related quantity of interest that has not previously been explored in any detail is the polarization extinction ratio. For many applications, a large extinction ratio is crucial to avoid problems related to walk-off effects from light coupled into the orthogonal mode. The extinction ratio is defined in the usual way to be ER_x[dB]=10 $\log_{10}(P_{max}/P_{min})$ where P_{max} (P_{min}) is the maximum (minimum) power that can be transmitted through a linear polarizer positioned at the output of the fibre when linearly polarized light is launched onto the *x*-axis of the fibre. Hence $P_{\max} = C_x^{(1)} L_x^{(1)} + C_x^{(2)} L_x^{(2)}$ and $P_{\min} = C_x^{(1)} L_y^{(1)} + C_x^{(2)} L_y^{(2)}$ where the overlap between a linear polarizer oriented in the α direction and mode *(n)* is defined by:

$$L_\alpha^{(n)} = \frac{\iint E_\alpha^{(n)} . E_\alpha^{(n)*} dxdy}{\iint E^{(n)} . E^{(n)*} dxdy} \qquad \text{-(2)}$$

and $C_\alpha^{(n)}$ is the coupling between mode *(n)* and a Gaussian polarized in the α direction, as defined by Eq.(1). For a perfectly linearly-polarized mode, it is possible to avoid exciting the orthogonal mode and so ER_x=∞dB. In real fibres, modal field curvature reduces the value of ER_x that can be achieved.

In Fig.1 (bottom left) the polarization extinction ratio is plotted for a range of HNLHFs. The extinction ratio worsens significantly for smallest Λ, which reflects the increasing deviation from linear polarization for the modes of these fibres. At first, it appears that the extinction ratio is independent of the air-filling fraction (d/Λ). However, by plotting the extinction ratio as a function of the effective mode area (see the insert) it is clear that the use of larger filling fractions leads to fibres with smaller mode areas without worsening the extinction ratio. In other words, for a specified mode area, the fibre with larger air-filling fraction has a higher extinction ratio. Note that larger air-filling fractions also produce fibres with lower confinement loss [8]. Hence HNLHFs with large d/Λ reduce the impact of coupling, polarization and coupling penalties in this sub-wavelength core regime.

Conclusions

We have identified practical penalties associated with HNLHFs. For structures with sub-wavelength cores, both the coupling efficiency and polarization extinction ratio are reduced. These penalties pose a challenge for the realization of HF-based dispersion compensators and evanescent field devices, both of which require small structure scales. For other devices, it is possible to design fibres that represent an acceptable compromise between nonlinearity and these penalties. For example, a fibre with Λ=1.8μm and d/Λ=0.9 has an extinction ratio of >25dB, coupling loss of <0.05dB and a small effective area (≈3μm^2). Such fibres reduce the power length product requirements of nonlinear devices to the 10W.m level.

References

1 J.C. Knight et al, Opt. Lett., **21** (1996), 1547
2 W. Belardi et al, Proc ECOC, paper PD1.2 (2002)
3 P. Petropoulos et al, Opt. Lett., **26** (2001) 1233
4 J.H. Lee et al, Proc. CLEO, paper CPDB5 (2002)
5 P.J. Bennett et al, Opt. Lett., **24** (1999), 1203
6 T.P. White et al, Opt. Lett., **26** (2001), 1660
7 M.J. Steel et al, Opt. Lett., **26** (2001), 488
8 V. Finazzi et al, Proc. OFC, (2002), 524