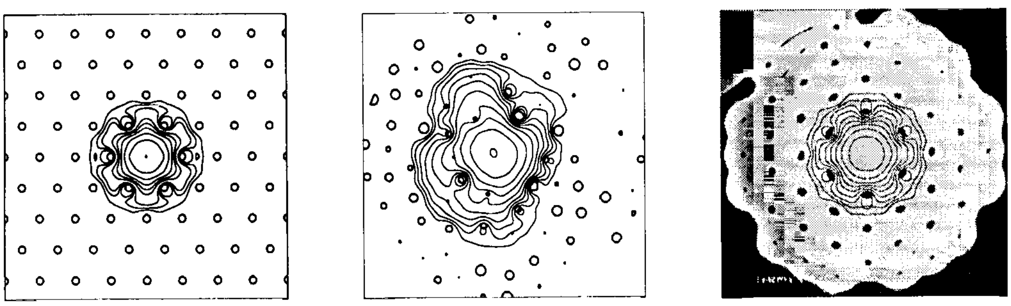
invited paper for : OFC'2000, Baltimore, March 5-10 2000.
1908

New possibilities with holey fibers

Tanya M. Monro, P. J. Bennett, N. G. R. Broderick and D. J. Richardson
Optoelectronics Research Centre, University of Southampton, SO17 1BJ, United Kingdom
Ph: +44 2380593141 Fax: +44 2380593142, email: tmm@orc.soton.ac.uk

1. Background

A new class of optical fiber has recently emerged which shows considerable promise; holey fibers have highly tailorable optical properties arising from their design flexibility [1, 2]. Typically holey fibers (HFs) are made from undoped silica, and have a cladding region formed by air holes running along the fiber length. The holes are often arranged in a periodic lattice [as in Fig. 1(a)], and the core is formed by an absent air hole. However the holes do not need to be periodically arranged or even be of constant size for the HF to guide light [3] [see Fig. 1(b)]. Either type of HF can guide because the cladding has a lower effective refractive index than the core. Although this guidance mechanism is conceptually simple, the optical properties of HFs vary dramatically depending on the hole arrangement. This is because the holes are on the same scale as the wavelength, and so the effective cladding index is strongly dependent on both the wavelength and the hole arrangement. A small subset of HFs of the type shown in Fig. 1(a) (i.e. with periodically arranged holes) can guide light via band gap effects [4], but we do not consider this more exacting mechanism here.



(a) (b) (c)

Figure 1: **(a)** HF with hexagonal hole arrangement **(b)** HF with randomly arranged/sized holes **(c)** actual HF [Predicted mode profiles are superimposed, with contours separated by 2 dB.]

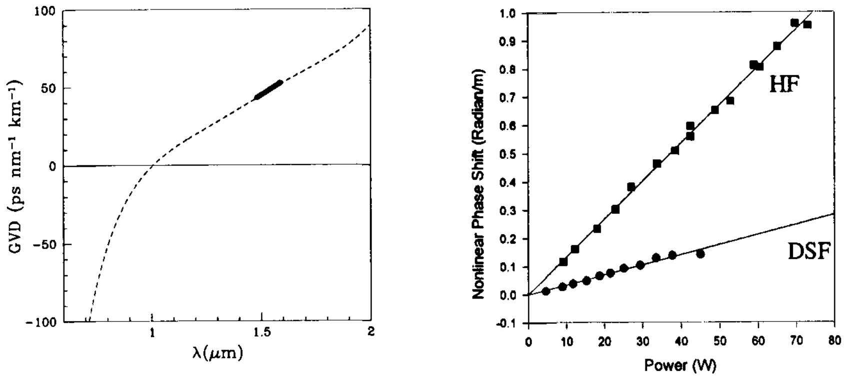
We review progress in HF technology, describing the optical properties which can be engineered making use of the novel geometry. Finally we outline some potential applications of HFs.

2. Practical HF technology

To successfully develop HF technology, it is necessary to have an accurate technique for modeling their somewhat unusual properties. The simplest approach is the effective index model [1], which ignores the complex refractive index profile. Although this model provides some insight into HF operation, it cannot predict characteristics such as dispersion [2]. To derive such information requires accurate modeling tools. One technique using plane wave decompositions can accurately model arbitrary profile HFs [5, 6]. However as it does not take advantage of the localization of guided modes it is not efficient. Also, the index profile is defined over a restricted region and extended using periodic boundary conditions, which is not a natural choice for HFs of the type in Fig. 1(b). We have developed a model [2] in which the fields and the core are described by localized functions and the hole distribution by a Fourier decomposition, allowing each quantity to be represented efficiently and accurately. This model works equally well for all the fibers in Fig. 1.

Long lengths of robust HF have been fabricated, which has allowed the first comprehensive characterization of HF properties. The dispersion of the HF from Fig. 1(c) has been measured at

1.5 μm, and found to be in excellent agreement with numerical predictions, as shown in Fig. 2(a) [7]. As dispersion is highly sensitive to the HF geometry this is a stringent test of the model. Fig. 2(b) shows the measured nonlinear phase shift in the same HF at 1.5 μm [8]. The HF is significantly more nonlinear than the dispersion shifted fiber (DSF), reflecting the fact that this HF has a significantly smaller mode area (14 μm^2). This mode area [which was extracted from the data in Fig. 2(b)] is also in excellent agreement with predictions.



(a) (b)

Figure 2: **(a)** Measured (solid line) and calculated (dashed line) dispersion for the fiber from Fig. 1(c) **(b)** Nonlinear phase shift for this same HF compared with DSF

Losses of 0.24 dBm^{-1} at 1.5 μm [7] and 0.05 dBm^{-1} at 1.3 μm [9] have been reported. These losses are not unreasonable at this early stage of fiber development, and significant improvements should be possible. Finally, it is possible to splice HFs to conventional fiber types [7], demonstrating that they can be integrated with established fiber technology.

3. Tailoring optical properties

Here the degree to which HF parameters can be tailored is explored along with the resulting design implications. Perhaps the most useful and novel property of HF is that it can be designed to support a single mode (or any given number) over all wavelengths [1]. The occurs because shorter wavelengths decay more rapidly when they encounter holes in the cladding and consequently *see* less air. The effective index difference between core and cladding is thus less than at longer wavelengths. This counteracts the increase in the number of modes which occurs in conventional fibers with decreasing wavelength. This only occurs when the holes are small [$d/\Lambda \lesssim 0.2$ - see definitions in Fig. 1(a)]; large hole HFs are multimoded at short λ, like conventional fibers.

One obvious tailorable property is the effective mode area (A_{eff}). By changing the inter-hole spacing (Λ) it is possible to tune A_{eff} over three orders of magnitude [2], from 1 $\rightarrow$ 800 μm^2 at 1.5 μm. Note that the single-moded property discussed above can be maintained regardless of the structure scale. The fraction of the modal power in the holes (PF_{holes}) can also vary significantly, from roughly 0.1 $\rightarrow$ 40%. However this parameter is linked to A_{eff}; in fibers like those in Fig. 1, PF_{holes} is tiny unless Λ is small relative to λ. The only way to obtain a significant fraction of light in the holes is to ensure that the field cannot decay significantly within the holes nearest to the fiber core. Hence a requirement for large PF_{holes} necessitates small mode areas in this type of HF.

The dispersion and dispersion slope can also be varied dramatically via the size and/or arrangement of the air holes. Unlike the properties discussed above, it is difficult to intuitively understand the relationship between the fiber design and dispersion, and it is necessary to rely on numerical modeling. To date a range of unique dispersion properties have been predicted in HF, such as an extended region of flattened dispersion around 1.5 μm [2], and also anomalous dispersion down below 1 μm, as in Fig. 2(a) [2, 10]. As a general rule, the range of possible values of the waveguide dispersion increases when the hole size is large relative to their spacing [3]. HFs have been designed with a dispersion slope of $\approx 0.01\,\text{ps}\,\text{km}^{-1}\,\text{nm}^{-2}$ over the range $\lambda = 1.3 \rightarrow 1.6\,\mu$m [2], comparable to that achieved in more conventional dispersion-flattened fibers. Dispersion properties are very sensitive to details in the fiber profile, particularly near the core, and very tight control of the fabrication process is required to make HFs with specific dispersion targets.

The shape of HF modes can also be modified by careful choice of the index profile. An example is shown in Fig. 2; (a) has a hexagonal-shaped mode typical of these HFs. Interstitial holes have been included in (b), and these smaller holes truncate the filaments in the hexagonal pattern, circularizing the mode. Indeed HFs with large holes typically have interstitials, and this circularization could simplify integration of HFs with conventional fiber systems by reducing the mode mismatch.

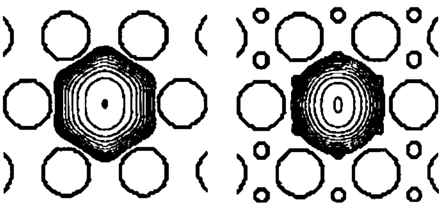

(a) (b)

Figure 2

4. Future possibilities

The tailorable properties of HF suggest a wide range of potential applications. A significant fraction of the modal power can be located in air, which suggests applications in gas sensing. Long path lengths can be achieved compactly in HF, and only tiny gas volumes are required [12]. Also, the combination of the confinement provided by the fiber and the endless single-moded operation possible in HF ensures good modal overlap between different wavelengths over long distances, which is advantageous for sensing. More speculatively, by designing HFs which have significant energy fractions in the air it may be possible produce fiber with very low transmission losses.

HFs with large mode areas could propagate extremely high powers without exciting unwanted non-linear effects. At the other extreme, small mode volume HFs could be used to explore non-linear effects. HFs can display anomalous dispersion at much shorter wavelengths than conventional fibers, allowing the possibility of short-wavelength solitons for the first time. Exploiting these two properties, efficient broadband continuum generation has been observed in HF [10].

It is possible to design HFs which could be used in dispersion compensation [11]. Also, HFs with broadband dispersion flattening have potential for ultra-broadband WDM applications [2]. By exploring more complicated types of HF designs or using different materials it should be possible to expand still further the range of applications of these novel fibers.

References

[1] T.A. Birks, J.C. Knight and P.St.J. Russell, Opt. Lett. **22**, 961 (1997).

[2] T.M. Monro, D.J. Richardson, N.G.R. Broderick and P.J. Bennett, J. Light. Tech. **17**, 1093 (1999).

[3] T.M. Monro, P.J. Bennett, N.G.R. Broderick and D.J. Richardson, Opt. Lett. (submitted) (1999).

[4] T.A. Birks, P.J. Roberts, P.St.J. Russell, D.M. Atkin and T.J. Shepherd, Elect. Lett. **31**, 1941 (1995).

[5] E. Silvestre, M.V. Andrés and P. Andrés, J. Lightwave Technol., **16**, 923 (1998).

[6] J. Broeng, D. Mogilevstev, S. Barkou and A. Bjarklev, Opt. Fib. Tech. **5**, 305 (1999).

[7] P.J. Bennett, T.M. Monro and D.J. Richardson, Opt. Lett. **24**, 1203 (1999).

[8] N.G.R. Broderick, T.M. Monro, P.J. Bennett and D.J. Richardson, Opt Lett. **24**, 1395 (1999).

[9] R.S. Windeler, J.L. Wagener, D.J. DiGiovanni, paper FG1, OFC'99 San Diego USA, (1999).

[10] J.K. Ranka, R.S. Windeler and A.J. Stentz, paper CPD8, CLEO'99 Baltimore USA, (1999).

[11] T.A. Birks, D. Mogilevstev, J.C. Knight and P.St.J. Russell, IEEE Phot. Tech. Lett. **11**, 674 (1999).

[12] T.M. Monro, D.J. Richardson and P.J. Bennett, Elect. Lett. **35**, 1188 (1999).