ECOC / 2002 2032
Invited paper

HOLEY FIBRES – A REVIEW OF RECENT DEVELOPMENTS IN THEORY, FABRICATION AND EXPERIMENT

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Abstract

Recent advances in the development of holey optical fibres are described. We review the basic physical properties of the various fibre types, the status of current fibre fabrication efforts and discuss numerous end applications.

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1: Introduction

The area of holey fibres i.e. optical fibres containing a fine array of air-holes that pass along the full fibre length (see Fig.1) has developed into a topic of acute fundamental scientific and technological interest in recent years. Indeed, it is no understatement to say that the growth and development of the field has been explosive since the first demonstration of guidance within such structures in 1996, by Phillip Russell and co-workers then at Southampton University [1]. There are now numerous university and industrial laboratories engaged in developing holey fibre technology and seeking to apply it to applications as diverse as dispersion compensation through to metrology. Furthermore, initial efforts at commercialisation of a restricted range of holey fibre types are already underway. The reason for this frenetic activity is quite simple - holey fibre technology allows one to obtain unique and technologically enabling optical properties for a waveguide that simply cannot be achieved with conventional fabrication approaches.

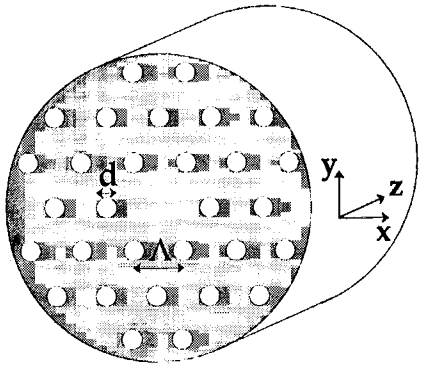

Fig.1 Schematic of a typical holey fibre.

Holey fibres can crudely be classified into three main types. The first category relates to those fibres that guide light due to volume average refractive index effects and for which we retain the generic label holey-fibre. The second category relates to those fibres that guide by photonic band gap (PBG-) effects and which we refer to throughout as photonic band gap fibres. The third and final category relates to fibres that guide light through some more conventional mechanism, but take advantage of the transverse microstructuring in some other way, for example by the way that the arrangement of holes affects the cladding mode distribution. For the purpose of this paper we refer to such fibres as microstructured fibres. We review now the fundamental properties and experimental progress to date for each fibre type.

2.1: Refractive index guiding holey fibres

Refractive index guiding fibres were the first form of holey fibre demonstrated [1]. Optical confinement is by virtue of a modified variant of the total internal reflection mechanism employed in conventional optical fibres. The basic physical requirement to achieve this form of guidance is that the volume average index in the core region of the fibre is greater than that of the surrounding regions within the structure. Such fibres are most usually fabricated by stacking together an array of capillaries and then replacing one, or possibly a number of capillaries, within the resulting macroscopic geometric stack with a solid rod. The resulting structure is then reduced to fibre dimensions in which the hole diameter d and pitch Λ are typically on the scale of order the wavelength λ. A typical holey fiber structure is shown in Fig.2.

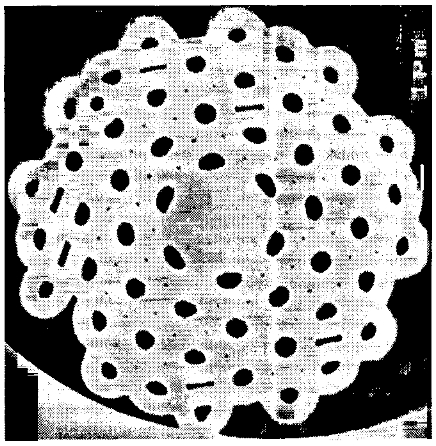

Fig.2 SEM image of a typical refractive index guiding holey fiber.

Note that for the purpose of this discussion we will describe structures by reference to the idealised periodic structure of Fig.1. However, it should be appreciated that periodicity of the refractive index of the structure is in fact not necessary in order for this guidance mechanism to be effective. Indeed, by virtue of recent advances in the numerical modelling of such structures we have shown that fibres with randomly distributed air holes within the cladding can guide via this mechanism and yet still possess all the unusual propagation described below. The fundamental physical difference between these fibres and conventional types arises from the way the guided optical mode 'experiences' the cladding region. In a conventional fibre this is to first-order largely independent of wavelength, however in a holey fibre the modes at short wavelengths are more able to distort themselves so as to avoid the low index air-holes. The result is an effective cladding-index that increases with decreasing wavelength and it is this that gives rise to the unique properties of these fibres.

Perhaps the most striking property of this fibre type is the fact that fibres with a low air fill fraction $d/\Lambda < 0.2$ can be single-moded at all wavelengths - a truly unique feature and one that has been validated in a number of experiments [3].

Due to the large difference in index between glass and air it is perhaps not surprising that such fibres can exhibit unusual dispersion properties. For example, it has been shown both theoretically [4,5], and more recently experimentally [6,7], that holey fibre with a small pitch (Λ~1-2μm) and large air holes can exhibit anomalous dispersion at short wavelengths. This feature has made the generation and propagation of optical solitons in the near-IR and visible regions of the spectrum a reality [8,9]. Moreover, such a shift in zero-dispersion wavelength to wavelength regions in which there are convenient short pulse sources, coupled to the small associated mode area, allows the development of efficient supercontinuum sources whose spectral content extends from the UV out to beyond 1.8μm [7,8]. Such sources are attractive for a range of applications including use within optical sensor systems, pulse compression and the definition of precise frequency standards [10]. It is also possible to design fibres with extremely high values of either anomalous, or normal dispersion [4,5,11]- the latter fibre type being of interest for dispersion compensation applications at 1550nm. Whilst experimental results are still eagerly awaited in this direction theoretical designs for fibres with dispersion values as high as -2000 ps/nm.km have been proposed. However, the key issues of fibre loss, nonlinearity and dispersion slope will need to be addressed before this can be considered competitive to existing approaches to dispersion compensation.

Other work has shown that dispersion-flattened holey fibres can also be designed [12,13]. For example in Fig.3 we show a plot of a dispersion-flattened fibre with close to zero-dispersion over an extended bandwidth from 1.3μm to 1.8μm. The dispersion slope of this fibre is 0.01 ps/nm^2/km, approximately five times less than that of conventional fibre designs [2]. Such fibres are of interest for a wide range of uses and not least for nonlinear optics applications, where the broadband, low dispersion can be used to efficiently phase-match nonlinear interactions over a broad spectral range.

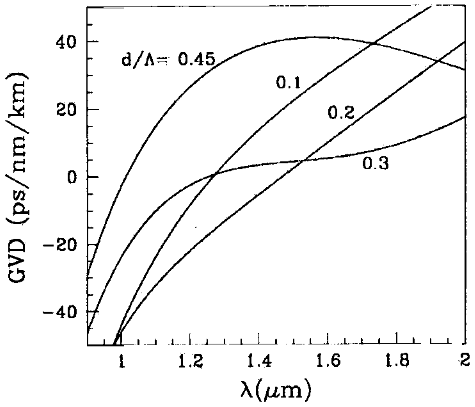

Fig.3 Dispersion profiles of average refractive index guiding holey fibres with various ratios of d/Λ. Fibres with dispersion flattened properties (d/Λ=0.3), and zero dispersion wavelengths shorter than 1.3μm (d/Λ=0.45) are readily obtained [4]. (Λ=2.3μm for each of the plots shown).

As already indicated holey fibres are also attractive from a nonlinear perspective. Calculations show that the effective mode areas of holey fibres at 1.55μm can be varied over three orders of magnitude from the order of 1μm^2 (large air holes, small-pitch) to >1000μm^2 (small air holes, large-pitch) [14]. Indeed, there exists a scaling law that shows that certain modal properties such as the number of bound modes of a given structure at a given wavelength are defined only by the ratio of d/Λ, and not with absolute Λ [15]. Hence a fibre that is single mode for a given design remains single-mode independent of the structure size. The only practical limit to the maximum spot size for a given scaled-structure is imposed by bend-loss as the mode size is increased. Single mode fibres with mode field diameters of the order 50λ have already been demonstrated at visible wavelengths [15]. Fibre with a large core size is of major interest in applications where nonlinearity is undesirable such as high power laser beam delivery and pulsed fibre lasers. Conversely, fibre with a small core-size is desirable for applications requiring a nonlinear response such as optical switching and wavelength conversion [16].

Finally, it is worth adding that holey fibres are also suitable for applications in which an interaction with an evanescent field is required—for example to obtain a nonlinear interaction, e.g. Raman scattering within a gas.

This might appear obvious application of a holey fibre when one looks at a typical fibre profile however theory shows that generally the overlap with air regions in such structures is rather small (<1% typically). In order to get significantly higher overlaps say >40%, one needs to use fibres with a relatively large air fill fraction ($d/\Lambda>0.7$) and small structure scale ($\Lambda<\lambda/2$) [17].

Fabrication of holey fibres has now reached the point that losses of order 0.2 to 0.05 dB/m are readily being achieved for certain fibre types and there should be every expectation that with further work these losses will drop still further. Moreover, the fabrication processes have extended to allow production of km scale lengths of fibre with protective glass over-jackets and polymer coatings [18]. This makes the holey fibres far more robust and their use more practical. Furthermore, it has been shown that such fibres can be cleaved and spliced in much the same way as conventional fibres [18], which allows them to be ready integrated with existing fibre components and systems.

2.2: Photonic band gap fibres

These particular forms of fibre guide by a completely different mechanism compared to average index effects and are reliant upon Bragg reflection effects in 2-D similar to those used so successfully in 1-D for fibre Bragg gratings [19]. A principle difference relates to the strength of the refractive index modulation which is clearly much higher in a holey fibre ($\Delta n=0.45$) relative to a fibre grating ($\Delta n=10^{-4}$). This results in the requirement for far less 'grating planes' to obtain a strong reflection and thereby transverse confinement of the optical field. The operation of these fibres thus depends critically on periodicity of the air holes, and light is confined within certain 'resonant' pass bands defined by the structure. This requirement places more stringent demand on the fibre fabrication process however such fibres offer truly unique optical properties [20]. For example they provide the possibility of confining a guided mode to an air defect of the structure allowing the development of fibres with extremely low nonlinearity, or fibres with a high power handling capacity. To date there have been relatively few predictions of the various modal properties e.g. dispersion, mode shape of photonic band gap fibres due to the complexity of the calculations and long run times required to accurately model such properties. However a considerable number of groups are now working on this exact topic [21,22], and without doubt a whole range of interesting properties and phenomena will duly be discovered.

The first experimental results concerning the observation of optical transmission at visible wavelengths within the distinct pass-bands of a PBG fibre with a low-index (air) defect have been reported [23,24]. These early results represent a truly significant development in the field, and although these experiments employed only relatively short lengths of fibre, they demonstrate that the fabrication technology has matured to the point that such fibres can be produced. Further improvements in photonic band gap fibre fabrication should be anticipated in the near future. Associated application experiments will without doubt also soon follow.

2.3: Microstructured fibres

Structuring of fibres can also be used to good effect to enhance, or extend, the properties of conventional fibre types, as well as to define the new guidance mechanisms described above. For example workers at Lucent have developed fibres with a conventional photosensitive core into which gratings have been written but which include holes within the cladding that can be filled with a polymer with a highly temperature dependent refractive index [25]. This allows one to modify and tune the cladding mode structure allowing fthe fabrication of long period gratings with an extended temperature tuning bandwidth, or conventional gratings with reduced cladding-mode resonances [26]. Micro-structured fibres are also attractive in the context of fibre lasers offering for example the possibility of numerical apertures in excess of unity for air-clad, cladding pumped rare earth doped fibres [27]. This later concept is significant in that it should allow for smaller dimension cladding areas and allow for shorter cladding pump devices, and higher pump intensities. This later feature is significant since it might allow for improved laser operation of important transitions such as the 976nm transition in ytterbium and which can be used to pump high power EDFAs.

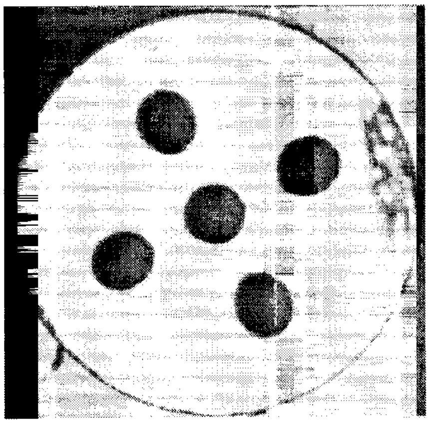

Fig.4 SEM of a holey fiber for atom optics applications. The four outer holes contain current carrying gold electrodes that can be used to create an intense magnetic field within the hollow central core [28]

As a final example we show in Fig.4 a microstructured fibre that we have produced for atom optics applications. Four closely spaced, miniature current carrying metal wires (inserted within the four outer holes) are used to create a large quadrupole magnetic field in the hollow central core of the fibre. This field can then be used to trap and guide ultracold atoms. Indeed our collaborators at Sussex University have recently experimentally demonstrated the concept successfully guiding atoms over tens of cm's of propagation distance and represents a significant advance in the emerging field of fibre atom optics [28].

3: Conclusions

In conclusion, we have briefly reviewed the properties and experimental status of the three main categories of holey fibre. It should be apparent that the technology offers the opportunity for the fabrication of a whole host of fibres with unique/useful optical properties, and that many of these properties are significant from a telecommunications perspective. The fabrication of holey fibres is still fairly immature. However, it has now developed to the point that the losses and robustness of holey fibres are suitable for many device applications within each of the fibre categories that we have defined herein, moreover there remains plenty of scope for further improvements on both counts. It is still too early to predict where, if anywhere, holey fibres will be used in the telecommunication arena, however this should become much clearer in the year ahead, what is certain is that we can expect many more interesting results and discoveries as we seek to answer this question.

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