Microstructured optical fibres: new opportunities for sensing

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ABSTRACT

The novel properties possible in microstructured optical fibres present new alternatives for a range of sensing applications. We review applications such as gas sensing, ultra-broadband sources, new source wavelengths, rotational sensing and bend sensing.

1. Introduction

In recent years an important new class of optical fibre has emerged: the *microstructured* or *holey* optical fibre. In a microstructured fibre, the transverse refractive index profile contains a number of air holes that run along the length of the fibre. The term holey fibre (HF) is used to describe those microstructured fibres in which light is guided by the effective refractive index difference (Δn) between the core and cladding. The cladding is typically laced with air holes, which do not need to be arranged periodically.[1] These fibres can be made from a single material, and a typical HF is shown in Figure 1. The index contrast Δn can be a strong function of wavelength, which leads to a host of highly unusual and tailorable optical properties.[2,3]

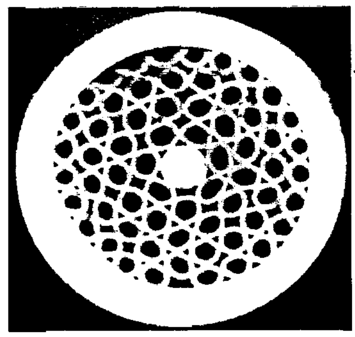

Figure 1. A holey optical fibre. The diameter of this fibre is approx. 250 microns.

Photonic bandgap or photonic crystal fibres (PCFs) are another type of microstructured optical fibre, and these fibres guide light by making use of the photonic bandgaps that can occur in a periodic structure.[4] A further example of a microstructured fibre is the atom guiding fibre.[5] In this example, metal electrodes are inserted into holes that run the length of the fibre, and these electrodes are used to define a magnetic potential, which then acts to guide atoms down another hole in the fibre.

The presence of air holes in microstructured fibres opens up a range of possible applications. For example, by filling the air holes of a HF with a gas or liquid, pollutant concentrations could be measured via evanescent field effects. In addition, the unusual optical properties possible in these fibres could have a significant impact on a range of sensing applications. In this paper we explore the potential of these new fibres in the field of sensing.

2. Holey fibres as evanescent field devices

The holes in the cladding of a HF open up new opportunities for exploiting the interaction of light with gases and liquids via evanescent field effects. For example, the concentration of pollutants in a gas could be determined by measuring the absorption that occurs as light propagates through the gas for a range of wavelengths.[6] The HF geometry can naturally provide extremely long optical path lengths in a compact fashion.[7] In order for HFs to be useful as evanescent field devices, a significant fraction of the modal field must be located within the holes. At first sight, a fibre like the one shown in Figure 1 looks promising for this type of device. However, when the optical properties of such fibres are calculated, there is typically only a very small overlap between the guided mode and the holes.[7] Indeed, for most of the HFs made to date, which typically have hole spacings in the range $\Lambda = 2 \rightarrow 3.5$ microns, less than 1% of the guided mode's power is located in the air holes. Here we explore the requirements for effective evanescent field devices using HFs.

The predictions for the optical properties of HFs which are described here were calculated using a hybrid orthogonal function approach which is described in detail in Refs [3] and [8]. This technique involves decomposing the transverse electric field distribution using localized functions. The central index defect and the air hole lattice are described independently using localized functions for the defect and periodic functions for the holes. This can be both efficient and accurate because the physical quantities are described by functions chosen carefully to suit. Using this model, we can calculate the fraction of the power of the fundamental mode that is located in the holes, and we label this parameter by PF_{holes}.

As described above, for the types of HFs which have been fabricated thus far, PF_{holes} is typically insignificant over the wavelength range from $\lambda = 0.5 \rightarrow 2$ microns. For example, see the lower set of curves in Figure 2, which correspond to a range of fibres with Λ =3.2 microns, the hole spacing for the HF shown in the insert.

In general, the field distribution for the fundamental mode depends strongly on the size of the features in the HF relative to the wavelength, and so PF_{holes} can be tailored. To understand how this can be done, consider a solid silica rod of diameter 1.25 Λ that is suspended in air, where Λ is the hole separation in HF. Although this suspended structure is clearly impractical, it gives a good approximation to large air fill HFs such as the one in Figure 2. The value 1.25 Λ is chosen because it allows good agreement with HFs in this step-index fiber analogy.[9] The modes of this simple suspended structure can be found exactly;[10] and it can be shown that a significant fraction of the fundamental is located outside the core when $V < 2$ (V is the fiber parameter). This leads to the requirement $\lambda \geq 2.2\ \Lambda$ in order for PF_{holes} to be significant. At telecommunications wavelengths, this condition is only satisfied for small Λ, which leads to fibres with very small mode areas (of order 1 μm^2). Hence such fibres also have potential applications in nonlinear experiments.

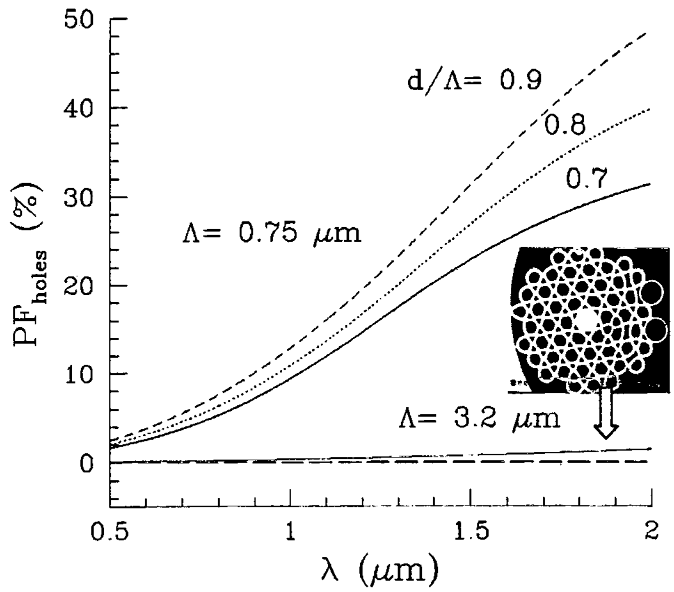

Figure 2. The fraction of the modal power located in the holes for a range of fibres. Insert shows a HF with a pitch of 3.2 microns.

The upper curves in Figure 2 show PF_{holes} for a range of HFs with Λ =0.75 microns; we have used the condition $\lambda \geq 2.2\ \Lambda$ from above to guide our choice of Λ, and d is the diameter of the holes. It is clear that using this smaller Λ has dramatically increased PF_{holes}. For example, $PF_{holes} \approx 30\%$ at 1.5 microns for a HF with a relative hole size $d/\Lambda = 0.8$ and separation Λ =0.75 microns. Also, note that better overlap is obtained when the air holes are large. Although HFs with large holes have been made[11], to our knowledge fibres with such small Λ have not yet been made. However, we expect that it should be practical to fabricate such fibers. The high degree of overlap between the fundamental mode and the holes evident in Figure 2 implies that HFs may indeed be useful as evanescent field devices.

To demonstrate the possibilities for using HFs in evanescent field devices, we consider the HF discussed above ($d/\Lambda = 0.8$, Λ =0.75 microns). Using 1.67 micron light would allow methane concentrations to be measured,[12] and for this fibre, Figure 2 predicts $PF_{holes} \approx 35\%$ at this wavelength. Hence less than 3m of this HF is required to obtain an equivalent free-space path length of 1m. By coiling the fibre, extremely long path lengths can be achieved compactly. Another advantage of this geometry is that only tiny gas volumes are required; 3m of this HF could be filled using only 30 nl of gas. Note however that there is a practical limit to the reduction of the scale-size of the fibre profile: if Λ is made too small, it becomes difficult to fill the holes with gas in a reasonable time, and it becomes difficult to fabricate the required fibre structure.

Kaiser et al. proposed another type of air-clad fiber[13]. In this structure, a thin spoke-like membrane supports the core, and such a structure can be single-mode. Clearly, this fiber is closely related to the suspended rod model described above. However, Kaiser et al. considered only structures where the membrane thickness $t \gg \lambda$, for which most of the light is located in the glass. By reducing the scale of this structure, which is analogous to reducing Λ in a HF, the overlap between the mode and the holes could be increased. We propose that in this way, this alternative single-material fiber design could also be used to create compact evanescent field devices.

Since fiber losses can be low, one could envisage HFs with extremely long equivalent free-space path lengths. The combination of the confinement provided by the fiber and the endless single-moded operation that is possible in HF ensures good modal overlap between very different wavelengths over long distances. This is advantageous for sensing, because the absorption signatures of different pollutants can be found at disparate wavelengths. In addition, HFs can be spliced to standard fibre types, which would allow them to be integrated with more conventional technologies.[16] Hence HFs have the potential to provide an ideal environment for evanescent field devices, and further optimization of the HF geometry is likely to significantly enhance this potential. Photonic bandgap fibres could also be used for evanescent field applications: these fibres offer an even larger potential overlap between the guided mode and the material that fills the holes.[4] However, it is more difficult to fabricate such fibres than it is to make HFs, and to date only short lengths have been possible.

3. Applying the novel optical properties of holey fibres

Thus far, we have described how holey fibres can be designed to be efficient evanescent field devices by optimizing the interaction between the guided modes of the fibre with the holes. This type of application makes direct use of the holes in the cladding of the fibre. The presence of these holes also leads to a range of novel optical propagation properties in HFs, and here we describe a range of optical properties that may have a significant impact on sensor applications.

The dispersion of light in an optical fibre can be divided into two components: material dispersion and waveguide dispersion. The material dispersion depends solely on the fibre composition, which for HFs is typically pure silica, although other materials could be used. The waveguide portion of the dispersion is induced by the holes, and is typically a strong function of wavelength in these fibres, particularly when the features in the cladding are of a similar scale to the wavelength. Changing the size and/or locations of the holes in a HF can radically alter the waveguide dispersion, and a range of useful regimes has been identified. For example, it is possible to design single-mode HFs with a zero dispersion wavelength anywhere in the range from 650 – 1300nm,[3,14] something that is not possible in conventional fibres. In addition, the mode size in a HF can be tailored over three orders of magnitude, so that both very large and small effective core areas are possible.[3] When a HF with a small effective core area (and hence a low threshold for nonlinear effects) is pumped with light near the zero dispersion wavelength, it is possible to efficiently generate a broadband continuum spectrum.

To demonstrate this, we show in Figure 3(b) the spectrum generated when the HF in Figure 3(a) was pumped at 1 micron using 600fs pulses with pulse energy of 1nJ. This fibre has an effective core area of 14 μm^2 (about four times smaller than dispersion shifted fibre), and a zero dispersion wavelength at about 1.1 microns.[15,16] Figure 3b shows that an extremely broad spectrum is generated within the fibre. Note also that this fibre guides just a single mode over this entire wavelength band. This spectrum can then be used to provide a range of new source wavelengths for sensing applications. One advantage of this approach is that the fibre's zero dispersion wavelength can be tailored to suit the available pump sources. In particular, this raises the possibility of producing new ultra-broadband all-fibre sources, which would have a number of advantages including compactness and simplified alignment. The combination of HF and high power Yb^{3+} doped fibre lasers is particularly appealing.

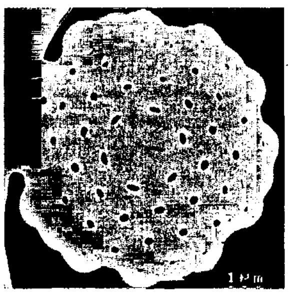

Figure 3(a). A nonlinear HF with zero dispersion @1μm.

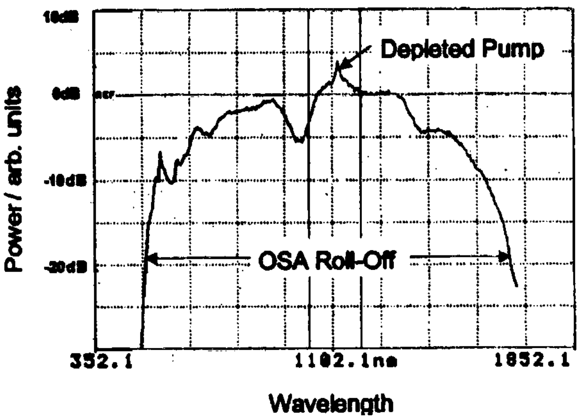

Figure 3(b) Continuum spectrum produced when fibre 3(a) is pumped at 1.1 μm.

4. Grating devices

It has recently been shown that gratings can be written into holey fibres that have a germanium-doped core region.[17] Long-period fibre gratings (LPGs) written in these fibres were shown to be highly insensitive to the external environmental conditions (such as temperature and humidity) when compared with conventional LPGs. Such gratings are likely to be useful for devices where fixed gratings are required, and the relative insensitivity to the environment should help to simplify packaging issues.

Another type of microstructured fibre in which LPGs have been written is described in Ref.[18]. A fibre with a conventional core/cladding was used, and a single ring of large air holes was added around the inner cladding. By filling these holes with a UV-curable acrylate-based polymer, the peak wavelength of the grating spectrum is shifted by 74nm/100°C (without the polymer, the shift is 3nm/100°C). It was found that the amplitude of the transmission spectrum was invariant over a wide range of temperatures, and such structures were proposed as ideal tunable filters for communications systems. Alternatively, such structures could be used as compact and accurate temperature sensors.

5. Bend sensing

Holey fibres can be adapted to monitor the deformation of a structure in three-dimensions. This is done by using a single HF with multiple single-mode cores in which there is no significant coupling between the cores.[19] This type of HF is no more difficult to fabricate than a single-core HF, as the additional cores are produced simply by replacing capillaries in the preform stack with solid rods. In this way, the core geometry/spacing can be easily controlled. When the multi-core fibre is deformed, the differential strain induced between the cores results in a phase difference between light propagating in each core. Any bending of the fibre is then detected by analyzing the fringes in the far-field pattern. Bend sensitivities of 2.33 radians/mm have been measured using this approach.[19] Using conventional fibres, this can only be done by embedding three separate fibres in a non-collinear geometry. Hence, HFs can offer significant simplification in the design and packaging of bend sensors.

6. Atom waveguides

Recently atoms have been guided along a microstructured fibre for the first time by making use of a magnetic potential within the structure.[5] The fibre geometry that was used is shown in Figure 4. Wires were inserted in the four outermost holes, and by running currents through these wires, a magnetic quadrupole field was established in the central hole. This field exerts a force perpendicular to transverse plane of the fibre, which enables atoms to be guided along the central hole in the fibre. Clouds of rubidium atoms have been guided in such a structure over many centimeters. The `holy grail' of atom optics would be to create truly single-mode atom waveguides in an integrated optical form. Once achieved, this would provide a route to a completely new range of unique ultra-sensitive sensor devices. For example, atoms are sensitive to gravitational fields. An atom interferometer would then present a direct means of measuring gravitational fields with unprecedented accuracy, and would be of great interest for a range of sensing applications including, for example, oil field detection. Atom interferometers also offer great potential for rotation sensing, magnetic field sensing, etc.

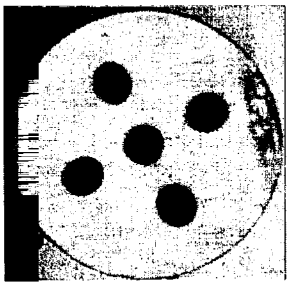

Figure 4. Profile of an atom waveguide.

7. Conclusions

We have reviewed a range of applications in which microstructured fibres may offer new alternatives for sensing technologies. These applications can be divided into two categories: those in which the transverse structure of the fibre is used directly, and those in which the novel optical properties of the fibre are exploited. Both of these categories have already demonstrated considerable potential for sensing applications. Moreover, we anticipate that further advances in the fabrication and understanding of these unusual structures are likely to open up new opportunities for sensing technology.

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