Photonic crystal fibers and applications in sensing

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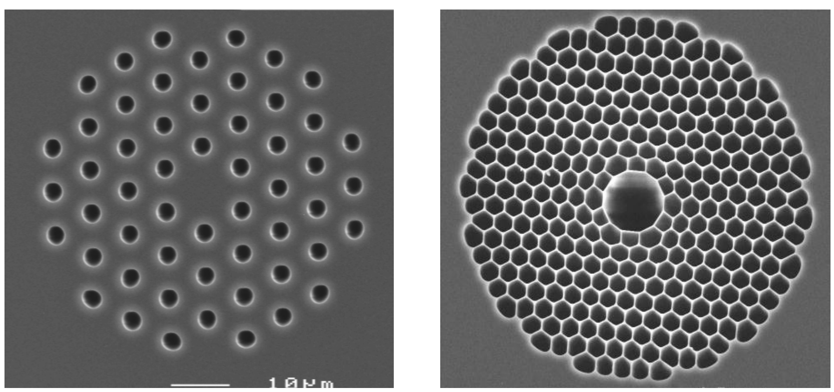
ABSTRACT

Photonic crystal fibers are pure silica optical fibers with an array of air holes that run along the length of the fiber. The development of these fibers, in both solid and hollow core varieties, has been significant over the past 15 years and they are increasingly finding new applications in a variety of sensing areas where they can offer opportunities distinct from conventional optical fibers

Keywords: Optical fiber, photonic crystal fiber, bandgap, polarization, fiber sensing

1. INTRODUCTION

Pure silica fibers with periodic arrays of air holes that run along their length are commonly known as photonic crystal fibers (PCF). The first light guiding PCF was report over 15 years ago by Knight et al.[1] where it was shown that by replacing an air hole at the center of the fiber structure with pure silica would form a high index core that confines light by total internal reflection. The cladding low index cladding is formed from the array of holes surrounding the core. A scanning electron micrograph of this fiber can be seen in Figure 1(a). There is another class of PCF that can confine light to a low index air core via the photonic band gap effect[2][3]. These are hollow core photonic crystal fibers (HC-PCF) and are uniquely classed to enable guidance in a hollow core that can be filled with either air or other gases. Photonic crystal fibers are becoming a more mature technology with significant research being conducted in many universities and companies, however new properties and applications are still being discovered.



(a) (b)

Figure 1 Scanning electron micrographs of (a) Photonic crystal fiber that confines light to a high index silica core via total internal reflection and (b) a hollow core photonic crystal fiber that guides light in a low index air core using photonic band gap confinement.

2. INDEX GUIDING PHOTONIC CRYSTAL FIBERS

Conventional step or graded index optical fibers confine light to a core using the well-known total internal reflection (TIR) mechanism[4]. Light can only be confined to the core in this way if the refractive index of the core, is higher than the cladding

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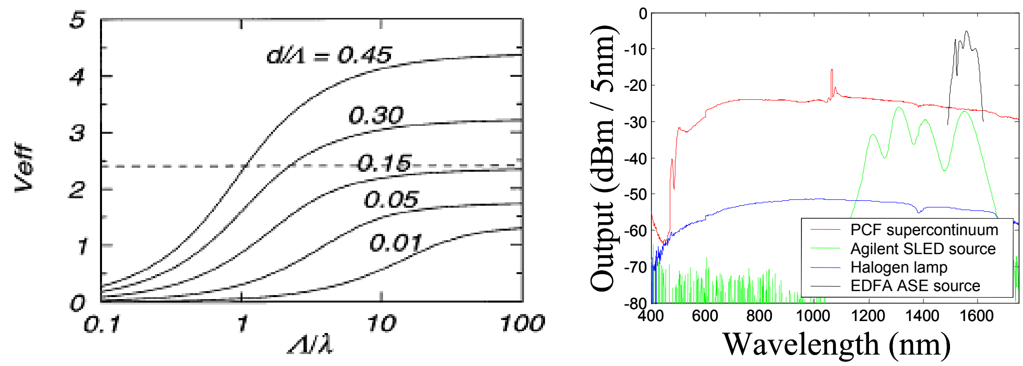
There then exists a range of values for the propagation constant, the component of the wave vector parallel to the axis of the fiber, where light can propagate in the core but is evanescent in the cladding. i.e. in this regime there are no modes of the cladding that the light in the core can couple to and leak out of the fiber. If we consider the cladding of the PCF shown in Figure 1(a) the refractive index is not as clear to define as the bulk refractive index of the material, rather we have to calculate the mode of the structure with the largest propagation constant[5]. This is called the fundamental space filling mode of an infinite photonic crystal cladding and defines the refractive index of the cladding.

In the most simple designs of index guiding PCF the effective index of the cladding increases when the wavelength tends to shorter values. From the equation above of the V-value[4], it can be seen that as the wavelength tends to a shorter wavelength (and hence a larger wavevector) the difference between the core index and cladding index becomes smaller. This has a very interesting effect so that if the correct parameters are chosen, i.e. the hole diameter to hole spacing ratio are below a 0.45, the fiber can be single mode at all wavelengths and not just for a range of wavelengths as in conventional single mode fibers. The value of V_{eff} for which the fiber must remain below for single mode operation was calculated to be 4.1[5].



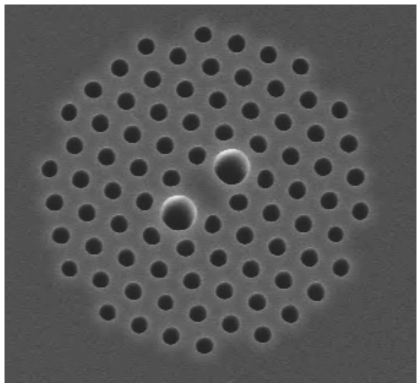
(a) (b)

Figure 2 (a) Variation of V_{eff} with Λ/λ for various relative hole diameters d/Λ. The dashed line marks V_{eff} - 2.405, the cutoff V value for a step-index fiber[3]. (b) A plot of the output spectra of different light sources to compare the broadband supercontinuum generated in PCF against the low power or narrow bandwidth alternatives.

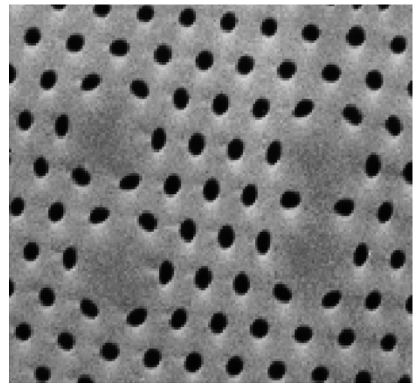
Figure 2 shows a graph of wavelength (λ), normalized to the pitch (Λ), the hole to hole spacing. The fibers can be considered to be scale invariant as the wavelength dependence of the structure scales with the pitch.. The wavelength increases from right to left on this graph and we can see that at the shorter wavelength the value of V_{eff} is increasing ever more slowly. For clarity, material dispersion was not taken into account for this plot. The plot shows that a fiber that is single moded remains as the structure is scaled by a thousand. At 1.55µm this would be cover a hole to hole spacing from 0.16-155µm, a remarkable range. At these extremes, however, the attenuation in the fiber would be sensitive to bend loss.

This is only one of many useful optical properties and design flexibility in PCF. Using rare earths or fluorides to dope silica in conventional optical fibers, a refractive index difference of, $\Delta n \approx 0.03$ is usually about the maximum that can be reached. With air/silica $\Delta n \approx 0.45$ which is on the order of 10 times larger. This enables tighter confinement to core and novel dispersion properties for nonlinear spectral broadening or conversion. In [7] the first supercontinuum generation was demonstrated in a nonlinear PCF with a core diameter of approximately 1.7µm and hole size of 1.3µm. The fiber was pumped with 100fs pulses with 800 pJ energy at 790nm and a supercontinuum was generated between 390nm and 1600nm. Soon after this other work has been published with different pump sources and fiber designs such as in [8] where a fiber with a significantly larger core size of 5µm was pumped with a nanopulse q-switched laser at 1064nm to generate a supercontinuum from 500nm to greater than 2µm, a typical spectrum is shown in Figure 2(b). Using the highly dispersive properties of the fiber the zero dispersion wavelength, which was previously dominated by material dispersion, was obtained at shorter wavelengths near the pump sources described above.

There are several wavelengths that are difficult achieve high power light at as no sources are traditionally available[9], however using the wavelength conversion of the broadband supercontinuum or four wave mixing[10][11] along with photonic crystal fibers with specifically engineered dispersion properties, these wavelengths can be reached.



(a)



(b)

Figure 3 Scanning electron micrographs of (a) A highly birefringent photonic crystal fiber with two holes with a larger diameter placed symmetrically about the core and (b) an example of a photonic crystal fiber with multiple cores, here there are two pairs of cores the strongly couple to each other.

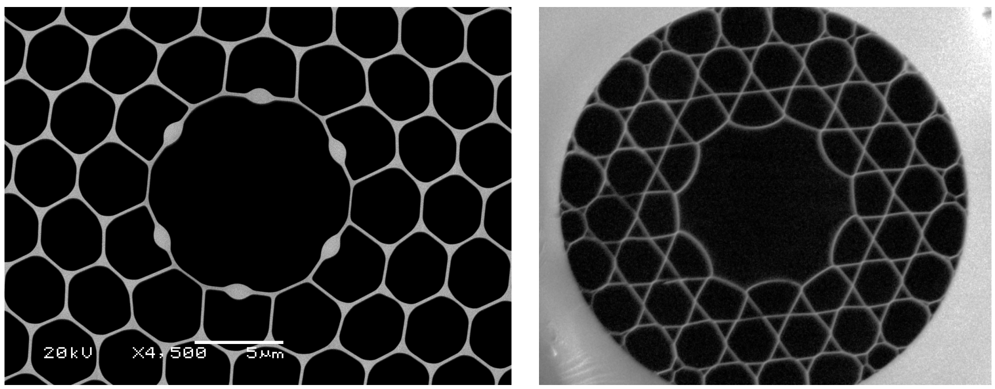
The stack and draw process lends itself easily to arranging holes of different sizes for birefringence[13][14], shown in Figure 3(a), high slope matched dispersion[16][17] and even placing multiple cores in the fiber[15]. The fiber is fabricated using a stack and draw process[1], an array of pure silica capillaries is assembled and then drawn down on an optical fiber drawing tower, usually in multiple stages, and form the array of holes in the PCF. The cores are formed by replacing the capillaries with rods. A multiple core photonic crystal fiber is fabricated by including two or more rods in the stack. The cores can be close enough together so that they couple to each other [15] as shown in Figure 3(b) or easily space further apart to inhibit coupling for applications such as bend and shape sensors[16]. As PCF's are typically fabricated from pure silica material, with no dopants, there is much more likelihood that the specific fibers can be highly stable under varying temperature conditions.

Interaction with the gases or liquids in photonic crystal fibers has been studied extensively [19]-[21]. The light of a guided mode in a high index core decays exponentially into the cladding and by designing a suitable structure so that the light is weakly confined to the core, the mode field can extend significantly into the cladding to increase the overlap of light with air holes and increase the interaction with any gas or liquid that has infiltrated the cladding holes. Another method is to not have a high index silica core, but to place a large air hole at the center of the fiber and fill that with water, this fiber was designed in such a way to remain single mode when filled with water[22]. These are just a few of the examples where index guiding photonic crystal fiber technology has been made useful for fiber based sensing applications.

3. HOLLOW CORE PHOTONIC CRYSTAL FIBERS

Hollow core photonic crystal fibers (HC-PCF) are low loss optical fibers that confine light to a hollow core using a photonic band gap. This novel type of optical fiber was first proposed over 10 years ago[24] and the benefits and limitations of the fibers have become very well understood since then. There has been significant effort to understand and reduce the optical attenuation in HC-PCF's[25]-[27]. This work has been focused primarily to the telecommunication wavelength bands due to the commercial potential that could be obtained if the attenuation was reduced below conventional optical fibers. HC-PCF attenuation is not limited to the refractive index fluctuations that cause Rayleigh scattering, the dominant loss mechanism in conventional low loss fibers, as most of the light is confined to the air core. They are, however, limited by the surface roughness at the air-silica interfaces which is created by frozen in capillary waves during the fabrication process[27]. To reduce the interaction of light at the air-silica interfaces a resonant core was demonstrated in [26]. The thickness of a silica core wall in a 19 cell HC-PCF was increased from the standard thickness (normally equal to the thickness of the struts in the cladding) until it was resonant at wavelengths within the bandgap. Using the anti-resonant core wall in a 19 cell hollow core fiber significantly reduced the attenuation to 1.2dB/km but a consequence of the thicker core wall is that unwanted lossy surface modes are guided that then couple to the fundamental mode of the core reducing the operating bandwidth of the fiber[25]. Recent work on 19 cell hollow core photonic worked on understanding the effects of the core wall and produced a fiber with a slightly higher attenuation but with a much broader wavelength range[27]. To increase the flexibility in the design of the HC-PCF anti-resonant elliptical features can be placed on the core wall[28], as shown in Figure 4(a).

The majority of applications using HC-PCF benefit from low attenuation in the fiber but it is not always the most important parameter. Due to the low overlap of light with the periodic silica cladding the non-linear effects are greatly reduced. This enables an improved performance in interferometric applications [30] and, with the anomalous dispersion properties of the fiber, high power short laser pulses (e.g. 100fs) can be delivered [31]-[34].



(a) (b)

Figure 4 Scanning electron micrograph of (a) a HC-PCF with anti-resonant core wall features and (b) a hollow core PCF with a large pitch few ring cladding.

There is another type of hollow core PCF know as a Kagome fiber that also confines light an air core via an inhibited coupling mechanism[35][36]. There are discrete modes in the cladding but as the light in the core does not significantly overlap with these modes the attenuation in the fiber is low. One distinct advantage to this fiber is the very broadband guidance of several hundred nanometers. Along with the very large holes size that can be obtained which allow for easier infiltration of gases for sensors, gas lasers or multi octave frequency combs[37][38].

As most of the light is in air and less than one percent of the light is in silica, HC-PCF can be attractive for guiding light at wavelengths much longer than is usually obtained in silica fibers. Guidance at 2µm[39] and 3µm[40] has been reported with development of the fibers towards surgical applications[41].

To use HC-PCF as a sensor an access path to the core, or even just the cladding must be created. Exposing the end of the fiber is of course an acceptable way to do this but unless there is some force to increase the flow of the molecules into the hollow core fiber or there is very strong absorption, this can be a very slow process. There have been two methods suggested for accessing the core of a hollow core fiber. By directly exposing the core to the atmosphere by removing the cladding holes along one row from the core all the way to the external to allow for larger exposure[42]. It was also reported that using a femtosecond laser holes can be 'drilled' into the core through the outer surface of the fiber leaving small access paths to the core, several holes over short length with very low increase in attenuation has been demonstrated[43][44]

There are many novel properties in PCF's and there has been a significant effort in the field to understanding and developing these fibers for uses in sensing. It's not obvious that any PCF has yet made a breakthrough into a mainstream application. However due to the robust design nature of the fibers there have been a lot niche applications and with all the design flexibility it is expected that PCF will continue to develop, especially in areas where optical properties such as dispersion, nonlinearity and temperature sensitivity are an issue.

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