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Fundamentals and applications of silica and non-silica holey fibers

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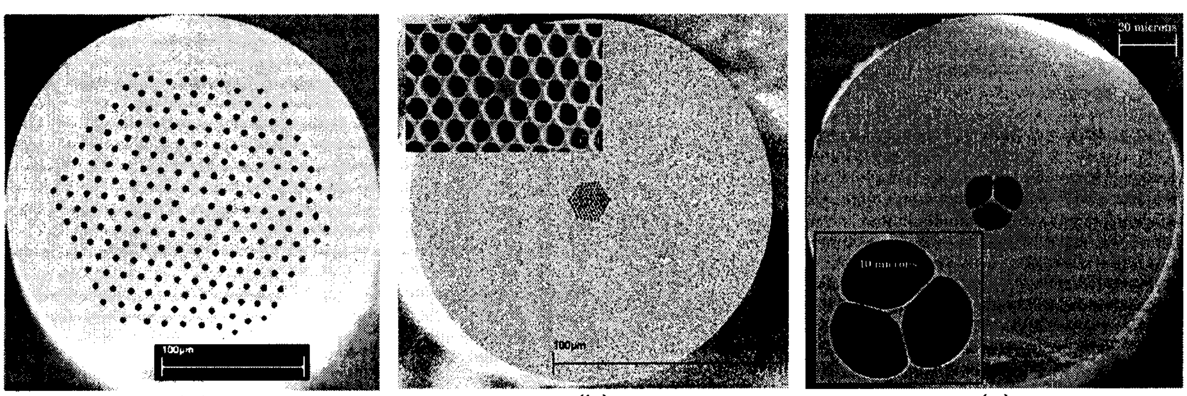
1. Introduction

Since the first demonstration in 1996 [1], microstructured fibers have attracted growing attention. They offer a wide range of unique optical properties, which cannot be provided by conventional fibers, and this opens up diverse potential applications in telecommunications, metrology, medicine and beyond [2]. Microstructured fibers contain an arrangement of air holes running along the fiber length, and examples are shown in Fig. 1. The holes within these fibers act as the fiber cladding, and light can be guided using either one of two quite different mechanisms.



(a) (b) (c)

Fig. 1: SEM photographs of some typical HFs: (a) large mode area silica HF (15µm core), (b) small core (1.2µm) silica HF, (c) small core (1.7µm) lead-silicate HF.

Index guiding microstructured fibers guide light due to the principle of modified total internal reflection, and such fibers are widely known as *holey fibers* (HFs). The holes act to lower the effective refractive index in the cladding region, and so light is confined to the solid core, which has a relatively higher index. The basic operation of HFs does not depend on having a periodic array of holes [3]. However, in practice the holes are typically arranged on a hexagonal lattice, and so these fibers are sometimes referred to as *photonic crystal fibers*.

An alternative guiding mechanism can operate if the holes are arranged on a periodic lattice. Such structures can exhibit photonic bandgaps, and frequencies located within the bandgap cannot propagate within the cladding. By breaking the periodicity of the cladding, it is possible to localize light, and so light can be guided in these *photonic bandgap fibers* within well-defined frequency windows [4].

Both types of microstructured fibers are typically made from silica. Recently, HFs have also been fabricated from highly nonlinear compound glasses [5,6] and polymers [7].

HFs have matured into a technology with the potential to revolutionize many areas in optical technologies. Here we aim to provide an overview of this emerging fiber type. We describe the fabrication techniques and results achieved so far. The relationships between HF features, unique optical properties and potential applications are reviewed.

2. Holey fiber fabrication

The vast majority of silica HF preforms produced to date has been fabricated using stacking techniques (Figs. 1a,b). Capillary tubes are stacked in a hexagonal configuration, and the central capillary can then replaced with a solid silica rod, which ultimately forms the fiber core. The stacking procedure is a flexible one: doped core rod and multi-core fibers can be produced. In addition, very regular structures can be made. The reproducibility depends on having long uniform capillaries to stack and achieving a good stacking configuration with many tubes. The drawback of stacking is that preform fabrication is labor intensive.

Recently, extrusion technique has been demonstrated for preform fabrication of lead-silicate glasses with low softening temperatures (Fig. 1c) [5,6]. In this process, a glass disk is pressed at temperatures near the softening point through a die, which determines the preform geometry. Once the optimum die geometry and process parameters have been established, the preform fabrication process can be automated. In this way, good reproducibility in the preform geometry has been achieved. However, more work is needed to identify the impact of temperature and pressure on the straightness of the extruded preforms and jacketing tubes (any slight bending of jacketing tubes decreases the usable length of the preform).

For larger scale features (Fig. 1a), fibers are drawn directly in a single step from the preform. For small scale features (Figs. 1b,c), the preform is first reduced to a cane of 1-2mm diameter on a drawing tower, and in a second step this cane is inserted in a solid jacketing tube and then drawn down to the final fiber. In the fiber drawing process, furnace temperature, preform feed speed, draw speed and the use of pressure/vacuum within the preform determine the size and shape of the features in the final fiber [8]. The drawing process has now developed to a degree where the cladding configuration can be controlled relatively well by careful choice of the process parameters.

Fabrication of silica HFs has now reached the point that losses as low as 0.6 dB/km [9] can be achieved for certain fiber types. Moreover, the fabrication processes have extended to allow production of km scale lengths of fiber with protective glass jackets and polymer coatings. This makes the HFs robust and their use more practical. To date extrusion is still at an early stage of development. Extruded lead-silicate glass HFs demonstrate higher losses of 4-10 dB/m [5,6], but further improvement in the preform and fiber fabrication process is envisaged to decrease the losses.

3. Optical properties and applications

The parameters that characterize a HF profile and determine their optical properties are the hole-to-hole spacing Λ, the hole diameter d, the air-filling fraction d/Λ and the number of rings of holes used to define the cladding. The effective index difference between core and cladding is a strong function of wavelength, since at longer wavelengths the field extends further into the air holes thereby reducing the effective cladding index. This results in a range of unique and potentially useful properties, which can be tailored via the HF geometry.

In order to exploit the range of novel properties that can be very sensitive to the hole size and arrangement, it is crucial to have accurate techniques for predicting these properties. However, the models developed for conventional fibers cannot generally be applied. HFs exhibit complex transverse index profiles resulting in complex mode field shapes and large index contrast between core and cladding. In addition, the presence of wavelength-scale features introduces a number of challenges for accurate modeling. However, several methods have demonstrated their suitability in modeling different types of HFs [2].

According to their relationships between geometry and properties, HFs can be classified into three types differing in the size of Λ and the air-filling fraction d/Λ. The different optical properties are of interest for a wide range of diverse potential applications. Moreover, issues in terms of practicality of HFs are also related to the different properties of HFs. In Table 1, we present the properties, applications and challenges for each of these classes of HFs.

HFs with large cores ($\Lambda \geq 5\mu m$), considerably greater than the wavelength of light guided in the HF, can exhibit large mode areas and thus low nonlinearity for small air-filling fractions ($d/\Lambda < 0.4$) [10,11]. In addition, such fibers exhibit endless single-mode guidance [12]. This makes large mode area HFs very attractive for delivery and generation of high power laser beams from the UV to near-infrared spectral range with high spatial mode quality and without exciting undesired nonlinear effects. Both Q-switched and mode-locked operation have been demonstrated for a cladding pumped laser based on a large mode area HF [13]. As for conventional fibers, macroscopic bend loss ultimately limits the mode area size that can be utilized in HFs. In contrast to conventional fibers, HFs exhibit a bend loss edge at short wavelengths in addition to the long wavelength edge that is also observed in conventional fibers [11].

At the other extreme, HFs having small cores (Λ=1-3μm) with diameters similar to the wavelength ($\Lambda \geq \lambda$) exhibit a high effective nonlinearity due to the tight mode confinement resulting in very small effective mode areas [2]. This allows a wide range of nonlinear devices with drastically reduced fiber lengths and power requirements compared with conventional fibers. For smaller air-filling fractions ($d/\Lambda<0.4$), single mode guidance at all wavelengths is possible [12], which allows single mode guidance at largely different wavelengths involved for instance in supercontinuum and second harmonic generation. The strongly wavelength-dependent index difference between core and cladding in small core HFs results in unusual dispersion properties. Mainly by varying the air-filling fraction, the magnitude, sign and slope of the dispersion can be tailored to suit the specific application. Shifting the zero-dispersion wavelength to regimes where there are suitable pump sources allows the development of efficient supercontinuum sources [14] which are attractive for DWDM transmitters, optical frequency metrology [15] and optical coherence tomography [16]. High anomalous dispersion in the visible and near-infrared range enables soliton-based devices at $\lambda<1.3\mu m$, which are not possible in conventional fibers. For example, soliton self-frequency shift was used as a basis for a femtosecond pulse source tunable from 1.06-1.33μm [17]. Very high anomalous dispersion at 1.55μm enhances the efficiency of Raman amplifier and modulator devices [18]. Data regeneration and optical thresholding utilizing spectral broadening by self-phase modulation followed by offset narrowband filtering technique have been demonstrated for small core HFs [19,20]. Moreover, wavelength conversion using cross-phase modulation [21] or four-wave mixing [22] has been presented in such fibers. Flattened low normal dispersion in the wavelength range of interest enables efficient wavelength conversion based on four-wave mixing by reducing the phase mismatch between the interacting waves. Flattened dispersion at 1.55μm is also advantageous for DWDM transmitters.

The nonlinearity of HFs can be enhanced drastically by using highly nonlinear compound glasses. The material nonlinearity of lead-silicate glasses is more than an order of magnitude larger than that of silica. The combination of these glasses with the small effective mode areas are possible in HFs has resulted in very high effective nonlinearities [6,23]. For a SF57 lead-silicate HF with a 2μm core, the nonlinearity has been found to be 550 times larger than that of standard single mode fibers [23].

In terms of practicality, small core HFs present a number of challenges. HFs made from a single material are inherently leaky since the core refractive index is the same as the index beyond the finite cladding region [24], and so they can exhibit high confinement losses. Increasing the number of rings always decreases the confinement loss but it also increases drastically the fabrication labor and decreases the robustness of the fiber. Fortunately, a modest increase in the structure scale can lead to dramatic improvements in the confinement of the mode without compromising the achievable effective nonlinearity significantly [25]. In addition to confinement loss, the effect of surface roughness at the air/glass boundary becomes more significant, which can increase the loss as a result of enhanced scattering [9]. In terms of integration of small core HFs to conventional fiber systems, splicing and coupling is challenging since the small wavelength-scale core leads to mode-mismatch with conventional fibers.

Table 1: Dimensions, properties, corresponding potential applications and practical issues for different types of HFs. References see text.

Λ	d/Λ	properties	applications	practical issues
large core $\Lambda \geq 5\mu m$ $\Lambda >> \lambda$	<0.4	endless SM	high power delivery	macro- and micro-bend loss
		very large mode area	high power cladding pumped fiber lasers	
		low NL		
	>0.4	multimode	single mode UV and visible transmitting fibers	
		moderately large mode area		
small core $\Lambda = 1\text{-}3\mu m$ $\Lambda \geq \lambda$	various	high NL	*see below*	confinement loss
	large	λ_0 shift	λ_0 at suitable pump source for SC used in metrology and optical coherence tomography	loss due to surface roughness/scattering at air/glass interfaces near the core
		anomalous dispersion in Vis/near-IR	soliton-based devices in Vis/near-IR	splicing and coupling is challenging
			nonlinear devices	
	various	flattened dispersion	DWDM telecoms devices	
		low normal dispersion	nonlinear devices, e.g. reduced coherence degradation in optical thresholding devices	
	<0.4	endless SM	SM over whole SC	
very small core $\Lambda \leq 1\mu m$ $\Lambda < \lambda$	very large ≥0.7	high normal dispersion	dispersion compensation	same as for small core HFs but more dramatic
		evanescent field effects	sensors	

SM = single mode guidance, NL = effective nonlinearity, SC = supercontinuum, λ_0 = zero-dispersion-wavelength

The third type of HFs possesses cores that are even smaller than the wavelength (Λ<1µm) and simultaneously exhibit very high air-filling fractions. Such HFs demonstrate very high normal dispersion at 1.5µm, which is of great interest for short-length dispersion compensation devices [26]. On the other hand, a very large fraction of the mode field can be located within the air holes. This allows strong interaction of light with gases or liquids in the holes via evanescent field effects, which can be utilized for sensor devices [27]. The practicality of very small HFs is limited by the same issues as described above for small core HFs but to a larger extent.

4. Conclusions

The field of HFs has developed rapidly, and a wide range of robust, low loss index-guiding HFs can now be routinely fabricated. The novel guidance regimes promise to lead to a new generation of optical devices with tailor-made optical properties. As HF technology matures, it seems likely that the many unique features of these fibers will lead to numerous applications within telecommunications and beyond.

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