Microstructured Optical Fibers: Overview of Novel Materials and Geometries for Applications Beyond Telecom

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Microstructured Fiber Sensors
(by far not a complete overview)

- Absorption and Phase Change Based Sensors for Chemical Detection
- Temperature and Stress Change Sensors
- Resonant Sensors, Plasmonic Resonance Sensors
Absorption and Phase Change Based Sensors for Chemical Detection
Absorption and Phase Change Based Sensors

Signal ∝ (Interaction length) × (Overlap) × exp(− Loss × Length)

Overlap

\[ \delta n_{\text{eff}} \approx \frac{\int \, dA \, \Delta \varepsilon \, |E|^2}{2 \sqrt{\varepsilon_0 \mu_0} \int \, dA \, R\{E^* \times H\} \cdot \hat{z}} \]

Amplitude change ~ (Interaction length) × Im(δn_{eff})

Phase change ~ (Interaction length) × Re(δn_{eff})

Figure 1. Optical fibre can dramatically improve the sensitivity of a sensor by increasing the interaction length between light and the sample. In a typical bulk configuration (top), light interaction with the sample may be limited to lengths of a few centimetres. We present specialty fibre designs that will allow interaction of guided light with a sample over a metre length and greater distances (middle). Interferometric detection of light (bottom) can also be used if mode-coupling in the waveguide can be controlled.

Holey Fiber (HF) Absorption Based Sensors

Main idea – put analyte where the light is

![HF images](image)

**Figure 1.** Three large air-filled holey optical fibres: (a) a large core HF (core diameter 45 μm), (b) a holey fibre with a 5 μm core and (c) a small core holey fibre with a 1.5 μm core.

The holes in the cladding of a HF open up new opportunities for exploiting the interaction of light with gases and liquids via evanescent coupling effects

Holey Fiber (HF) Absorption Based Sensors

- The concentration of pollutants in a gas could be determined by measuring the absorption that occurs as light propagates through the gas.
- Fiber based sensors can exhibit extremely long interaction lengths, while designed in a compact fashion (10s of meters) which is impossible to achieve in bulk samples.
- Tiny gas volumes are needed for measurement (nanoliters).
- Infinitely single mode HFs allow reliable sensing at widely different wavelengths.
- In order for HFs to be superior to other evanescent field sensors, a significant fraction of the modal field must be located within the holes (>20%).
- Fiber propagation loss should be small to allow long sensors (fraction of a dB per meter).
- Gas filling time of HFs can be large due to very small holes.
The evanescent field in the air holes is absorbed by the gas species, and the gas concentration can be obtained from the intensity attenuation through the Beer–Lambert law:

\[ I(\lambda) = I_0(\lambda) \exp[-r \alpha_m(\lambda) l C]. \]

\( I \) and \( I_0 \) are the output light intensities with and without the presence of gas being detected, \( \alpha_m \) is the bulk absorption coefficient of a gas being measured, \( l \) is the length of the HF sensor, \( C \) is the gas concentration and \( r \) is a relative sensitivity coefficient defined as:

\[ r = \left( \frac{n_r}{n_e} \right) f, \]

where \( n_r \) is the index of the gas \( \sim 1 \), \( n_e \) is the effective index of the guided mode, and \( f \) is the fraction of the total power located in the holes.

Power Fraction (PF) \( f \) can be calculated by integrating the optical power inside the air holes and dividing it by the total power carried by that mode:

\[ f = \frac{\int_{\text{holes}} (E_x H_y - E_y H_x)\,dx\,dy}{\int_{\text{total}} (E_x H_y - E_y H_x)\,dx\,dy}, \]

Improving HF detection sensitivity

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

Longer Wavelengths

Core Design to Increase Sensitivity

Air hole of diameter $d$

![Figure 5. Modified evanescent-field geometry.](image)

Air hole of diameter $d_{\text{core}} < d$ in the core pushes the core mode into the porous cladding

![Figure 7. Modified evanescent-field fibre overlap plotted versus loss.](image)

Figure 7. Modified evanescent-field fibre overlap plotted versus loss.


One concern in using HF s as evanescent field sensors may be the limited response time due to the long time required for a gas to diffuse into the holes.

When \( l \) is 1 m the time for \( \text{C}_2\text{H}_2 \) gas to reach 90\% \( \text{Co} \) is 200 min. Pressure differencing of the fiber ends to decrease response time is hindered by very small hole sizes.

\[
\begin{align*}
C(x, t) &= C_0 \left( 1 - \frac{4}{\pi} \sum_{j=1,3,5}^\infty \frac{1}{j} \times \frac{\sin(j\pi x/l)}{l} \exp\left[-\frac{(j\pi/l)^2Dt}{l^2}\right] \right),
\end{align*}
\]

Sensor Power Budget and Sensitivity

\[
P_s - \alpha_f L - r \alpha_m C_{\text{max}} L \geq P_D
\]

\(\alpha_m = 0.012\) dB/m is the absorption coefficient of acetylene gas at 1.5315 \(\mu\)m
\(\alpha_f = 0.1\) dB/m is the loss of the HF
\(r = 13.7\%\) is the relative sensitivity of a particular HF
\(P_s = 5\mu\)W(7 dBm) is a typical input power
\(P_D = 10\)nW(-50 dBm) is a detection threshold
\(C_{\text{max}} = 5\%\) is maximum gas concentration – Sensor Range

The maximum sensor length is \(L = 4.87\) m. This is equivalent to an open-path gas cell with an equivalent length of \(4.87 \times 13.72\% = 0.668\) m

Sensor sensitivity for \(L = 4.87\)m of HF is \(\sim 6\) parts per million

Sensing Using Gas Filled Hollow Core Photonic Band Gap Fibers

Sensor sensitivity for $L=0.07\text{m}$ of HF is $\sim 0.04$ parts per million (compare with 6 ppm of a HF)

Gas Sensing Experimental Setup

Hollow Photonic Crystal Fiber (PCF) versus Holey Fiber Absorption Based Sensors

• Much larger fraction (compared to HF) of the core mode power is located within the hollow core ~90-99%
• Much larger compared to HF (while still very small) gas volumes are used for measurement (millilitres), increasing sensitivity
• Gas filling time of hollow PCFs under pressure is much smaller (~1-5 min) than that of HF (~200min) due to a much larger PCF core size
• Hollow core PCFs can be designed to operate at almost any wavelength as bulk material losses of their constituent materials are greatly suppressed due to modal propagation in the hollow core
• Effectively single mode operation allows reliable sensing only in a finite bandwidth window of operation, while HF are considerably more broadband
• Modal propagation loss of a core mode in PCFs is typically higher than that of HF (dB per meter range)
• Fabrication of PCFs is considerably more difficult than HF
Sensing Using Gas Filled Hollow Core Photonic Band Gap Fibers

f = 98% of the guided mode field energy can propagate in the air regions of the gas filled fiber.

Fiber propagation losses:
- a) 0.1 dB/m
- b) 0.2 dB/m

Effectively single mode regime in a limited bandwidth window ~2 µm

LED+OSA vs. Tunable Laser Source

Fig. 8. Normalized absorption spectra of R-branch of $^{12}\text{C}_2\text{H}_2$ in a 1 m long PBF1500 measured using a LED. The resolution of the OSA is 0.1 nm. The lines appear broader due to the limited resolution of the OSA.

Fig. 9. For comparison, the same spectrum recorded using a laser (step size 1 pm) and a reduced pressure of 10 mbar.

Figure 8. For high enough air-fill-fraction, the average index of a silica–air cladding can drop below the index of water, allowing index-guidance of light in a water core. The average index is here quantified by the wavelength-dependent total-internal-reflection edge, $n_{\text{IR}}(\lambda)$, which crosses $n_{\text{water}} \approx 1.33$ for all $d/\Lambda$ greater than around 0.54. Also shown are analytical mode line estimates (dashed), suggesting that strong confinement of light in the water core will require $d/\Lambda$ values closer to 0.7.

The theoretical loss of a water filled core guide $n_h/n_l=1.6/1.42$, $R_c=10\mu m$, $\lambda=1\mu m$, is $0.2dB/m$.


Temperature and Stress Change Sensors
Temperature Sensing with Holey Fibers Using Direct Interferometric Methods

A resultant change of the refractive index of silica ($\Delta n_{Si}$) and the phase change ($\Delta \phi$) connected with the temperature change can be written as:

$$\Delta n_{Si} = \gamma \cdot \Delta T$$  \hspace{1cm} (3)

$$\Delta \phi = k \cdot n_{eff} \cdot L \cdot \alpha \cdot \Delta T + k \cdot L \cdot (n_{eff1} - n_{eff})$$  \hspace{1cm} (4)

where $\gamma$ is the thermo-optic coefficient, $\alpha$ is the thermal expansion coefficient and $n_{eff}$ and $n_{eff1}$ are the effective refractive indices before and after temperature change, respectively.

Temperature and elongation sensitivities of HFs are somewhat lower than sensitivities of the conventional step-index fiber.

Polarimetric optical fiber sensors rely on the modulation of the state of polarization of the optical signal as a function of external perturbations (e.g., temperature, strain, stress or hydrostatic pressure, etc.). These sensors mainly involve polarization maintaining (birefringent) fibers.

One of the crucial factors impacting the applicability of birefringent fibers to specific sensing applications is their polarimetric sensitivity to temperature. Such sensitivity of HFs is an order of magnitude lower than that in regular PMFs because of the absence of stress inducing regions in HF structure.

Moreover, HF based PMFs can be designed to further lower their temperature sensitivities making them several orders of magnitude lower than in traditional PMFs.

Designing of Temperature-Desensitizes Highly Birefringent Holey Fibers

Thermal properties of birefringent fibers are characterized with a parameter known as polarimetric sensitivity to temperature, which is defined as:

\[
K_T = \frac{d\Delta \phi}{dT} = \frac{2\pi}{\lambda} \left( \frac{dB}{dT} + B\alpha \right),
\]

Where thermal expansion coefficient is \( \alpha \), thermo-optic coefficient is \( \gamma \), and birefringence is defined as:

\[
B = \frac{\lambda}{2\pi} (\beta_x - \beta_y)
\]

Dominant term is silica glass which has to be minimized by geometrical design.

Reduced Temperature Sensitivity of Specialty Design Highly Birefringent HF

Compare with sensitivities of:
0.5 rad/Kxm in elliptical core fibers
5.0 rad/Kxm in fibers with stress-applying elements

Kt=0.004 rad/Kxm

Kt=0.1 rad/Kxm

Kt=0.05 rad/Kxm
Upon placing a high index liquid $n = 1.80$ into the holes Figure 1, a strongly wavelength dependent Band Gap guidance is observed, Figure 2.

A Photonic Crystal Fiber has been filled with a cholesteric liquid crystal. A temperature sensitive Photonic Band Gap effect was observed, which was especially pronounced around the liquid crystal phase transition temperature.

The bands have a temperature sensitivity of approximately 2.5-3nm/°C from 25°C to 75°C. Above 75°C the band structure begins to change and changes drastically when the temperature approaches TC.

Figure 1 End facet of a Photonic Crystal Fiber where green light is guided by the Photonic BandGap effect.

Figure 3 Normalized transmission spectra for the filled PCF at 90°C, 95°C and 100°C.

Stimulated Brillouin Scattering to Measure Strain and Temperature

• Simple explanation of a Stimulated Brillouin Scattering
  – Pump generate an “acoustics Phonon”
  – Acoustic wave modulates the medium refractive index
  – pump induced index grating scatters the pump through Bragg diffraction

• SBS shift and amplitude are very sensitive to temperature and strain as these are the control parameters of the phonon properties
• The spectral width of gain spectrum related to damping time of acoustics wave or the “acoustics phonon” life time

\[ \nu_B = \frac{\Omega_B}{2\pi} = \frac{2n\nu_A}{\lambda_p} \]

\[ \lambda_p = 1.55 \mu m, \quad n = 1.45, \quad \nu_A = 5.96 \text{ km/s} \quad \Rightarrow \quad \nu_B \approx 11 \text{GHz} \]

\[ \text{acoustic wave decay} \propto \exp[-\Gamma_B t] \]

\[ \text{phonon lifetime} : T_B = \Gamma_B^{-1} \approx 10 \text{ns} \]

The simultaneous measurement of temperature and strain is not directly possible for the usual Brillouin based sensors with a single-mode fiber because the Brillouin spectrum has only one peak whose frequency is sensitive to both temperature and strain variations.

Solution: multicomposition fiber core that results in a multipeak Brillouin spectrum.

For a HF the temperature and strain coefficients are different for two Brillouin peaks that originated from two different materials of the core.

Peaks a and c are due to the scattering from longitudinal acoustic waves in the Ge-doped center region and the solid pure-silica region of the core, respectively.

The PCF has a 2.3 mm-diameter solid silica core that comprises a 0.8-mm-diameter Ge-doped center region with a parabolic refractive index profile.

SBS Holey Fiber Sensors

Errors of temperature and strain are found to be:

Multicomposition HF: 3.9°C and 83 µε
These results show higher measurement accuracy compared with:
Multicomponent MMF: 27°C and 570 µε
SMF (T and strain contributions are hard to distinguish) 4.1°C and 140 µε
This difference may be attributed to the higher power density for a small core of the PCF, which results in higher Brillouin gain–loss and a better signal-noise ratio.

Group

Resonant multicore HF s for Sensing


Fig. 5. Bandpass filtering characteristics of three-core PCF filter.
Conclusions

• In PCFs it is the **geometry** rather than **properties** of the constituent materials that offers a versatile design parameter

• The holes in the cladding or a core of PCFs open up new opportunities for exploiting the interaction of light with gases and liquids via evanescent or direct coupling

• PCF geometry can be designed to enhance light-matter interaction – putting the light where the analyte is

• PCF geometry can be designed to reduce unwanted effects such as temperature sensitivity of fiber response

• PCF geometry can be designed to facilitate phase matching between the power guiding optical modes and resonant “sensing” modes such as plasmons
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