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HOLLOW CORE PHOTONIC CRYSTAL FIBERS FOR TEMPERATURE MEASUREMENT IN HYDROGEN COMBUSTORS

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The temperature in hydrogen combustor turbines must be monitored in a non-intrusive way in order to prevent expensive damage from flashback and thermoacoustic instabilities. We propose and analyze a novel method of temperature detection based on hollow core photonic crystal fibers. It exploits the measurement of the thermal vibrations of a microsphere that is optically trapped inside the fiber. This configuration realizes an optical probe allowing to determine remotely the temperature at a chosen point within the turbine. An optical force model is employed to predict the characteristics of our approach. The system allows a tunable temperature sensitivity, dependent on pressure inside the fiber, to be obtained together with high spatial resolution.
Keywords: Temperature measurement, Photonic crystal fiber

1. Introduction

The emerging technology of hydrogen combustion could provide carbon neutral energy at a national scale but in order to for this to be feasible, one of the main problems associated with the combustors must be addressed, flashback. Flashback is the result of thermo-acoustic oscillation build up inside the burners which results in expensive damage to combustor components. This paper proposes a non-intrusive and remotely controlled system for temperature measurement which exploits the local viscosity dependent oscillations of microspheres inside the hollow core of a hollow core photonic crystal fiber (HCPCF). Hollow core photonic crystal fibers were first reported in 1999 [1] but it wasn't until the last ten years that the possibility of introducing microparticles, held in optical traps inside the hollow core, was explored. Notably, both standing wave and multimode traps have been realized and used to trap and control microparticles [2] [3], they have also been used for metrology purposes with applications in pollution monitoring [4]. Relevant for the proposals made in this paper, both a flying-particle temperature measurement [5] and a temperature measurement in a liquid filled HCPCF, which exploits whispering gallery mode oscillations [6], have been performed. However up until now, a method of remotely operated temperature measurement at a position of choice inside an air-filled HCPCF has not been proposed, such a method could be scaled to higher temperatures, suitable for hydrogen burners, through the use of materials different from silica for the fiber, such as sapphire. A system like this would be not be intrusive due to the small profile of HCPCFs and would therefore constitute an ideal way to measure the temperature in combustor components, and provide an early warning system for flashback.

2. Hollow Core Photonic Crystal Fiber (HCPCF)

A HCPCF is a type of optical fiber that confines light in a hollow core, the confining mechanism is different to a conventional optical fiber and is governed by diffraction rather than reflection, this process occurs due to the array of air holes around the core; a photo of a cross-section of fiber taken with a microscope system (Objective 20X *Mitutoyo* Plan Apo NIR, NA=0.4) is shown in Fig. 1. The modes that propagate inside the core are similar to those that propagate in traditional dielectric fibers [7], these modes are approximated by the linear polarised or LP modes whose intensity profile is shown in Fig. 2.

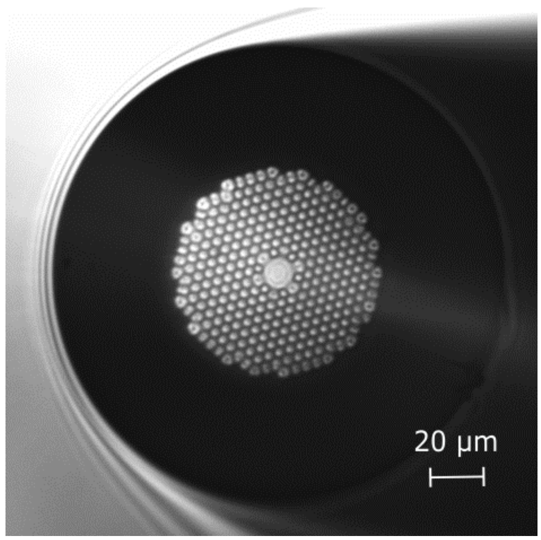

Figure 1: Cross sectional view of HC-1060-02, *NKT Photonics*, which shows hollow core surrounded by hole structure taken with NIR miroscope imaging system.

3. Temperature Measurement

3.1 Mixed mode trap

If a mixture of the LP_{01} and LP_{11}-like modes are sent with the same polarisation inside the fiber, they interfere with one another to create an intermodal beating pattern, due to their differing longitudinal frequencies. If the radiation pressure inside the fiber is balanced with a counter propagating LP_{01} mode in orthogonal polarisation, a series of trapping positions are created where the total force is equal to zero; as schematized in Fig. 3. A trapping system like this has already been realized [3], which makes use of a

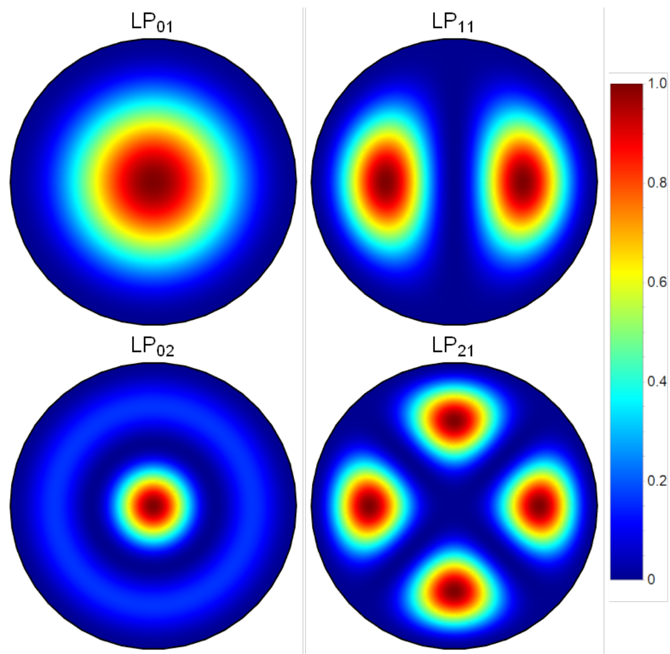

Figure 2: The intensity profile of the first modes in a hollow dielectric waveguide, intensity scale marked in arbitrary units.

Spatial Light Modulator (SLM) to control the mode mixture, in the following section a method to extract temperature measurements with high spatial resolution is proposed.

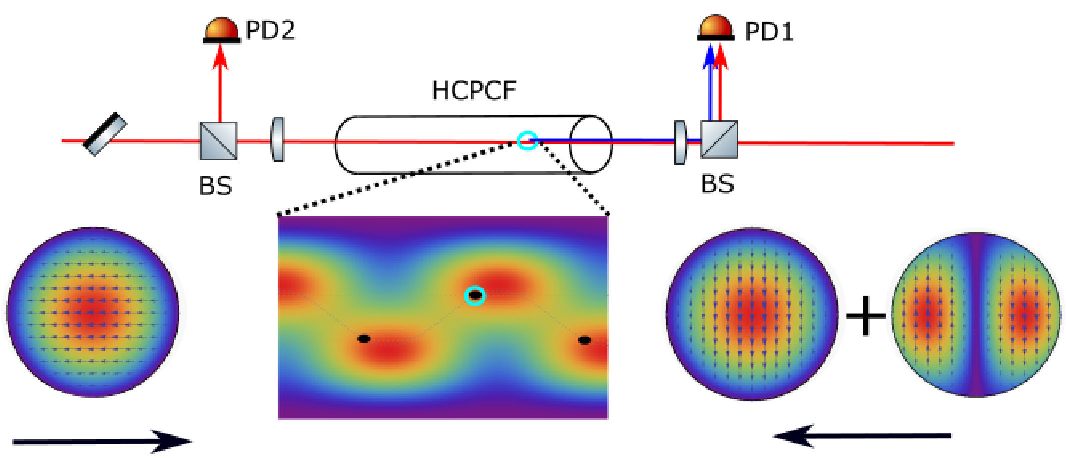

Figure 3: Proposed experimental set-up for mixed mode trap temperature measurement. As illustrated, from one side of a Hollow Core Photonic Crystal Fiber (HCPCF) a mixture of LP_{01} and LP_{11} modes are coupled, from the other side a LP_{01} mode with orthogonal polarisation is coupled. All output signals regarding particle motion are captured by the photodiodes, PD. The beating pattern is illustrated below the HCPCF, with equilibrium positions marked in black and the particle represented as a blue circle. BS: Beam Splitter.

3.2 Damped oscillations of particle

The equilibrium position of the particle may be changed by changing the relative phase between the co-propagating LP_{01} and LP_{11} modes. The particle will start to oscillate around the new equilibrium position, with particle motion given approximately by the damped harmonic motion equation:

$$\ddot{x} + \gamma\dot{x} + \omega_0^2 x = 0, \tag{1}$$

where x is the displacement from the equilibrium position, ω_0 is the natural angular frequency of the undamped oscillator and γ is the damping coefficient. The damping experienced by these oscillations will be due to the local viscosity of the air surrounding the particle. For a sphere of radius r_p, in a fluid of viscosity η we have [5]

$$\gamma(p,T) = \frac{K 6\pi r_p \eta(p,T)}{m}, \tag{2}$$

where K is the *Faxén correction factor* [8] that takes into account the additional drag force arising from the confinement of the fluid to a narrow cylindrical channel and m is the mass of the microsphere. The viscosity is the parameter from which temperature is extracted [5],

$$\eta(p,T) = \frac{\eta_0}{1 + Kn(p,T)(\alpha_1 + \alpha_2 e^{-\alpha_3/Kn(p,T)})}, \tag{3}$$

$$Kn(p,T) = \frac{\lambda(p,T)}{2r_p}, \tag{4}$$

$$\lambda(p,T) = \frac{k_B T}{\sqrt{2}\pi d^2 p}, \tag{5}$$

Kn is known as the Knudsen number, which is the ratio of the free path λ and the particle diameter and $d = 3.6 \times 10^{-10}$m is the collision diameter for air molecules. For spherical solid particles of diameter 1.0-2.2 μm in dry air, with Knudsen numbers ranging from 0.06 to 500 and pressure in the range 0.26-1013 mbar, the values obtained were $\eta_0 = 1.84 \times 10^{-5}$Pa s, $\alpha_1 = 1.231$, $\alpha_2 = 0.469$, $\alpha_3 = 1.178$ [9].

3.3 Doppler velocimetry for axial oscillations

By considering a small displacement in the intermodal beating pattern, which induces oscillations predominantly in the axial direction, solving Eq. (1), we have

$$\mathrm{x}(t) = Ae^{-\frac{\gamma t}{2}}\sin(\omega_d t + \phi)\hat{z} \tag{6}$$

where $\hat{z}$ indicates that the motion is along the axial direction, $\omega_d = \sqrt{\omega_0^2 - \frac{\gamma^2}{4}}$ is the damped angular frequency of oscillation and ϕ indicates a generic phase to match the initial conditions. The velocity is then

$$\mathrm{v}_{pz}(t) = \frac{\mathrm{d}z}{\mathrm{d}t} = A\omega_0 e^{-\frac{\gamma t}{2}}\cos\left(\omega_d t + \phi + \arctan\left(\frac{\gamma}{2\omega_d}\right)\right)\hat{z}. \tag{7}$$

When the trapping light scatters from the particle, it is Doppler shifted in frequency according to the particle's velocity. The shift in frequency from a source at velocity v_{pz} along the z axis is [10]

$$\Delta\nu = -\frac{2\mathrm{v}_{pz}}{c}\nu_0\hat{z}, \tag{8}$$

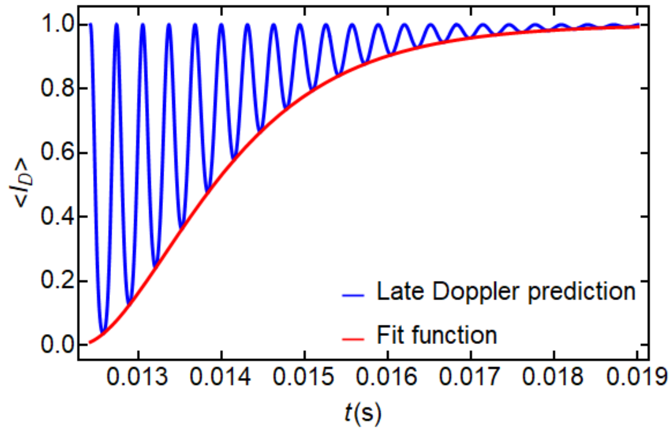

Figure 4: Predicted late Doppler signal received at photodiode as a function of time plotted in blue. By fitting the intensity minima to the function $\cos^2(\ te \ ^{t})$ (red continuous line), can be derived, and hence temperature. To generate this plot, the following parameters were used: =1.064 m, ω_0=10^4 rad/s, =10^3 rad/s, A=1 m.

where $_0$ is the unshifted frequency of the laser and c is the speed of light. Combining equations 7 and 8:

$$(t) = \frac{2A\,\omega_0}{\quad} e^{\ \frac{t}{2}} \cos \ \omega_d t + \ + \arctan \frac{\quad}{2\omega_d} \ \ \frac{}{2}; \tag{9}$$

where is the wavelength of the laser beam. The Doppler shifted light interferes with the light reflected at the fiber tip, the resulting beating signal has a high and low frequency component. By averaging out the component at high frequency and considering the frequency-shifted and reference (tip-reflected) beam of the same amplitude, we have the following intensity relation:

$$\langle I_{\mathrm{D}} \rangle = \frac{\varepsilon_0 c}{2} \ 2B^2 \cos^2(\quad t + \ ) \tag{10}$$

where $\langle I_{\mathrm{D}} \rangle$ is the resulting intensity of the Doppler beating signal, B is a constant and is the relative phase between the incident and reflected beams which depends on the microsphere position, assuming $(x = 0) = 0$, the relative phase evolves with time as

$$(\mathrm{x}(t)) = \frac{2 \ \mathrm{x}(t)}{\quad} = \frac{2 \ A}{\quad} e^{\ \frac{t}{2}} \sin(\omega_d t + \ ); \tag{11}$$

where a substitution was made from equation 16. We can identify two parts to the time dependent intensity signal, an early part and a late part with a enveloped sinusoidal form. This late behaviour starts when the peak velocity and amplitude of the probe will eventually decrease in modulus below the threshold where the argument of the Doppler signal can no longer oscillate by more than $\frac{}{2}$. To find the time at which this change happens, we impose the following condition

$$\max | \quad (t)t + \ | < \frac{}{2} \tag{12}$$

For typical working conditions in which ω_0 , can generally be neglected, equation 12 becomes

$$| \quad_{\mathrm{peak}}(t)t| < \frac{}{2} \tag{13}$$

where $_{\mathrm{peak}}(t)$ indicates the Doppler phase shift in which the oscillation is neglected and just the damping part is preserved

$$_{\mathrm{peak}}(t) = \frac{2A\,\omega_0}{\quad} e^{-\frac{t}{2}}. \tag{14}$$

Using equation 14 and considering the limit of the inequality in relation 13, we obtain an equation for the onset of the late Doppler at time t_{D}:

$$e^{\frac{t_{\mathrm{D}}}{2}} = 4A\frac{\omega_0}{\quad}t_{\mathrm{D}}. \tag{15}$$

For $t < t_{\mathrm{D}}$, a complex interpretation of the signal is obtained. The value of can be obtained by fitting the function $\cos^2(\ te\ ^{t})$ to the envelope of the late Doppler for $t > t_{\mathrm{D}}$ (Figure 4), where and are parameters to be fitted and $= \frac{}{2}$, and hence temperature can be extracted.

3.4 Intensity modulation for transverse oscillations

A somewhat more simple approach is to change the phase in the intermodal beating pattern by $\frac{}{2}$, which would shift the equilibrium position only in the transverse direction, initiating predominantly transverse oscillations. Here it is enough to look at the transmitted intensity signal, $I(t)$, where the oscillations in intensity directly correspond to oscillations in transverse position (Figure 5). Hence the transmitted intensity may be fitted to

$$I(t) = Be^{-\frac{t}{2}}\sin(\omega_d t + \ ) + C; \tag{16}$$

where B and C are constants to be fit, in this way and therefore temperature may be extracted.

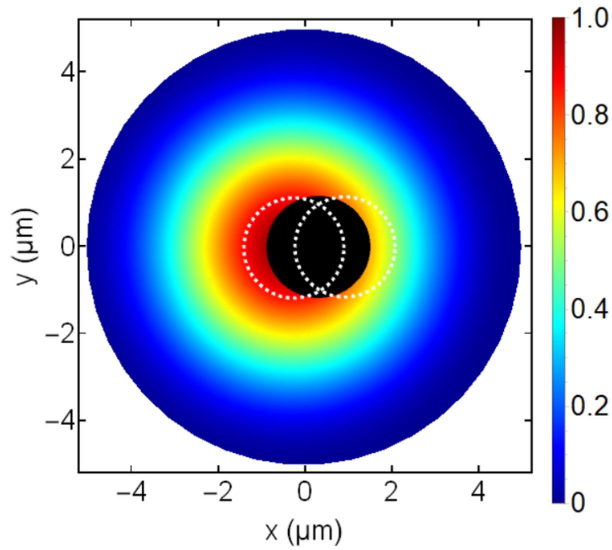

Figure 5: Representation of particle (illustrated by filled black circle) eclipsing the laser beam as it oscillates transverse to the fiber axis. The dotted circles in white denote the maxima of particle oscillation. Changes in the transmitted intensity signal directly correspond to particle motion. Intensity scale of laser beam marked in arbitrary units.

4. Predictions using ray optics model

To analyse key properties of the optical trap and the oscillation, the ray optics force model was employed [3].

4.1 Trap stiffness

The harmonic trap stiffness is an important quantity because it allows us to determine whether the particle oscillation is overdamped, which would result in difficulty interpreting the signal. The quantity that determines damping is defined as

$$(p;T) = \frac{(p;T)}{2}\sqrt{\frac{m}{k}}; \tag{17}$$

where $(P;T) > 1$ results in overdamping and and k is the trap stiffness.

The predicted optical trap stiffnesses generally increase with radius of particle, hence a larger size particle is preferred, though having too large a particle may be undesirable for other reasons, such as difficulty loading the particle inside the fiber core. Using the predicted stiffnesses, the particle oscillations are predicted to be overdamped at ambient pressure and temperature for a silica particle of radius r_p = 2 m. The limit in pressure over which the oscillations are overdamped is 3 mbar in both radial and transverse directions with the power in the LP_{11} mode 10% of that of the co-propagating LP_{01} mode, and total laser power of 515 mW in the propagating and counterpropagating directions. At 1500 K, similar to the operating temperature of a hydrogen combustor, the pressure can be raised up to 20 mbar before the oscillations become overdamped. The proposed fiber material of silica has minimum softening and melting points of 1948 K and 2063 K respectively [11]; to have a material more resistant to high temperatures, sapphire could be used with a melting point of 2327 K. Sapphire photonic crystal fibers have already been realized [12]. At high temperatures, detailed simulations should take account both of fiber deformation and of change in microsphere parameters such as density and refractive index.

5. Conclusion

In this paper, two methods are proposed which exploit the damped harmonic oscillations of microspheres in the core of a hollow core photonic crystal fiber to extract the temperature. One involves longitudinal oscillations and using Doppler velocimetry to analyse the motion, the other relies on observing intensity oscillations which directly correspond to the damped oscillations of the particle, this latter would provide a more simple readout and involves higher trap stiffnesses which means the temperature measurement can be performed at higher pressures. Both would provide a remote way to measure the temperature inside a hydrogen combustor. A ray optics force model has been used to analyse the trap stiffness, which is useful in determining whether or not the oscillations are overdamped. At ambient pressure, using 515 mW of total laser power at 1064 nm, we predict overdamping both at ambient temperature and 1500 K, hence a vacuum system is required to perform the temperature measurement.