Study on the possibility of Φ-OTDR sensing in hollow-core fibres

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ABSTRACT

The backscattering process in hollow core fibres shows a large similarity with Rayleigh scattering, offering the potential to be exploited for distributed sensing. A classical Φ-OTDR implementation is used to observe the backscattering signal from the surface roughness at the silica-air interface in hollow-core photonic bandgap fibres. In contrast with standard single mode silica-core fibres, the hollow core photonic bandgap fibre shows a chaotic response when the temperature is slightly changed, but stable results under strictly constant temperature conditions. Another temperature-dependent effect is highly perturbing the coherent scattering response, and it is believed that higher-order guided modes cause detrimental interferences totally jamming the response. By using single-mode hollow core fibres it should be in principle possible to obtain the relevant temperature measurement pattern, though as anticipated the extreme weakness of the signal certainly represents an insurmountable challenge.

Keywords: Optical fibre sensing, Rayleigh scattering, hollow core fibre, distributed sensing.

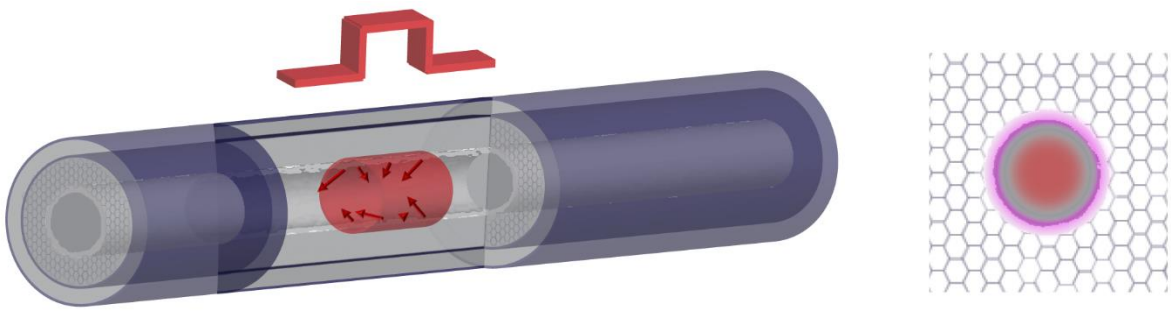

Figure 1. Propagation of pulsed light in a hollow-core fibre experiencing coherent surface roughness scattering (left) and the light distribution over the fibre cross section (right). The incoming light is mostly confined to the air core region, shown in red, while a weak ring-shaped backscattering radiation is generated due to surface roughness scattering, shown in magenta.

1. INTRODUCTION

The residual loss in hollow core fibres results from the scattering of light caused by surface roughness at the silica-air interfaces, which is due to irreducible thermodynamic fluctuations[1,2,3]. This scattering shows features similar to Rayleigh scattering and most of the research efforts in hollow core fibres are dedicated to reduce the amount of scattering by minimising the fraction of light present at the silica-air interfaces[2,3], with the ultimate goal to reach a loss lower than Rayleigh scattering in solid silica fibres.

For sensing purposes Rayleigh scattering is widely exploited to realise distributed measurements with extreme sensitivity using the Φ-OTDR technique[4]. However, exploiting the specific scattering process in hollow core fibres due to surface roughness has never been proposed and demonstrated so far. This would open new avenues by adding a degree of freedom, since the sensitivity can be to a wide extent modified by the specific response of the fluid present in the hollow region.

In this paper, for the first time we study and observe the possibility and the potentiality to implement a Φ-OTDR system based on surface roughness scattering in hollow core fibres. The scattered wavelets from distinct points on the surface interfere within the region covered by one pulse-width, forming a random pattern similar to that observed using Rayleigh scattering. The interference pattern is determined by the random distribution of the surface roughness and turns out to be position-dependent and to vary with the frequency of the light, just like in a Φ-OTDR measurement in a solid silica fibre.

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2. EXPERIMENTAL DEMONSTRATION

2.1 Measurement set up

The Φ-OTDR set-up to test the hollow core fibres is based on a classical Φ-OTDR implementation, though with some additional amplification and a gating feature regarding the spurious reflections blinding the system at connections between solid core and hollow core fibres. It has also to be considered that the recapture coefficient of the scattered light is much lower than in solid core fibres, since the emitted wavelets are distributed over a ring pattern at the inner tube interface. For this reason we opted for a hollow core photonic-bandgap fibre (PBF) since it shows a stronger back scattering signal than other kind of hollow core fibres, such as antiresonant hollow core fibres.
A 1 MHz linewidth distributed feedback (DFB) continuous-wave laser with a central wavelength at 1550 nm is used as the coherent light source for the Φ-OTDR interrogation system. Pulse shaping of the continuous-wave light is achieved using a high extinction ratio semiconductor optical amplifier (SOA) leading to the generation of coherent Fourier-Transform-limited optical pulses, showing the target spatial resolution for the measurement (10 ns pulse width or 1.5 m spatial resolution for a refractive index close to 1 in the hollow core).

The power of the pulse is then boosted by a two-stage Erbium-doped fibre amplification (EDFA) to a peak power of approximately 11.2 W to generate significative backscattering. After amplification, the laser travels through the fibre under test, made of a few metres of connecting standard fibre followed by a 50 m segment of hollow core fibre.

A third amplification stage is required to post-amplify the back-scattered signal before detection, then passing through a 1 nm passband optical filter, required to filter out the amplified-spontaneous emission noise generated by the EDFAs. The signal is then detected by a 125 MHz photoreceiver and acquired by a data acquisition card at a sampling rate of 500 MSa/s. The frequency sweeping of the interrogating pulse is carried out by remotely controlling the current delivered by the laser current supply to the DFB laser. The frequency scan is performed over a 5 GHz range by steps of 20 MHz. It must be mentioned that the fibre is placed in a vibration-isolated box, itself placed in a temperature-controlled chamber.

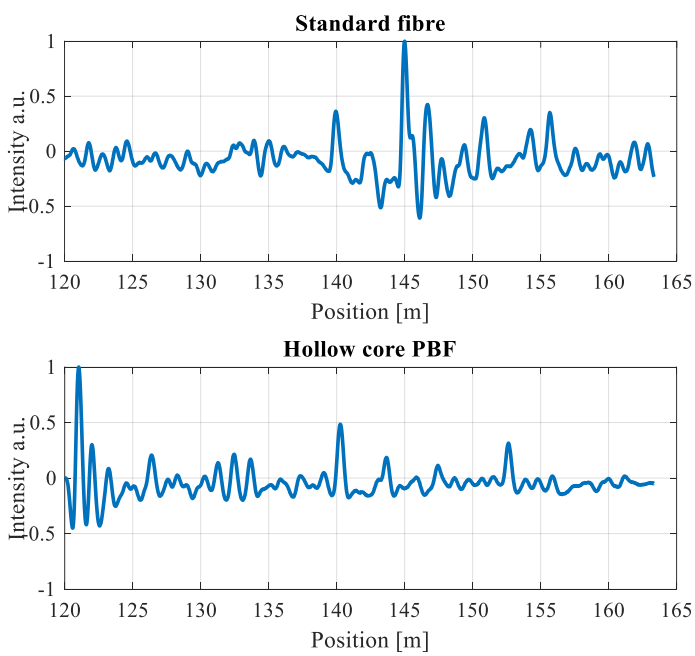

Figure 2. Temporal response (converted to position) of the coherent backscattered intensity from a standard single mode fibre (top) and a hollow core photonic bandgap fibre. A DC offset is subtracted from the 2 traces due to a residual constant ASE signal to deliver a trace with a null average. The noise contribution is made negligible by proper averaging.

As shown in Figure 2, the time-domain signal from the hollow core PBF shows a jagged response similar to that of a standard fibre, formed by interferences from the coherent backscattered light and totally repeatable and temporally stationary in unchanged experimental conditions, suggesting that this signal can also be potentially exploited for sensing purpose.

2.2 Temperature change measurement

The temperature in the test chamber was raised by ~0.8 ℃ over some 40 minutes and a dozen of Φ-OTDR time domain traces of standard and hollow core PBFs were independently measured while the temperature was slowly rising. Air was evacuated from the hollow core using a primary vacuum pump to minimise the influence of the gaseous medium. As expected using standard fibres, Figure 3 clearly shows that the experimental data, plotted in the frequency-domain at each position, present a well-defined cross-correlation peak for any two different temperatures along the fibre, showing a linear frequency shift while the temperature is changing. Irregularities in the distribution are simply due to the presence of temperature non-uniformities in the box, as evidenced by the periodic fluctuations correlated with the fibre coiling.
However, for the measurement using hollow core PBF, cross-correlations between traces are chaotic, even for two sets of measurements with a temperature difference of only 0.05 ℃. This surprising and counter-intuitive result shows that such a hollow core fibre shows a distinctive response to scattering when temperature is changed.

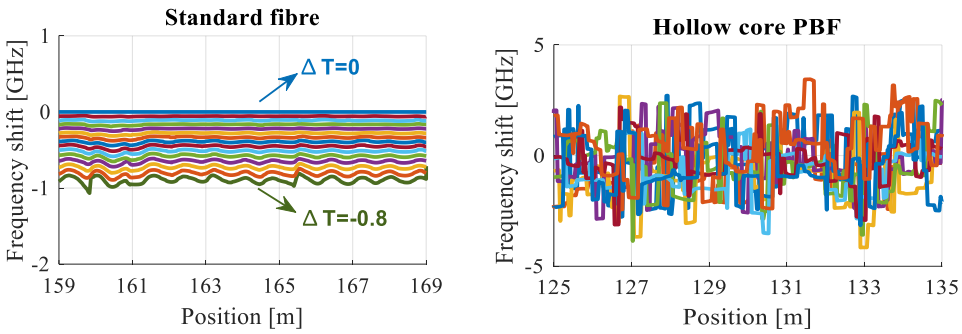

Figure 3. Cross-correlation peaks of frequency-domain traces at each position, showing the frequency shift when measuring temperature changes using a standard single mode fibre (left) and a hollow core photonic bandgap fibre. The temperature range and ramp-up time are the same in both measurements.

To clarify this issue the measurement process was repeated along both the standard fibre and the hollow core PBF, respectively, while keeping the temperature in the test chamber at 34 ℃, as constant as possible over a period of 1.5 hours. As shown in Figure 4, the frequency domain cross-correlation between any two sets of measurements was stable at any position, for the two kinds of fibre, demonstrating the repeatability and that the loss of correlation is not due to a modification of the surface roughness with time. The residual frequency shifts are fully compatible with the overall effect of laser frequency drifting. Since the behaviour of the hollow core PBF is fairly constant during this measurement, we can assume that another temperature-dependent effect is highly perturbing the coherent scattering response, discussed in the next section.

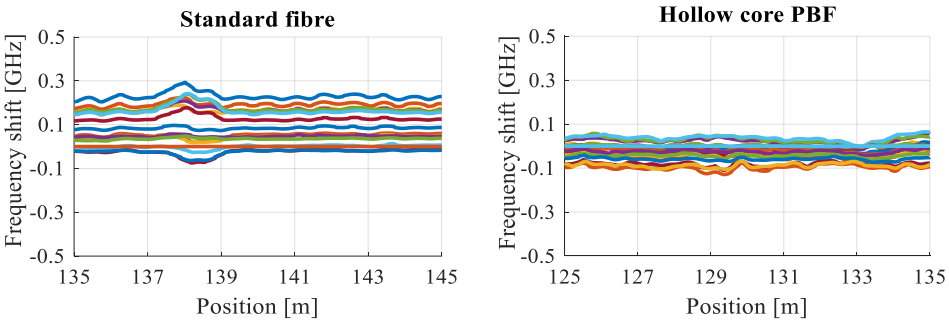

Figure 4. Cross-correlation peaks of frequency-domain traces at each position, showing the frequency shift under constant temperature condition using a standard single mode fibre (left) and a hollow core photonic bandgap fibre. Each measurement lasts 1.5 hours.

3. DISCUSSION AND CONCLUSIONS

By comparing the two sets of measurements in the hollow core fibre, we can draw a preliminary conclusion that hollow core fibres have intrinsically the potential to be used in Φ-OTDR measurements, but there is an obstacle arising from an unknown perturbation, which is not structurally inherent to the fibres as it only occurs when the fibre conditions change

and is also not reproducible. We favour the explanation that this obstacle is due to the multimode propagation in hollow core PBFs, creating multipath interreferences and a speckle-like pattern at the recoupling point when the scattered light is returned to a standard single mode fibre. Although we paid attention to mostly launch the interrogating pulse into the fundamental mode of the PBF, the ring-shaped scattering, as shown in Figure 1, will preferably populate the higher order modes for the backpropagation of the scattered light. This truly contrasts with standard fibres designed for single-mode guidance only and the volume emission of Rayleigh scattering that favours a sizeable recapture by the fundamental mode.

Due to their intrinsic limitations, it turns out to be challenging to realise low-loss single mode hollow core PBFs; even antiresonant fibres are not true single-mode waveguides, the higher order modes being simply significantly more lossy. During the measurement, the light coupling into the hollow core PBF populates several higher-modes, which are more lossy but give rise to a higher scattering due to their spatial transversal distribution, explaining the rapid decay of the backscattered signal along the fibre in Figure 2. Under constant measurement conditions, these higher order modes are quasi-stable and therefore the Φ-OTDR measurements show consistency, as shown in Figure 4. In presence of environmental changes such as temperature differences, even very small, the speckle-like pattern created by intermodal interferences is modified, causing stray intensity differences that are comparable to, or even stronger than, those caused by thermal expansion of the scattering surface. In this case, the temperature information is jammed by the intermodal interferences, causing the inconsistent cross-correlations in Figure 3.

We believe that by using single mode hollow core fibres we can certainly obtain a relevant temperature measurement pattern. This can be potentially be realised using anti-resonant hollow-core fibres and we carried out a trial test using this type of fibre. In this case, the light is well confined to the air core region to remain single-mode, generating a very weak surface roughness scattering, which is moreover very poorly back-coupled to the fundamental mode regarding its peripheral ring-shaped radiation, as shown in Figure 1. For this reason we could observe essentially no trace exploitable for Φ-OTDR.

In conclusion, it has been assessed that a backscattering signal can be obtained that would be potentially suitable for Φ-OTDR measurements, but a robust information can only be obtained for a strict single-mode operation. It has been discussed that this condition is highly incompatible with a sufficiently intense signal for a proper measurement.

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