On feasibility of longitudinal characterisation of photonic structures via transverse excitation of whispering gallery modes

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Remote side excitation of whispering gallery modes in a photonic crystal fibre reveals longitudinal properties of its intrastructure usually requiring a long propagation length and endface access. By tuning the excitation to maxima of observed morphology resonances, initiating axially expanding whispering gallery modes in the fibre cladding and in its microstructure, characteristic spectral windows resembling ones at the fibre longitudinal transmission are observed. This outcome opens up possibilities of remote characterisation of rotationally-symmetric photonic structures in situ and in locations only assessable via side excitation using external light beams.

Introduction: The photonic crystal structures [1], such as antiresonant fibres and waveguides [2, 3], offer physical properties allowing to expand capabilities of silica fibres [4]. Excitation of whispering gallery modes (WGMs) in a fibre cladding enabled characterization of the fibre diameter with sub-nanometre level of sensitivity [5, 6]. Recently, we have reported direct side-coupling of light to internal fibre microstructure from WGMs excited in the fibre cladding, which permitted observing banded spectral resonances associated with distinct capillaries of the fibre [7]. At the same time, direct excitation of WGMs in individual capillaries of the antiresonant fibres to characterize their dimensions were also described [8]. Here we report for the first time on the observation of characteristic spectral windows associated with longitudinal propagation of light inside a hollow core fibre via side excitation of axially extending WGMs in fibre capillaries and its cladding, enabling to sense resonant features of a fibre.

Observations: The goal of our study was to investigate the possibility of external characterization of a hollow core fibre in an assembled preform, in the latter homothetic extension into a fibre cane, and while drawing the fibre. In setting up a system for characterization of fibres and canes we intended to use remote light beams versus phase-matched excitation by a taper [9] to enable detached coupling of light into a fibre microstructure. The diverging-beam excitation of cladding modes enhanced spreading of internally reflected rays in a fibre and filling-in capillaries of its structure (see Fig. 1). Since the propagation constant for a silica fibre is always closest to that of the lowest radial mode number for a whispering gallery mode (WGM), leaking higher order cladding modes were broadly guided into all antiresonant elements, such as the inner and outer capillary tubes. Spectral maxima of WGM resonances in a fibre cladding/capillaries $|\alpha|^2$ and transmission resonances past the fibre $|\tau|^2$ are given by relations [10]:

$$|\alpha|^2 = \frac{(\alpha - |\tau|^2)}{(1 - |\alpha|^2)}$$

$$|\tau|^2 = \frac{\alpha^2 (1 - |\tau|^2) + \alpha (1 - \alpha^2)}{(1 - |\alpha|^2)^2}$$

Here $\alpha, \tau$ are the inner-ring circulation and complex transmission factors.

Fig. 1 Schematic illustration of side excitation: either a left or right beam is focused onto a periphery of fiber while the latter position is moved into the beam (vertical arrow) until the maximum intensity of WGM is reached

Fig. 1 shows an enlarged profile of Nested Antiresonant Nodeless Fibre (NANF) [11] with outer/inner tubes of diameter Dd at the capillary wall thickness L. The optical system assembled to investigate fibre properties via side scattering is depicted in Fig. 2. Our intent was to observe changes of birefringence in a fibre cross section in transmitted plus reflected light [12] similarly to two-beam interferometric conception applied in Ref. [6].

Distinct emission sources: coherent, partially coherent, and spontaneous (Fig. 2), were consequently coupled into a fibre or cane. Observations of scattering at maxima of WGMs excitation revealed interference patterns and banded spectral resonances linked to fibre microstructure (Figs. 3, 4).

Initially, a 90° camera or collecting spectrometer fibre (see Fig. 2) were placed along a tested fibre away from 90° position over axially-extending WGM pattern until the maxima of intensity were found always at 90°. To observe images of Figs. 3, 4, the 20X capture objective and colour camera (Fig. 2) were used, or wide-angle and high resolution cameras. Following the observed retrieval of side-scattered light inside silica capillaries of intrafiber structures in diverse types of fibres, for example confirmed by low-intensity red light beam longitudinally exiting the cane or green and red outer/inner-tube microstructure resonances, one would expect bottle WGM modes, for which light spirals back and forth along the axis of a cylindrical resonator with thickness variations of the adiabatically drawn fibre [15], to exhibit a resemblance to transmission properties of the fibre.

Spectral measurements: Maxima of WGM resonances confirmed via 90° scattering visually or by a spectrometer were replicated at spectral studies of side transmittance and scattering. Low loss 1.3-dB/km NANF [16] was
tested versus a Solid (coreless) Fibre (SF), a single-capillary Tube Fibre (TF), single-mode fibre SMF-28 (Corning, Inc.), and three experimental NANFs with two outer tubes touching or not touching each other. Fig. 4, c depicts a version NANFb with tubes partially touching, compared to a fully touching NANFb and not-touching section NANFc of that fibre. All spectrums below were obtained via 200-micron multimode fibre placed at the 15.4 mm gap above a studied fibre, irradiated by visible light from either the Supercontinuum or a combined source – comprising Thermal plus LED lights. To integrate sharp extrema of WGM interference in fibre cladding all measurements were performed at a 10-nm spectral resolution.

Fig. 5 shows 90°-scattering spectrum of NANF fibre at the maximum of visible WGMs via side scattering in Supercontinuum light, revealing relatively narrow green and red resonance peaks, likely pointing to its all equivalent capillary pairs. Fig. 6-spectrum of NANFb fibre with touching tubes depicts multiple resonances in the green and red spectral windows and the leakage of light between 550 – 600 nm due to two joint capillaries.

Further studies via spectrally stable combined LED–Thermal source of Fig. 2 helped removing ambiguities associated with lower reproducibility of Supercontinuum source, while lacking the phase matching for partially coherent beams among individual cladding and microstructure resonators and reducing penetration of spontaneous light into a fibre. The combined source had LED-dominated spectral content from 400 to 700 nm with the thermal source adding its intensity contribution between 700 and 750 nm.

Side transmission spectrums Ti of Fig. 7 were obtained at exactly same individual fibre positions as 90°-scattering via the maximum intensity of WGM resonances. All transmittance values are in absolute scale referred to the combined source intensity. The spectrums here are zoomed into the region of three attenuation windows observed for blue/green wavelengths while no other bands, such as red resonances of Figs. 3, 4 were observed. Fig. 8 shows 90°-scattering spectrums Sb of tested fibres at the absolute scale of scattering projected for 2π-space from 0.0130-radian solid angle. Subsequent spectrums of intrafibre capture in Fig. 9 were calculated from transmittance and scattering as Cb = 1−Ti−Sb. Three spectral windows seen as dips in capillary-fibre spectrums resemble antiresonant properties for 11th 10th and 9th order of the fibres resonant transmission [3]. Fitting central wavelengths of 517.0, 465.3, 423.0 nm to one effective pathlength thickness of 4653.00 nanometres predicts 1551-nm centre wavelength of the 3rd order. Based on 1170±29 nm wall thickness for outer capillaries of the NANF measured in Ref. [16], the design wavelength for its 2nd window is 1551.4-nm, only 0.4 nanometer off the value measured above.

To verify the observed phenomena, best samples NANF, NANFb, and NANFc were remeasured at 3-point averaging of OSA signal acquisition. Enhanced WGM transmittance and scattering spectrums of Fig. 10 reveal a notably broad 512.00–538.95 nm antiresonant window for the NANF, intended for CL-band transmission, at equal coordinates for transmission and scattering. Intrafibre capture spectrums of Fig. 11 were obtained as ones of Fig. 9 via 3-point averaged transmittance values of Fig. 10 and correlated 3-point total scattering spectrums, similar to the ones of Fig. 8.

For 3-point spectrums all 10th order dips were much narrower, fading away since not supported by the antiresonant fibre design, and thus were ignored in further analysis. Since the fibre capillary wall thickness t2, had been optimized to be antiresonant for minimal propagation losses [3, 17]: 

\[ T = \frac{(2k + 1)\pi}{k} \quad k = 0, 1, 2, \ldots \]

the beginning and the end of 6th and 5th windows, or the 11th at k=5 and 9th at k=4 orders, were utilized to calculate the start and end of other windows up to 1st one. Afterward, the
coordinate of a window centre along with values of refractive index $n_j$ were applied to compute the mean thickness $t_{av}$ of capillary walls. Based on $423.45-436.4$ nm $5^\text{th}$ window, $t_{av}=1101.22$ nm, and on $5^\text{th}$ one, $t_{av}=1105.65$ nm, pointing to centres of 2nd and 1st transmission windows at $1513.65:6.5$ nm and $4541.4:18.1$ nm. The actual design thickness of capillary wall of NANF measured in Ref. [16] of 1170 nm had been held for its outer tubes, while the inner tube wall thickness was reduced to 1080 nm at the average of $1125:30$ nm, only 20 nanometres higher our result above. The centre of its $2\text{nd}$ longhaul transmission window measured for 500-m sample had also shifted farther away from our 1535.6 nm evaluation to near 1450 nm.

but showing out-of-band leakage (Fig. 4, c and Fig. 6) behaved closest to NANF, with the eminent lowest loss for SMF-28. One transmission band centred at 479.8 nm for Solid Fibre could be indicative of its overall size.

Conclusion: Detecting characteristics of longitudinal structure properties at transverse excitation of whispering gallery modes in hollow core fibres offers potentials for remote evaluation of otherwise inaccessible samples.

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