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Doppler-Assisted Tomography of Photonic Crystal Fiber Structure by Side-Scattering

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Abstract: Using a non-destructive side-scattering technique, the internal structure of a microstructured fibre is determined. The rotating fiber is illuminated by a laser beam and an inverse Radon transform is applied to the frequency-modulated scattered signal.

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It would be highly desirable to be able to measure the internal structure of a microstructured fibre in real-time as it emerges from the drawing tower (in current systems only the external diameter of the glass fibre is monitored). This would enable the correct setting of pressure, temperature and drawing speed so as to obtain a desired microstructure. It would also allow the implementation of an automatic control system to keep the structure constant, or vary it slowly or periodically, over long fibre lengths. Currently the PCF structure is monitored manually by collecting fibre samples, cleaving them and examining them in optical and scanning electron microscopes (SEMs). This does not provide real-time feedback and in particular is not feasible at high drawing speeds. Other less destructive techniques require filling the holes with liquids, which is not possible during fibre drawing [1-2].

In this paper we report a Doppler-assisted side-scattering technique that relies on spinning the fibre and monitoring the strength and frequency of the scattered signal in a fixed direction (in a final implementation on a fibre drawing tower the direction of the incident laser beam would be spun instead). Each structural feature in the PCF structure scatters light, with a Doppler-shift that depends on its radial and angular position, as well as the rotational speed of the fibre. The scattered light is then mixed with a frequency-shifted reference beam and the beat-note detected at a photodiode (Fig. 1). This procedure allows positive and negative Doppler-shifts to be distinguished – essential for extraction of the full scattering information (as pointed out by Hänsch [3], frequency-based techniques allow very accurate measurements, and are robust against amplitude fluctuations). The Doppler shift for the i-th scatterer takes the form:

$$f_D(t) = \frac{c}{\lambda}\left(\frac{\sin(\omega_{\mathrm{rot}}t+\phi_i-\alpha)-\sin(\omega_{\mathrm{rot}}t+\phi_i)}{\sin(\omega_{\mathrm{rot}}t+\phi_i-\alpha)+c/(\omega_{\mathrm{rot}}n\rho_i)}\right) \approx -\frac{2\omega_{\mathrm{rot}}n\rho_i}{\lambda}\cos(\omega_{\mathrm{rot}}t+\phi_i-\alpha/2)\sin(\alpha/2) \qquad (1)$$

where $\omega_{\mathrm{rot}} = 2\pi f_{\mathrm{rot}}$ is the rotational frequency (rad/sec), $\lambda = 633$ nm the vacuum wavelength of light, c the speed of light in vacuum, ρ_i and ϕ_i the distance and angle of the i-th feature from the axis at $t = 0$, α the angle between the incident and scattered wavevectors and n the refractive index of the glass (Fig.1).
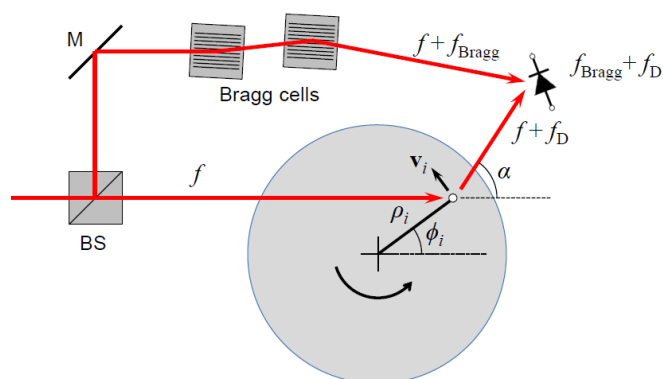

Fig. 1: Schematic of the set-up at $t = 0$ (not to scale). One part of the laser beam is incident on the rotating fibre, the other being frequency shifted at a pair of Bragg cells (frequency difference 10 kHz). The Doppler-shifted scattered light ($f_D \sim 1$ kHz is a typical value at $f_{\mathrm{rot}} \sim 300$ rpm) is combined with the frequency-shifted light and the beat-note detected at a square-law detector

In a first experiment, a fibre containing three off-centre holes was analysed for a scattering angle $\alpha = 90°$ (Fig. 2(a)). The corresponding windowed (16 ms) fast Fourier transform (FFT) of the scattered light shows several clear curves (b), each corresponding to a single scattering centre. This spectrogram was used to reconstruct the fibre structure (c) via an inverse Radon transform, a technique well-known in medical imaging [4]. The measurements are in excellent agreement with SEMs. In addition, the reconstructed structure (c) unexpectedly included a fourth feature

that was invisible in the optical microscope. A high-resolution SEM image confirmed the existence of a 150-nm-wide channel at the indicated position (such unwanted defects are caused by uncollapsed channels in the fibre preform and often cannot be detected in an optical microscope).
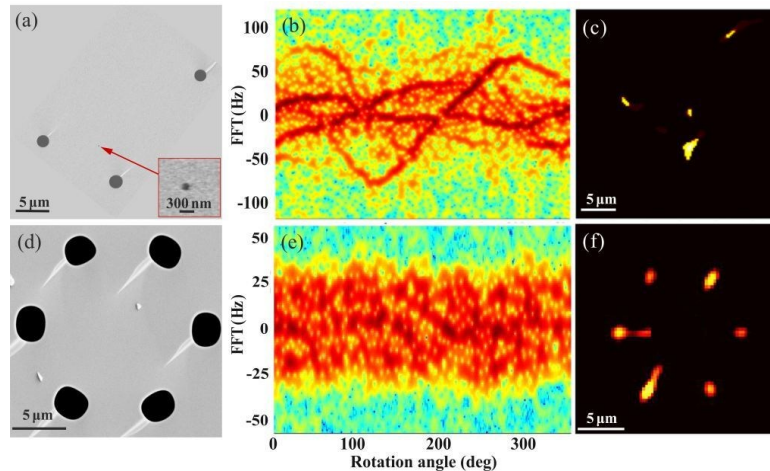
Fig. 2: (a,d) SEMs of simple structures. (b,e) Apertured FFTs. (c,f) Reconstructions.

In a second experiment, a PCF with six hexagonally-placed channels (diameter ~ 3 µm, spacing 8.2 µm) was investigated (Figs. 2(d-f)). This time the scattering data (e) was significantly disturbed by multiple scattering, making it impossible to distinguish distinct individual curves on the spectrograms. Nevertheless, the inverse Radon transform proved robust enough to allow retrieval of the positions of the six holes (Fig. 2(f)).

The method was also applied to a tapered PCF (such tapers are useful, e.g., in supercontinuum generation [5]). The top row of Fig. 3(a) shows optical micrographs taken through the side at four positions along the taper. The corresponding windowed FFT and the inverse Radon reconstruction are shown in the middle and lower rows of Fig. 3(a), respectively. While the internal structure is not perfectly reconstructed due to multiple scattering, the maximum diameter of the internal microstructure of the untapered region (at $z = 0$ mm), as well as the fibre orientation are in excellent agreement with those measured in the SEM (Fig. 3(b)). This is the first time the microstructure along a tapered PCF has been measured non-destructively.
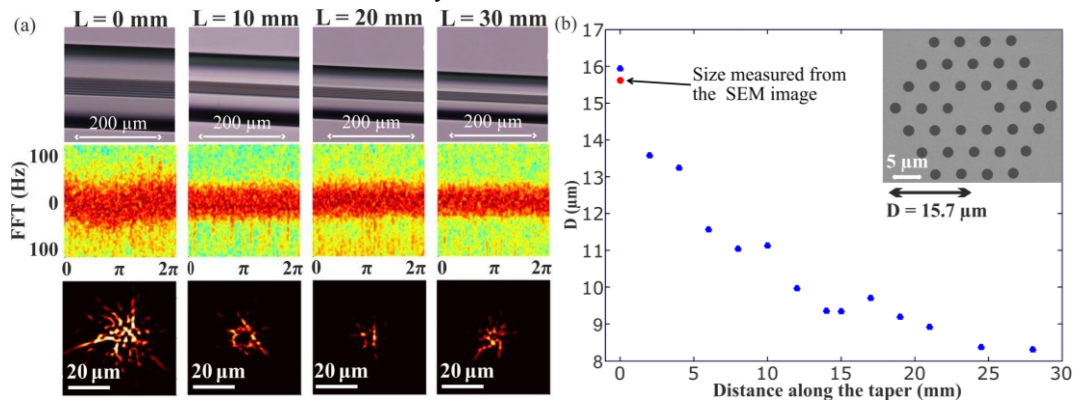
Fig. 3: (a) Measurements on a fibre taper. Optical side-images of the PCF (top row). FFT of the scattering data as a function of rotation angle (middle row). Inverse Radon transform of the data (bottom row). (b) Diameter of the internal structure, from scattering data, versus position along the taper. Inset: SEM of the fibre structure.

In conclusion, the internal microstructure of a PCF can be reconstructed non-invasively by spinning it and measuring the time-varying Doppler-shifted scattered spectrum. In future work we plan to focus on improving the technique and implementing it on the fibre drawing tower. The technique could be adapted to measure the internal structure of any axially invariant, microstructured, strand of transparent material.

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