industrial applications is highly unlikely due to practical limitations. Near-field probes are extremely delicate, both in preparation and operation (as any frustrated PhD student can confirm), and ultimately too fragile for the routine characterization of hundreds of chips. In addition, the scanned area is generally limited to a few hundred micrometres and the scanning is quite slow. Furthermore, because the probe has to be in physical contact with the device, the characterization must be performed before any protective layer is applied to the photonic chip.

Fortunately, the novel far-field characterization approach reported by Bruck and co-workers[1] overcomes all of these limitations and still retains most of the advantages of near-field microscopy — providing local investigation of individual integrated elements in the frequency and time domain.

In a similar manner to near-field microscopy, Bruck's ultrafast photomodulation spectroscopy (UPMS) approach creates a 'movable imperfection' in a silicon photonic circuit by realizing a local perturbation of its refractive index (Fig. 1a). This perturbation is achieved by optically exciting free carriers with a tightly focused ultrafast pump laser at a wavelength of 400 nm (much shorter than the circuit's operation wavelength of 1,500 nm). The effect on the circuit is then probed with another ultrafast light beam. The perturbation locally modifies the photonic response of the circuit, affecting the spectrum of its transmission. The focused pump beam is scanned over the circuit and the perturbed transmission spectrum is recorded for each focus position. This refractive index perturbation is analogous to an oscilloscope probe that is commonly used to test single elements of electronic circuits, yielding a great deal of information. Due to the time and frequency resolution of the pump–probe approach, a multi-spectral data set (space, time and frequency) of the photonic element can be obtained. The authors show the flexibility of the approach by studying different devices, with increasing photonic complexity.

Among the various circuits the authors characterized, one deserves particular attention. Vernier racetracks are composed of two cascaded ring resonators with intentionally non-overlapping resonance frequencies. The two resonances are, however, very close together and thus distinguishing them in transmission measurements is very difficult. By employing UPMS, the authors were able to separately test the two resonators and found a free spectral range variation of 80 pm (Fig. 1b). This methodology not only yields a spectral characterization of individual components but also allows reconstruction of the complex spatial intensity distribution of interference-based devices. By scanning the probe beam above a multimode interference splitter while monitoring the transmission of both outputs, the authors were able to separate the intensity distribution contributing to the coupling of each port with a resolution comparable to the operating wavelength.

The proposed set-up is very promising for industrial applications, especially as it does not rely on delicate components or consumables of any kind, in sharp contrast with near-field microscopy. The scanning of the laser spot is fast and in principle only limited by the mechanical actuation of the optics. The rather expensive and large parametric oscillator employed in this work is probably not suited for industrial applications but the low pump-pulse energy (about 0.1 nJ) required to perform the ultrafast photomodulation spectroscopy suggests that the use of low-cost fibre lasers is a possibility. The most important limitation is the usual suspect in optical microscopy: spatial resolution. Although the basic principle of this approach could be applied to nanophotonics devices, such as photonic crystal or plasmonic structures, the current resolution of the microscope does not allow a thorough spatial characterization. In principle, with the Abbe limit being around half of the pump wavelength, the resolution can be pushed down to near-field microscopy standards, but this will come at the cost of a reduced field of view or scanning area. Bruck and co-workers demonstrate a reasonable compromise between high resolution and large field of view for state-of-the-art integrated photonic circuitry, but for highly integrated nanophotonic devices further work is required. ❐

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PHOTONIC-CRYSTAL FIBRE

Mapping the structure

The demonstration of real-time and non-destructive Doppler-assisted tomography of the internal structure of photonic-crystal fibres could aid the fabrication of high-quality fibres with enhanced performance.

Christos Markos

Photonic-crystal fibres (PCFs), also known as microstructured or 'holey' fibres, are usually fabricated from glass[1], polymer[2] or a combination of materials[3] and are a popular medium for applications in nonlinear optics and sensing. Conventional PCFs are normally composed of a solid-core surrounded by a hexagonally-arranged array of small holes running along the full length of the fibre. This intricate pattern of holes modulates the refractive index of the cladding and thus introduces a guiding mechanism based on total internal reflection[1]. The optical properties of the PCF are therefore strongly connected with its microstructure geometry. Any defect or imperfection introduced during the fabrication of the

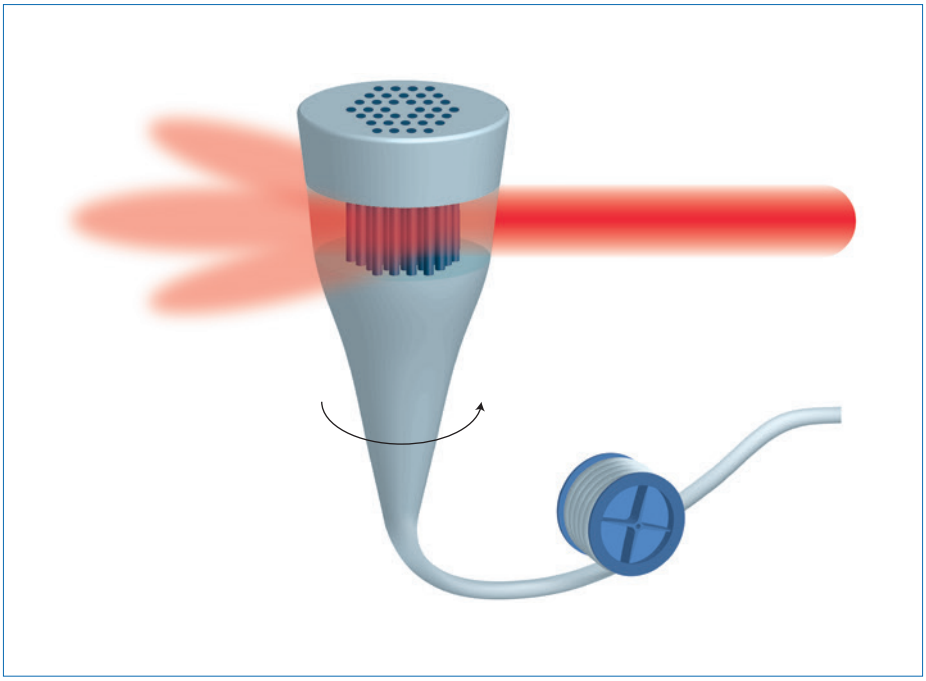

Figure 1 | The principle of Doppler-assisted tomography of photonic-crystal fibres. Red laser light illuminates the fibre from the side while it is spun at a constant rate. A photodetector collects the scattered light, which is then analysed to determine the internal structure of the fibre.

fibre — such as a variation of the hole diameter, for example — can have a major impact on its final performance and quality. Thus a convenient, non-destructive scheme for monitoring the internal structure of a PCF during fabrication is highly desirable.

Now, writing in *Optics Express*, Alessio Stefani and colleagues[4] report such a scheme. Their Doppler-assisted tomography technique allows near-instantaneous characterization and reconstruction of the internal microstructure of a solid-core PCF. The proposed concept meets the requirements for fast, accurate, robust and high-resolution imaging and thus is probably the most suitable candidate for use in a fibre drawing tower system.

Unlike conventional optical fibres, the fabrication of PCFs is a complex process that requires a strict monitoring of the drawing parameters such as air pressure, temperature, drawing speed and tension. For high-quality PCFs, more sophisticated and accurate control of the drawing process is required. In conventional step-index fibres, for example, there are different index profiling methods that can provide real-time feedback during the fabrication of the fibre[5]. However, these methods cannot be applied to the complex structures with high refractive index contrast found in PCFs.

A practical scheme for real-time monitoring of the PCF structure during the fabrication process has not yet been developed. Instead, researchers have had to remove a piece of the fabricated fibre and inspect its internal structure using either an optical or electron microscope. The same procedure must be repeated every time that a drawing parameter (pressure, temperature and so on) is adjusted. Furthermore, it is difficult to detect nanometre-scale or orientation-based defects even when using a scanning electron microscope, and the inspection process takes considerable time. Moreover, the drawing process cannot be paused, which leads to several metres of fibre with undesired geometric dimensions ending up in the waste bin. On top of that, any rapid variation in the structure of the fibre cannot be identified simply because the minimum cleaving distance from point-to-point in the fibre is limited to the millimetre range.

It is therefore of great interest to the PCF community to find an experimentally feasible and efficient way to monitor the fabrication of fibres in a non-destructive way. The method proposed by Stefani *et al.*[4] relies on Doppler-assisted side-scattering of light. The fibre is spun at a constant rate while it is side-illuminated with a visible laser (Fig. 1) and the strength and frequency of the scattered signal is recorded. The idea of illuminating the PCF from the side and measuring the scattered signal to extract information about its geometry is certainly not new. Filling the hollow capillaries of the PCF with a fluid with a refractive index close to silica to allow tomographic reconstruction of a fibre's structure has already been demonstrated[6]. However, this method is invasive and the long post-processing duration of the measured data makes it impractical for real-time monitoring applications. Similarly, an alternative method using X-ray tomography proposed by Sandoghchi *et al.*[7] can provide high-resolution imaging of a fibre, but the minimum scan duration is 30 minutes. Therefore, the main significance of the latest work by Stefani *et al.* is the immediate capture of the tomography of the fibre structure.

The imaging approach proposed by Stefani *et al.*[4] involves modest hardware: a monochromatic laser source with a wavelength of 633 nm, a beam splitter, two Bragg cells and a photodetector. The input beam is split into an active beam that illuminates the fibre (spinning at a rate of 10 Hz) from the side and a reference signal that is slightly frequency-shifted using the two Bragg cells. The scattered signal from the PCF structure is mixed with the reference signal and detected using simply a photodetector and an oscilloscope. The second important aspect of this method is the post-processing of the measured signal. The intensity of the scattered signal is recorded as a function of time and time-windowed. A Fourier transform then converts the signal from the time to the frequency domain. To identify and map the exact location of the scatterers (the holes in the fibre), a similar procedure to inverse Radon transform (a widely used method in computed tomography) is applied. The scheme has a unique advantage in that the spatial resolution is not limited by an imaging system. This is because spatial information about the microstructure of the fibre is captured using only a photodetector. Experiments performed on various fibres with different structures revealed a minimum resolution of better than 100 nm.

Although this technique opens the door to the possibility of monitoring and mapping the PCF structure in real-time, it comes with some limitations. First of all, the reconstructed holes are not perfectly circular, as the holes of the PCF are not point-scatterers but instead have a finite diameter. In addition, the fabricated holes themselves are not ideal cylinders, thus introducing an additional difficulty. This could possibly be improved by using multiple photodetectors to collect

the scattered signal and enhance the reconstruction. Furthermore, there is a limitation on the number of scatterers that can be identified. For a PCF structure with a large number of holes, identifying their positions is quite a difficult task. The reason is simply that there is always a trade-off between the spot-size of the beam and the Rayleigh length — the extent of the beam that can be considered to be collimated.

In conclusion, there is no doubt that the Doppler-assisted tomography technique proposed by Stefani *et al.* constitutes a significant step towards real-time monitoring of the structure of PCFs during fabrication. There is still plenty of space for improvements, including better determination of the shape of the holes and reconstruction of PCF structures with more complicated cross-sections as well as hybrid fibres, either polymer or silica[8,9]. Last but not least, another important future investigation is to determine whether Doppler-assisted tomography can actually be applied to hollow-core PCFs, where the accurate monitoring of the structure plays a crucial role in determining the final losses of the fibre. It is quite possible that in the future an optimized Doppler-assisted tomography technique could have real value in commercial drawing tower systems. ❐

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ACOUSTIC VIBRATIONAL SPECTROSCOPY

Raman extraordinaire

Fluctuations in light transmitted through a plasmonic nanohole-structure provide a way of mapping Raman transitions in nanoscale objects, including single proteins.

Alexander Weigel and Philipp Kukura

How is it possible to characterize the structure, composition and dynamics of molecules? At first sight, this appears to be a silly question given the vast array of techniques currently at our disposal. A closer look, however, reveals a common scheme behind most approaches: we subject the sample to electromagnetic radiation and observe the signature of the interaction that results, typically in an absorption or scatter event. Using incident radiation of different wavelengths yields complementary information. For example, X-rays probe electron density, infrared light tells us about molecular vibrations and thus which functional groups are present, whereas radiofrequency radiation sends nuclear spins into orbit and reveals how the atoms are interconnected in space. One slightly frustrating aspect of all of these techniques is their limited sensitivity — they typically require many molecules and thereby can only provide ensemble-averaged information. As a result, scientists have long been fascinated with the idea of probing one molecule at a time[1]. The value of this capability received international recognition recently, albeit in a slightly different form, as this year's Nobel Prize in Chemistry was awarded for super-resolution and single-molecule imaging[2].

The reason it is so difficult to study single molecules or other nanoscopic objects using light is simple: they are very small, at least compared with the smallest area light can be confined to. Most of the light therefore completely misses the target, making the interaction weak and difficult to measure — a problem that is typically alleviated by increasing the number of target particles. This issue becomes worse if the interaction between the molecule or nano-object and the incident light is intrinsically weak, for example in the case of Raman scattering — a particularly informative but also exceptionally weak effect. In this issue of *Nature Photonics*, Skyler Wheaton and co-workers[3] report experimental signatures of very low-frequency Raman transitions in both nanoparticles and single protein molecules by monitoring the light transmitted through a plasmonic nanostructure, which conveniently also traps the molecule and keeps it in place for long enough so that the measurement can be performed.

The use of plasmonic nanostructures to enhance light–particle interactions is a well-established concept[4]. Indeed, surface-enhanced Raman scattering[5] can operate down to the single molecule level[6]. Similarly, plasmon-enhanced optical trapping has been demonstrated even down to the single protein level[7]. The novelty of the study by Wheaton *et al.*[3] is in the recognition that the light transmitted through such a structure carries specific information about the trapped object, even if it is only a single protein.

The experimental approach is conceptually simple (Fig. 1). Light is focussed onto a double nanohole (DNH), which is basically a dumbbell-shaped hole milled into a thin gold film. When a dielectric particle enters the trap, it changes the refractive index and effectively increases the hole size 'felt' by the incoming light. Thus, the step change in light transmission heralds the arrival of a particle, down to the single protein level, without requiring any label. The key concept is that the light transmission also depends on the thermal motion of the particle in the trap, directly translating into intensity fluctuations. The authors use this local temperature sensitivity as a novel approach to detect the excitation of vibrational modes in single nanoscopic particles. Two frequency-detuned lasers illuminate the trap and drive low-frequency Raman-active vibrations. When scanning the frequency difference between the two lasers, the amplitude of the intensity fluctuations maps the vibrational excitation spectrum. This surprisingly simple technique can record vibrational spectra without complex dispersion optics in the detection path, and since it is only sensitive to absorbed vibrational