# Scattering in focus

Sustaining the ongoing revolution in optical microscopy will require gaining detailed insight into the optical fields in focal spots. Researchers have developed an elegant method for mapping the full electric vector field using just a metal nanosphere on a glass substrate.

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Measuring the amplitude and phase of nanostructured light fields is normally only possible using sophisticated near-field microscopes. Now, researchers in Germany demonstrate that it can be done using a simple metal nanosphere on a glass substrate[1].

In the past decade, light microscopy has undergone a revolution. New means have been developed to overcome the diffraction limit, which restricts the highest spatial resolution attainable by conventional far-field microscopy. Innovative ways have been developed to exploit the physical saturation properties of light-emitting labels, enabling a highly nonlinear response to be generated, and hence greatly increasing the spatial resolution[2]. Advancing these novel microscopy techniques depends critically on having a detailed knowledge of the optical fields inside the focal spot(s) of the microscope. Obtaining that information is, however, far from trivial as these foci are necessarily generated by operating at the very frontiers of the diffraction limit. Optical fields with deeply subwavelength structure have been mapped using single molecules[3,4] and small metal particles[5,6]. However, none of these techniques reveals the local phase of the light; this requires using bulk interferometric techniques[7].

Now, Thomas Bauer and co-workers have devised a simple and elegant nanointerferometric method that allows them to reconstruct both the amplitude and the phase of tightly focused light beams. One could argue that they have inverted the original idea of Edward Synge for realizing a near-field microscope[8] (which Albert Einstein expected would never work in the real world). Synge proposed the realization of ultrahigh-resolution optical microscopy by using a (deeply) subwavelength hole in an opaque screen — an optically thick metal film. By scanning the hole across a sample, an image could be obtained with a resolution given by the size of the hole. Bauer *et al.* have flipped this approach on its head: they map light fields with extremely high resolution using a small metal particle on a transparent substrate.

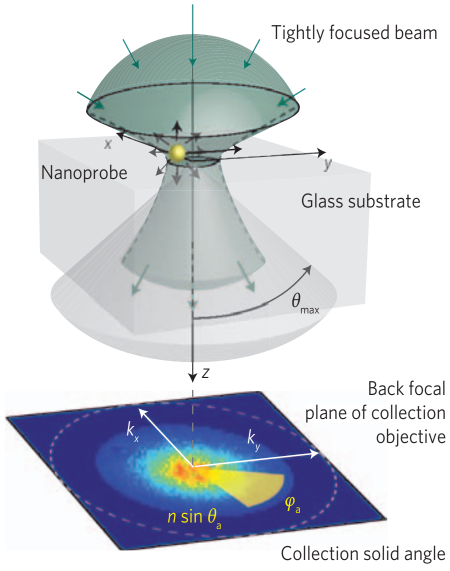

**Figure 1 |** Schematic of the measurement scheme. A spherical nanoparticle is supported on a macroscopic glass substrate. The substrate is scanned in the *x*-*y* plane with respect to the light field to be mapped (in this case, a tightly focused, radially polarized beam).

In their study, they use a metal nanoparticle as a local probe of the optical field. The nanoparticle scatters the local light field. The direction in which it scatters the light depends on the exact vector field at its location. Bauer *et al.* collect the optical pattern behind the nanoparticle. This pattern has two contributions: the scattered and unscattered fields. Because these contributions can interfere, the measured pattern contains not only information on the amplitude of the vector field scattered by the particle, but also information about its phase. The nanoparticle is scanned across the complex light field, and the resulting pattern is recorded at each point. Figure 1 shows a schematic of the method.

The researchers developed a robust reconstruction method for obtaining the unknown light field under investigation from the recorded pattern. They show how the pattern resulting from the interference of the scattered and the directly transmitted light can be calculated from a known incident field by using the full scattering matrix of the nanoparticle, as determined by Mie theory. In this calculation, the incident field is expanded in spherical harmonics. The whole procedure accounts for the presence of the particle and the substrate. Conversely, an inversion of this calculation allows an unknown optical vector field at the particle location to be directly reconstructed from a measured pattern.

In principle, the theoretical framework allows a particle of any material or shape to be used as long as it can be described by Mie theory. In practice, however, the reconstruction scheme is simpler for higher symmetry systems. In their experiments, Bauer *et al.* used a spherical nanoparticle to obtain cylindrical symmetry, which facilitated the demonstration of the new technique. Although the formalism is able to deal with arbitrary optical responses of a particle having higher-order multipoles in addition to a dipole response, the procedure is simplified when the dipole response dominates. The researchers hence had to strike a balance between (i) maximizing the dominance of the dipole response by minimizing the particle size and (ii) maximizing the signal (and hence the signal-to-noise ratio) by maximizing the particle size. In the end, they performed the experiment with the combination of a ~80-nm-diameter particle and 530-nm-wavelength light.

Clearly, the quantitative reconstruction hinges on knowing the full scattering matrix of the nanoparticle. The geometry and the optical properties of the nanoparticle are therefore measured independently: the geometry is measured by transmission electron microscopy, whereas the optical properties are measured by spectroscopy.

To demonstrate the new method, a light field was generated by tightly focusing a radially polarized light beam. This results in an optical pattern containing all three components of the electrical field vector

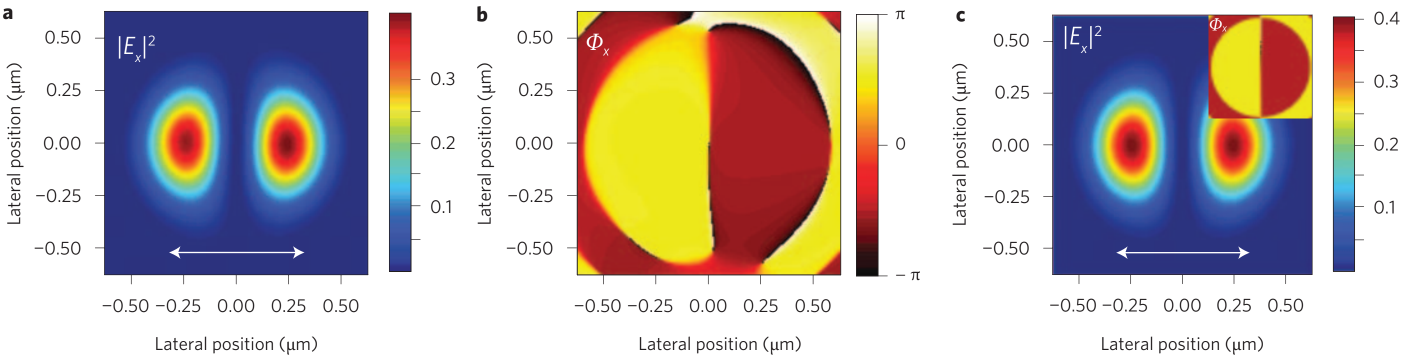

**Figure 2 |** Experimental results and theoretical calculations for a tightly focussed, radially polarized vector beam. **a**,**b**, Colour-scale representations of the experimentally reconstructed distributions of $|E_x|^2$ (**a**) and $\Phi_x$ (**b**). Two lobes with a lateral size of roughly 250 nm are easily resolved. The phase image shows that the left-hand side of the focus is out of phase with respect to the right-hand side. **c**, Colour-scale representation of the distributions of $|E_x|^2$ and $\Phi_x$ as calculated by vector diffraction theory.

with a spatial intensity distribution whose typical feature size is of the order of 250 nm. Figure 2 shows both the reconstructed distribution of $|E_x|^2$ and $\Phi_x$ and the same entities as calculated by vector diffraction theory. It is immediately apparent from this figure that excellent agreement is obtained between the measurement and reconstruction on the one hand and the fields calculated by diffraction theory. The power of the technique, however, is exemplified by the small (subwavelength) deviations between the measurement and the theory. A detailed analysis of the results shows that these subtle deviations, rather than showing the limits of the technique, indicate minute imperfections in the focusing system.

It is precisely this ability that is anticipated to aid advances in modern optical microscopy. Such advances rely on using combinations of multiple foci and nonlinear interactions, such as saturation. Advancing optical microscopy therefore requires a detailed knowledge of the complex optical field distributions at the focus, which can now be easily characterized. This will facilitate data interpretation, help optimize the resolution and aid the development of new microscopy schemes. The method can also be used to map other (nano)structured light fields with phase sensitivity, so long as a propagating far-field reference can be provided. It may allow the characterization of near-field probes if rescattering of light from the probe can be neglected. Mapping the full vector field of light will also be crucial for exploring novel knotted solutions of Maxwell's equations[9]. Ultimately, if the original objection of Einstein to Synge's scheme, namely having a large substrate close to (and evanescently coupled to) the sample, can be overcome, the method could be used to realize quantitative microscopy of confined fields.

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