on the orientation of the electric field. By extracting this information we can uncover new effects at play.

With their microscope, Lee and co-workers have constructed detailed electric-field maps for light in three simple set-ups. First, for evanescent standing waves generated by total internal reflection of two counter-propagating beams inside a dielectric prism; second, for surface plasmons at a gold–air interface; and, finally, for surface plasmons produced when light passes through a single slit cut into a thick metal film. One would expect that the image resolution is related to the diameter of the nanoparticle (about 100 nm in this case) but, rather surprisingly, comparisons of the experimental field maps obtained from theory suggest that the attainable resolution is much better, at least in the three geometries investigated. Further analysis will be needed to understand the origin of this unusually high resolution.

In these studies, the electric field is two-dimensional, that is, its vector components lie in one plane. The researchers suggest that by using two independent, orthogonally oriented polarizers, they could achieve full three-dimensional imaging of the electric-field vector. If this idea works, their technique will become an efficient experimental tool with which to explore the complex electric fields that arise when light interacts with matter on the nanoscale.

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### PLASMONICS

# Superfocusing of terahertz waves

The promising field of terahertz imaging has long been limited by poor resolution. Researchers now believe that the intriguing properties of surface-plasmon polaritons on corrugated wires could help beat the diffraction limit and inspire a new generation of terahertz photonic devices.

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Spectroscopy and imaging in the terahertz (far-infrared) band of the electromagnetic spectrum are now benefiting diverse areas of science[1] and starting to find important commercial applications. For example, the pharmaceutical, medical and security industries are exploring the idea of using the technology to measure the thickness of tablet coatings, detect skin cancer and image weapons hidden beneath clothes.

Unfortunately, the long wavelength (about 300 μm) of terahertz radiation creates serious limitations for the imaging resolution, which is very poor compared with visible imaging techniques, which operate at far shorter wavelengths. This is more than an aesthetic problem for applications of terahertz imaging in nanotechnology and clinical medicine, where subwavelength image resolution is required to resolve microscopic features or perform spectroscopy on small volumes.

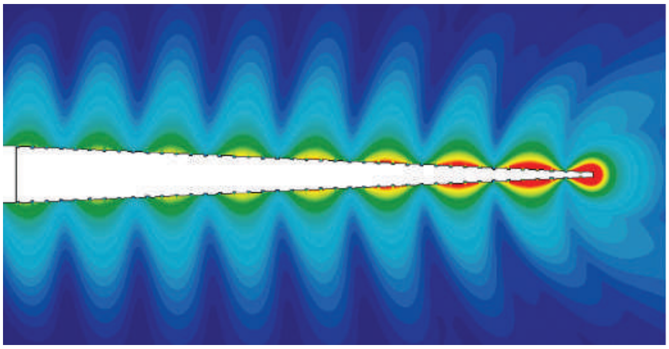

**Figure 1** Calculated electric-field distribution of an SPP on a corrugated cone[2]. Note that a subwavelength 'superfocus' is evident at the tip of the 2-mm long structure. The false colour scale represents the magnitude of the electric field over a (logarithmic) scale of two orders of magnitude.

Fortunately, a solution may soon be at hand. Reporting in *Physical Review Letters*, Maier and colleagues from the United Kingdom and Spain propose an elegant solution to this problem using surface-plasmon polaritons (SPPs) on corrugated wires to guide and 'superfocus' terahertz radiation[2]. The results are particularly promising for the development of new types of terahertz photonic devices including a near-field terahertz endoscope with enhanced resolution.

An SPP is a coupled electromagnetic and electron-plasma polarization wave that can be excited at the surface of a metal[3]. At frequencies approaching the plasma resonance of the metal (often in the UV or visible), the unique propagation characteristics (dispersion) of an SPP open the door to a variety of interesting effects, such as the generation of intense, localized electric fields on subwavelength structures.

Great progress has been made in recent years in engineering compact 'plasmonic' devices from micro- and nanostructured metals to exploit the properties of SPPs at visible frequencies. Subwavelength localized plasmonic waveguides and plasmonic devices have been demonstrated[4] and intense subwavelength 'superfocusing' of SPPs at the apex of metal cones has been predicted[5]. One of the most important examples of plasmonics in action is surface-enhanced Raman spectroscopy, which uses the intense electric fields of SPPs in metal nanoparticles to perform spectroscopy on single molecules with unprecedented sensitivity.

Unfortunately, subwavelength field localization occurs only for SPPs with frequencies close to the (visible–UV) plasma frequency of the metal. As a result, the success of plasmonics in the visible region is not easily transferable to the terahertz world.

Maier *et al.*[2] have now made the important step of showing that subwavelength confinement of SPPs, already studied at visible frequencies, should also be achieved at terahertz frequencies. Their computer simulations suggest that metal cylindrical wires with a periodic array of microstructured radial grooves can artificially modify the dispersion of terahertz SPPs, enabling confinement effects and robust guidance with low bend loss. The results complement earlier findings that discussed the possibility of guiding and coupling terahertz SPPs in conventional wires[6,7].

Perhaps most interestingly, Maier *et al.* report that by (adiabatically) reducing the depth of the periodic grooves they can concentrate the electric field by a factor of ten, which could have important applications in sensing. Furthermore, they show that by tapering a periodically grooved wire it should be possible to superfocus terahertz SPPs (Fig. 1). The tapered wire structure they designed was optimized for 0.6 THz ($\lambda = 500$ μm) radiation, having its surface patterned with (10 μm wide, 5 μm deep) radial grooves that were repeated every 50 μm along the wire. The wire was thinned from an initial radius of 100 μm down to 10 μm at the tip over a length of 2 mm thereby forming a grooved truncated cone. Calculations suggest that most of the terahertz radiation at the tip of the cone would be confined within a radius of about 20 μm, implying that a spatial resolution of about $\lambda/25$ may be achievable. Such a structure is extremely promising for use as the tip of a near-field terahertz microscope or as a terahertz 'micro-endoscope'.

The UK–Spanish team are not the only researchers exploring how plasmonics can help improve terahertz optics and imaging. Ishikara and colleagues in Japan have reported that a 'bull's eye' design of concentric metal grooves surrounding a central 'bow-tie' antenna can act as an effective aperture for near-field terahertz imaging. They claim that the intensity of terahertz radiation at the centre of their aperture can be enhanced by a factor of 1,780 as a result of the resonant excitation of SPPs in the bull's eye structure and electric-field enhancement at the sharp tips of the bow-tie feature. The Japanese researchers have already fabricated a device optimized for operation at 1.45 THz ($\lambda = 207$ μm) by diamond-milling concentric grooves (66 μm wide, 13 μm deep) with a radius periodicity of 132 μm in a planar sheet of resin and coating the structure with gold. They demonstrated this aperture experimentally by resolving a 20-μm wide chromium strip with $\lambda/17$ (about 12 μm) spatial resolution.

However, the advantage of the Maier *et al.*[2] approach to near-field imaging is the ease with which a tip could be used in a practical imaging system or endoscope. In fact, a prototype may not be far away as the researchers claim that existing laser-machining technology could be used to mill the 5-μm deep features required to pattern the wires.

Of course, both these plasmonic approaches to terahertz imaging do have some drawbacks. Most importantly, the structures are designed for a specific frequency, so they are not immediately appropriate for broadband terahertz spectroscopy. Additionally, in the case of the corrugated wires, suitable methods of generating and coupling terahertz radiation into the structures and also of detecting that radiation need to be found. As we are at the very start of the development of plasmonic terahertz technologies, it is likely that these and many other exciting devices are waiting to be invented.

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## FIBRE LASERS

# Keeping cryptographic keys safe

Turning an optical fibre into a giant laser may allow for practical key generation without requiring fragile quantum states.

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Distributing shared secret keys for cryptographic purposes by exploiting the laws of quantum physics has been extensively studied over the past 20 years[1,2]. Although such quantum key distribution (QKD) schemes promise very high degrees of quantifiable security, they are also difficult to use owing to the fragility of quantum states and the technical demands in creating practical, high-performance quantum devices such as single-photon emitters and detectors.

Recent innovative work by Scheuer and Yariv[3] suggests an alternative method for distributing cryptographic keys. Their method is a physical technique that is not based on quantum physics.