photonic crystal. The final result is simple, but amazingly effective.

These results open up the way to realizing optical control in structures based on photonic crystals and other polymer-based photonic devices. In addition to polymer structures, which are limited in terms of the contrast of the refractive index that can be obtained, the concept could also be integrated with higher-contrast materials, such as silicon. Ideally the doped polymers would be incorporated locally in individual pores of a photonic crystal (see Fig. 1). Their function in this case would become twofold. On one hand the local change of the refractive index would create waveguide and resonator structures, and on the other hand, the nonlinearity of the doped polymer would allow the central wavelength of the resonators and waveguides to be tuned. A design in which a specific refractive index and nonlinear constant could be assigned to each individual pore could lead to the construction of devices, such as optical multiplexers and optical controlled-delay lines.

An issue that remains to be tackled is that of intrinsic disorder in the sample. Regular crystals, as used in electronics, are made from atoms or molecules that are naturally all the same size. This enables them to be extremely pure and ordered. Photonic crystals, on the other hand, are constructed from building blocks, such as pores in slab waveguides or microspheres in the case of three-dimensional structures. These building blocks have size variations that are small but intrinsically present. Photonic crystals therefore suffer more from structural disorder than electronic ones.

Ironically, whereas disorder is now seen as a major bottleneck for the implementation of photonic-crystal technology, it was originally one of the inspirations to investigate such structures in the first place. The original motivation to realize and study photonic crystals was conceived within the context of confining light with disorder[2]. This effect, called localization, is caused by interference in disordered structures, which occurs both for electrons and light. Localization can trap waves that are multiply scattered, and the phenomenon is expected to be strongly enhanced inside a photonic-crystal structure[2]. Although the physics behind this complex phenomenon is not yet fully understood, it could provide an opportunity to solve the disorder bottleneck. The effect of a strong optical nonlinearity on localization would be fascinating from a fundamental point of view and could also be applied in nonlinear components. The doped polymers realized by Hu *et al.* would be ideal for creating the appropriate nonlinearities.

The field of photonic crystals is maturing, and the challenging applications originally envisioned related to optical data processing[9] might start to become a reality in the near future. The lesson we can learn from the development of the field is that promises of future applications can become a reality, but thorough fundamental research is nearly always required before such devices can be designed and developed.

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TERAHERTZ

The art of confinement

By structuring the surface of a metal with an array of holes, photonics researchers show that it is possible to tightly confine terahertz surface waves, reducing their decay length into air by two orders of magnitude. The results could lead to new approaches to waveguiding.

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Methods for confining and guiding electromagnetic radiation into the smallest possible volume have been pursued since the first studies of electromagnetism. Transmission lines, optical fibres and waveguides are some examples of instruments developed for this purpose. A very compact approach to guiding electromagnetic waves is to couple them to the collective oscillation of free electrons at the interface between a conductor and a dielectric, forming so-called surface plasmon polaritons (SPPs). On page 175 of this issue[1], Christopher Williams and co-workers report that by structuring the surface of a metal with an array of holes it is possible to mimic SPPs, enhancing the confinement of the electromagnetic field at the interface by two orders of magnitude with respect to an unstructured sample. They have demonstrated this at terahertz frequencies, a region of the electromagnetic spectrum that is of considerable interest for gas and biomolecular spectroscopy.

Surface plasmon polaritons propagate at the interface between a conductor (usually a metal) and a dielectric, decaying evanescently into these two media. The strength of the coupling between the radiation and the free electrons is determined by the electromagnetic impedance mismatch at the interface, which is dictated by the electric permittivity of the metal. The impedance mismatch is small when the permittivity of the metal has a low absolute value. This is the case for radiation with a frequency close to the plasma frequency of the metal — the frequency at which a metal starts behaving as a dielectric. For most metals this corresponds to radiation at optical frequencies. At these frequencies, the coupling of the electromagnetic field

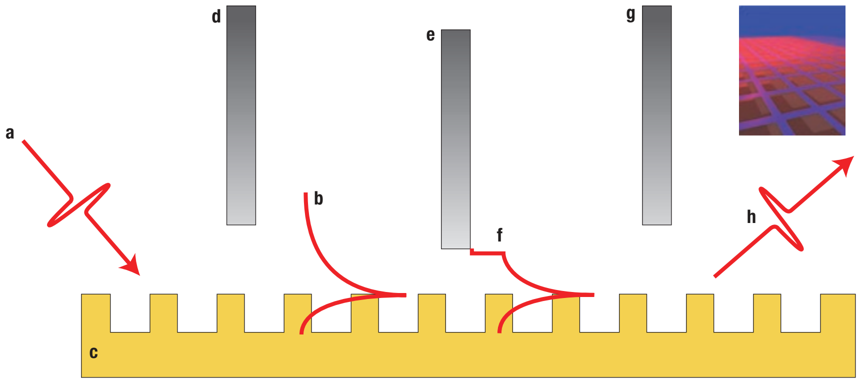

Figure 1 Schematic representation of the set-up used by Christopher Williams and co-workers. A terahertz pulse (a) couples to spoof SPPs (b) on the structured surface of a metal (c) by scattering off an aperture defined by a razor blade perpendicular to the sample surface (d). A second razor blade (e) probes the extent of the spoof SPPs (f), and a third blade (g) couples the spoof SPPs back to radiation (h), which can be detected. By moving the probing blade in the vertical direction, the decay length of the spoof SPPs from the surface (that is, the degree of confinement) can be measured. The inset shows an artistic representation of the metal surface.

to the free electrons is strong, which leads to a short decay length into the dielectric. The propagation length of SPPs on the surface is determined by ohmic losses in the metal and by the radiative damping as they are scattered into free-space radiation by surface corrugations.

The plasma frequency of most metals lies in the UV. This means that the decay lengths of SPPs into the metal and the dielectric are of the order of 10 nm and 100–1,000 nm, respectively, for visible and near-infrared light. The propagation length along the surface is of the order of several tens to hundreds of micrometres. Because of this strong confinement of the electromagnetic field to a subwavelength depth at the surface, SPPs are often referred to as low-dimensional electromagnetic waves. The possibility of subwavelength guiding of electromagnetic radiation has sparked tremendous interest in the field of surface-plasmon optics or plasmonics, owing to its promising prospects in integrated optical circuits, sensor technology and nonlinear optics.

In contrast with visible and near-infrared frequencies, the expectations for low-frequency (that is, far-infrared, terahertz and microwave) plasmonics have not been so high. According to the Drude free-electron model[2], the permittivity of metals scales inversely with the square of the frequency of the incident radiation. At terahertz frequencies (1 THz corresponds to a wavelength of 300 μm in vacuum), both the real and imaginary values of this permittivity are huge, with typical absolute values of the order of 10^5. These values of the permittivity give rise to weak coupling of the electromagnetic field to the electrons in the metal. Therefore, the field extends over distances of several centimetres into the dielectric and the usefulness of these surface waves for compact waveguiding or sensing is lost. In this regime SPPs are called Zenneck waves (or Sommerfeld waves in cylindrical surfaces) after the pioneering works on radio waves of Arnold Sommerfeld and Jonathan Zenneck at the beginning of the twentieth century[3]. It is worth noting that as a consequence of the weak coupling of the electromagnetic wave to the electrons, Zenneck waves can propagate several metres at terahertz frequencies, in spite of the substantial values of the imaginary component of the permittivity that defines the ohmic losses. These characteristics make Zenneck waves resemble radiation that travels at a grazing angle to the surface rather than SPPs bound to the surface.

To make Zenneck waves behave like bound SPPs, that is, to generate a truly two-dimensional surface wave at terahertz frequencies, the electromagnetic field has to be sufficiently tightly confined to the surface of the metal. This is just what Williams and co-workers have demonstrated using copper surfaces perforated by arrays of square holes (Fig. 1). In doing so, they are following through theoretical predictions made by Pendry and colleagues[4]. The indentations in the surface give rise to increased field penetration into the perforated metal and thereby to the reduction of the impedance mismatch at the interface. The existence of surface modes on structured surfaces was recognized long ago[3,5]. However, it is after the work of Pendry and colleagues that these modes have been called ‘spoof SPPs’ because they mimic SPPs even on perfect conductors, that is, metals with an infinite permittivity on which SPPs cannot exist.

Shortly after the introduction of the concept of spoof SPPs, Hibbins *et al.*[6] measured their dispersion relation at gigahertz frequencies. Williams and colleagues[1] have now measured the decay of spoof SPPs from structured metallic surfaces, demonstrating a strong confinement of the terahertz field to the surface with a decay length into air of the order of the wavelength. As pointed out by the authors, the enhanced confinement of the field is a very promising way of improving the sensitivity of terahertz sensors.

The measurements of Williams *et al.* open up new approaches for plasmonics. The characteristics of spoof SPPs are determined by geometric factors rather than material properties. Therefore, by varying the size of the holes it is possible to tune the effective plasma frequency of this material and thus the confinement and propagation of the surface mode. Stronger confinement can be achieved by filling the holes with a high-dielectric-constant material. Another exciting possibility would be to structure the surface of doped semiconductors; the plasma frequency of semiconductors is much lower than that of metals, which means that the characteristics of spoof SPPs at terahertz frequencies on semiconductors are determined by both material and geometrical factors, leading to a stronger confinement of the field at the surface.

Important questions are still to be addressed. For example, what limits the propagation length of spoof SPP modes? Indentations in a flat surface give rise to SPP losses as a result of scattering into radiation, which must be carefully considered when designing plasmonic surfaces. Nevertheless, with this work, Williams and co-workers have shown that it is possible to strongly modify the characteristics of surface waves simply by tinkering with the surface. This could pave the way towards new subwavelength waveguiding techniques.

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