Toss a rock into a quiet pond, and watch the ripples spread out across its surface. This is pretty much what happens when a photon hits the surface of a metal — except that in this case, the ‘ripples’ consist of electrons oscillating en masse and have wavelengths measured in nanometres. Once they are set in motion, these ‘surface plasmons’, as the oscillations are known, can pick up more light and carry it along the metal surface for comparatively vast distances. “A river of light” is how Satoshi Kawata, a physicist at Osaka University in Japan, describes the phenomenon to his students.

Plasmons can also focus light into the tiniest of spots, direct it along complex circuits or manipulate it many other ways. And they can do all of this at the nanoscale — several orders of magnitude smaller than the light’s own wavelength, and therefore far below the resolution limits of conventional optics.

The result is that plasmonics has become one of the hottest fields in photonics today, with researchers exploring potential applications in solar cells, biochemical sensing, optical computing and even cancer treatments (see ‘Plasmons at work’).

Their efforts, in turn, have benefited greatly from the flowering of nanotechnology in general over the past decade, which brought with it a proliferation of techniques for fabricating structures at the nanoscale — exactly what plasmonics needed to progress from laboratory curiosity to practical applications. “The late 1990s was kind of the turning point” for plasmonics, says Harry Atwater, a physicist at the California Institute of Technology in Pasadena.

One surprising example of the light-carrying phenomenon was witnessed in 1989 by Norwegian-born physical chemist Thomas Ebbesen, now at the Louis Pasteur University in Strasbourg, France. As he held to the light a thin film of metal containing millions of nanometre-sized holes, he found that it was more transparent than he expected. The holes were much smaller than the wavelength of visible light, which should have made it almost impossible for the light to get through at all. “I first thought, ‘Here was some kind of mistake,’” says Ebbesen.

But it wasn’t a mistake, although it took Ebbesen and his colleagues the better part of a decade to work out what was happening. When the incoming photons struck the metal film, they excited surface plasmons, which picked

Surfing the wave

Small oscillations of surface electrons that manipulate light on the nanoscale could be the route to applications as disparate as faster computer chips and cures for cancer. **Joerg Heber** reports.

Light manipulation: surface plasmons could be generated (above) to help direct light using nanoantennas in devices such as solar cells (left).

up the photons’ electromagnetic energy and carried it through the holes, re-radiating it on the other side and giving the film its transparency¹.

Hole arrays are increasingly finding their way into applications, for example as selective filters for colour sensors. It turns out that the increased transmission through the sheet works only for light around the plasmons’ natural oscillation frequency. But this frequency, which is typically in the visible or near-infrared part of the spectrum, can be adjusted by changing the geometry of the holes and their spacing. So hole arrays can be

made into highly selective filters for sensors that depend on detecting specific colours, or for efficiently extracting monochromatic light from light-emitting diodes (LEDs) and lasers. Indeed, a number of commercial research labs, such as the Panasonic laboratory in Kyoto, Japan, and NEC in Tsukuba, Japan are working on prototypes of plasmon-enhanced devices for displays and telecommunications.

Hole arrays can also be used to channel light into optical devices. In imaging chips for digital cameras, for example, researchers are studying how hole arrays placed on top of individual pixels might help capture incoming light

Plasmons at work

Although plasmonic effects have been known for more than a century, the history of plasmon-based applications began in the early 1970s, when Martin Fleischmann, a chemist at the University of Southampton, UK, and others began to study how light scatters from molecules stuck to a silver surface⁷. Richard Van Duyne, a chemist at Northwestern University in Evanston, Illinois, then discovered this scattering to be enhanced by a seemingly incredible six orders of magnitude⁸.

In today's optimized devices, this enhancement, known as surface-enhanced Raman spectroscopy (SERS), can be several orders of magnitude larger still — strong enough to detect a single molecule⁹. Moreover, SERS has proved very useful in the biochemical and materials sciences by providing information on the chemical composition of molecules at very small concentrations.

SERS is a plasmonic effect: silver nanoparticles act as antennas that take the incoming laser light and, through their surface plasmons, concentrate it. The concentrated light is then scattered by nearby molecules and amplified again by the silver nanoparticles on the way back out. This dual amplification results in a huge overall signal enhancement.

Some applications have reached the market. For example, in

specifically prepared colloids of gold nanoparticles, a clustering of these nanoparticles is triggered by the presence of pregnancy hormones. This leads to a colour change induced by plasmonic effects that has been widely commercialized in pregnancy tests.

The commercialization of SERS has been hampered in many areas by difficulties in achieving highly accurate control over the surface nanostructures. For this reason, researchers are also looking at other sensing techniques such as localized surface plasmon resonance (LSPR). The idea is that, when a surface is covered with nanostructures in the shape of rods or triangles, their plasmonic properties depend strongly on the properties of medium that surrounds them. For example, a solution containing a certain type of molecule has

a refractive index that varies with the concentration of those molecules¹⁰. "These changes to the refractive index lead to measurable changes to the surface plasmon resonance wavelength, which can be observed experimentally," says Stefan Maier from Imperial College London, who studies plasmonic nanostructures and their applications. "The effects can be dramatic." Devices based on LSPR are becoming so sensitive that Van Duyne thinks that they, too, are about to reach the limit of single-molecule detection.

And at Rice University in Houston, Texas, biomedical engineer Naomi Halas is pursuing an optical technique to destroy cancer cells. She hopes to inject cancer patients with gold nanoparticles that will be guided to the tumour by antibodies bound to the particles' surface. Once the

nanoparticles are in place, she can illuminate the area with a low dose of infrared laser light that leaves healthy tissue undamaged, but gets absorbed to create plasmons in the gold. The energy heats up the nanoparticles and kills the cancer cells¹¹.

So far, Halas's cancer therapy has been successful in trials with mice, where she achieved seemingly complete elimination of the tumours. The technology is now in human clinical trials with patients who have head and neck cancers. Halas says the results have been very encouraging so far. "There is no reason one would expect complications from something like this in humans relative to animal trials, because you are using physical mechanisms, heat and light, to induce cell death." Halas is also optimistic that the treatment will be approved for use more quickly than a drug, which can involve difficult and expensive trials and many years to reach the clinic. She says the technique is being considered as a 'device' by the US Food and Drug Administration rather than a drug, which could also accelerate the approval process. **J.H.**

Naomi Halas (centre, above) wants to use plasmons to fight cancer; others use them as sensors (inset) to detect single molecules.

more efficiently, and thus reduce pixel noise and improve camera sensitivity.

Another plasmonic technique for channelling light into a device is to sprinkle its surface with nanoscale particles made of a metal such as gold. These nanoparticles function like an array of tiny antennas: incoming light is taken up by plasmons and then redirected into the device's interior.

Slimming down

From a commercial perspective, perhaps the most promising application of such nano-antennas — or indeed, of hole arrays — is in the improvement of solar cells. Present-day solar cells are made from semiconductors such

as silicon. But to catch as much light as possible from the broadest range of wavelengths, particularly in the red and infrared part of the spectrum, the semiconductor layer has to be relatively thick. "Right now a silicon solar cell is up to 300 micrometres thick," says Albert Polman, a photonics researcher who directs the AMOLF institute in Amsterdam, where he works on improving solar-cell designs. And when cells are being deployed in arrays that cover a rooftop or more, he says, that adds up to a lot of expensive silicon. The price would come down a long way if the silicon was only 1 micrometre thick. "But then you don't catch

the red light because it goes straight through the chip," he says, thus wasting much of the sunlight's available energy. Other solar-cell materials have the same problem.

With plasmonics, however, the problem goes away. In one approach that researchers are exploring, gold nanoparticles on the surface would act as reflectors that focus light into the semiconductor, where absorption efficiency increases with the light concentration. In another scheme, tiny gold nanoantennas could redirect sunlight by 90°, so that it propagates along the semiconductor rather than passing straight through. Either way, the cell

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could get by with a much thinner semiconductor layer.

Even as plasmonic techniques are decreasing the cost of the cells, they could also greatly improve the cells' efficiency at extracting the available energy from sunlight — in a field in which even a few percentage points in efficiency improvement are celebrated. Overall, the use of plasmonics could increase the absorption two to five times, says Atwater, who has co-founded Alta Devices in Santa Clara, California, to commercialize such solar cells. For cells made from amorphous silicon, which today have efficiencies of around 10–12%, the predicted enhancements could translate into efficiencies of about 17%. For crystalline silicon cells, which currently have efficiencies around 20%, the new figure could approach the theoretical maximum of 29%. For commercial applications, the remaining challenges include developing workable device designs and fabrication techniques for mass production.

Guiding light

Plasmonics researchers are also grappling with a longer-term challenge: the integration of optics and electronics on a single microchip. The decades-old idea is that, just as a fibre-optic cable can carry much more information than a copper wire, a light beam could, in principle, relay information through the chip on more channels and at a higher speed than conventional integrated circuitry can handle. But the experimental optical devices produced to date have been too large, and have showed rather high losses in the optical signal strength.

"You want to bring the optics closer in size to the transistor," says Polman. And that's the beauty of plasmonics, which can offer optical pathways on virtually the same scale as the silicon structures found in advanced microchips. "Metals can be well integrated with the chip design," says Polman, "so you may be able to distribute light over an integrated circuit by plasmons." Indeed, structures such as silver nanowires² or grooves etched into metal surfaces³ can provide pathways that guide light across a chip in whatever direction the designers might need.

But there is a trade-off as the structures get smaller. If the plasmons are forced to travel through a channel that's too narrow, they start

Plasmon resonance could be used to make very sensitive biochemical sensors (yellow bars). The waves here represent absorption spectra.

"Plasmonics has given photonics the ability to go to the nanoscale."

— Harry Atwater

to leak out from the sides and get lost, says Sergey Bozhevolnyi from the University of Southern Denmark in Odense, who is leading a European research project into integrated plasmonic circuits. Nevertheless, researchers can guide surface plasmons over distances of more than 100 μm , which is roughly a thousand times bigger than the features on a current-generation microchip. This is enough to open rich possibilities for plasmonic nanocircuits, in which light would carry information along complex paths and through many processing steps.

Plasmonic waveguides are particularly promising if the light source — typically a laser — can be incorporated on the chip as well. This has been done with comparatively large lasers, on the order of the wavelength of the laser light. But plasmonics now offers the possibility of doing so at the nanoscale, at lengths much shorter than the wavelength. Rather than amplifying light in a conventional laser cavity, a plasmonic 'spaser' would amplify it with the help of plasmons — the first experimental evidence for such plasmon-based lasing was published in August^{4,5}. To fully integrate these plasmon lasers into standard microcircuitry,

however, researchers will need to find a way to trigger the spasers using standard electrical currents.

In addition to creating light and guiding it across a chip, optical computing will require a way to turn the flow of plasmons on and off at high speeds, so that the flow becomes a series of bits in a digital data stream. Many people have been working on such devices, and a plasmonic modulator based on silicon technology has been realized by Atwater's group. Like a conventional transistor, in which an electric voltage controls a tiny electrical current, the group's device is based on the use of an electric field to control the propagation of surface plasmons through the device⁶. Apart from their small size, compared with conventional optical counterparts, the operation frequency of plasmonic modulators can easily reach tens of terahertz, well above the gigahertz regime of modern computers.

Many roadblocks still remain to the commercialization of such technologies — ranging from the integration with silicon to device issues. "The key thing that keeps coming back are losses in the metals," says Mark Brongersma, a materials scientist at Stanford University in California. However, he adds, smart design of the plasmonic structures could, in principle, reduce losses to acceptable levels.

Plasmonics research has made remarkable progress in the past decade, and researchers are working on pushing our knowledge of plasmons even further, for example to understand the physics very close to the metal surface. Nonetheless, says Atwater, "what has happened in the past seven or eight years is that plasmonics has given to photonics the ability to go to the nanoscale and properly take its place among the nanosciences."

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