NEWS & VIEWS

PHOTONICS

Light in chains

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Diffraction places a fundamental limit on the smallest scales at which light can be controlled. A nanoscale silver array not only circumvents the barrier, but steers different-coloured light to different places.

Is it possible to control the concentration of light energy on the nanometre scale? This 'nanofocusing challenge' has implications for a whole host of areas, including small-scale sensing and lasing techniques, high-resolution optical imaging, super-compact photonic circuitry and ultra-sensitive biochemical analysis. It is no surprise, therefore, that it lies at the heart of a lively body of research.

Sharp points on metallic particles and tiny gaps between the particles have already been explored extensively in the quest to generate optical hotspots. In taking on the nanofocusing challenge, de Waele *et al.*[1] choose another direction. Writing in *Nano Letters*, they show that a chain of tiny silver particles can be used to concentrate light at either of its ends, rather as an antenna concentrates radio waves. Not only that, but the position at which the light is located is determined by the light's colour, with a sharp switch in position occurring at a precise wavelength. The achievement is a notable step towards producing devices that can switch and steer light at the nanoscale.

But why not just make a better lens? Unfortunately, conventional devices for steering light, such as lenses or mirrors, no matter how perfectly made, are limited by diffraction. This means that any focusing effect is limited to the scale of the light's wavelength — a few hundred nanometres at best. Plasmonic antennas of the sort exploited by de Waele *et al.* take advantage of the fact that the light becomes coupled to the 'plasma' of free electrons that suffuses any metal. Such antennas are generally accepted as the best way to get round the limitation imposed by diffraction and so convert light into nanoscale-localized energy. Proven concepts used for radio and microwave antennas have thus been revisited and scaled down to the smaller-wavelength domain of visible light. Optical dipole[2] and monopole[3] antennas — analogous to the most basic radio-antenna technologies — have been fabricated and used to confine green light fields (wavelength around 500 nm) to a region of just 20 nm.

So far, so simple, it would seem. But the optics of metals has its own peculiarities and attractions. Among the peculiarities is that metals are not perfect conductors at visible
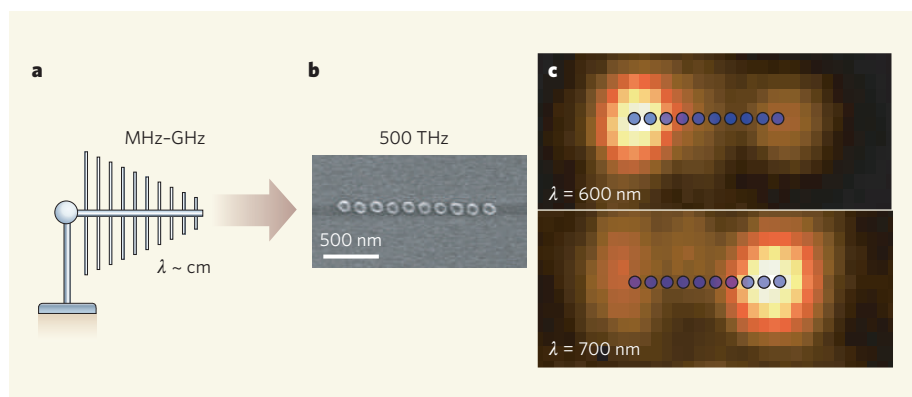

Figure 1 | Signal success. Multi-element antennas concentrate the energy from a source in a specific direction on a single element. The concept is familiar for radio waves in the megahertz–gigahertz bands (**a**). As de Waele *et al.*[1] show (**b**), it works equally well for light waves of submicrometre wavelength (frequency around 500 terahertz). In this case, the light energy is localized at the front or back of the antenna element, depending on the colour of the incident light (**c**), opening up a range of new applications.

wavelengths, as they are for radio waves. Instead, a metal becomes somewhat transparent: light penetrates into its surface, where oscillations of the metal's free-electron plasma take over some of the light's energy to form a resonant energy package known as a plasmon. To keep optical nanoantennas perfectly tuned, therefore, a tailored rescaling is needed that depends on the metal of choice, the shape of the antenna, the colour and polarization of the light, and so on[4]. But these complications are more than rewarded by the fact that resonant oscillation of the free-electron plasma results in strongly enhanced local fields — the desired optical hotspots — that are again determined by the metal and its geometry, and by the light's frequency. Essentially, this is an advantage, as it allows lots of creativity in designing plasmonic antennas.

With steady advances in fabrication techniques, a host of different plasmonic nanostructures has been crafted: particles, holes, wires, shells, gaps, dimers, bow-ties, arrays, to name just a few. Local optical hotspots are indeed found in most of them, mainly at edges and in gaps. The quest for active control of these hotspots has started. For example, attempts have been made to tweak the polarization of the incident light and thus switch the position of the hotspots[5]. In a recent landmark experiment, a tiny spot of light was produced at a predefined position using a technique known as adaptive pulse control[6], in direct analogy to the coherent control of molecular dynamics.

Chains of nanoparticles are, like multi-element radio antennas, particularly flexible structures[7] (Fig. 1a). In these chains, both plasmon coupling and interference can be engineered to optimize photon energy transport and localization. Already, light has been guided along nanowires of silver particles much thinner than its wavelength[8], in contravention of the diffraction limit, and its coupling to localized plasma resonances has been used to measure nanometre-scale distances[9]. Recently it has been predicted that, when a nanoparticle chain is illuminated from one direction, the plasmon interferences can sweep up the electric field from the first to the last particle along the chain, leading to a huge enhancement in the field at the chain's far extremity[10].

This is the effect now exploited by de Waele and colleagues[1]. In their experiment, a chain of ten silver particles, 110 nm in lateral diameter and 50 nm tall, is embedded in a homogeneous glass–oil environment and illuminated from one end (Fig. 1b). Light scattered by the chain

is viewed by a powerful confocal microscope. Remarkably, as the colour of the incident light is changed from green to red (increasing its wavelength), the area of the chain where the light is confined, as shown by the maximum amount of scattered light, flips from the front end to the back end, in a sharp transition at around 675 nm (Fig. 1c).

This extreme sensitivity of the light confinement to the incident colour points to wavelength-dependent interference effects, possibly enhanced by delayed interactions of the light with more distant parts of the nanoparticle array. Indeed, nice agreement with the measured switching is obtained in a full dynamic calculation that includes such retardation effects. The authors stress that a quasistatic approach — one that takes into account interactions only in a particle's near field — produces no asymmetric light localization.

Efficient funnelling of the light to a localized spot therefore requires proper tailoring of the interferences caused by coupling between several resonant plasmonic particles. Moreover, the fact that the widely used quasistatic approach is invalid is a severe caveat concerning the reliability of many near-field calculations on plasmonic nanostructures. In this context, it should be noted that a scattering image such as that viewed by de Waele et al. is dominated by areas where the plasmon is converted into emitted light, and it would be interesting to compare this image with a map of the plasmon mode in its near field.

As a final point, it is interesting to return to the comparison of the nanoparticle array to the traditional dipole-array (Yagi Uda) antenna (Fig. 1a) used to pick up radio or television signals from a station in a specific direction. The spacing between the elements in such an antenna is optimized for constructive interference to enhance the directional sensitivity and concentrate the response at the final element — in full analogy to de Waele and colleagues' optical array[1]. Yet there is a significant difference: the nanoparticle antenna relies on electron-plasma oscillations that can be tuned and exploited independently. Moreover, the optical antenna is resonant at wavelengths similar to those of the optical transitions of molecules and quantum dots. One can expect that this resonant coupling will soon be exploited to produce ultra-small, wavelength-sensitive directional sensors or emitters based on nanoparticle chains. In this dynamic field, stay tuned for new surprises soon. ■

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GENE TRANSCRIPTION
Extending the message

Patrick Cramer

During transcription, RNA polymerase catalyses the addition of nucleotides to the growing RNA chain. High-resolution structural snapshots indicate that the polymerase first identifies its substrate, and then incorporates it.

Life is chemistry — well, at least it is to the molecular biologist. But chemical details remain unclear even for some of the fundamental cellular processes such as gene transcription. In two papers published on pages 157 and 163 of this issue, however, Vassylyev and colleagues[1,2] provide detailed structural insights into the process of transcription and suggest a two-step mechanism for adding building blocks to a growing RNA chain.

In all living cells, gene transcription is the first step in the decoding of genetic information. During transcription, the enzyme RNA polymerase (RNAP) moves along a DNA template and synthesizes a complementary chain of ribonucleotides — the messenger RNA. Extension of the RNA chain begins with the binding of a nucleoside triphosphate (NTP) substrate to the transcription elongation complex, which consists of RNAP, DNA and RNA. Catalytic addition of the nucleotide to the growing end of the RNA chain then releases a pyrophosphate ion. Finally, translocation of DNA and RNA over the RNAP surface frees the substrate-binding site for the next NTP.

In previous attempts to understand the mechanism of transcription, structural information on the elongation complexes containing eukaryotic RNAPII or bacterial RNAP was obtained[3–7]. These studies showed that DNA enters a cleft-like channel in RNAP. A short hybrid duplex then forms between the DNA template strand and the RNA product above the active site of RNAP at the floor of the cleft. These studies had also indicated possible mechanisms both for the separation of the two DNA strands close to the active site and for RNA–DNA separation at the end of the hybrid.

In some elongation-complex structures, NTP-binding sites were also observed within RNAPII (refs 4–6). The NTP substrate was found to be trapped in the insertion site of RNAP[4,6] — which is apparently occupied during the catalytic extension of the RNA chain — but also in an overlapping position that slightly differed, indicating the existence of a catalytically inactive NTP-bound state[5].
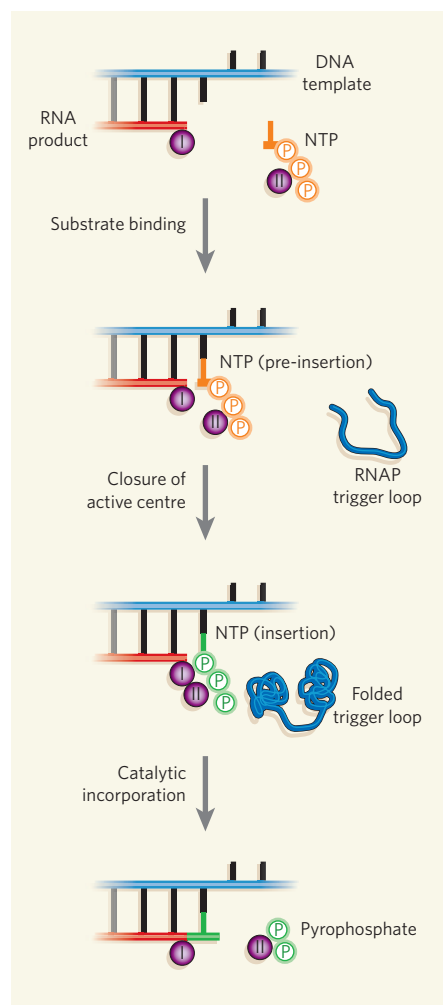

Figure 1 | Two-step mechanism of RNA chain elongation during transcription. Vassylyev et al.[1,2] found that, during transcription from a DNA template, elongation of an RNA sequence involves the binding of a nucleoside triphosphate (NTP) to the RNA polymerase (RNAP) enzyme in an inactive 'pre-insertion' state; this is characterized by partial folding of the RNAP trigger loop. Complete folding of the trigger loop brings the two metal ions, I and II, of RNAP close together, delivering the NTP to the insertion site, where catalysis leads to nucleotide incorporation and the release of pyrophosphate.