PLASMONICS

Finer optical tweezers

The use of nanostructured gold substrates is now allowing optical tweezers to exploit plasmonics and confine nanoparticles to ever smaller dimensions.

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The development of optical trapping techniques to control objects at the nanoscale is an important and challenging endeavour. Optical tweezers with nanometre precision offer a means to study the dynamics of single macromolecules[1], probe subcellular compartments of living cells[2] and construct structures from nanoscale objects[3]. On page 365 of this issue, Alexander Grigorenko and co-workers[4] demonstrate a new implementation of nanoscale optical tweezers that exploits a nanopatterned plasmonic substrate. Their approach shows much promise for creating large-scale arrays of highly precise optical traps for nanoscale objects, with potential applications in areas such as surface-enhanced Raman scattering (SERS).

Part of the challenge in extending the range of conventional optical tweezers to nanometre-sized particles is to create an optical potential that is significantly greater than the thermal energy associated with the particle's brownian motion. In conventional optical tweezers an approximately parabolic potential is generated by optical gradient forces in a strongly focused laser beam. When a microscopic object is brought into the vicinity of the focus, it is drawn into and held in the region of high intensity by the gradient forces, as illustrated in Fig. 1a. When this approach has been used with highly polarizable objects, such as metallic nanoparticles, optical trapping of objects with dimensions as small as 18 nm has been achieved. However, there are practical limitations with this technique. First, optical powers in the range of several hundred milliwatts to watts are required to create a large enough trapping potential to hold a single nanoparticle, and at these levels optical absorption, radiation damage and heating become important. Second, as the trapping volume is large compared with the object dimensions, this allows the nanoparticle to migrate several hundred nanometres within the focused beam.

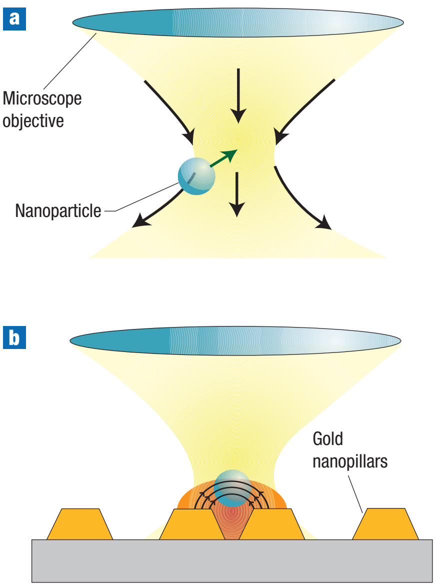

Figure 1 Plasmonic nanotweezers. **a**, When a microscopic object is brought close to a tightly focused laser beam, it will be drawn to the centre of the beam and become trapped by optical gradient forces. The object is not static within the trap, but fluctuates as a result of thermal brownian motion. (Black arrows denote field lines.) **b**, In the presence of the patterned substrate, the trapping beam simultaneously excites localized surface plasmons causing a strong field enhancement. The presence of the plasmon modes creates additional optical gradient forces, which suppress the brownian motion of the trapped object, thus offering better confinement.

Ultimately, the size of the trapping volume of conventional optical tweezers is limited by diffraction, in particular the diameter of the focused light beam performing the trapping. Now Grigorenko and colleagues have implemented a near-field approach to circumvent many of the problems described above. The team use electron-beam lithography to create substrates featuring arrays of electromagnetically coupled gold pillars. These arrays are then used as a substrate in an optical trapping experiment. The trapping beam excites localized surface plasmon modes in the gap between the pillars to generate additional forces that yield subdiffraction-limited trapping volumes (see Fig. 1b). As the plasmon resonance provides an enhanced optical field near the trapping site, this also reduces the input power requirements for creating the trap. From simulations of the coupled nanopillars they found that for substrates fabricated with the smallest pillar gap, the trapping volume was of the order of 100 nm and the local field was enhanced by two orders of magnitude.

Grigorenko and colleagues demonstrate the potential of this new arrangement by studying the dynamics of an optically trapped 200-nm polystyrene sphere brought in close proximity to the coupled nanopillars. The trapping beam excites the coupled nanopillars and, in the presence of localized plasmon modes, they observe a strong suppression of the brownian motion of the particles, with the variation in trapped-particle position reducing by an order of magnitude from 176 nm to 18 nm. This implies that the trap stiffness (and the optical potential) in the presence of the plasmon modes increases by over two orders of magnitude. They verified these results using escape-velocity measurements, which showed a similar level of trapping enhancement. Importantly they showed also that the escape velocity was strongly dependent on the gap between the pillars; this indicated that the enhanced trapping originated from the localized plasmon modes.

This work is the first experimental demonstration of trapping using localized modes and represents a natural extension of previous studies that incorporate near-field trapping[5,6]. The use of localized surface plasmons also circumvents the problem of heating, which was a major limitation in previous plasmon trapping experiments[7,8]. The method developed by Grigorenko *et al.* may be easily extended to multiple trapping sites by simultaneously exciting several locations within the array of coupled pillars. In addition, different arrangements of trapped nano-objects may by achieved by using different substrate patterning geometries.

Although not demonstrated yet, such arrays of coupled nanopillars could act simultaneously as a SERS substrate for label-free *in situ* monitoring of molecular interactions in complex systems, such as at cell membranes or within subcellular compartments. The advantage here is that the nanotrap provides a method for localizing the objects precisely and reproducibly over the regions where the high-intensity field is generated.

Although the experiments by Grigorenko *et al.* show that the presence of localized surface plasmon modes significantly increases the degree of confinement, the results represent a proof of concept rather than a demonstration of the full capability of localized-surface-plasmon traps. An obvious next test for these plasmonic tweezers will be to apply the new technique to probing biological systems. In addition, owing to the experimental conditions (such as the use of immersion oil as a trapping medium) the technique was demonstrated with optical powers much larger than would normally be used for optical trapping experiments.

References

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SOLITONS

Self-trapping of speckled light beams

A speckle beam of light breaks up into small fragments as it propagates in a standard self-focusing nonlinear material. Now, by exploiting the non-local thermal response of a material, it is possible to trap a speckle beam in a self-induced waveguide.

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A collimated coherent beam of light diffracts and spreads out as it propagates. In a nonlinear medium, however, the index of refraction may increase with the intensity of the beam, which leads to the phenomenon of self-trapping: as the index of refraction is greater at the centre of the beam than at its wings, the beam creates an effective waveguide lens for itself. The beam then propagates without spreading in this self-formed waveguide. This so-called spatial optical soliton results from a balance of two opposing tendencies, the tendency of the beam to expand due to diffraction, and the tendency for the beam to contract due to the self-focusing nonlinear effect.

Optical solitons have been studied for a number of years with coherent laser-light beams. It is a natural and important question to ask whether the light emitted by an incoherent source, such as the Sun or an incandescent light-bulb, can also self-trap in a nonlinear medium. The discovery of spatial incoherent optical solitons in 1996 by Mordechai Segev's group, working at Princeton University, was a major breakthrough in nonlinear science[1,2]. Most experiments on incoherent solitons were realized in biased photorefractive materials and their remarkable simplicity enabled a fruitful investigation of partially coherent nonlinear optical fields[3].

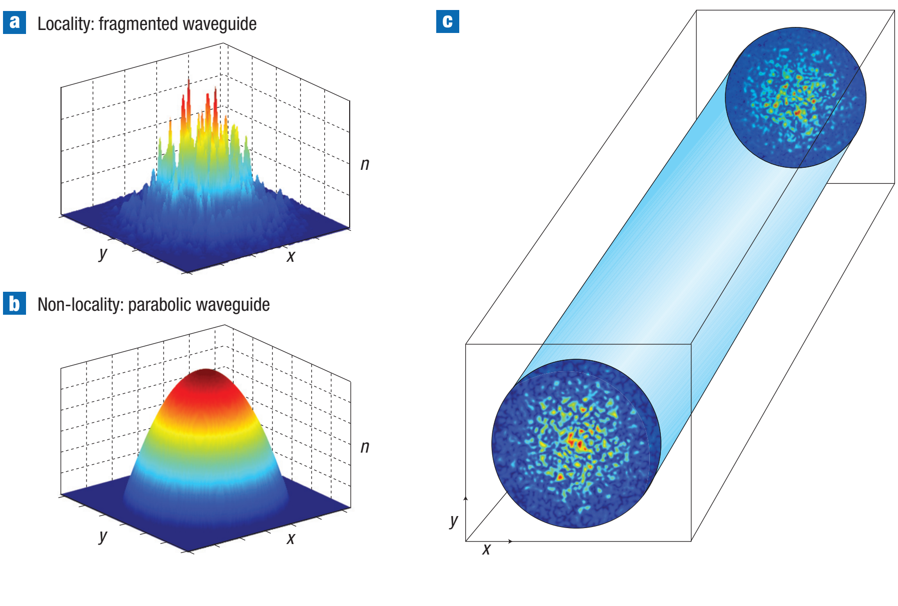

Figure 1 Self-trapping of a speckle beam in a non-local nonlinear material. **a**, The fragmented nonlinear index (*n*) change induced by the speckle beam in a self-focusing material leads to the break-up of the beam as it propagates. **b**, Such fragmented variations of the refractive index are smoothed out by a non-local material response: the speckle beam induces a parabolic-shaped index change in the material. **c**, The parabolic index change acts as a guide for the speckle beam, which is thus self-trapped by its own-induced waveguide.

The spatial self-trapping of an incoherent beam is possible because of the very slow response time of the photorefractive nonlinearity, τ. The rapid fluctuations of the incoherent field are averaged-out by this slow response time, which is much longer than the time correlation, t_c, of the incoherent beam, that is, $t_c \ll \tau$. In other words, the medium responds to the time-averaged intensity and not to the instantaneous