

## OPTOELECTRONIC TWEEZERS

## Organizing nanowires

An optoelectronic method for sorting nanowires of different compositions and assembling them into reconfigurable arrays could be important for creating future nanodevices.

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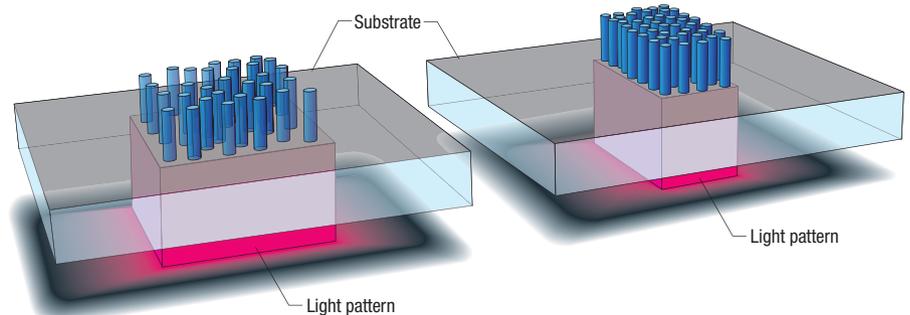
Imagine if nanowires could be sorted, organized and assembled into arrays of controllable size and density using a pattern of light. Imagine if the same technique could also separate individual nanowires of different compositions and manipulate their position and orientation. On page 85 of this issue, Ming Wu and his colleagues report a method that demonstrates all these capabilities<sup>1</sup>.

Over the past decade, chemists and materials scientists have invented powerful tools for synthesizing nanoscale materials in many diverse structural forms. Metals, semiconductors and other materials can now be fabricated in large quantities with well-controlled shapes on the nanoscale, such as wires, sheets, ribbons, stars, spheres and tubes.

The unique physical properties of these nanomaterials make them attractive for building new types of devices. These include chemical and biological sensors with single-molecule sensitivity, high-frequency mechanical resonators, memory devices or electronics with exceptional levels of performance or unconventional characteristics such as mechanical flexibility, and light sources or other photonic components with nanoscale dimensions.

Moving beyond one-of-a-kind, proof-of-concept demonstrations of such devices will require high-speed, efficient methods for sorting, assembling and integrating these nanomaterials into well-defined architectures. Recent approaches investigated include the use of fluid flows<sup>2,3</sup>, directed growth<sup>4,5</sup>, transfer printing<sup>6,7</sup> and others; none of these, however, provides a complete and satisfactory solution.

The approach demonstrated by Wu *et al.* in this issue could help.



**Figure 1** A light pattern defined by a programmable spatial light modulator can be used to position and align nanowires. For example, decreasing the cross-sectional area of the light pattern (as shown on the right) causes the nanowires to be positioned closer together.

It extends their previous work<sup>8</sup> on an unusual kind of technology that they refer to as optoelectronic tweezers (OET), by demonstrating its use in manipulating and sorting nanowires.

The OET method cleverly combines two proven concepts to yield a new approach with impressive capabilities for manipulation. The first builds on the discovery by Arthur Ashkin of Bell Laboratories that focused light can trap and guide the assembly of small objects in solution<sup>9</sup>. Ashkin's so-called optical tweezers have proven to be remarkably useful for many applications, and are now in widespread use in laboratories around the world. The most advanced systems offer many independently controlled tweezers to create artificial assemblies of cells, colloids and other objects in full three-dimensional space<sup>10</sup>. The main disadvantage of this approach, however, is that the optically generated forces are weak. Increasing the light intensity helps, but practical limits due to the available laser power or the sample damage threshold are often encountered before sufficiently large forces are achieved.

The OET scheme devised by Wu *et al.* overcomes this problem by replacing Ashkin's light forces with those created by externally applied alternating electric

fields. The underlying effect, known as dielectrophoresis<sup>11</sup> (a phenomenon where a force is produced on a dielectric particle by exposing it to a non-uniform electric field that often varies with time), is used widely for manipulating wires, tubes and colloids.

In its usual form, dielectrophoresis requires pre-patterned metal electrodes to establish the required electric fields. This requirement is a significant limitation because it does not allow dynamic user control over the force fields, as with optical tweezers. Wu *et al.* avoid this problem by using 'virtual' electrodes formed in a layer of a photoconductor illuminated through a programmable, spatial light modulator. In this way, OET achieves both dynamic optical addressability and large forces at low light intensities.

Although initial reports of OET were confined to manipulating particles with sizes on the microscale, Wu *et al.* have now investigated what happens if the technique is applied to particles that are two orders of magnitude smaller in size. First, they show that although the dielectrophoresis forces decrease rapidly with object size, these forces can still be considerable as long as at least one dimension of the object is large, that is microscale, such as the length of a wire.

In such cases, torques are also created, enabling OET to both position and align nanostructures (Fig. 1). Furthermore, the forces depend on the properties of the material and can thus be exploited to sort objects by material class.

The ability of OET to exploit these features simultaneously for sorting and assembly represents an important result in the field of optical manipulation. To demonstrate the potential of the technique, Wu and colleagues show that by performing OET in a photocurable liquid, arrangements of sorted wires can be 'locked' into place by flood exposure to UV light after assembly.

The results of Wu *et al.* are valuable for at least three reasons. First, they appear to provide new tools with which researchers can manipulate

wires and other nanomaterials. Second, these types of ideas for assembly and integration are critically important for turning nanoscience into practical nanotechnologies. Lastly, their work provides many interesting opportunities for further development. For example, by simultaneously creating and controlling a million or more tweezers, large-scale arrays of semiconducting wires can possibly be assembled to form active channels of transistors for display circuits.

Many important questions remain to be investigated. Is it possible to extend the current two-dimensional capabilities of OET to three dimensions? Can similar approaches be used for manipulating molecular-scale objects such as DNA or single-walled carbon nanotubes?

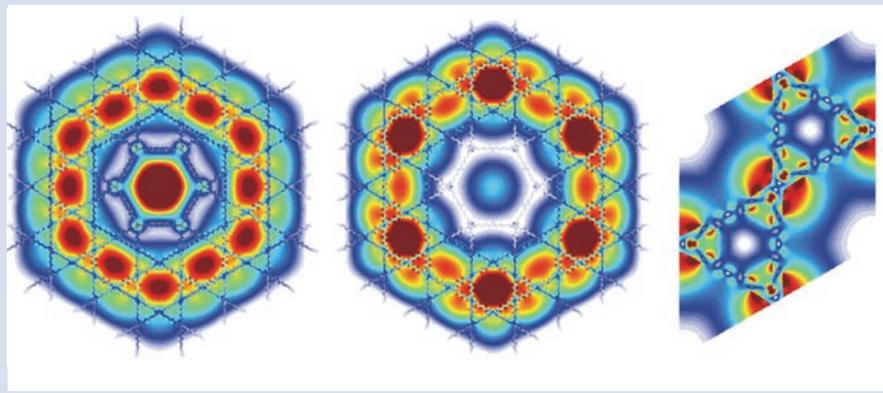
These and many other lines of inquiry might lead to fruitful directions for new research, with important scientific and technological implications.

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OPTICAL FREQUENCY GENERATION

A route to new combs



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The creation of broad, coherent optical combs is important for attosecond science and the study of ultrafast physical processes. Now researchers in the UK, Denmark and the USA describe the design and fabrication of a type of photonic-crystal fibre that can be used to generate optical-frequency combs spanning several octaves, with much less power than previous techniques (*Science* **318**, 1118–1121; 2007).

François Couny *et al.* studied the detailed properties of a hollow-core photonic-crystal fibre (HC-PCF) that is filled with molecular hydrogen. Hollow-core PCFs can bring together gases and light into tiny modal areas (on the order of square micrometres) and keep them confined over long length scales (up to several metres). The increased confinement distances maximize the level of interaction with

incoming light and provide access to nonlinear responses in gaseous materials at unprecedentedly low light powers. So far, however, the bandwidth of the generated spectra has been limited to about 70 THz, which is much smaller than the 1,000-THz bandwidth needed to generate attosecond pulses that range from the infrared to the UV.

The team uses an infrared pump laser of wavelength 1,064 nm to generate higher-order stimulated-Raman-scattering spectra in the hydrogen-filled fibre. Their fibre is made from silica glass struts that are 290 nm thick, with a pitch of about 12 µm. This structure provides wide high-transmission bands, which maximizes the bandwidth for frequency generation, and reduces the dispersion.

The paper describes frequency combs that are 1,000 THz wide, being

successfully generated and guided along the fibre. This bandwidth corresponds to a three-octave spectral comb with wavelengths ranging from 325 nm in the UV to 2,300 nm in the infrared. Compared with previous techniques, pumping is done with a longer wavelength and peak powers that are six orders of magnitude lower (around 10 kW), making the approach more practical.

The confinement of light in the HC-PCF relies on a new mechanism in which light is guided not by a photonic bandgap, but by the fact that there is inhibited coupling between the core and cladding modes of the fibre. The fibre-guided core modes and the cladding modes interact only weakly, as a result of the strong mismatch in the transverse field of the two modes. This very weak mode overlap has been observed before but was not fully understood until now. Because very little field penetrates into the cladding, the core mode undergoes little propagation loss (about 0.5 dB m<sup>-1</sup>).

By using the HC-PCF in other Raman excitation regimes, the authors say they will be able to improve the conversion efficiency and further reduce the pumping powers needed, while providing better control over the phases of the various spectral components. These findings should open up a new route for the design of next-generation, broadband HC-PCFs.

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