We report the first demonstration that carbon nanotubes can be trapped and manipulated by optical tweezers. This observation is surprising because individual nanotubes are substantially smaller than the wavelength of light, and thus should not be amenable to optical trapping. Even so, nanotube bundles, and perhaps even individual nanotubes, can be transported at high speeds, deposited onto substrates, untangled, and selectively ablated, all with visible light. The use of holographic optical tweezers, capable of creating hundreds of independent traps simultaneously, suggests opportunities for highly parallel nanotube processing with light.

Prized for their mechanical, chemical, electrical and optical properties, carbon nanotubes are archetypal nanotechnological building blocks. Fully realizing their promise for device and materials applications requires methods for sorting nanotubes by structure and function, for arranging them into useful and interesting configurations, and for chemically processing them once they are in place. This need is particularly pressing if nanotubes are to be integrated into heterostructures whose other components are incompatible with available lithographic techniques. A variety of alternative approaches already have been demonstrated, ranging from single-tube manipulation with atomic force microscopes and self-assembly guided by molecular-scale interactions to bulk processing through mixing and extrusion. A few of these, such as flow-field alignment, address the need to process large numbers of nanotubes over relatively large areas with sub-micrometer resolution. None, however, take advantage of opportunities offered by optical manipulation, primarily because carbon nanotubes are so much smaller than the wavelength of light that optical trapping should not be feasible. Here we demonstrate trapping, deposition, and photochemical transformation of single-wall carbon nanotubes (SWNTs) using dynamic holographic optical tweezers (HOTs).

Our samples consist of commercial SWNTs (Sigma-Aldrich 519308) dispersed in water by sonication with 0.5% sodium dodecyl sulfate (SDS) for 30 minutes, with typical lengths ranging from 100 nm to 200 nm. Although the tubes’ characteristic 1.3 nm diameters are two orders of magnitude smaller than the wavelength of visible light, bundles of tubes still can be detected through conventional dark-field optical microscopy. Drops of the SWNT dispersion were placed on #1 glass coverslips and mounted on the stage of a Nikon TE-2000 microscope integrated into an Arryx BioRyx 200 holographic optical trapping system. Images were created with a Hamamatsu C7190-23 electron bombardment charge-coupled device (CCD) camera.

Like conventional optical tweezers, HOTs use forces exerted by a strongly focused beam of laser light to trap mesoscopic objects. Rather than forming a single trap, however, HOTs use computer-designed holograms to create arbitrary three-dimensional configurations of traps from a single input beam. Updating the hologram in real time updates the configuration, allowing each trap to move independently in three dimensions.

Figure 1(a) shows a typical snapshot of freely diffusing nanotubes, the smallest visible features corresponding to single nanotubes. Powering a single 30 mW optical tweezer at a wavelength of 532 nm gathers all the nanotubes in the vicinity to the focus, as in Fig. 1(b). Our observations suggest that even a single nanotube can be trapped, although trapping is more robust once large numbers have fallen into the potential well. To the best of our knowledge, this is the first report of optical trapping of carbon nanotubes. Projecting a closely-spaced sequence of traps translates the gathered bundles through the water, as shown in the time-lapse image in Fig. 1(c).

Turning off the laser trap at this point frees the particles to diffuse back to their initial random state.

Gathering and moving nanotube bundles is a useful step toward fabricating structures. Pressing the trapped bundles onto a substrate such as a glass surface and briefly increasing the applied laser power to 50 mW (Fig. 1(d)) irreversibly deposits the trapped tubes, as shown in Fig. 1(e). This process can be repeated to create permanent large-scale structures such as the letter “C” in Fig. 1(f). This image was created in bright-field illumination.

In addition to manipulating free-floating nanotubes, optical tweezers also can prise apart stationary nanotube bundles. The sequence of images in Fig. 1(g), (h) and (i) shows a nanotube rope being pulled free from a large bundle with a single optical tweezer. Unlike the other samples, this bundle consisted of multi-walled nanotubes (MWNTs) (Sigma-Aldrich 406074) dispersed in a 0.5% SDS solution without sonication to avoid breaking up the fibers. The extracted rope can be transported, bent, straightened, and rotated freely in three dimensions using...
FIG. 1: Images of carbon nanotubes processed with holographic optical tweezers. (a-c) A dispersion of SWNTs is gathered into an optical trap and translated through water at up to 100 \( \mu \text{m/sec} \). Arrows in (c) indicate the direction of motion. A burst of intense illumination that saturates the CCD camera (d) deposits the nanotubes onto a substrate (e). (f) Repeating this process forms extended structures. (g-i) A single optical tweezer can extract a rope of nanotubes from a bundle. The arrows in (h) and (i) indicate the tweezer’s position. (j) and (k) show bundles of SWNTs trapped and spun by an optical vortex with helical pitch \( \ell = 10 \). (l) Shows four geometric shapes simultaneously cut into bucky paper with four holographic optical tweezers. The square in this figure is 2.9 \( \mu \text{m} \) across and serves as a scale bar for the images.

multiple optical tweezers.

Reshaping the trapping light’s wavefronts makes possible more sophisticated transformations than can be accomplished with conventional optical tweezers [4]. For example, molding the laser’s planar wavefronts into \( \ell \)-fold interlocking helices transforms the optical traps into ring-like optical vortices capable of exerting torques as well as forces [8, 9, 10]. Figure (j) shows a snapshot of several nanotube bundles trapped on the periphery of an \( \ell = 10 \) optical vortex. The nanotubes both absorb and scatter radiation from the beam, thereby absorbing some of its orbital angular momentum. The resulting torque causes the bundles to travel around the ring’s circumference, as can be seen in the time-averaged image in Fig. (k).

This demonstration of nanotube spinning by photon orbital angular momentum complements a recent proposal that photons’ spin angular momentum could be used to twirl nanotubes through Umklapp processes [11]. By contrast, trapping and spinning in optical vortices results from first-order scattering and absorption, and does not necessarily disturb the nanotubes’ electronic state. This further suggests that nanotubes are trapped through conventional optical gradient forces, rather than a more exotic mechanism.

While avoiding nonlinear optical processes can be beneficial, photochemically induced transformations also are useful for processing nanotube structures, as demonstrated by the image in Fig. (l). Here, a uniform mat of SWNTs, also known as bucky paper, roughly 2 \( \mu \text{m} \) thick was deposited on a glass coverslip and then dried. The dried mat was illuminated with four optical tweezers, each powered by 10 mW of laser light, which suffices to ablate the nanotubes in air, but not to ignite them. In this case, the holographically projected points of light act as optical scalpels [12, 13] rather than traps. Scanning the optical scalpels across the sample created the pattern of geometric shapes in just over two seconds. Precise laser sculpting of aligned nanotube arrays has been demonstrated using single optical tweezers [14, 15]. The ability to create multiple holographic scalpels offers opportunities for highly parallel processing. Consequently, this approach is complementary to dielectrophoretic deposition [16, 17], which requires a fluid medium, and offers additional possibilities for post-processing through gas-phase photochemistry.

While the present communication has focused on manipulation and ablation of carbon nanotubes, optical processing may hold even further promise. For instance, insulating, semiconducting, and metallic SWNTs differ in their optical scattering characteristics, and so might be amenable to sorting through optical fractionation [18, 19] in large arrays of optical traps.

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