METAMATERIALS

Towards the dark side

How black is black? An ideally black material would absorb light perfectly at all angles for all wavelengths. Using arrays of carbon nanotubes, researchers based in New York have now engineered a metamaterial that constitutes the darkest material ever made.

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A perfect absorber would be able to capture all the light that hits its surface, and no light would be reflected. In the search for this ideal blackbody, Zu-Po Yang and colleagues[1] have manufactured a carbon-based metamaterial that can absorb up to 99.955% of incoming visible light, reflecting 200 times less light than glassy carbon. As the reflectance is three times lower than the previous record-holding material, the authors have applied to be entered into the Guinness World Records.

Their new carbon-based material is made of a very low-density array of vertically aligned carbon nanotubes that are prepared by water-assisted chemical vapour deposition. Carbon nanotubes are formed from one-atom-thick sheets of graphite that are rolled up into cylinders, akin to cylindrical spring onions made of graphite layers. The team, from Rensselaer Polytechnic Institute in New York, uses extremely thin, long nanotubes that are about 8–10 nm in diameter and 300 μm long. The average spacing between different tubes is around 50 nm, so that the nanotube volume-filling fraction — that is, the fraction of the material's total volume occupied by the nanotubes — is only 3% (the other 97% of the structure is occupied by air). As can be seen in the scanning electron micrograph image of the sample (Fig. 1), the material structure resembles a forest of long, narrow nanotubes.

Reporting in *Nano Letters*[1], Yang and colleagues measure a total reflectance value (integrated over all angles of reflected light) of just 0.045% for normally incident radiation with a wavelength of 633 nm. As the wavelength of the light is reduced, the reflectance increases slightly, reaching 0.07% for a wavelength of 457 nm. They also find that these very low reflectance values are maintained when the angle of incidence is increased up to 60°. These statistics make this carbon derivative the darkest man-made material ever and, probably, darker than any naturally occurring material on Earth (see Fig. 2).

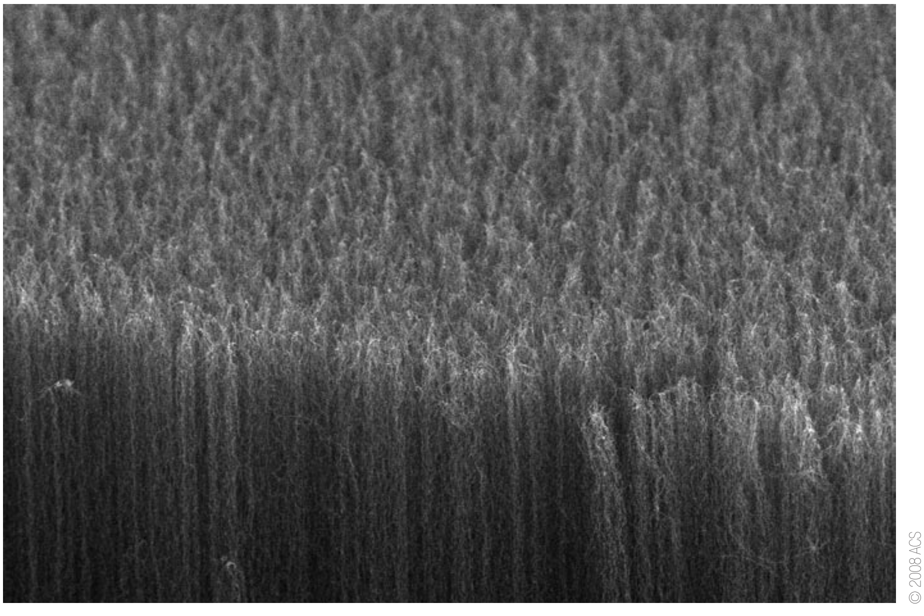

Figure 1 Needles in a haystack. A side-view scanning electron micrograph of a sample of vertically aligned carbon nanotubes. Reprinted with permission from ref. 1.

But why is this material so black? It seems counterintuitive to create a material that is blacker than graphite by reducing the amount of carbon in the structure. The solution, which is presented in the paper by Yang and colleagues, is based on a theory published ten years ago[2]. As the average distance between the nanotubes is much smaller than the wavelength of the light, the structure behaves as a metamaterial in which the effective dielectric function, ε, depends only on the material's constituents (graphite and air in this case) and the volume-filling fraction. Moreover, in the very low-density limit, this effective ε is simply a weighted average of the dielectric functions of graphite and air. The refractive index of graphite at visible frequencies is about two, and as the volume fraction of graphite is only 3%, the effective refractive index of the structure should be close to one. Indeed, calculations show that its average value is around 1.03. This reduction in the refractive index compared with ordinary graphite is important because it strongly suppresses the reflectance of the system.

But there is a price to pay. The effective absorption length (the length that a photon travels before being absorbed by the structure) in the sparse array of carbon nanotubes is much longer than the absorption length of pure graphite. This is why the nanotubes need to be so long: the length is needed to absorb the light. They have to be much

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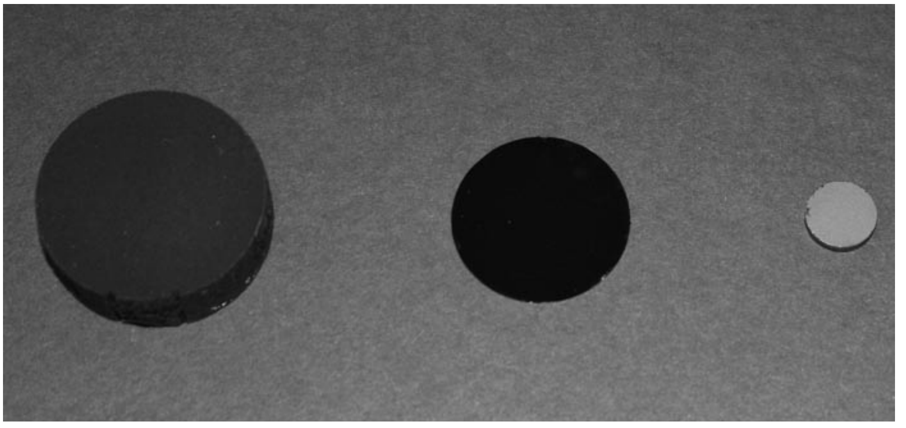

Figure 2 Under the spotlight. A photograph taken of three different materials under illumination: a National Institute of Standards and Technology (NIST) reflectance standard giving 1.4% total reflectance (left), a carbon nanotube sample (centre) and a piece of glassy carbon (right).

longer than 10 μm, which is the effective absorption length for a material with a 3% volume fraction. In simple terms, by nanostructuring a graphite film with nanotubes a light 'trap' can be created. By reducing the amount of carbon, the reflectance is decreased and much more light — up to 200 times more — can enter the structure. The trick is to absorb the light in the bulk of the structure and not within the uppermost layers, as happens in natural graphite, and provides another beautiful example of how structuring a material at scales much shorter than the wavelength of light enables its optical properties to be tuned at will. This general rule also operates at the atomic scale: diamond and graphite are made of carbon atoms but their distinct atomic arrangements lead to completely different optical responses.

In an era where the threat of global warming looms, and in which scientists are eagerly searching for alternative sources of clean energy, it is clear that a nearly perfect light absorber could be used for solar energy conversion, and in any application that relies on the harvesting of light. However, some caveats exist, namely that in these structures electromagnetic energy is primarily converted into heat.

Apart from the visible range, enhanced absorption of light over a broadband frequency could also have practical relevance. Some encouraging results along this line have been published very recently[3]. It would also be interesting to check the ability of very low-density arrays of carbon nanotubes to absorb electromagnetic waves at other frequency ranges. Carbon nanotubes offer some practical advantages as they are mechanically robust to temperature and oxidation, not to mention the fact that they can be handled relatively easily.

From a more fundamental point of view, there is ample room for improving the reflection properties demonstrated here. Even darker metamaterials could be created by further reducing the volume-filling fraction occupied by the carbon nanotubes. In that case, carbon nanotubes with lengths of the order of millimetres would be needed to accommodate the longer absorption length of light in such a medium. There does not seem to be a fundamental limitation to this approach, and I am curious to see how close to the 100% light-absorption limit arrays of carbon nanotubes can lead us in the near future.

References

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VIEW FROM…ASSP 2008

Ceramic future

Ceramic lasers look poised to make an impact in photonics thanks to the tantalizing possibilities of high output power, ultrashort-pulse generation and cost-effective production.

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Ceramic laser technology is rapidly maturing and will become increasingly important in photonics in the future. This was clearly the message that emerged from the 23rd Topical Meeting on Advanced Solid-State Photonics, which was held from 27 to 30 March 2008, and for the first time, in Japan. The annual event is undoubtedly still the world's premier forum for discussing new developments in solid-state lasers and nonlinear optical materials. The 2008 event in the city of Nara attracted more than 300 attendees from all over the globe and featured 13 invited speakers, 45 contributed oral presentations and 120 poster presentations.

Along with the progress reported in the areas of solid-state laser design, ultrafast oscillators and amplifiers, fibre lasers, nonlinear optics and diffractive optical elements, a special session — the Ceramic Lasers Summit — was added this year to highlight the strategic advances in ceramic laser materials.

Although yttrium aluminium garnet (YAG) is well known as a laser crystal, especially when doped with neodymium ions (Nd^{3+}) to create the ubiquitous Nd:YAG