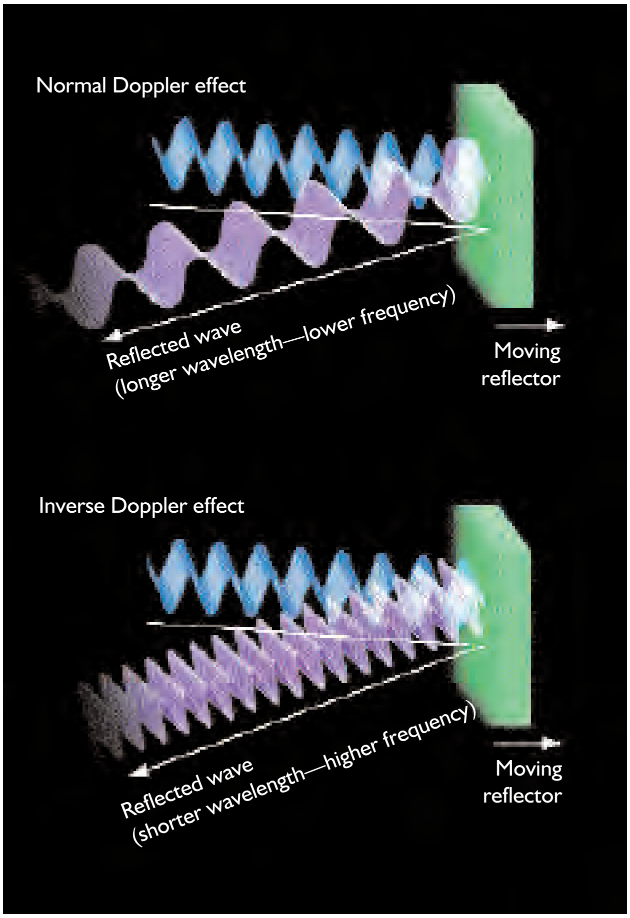
Inverse Doppler effect

The Doppler effect, as any physics student knows, causes light from a receding object to shift to the red and light from an approaching object to shift to the blue. But astrophysicists have known for more than 40 years that in strongly magnetized plasmas, the interaction of electromagnetic waves with the plasma magnetic field can create strange effects. In a narrow range of frequencies above the gyro-frequency (the frequency at which electrons circle around magnetic field lines), the Doppler effect may reverse and cause approaching objects to be red-shifted rather than blue-shifted.

Manipulating the Doppler effect over a broader range of frequencies would be useful, as it could provide a way of tuning the frequency of radiation, such as terahertz waves, that cannot be easily tuned otherwise. At BAE Systems' Advanced Technology Centre in Bristol, England, Nigel Seddon and Trevor Bearpark have developed a way to generate the inverse Doppler effect without using plasmas (*Science* **2003**, *302*, 1537). They use a transmission line, and the nonlinear magnetic effect is produced by soft ferrites in inductors instead of the magnetic field of a plasma.



BAE Systems, Bristol, England

Normally, a wave reflected from a receding object shifts to a lower frequency, but when an electrical pump pulse is injected into a segmented transmission line, the reflected wave moves to a higher frequency.

The 55-cm-long transmission line consists of 118 sections. Each section is linked to an inductor and capacitor, and each odd-numbered section is linked to the next odd-numbered section through a second capacitor, as are each of the even-numbered sections. The arrangement of capacitors and inductors creates the dispersion needed for the anomalous Doppler effect, which allows the transmission line to have a negative refractive index.

In their experiments, the researchers injected an electrical pump pulse into the transmission line. As the pulse traveled down the line, it put energy into the inductors, saturated the ferrite magnetic materials, and produced a traveling shock discontinuity between the saturated and unsaturated inductors. The pump pulse also produced a wave, which the team varied between 1.2 and 1.4 GHz, that traveled in the same direction as the shock and reflected back from the receding discontinuity. The team then measured the radio-frequency spectrum that was reflected back from the moving discontinuity.

As the researchers predicted by numerical simulations, they observed a primary signal at the same frequency as that originally generated, and a Doppler-shifted signal displaced toward the blue (shorter wavelengths). This signal from the receding reflection boundary was shifted 20% higher in frequency. Surprisingly, the amount of the Doppler shift was significantly more than would have occurred in a conventional Doppler shift at the velocity that the shock boundary was receding—1/15 the speed of light.

In a plasma Doppler shift, only a narrow range of frequencies exhibit the anomalous change, but in the transmission line, the inverse Doppler effect occurs across a much broader frequency range. "The upper limit on the transmission frequency is just set by the dispersion characteristics of the transmission line," says Seddon, "so the effect operates at any frequency under that limit." Seddon and Bearpark have calculated that Doppler blueshifts of more than double the original frequency could be achieved with suitable transmission-line designs, and they could be extended at least to the 100-GHz region and possibly to 1 THz.

DNA-guided nanotubes

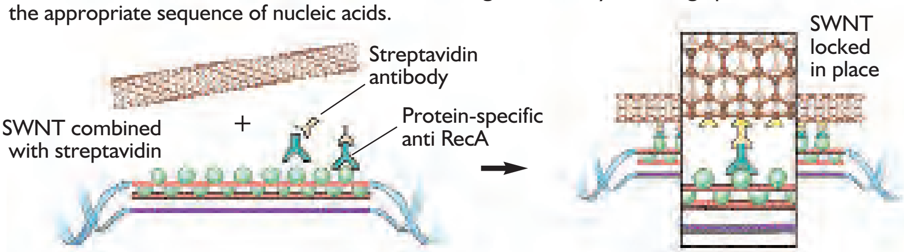
One key to using nanotubes as the next generation of electronic components is to organize them into patterns more precise than those now possible with conventional lithography. Some form of self-assembly presents an attractive possibility. In organisms, DNA and RNA organize molecules, so it seems logical to try to use DNA to organize nanotubes. A team at the Technion-Israel Institute of Technology has done just that, creating single-nanotube transistors by guiding the nanotubes in a solution into place with DNA (*Science* **2003**, *302*, 1380). However, many steps lie between this initial proof of principle and working circuits.

The Israeli process acts to position the nanotubes on a specific section of a long DNA scaffolding molecule. This double-stranded molecule (dsDNA) was placed on a substrate, and a short, single-stranded DNA molecule (ssDNA) with a sequence identical to part of the long DNA is used as a locator. The first step in the process combines RecA protein molecules from *E. coli*

DNA SELF-ASSEMBLES NANOTUBE TRANSISTORS

Protein molecules are combined with single-stranded DNA to form a nucleoprotein filament.

Filament binds to a double-stranded DNA scaffolding molecule by matching up with the appropriate sequence of nucleic acids.



Protein-specific antibodies bind to the protein and act as markers, and streptavidin antibodies bind to the primary antibodies. A semiconducting single-walled nanotube (SWNT) combined with streptavidin in solution binds to the antibodies on the DNA scaffold, locking the SWNT into its designated post.

DNA scaffold is moved to a silica substrate, where a silver layer binds to the ends of the SWNT not covered with the protein. Gold covers the silver nucleus to create contact wires and complete the transistor—a semiconducting SWNT forming a gate over the silica substrate, connected to two electrodes.

Department of Physics, Technion-Israel Institute of Technology/Tom Moore

bacteria with the ssDNA molecules to form a nucleoprotein filament that preserves the same protein sequence as the ssDNA.

The resulting protein molecule binds to the dsDNA scaffolding at the designated spot by matching up with the appropriate sequence of nucleic acids. Then protein-specific antibodies added to the solution bind to the protein and act as little markers. Next, secondary antibodies, specific to a molecule called streptavidin, bind to the primary antibodies. A semiconducting single-walled nanotube (SWNT) is combined with streptavidin. When the streptavidin–SWNT combination is placed in solution near the DNA scaffolding, it swiftly binds to the antibodies, locking the SWNT into its designated post.

After the DNA scaffolding is moved to a silica substrate, a silver layer is applied to form the electrodes. The RecA protein prevents the metal from binding to the SWNT, but the silver does bind to the exposed ends of the nanotube that stick out beyond the RecA. The silver then acts as nucleation centers for the formation of gold wires contacting the nanotubes. The final result is a tiny transistor, with the semiconducting SWNT forming a gate over the silica substrate, connected to the two electrodes.

Although the Israeli results demonstrate in principle the use of DNA to build nanotube circuit elements, many technical challenges remain. The research team found that many individual transistors did not work because metallic SWNTs were mixed in with semiconducting SWNTs, a problem common to many potential nanotube applications (see *The Industrial Physicist*, February/ March 2004, pp. 24–27).

"We are working on separating the metallic SWNTs from the semiconducting ones, but there are difficult problems that will take time to solve," says Erez Braun, a leader of the Technion group. In addition, the current technique creates wires that dwarf the nanotubes, preventing the creation of ultrasmall devices, and so the approach needs improved metallization schemes.

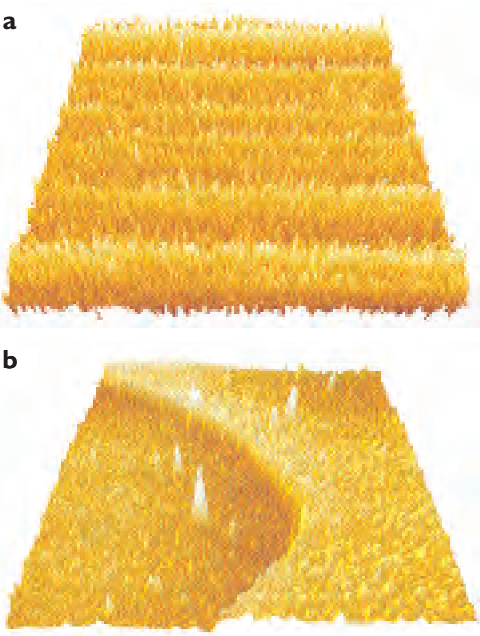
Beyond working on these tough problems, the researchers are looking to develop three-contact transistors, which are essential for building microcircuits. For this, they hope to use a three-armed DNA junction. But it remains an open question as to whether the DNA route can advance quickly enough to compete with other nanotube fabrication techniques (see *The Industrial Physicist*, December 2000, pp. 17–18 and 26–29).

Magnetic graphite

In 2000, a team of researchers at Leipzig University in Germany discovered the first hints of ferromagnetism in an organic material called highly oriented pyrolytic graphite (HOPG), a form of graphite that has a high degree of alignment between layers of carbon atoms. Organic ferromagnetism would have important implications for magnetic recording technology, biophysics, and astrophysics, but many scientists greeted the discovery with skepticism because the atomic structure of carbon did not seem to lend itself to ferromagnetism. Now, the same team has demonstrated the generation of organic ferromagnetism by bombarding HOPG samples with beams of protons to create ferromagnetism with about 1% of the gram-for-gram strength of magnetite (*Phys. Rev. Lett.* **2003**, *91*, 2227210-1).

a

b



Organic ferromagnetism is observed in highly oriented pyloric graphite that has been bombarded with beams of protons, as shown in these magnetic force microscopy (a) and topographic (b) images of a 20 × 20 μm sample.

Superconductivity and Magnetism Division, Institut fuer Experimentelle Physik II, Fakultaet fuer Physik und Geowissenschaften, Leipzig, Germany

The Leipzig group, led by Pablo Esquinazi, had focused on the possible role of hydrogen impurities in ferromagnetism based on earlier reports that the more hydrogen an organic compound contained, the more the magnetization. Theoretical work indicated that the mixture of bonds between hydrogen and carbon atoms could produce the sort of asymmetries needed for ferromagnetism. To create a high level of hydrogen impurities in HOPG, they irradiated a millimeter-sized sample using a proton beam with a particle energy of 2.25 MeV. The researchers implanted 1 hydrogen atom for about every 10,000 carbon atoms. They then tested for ferromagnetism by measuring the magnetic moment of the sample as they cycled an imposed 1-T magnetic field.

The team observed induced fields of about 10^{-2} T and an estimated magnetization of 1.1 emu/g, about 1% that of magnetite, the standard iron-based magnetic compound. The role of iron impurities (which were measured at every irradiation step) was ruled out, as these would only create magnetization about 0.01% as strong as that observed.

One possible application of the new discovery is to create ultrasmall magnetic storage devices by irradiating protons into carbon nanotubes, which researchers have explored as the basis for a new generation of electronics. “If magnetism can be induced not only in graphite but in other organic matter, our brain could possibly utilize magnetism for information storage as well,” Esquinazi points out. If human brains do indeed have intrinsic sensitivity to magnetic fields, this could be a mechanism for the reported biological effects of electromagnetic fields and radiation from sources such as cell phones. It could also help explain how the brain interacts with the electromagnetic fields that it generates itself.

Because large amounts of carbon dust exist in the vast reaches of space between galaxies, cosmic-ray bombardment could have created huge amounts of intergalactic magnetized material. Such magnetized dust might, for example, distort or scatter radio and microwave radiation in the universe—effects that could change astronomers’ views of phenomena such as the cosmic background radiation.

Before either technological or theoretical implications are worked out, however, the Leipzig researchers will have to perform systematic studies of the effects of irradiation parameters, carbon structure, and temperature on the magnetization phenomenon. Such studies are now under way.

Butterfly blues

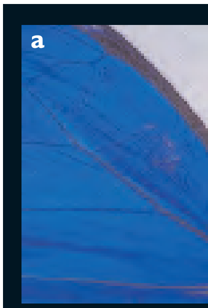
The iridescent colors of some butterflies’ wings and of peacock feathers come not from pigments but from interference effects caused by the organisms’ physical microstructure. The Blue Morpho butterfly in particular has microscopic ridges on its wings arranged in a branching, Christmas-tree-like manner, such that interference effects reinforce blue light in a wide range of viewing directions. The reflectivity in the blue can be as high as 70% and the interference effect produces a pure spectral color.

In contrast to the butterfly wings, whose color can be viewed from any angle, artificial diffraction gratings produce colors that vary according to the viewing angle. Such gratings can produce colorful rainbow effects but not reliable, intense pure colors. A collaboration between researchers at the Applied Research Center, Old Dominion University (Newport News, VA) and Alcoa Corp.’s Packaging Technology Center (Richmond, VA) has now imitated the butterfly wings to produce an artificial grating that is blue over a wide viewing angle. The accomplishment may open up a new technology for color reproduction (*Optics Lett.* **2003**, 28, 2342).

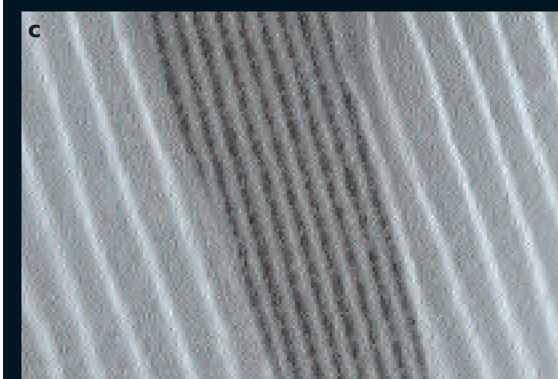
The basic idea of the new grating structure is to form it from many small gratings, each with a different, random orientation. A hexagonal pattern was used for the overall grating structure, and within each hexagon, the grating was aligned in one of six directions. The researchers used an electron beam to fabricate the grooves with a spacing of 440 nm and a depth of 125 nm.

Gratings aligned in the same direction reinforced each other, producing a complex diffraction pattern in monochromatic light. But in white light, the gratings appeared blue at viewing angles ranging from 16° to 90° to the horizontal, and appeared green at angles of less than 16°. This was similar to the performance of the butterfly wing, which appeared blue at viewing angles of more than 30°.

“We are now working to improve diffraction efficiency and develop gratings for other colors,” says Mool C. Gupta, director of the Applied Research Center at Old Dominion. “These are steps to developing applications that substitute gratings for paints, and to use them in display devices.” The team is looking at fabrication techniques similar to those used to manufacture compact discs in hopes of finding economical reproduction techniques. Eventually, using spectral colors instead of those produced by pigments and dyes could greatly increase the intensity and accuracy of color reproductions and reduce the need for waste disposal.



The iridescent color (a) of a Blue Morpho butterfly wing (b) is reinforced by interference effects caused by microscopic ridges (c). An artificial diffraction grating can imitate this effect when composed of many small hexagonal gratings, each inscribed with tiny grooves aligned in one of six directions (d).



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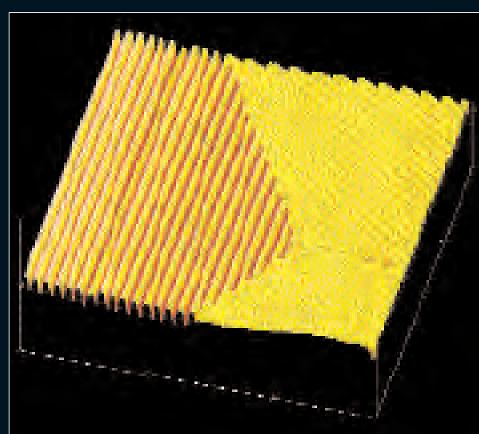

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