fied. New techniques—developed to visualize morphological changes in dendritic spines after long-term potentiation in vitro (*11*)—should provide answers to some of these questions.

Other notable areas that require clarification include the time course and the window of opportunity during which these changes in auditory cortical circuitry take place. Regarding the length of time for which sustained stimulation should be applied, Klinke and colleagues observed substantial changes in hearing capabilities after several weeks (but much shorter periods of stimulation may also prove beneficial). The rapidity of plastic changes under certain circumstances has been demonstrated in various parts of the cerebral cortex, even in adult animals (*12*). Klinke *et al.* and others believe that the most dramatic changes in cortical circuitry are possible if animals are given implants early enough due to the greater plasticity of the brain at a younger age (*4*).

The literature on cochlear implants in humans abounds with examples of failure, particularly for prelingually deaf adults. They never gain language competence and often request that the implant be removed. By contrast, in early-implanted prelingually deaf patients cochlear implants have recently proved quite successful (*13*, *14*). Cochlear implants are highly controversial in the deaf community, their opponents arguing that they violate the physical integrity of individuals who consider themselves different but not disabled (*14*). Visual communication by means of sign language and lip reading are considered good substitutes. This seems to be supported by neuroimaging studies demonstrating a reorganization of language systems in deaf humans capable of comprehending American Sign Language (*15*). Possibilities of compensatory plasticity and sensory substitution (*16*) notwithstanding, the tide is beginning to turn in the deaf community with the advent of a new generation of cochlear implants that combine multichannel technology with intelligent high-speed processors. These new devices permit word recognition rates of 80 to 100% (70% is sufficient to lead a phone conversation) and usually provide immediate success in adults who become deaf late in life. They are in demand by such individuals as well as by hearing parents of deaf children, and the costs of implant surgeries (about U.S.$40,000) are now covered by many U.S. health insurance companies and the British National Health Service.

In the case of early or congenitally deaf individuals, experience has shown that early implantation enhances later success. Even when cochlear implants do not provide a complete electrical code equivalent to that evoked during normal hearing, the brain is clever enough to figure out the rest. The Klinke study shows that the remarkable plasticity of the auditory cortex in young individuals is a major factor in this process, because it permits a representational adaptation to the new electrical code. Animal studies using multichannel devices to stimulate the central auditory system, combined with neuroimaging in humans (*17*), should help to further determine the temporal and spatial constraints of plastic reorganization of the auditory cortex after cochlear implant surgery.

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PERSPECTIVES: APPLIED PHYSICS

Playing Tricks with Light

John Pendry

The notion that altering the structure of a material can profoundly alter its electromagnetic properties has led to concepts such as the photonic insulator, enabling new technologies that offer control over light not previously thought possible. These new materials, often referred to somewhat imprecisely as "photonic materials," have in common the property of strong interaction with light.

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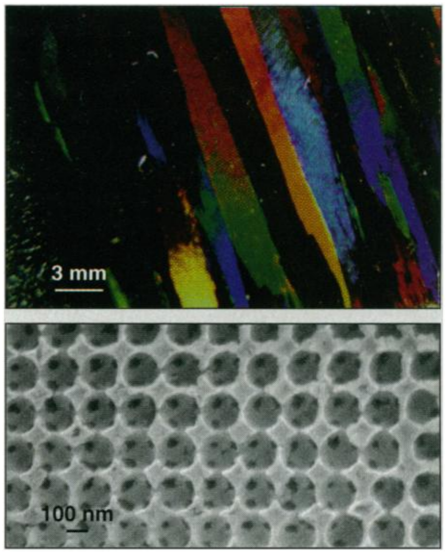
Yablonovitch (*1*) and John (*2*) first pointed out the importance of structure for electromagnetic properties by drawing analogies between light and electrons. Both have a wave-like nature and can therefore be diffracted. We are accustomed to electronic behavior being dictated by the diffraction of electrons from the periodic potential of an atomic lattice. In a normal metal, it is possible to excite the electrons by giving them a small amount of energy to set them in motion, whereas this is forbidden for insulators because of a gap in energy right above the occupied electronic levels. This gap arises from the diffractive interaction of the electron wave function with the atomic lattice, resulting in destructive interference at certain wavelengths.



Strong light diffraction. Assemblies of hollow graphitic spheres show brilliant opalescence. At higher resolution, the regularity of the assembly giving rise to this strong interaction with visible light can be seen (**bottom**). [From (*9*)].

What about light? The interaction of light with a material can be described by the material's refractive index or dielectric constant. Yablonovitch was the first to realize that setting up a periodic refractive index can result in a similar 'band theory' for

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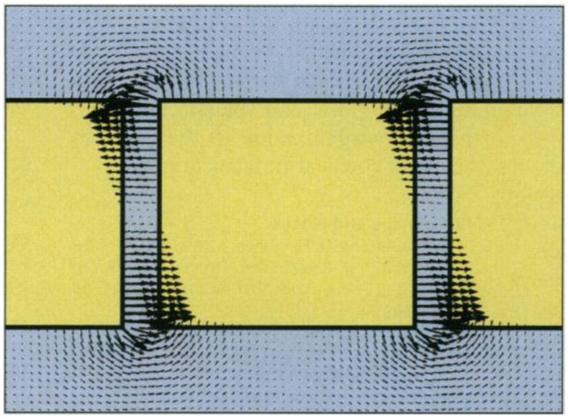
photons where certain frequencies cannot propagate. Such a material would be the photonic equivalent of an insulator. However, visible light has a much longer wavelength than electrons, just under 1000 nanometers as opposed to around 0.1 nanometers, so to see diffractive effects we must make large artificial "atoms" on the same scale as the wavelength. Photonic insulators and materials with a photonic band gap may be the key to controlling and exploiting light. At a time when the electronics industry turns increasingly to optical devices for extra speed and capacity, this may turn out to be extremely important (*3*, *4*).

Since Yablonovitch first demonstrated a photonic band gap material using microwaves (*5*), there have been numerous attempts to realize the technology at visible wavelengths with a variety of approaches: electrochemical etching (*6*), patterned growth (*7*), hole-drilling (*8*), and self-assembly of colloids. The latter process has been made more flexible by the ability to infill the colloidal structure with a second refractory material and then burn away the original colloidal material (see the figure on the previous page) (*9*). Realizing the photonic insulator immediately gives access to new technologies for controlling light. Wrap such an insulator around a conventional dielectric (such as vacuum) and you have a "light pipe" (*10*). Potentially more compact than a conventional optical fiber and not constrained to avoid tight corners, the light pipe is compatible with integrated circuit technology. Lasers produce their light inside resonant cavities whose design dictates the properties of the light emitted. The new technology facilitates formation of such resonant cavities: A hole of any shape in a photonic insulator will do, provided its diameter is on the order of the required wavelength. A photonic insulator could also be used to eliminate selectively undesirable optical transitions in lasers by positioning the gap such that the transitions become forbidden.

In addition to this structural route to photonic materials, the concept of "negative epsilon" can be exploited to make photonic materials. We are all familiar with materials having negative ε: Most metals have this property for visible light and are thus photonic insulators. They achieve light insulation not through structure but through interaction of light with a free electron plasma. This property underlies the opaqueness of metals and their ability to reflect light. The electric field E of an ordinary light wave depends exponentially on the wave vector k. If the dielectric constant ε of the material through which the light travels happens to be negative, the wave vector k becomes purely imaginary and the fields decay exponentially—just as they do inside a structural photonic insulator. So in some ways, the photonic insulator is behaving like a material with a negative dielectric constant. This concept of "negative epsilon" is central to new developments in photonic materials.



Light plays Houdini. Like the famous escape artist, light disappears through a slit it should not fit through and reappears on the other side (*12*). Arrows represent the strength and direction of the electric field when light is transmitted through narrow slits cut in a thin silver film. Note the huge enhancement of fields in the slit. Transmitted light intensity is correspondingly enhanced.

How can this property of metals be exploited for controlling light? It turns out that simply cutting holes into a metal has interesting consequences. Surfaces of negative epsilon materials are decorated with electromagnetic modes different from those in the bulk of the metal. Derived from the longitudinal modes of a plasma, these modes have an extremely high density in the immediate vicinity of the surface. Unlike bulk modes, the surface modes can couple to external transverse radiation. This coupling has been dramatically demonstrated in recent experiments by Ebbesen *et al.* (*11*), who studied transmission of light at a wavelength of 1500 nanometers, through a 200-nanometer-thick silver film into which cylindrical holes with a diameter of 150 nanometers had been cut. In this system, the wavelength of the light is much larger than the diameter of the holes, and one would expect only about 0.1% of the photons hitting the holes to squeeze through. But the experiments measure 100 times this transmitted intensity. Light plays this Houdini-like trick by coupling to surface modes of the metal that are very closely confined to the surface and therefore find it much easier to filter through the tiny holes.

Calculations (*12*) made for a similar system, except that the holes are slits rather than cylinders, clearly show the slits sucking light through the film (see the figure on this page). The very large electric field enhancement is typical of slits and of highly curved surfaces that trap the surface modes as local resonances. This also happens at the point where two metal spheres touch or at any sharp cusp on a surface. The scale of these local structures may be very small, limited only by the validity of the dielectric function of the material. In contrast to diffractive photonic materials, negative epsilon photonic materials may thus have structures defined on the scale of only a few nanometers. The local density of electrical energy may be 10^3 or 10^4 times as great as that in the original incident wave. This enhancement is the basis of the surface-enhanced Raman scattering effect (*13*) whereby Raman signals from molecules at rough silver surfaces may be as much as 10^6 times as great as those at smooth surfaces (*14*).

Such nanofocusing offers the possibility of huge concentrations of radiative energy in very small volumes, impossible to achieve with conventional focusing with lenses. For very modest power input, local concentrations of energy may be great enough to excite nonlinear effects that depend on the intensity. In a linear system, beams of light pass through one another undisturbed, but in the presence of nonlinearity one beam of light can deflect another, switching it from one location to another. This is the missing ingredient in the electron-photon analogy. First, we had the photonic insulator, which enabled us to control where the photons go. Now we have the theoretical possibility of making photons interact with one another, that is to say switching light with light. No wonder people are confused about photonic materials: We keep expanding the definition.

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