small grain size while achieving near full density is the work on $BaTiO_3$ capacitors (*4*, *5*). In this process, particles with diameters of 10 to 30 nm were dispersed in organic solvents of low dielectric constant to avoid particle solubility and to limit interparticle forces. With careful atmosphere control, multistep sintering cycles, and dopants, fully dense $BaTiO_3$ with grain sizes of <100 nm are commercially produced; experimentally, $BaTiO_3$ with <50-nm grain size has been achieved. These techniques are equally applicable to other ceramic systems but have only been demonstrated in $BaTiO_3$ such small dimensions are required to meet the demands for today's commercial, miniaturized electronic components.

An example of sintering pore-free, nanograined ceramics that enables new properties is the demonstration of transparent, polycrystalline Al_2O_3. Because it is optically birefringent, fully dense polycrystalline Al_2O_3 with micrometer-sized grains is translucent, but by refining the grain size to below 100 nm and sintering to over 99.9999% density, the dominant light-scattering mechanism is changed, allowing the material to become transparent (*3*). Despite the successes with $BaTiO_3$ and Al_2O_3, demonstrations of pore-free, nanograined ceramics remain rare; other methods have therefore been developed to aid densification.

For high-reliability ceramics like hip prostheses and optical components, pressure can be an additional driving force for densification. Mechanical hot pressing and hot isostatic pressing (where gas is used as the pressure-transmitting medium) are used commercially to achieve fully dense ceramics. By enabling pressures of 200 MPa or more, hot isostatic pressing has become the standard for commercial applications requiring total pore elimination, but cost and contamination limit its general applicability to a few ceramic systems.

Recently, novel heating methods like microwave and spark plasma sintering processes have gained much attention for sintering ceramics. Compared to conventional sintering, microwave sintering enables faster densification, but there are still no definitive physical mechanisms to explain this observation. Spark plasma sintering applies pressure like a hot press but simultaneously heats the ceramic by pulsing an electric current through it. It has been successful in limiting grain growth by reducing densification time from hours to minutes. Again, there is considerable controversy over why rapid densification happens. A recent model (*6*) shows that the electrical current induces local spatial temperature gradients that lead to enhanced diffusional processes. The authors contend that these spatial temperature gradients are the source of increased densification kinetics during spark plasma sintering. These novel electric field–enhanced methods challenge our thinking on thermal sintering. Improved understanding should lead to the development of even better electric-field densification techniques for fabricating bulk, pore-free nanostructured ceramics.

A major limitation in studying sintering is that we cannot probe the real-time, three-dimensional evolution of submicrometer pores during the last stage of densification. To appreciate the complexity of this problem, consider a material that is 99.9999% dense (a density that cannot be physically measured by conventional techniques). Such a material has $\sim 5 \times 10^{16}$ pores/cm^3 if the pores are 100 nm in diameter.

Magnetic resonance imaging and x-ray tomography have been used to study pore evolution but lack the resolution to observe submicrometer pores. Confocal optical microscopy, which has a lateral resolution of 200 to 300 nm, has been used to explore grain boundary structure in three dimensions (*7*) and has potential for observing submicrometer pores. Near-field scanning optical microscopy can image surface pores down to 40 to 50 nm. Scanning acoustic microscopy (*8*), scanning electron acoustic microscopy (*9*), and scanning near-field acoustic microscopy (*10*) have potential for detecting subsurface pores and can in principle achieve submicrometer resolution. Linear scattering spectroscopy can sensitively provide information on the size, size distribution, and shape of the pores (*11*).

Spectroscopists and microscopists must develop these tools with materials scientists so that we can observe nanopore changes inside the ceramic, preferably in real time and during sintering. The development of these new tools for the study of sintering would be a breakthrough in our ability to study this important process.

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PHYSICS

Transforming Light

Vladimir M. Shalaev

Materials with optical properties not found in the natural world can now be designed, offering unprecedented control over light and enhanced device functionality.

Recent advances in micro- and nanofabrication methods are presenting opportunities to control light in a way that is not possible with the materials provided to us by nature. Synthetic structures built up from subwavelength elements can now be fabricated with a desired spatial distribution of effective electric permittivity ε and magnetic permeability μ, thereby offering the potential to guide and control the flow of electromagnetic energy in an engineered optical space. These "metamaterials" have opened the door to a number of applications that had been previously considered impossible. No longer are we constrained by the electromagnetic response of natural materials and their chemical compounds. Instead, we can tailor the shape and size of the structural unit of the metamaterial and tune their composition and morphology to provide new functionality.

The field of transformation optics, which is enabled by metamaterials, has inspired a fresh look to be taken at the very foundations of optics. Analogous to general relativity, where time and space are curved, transformation optics shows that the space for light can also be bent in an almost arbitrary way. The ability to design and engineer optical space provides the possibility of controlling the flow of light with nanometer spatial precision. Thus, general relativity may find practical use in a number of novel optical devices based on transformation optics, guiding how, using metamaterials, the space for light can be curved in a predesigned and well-controlled way. The relation between light propagation and effective space-time

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geometries was considered, for example, in early papers by Tamm (*1*, *2*), with the basics of transformation optics established later (*3*–*5*); these important early studies were not fully appreciated and were almost forgotten. Only recently has the field of transformation optics been reestablished (*6*–*10*).

Generally, light propagates so that the optical path, which is given by the product of the physical length and the refractive index, is minimized. Thus, by creating a complex distribution for the refractive index *n*, the geometrical path that minimizes the optical path can be curved in an almost arbitrarily complex way. One might think that such a molding of a light path is possible only in the limit of geometrical optics, which implies a scale much larger than the wavelength. Provided that the basic optical parameters of materials, ε and μ, are also transformed appropriately, and because of the generic invariance of Maxwell's equations, transformation optics makes it possible to mold and control light on all scales, from macroscopic sizes down to the deeply subwavelength scale. By creating a desired distribution of ε and μ, and thus a distribution of refractive index *n*, one can "curve" the space for light in a nearly arbitrary way, making it possible to propagate light not only in the backward direction (when *n* is negative) but also along nearly any curved line. As a result, a myriad of fascinating devices are achievable using transformation optics and metamaterials.

One of the most exciting applications is an electromagnetic cloak that can bend light around itself, similar to the flow of water around a stone, making invisible both the cloak and an object hidden inside (*6*, *11*). By excluding light from a certain area of space and bending the light around the space, one can make an object in that area invisible (*12*) (see the figure, left panel).

However, practical applications of transformation optics go far beyond just cloaking. Theory allows the control of light in an extreme and ultimate manner by providing a general recipe for obtaining complex spatial distributions of anisotropic permittivity and permeability. Using these distributions, a "curvilinear" optical space is molded, thereby creating the channel for the desired flow of light. The core challenge here is to approximate the required ideal optical space by manufacturable nanostructured metamaterials, with minimal loss of the required functionality, and thereby move from the theoretical description to actual prototypes.

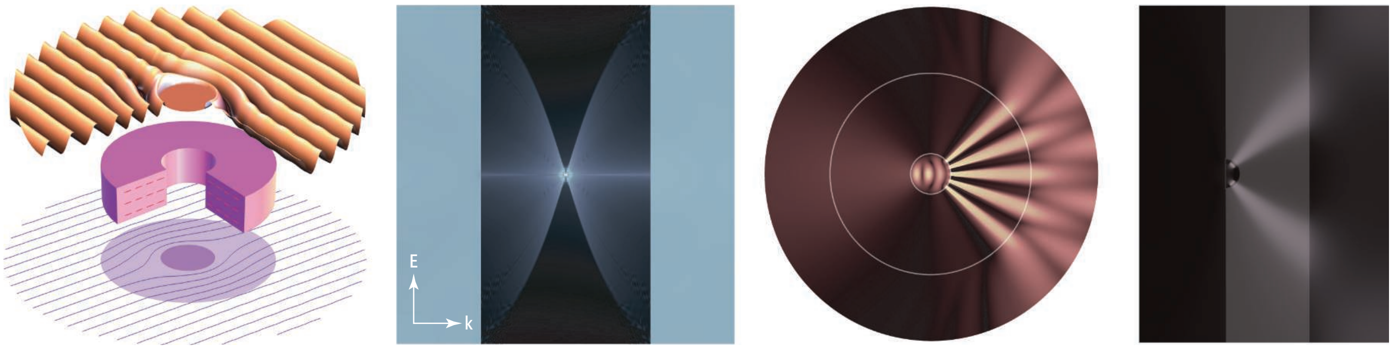
One cannot only exclude light from some region, as in a cloak, but also do the opposite and concentrate light within a certain area of the space. In such a concentrator, light could be collected from all directions onto an arbitrarily small spot, leading to extremely high intensities [see the figure, middle left panel (*13*)]. The light concentrator may enable applications such as omnidirectional solar light collection and field-enhanced sensing.

Transformation optics can also enable a magnifying, planar hyperlens, which is probably the most exciting and promising metamaterial application to date. The information about the subwavelength features of an object is carried by evanescent waves that exponentially decay with distance. This decay results in the loss of the subwavelength details in the far-field image and thus limits the imaging resolution. The hyperlens transforms the evanescent fields into propagating waves, producing magnified far-field images of the subwavelength features (*14*–*17*).

However, the originally proposed hyperlens suffers from strong reflections at its inner and outer cylindrical surfaces, causing reduced light throughput. With local control of the electromagnetic response of metamaterials, the impedance matching at these boundaries can be improved (*18*) (see the figure, middle right panel). Moreover, the actual fabrication and use of the hyperlens is extremely challenging, as in its original concept it requires cylindrical symmetry. Such symmetry is needed to slowly increase the electromagnetic mode wavelength as the wave spreads away from the center of the device to the point where propagation in air becomes possible (*19*). In addition, its cylindrical symmetry limits applications, because placing an object of interest in the hyperlens' inner cylindrical cavity is often impossible. One would be better served by a planar hyperlens—if it were possible.

The approach of "engineering optical space" with local control of a metamaterial's response offers a direct solution to this problem. The process of "slowing down" the evanescent waves required for converting them into propagating waves in air can be achieved by properly varying the dielectric tensor within the hyperlens. Simulations for the proposed flat hyperlens (*13*) show that it can produce magnified far-field images of sub-λ structures (see the figure, right panel). Such a planar, magnifying hyperlens could eventually become a standard add-on to conventional microscopes. By enabling nanoscale resolution in optical microscopy, metamaterial-based transformation optics could allow one to literally see extremely small objects with the eye, including biological cells, viruses and, possibly, even DNA molecules.

Transformation optics enabled by metamaterials transforms the science of light and opens up many exciting applications that often go beyond what we could imagine until very recently.



Optical transformations. (**Left**) Optical cloaking. (**Middle left**) Light concentrator [adapted from (*13*)]. (**Middle right**) Impedance-matched hyperlens [adapted from (*18*)]. (**Right**) Planar hyperlens [adapted from (*13*)].

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PHYSICS

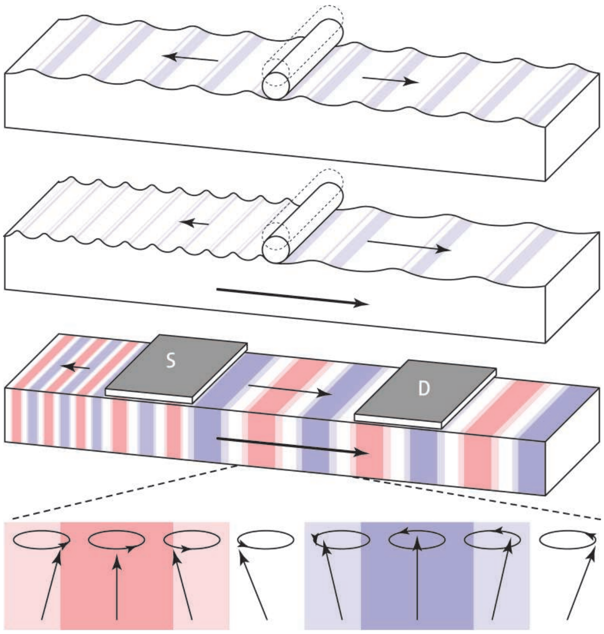
A New Spin on the Doppler Effect

Direct measurements can now be made of electron spin currents, which play a key role in advanced memory applications.

R. D. McMichael and M. D. Stiles

Electrical currents transport charge, but certain experimental setups allow them to transport spin as well. Such spin currents (excess flow of either spin-up or spin-down electrons) can by created by passing an electrical current through a ferromagnetic film; spins parallel to the film's spin orientation pass through more easily, whereas those of opposite sign are scattered more strongly. Spin currents are used in magnetic memories and are potentially useful in novel electronic switches (spintronics), because switching spin orientations may require less energy than is needed to turn a charge current on and off (*1*). One experimental challenge in developing such technology is that it is difficult to measure the flow of spin currents. On page 410 of this issue, Vlaminck and Bailleul (*2*) overcome this challenge by using a novel version of the Doppler effect to quantify the flow of spin currents in a ferromagnetic wire. They measure changes in the propagation of spin waves, which are oscillations of the spin orientation (see the figure, bottom panel).

The most prominent example of harnessing spin currents is the giant magnetoresistance (GMR) effect (*3*, *4*), which occurs when electrical current flows through two ultrathin ferromagnetic layers separated by a nonmagnetic spacer layer. When the magnetic domains of the ferromagnetic layers have parallel orientation, current flows more readily than when they are antiparallel, because the current of only one spin type (spin down, for example) undergoes extensive scattering. GMR has found numerous technological applications, including read heads in hard-disk drives, magnetic sensors, and magnetic random-access memory (MRAM). In many of these applications, the metallic spacer layer is replaced by a tunnel barrier made of oxides such as MgO. The associated resistance changes in such tunneling magnetoresistance (TMR) devices can be much greater than those in GMR devices.



Doppler effects in moving media. (**Top**) Water waves propagate away from a moving cylinder with a frequency set by its oscillation frequency and a wavelength determined by the properties of the water. (**Middle**) Water flows past the cylinder (large arrow); the waves have the same frequency as before, but the downstream-propagating waves have a longer wavelength and the upstream-propagating waves have a shorter wavelength. The speed of the water can be determined from the change in the wavelength of the waves. (**Bottom**) A cartoon of the spin waves excited in the experiment of Vlaminck and Bailleul; the color shading corresponds to different points in the spin's precession (lower expanded view), while the different lengths of the blocks correspond to different propagation rates. Again, the spin waves propagating to the left and right of the source S have different wavelengths because of the spin current (large arrow) present in the system. The source and detector D are efficient only for a narrow range of wavelengths, so the maximum detector output occurs at a different frequency when the current flows. This transmission frequency shift yields the velocity of the effective magnetic medium of the spin waves.

In today's MRAM devices, spin currents are used only in the reading step through the GMR or TMR effects. In the writing step, the orientation of one of the ferromagnetic layers (the "soft layer") is changed by applying an external magnetic field. In a new generation of MRAM under development, spin currents are also used to write the bits (*5*). When a current passes through the spacer layer, the transport of angular momentum accompanying the spin current provides a spin transfer torque (*6*) that drives switching of one of the magnetic layers, performing the writing step.

If such development is successful, MRAM is projected to scale down to much smaller dimensions and could compete with dynamic random access memory (DRAM), which is presently used in computer memory. MRAM has the additional advantage of being nonvolatile like hard-disk drives, but even if MRAM could be scaled as far as conceivable with advanced lithographic fabrication methods, it will not approach the storage density available in hard-disk drives.

In MRAM applications, spin transfer torques act across a spacer layer; they also act within a single material and can be used to move the pattern of magnetic domain walls (which separate regions of opposite magnetic orientation) along a wire (*7*, *8*). A proposed "racetrack memory" (*9*, *10*), based on moving domain walls by spin

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