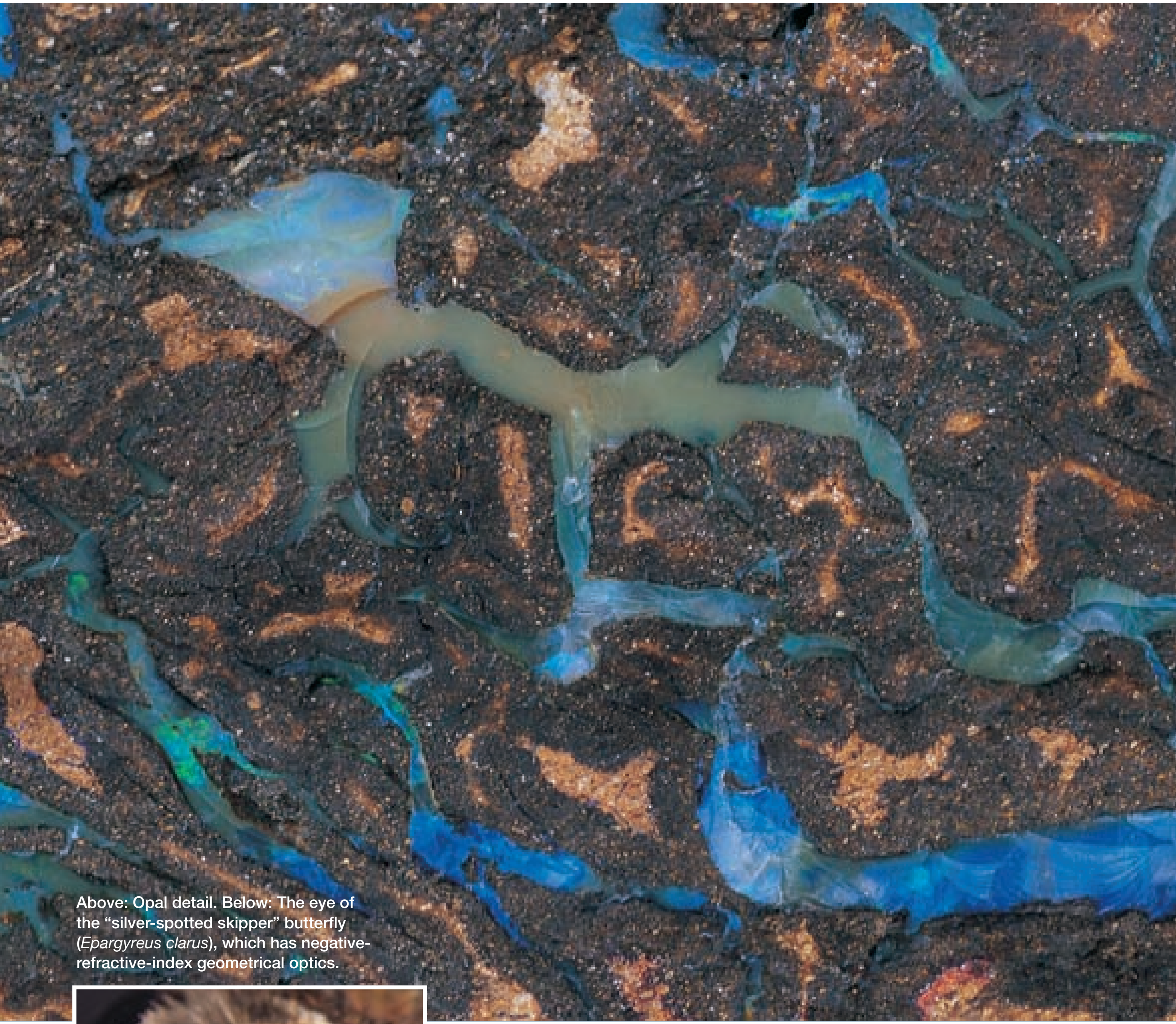
Bill Bachman, Getty Images



Above: Opal detail. Below: The eye of the "silver-spotted skipper" butterfly (*Epargyreus clarus*), which has negative-refractive-index geometrical optics.

D.G. Stavenga, University of Groningen, The Netherlands

Akhlesh Lakhtakia and Tom G. Mackay

Meet the

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Among optics and electromagnetics researchers today, the term “metamaterials” is often taken to be synonymous with materials that have a negative refractive index, but there is much more to metamaterials than that. As research evolves, these unique composite materials will be fabricated with new, multifunctional architectures that will enable applications in sensing, security, transportation and other areas.

Metamaterials

Metamaterials have captured the imagination of a generation of researchers. They will be conceived from deep understandings of physical, chemical and biological phenomenons at submicron length scales, designed with adaptive algorithms implemented on powerful but tiny computers, and fabricated with automated technologies with nanoscale precision. These materials, which are still in their infancy, shall one day perform robustly and reliably to satisfy a multitude of requirements in complex environments—even inside human beings and other animals, and perhaps far away from the third planet orbiting our Sun.

In the year 2000, Rodger M. Walser of the University of Texas at Austin coined the name metamaterials for artificial materials fabricated by first downscaling macroscopic material architectures to submicron and nanometer length scales and then combining different downscaled architectures into macroscopic composite materials that would not only exceed their conventional counterparts in performance but perhaps also satisfy complex multifunctional requirements.

Shortly thereafter, Walser formally defined metamaterials as "macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of *two or more responses* [emphasis in the original] to specific excitation."

But early definitions are evolutionary—ask any solar-system astronomer! We can relax the requirements of periodicity today, though not of cellularity. Furthermore, we must not exclude naturally occurring metamaterials. Living objects are far more complex than manufactured ones; in 2006, the eyes of certain lepidopterans and lobsters were found to contain metamaterials. In addition, natural analogs of artificial structures such as photonic crystals are frequently reported; opals are a good example.

The issue of multifunctionality is likely to divide researchers into two camps, as is exemplified by varying answers to the following question: Should permittivity and the inverse of the permeability be considered as entirely separate performance parameters, even though they are really part of a single constitutive tensor or dyadic that relates the primitive electromagnetic field (comprising the conventional **E** and **B**) to the induction electromagnetic field (comprising **D** and **H**)?

A working definition of a metamaterial is as follows: It is a composite material exhibiting response characteristics that either are not observed in, or are enhanced relative to, the individual responses of its constituent materials, each of which is chemically inert with respect to the others in its immediate proximity. The latter restriction excludes molecularly pure materials containing two or more types of atoms from being classified as metamaterials. Multifunctionality is considered simply a desirable attribute of metamaterials for now, but will be required within a decade for a tighter definition.

Early examples

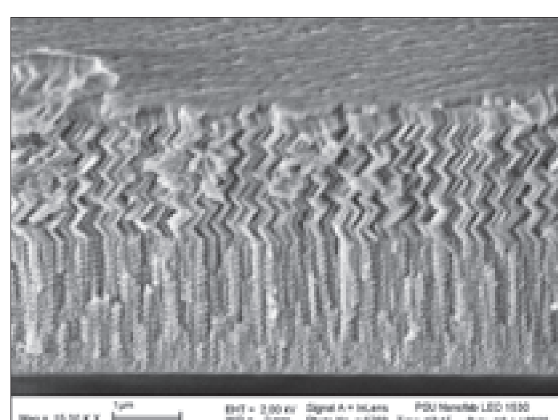
As the working definition suggests, metamaterials were fabricated before the term was. An example dating back to the 1890s is that of isotropic chiral materials made by dispersing electrically small spirals in a host medium. These composite materials would alter both the orientation and the eccentricity of the vibration ellipse of an electromagnetic plane wave in

[Sample of an isotropic chiral material]

This material was fabricated for microwave applications by dispersing miniature springs in epoxy.

Álvaro Gómez, Universidad de Cantabria, Spain

[A scanning electron microscope image of a sculptured thin film]



This chiral sculptured thin film was made by evaporating silicon oxide in an evacuated chamber containing a rotating substrate.

Mark W. Horn, Pennsylvania State University some spectral regime, although the constituent materials by themselves cannot.

Isotropic chiral materials exhibiting that response in the optical regime are commonplace in nature; their molecules are not coincident with their mirror images. But composite materials demonstrating that effect in the microwave regime must be artificially made—e.g., by dispersing tiny metallic springs in epoxy. The shapes of the spirals engender the alteration of the vibration ellipse. Electromagnetic research on isotropic chiral materials intensified during the late 1980s and early 1990s, and may now be back in vogue in the context of negative refraction.

Sculptured thin films provide another example. These composite materials are assemblies of shaped parallel nanowires made of clusters less than 5 nm in size. The nanowire shapes impart response characteristics to this type of metamaterial that are not evinced by the bulk material that was evaporated to make it.

For instance, chiral sculptured thin films are useful as circular-polarization filters because they display the circular Bragg phenomenon arising from the helical shape of their nanowires, which also contributes to a reduction of residual stress in comparison with columnar thin films that are assemblies of parallel straight nanowires.

Magnetoelectric composite materials provide yet another example. These materials exist in nature as crystals. They develop a magnetization in response to the application of an electric field, and a polarization in response to a magnetic field. Magnetoelectric composite materials in the form of multilayers with alternate piezoelectric layers (such as barium titanate) and magnetostrictive layers (such as terfenol-D) were proposed and experimentally investigated by Girish Harshe, formerly at Pennsylvania State University.

These composite materials exploit the interaction of the electric/magnetic field with the strain tensor in two different classes of materials to deliver magnetoelectric coefficients that are much higher than in their natural counterparts. Of course, neither piezoelectric nor magnetostrictive materials are magnetoelectric.

Homogenized composite materials

Metamaterials are composite materials. Provided that their constituent materials are evenly dispersed as electrically small inclusions or particles—much like a batter of both yellow and chocolate cake mixes—composite materials can be homogenized.

Researchers have been predicting the effective constitutive properties of a homogenized composite material (HCM) for the past two centuries. The homogeneity of HCMs is a consequence of the electromagnetic wavelengths being much larger than the inclusion dimensions. Similarly, a sample of quartz appears homogeneous to the naked eye, but its crystal structure is revealed under X-ray illumination.

> In 2006, the eyes of certain lepidopterans and lobsters were found to contain metamaterials. In addition, natural analogs of artificial structures such as photonic crystals are frequently reported; opals are a good example.

Although homogenizability should not be construed as a defining attribute of metamaterials, HCM-metamaterials present interesting technoscientific opportunities. Here are several recent electromagnetic examples:

▸ *Bianisotropy*. The most general linear electromagnetic material is called bianisotropic—which refers to the anisotropic coupling of **D** and **H** to **E** and **B**. The huge parameter space associated with bianisotropic materials implies an exceedingly rich palette of electromagnetic responses. Bianisotropic HCMs may be readily conceptualized as arising from commonplace constituent materials.

One of the constituent materials has to be anisotropic whereas the other is isotropic but exhibits magnetoelectric coupling. For example, the homogenization of a biaxial dielectric material with an isotropic chiral material results in a biaxial bianisotropic HCM. Bianisotropic materials are best used for single-step tailoring of both the polarization state and the bandwidth.

▸ *Voigt-wave propagation*. Planewave propagation in biaxial dielectric materials is generally birefringent—i.e., two different wave vectors are associated with propagation in a given direction in a biaxial dielectric material. In exceptional cases, the two plane waves coalesce to form a single plane wave called the Voigt wave, named in honor of Woldemar Voigt, who reported his experimental observations more than 100 years ago. Any Voigt wave exhibits an unusual property: Its amplitude is linearly dependent upon propagation distance.

[Positive/negative phase velocity]

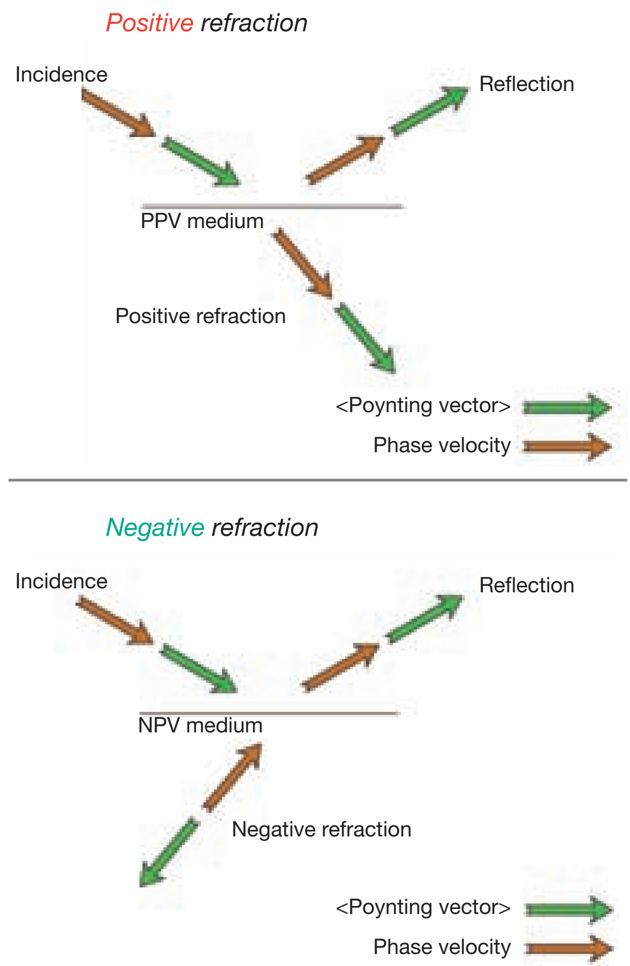


Illustration of positive/negative phase velocity and positive/negative refraction due to an isotropic dielectric-magnetic material.

Iolite and amethyst are two naturally occurring crystals that allow Voigt-wave propagation.

Voigt-wave propagation cannot occur in isotropic or uniaxial dielectric materials. A composite material comprising two uniaxial dielectric constituent materials may yield a biaxial HCM, provided that the distinguished axes of the uniaxial constituent materials are not aligned with each other. In so doing, biaxial dielectric HCMs that support the propagation of Voigt waves can be conceptualized, even though their uniaxial constituent materials do not support such propagation.

The void regions of a porous dielectric composite material may be engineered to allow Voigt waves to propagate ordinarily but not when the material is immersed in a certain fluid. Thus, researchers can exploit the phenomenon for optically sensing for the presence and density of an infiltrating fluid.

▸ *Negative phase velocity.* The familiar description of plane wave propagation, as presented in many standard electromagnetism textbooks, is that of positive phase velocity (PPV). That is, the phase velocity casts a positive projection onto the direction of the rate of energy flow as quantitated by the time-averaged Poynting vector. On the other hand, the phenomenon of negative phase velocity (NPV)—wherein the direction of the phase velocity is opposed to the direction of the rate of energy flow—has generated much excitement over the past five years.

Of the several unusual phenomenons that follow as a consequence of NPV, the most notable is negative refraction. Prospective technological applications of NPV propagation, such as near-perfect lenses, continue to motivate research efforts.

Early experimental research on microwave negative refraction was done with metamaterials comprising cells containing metallic wires and rings embossed periodically on plastic sheets. There is now hope for simpler NPV metamaterials—e.g., random assemblies of spherical inclusions of two different isotropic homogeneous, dielectric-magnetic materials, with relative permittivities ε^a and ε^b and relative permeabilities μ^a and μ^b, respectively.

Provided that the values of $\varepsilon^{a,b}$ and $\mu^{a,b}$ lie within certain ranges, with the real parts of $\varepsilon^{a,b} < 0$ and the real parts of $\mu^{a,b} > 0$ (or vice versa), the bulk constituent materials cannot support NPV propagation, whereas the HCM may. Whether NPV propagation is supported by the HCM depends upon the relative proportions of the constituents, as well as the size and distribution of the inclusions.

The scope for realizing NPV propagation in HCMs may be extended by using constituent materials that are more complex than isotropic dielectric-magnetic materials. For example, numerous studies have revealed that a bianisotropic HCM, in the form of a Faraday chiral material, may support NPV propagation, whereas its constituent materials do not. A Faraday chiral material can develop from the homogenization of an isotropic chiral material with a magnetically biased ferrite.

▸ *Enhancement of group velocity.* Group velocity—the velocity of the peak of a pulse—is meaningful only when the pulse is not seriously distorted while traversing a medium. Suppose we consider a composite material made of 1) a constituent material with relatively high relative permittivity ε^a and low frequency-dispersion $d\varepsilon^a/d\omega$ and 2) a constituent material with relatively low ε^b and high $d\varepsilon^b/d\omega$, in a spectral regime of interest.

Both constituent materials are randomly distributed as electrically small spherical inclusions, so that the HCM is also an isotropic dielectric material. The group velocity in the HCM can exceed in magnitude the group velocity in either constituent material for certain relative proportions of the constituent materials. Group-velocity-enhancing metamaterials may be useful for reducing information delay in solid-optics components, possibly in optoelectronic chips.

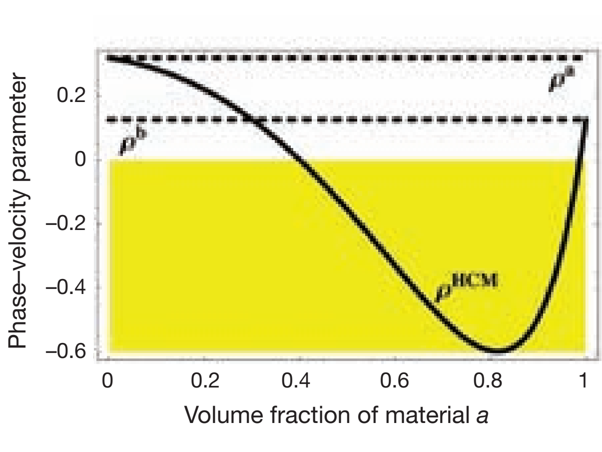
The group-velocity enhancement brought about by homogenization also arises in anisotropic HCMs. For example, if the constituent materials are dispersed as oriented spheroids, in certain directions the group velocities associated with both the ordinary and extraordinary wave vectors in the corresponding anisotropic dielectric HCM can exceed in magnitude the group velocity in either constituent material. The degree of group-velocity enhancement is sensitively dependent upon the eccentricity and orientation of the inclusions.

► *Nonlinearity enhancement*. Finally, let us turn to nonlinear materials. Metamaterials with enhanced nonlinearity would be useful for more efficient harmonic generation, amplification, etc. In a similar manner to that described for group-velocity enhancement, HCMs may be conceptualized to exhibit nonlinear responses that are enhanced compared to those of their constituent materials.

This has been demonstrated for a wide range of cubically nonlinear HCMs, including isotropic and anisotropic dielectric HCMs, as well as isotropic chiral HCMs. The achievable

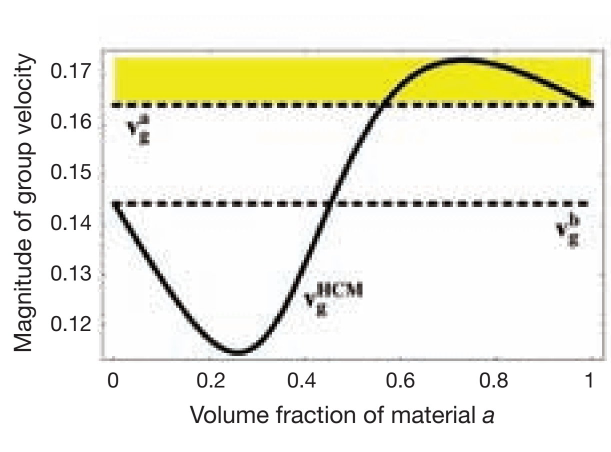
Early experimental research on microwave negative refraction was done with metamaterials comprising cells containing metallic wires and rings embossed periodically on plastic sheets. There is now hope for simpler NPV metamaterials.

[Direction of phase velocity relative to time-averaged Poynting vector in an HCM]



The HCM comprises electrically small spherical inclusions of 1) an isotropic dielectric-magnetic material *a* with $\varepsilon^a = -5.9 + 0.8i$ and $\mu^a = 1.5 + 0.2i$, and 2) an isotropic dielectric-magnetic material *b* with $\varepsilon^b = -1.5 + i$ and $\mu^b = 2 + 1.1i$. The phase–velocity parameter ρ indicates whether the phase velocity is positive or negative. In other words, negative (positive) phase velocity is signified by $\rho < 0$ ($\rho > 0$). The phase-velocity parameter ρ^{HCM} is plotted against the volume fraction of material *a* (solid line), along with $\rho^{a,b}$ (dashed lines). The NPV regime is shaded.

[Enhancement of group velocity in an HCM]



The HCM comprises spherical inclusions of 1) an isotropic dielectric material *a* with relative permittivity $\varepsilon^a = 32$ and $d\varepsilon^a/d\omega|_{\omega=\Omega} = 5/\Omega$ and 2) an isotropic dielectric material *b* with $\varepsilon^b = 1.25$ and $d\varepsilon^b/d\omega|_{\omega=\Omega} = 13/\Omega$. The magnitude of the HCM's group velocity $\mathbf{v}_g^{HCM}$ (solid line) and the magnitudes of the constituent materials' group velocities $\mathbf{v}_g^{a,b}$ (dashed lines) are plotted as functions of the volume fraction of material *a*. All speeds are normalized with respect to the speed of light in free space. The regime of group-velocity enhancement is shaded.

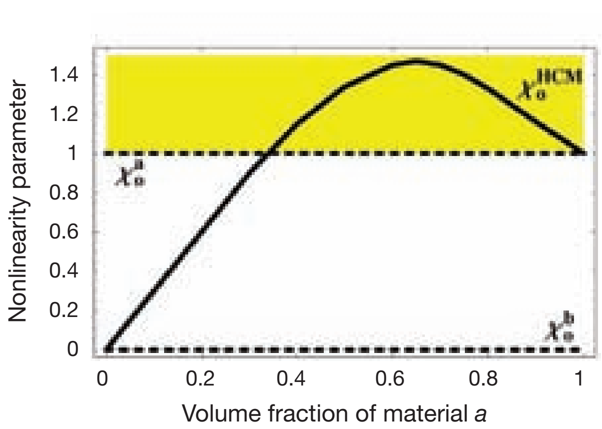
degree of nonlinearity enhancement is sensitive to the shape and distribution of the constituent inclusions in addition to the relative proportions of the constituent materials.

Nonhomogeneous metamaterials

Nonhomogeneous metamaterials, whose constitutive properties are designed to vary with position, are functionally graded materials. Nonhomogeneous metamaterials with complex microstructures have lately become a reality due to breakthroughs in manufacturing techniques. Indeed, a U.S. research group has now demonstrated graded negatively refracting lenses for microwave focusing.

Also, the nonhomogeneity of metamaterials presents opportunities for cloaking—that is, through judicious spatial variation in its constitutive properties, a metamaterial shroud may be used to conceal, at least partially, an object. At least four cloaking schemes have been reported from the United States and the United Kingdom. Most recently, a combined U.S.-U.K. research effectively cloaked a quasi-two-dimensional metallic object from a continuous-wave source radiating at 8.5 GHz. However, the accomplishment of the same feat for optical sources or ultrawideband sources remains a daunting challenge for technoscientists.

[Nonlinearity parameter of an HCM]



The HCM comprises spherical inclusions of 1) a cubically nonlinear isotropic dielectric material *a* with relative permittivity $\varepsilon^a = 2$ and nonlinear susceptibility $\chi^a = 9.07571 \times 10^{-12}\ m^2 V^{-2}$ and 2) a linear isotropic dielectric material *b* with $\varepsilon^b = 8$. The HCM is a cubically nonlinear material with nonlinear susceptibility χ^{HCM}. The nonlinearity parameter $\chi_0^{HCM} = \chi^{HCM}/\chi^a$ is plotted as a function of the volume fraction of material *a* (solid line). Also shown are the nonlinearity parameters $\chi_0^a = 1$ and $\chi_0^b = 0$ (dashed lines). The regime of nonlinearity enhancement is shaded.

Multifunctionality

The HCMs presented earlier show responses that are either not exhibited at all by their constituent materials or not exhibited to the same degree by any of their constituents. The techno-scientific opportunities offered by such HCM-metamaterials are indeed tremendous in optics and electromagnetics, but any multifunctionality that they exhibited would be either incidental or anemic.

Robust multifunctionality lies at the heart of intelligent materials design. Materials have many different types of responses: electromagnetic, elastodynamic, thermal, piezoelectric, pyroelectric, magnetoelastic and so on. Design for just one type of response cannot generally satisfy the multitude of requirements for efficient and durable functioning in complex systems and environments.

Nanotechnological approaches appear promising for the fabrication of multifunctional metamaterials, because different types of nanoparticles could be intimately mixed to yield materials with desirable macroscopic responses to different types of excitations. Very likely, more than one approach could deliver the desired responses, as can be gleaned from the following rather simple argument modeled after the celebrated Maxwell Garnett formula for homogenizing particulate composite materials.

Let us consider only linear HCM metamaterials. Typically, the formulation of macroscopic responses requires a set of primitive fields, a set of induction fields and a set of constitutive linkage parameters. Let $\mathbf{p}_k$ (k = 1,2,…) denote the primitive fields. These fields can be tensors of arbitrary order; for instance, $\mathbf{p}_1$ can be the electric field (which is a first-order tensor), and $\mathbf{p}_2$ can be the strain (which is a second-order tensor).

Similarly, let $\mathbf{q}_k$ (k = 1,2,…) denote the induction fields. Then, $\mathbf{q}_1$ can be the electric displacement, and $\mathbf{q}_2$ can be the stress, for example. Forming the poly vectors $P = \{\mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3,\ldots\}$ and $Q = \{\mathbf{q}_1, \mathbf{q}_2, \mathbf{q}_3,\ldots\}$, we can set up the linear constitutive relation $Q = \mathsf{M}\ P$, where the constitutive object M encodes linkages between every pair $\{q_j, p_k\}$ of the form $\mathbf{q}_j = \mathbf{m}_{jk} \bullet \mathbf{p}_k$, with • denoting an appropriate multiplication.

Let an electrically small inclusion be embedded in a dissimilar host medium, with their respective constitutive objects denoted by M^{inc} and M^{host}, respectively. The response function of this inclusion is not a straightforward calculation and may not be known except in special circumstances. Suppose, however, that both materials are poly-isotropic, the inclusion is spherical, and the boundary conditions at the bimaterial interface are particularly beneficent.

Poly-isotropy implies that every constitutive linkage $\mathbf{m}_{jk}$ is actually a scalar (i.e., $\mathbf{m}_{jk} = m_{jk}\ \mathbf{d}_{jk}$, where $\mathbf{d}_{jk}$ is the appropriate idempotent). Then the response function of the embedded inclusion may be captured reasonably well—at least, for this argument—via the poly-polarizability density $\mathsf{A} = (\mathsf{M}^{inc} - \mathsf{M}^{host})\bullet[(\mathsf{I} + \mathsf{N}\bullet(\mathsf{M}^{inc} - \mathsf{M}^{host})]^{\dagger}$, where † denotes the reciprocation operation, N is some appropriate constant depending on M^{host} as well as the shape of the inclusion, and I is the idempotent.

The effective constitutive object of a composite material wherein the volume fraction f^{inc} of the inclusion material is sufficiently small may be estimated as $\mathsf{M}^{HCM} = \mathsf{M}^{host} + f^{inc}\,\mathsf{A}\bullet(\mathsf{I} - f^{inc}\,\mathsf{N}\bullet\mathsf{A})^{\dagger}$. It must thus contain terms dependent on A. A significant attribute of A is that it can give rise to indirect connections between a particular pair of induction and primitive fields—say, $\mathbf{q}_3$ and $\mathbf{p}_6$—in the HCM, even though the constitutive linkage $\mathbf{m}_{36}$ is null-valued in the constituent materials. Many such connections may exist between $\mathbf{q}_3$ and $\mathbf{p}_6$, and each connection may perambulate through more than one constitutive linkages other than $\mathbf{m}_{36}$.

Furthermore, a particular constitutive linkage may be involved in more than one perambulation, which suggests the possibility of more than one route towards a desired multifunctionality. The goal of multifunctionality would lead to overlap among currently distinct research disciplines, thereby promoting interdisciplinarity in research institutions and multidisciplinarity in research careers.

Charles Bakis (Pennsylvania State University) recently suggested to us a splendid example of multifunctionality: the skin of the Boeing 787 Dreamliner. This skin is made of a composite material. Low weight for fuel efficiency, high stiffness for resistance to deformation, and high strength for resistance to rupture are age-old requirements for any airborne mechanical structure.

In addition, the 787's skin was designed to dampen sound in order to isolate acoustically the cabin from the wing-mounted engines and thus reduce noise in the cabin. The skin was also designed for thermal isolation from low external temperatures during flights in order to prevent internal condensation on it, which, in turn, allows higher humidity in the cabin and greater comfort for the passengers.

The multifunctionality of airplane skins will be further enhanced in the future when 1) a network of embedded optical fibers will allow simultaneous monitoring of the skin's mechanical integrity and external environmental variables, 2) embedded antennas would enable numerous channels of communications with aircraft traffic controllers and Internet service providers, and 3) a network of embedded actuators to morph the shape of the airplane to reduce drag and further increase fuel efficiency and reduce vibrations.

Outlook

The future is bright for metamaterials science and technology. The emergence of metamaterials coincided with the rapid gain in popularity of nanotechnology as a research discipline with financial backing from governments and industries. Metamaterials with new types of architectures will be fabricated by molecular self-assembly, layer-by-layer deposition, nanoimprinting and other nanotechnological methods.

Such metamaterials will be multi-functional and their fabrication will enable new sensors and actuators for monitoring the health and controlling the performance of complex structures operating in extreme or delicate environments, including biological and extraterrestrial. Who could ask for anything more? ◭

> Nanotechnological approaches appear promising for the fabrication of multifunctional metamaterials.

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