Absolute concentration robustness and invariants are systems properties that arise from the coordinated behavior of all the components in the network. Such integrative analysis is still in its infancy. Does some evolutionary advantage accrue to the organism from absolute concentration robustness? This property can be verified experimentally for certain networks and we can speculate about why it is needed, yet the answer lies not in the network but in the environments in which the organism exists. *E. coli* is a gut microbe. Did absolute concentration robustness evolve in osmoregulation and in utilization of two-carbon sugars because of the intestinal physiology and ecology of the gut microbiota, or is it merely a spandrel in some molecular architecture that we cannot yet perceive (*11*)?

"Systems" thinking has always been present in biology, even if its importance has waxed and waned with changes in experimental capabilities. The disciplinary histories of embryology, ecology, genetics, physiology, immunology, and neuroscience, among others, suggest that mathematical tools become important when attention shifts from identifying the components to understanding their collective function. What is different today is that the molecular details are at the bottom of the biological hierarchy. Molecular biology was reductionism's finest hour. Now, there is nowhere left to go but up.

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APPLIED PHYSICS

The Road Ahead for Metamaterials

Metamaterials enable us to design our own "atoms" and thus create materials with new properties and functions.

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Metamaterials are artificial media structured on a size scale smaller than the wavelength of external stimuli. Whereas conventional materials derive their electromagnetic characteristics from the properties of atoms and molecules, metamaterials enable us to design our own "atoms" and thus access new functionalities, such as invisibility and imaging, with unlimited resolution.

The next stage of this technological revolution will be the development of active, controllable, and nonlinear metamaterials surpassing natural media as platforms for optical data processing and quantum information applications (*1*). Metamaterials are expected to have an impact across the entire range of technologies where electromagnetic radiation is used, and will provide a flexible platform for modeling and mimicking fundamental physical effects as diverse as superconductivity and cosmology and for templating electromagnetic landscapes to facilitate observations of phenomena that would otherwise be difficult to detect.

In terms of a Tree of Knowledge with roots embedded deep in the soil of microwave technology (see the figure), metamaterials became a big issue when the tree brought forth the "forbidden fruit" of negative-index media. Agressively contested when it frst appeared, the concept of negative index is now widely accepted and the focus of research has moved toward application. Other developments have been metamaterials with strong magnetic response and "magnetic mirror" functionality at optical frequencies, the discovery of structured surfaces exhibiting directional asymmetry in transmission, and metal structures invisible to electromagnetic radiation. Substantial effort has gone into the development of chiral "stereo" metamaterials for controlling the polarization state of light and achieving negative refraction. Metamaterials exhibiting properties suitable for use in delay lines and sensors have also been demonstrated across the entire spectral range, from microwaves to optics. Another active area of research has been in waveguide applications. The fascinating "transformation optics" idea of controlling the fabric of "electromagnetic space" (and thus light propagation) by filling it with metamaterial is being developed, requiring media with coordinate-dependent parameters, and offers cloaking and light-channeling solutions such as sophisticated lenses and "mirage" devices.

In developing active gain-assisted metamaterials, the main goal is the compensation of losses that dampen the coupled oscillations of electrons and light (known as plasmons) in the nanostructures. These losses render photonic negative-index media useless. One solution is to combine metamaterials with electrically and optically pumped gain media such as semiconductor quantum dots (*2*), semiconductor quantum wells, and organic dyes (*3*) embedded into the metal nanostructures. Electrically and optically pumped semiconductor gain media and emerging technology of carbon monolayers (graphene) could be expected to provide loss compensation from optical to terahertz spectral ranges. Alloys and band-structure engineering of metals also promise better plasmonic media.

Another grand goal is to develop a gain-assisted plasmon laser, or "lasing spaser" device (*4*): a flat laser with its emission fueled by plasmonic excitations in an array of coherently emitting metamolecules. In contrast to conventional lasers operating at wavelengths of suitable natural molecular transitions, the lasing spaser does not require an external resonator and its emission wavelength can be controlled by metamolecule design. Finally, the use of nanostructured high-permittivity materials offers the possibility of tailoring the electric and magnetic response in metamaterials consisting only of dielectric, thus removing the issue of losses at the source (*5*).

The development of nanoscale all-optical data processing circuits depends on the availability of fast and highly responsive nonlinear media that react to light by changing their refractive index and absorption. In all media where functionality depends on electronic or molecular anharmonicity, stronger responses come at the expense of longer reaction times, a constraint that is practically impossible to break. The plasmonic nonlinearity of metals constituting metamaterial nanostructures is extremely fast and could provide terahertz modulation, but requires high intensities to

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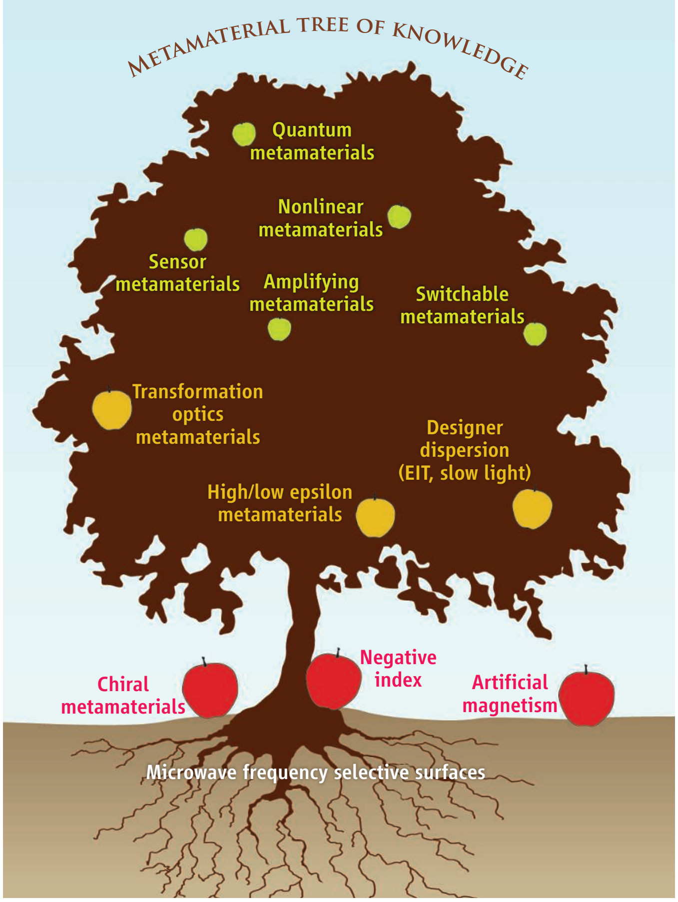
operate (*6*). Combining conventional nonlinear media with metamaterial nanostructures is a powerful way of engineering an enhanced response. Metamaterials can slow light, thereby increasing the interaction time with nonlinear medium embedded in it, or they can help by concentrating the local field and thus enhancing a nonlinear response. Prime contenders emerging for hybridization with metamaterials are semiconductors and semiconductor multiple–quantum well structures used as substrates for metallic framework, liquid crystals, conjugated polymers, carbon nanotubes (*7*), and fullerenes implanted into the fabric of the meta materials.

The ability to tune and switch the properties of materials, something very rarely offered by nature, can be achieved in metamaterials. Consider a metal metamaterial structure on a thin layer of dielectric, the properties of which can be controlled by external stimuli. A change in the refractive index in the layer will modify the plasmon resonances of the nanostructure. This will lead to a strong change in the resonant transmission and reflection of the hybrid (*8*). "Phase-change" materials are prime agents for switching: Chalcogenide glasses have been used in rewritable optical disk technology for several decades, providing fast and reproducible changes in optical properties in response to excitation. This functionality is underpinned by phase transitions between crystalline and amorphous states and may be engaged by optical or electrical stimulation; a nanoscale metamaterial electro-optical switch using chalcogenide glass has already been demonstrated (*9*). Similar properties are exhibited by transition metal oxides, in particular vanadium oxide (*10*, *11*). Switchable metamaterials based on arrays of micro- and nano-electromechanical devices are also being developed.

Conducting oxides and graphene are other favorites that promise to add electro-optical capability to metamaterials, in particular in the infrared and terahertz domains, by exploiting the spectral shift of electromagnetic response driven by applied voltage (*12*). The magnetic control of plasmons in layered structures of ferroelectric and noble metal can also be engaged to tune metamaterials (*13*). Sensor applications are another growth area in metamaterials research where planar structures with narrow resonances are well suited to detect low-concentration analytes; for instance, a single molecular layer of carbon can induce a multifold change in the transmission of a metamaterial (*14*).



Fruit for the picking. The metamaterial Tree of Knowledge shows the progression and future of metamaterials research. The "forbidden fruit" of negative-index metamaterials is ripe: The concept is now widely accepted and research is now moving into the domain of application. Chiral metamaterials and those exhibiting artificial magnetism are also well researched. Studies on the control of electromagnetic response and its spatial distribution and dispersion are currently flourishing. Emerging directions of investigation are nonlinear, switchable, gain-assisted, sensor and quantum metamaterials.

Superconducting metamaterials (*15*) offer an incredibly fertile arena, as losses there are much lower than those of copper. Nonlinear and multistable behaviors could be observed in superconducting metamaterials, which may be extremely sensitive to external stimuli such as magnetic field, light, and current, promising highly reactive, switchable devices. Even more intriguing is the fact that the classical object of metamaterials research, the ubiquitous split ring metamolecule, has much in common with a fundamental unit of superconductivity, the Josephson junction ring. This invites one to think about exploiting quantum coherence in metamaterials: an array of superconducting Josephson phase qubits, each of which can be considered as macroscopic metamolecules with a multilevel quantum structure. By replacing the classical plasmonic resonators of today's metamaterials, Josephson qubits will allow for the engineering of truly quantum metamaterials, capable of demonstrating the entire palette of atomic spectroscopy phenomena. Their functionality will be limited to the microwave and terahertz spectral domain, as higher frequencies destroy the superconducting phase.

No progress in metamaterials research will be possible without further developments in fabrication, however. New techniques will have to achieve perfection of nanostructures at close to the molecular level, and at low cost. We need to go beyond electron beam lithography, focused ion beam milling, and nano-imprint techniques. The new techniques will have to occupy a position between chemical processes controlled by self-organizing forces on the truly molecular level and the less accurate, top-down methods, which can build metamaterials to almost any blueprint.

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