A Roadmap for Metamaterials

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Metamaterials have rapidly advanced over the past few years—from being a paradigm for engineering unique electromagnetic properties to forming a material base for functional devices with tuneable, switchable and nonlinear capabilities. In the future, they will allow for dynamic quantum-effect-enabled systems offering exciting applications that we have not yet imagined.

The quick and widespread proliferation of new nanofabrication techniques has opened many opportunities for researchers to create artificial media known as metamaterials, which are designed to control and interact with electromagnetic waves. Research in this field is developing at an incredible pace. In natural solids, optical response is determined by the quantum energy-level structure of the constituent atoms or molecules. By contrast, the electromagnetic properties of metamaterials are derived from the resonant characteristics of the subwavelength plasmonic resonators from which they are constructed.

The metamaterial paradigm is an incredible one that promises groundbreaking new functionalities such as invisibility and imaging with unlimited resolution. It allows the tailoring of boundary conditions, frequency and spatial dispersion of electromagnetic response and thereby leads to applications in slow light and asymmetric transmission devices, polarization control and absorption management. The next stage of development will be the widespread use of active (gain-assisted, controllable and nonlinear) metamaterials and metamaterials for sensing and energy applications.

We anticipate that another radical advance in expanding the metamaterial paradigm will occur when the arrays of classical plasmonic resonators found in today’s metamaterials are replaced with arrays of superconducting quantum interference devices to create truly quantum artificial electromagnetic media. Controlling the fabric of “electromagnetic space” (and thus light propagation) with metamaterials that have coordinate-dependent parameters offers additional technological opportunities, which are not feasible with conventional homogeneous optical materials. Known as “transformation optics,” this idea offers new solutions for sophisticated lenses, interconnect applications, waveguides and “mirage” (cloaking) devices.

Laser sources

The idea of combining gain media with metamaterials has attracted increasing attention within the research community. This new generation of metamaterials will play a key role in developing novel laser sources.

Indeed, it is now experimentally confirmed that hybridizing a gain medium (semiconductor quantum dots or quantum well structures) with a plasmonic metamaterial can lead to a multi-fold-intensity increase and a narrowing of their photoluminescence spectra. The luminescence
We envision that, in the future, electrically pumped semiconductor gain media will provide a practical solution for metamaterial-based lasers at visible and telecom frequencies, while quantum cascade semiconductor amplifiers show promise for tackling losses and providing gain in the infrared. Electrically and optically pumped graphene is expected to show strong plasmonic amplification in the terahertz part of the spectrum. Adding gain to metamaterials also compensates for the joule losses that damp plasmons in metal nanostructures. Lowering losses is crucial for the performance of metamaterial-based negative-index devices, waveguides, spectral filters, delay lines and, in fact, practically any application of metamaterials.

Switchable metamaterials

Switchable and tuneable metamaterials are other rapidly expanding areas of research. Indeed, the development of nanophotonic 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. This is difficult to deliver in nanoscale-size devices using electronic or molecular nonlinearities, where stronger responses often come at the expense of longer reaction times and where the optical path through the nonlinear medium is shorter than the wavelength of light.

When high speed switching is not the prime objective, metamaterials can be reliably and reversibly controlled by microelectromechanical (MEMS) actuators that reposition parts of the metamolecules. This has been convincingly demonstrated for terahertz and far-infrared metamaterials. Reconfigurable optical metamaterials require moving components on the scale of a few tens of nanometers (NEMS actuators) to realize a profound change in optical properties.

Metamaterials in which metal nanostructures are hybridized with nonlinear and switchable dielectrics or semiconductors provide a way to achieve changes faster than they can be achieved by mechanical repositioning of parts.
This can lead to a strong change in the resonant transmission and reflec-
tion of the hybrid. Prime candidates for hybridization with metamaterials
are semiconductors and semiconductor multiple-quantum-well structures
used as substrates for a metallic framework, carbon nanotubes and fullerenes
implanted into the fabric of the metama-
terials and organic nonlinear media.

Scientists have already demonstrated
the ability to change a metamaterial’s
response at terahertz frequencies by
injection or optical generation of free-
carriers into a gallium-arsenide sub-
strate. Recent experiments show that the
ultrafast nonlinear response of silicon
can be strongly enhanced by adding a
metamaterial layer. Single-wall semi-
conductor carbon nanotubes deposited
on metamaterials exhibit an order-of-
magnitude higher nonlinearity than the
already extremely strong response of the
nanotubes themselves, due to a resonant
plasmon-exciton interaction.

So-called “phase-change” materi-
als are prime agents for switching:
chalcogenide glasses have been used
in rewritable optical disk technology
for several decades. They provide 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
been demonstrated.

Similar properties are exhibited by
transition metal oxides, in particular
vanadium dioxide. In another example,
the transition between different meta-
stable phases in polymorphic elemental
gallium leads to dramatic change in
dielectric and plasmonic properties,
making it another candidate for use in
switchable metamaterials, alongside
with liquid crystals.

A very substantial change in the
dielectric properties of a nanometer-
neighbor layer may be achieved in conduc-
tive oxides through the injection of
free-carriers, which should be enough
to control resonant transmission in a
hybrid metamaterial. Graphene is
another favorite that promises to add
electro-optical capability to metamater-
ials, in particular in the IR and terahertz
domains, by exploiting the spectral shift
of electromagnetic response driven by
applied voltage.

Sensor applications

Sensor applications represent another
rapidly growing area in metamaterials
research. For instance, asymmetrically
split ring resonators supporting high-
quality Fano resonances or metamaterial
arrays of nanoscale antennas are well
designed to detect low-concentration
analytes such as sugar, hydrogen, etc.,
through variations in their transmis-
sion and reflection characteristics. A
single molecular layer of graphene, for
example, can induce a multifold change
in the transmission of a metamaterial.
Plasmonic metamaterial nanostructures
can also be used to improve light-har-
vesting solutions, permitting a consid-
erable reduction in physical thickness and
improved efficiency in solar photovoltaic
absorber layers.

Superconducting and
quantum metamaterials

Superconducting metamaterials have
recently emerged to offer a radically
new paradigm for data processing and
information technologies. They will
provide a dramatic reduction of losses,
accompanied by access to the extreme
sensitivity of the superconducting state
to external stimuli and the exceptional
nonlinearity of superconductors (orders
of magnitude higher than $p-n$ junctions),
enabling low energy switching at the
subattojoule level.

Negative dielectric constants and
dominant kinetic resistance also make
superconductors an intriguing plasmonic
media. Moreover, a fundamental change
in the nature of information carriers is
produced by superconductivity: In some
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ials, in particular in the IR and terahertz
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of electromagnetic response driven by
applied voltage. A recent demonstration
of the magnetic control of plasmons in
layered structures of ferroelectric and
noble metals can also be translated to
the tuning of metamaterials.

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<table>
<thead>
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<th>[Conventional metamaterials vs. future “quantum metamaterials”]</th>
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<tr>
<td>Conventional metamaterials (current paradigm)</td>
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<td>Building block of the technology</td>
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<td>Excitation/information carrier</td>
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underpinned by flux quantization and quantum interference effects. Indeed, the classical object of metamaterials research—the ubiquitous split-ring metamolecule—has much in common with the fundamental unit of superconductivity, the Josephson junction ring.

An array of superconducting Josephson rings could be a truly quantum metamaterial, where each metamolecule is a multilevel quantum system supporting phase qubits. However, applications of superconducting metamaterials will be limited to the microwave domain for niobium-based metamaterials, and to the terahertz spectral domain if high-temperature superconductors are used. This is because higher frequencies destroy the superconducting phase.

Researchers have demonstrated the fabrication of metamaterials from niobium films and the use of patterned high-critical-temperature perovskite-related cuprates. However, the manufacture of large metamaterial arrays of Josephson rings is a highly sophisticated process that is not yet widely available. The table on p. 33 presents a comparison between conventional metamaterials that support classical plasmonic excitations and future superconducting metamaterials. Note that the cryo-cooling requirement for superconductors is no longer a serious technological limitation as compact cryo devices are now widely deployed in telecommunications and sensing equipment.

Fabrication

No progress in metamaterials research will be possible without further developments in fabrication. New techniques will be needed to achieve close-to-molecular perfection in nanostructures, and they must be inexpensive. We need to go beyond electron-beam lithography, focused ion beam milling and nanoimprint. Most of the research so far has dealt with quasi-two-dimensional metamaterial structures or few-layer assemblies. The real challenge is to create truly volume metamaterials, and a great deal of inspiring and creative effort is now being concentrated on that. This includes prototyping of metamaterials using sophisticated two-photon resist polymerization techniques followed by metalizing the dielectric framework or directly releasing metallic silver from a silver halide through a two-photon absorption process.

Another promising approach is membrane projection lithography, which enables the creation of nearly arbitrary metamaterial unit cells with metal inclusions (such as split-rings) along each of the coordinate axes. Recently introduced three-dimensional indented (“intaglio”) or raised (“bas-relief”) subwavelength “continuous-metal” metamaterials offer interesting opportunities for controlling the electromagnetic properties of surfaces. They may easily be manufactured by focused ion-beam milling or high-throughput nanoimprint lithography. The fabrication of complex volume metamaterial structures also opens radical new opportunities such as the exploitation of intriguing toroidal electromagnetic excitations.

Some research groups are exploring self-assembly strategies for fabricating metamaterials. For instance, one may overcome the limitation of inherently two-dimensional lithographic processes by transforming prepatterned lithographic templates into mechanically robust and precisely patterned three-dimensional nanoscale structures. This can be done by curving, rotating, aligning and bonding them using forces derived from a minimization of surface area of liquefying or coalescing metallic grains.
The past and the future of metamaterials

Metamaterials have undergone a remarkable evolution, from primitive frequency-selective microwave surfaces to today’s three-dimensional plasmonic nanostructures created by sophisticated metalworking techniques such as e-beam lithography and focused ion-beam milling. The future of metamaterials will be in developing nonlinear, switchable, gain and quantum metamaterials and media for energy and sensing applications, which will be achieved by adopting new materials (such as superconductors or graphene) and hybridizing plasmonics metal nanostructures with other functional materials such as nanocarbon, organics, nanosemiconductors, organic polymers and phase-change media.

The current trend is to think of metamaterials as devices, where the structuring of metal and the hybridization with functional agents brings new functionality and response becomes tuneable, switchable or nonlinear. In the near future, we will be able to enter the field of quantum metamaterials. Moreover, by exploiting the concept of transformation optics, metamaterials with spatially variable parameters and active metamolecular switches imbedded in the strategic location will allow combining complex quantum-level switching and memory functions with the waveguiding of electromagnetic radiation across the body of a metamaterial volume. Rather than materials or devices, we will begin to think of metamaterials as dynamic systems.

References and Resources

- B. Luk’yanchuk et al. Nat. Materials 9, 707 (2010).