Engineered materials composed of designed inclusions can exhibit exotic and unique electromagnetic properties not inherent in the individual constituent components. These artificially structured composites, known as metamaterials, have the potential to fill critical voids in the electromagnetic spectrum where material response is limited and enable the construction of novel devices. Recently, metamaterials that display negative refractive index – a property not found in any known naturally occurring material – have drawn significant scientific interest, underscoring the remarkable potential of metamaterials to facilitate new developments in electromagnetism.
which is defined as $n(\omega)$, for most materials, the two complex quantities which are the electric component of light and the other, $\mu(\omega)$, to the magnetic component at a frequency $\omega$. Both of these parameters are typically frequency-dependent complex quantities, and thus there are in total four numbers that completely describe the response of an isotropic material to EM radiation at a given frequency, $\varepsilon(\omega) = \varepsilon_r(\omega) + i\varepsilon_i(\omega)$ (1)

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A commonly used EM parameter is that of the index of refraction, which is defined as $n(\omega)^2 = \varepsilon(\omega)\mu(\omega)$. The index of refraction provides a measure of the speed of an EM wave as it propagates within a material. In addition, the refractive index also provides a measure of the deflection of a beam of light as it crosses the interface between two materials having different values for their refractive indices. The quantitative measure of this bending was provided by Willebrord Snell in 1621, who showed that, $n_1\sin\theta_1 = n_2\sin\theta_2$. (2)

EM response of materials

To understand MMs, it is necessary to understand material response to EM waves in general: EM response in homogeneous materials is predominantly governed by two parameters. One of these parameters, $\varepsilon(\omega)$, describes the response of a material to the electric component of light (or other EM wave) and the other, $\mu(\omega)$, to the magnetic component at a frequency $\omega$. Both of these parameters are typically frequency-dependent complex quantities, and thus there are in total four numbers that completely describe the response of an isotropic material to EM radiation at a given frequency, $\varepsilon(\omega) = \varepsilon_r(\omega) + i\varepsilon_i(\omega)$ (1)

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constructed material or composite having distinct and possibly superior properties as compared with the constituent materials from which it is composed. Other types of media exist to which this term might equally well apply. Photonic crystals, for example, are periodic dielectric or metallic structures capable of achieving negative phase velocity and thus NI. However, these structures are not easily described by bulk parameters such as $\varepsilon$ and $\mu$, and hence we exclude them from our discussion\textsuperscript{20-23}. Rather, we are concerned here with those artificial structures that can be viewed as homogeneous, described by values of $\varepsilon$ and $\mu$. The desired material consists of an array of subwavelength elements, designed independently to respond preferentially to the electric or magnetic component of an EM wave. To describe the conceptual basis of a NI MM, it is first useful to summarize the design of the constituent magnetic and electric elements that respectively give rise to negative $\mu$ and negative $\varepsilon$.

**Magnetic response**

The split ring resonator (SRR) has been the element typically used for response to the magnetic component of the EM field. This ‘magnetic atom’ was proposed by Pendry in 1999\textsuperscript{2}. In Fig. 2a we show a schematic of this MM and in Fig. 2b how this element is arranged in an array to form an effective magnetic material. In the simplest representation, the SRR can be thought of as an LC resonator. A time varying magnetic field polarized perpendicular to the plane of the SRR will induce circulating currents according to Faraday’s law. Because of the split gap in the SRR, this circulating current will result in a build up of charge across the gap with the energy stored as a capacitance. The SRR can thus be viewed as a simple LC circuit, with a resonance frequency of $f_0 = \sqrt{1/\varepsilon C}$, where the inductance results from the current path of the SRR. For frequencies below $f_0$, currents in the SRR can keep up with the driving force produced by the externally varying magnetic field and a positive response is achieved. However, as the rate of change (frequency) of the external magnetic field is increased, the currents can no longer keep up and eventually begin to lag, resulting in an out-of-phase or negative response.

The general form of the frequency dependent permeability of the SRR\textsuperscript{19} has the generic form

$$\mu_{eff}(\omega) = 1 + \frac{F\omega^2}{\omega_0^2 - \omega^2 - i\Gamma\omega}$$

The elements used for construction of MMs are shown in Fig. 2. In (a) we show an SRR with an external magnetic field incident upon it. When the SRR shown in (a) is arranged into an array (b), it behaves as an effective material and described by a magnetic response. In (c) we show a medium used for electric response, the straight wire medium. A new element used for electric response is shown in (d). The orientation of the external electric field is shown. This new electric particle is also arranged in a planar array for an effective response.
Negative refractive index metamaterials

**Box 1**
The index of refraction is a product of two complex functions, ε(ω) and µ(ω). By representing the magnetic and electric response functions by Lorentz oscillators (eq 4) in complex form we see that the index squared is \( n^2 = (\varepsilon - \varepsilon_0)/\varepsilon_0\). The complex index of refraction then becomes \( n = \sqrt{\varepsilon(\omega)/\mu(\omega)}\). Note the phase of the index of refraction is simply the average of the phases of the magnetic permeability and the electric permittivity, i.e. \( \theta_n = (\theta_\varepsilon + \theta_\mu)/2\). This indicates that the vector describing the index of refraction must lie in quadrant I of the complex space. Thus finally we see that although there is ambiguity in which sign to take for the real part of the index, i.e. \( n = n_1 + in_2 = \pm \sqrt{\varepsilon(\omega)/\mu(\omega)}\), when we consider causal functions it is clear that the index of refraction is required to be negative \( n_1 < 0\).

**Electric response**

Naturally occurring materials that yield a negative response to the electric component of light have been known for several decades. Any metal below its plasma frequency (the frequency at which it becomes transparent) yields negative values of the permittivity. This \( \varepsilon_1 < 0\) response results from the free electrons in the metal that screen external EM radiation. But a bulk metal is not the only material that exhibits negative electric response; a distributed array of conductors, or even a grating on a conductor, can give the same result. Many decades ago researchers fabricated structures having \( \varepsilon < 0\) using arrays of conducting wires and other unique shapes.\(^{11,17}\) This technology was recently reintroduced with a more physics-oriented understanding\(^{18,29}\).

Currently, variations of the wire lattice being used to create \( \varepsilon_1 < 0\) media include straight wires, cut-wire segments, and loop wires.\(^{20}\) A straight wire medium is depicted in Fig. 2c. In addition, there have been further advances in the development of electric MMs with new designs analogous to the SRR being demonstrated (Fig. 2c).\(^{21,22}\)

**Negative index metamaterials**

Having identified artificial structures that can separately provide \( \varepsilon_1 < 0\) and \( \mu_1 < 0\), we can combine the two, according to Veselago’s prescription, and construct a material with \( n < 0\). But what, if anything, is actually unusual about a NI material?

Veselago pointed out that a medium having an NI of refraction would essentially add a new twist to virtually every EM phenomenon. The phase velocity of a wave is reversed in NI materials; the Doppler shift of a source relative to a receiver is reversed. Cerenkov radiation emitted by a moving charged particle is in the backward rather than the forward direction; radiation pressure is reversed to become a radiation tension; converging lenses become diverging lenses and vice versa. These are just some of the changes to basic EM phenomena that would result in a NI material.

As intriguing as Veselago’s predictions were, naturally occurring materials with a NI were not known at the time and his results remained largely overlooked. However, in 2000 Smith et al.\(^{1}\) fabricated an NI material using artificially constructed MMs. This NI MM
Negative refractive index metamaterials

Mathematically, all EM sources can be expressed as a superposition of propagating plane waves and exponentially decaying near-fields. These exponentially decaying terms cannot be recovered by any known positive index lens. Since the near field is responsible for conveying the finest details of an object, their absence limits the resolution of positive index lens. Since the near field is responsible for conveying the finest details of an object, their absence limits the resolution of positive index lens.

In 2004, Grbic and Eleftheriades demonstrated experimentally subwavelength focusing with a NI material. This microwave experiment was performed near 1 GHz and showed the ability of a planar left-handed lens, with a relative refractive index of -1, to form images that overcome the diffraction limit. The NI lens consists of a planar slab constructed from a grid of printed metallic strips over a ground plane, loaded with series capacitors and shunt inductors. The measured half-power beamwidth of the point source image formed by the NI lens is 0.21 effective wavelengths, which is significantly narrower than that of the diffraction-limited image corresponding to 0.36 wavelengths.

In the right panel of Fig. 1, we show how this focusing occurs for a medium of $n = -1$. In the top portion of Fig. 1, a ray tracing diagram shows how rays are focused by the slab. But the ray tracing picture leaves out the evanescent, or exponentially decaying, components. The diagram in the bottom right of Fig. 1 shows an evanescent component that is, in some sense amplified, by the slab – growing exponentially as a function of distance and then decaying exponentially until it reaches its original magnitude at the image.

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Natural materials

While the most familiar examples of NI materials have made use of artificially patterned MMs, combinations of naturally occurring...
Fig. 4 Summary of MM results from RF to near optical frequencies. In the left column we detail the frequency range in which each MM was demonstrated and note the reference number in this review. The middle column shows a photo of the MM from each publication, and the third column shows some data detailing the MM response. The top row is an investigation of ‘swiss-roll’-type magnetic structures to guide magnetic flux in magnetic resonance imaging machines. The second row is the original work in which NI materials were discovered at microwave frequencies. The third row shows some recent work on MMs at millimeter-wave frequencies. The next column details the first work extending MMs out of the microwave into the terahertz regime. The bottom two columns show further extension of the SRR magnetic MM medium to MIR and NIR frequencies. [Part (a) reproduced with permission from© 2001 American Association for the Advancement of Science (AAAS). Part (b) reproduced with permission from© 2000 American Physical Society (APS). Part (c) reproduced with permission from© 2004 AAAS. Part (d) reproduced with permission from© 2004 AAAS. Part (e) reproduced with permission from© 2005 APS.]
materials may yet play a role in negative refraction. Recently, it has been demonstrated that an NI can be exhibited by magnetodielectric spherical particles, superlattices of natural materials, and uniaxial crystals. There are many theoretical suggestions of various other methods one might use to achieve an NI at NIR and optical frequencies. It is worthwhile to note that although the NI in these materials comes about ‘naturally’, since these materials are engineered or special cases they can also be considered MMs, as they are constructed in particular shapes and/or combinations. In Fig. 5, we show one example of a NI material constructed from natural elements – insulating magnetodielectric spherical particles embedded in a background dielectric material. The effective permeability and permittivity of the mixture has been shown to be simultaneously negative at a particular frequency, thus exhibiting NI.

Tunable metamaterials

As emphasized above, all current implementations of NI media have been accomplished over a narrow frequency range in the vicinity of the resonant frequency \( \omega_0 \). The latter parameter is rigidly determined by the geometrical dimensions of the SRR and possibly other elements used to construct NIMs. Both from the viewpoint of applications, as well as for the purpose of the understanding of the intrinsic properties of negative media, it is desirable to implement structures with tunable and reconfigurable resonant properties. Some possible solutions to this intriguing problem have been proposed recently.

The SRR structure is interesting not just for its magnetic properties, but also because large electric fields can potentially build up in the gap region between the rings. Methods that alter the local dielectric environment, then, have the potential to shift the resonant frequency of the SRR, which has the approximate analytic form:

\[
\omega_0 = \sqrt{1/\varepsilon_0 \mu_0 C r^3}
\]

where \( r \) is the ring radius, \( \mu_0 \) is the static magnetic permeability, and \( C \) is the capacitance per unit area between the two rings. Detailed simulations have confirmed that the resonant frequency of the SRR is indeed very sensitive to the SRR capacitance, which in turn depends on the value of the dielectric constant of the substrate \( \varepsilon_s \). The frequency of operation of the SRR thus scales as \( (1/\sqrt{\varepsilon_s}) \), modify the substrate dielectric value and the resonant permeability will shift accordingly. This form of dynamic tuning has been accomplished recently by Padilla et al., who control and modify the substrate dielectric by photodoping an SRR array patterned on an insulating GaAs substrate. A 50 fs pulse of 800 nm light is used to excite photocarriers across the band gap of the GaAs substrate. Because photodoped charges are relatively long lived (1 ns), the quasi-steady state response of the composite MM sample can be studied using terahertz time domain spectroscopy. Representative data from this work are displayed in Fig. 6. In this particular experiment, the conductivity arising from mobile photocharges shunts the low-frequency resonance at \( \omega_0 = 0.5 \) THz associated with circulating (magnetic) currents, whereas the higher energy (electric) mode at \( \omega_1 = 1.6 \) THz remains nearly unaffected. This work has revealed the potential of SRR/semiconductor hybrid structures to develop terahertz switches. Response times in the 1-10 ps range would be possible provided materials with faster recombination times are used as the substrate.

Alternative ways of tuning NI materials can be realized by integrating SRR arrays into a metal-insulator-semiconductor (MIS) architecture. Applying a dc electric field between the ring arrays and a semiconducting substrate allows tuning of the dielectric constant of the insulating layer in the MIS device, provided the insulator is fabricated from a high dielectric constant or ferroelectric material. In order to maintain the electric field across the insulator in the area within the split gaps of the SRRs, it is desirable to fill these structures with semiconducting polymers. Charge injection into a polymer allows one to achieve an electric field in MIS structures over large areas.

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Fig. 5 MM constructed from natural materials, magnetodielectric spherical particles embedded in a matrix, which exhibits an NI.

Fig. 6 Transmission spectra as a function of photodoping fluence for the electric resonance of the SRRs. Free carriers in the substrate short out the gap of the SRR and eventually kill the resonant response. (Reprinted with permission from35. © 2006 American Physical Society.)
without appreciably changing the dc conductivity of the polymer. Therefore, in MS-based devices the dielectric constant and therefore the resonant frequency can be tuned by varying the applied dc voltage. One can envision that each of the rings in an SRR array could allow one to achieve the controlled distribution of the resonant frequencies over a planar array, thus in principle enabling reconfigurable lenses and other microwave/terahertz components.

Outlook: devices and limitations

In this review we have stressed the novelty of EM-MMs and shown the great flexibility that we now have to design materials with the power to control EM radiation. The ‘knobs’ available to control the two components of EM radiation individually form the basis for such versatility and provide significant advantages over, for example, photonic band gap media. However, there are limitations to the amount of ‘tuning’ of which these materials are capable.

The SRR shown in Fig. 2 depends upon the ‘bulk’ conductivity of a metal. That is, we need macroscopically circulating currents in order to exhibit an effective magnetic response. At optical and ultraviolet wavelengths, metals become transparent to light and thus lose their metallic ‘free-electron’-like properties, including their conductivity. It is expected therefore that EM-MMs will not work at such high frequencies. Also, since wavelength and frequency scale inversely, the cell-size-to-wavelength parameter, λcell/λ << 1, is no longer satisfied and we are thus not in the effective material regime. Both of the above limitations seem to indicate that EM-MMs will begin to fail for increasing frequencies somewhere around the optical range. However, natural losses in metals will likely contribute to the degradation of the effective material response and the real limitation may be somewhere in the NIR regime. If we wish to overcome these limitations, we must consider different paradigms in the design of artificial magnetic response or alternatively seek methods to compensate for these losses, i.e. active materials.

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23. Material parameters are often only considered to depend upon the frequency, e.g. ε(ω) and µ(ω). However they are in general functions of both frequency and the wave vector k(ω) and p(ω). For small values of k they can still be approximated and described by ε(ω) and µ(ω). However, if the size of the object is about the same as the wavelength or larger, then there is a significant dependence of the material parameters on k, and it is no longer correct to describe the properties of the material by material parameters that ascribe a separate electric ε(ω) and magnetic µ(ω) dependence.

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