

# Metamaterials Handbook

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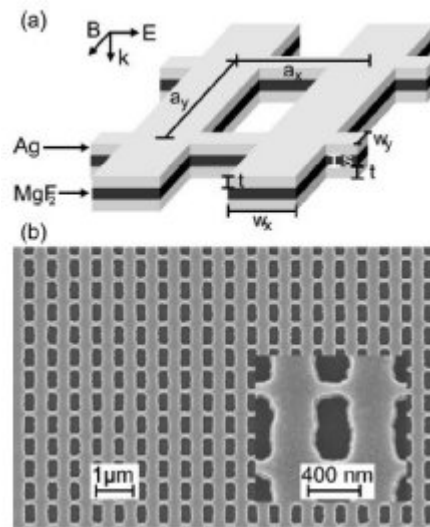
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## Chapter- 1

# Metamaterial



Schematic diagram for light bending metamaterial, at 1.5 micron wavelength. Courtesy of G. Dolling et al., Opt. Lett. 31, 1800 (2006).

**Metamaterials** are artificial materials engineered to have properties that may not be found in nature. Metamaterials usually gain their properties from structure rather than composition, using small inhomogeneities to create effective macroscopic behavior.

The primary research in metamaterials investigates materials with negative refractive index. Negative refractive index materials appear to permit the creation of superlenses which can have a spatial resolution below that of the wavelength. In other work, a form of 'invisibility' has been demonstrated at least over a narrow wave band with gradient-index materials. Although the first metamaterials were electromagnetic, acoustic and seismic metamaterials are also areas of active research.

Potential applications of metamaterials are diverse and include remote aerospace applications, sensor detection and infrastructure monitoring, smart solar power management, public safety, radomes, high-frequency battlefield communication and lenses for high-gain antennas, improving ultrasonic sensors, and even shielding structures from earthquakes.

The research in metamaterials is interdisciplinary and involves such fields as electrical engineering, electromagnetics, solid state physics, microwave and antennae engineering, optoelectronics, classic optics, material sciences, semiconductor engineering, nanoscience and others.

## **Electromagnetic metamaterials**

Metamaterials have become a new subdiscipline within physics and electromagnetism (especially optics and photonics).

They show promise for optical and microwave applications such as new types of beam steerers, modulators, band-pass filters, lenses, microwave couplers, and antenna systems. Metamaterials consist of periodic structures.

An electromagnetic metamaterial affects electromagnetic waves by having structural features smaller than the wavelength of light. In addition, if a metamaterial is to behave as a homogeneous material accurately described by an effective refractive index, its features must be much smaller than the wavelength. To date, subwavelength structures have shown only a few questionable results at visible wavelengths.

For microwave radiation, the structures need only be on the order of few centimeters. Microwave frequency metamaterials are usually synthetic, constructed as arrays of electrically conductive elements (such as loops of wire) which have suitable inductive and capacitive characteristics. These are known as split-ring resonators.

Another structure which can exhibit subwavelength characteristics are frequency selective surfaces (FSS) known as Artificial Magnetic Conductors (AMC) or alternately called High Impedance Surfaces (HIS). These also have inductive and capacitive characteristics, which are directly related to its subwavelength structure.

Photonic crystals and frequency-selective surfaces such as diffraction gratings, dielectric mirrors, and optical coatings do have apparent similarities to subwavelength structured metamaterials. However, these are usually considered distinct from subwavelength structures, as their features are structured for the wavelength at which they function, and thus cannot be approximated as a homogeneous material.

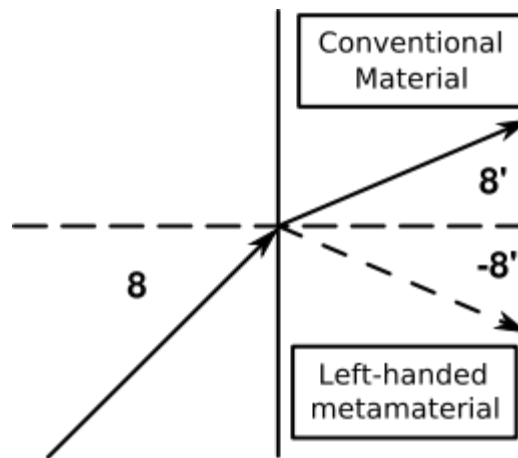
However, novel-material structures such as photonic crystals are effective with the visible light spectrum. The middle of the visible spectrum has a wavelength of approximately 560 nm (for sunlight), the photonic crystal structures are generally half this size or smaller, that is <280 nm.

Winston E. Kock developed materials that had similar characteristics to metamaterials in the late 1940s. Materials, which exhibited reversed physical characteristics were first described theoretically by Victor Veselago in 1967. A little over 30 years later, in the year 2000, Smith et al. reported the experimental demonstration of functioning electromagnetic metamaterials by horizontally stacking, periodically, split-ring resonators

and thin wire structures. Later, a method was provided in 2002 to realize negative index metamaterials using artificial lumped-element loaded transmission lines in microstrip technology. At microwave frequencies, the first real invisibility cloak was realized in 2006. However, only a very small object was imperfectly hidden.

In 2007, one researcher stated that for metamaterial applications to be realized, several goals must be achieved. Reducing energy loss, which is a major limiting factor, keep developing three-dimensional isotropic materials instead of planar structures, then finding ways to mass produce.

## Negative refractive index



A comparison of refraction in a left-handed metamaterial to that in a normal material

The greatest potential of metamaterials is the possibility to create a structure with a negative refractive index, since this property is not found in any non-synthetic material. Almost all materials encountered in optics, such as glass or water, have positive values for both permittivity  $\epsilon$  and permeability  $\mu$ . However, many metals (such as silver and gold) have negative  $\epsilon$  at visible wavelengths. A material having either (but not both)  $\epsilon$  or  $\mu$  negative is opaque to electromagnetic radiation.

Although the optical properties of a transparent material are fully specified by the parameters  $\epsilon$  and  $\mu$ , refractive index  $n$  is often used in practice, which can be determined from  $n = \pm\sqrt{\epsilon\mu}$ . All known non-metamaterial transparent materials possess positive  $\epsilon$  and  $\mu$ . By convention the positive square root is used for  $n$ .

However, some engineered metamaterials have  $\epsilon < 0$  and  $\mu < 0$ . Because the product  $\epsilon\mu$  is positive,  $n$  is real. Under such circumstances, it is necessary to take the negative square root for  $n$ . Physicist Victor Veselago proved that such substances can transmit light.



Negative refraction of light at uniform planar interface

The foregoing considerations are simplistic for actual materials, which must have complex-valued  $\epsilon$  and  $\mu$ . The real parts of both  $\epsilon$  and  $\mu$  do not have to be negative for a passive material to display negative refraction. Metamaterials with negative  $n$  have numerous interesting properties:

- Snell's law ( $n_1 \sin \theta_1 = n_2 \sin \theta_2$ ), but as  $n_2$  is negative, the rays will be refracted on the *same* side of the normal on entering the material.
- The Doppler shift is reversed: that is, a light source moving toward an observer appears to reduce its frequency.
- Cherenkov radiation points the other way.
- The time-averaged Poynting vector is antiparallel to phase velocity. This means that unlike a normal right-handed material, the wave fronts are moving in the opposite direction to the flow of energy.

For plane waves propagating in electromagnetic metamaterials, the electric field, magnetic field and wave vector follow a left-hand rule. This is a reversal of direction when compared to the behavior of conventional optical materials.

Negative refractive index is an important characteristic in metamaterial design and fabrication. As reverse-refraction media, these occur when both permittivity  $\epsilon$  and permeability  $\mu$  are negative. Furthermore, this condition occurs mathematically from the vector triplet  $\mathbf{E}$ ,  $\mathbf{H}$  and  $\mathbf{k}$ .

In ordinary, everyday materials - solid, liquid, or gas; transparent or opaque; conductor or insulator - the conventional refractive index dominates. This means that permittivity and permeability are both positive resulting in an ordinary index of refraction. However, metamaterials have the capability to exhibit a state where both permittivity and permeability are negative, resulting in an extraordinary, index of negative refraction.

## Different classes of electromagnetic metamaterials

With metamaterials, the lower density of materials means that components, devices, and systems can be lightweight and small, while at the same time enhancing system and component performance.

The border between synthetic materials and metamaterials is vague and novel properties are being discovered in natural materials. This is because unusual properties are also produced in conventional materials by processing them at nanoscales. However, a distinguishing feature of metamaterials is that they can be specifically fabricated to fulfill a certain objective and to fit the desired application. The size and spacing of elements in the material are created smaller than the radiated wavelength. Consequently, incident radiation cannot distinguish the collection of elements from a homogeneous material.

Electromagnetic metamaterials have also been synthesized by embedding various constituents/inclusions with novel geometric shapes and forms in some host media. In this type of composite media electromagnetic waves interact with the designed inclusions, inducing electric and magnetic moments, which in turn affect the macroscopic effective permittivity and permeability of this, bulk composite "medium".

Since electromagnetic metamaterials can be synthesized by embedding artificially fabricated inclusions (as large-scale artificial atoms) in a specified host medium, or on a host surface, this provides the designer with a large set of available, independent parameters. Those parameters define how the metamaterial is to be engineered. They include the properties of the host materials, and the size, shape, and composition of the inclusions. Other parameters to consider are the density, arrangement, and alignment of these inclusions. By defining all these parameters during fabrication, a metamaterial is engineered for specific electromagnetic responses. Additionally, these responses are not found in the individual constituents. All these design parameters can play a key role in the final outcome of the synthesis process.

Various types of composite material, both electromagnetic and other types are being studied by various research groups worldwide. Electromagnetic metamaterials are represented by different classes, as follows:

### Negative index materials

In *negative index metamaterials* (NIM), both permittivity and permeability are negative resulting in a negative index of refraction. Hence, because of the double negative parameters these are also known as Double Negative Metmaterials or double negative materials (DNG) Other terminologies for NIMs are "left-handed media", "media with a negative refractive index", and "backward-wave media", along with other nomenclatures.

In optical materials, if both permittivity  $\epsilon$  and permeability  $\mu$  are positive this results in propagation in the *forward* direction. If both  $\epsilon$  and  $\mu$  are negative, a *backward* wave is produced. If  $\epsilon$  and  $\mu$  have different polarities, then this does not result in wave

propagation. Mathematically, quadrant II and quadrant IV have coordinates (0,0) in a coordinate plane where  $\epsilon$  is the horizontal axis, and  $\mu$  is the vertical axis.

In 1968 Victor Veselago published a paper theorizing plane wave propagation in a material whose permittivity and permeability were assumed to be simultaneously negative. In such a material, he showed that the phase velocity would be anti-parallel to the direction of poynting vector. This is contrary to wave propagation in natural occurring materials. In the years 2000 and 2001, papers were published about the first demonstrations of an artificial material that produced a negative index of refraction. By 2007, research experiments which involved negative refractive index had been conducted by many groups.

To date, materials exhibiting a negative index of refraction have only been demonstrated as artificially constructed materials.

### **Single negative metamaterials**

In single negative (SNG) metamaterials either permittivity or permeability are negative, but not both. These are ENG metamaterials and MNG metamaterials discussed below. Interesting experiments have been conducted by combining two SNG layers into one metamaterial. These effectively create another form of DNG metamaterial. A slab of ENG material and slab of MNG material have been joined to conduct wave reflection experiments. This resulted in the exhibition of properties such as resonances, anomalous tunneling, transparency, and zero reflection. Like Negative index materials, SNGs are innately dispersive, so their permittivity  $\epsilon$ , permeability  $\mu$ , and refraction index  $n$ , will alter with changes in frequency.

- Epsilon negative media (ENG) – permittivity  $\epsilon$  is negative while permeability  $\mu$  is positive. Many plasmas exhibit this characteristic. For example noble metals such as gold or silver will exhibit this characteristic in the infrared and visible spectrums.
- Mu-negative media (MNG) – permittivity  $\epsilon$  is positive while permeability  $\mu$  is negative. A material, which called *gyrotropic* or *gyromagnetic* exhibits this characteristic. A *gyrotropic* material is a medium that has been altered by the presence of a quasistatic magnetic field. This results in the *magneto-optic effect*. A *magneto-optic effect* is any one of a number of phenomena in which an electromagnetic wave propagates through a medium that has been altered by the presence of a quasistatic magnetic field. In such a material, left- and right-rotating elliptical polarizations can propagate at different speeds, leading to a number of important phenomena. When light is transmitted through a layer of magneto-optic material, the result is called the Faraday effect: the plane of polarization can be rotated, forming a Faraday rotator. The results of reflection from a magneto-optic material are known as the magneto-optic Kerr effect. Two gyrotropic materials with reversed rotation directions of the two principal polarizations are called optical isomers.

## Electromagnetic bandgap metamaterials

Electromagnetic bandgap metamaterials control the propagation of light. This is accomplished with either a class of metamaterial known as photonic crystals (PC), or another class known as left-handed materials (LHM). Both are a novel class of artificially engineered structure, and both control and manipulate the propagation of electromagnetic waves (light). PCs can prohibit light propagation altogether. However, both the PC and LHM are capable of allowing it to propagate in certain, designed directions, and both can be designed to have electromagnetic bandgaps at desired frequencies.

In addition, metamaterials such as Photonic crystals (PC) are complex, periodic, materials and are considered to be electromagnetic bandgap material. However, a PC is at first distinguished from sub-wavelength structures, such as tunable metamaterials, because the PC derives its properties from its band gap characteristics. In addition the PC operates at the wavelength of light, compared to other metamaterials which operate as a sub-wavelength structure. Furthermore, the complex response of photonic crystals functions by diffracting light. In contrast, a permittivity and permeability defines metamaterials (also a complex response), which is derived from their sub-wavelength structure and diffraction must be eliminated.

The PC is also a material in which periodic inclusions inhibit wave propagation due to destructive interference from scattering from the periodic repetition. The photonic bandgap property of PCs makes them the EM analog of the electronic semi-conductor crystals.

Intended material fabrication of EBGs has the goal of creating periodic, dielectric structures, with low loss, and that are of high quality. An EBG affects the properties of the photon in the same way semiconductor materials affect the properties of the electron. So, it happens that the PC is the perfect bandgap material, because it allows no propagation of light. Each unit of the prescribed periodic structure acts like large scale atoms.

Electromagnetic bandgap structured (EBG) metamaterials are designed to prevent the propagation of an allocated bandwidth of frequencies, for certain arrival angles and polarizations. With *EBG materials* new methods utilize the properties of various dielectrics to achieve better performance. A variety of geometries and structures have been proposed to fabricate the special *EBG metamaterial* properties. However, in practice it is impossible to build a flawless EBG device. Factors such as advances in ideas, research, testing and development, along with the prospects of significant technological solutions, have driven the development of EBG applied science.

Commercial production of dielectric EBG devices has lagged, because commercial rewards are not readily apparent. However, start-up companies are cropping up solely focused on exploiting EBG metamaterials. These metamaterials have been manufactured for frequencies ranging from a few gigahertz (GHz) up to several terahertz (THz). In other words, applications have achieved fabricated media for radio frequency, microwave

and mid-infrared regions. "It now appears that EBG concepts can, in many cases act as improved replacements for conventional solutions to electromagnetic problems." Applicable developments include an EBG transmission line, fabricated utilizing the special properties of metamaterials, EBG woodpiles made of square dielectric bars, and several different types of low gain antennas.

An EBG is a result of a metamaterial that functions in the regime where the period is an appreciable amount of the wavelength, and constructive and destructive interference occur.

### **Double positive medium**

Double positive mediums (DPS) do occur in nature such as naturally occurring dielectrics. Permittivity and magnetic permeability are both positive and wave propagation is in the forward direction. Artificial materials have been fabricated which have DPS, ENG, and MNG properties combined.

### **Bi-isotropic and bianisotropic metamaterials**

Categorizing metamaterials into double or single negative, or double positive, is normally done based on the assumption that the metamaterial has independent electric and magnetic responses described by the parameters  $\epsilon$  and  $\mu$ . However in many examples of electromagnetic metamaterials, the electric field causes magnetic polarization, and the magnetic field induces an electrical polarization, i.e., magnetoelectric coupling. Such media are denoted as being bi-isotropic. Media which exhibit magneto-electric coupling, and which are also anisotropic (which is the case for many commonly used metamaterial structures), are referred to as bi-anisotropic.

Intrinsic to magnetoelectric coupling of *bi-isotropic media*, are four material parameters interacting with the electric (**E**) and magnetic (**H**) field strengths, and electric (**D**) and magnetic (**B**) flux densities. These four material parameters are  $\epsilon$ ,  $\mu$ ,  $\kappa$  and  $\chi$  or permittivity, permeability, strength of chirality, and the Tellegen parameter respectively. Furthermore, in this type of media, the material parameters do not vary with changes along a rotated coordinate system of measurements. In this way they are also defined as invariant or scalar.

The intrinsic magnetoelectric parameters,  $\kappa$  and  $\chi$ , affect the phase of the wave. Furthermore, the effect of the chirality parameter is to split the refractive index. In *isotropic media* this results in wave propagation only if  $\epsilon$  and  $\mu$  have the same sign. In bi-isotropic media with  $\chi$  assumed to be zero, and  $\kappa$  a non-zero value, different results are shown. Both a backward wave and a forward wave can occur. Alternatively, two forward waves or two backward waves can occur, depending on the strength of the chirality parameter.

## Chiral metamaterials

When a metamaterial is constructed from chiral elements then it is considered to be a chiral metamaterial, and the effective parameter  $k$  will be non-zero. This is a potential source of confusion as *within the metamaterial literature there are two conflicting uses of the terms left and right-handed*. The first refers to one of the two circularly polarized waves which are the propagating modes in chiral media. The second relates to the triplet of electric field, magnetic field and Poynting vector which arise in negative refractive index media, which in most cases are not chiral.

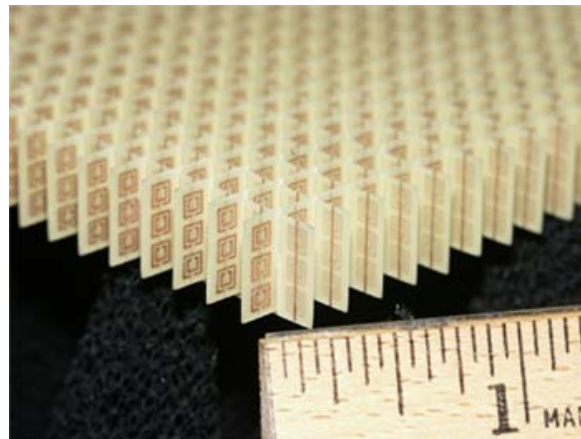
Some of the earliest structures which may be considered metamaterials date back to Jagadish Chandra Bose who in 1898 researched substances with chiral properties and to studies by Karl Ferdinand Lindman on wave interaction with metallic helices as artificial chiral media in the early twentieth century. In the 1950s and 1960s, artificial dielectrics were studied for lightweight microwave antennas. Microwave radar absorbers moved into the research arena in the 1980s and 1990s as applications for artificial chiral media.

Wave propagation properties in chiral metamaterials demonstrate that negative refraction can be realized in chiral metamaterials with a strong chirality, with neither negative  $\epsilon$  nor  $\mu$  as a requirement. This is because the refractive index of the medium has distinct values for the left and right, given by

$$n = \sqrt{\epsilon\mu} \pm \kappa$$

It can be seen that a negative index will occur *for one polarization* if  $\kappa > \sqrt{\epsilon\mu}$ . In this case, it is not necessary that either or both  $\epsilon$  and  $\mu$  be negative for *backward* wave propagation.

## Split-ring resonators



Left-handed metamaterial array configuration, which was constructed of copper split-ring resonators and wires mounted on interlocking sheets of fiberglass circuit board. The total array consists of 3 by 20×20 unit cells with overall dimensions of 10×100×100 mm.

A *split-ring resonator (SRR)* is a component part of a negative index metamaterial (NIM), also known as double negative metamaterials (DNG). They are also component parts of other types of metamaterial such as Single Negative metamaterial (SNG). SRR's are also used for research in Terahertz metamaterials, Acoustic metamaterials, and Metamaterial antennas. SRRs are a pair of concentric annular rings with splits in them at opposite ends. The rings are made of nonmagnetic metal like copper and have small gap between them.

A magnetic flux penetrating the metal rings will induce rotating currents in the rings, which produce their own flux to enhance or oppose the incident field (depending on the SRR's resonant properties). This field pattern is dipolar. Because of splits in the rings, the structure can support resonant wavelengths much larger than the diameter of the rings. This would not happen in closed rings. The small gaps between the rings produces large capacitance values which lower the resonating frequency, as the time constant is large. The dimensions of the structure are small compared to the resonant wavelength. This results in low radiative losses, and very high quality factors.

At frequencies below the resonant frequency, the real part of the magnetic permeability of the SRR becomes large (positive), and at frequencies higher than resonance it will become negative. This negative permeability can be used with the negative dielectric constant of another structure to produce negative refractive index materials.

## **Application of metamaterials**

Below are applications of metamaterials (or types of metamaterials), which are at different stages of research. *Metamaterial antennas* are commercially available.

## **Terahertz metamaterials**

Terahertz radiation lies at the far end of the infrared band, just before the start of the microwave band.

*Terahertz metamaterials* are metamaterials which interact at terahertz frequencies. For research or applications of the terahertz range for metamaterials and other materials, the frequency range is usually defined as 0.1 to 10 THz. This corresponds to the millimeter and submillimeter wavelengths between 3 mm (EHF band) and 0.03 mm (long-wavelength edge of far-infrared light).

## **Photonic metamaterials**

A *Photonic metamaterial* is an artificially fabricated, sub-wavelength, periodic structure, designed to interact with optical frequencies (mid-infrared). The sub-wavelength period distinguishes the photonic metamaterial from photonic band gap structures.

## Tunable metamaterials

A *tunable metamaterial* is a metamaterial which has the capability to arbitrarily adjust frequency changes in the refractive index at will. A tunable metamaterial encompasses the development of expanding beyond the bandwidth limitations in left-handed materials by constructing various types of metamaterials.

## Frequency selective surface (FSS) based metamaterials

*FSS based metamaterials* have become an alternative to the fixed frequency metamaterial. The former allow for optional changes of frequencies in a single medium (metamaterial), rather than the restrictive limitations of a fixed frequency response. Other applications are also being explored.

## Nonlinear metamaterials

Metamaterials may also be fabricated which include some form of nonlinear media - materials which have properties which change with the power of the incident wave. Nonlinear media are essential for nonlinear optics. However most optical materials have a relatively weak nonlinear response, meaning that their properties only change by a small amount for large changes in the intensity of the electromagnetic field. *Nonlinear metamaterials* can overcome this limitation, since the local electromagnetic fields of the inclusions in the metamaterial can be much larger than the average value of the field. In addition, exotic properties such as a negative refractive index, open up opportunities to tailor the phase matching conditions, which must be satisfied in any nonlinear optical structure.

## Metamaterial absorber

A **metamaterial absorber** manipulates the loss components of the complex effective parameters, permittivity and magnetic permeability of metamaterials, to create a high electromagnetic absorber. Loss components are often noted in applications of negative refractive index (photonic metamaterials, antenna systems metamaterials) or transformation optics (metamaterial cloaking, celestial mechanics), but often not utilized in these applications.

## Superlens

A *superlens* uses metamaterials to achieve resolution beyond the capabilities of ordinary lenses (beyond the diffraction limit). The diffraction limit is inherent in conventional optical devices or lenses.

## Cloaking devices

Metamaterials are a basis for attempting to build a practical cloaking device. The possibility of a working invisibility cloak was demonstrated on October 19, 2006. A team led by scientists at Pratt School of Engineering, Duke University has demonstrated the first working "invisibility cloak." The cloak deflects microwave beams so they flow around a "hidden" object inside with little distortion, making it appear almost as if nothing were there at all. Such a device typically involves surrounding the object to be cloaked with a shell which affects the passage of light near it. The associated report was published in the journal *Science*.

In related research, it may eventually be possible to use plasmons to cancel out visible light or electromagnetic radiation emanating from an object. This plasmonic cover would work by suppressing the scattering of light by resonating with illuminated light, which could render objects "nearly invisible to an observer." The plasmonic screen would have to be tuned to the object being hidden, and would only suppress a specific wavelength—an object made invisible in red light would still be visible in multicolored daylight.

In October 2006, a US-British team of scientists created a metamaterial which rendered an object invisible to microwave radiation. As the visible spectrum is one of the bands of electromagnetic radiation, this was considered the first step toward a cloaking device for visible light, although more advanced nanoengineering techniques would be needed due to light's short wavelengths.

On 2 April 2007, Vladimir Shalaev at Purdue University announced a theoretical design for an optical cloaking device based on the 2006 British concept. The design deploys an array of tiny needles projecting from a central spoke that would render an object within the cloak invisible for red light (wavelength of 632.8 nanometers).

In 2009, at Duke University the latest advance—a series of algorithms were developed, to guide the design and fabrication of new metamaterials. David Smith of the Duke Engineering department, comparing the 2006 device, is quoted: "The difference between the original device and the latest model is like night and day. The new device can cloak a much wider spectrum of waves—nearly limitless—and will scale far more easily to infrared and visible light. The approach we used should help us expand and improve our abilities to cloak different types of waves."

## Metamaterial antennas

*Metamaterial antennas* are a class of antennas which use metamaterials to improve the performance of the antenna systems. Applying metamaterials to increase performance of antennas has garnered much interest. Demonstrations have shown that metamaterials could enhance the radiated power of an antenna. Materials which can attain negative permeability could possibly allow for properties such as an electrically small antenna size, high directivity, and tunable operational frequency.

## Acoustic metamaterials

*Acoustic metamaterials* are artificially fabricated materials designed to control, direct, and manipulate sound in the form of sonic, infrasonic, or ultrasonic waves, as these might occur in gases, liquids, and solids. The hereditary line into acoustic metamaterials follows from theory and research in electromagnetic metamaterials. Furthermore, with acoustic metamaterials, sonic waves can now be extended to the negative refraction domain.

Control of the various forms of sound waves is mostly accomplished through the bulk modulus  $\beta$ , mass density  $\rho$ , and Chirality. The bulk modulus and density are analogies of the electromagnetic parameters, permittivity and permeability, in electromagnetic metamaterials. Related to this is the mechanics of sound wave propagation in a lattice structure. Also materials have mass, and intrinsic degrees of stiffness. Together, these form a resonant system, and the mechanical (sonic) resonance may be excited by appropriate sonic frequencies (for example pulses at audio frequencies).

## Seismic metamaterials

*Seismic metamaterials*, are metamaterials which are designed to counteract the adverse effects of seismic waves on man-made structures, which exist on or near the surface of the earth.

### Other uses

Metamaterials have been proposed for designing agile antennas. Research at the National Institute of Standards and Technology has demonstrated that thin metamaterial films can greatly reduce the size of resonating circuits that generate microwaves, potentially enabling even smaller cell phones and other microwave devices. It has been theorized that metamaterials could be built to bend matter around them because of the subatomic properties of matter. Such a matter cloak could for example bend a bullet around a person rather than absorb the impact as traditional bulletproof vests do.

## Theoretical models

Left-handed materials were first described theoretically by Victor Veselago in 1967.

John Pendry was the first to theorize a practical way to make a left-handed metamaterial. Left-handed in this context means a material in which the right-hand rule is not followed, allowing an electromagnetic wave to convey energy (have a group velocity) in the lode against its phase velocity. Pendry's initial idea was that metallic wires aligned along the direction of propagation could provide a metamaterial with negative permittivity ( $\epsilon < 0$ ). Note however that natural materials (such as ferroelectrics) were already known to exist with negative permittivity; the challenge was to construct a material which also showed negative permeability ( $\mu < 0$ ). In 1999 Pendry demonstrated that a split ring (C shape) with its axis placed along the direction of wave propagation could provide a negative

permeability. In the same paper, he showed that a periodic array of wires and ring could give rise to a negative refractive index. A related negative-permeability particle, which was also proposed by Pendry, is the Swiss roll.

The analogy is as follows: All materials are made of atoms, which are dipoles. These dipoles modify the light velocity by a factor  $n$  (the refractive index). The ring and wire units play the role of atomic dipoles: the wire acts as a ferroelectric atom, while the ring acts as an inductor  $L$  and the open section as a capacitor  $C$ . The ring as a whole therefore acts as an LC circuit. When the electromagnetic field passes through the ring, an induced current is created and the generated field is perpendicular to the magnetic field of the light. The magnetic resonance results in a negative permeability; the index is negative as well. (The lens is not truly flat, since the capacitance of the structure imposes a slope for the electric induction.)

In peer reviewed journal articles, there are several (mathematical) material models which describe frequency response in DNGs. One of these is the Lorentz model. This describes electron motion in terms of a driven-damped, harmonic oscillator. When the acceleration component of the Lorentz mathematical model is small compared to the other components of the equation, then the Debye model is applied. When the restoring force component is negligible, and the coupling coefficient is generally the plasma frequency, then the Drude model is applied. There are other component distinctions that call for the use of one of these models, depending on its polarity, or purpose.

## **Institutional networks engaged in metamaterial research**

### **Novel electromagnetic materials**

The number of groups studying metamaterials is continuously increasing. For example, Duke University has initiated an umbrella organization researching metamaterials under the banner "*Novel Electromagnetic Materials*" and became a leading metamaterials research center. The center is a part of an international team, which also includes California Institute of Technology, Harvard University, UCLA, Max Planck Institute of Germany, and the FOM Institute of the Netherlands. In addition, there are currently six groups connected to this umbrella organization, which are conducting intense metamaterial research:

### **MURI**

**MURI** stands for Multidisciplinary University Research Initiative. Tens of Universities and a few government organizations participate in the *MURI* program. A *MURI* Metamaterials web page can be found at UC Berkeley. A few other Universities which participate in MURI are UC Los Angeles, UC San Diego, Massachusetts Institute of Technology, and Imperial College in London, UK. The sponsors are Office of Naval Research (ONR) and the Defense Advanced Research Project Agency (DARPA).

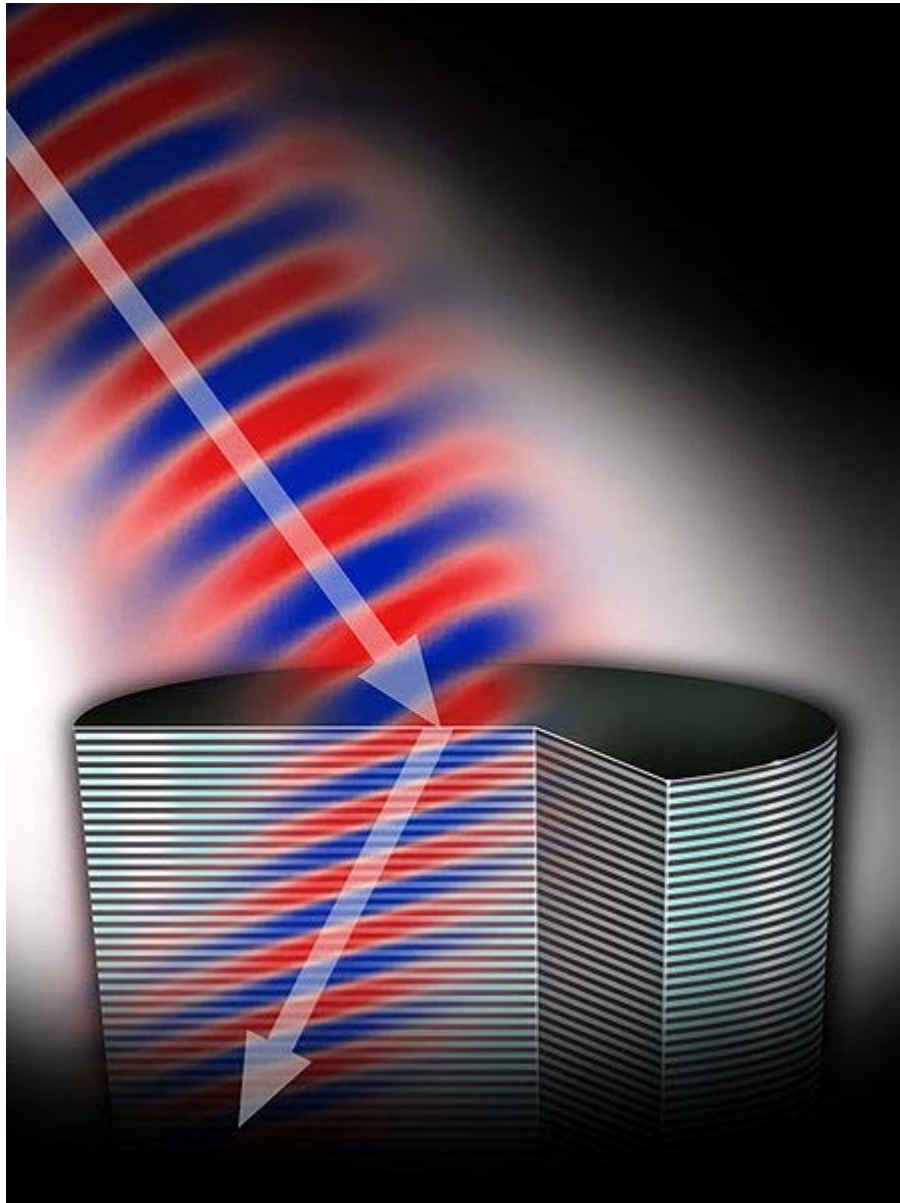
The **MURI** program supports research by teams of research investigators that intersect more than one traditional science and engineering discipline in order to accelerate both research progress and transition of research results to application. Most MURI efforts involve researchers from multiple academic institutions and academic departments. Based on the proposals selected in the fiscal 2009, a total of 69 academic institutions are expected to participate in 41 research efforts.

## **Metamorphose**

The Virtual Institute for Artificial Electromagnetic Materials and Metamaterials "*Metamorphose VI AISBL*" is a non-profit international association whose purposes are the research, the study and the promotion of artificial electromagnetic materials and metamaterials. Some of their stated main tasks are to spread excellence in this field, in particular, by organizing scientific conferences and creating specialized journals in this field; create and manage research programs in this field; activate and manage training programs (including PhD and training programs for students and industrial partners); and transfer new technology in this field to the European Industry.

## Chapter- 2

# Negative Index Metamaterials



A negative index metamaterial causes light to refract, or bend, in a manner that wouldn't occur naturally

**Negative index metamaterials** (NIMs) are artificial structures where the refractive index has a negative value over some frequency range. This does not occur in any known natural materials, and thus is only achievable with engineered structures known as *metamaterials*. Metamaterial broadly refers to any synthetic material with unusual refractive properties, among other descriptions.

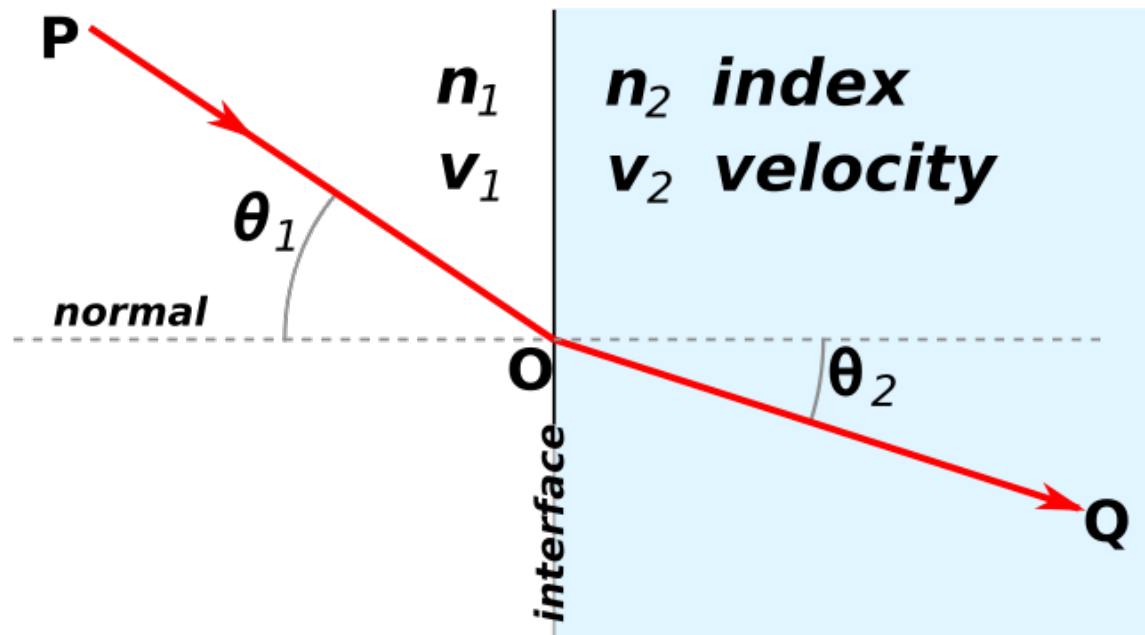
Metamaterials which exhibit a negative value for the refractive index (NIM) are often referred to by any of several names and terminologies: "left-handed media (LHM), backward wave media (BW media), media with negative refractive index, double negative (DNG) metamaterials, and other similar names.

## Overview

Metamaterials are incarnations of materials first proposed by a Russian theorist Victor Veselago in 1967. Also known as left-handed or negative index materials, the proposed materials were theorized to exhibit optical properties opposite to those of glass, air, and the other right-handed—or positive index—materials of our everyday world. In particular, energy is transported in a direction opposite to that of propagating wave fronts, rather than traveling in lockstep, as is the case in positive index materials. As a result, when juxtaposed with a positive index material, negative index materials were predicted to exhibit counter intuitive properties, like bending, or refracting, light in unnatural ways. The system exploits the bulk materials properties of each component, but the collective result is an outsize response to light. The composition of the materials are ordered in geometric arrangements with dimensions that are fractions of the wavelength of interest - microwave, infrared, or terahertz frequencies.

Furthermore, metamaterials are tailor-made composites--combinations of materials designed to achieve optical properties not seen in nature. The properties stem from the unique structure of the composites, with features smaller than the wavelength of light separated by sub-wavelength distances. By fabricating such metamaterials, researchers are attempting to overcome fundamental limits tied to the wavelength of light. Light hitting a metamaterial is transformed into electromagnetic waves of a different variety, which are shorter in wavelength than the incident light. This transformation leads to unusual and counter intuitive properties that might be harnessed for practical use.

## Manipulating permittivity and permeability



Refraction of light at the interface between two media of different refractive indices, with  $n_2 > n_1$ . Since the velocity is lower in the second medium ( $v_2 < v_1$ ), the angle of refraction  $\theta_2$  is less than the angle of incidence  $\theta_1$ ; that is, the ray in the higher-index medium is closer to the normal.

To describe any electromagnetic properties of a given material such as an optical lens, two significant parameters should be noted. These are permittivity,  $\epsilon$ , and permeability,  $\mu$ , which could allow for accurate prediction of light waves traveling within materials, and electromagnetic phenomena that occur at the surface between two materials (interface).

For example, refractive index is an electromagnetic phenomenon which occurs at the surface (or interface) between two materials. Snell's law states that the relationship between the radiated angle of incidence, and the resulting refracted angle of transmission, rests on the refractive index,  $n$ , of the two media (materials). Mathematics provides a visualization with  $n = \pm \sqrt{\epsilon\mu}$ . Hence, it can be seen that the behavior of the refractive index is dependent on the association of these two parameters, as well as their quantitative values. Therefore, if designed or arbitrarily modified values can be inputs for  $\epsilon$ , and  $\mu$  then the behavior of propagating electromagnetic waves inside the material can be manipulated at will. This capability then allows for intentional determination of the refractive index.



Negative refraction of light at uniform planar interface.

For example, in 1967, Victor Veselago analytically determined that light will refract in the reverse direction (negatively) at the interface between a material with negative refractive index and a material exhibiting conventional refractive index. This extraordinary material was realized, on paper, with simultaneous negative values for  $\epsilon$ , and,  $\mu$ , and could be termed a double negative material. However, in Veselago's day, a material which exhibits double negative parameters simultaneously seemed impossible, because no natural materials exist which can produce this effect. Therefore his work was ignored for three decades.

In general, the physical properties of natural materials cause limitations. Most dielectrics only have positive permittivities,  $\epsilon > 0$ . Metals will exhibit negative permittivity,  $\epsilon < 0$  at optical frequencies, and plasmas exhibit negative permittivity values in certain frequency bands. Pendry et al. demonstrated that the plasma frequency can be made to occur in the lower microwave frequencies for metals, with an effective medium of metal rods that replaces the bulk metal. However, in each of these cases permeability remains always positive. At microwave frequencies, it is possible for negative  $\mu$  to occur in some ferromagnetic materials. But, the inherent drawback is they are difficult to find above terahertz frequencies. In any case, a natural material that can achieve negative values for permittivity and permeability simultaneously has not been found, or discovered. Hence, all of this has led to constructing artificial composite materials known as metamaterials to achieve desired results.

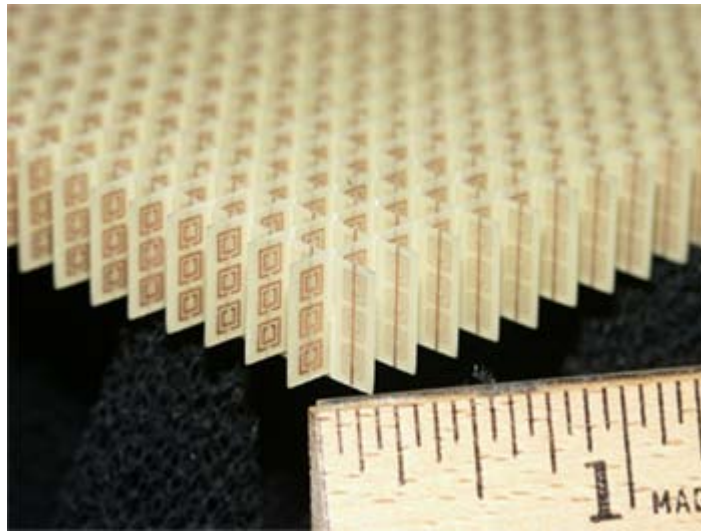
## **Physical properties never before produced in nature**

Theoretical articles were published in 1996 and 1999 which showed that artificially fabricated materials could be constructed to purposely exhibit an effective permittivity and permeability, respectively. These papers, along with Veselago's 1967 theoretical analysis of the properties of negative index materials, provided the background when

finally fabricating a metamaterial with simultaneous effective permittivity and permeability, for the first time.

Essentially, a metamaterial developed to exhibit negative index behavior is typically formed from individual components. Each component responds independently to a radiated electromagnetic wave as it travels through the material. Each component has its own response to the electric and magnetic fields of the radiated source. Since these components are smaller than the radiated wavelength it is understood that a macroscopic view includes an effective value for both permittivity and permeability.

### **Composite material**



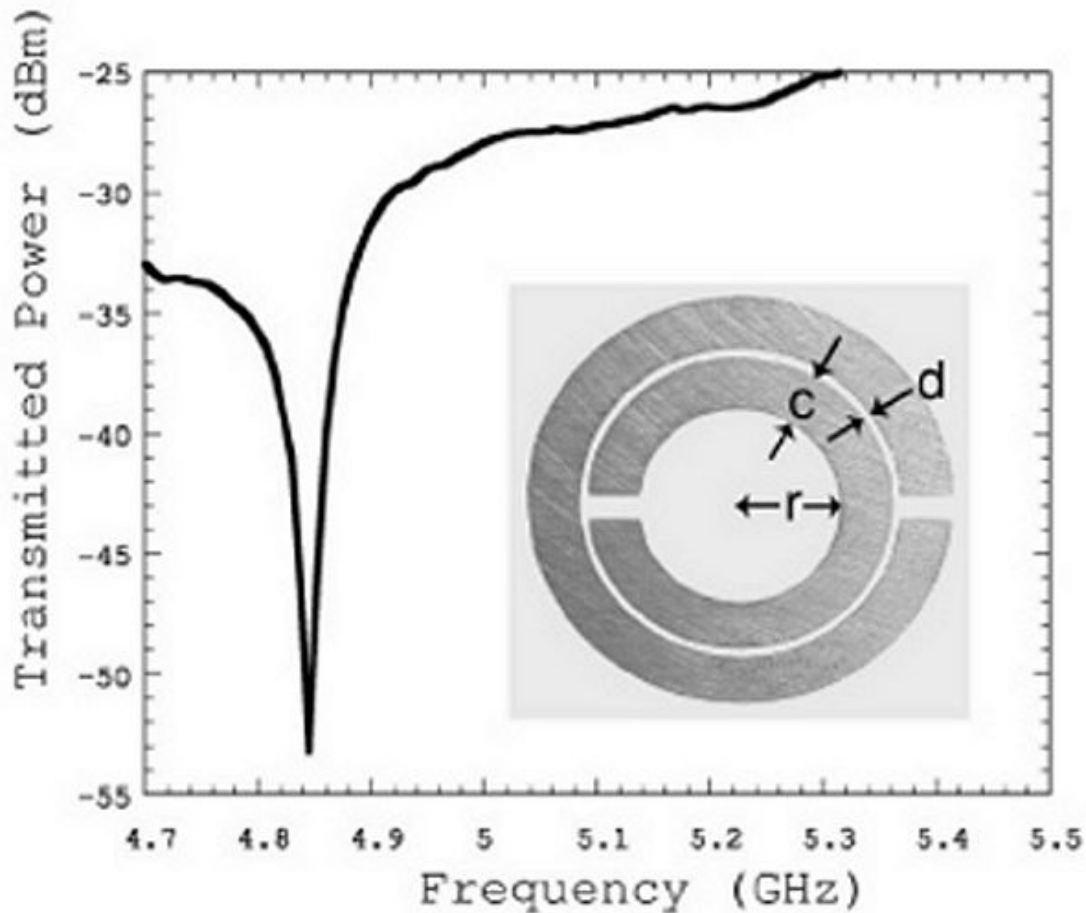
A split-ring resonator array is configured as a material that produces negative index of refraction. It was constructed of copper split-ring resonators and wires mounted on interlocking sheets of fiberglass circuit board. The total array consists of 3 by 20×20 unit cells with overall dimensions of 10×100×100 mm.

In the year 2000 a team of UCSD researchers produced a new class of composite materials which exhibited unusual physical properties that were never before produced in nature. These materials obey the laws of physics, but behave differently from normal materials. In essence these *negative index metamaterials* were noted for having the ability to reverse many of the physical properties that govern the behavior of ordinary optical materials. One of those unusual properties is the capability to reverse, for the first time, the Snell's law of refraction. Until this year 2000 demonstration by the UCSD team, the material was unavailable. Advances during the 1990s in fabrication and computation capabilities allowed these first metamaterials to be constructed. Thus, the "new" metamaterial was tested for the effects described by Victor Veselago 30 years earlier, but only at first in the microwave frequency domain. Reversal of phase velocity was established during this first test. Studies of this experiment, which followed shortly thereafter, announced that other effects had occurred.

To date (March 2010) these materials have only been commonly demonstrated at wavelengths longer than those in the visible spectrum. In addition, NIMs are fabricated from opaque materials, and usually made of non-magnetic constituents. However, as an illustration – if these materials could be demonstrated at visible frequencies, and a flashlight is shone on a NIM slab, the material should focus the light at a point on the other side. This is not possible with a sheet of ordinary opaque material.

When first demonstrated this composite material (NIM) was limited to transmitting microwave radiation at frequencies of 4 to 7 gigahertz. This is approximated to be the range of operating frequencies between household microwave ovens (2.45 GHz) and military radars (10 GHz). At demonstrated frequencies, pulses of electromagnetic radiation moving through the material in one direction are composed of constituent waves moving in the opposite direction.

The metamaterial was constructed as a periodic array of copper conducting elements. The design was such that the cells, and the lattice spacing between the cells, were much smaller than the radiated electromagnetic wavelength. Hence, it behaves as an effective medium. The material has become notable because its range of (effective) permittivity  $\epsilon_{\text{eff}}$  and permeability  $\mu_{\text{eff}}$  values have exceeded those found in any ordinary material. Furthermore, the characteristic of negative (effective) permeability evinced by this medium is particularly notable, because it has *not* been found in ordinary materials. In addition, the negative values for the magnetic component is directly related to its left-handed nomenclature, and properties (discussed in a section below). The split-ring resonator (SRR), based on the prior 1999 theoretical article, is the tool employed to achieve negative permeability. This first composite *metamaterial* is then composed of split-ring resonators and electrical conducting posts.



A single copper split-ring resonator (SRR) and the mapped resonance curve to the left. The dimensions of the SRR are:  $c = 0.8$  mm,  $d = 0.2$  mm, and  $r = 1.5$  mm. Quality factor at around 600. The SRR has its resonance at about 4.845 GHz.

With antiferromagnets and certain types of insulating ferromagnets, effective negative magnetic permeability is achievable when polariton resonance exists. However, to achieve a negative index of refraction, permittivity with negative values must occur within the same frequency range. The artificially fabricated split-ring resonator is a design that accomplishes this, along with the promise of dampening high losses. With this first introduction of the metamaterial, it appears that the losses incurred were smaller than antiferromagnetic, or ferromagnetic materials.

## Simultaneous negative permittivity and permeability

Negative permittivity  $\epsilon_{\text{eff}} < 0$  had already been discovered and realized in metals for frequencies all the way up to the plasma frequency, before the first metamaterial. There are two requirements to achieve a negative value for refraction. First, is to fabricate a material which can produce negative permeability  $\mu_{\text{eff}} < 0$ . Second, negative values for both permittivity and permeability must occur simultaneously over a common range of frequencies.

Therefore, for the first metamaterial, the nuts and bolts are one split-ring resonator electromagnetically combined with one (electric) conducting post. These are designed to resonate at designated frequencies to achieve the desired values. Looking at the make-up of the split ring, the associated magnetic field pattern from the SRR is dipolar. This dipolar behavior is notable because this means it mimics nature's atom, but on a much larger scale, such as in this case at 2.5 millimeters. Atoms exist on the scale of picometers.

The splits in the rings create a dynamic where the SRR unit cell can be made resonant at radiated wavelengths *much larger* than the diameter of the rings. If the rings were closed, a half wavelength boundary would be electromagnetically imposed as a requirement for resonance.

The split in the second ring is oriented opposite the split in the first ring. It is there to generate a large capacitance, which occurs in the small gap. This capacitance substantially decreases the resonant frequency while concentrating the electric field. The individual SRR depicted on the right had a resonant frequency of 4.845 GHz, and the resonance curve, inset in the graph, is also shown. The radiative losses from absorption and reflection are noted to be small, because the unit dimensions are much smaller than the free space, radiated wavelength.

When these units or cells, are combined into a periodic arrangement the magnetic coupling between the resonators is strengthened, and a *strong magnetic coupling occurs*. Properties unique in comparison to ordinary or conventional materials begin to emerge. For one thing, this periodic strong coupling creates a material which now has an effective magnetic permeability  $\mu_{\text{eff}}$  in response to the radiated-incident magnetic field.

One fundamental limitation was demonstrated theoretically and is unavoidable in practice. Dispersion with frequency is a necessary but not sufficient condition for a negative index. As all materials are dispersive to some degree, this is not truly a problem.

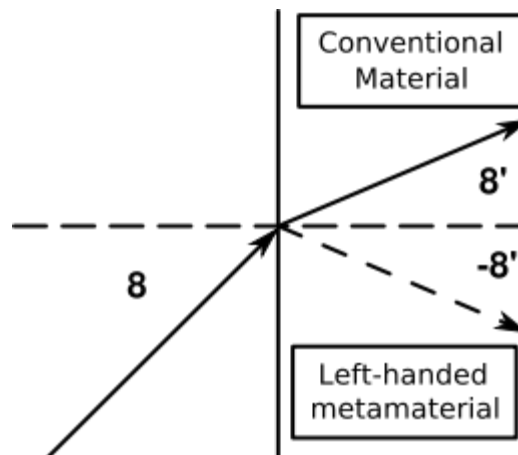
## Composite material passband

Graphing the general dispersion curve, a region of propagation occurs from zero up to a lower band edge, followed by a gap, and then an upper passband. The presence of a 400 MHz gap between 4.2 GHz and 4.6 GHz implies a band of frequencies where  $\mu_{\text{eff}} < 0$  occurs.

Furthermore, when wires are added symmetrically between the split rings, a passband occurs within the previously forbidden band of the split ring dispersion curves. That this passband occurs within a previously forbidden region indicates that the negative  $\epsilon_{\text{eff}}$  for this region has combined with the negative  $\mu_{\text{eff}}$  to allow propagation. This fit with theoretical predictions. Mathematically, the dispersion relation leads to a band with negative group velocity everywhere, and a bandwidth that is independent of the plasma frequency, within the stated conditions.

Mathematical modeling and experiment have both shown that periodically arrayed conducting elements (non-magnetic by nature) respond predominately to the magnetic component of incident electromagnetic fields. The result is an effective medium and negative  $\mu_{\text{eff}}$  over a band of frequencies. The permeability was verified to be the region of the forbidden band, where the gap in propagation occurred - from a finite section of material. This was combined with a negative permittivity material,  $\epsilon_{\text{eff}} < 0$ , to form a "left-handed" medium, which formed a propagation band with negative group velocity where previously there was only attenuation. This validated predictions. In addition, a later work determined that this first metamaterial had a range of frequencies over which the refractive index was predicted to be negative for one direction of propagation. Other predicted electrodynamic effects were to be investigated in other research.

### Describing a left-handed material



A comparison of refraction in a negative index metamaterial to that in a conventional material having the same, but positive refractive index. The incident beam 8 enters from air and refracts in a normal (8') or metamaterial (-8').

From the conclusions in the above section a left-handed material (LHM) can be defined. It is a material which exhibits simultaneous negative values for permittivity,  $\epsilon$ , and permeability,  $\mu$ , in an overlapping frequency region. Since the values are derived from the effects of the composite medium system as a whole, these are defined as effective permittivity,  $\epsilon_{\text{eff}}$ , and effective permeability,  $\mu_{\text{eff}}$ . Real values are then derived to denote the value of negative index of refraction, and wave vectors. This means that in practice losses will occur for a given medium used to transmit electromagnetic radiation such as

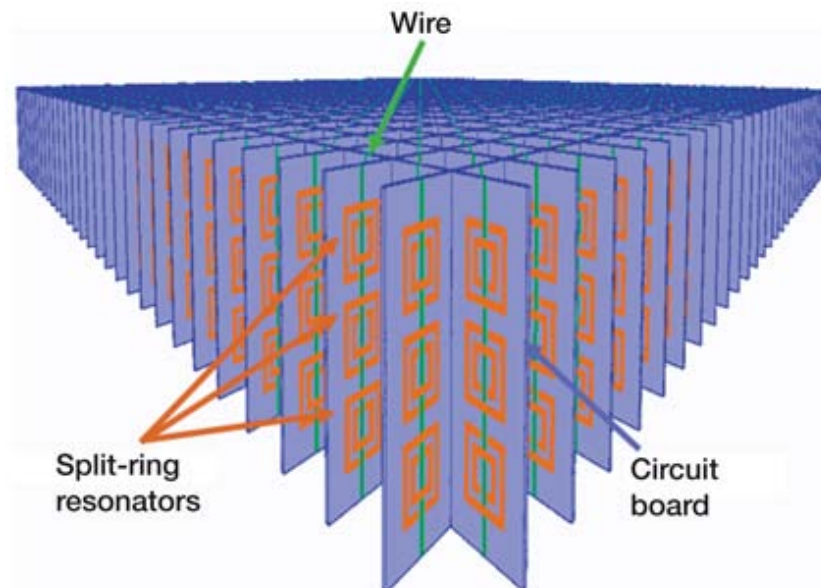
microwave, or infrared frequencies, or visible light - for example. In this instance, real values describe either the amplitude or the intensity of a transmitted wave relative to an incident wave, while ignoring the negligible loss values.

## Isotropic, negative index in two dimensions

In sections above, the first fabricated metamaterial was constructed with resonating elements, which exhibited one direction of incidence and polarization. In other words, this structure exhibited left-handed propagation in one dimension. This was discussed in relation to Veselago's seminal work 33 years earlier (1967). He predicted that intrinsic to a material which manifests negative values of effective permittivity and permeability, are several types of reversed physics phenomena. Hence, there was then a critical need for a higher dimensional LHMs to confirm Veselago's theory, as expected. The confirmation would include reversal of Snell's law (index of refraction), along with other reversed phenomena.

In the beginning of 2001 the existence of a higher dimensional structure was reported. It was two dimensional and demonstrated by both experiment and numerical confirmation. It was an LHM, a composite constructed of wire strips mounted behind the split-ring resonators (SRRs) in a periodic configuration. It was created for the express purpose of being suitable for further experiments to produce the Veselago predicted effects.

## Experimental verification of a negative index of refraction



Split-ring resonator consisting of an inner square with a split on one side embedded in an outer square with a split on the other side. Split-ring resonators are on the front and right surfaces of the square grid, and single vertical wires are on the back and left surfaces.

According to Snell's law, when refraction of light is measured or observed for ordinary materials surrounded by air, the value is always greater than one,  $n > 1$ . A refracted ray entering a material from air will be bent towards, but never end up on the same side as the normal. In addition, the science and practice of optical lensing and imaging is based on the knowledge that any material with a refractive index different from its environment will alter the direction of incoming rays which do not arrive in a straight line in relation to the interface (of the material surface and air). Also, lenses have been designed focus and steer the various spectra of light (EM radiation) in frequency ranges from radio to the visible spectra. Furthermore, all known natural occurring materials demonstrate refractive indices that are positive. However, a theoretical work in 1967 showed that a refractive index with negative values is possible and that this does not violate the laws of physics. As discussed previously (above), the first metamaterial had a range of frequencies over which the refractive index was predicted to be negative for one direction of propagation were reported in May of the year 2000.

In 2001, a team of researchers constructed a prism composed of metamaterials (negative index metamaterials) to experimentally test for negative refractive index. The experiment used a waveguide to help transmit the proper frequency and isolate the material.

The experimental demonstration of negative refractive index was followed by another demonstration, in 2003, of a reversal of Snell's law, or reversed refraction. However, in this experiment negative index of refraction material is in free space from 12.6 to 13.2 GHz. Although the radiated frequency range is about the same, a notable distinction is this experiment is conducted in free space rather employing waveguide.

Furthering the authenticity of negative refraction, the power flow of a wave transmitted through a dispersive left-handed material was calculated and compared to a dispersive right-handed material. The transmission of an incident field, composed of many frequencies, from an isotropic nondispersive material into an isotropic dispersive media is employed. The direction of power flow for both nondispersive and dispersive media is determined by the time-averaged Poynting vector. Negative refraction was shown to be possible for multifrequency signals by explicit calculation of the Poynting vector in the LHM.

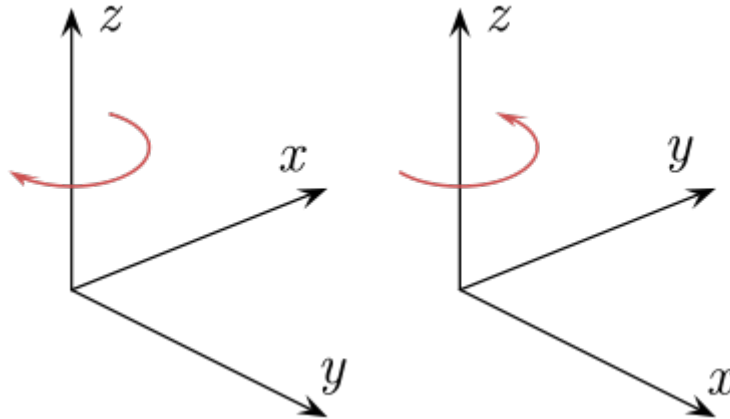
### **Fundamental electromagnetic properties of the NIM**

In a slab of conventional material, with an ordinary refractive index – a right-handed material (RHM) – the wave front is transmitted away from the source. In a NIM the wavefront travels toward the source. However, the magnitude and direction of the flow of energy essentially remains the same in both the ordinary material and the NIM. Since, the flow of energy remains the same in both materials (media) the impedance of the NIM matches the RHM. Hence, the sign of the intrinsic impedance is still positive in a NIM.

Light incident on a left-handed material, or NIM, will bend to the same side as the incident beam, and for Snell's law to hold, the refraction angle should be negative. In a

passive metamaterial medium this determines a negative real and imaginary part of the refractive index.

## Negative refractive index in left-handed materials



The left-handed orientation is shown on the left, and the right-handed on the right.

In 1968 Victor Veselago's paper showed that the opposite directions of EM plane waves and the flow of energy was derived from the individual Maxwell curl equations. In ordinary optical materials, the curl equation for the electric field show a "right hand rule" for the directions of the electric field  $\mathbf{E}$ , the magnetic induction  $\mathbf{B}$ , and wave propagation, which goes in the direction of wave vector  $\mathbf{k}$ . However, the direction of energy flow formed by  $\mathbf{E} \times \mathbf{H}$  is right-handed only when *permeability is greater than zero*. This means that when permeability is less than zero, e.g. *negative*, wave propagation is reversed (determined by  $\mathbf{k}$ ), and contrary to the direction of energy flow. Furthermore, the relations of vectors  $\mathbf{E}$ ,  $\mathbf{H}$ , and  $\mathbf{k}$  form a "*left-handed*" system – and it was Veselago who coined the term "left-handed" (LH) material, which is in wide use today (2010). He contended that an LH material has a negative refractive index and relied on the steady-state solutions of Maxwell's equations as a center for his argument.

After a 30 year void, when LH materials were finally demonstrated, it could be said that that the designation of negative refractive index is unique to LH systems; even when compared to photonic crystals. Photonic crystals, like many other known systems, can exhibit unusual propagation behavior such as reversal of phase and group velocities. But, negative refraction does not occur in these systems, and not yet realistically in Photonic crystals.

## Negative refraction at visible frequencies

As of May 2010 - In previous years, several anomalous studies have announced negative refraction at one single frequency, or other, in the visible spectrum. But the results of two

such demonstrations are considered ambiguous by later studies. Another most recent, published, demonstration at one single visible frequency is still not the norm, or common, for the large body of work that has been produced in the field of metamaterials. To date, hundreds of scientific, peer reviewed, articles have been published regarding some aspect of metamaterials. This is compared to some miniscule number, the studies that have apparent results in the visible spectrum. In an encyclopedia article such as this it is problematic to give undue weight to such studies, until these become common, or part of the norm, for metamaterials.

Moreover, although previous research efforts have announced negative refraction of one single frequency in the visible light spectrum, this most recent (April, 2010) is being reported as "the first one that operates on visible light." Also as before, the stated achievement is for one single frequency in the visible spectrum. In other words there is no broad band capability.

## **Experimental verification of reversed Cherenkov radiation**

Besides reversed values for index of refraction, Veselago predicted the occurrence of reversed Cherenkov radiation (also known simply as CR) in a left-handed medium. In 1934 Pavel Cherenkov discovered a coherent radiation (laser) that occurs when certain types of media are bombarded by fast moving electron beams. In 1937 a theory built around CR stated that when charged particles, such as electrons, travel through a medium at speeds faster than the speed of light in the medium only then will CR radiate. As the CR occurs, electromagnetic radiation is emitted in a cone shape, fanning out in the forward direction.

CR and the 1937 theory has led to a large array of applications in high energy physics. A notable application are the Cherenkov counters. These are used to determine various properties of a charged particle such as its velocity, charge, direction of motion, and energy. These properties are important in the identification of different particles. For example, the counters were applied in the discovery of the anti-proton and the J particle. Six large Cherenkov counters were used in the discovery of the J particle.

It has been difficult to experimentally prove the reversed Cherenkov radiation.

## **Paraxial approximation of DNG slabs**

Theoretical work, along with numerical simulations, began early in the decade of the new millennium on the capabilities of the DNG slab for subwavelength focusing. The research began with Pendry's proposed "Perfect lens". Several research investigations that followed Pendry's concluded that the "Perfect lens" was possible in theory but not practical. One direction in subwavelength focusing proceeded with the use of negative index metamaterials, but based on the enhancements for imaging with surface plasmons. In another direction researchers explored paraxial approximations of DNG slabs.

## **US patent on left-handed composite media**

The first US patent granted for a fabricated metamaterial is U.S. Patent 6,791,432 B2, titled "Left handed composite media." The listed inventors are David Smith, Sheldon Schultz, Norman Kroll, Richard A. Shelby.

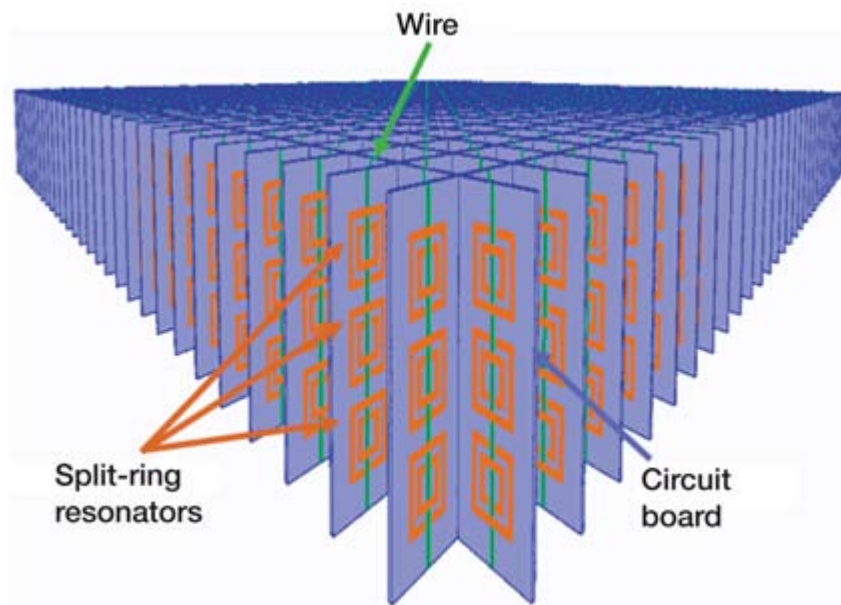
The invention achieves simultaneous negative permittivity and permeability over a common band of frequencies. The material can integrate media which is already composite or continuous, but which will produce negative permittivity and permeability within the same spectrum of frequencies. Different types of continuous or composite may be deemed appropriate when combined for the desired effect. However, the inclusion of a periodic array of conducting elements is preferred. The array scatters electromagnetic radiation at wavelengths longer than the size of the element and lattice spacing. The array is then viewed as an effective medium.

## **Anomalous dispersion**

Propagation of a Gaussian Light Pulse through an Anomalous Dispersion Medium. However the speed of transmitting information is always limited to  $c$ .

## Chapter- 3

# Split-ring Resonator



Split-ring resonator consisting of an inner square with a split on one side embedded in an outer square with a split on the other side. Split-ring resonators are on the front and right surfaces of the square grid, and single vertical wires are on the back and left surfaces.

A **split-ring resonator (SRR)** is a component part of a Negative index metamaterial (NIM), also known as Double negative metamaterials (DNG) or Left-handed medium (LHM). They are also component parts of other types of metamaterial such as Single Negative metamaterial (SNG). SRRs are also used for research in Terahertz metamaterials, Acoustic metamaterials, and Metamaterial antennas. A single cell SRR has a pair of enclosed loops with splits in them at opposite ends. The loops are made of nonmagnetic metal like copper and have a small gap between them. The loops can be concentric, or square, and gapped as needed.

A magnetic flux penetrating the metal rings will induce rotating currents in the rings, which produce their own flux to enhance or oppose the incident field (depending on the SRRs resonant properties). This field pattern is dipolar. Due to splits in the rings the structure can support resonant wavelengths much larger than the diameter of the rings.

This would not happen in closed rings. The small gaps between the rings produces large capacitance values which lower the resonating frequency, as the time constant is large. The dimensions of the structure are small compared to the resonant wavelength. This results in low radiative losses, and very high quality factors.

At frequencies below the resonant frequency, the real part of the magnetic permeability of the SRR becomes large (positive), and at frequencies higher than resonance it will become negative. This negative permeability can be used with the negative dielectric constant of another structure to produce negative refractive index materials.

## **SRR electromagnetic metamaterials**

In 1967 a paper was published that was written by Victor G. Veselago. In a straightforward manner he stated that  $\epsilon$  (permittivity) as a dielectric constant and  $\mu$  (magnetic permeability) "are the fundamental characteristic quantities which determine the propagation of electromagnetic waves in matter." Furthermore, these quantities determine the index of refraction "n". He realized, that materials with simultaneous negative values for  $\epsilon$  and  $\mu$  can exist within the laws of physics, and that these substances have some properties different from materials with positive values for  $\epsilon$  and  $\mu$ . Veselago described the unusual consequences of such a left-handed substance; a refraction that is reversed, an inversion of the Doppler and Cerenkov effects, the vectors E, H, and k occur as a left-handed set, a sign change of the group velocity, bi-concave and bi-convex lenses change roles, and the reversal of radiation pressure to radiation tension. In other words, dramatically different propagation characteristics.

Thirty years later physicists would agree when practical structures that exhibit negative values for  $\epsilon$ ,  $\mu$ , and n were fabricated and demonstrated in the year 2000. These are called electromagnetic metamaterials, and the first of these used a nested split ring resonator design and are still in use today for research. However, the research has gone from negative values for  $\epsilon$ ,  $\mu$ , and n in the microwave - gigahertz range up to terahertz and infrared frequencies.

The nested split ring resonator in a periodic configuration is defined as a composite at times, and homogeneous material, at other times. The view of homogeneous or composite depends on the discussion underway. The composite description is employed when discussing the individual components of the medium, above the atomic level. The original purpose of defining permittivity,  $\epsilon$ , and permeability,  $\mu$  was to support a homogeneous view of an electromagnetic medium. In this view, the contents of the cell (split-ring resonator) will define the system wide response of  $\epsilon$ , and  $\mu$ . Long wavelength radiation will not detect internal structure smaller than the wavelength, and the micro-structure then becomes related to  $\epsilon$ -eff and  $\mu$ -eff, which are electromagnetic components of a homogeneous material.

Microstructuring a material simply to generate a particular  $\mu$ -eff can be explained. Atoms and molecules naturally tend to have weak magnetic response to external radiation. Therefore constructing a magnetic material from non-magnetic material such as a circuit

board substrate becomes very difficult. Nature, as it occurs, allows only a restrictive set of parameters, when working with atoms (atomic dipoles) and molecules. In addition, any magnetic response tends to fall off at frequencies in the gigahertz range.

Negative  $\mu$ -eff has been shown to be possible when a polariton resonance exists in the permeability, such as in the antiferromagnets  $MnF_2$  and  $FeF_2$ , or certain ferromagnets. However, these are only moderately active when compared to artificially constructed materials, such as SRRs, which are designed for considerable magnetic activity in both the diamagnetic and paramagnetic domains. In addition, compared to the newly available artificial materials these are heavy with less than desirable mechanical properties. Moreover, if so desired, the artificial composite can be made extremely light. The strong magnetic activity of the artificial composite implies strong inhomogeneous fields inside the material. This also implies the availability of a number of intentionally placed, sometimes strong, local field concentrations, as part of the material. Doping the composite with nonlinear material at the critical locations of field concentration gives enhanced non-linearity, reducing power requirements. This is not an option available in a conventional magnetic material.

The artificial composite (SRR) is a non-magnetic, micro-structured, periodic, material.

There is a variety of split-ring resonators - rod-split-rings, nested split-rings, single split rings, deformed split-rings, spiral split-rings, and extended S-structures. The variations of split ring resonators have achieved different results, including smaller and higher frequency structures.

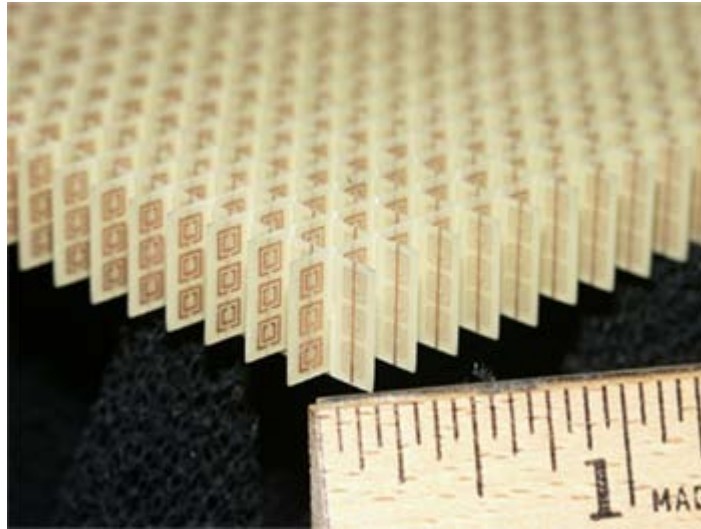
To date (December 2009) the capability for desired results in visible spectrum has not been achieved. However, in 2005, it was noted that, physically, a nested circular split-ring resonator must have an inner radii of 30 to 40 nanometers for success in the mid-range of the visible spectrum.

Microfabrication and nanofabrication techniques utilize direct laser beam writing or electron beam lithography, and this depends on the desired resolution.

## **First demonstrations with the SRR**

May 2000. A composite medium, based on a periodic array of interspaced conducting nonmagnetic split ring resonators and continuous wires, that exhibits a frequency region in the microwave regime with simultaneously negative values of effective permeability and permittivity.

## SRR configuration



A split-ring resonator array is configured as a material that produces negative index of refraction. It was constructed of copper split-ring resonators and wires mounted on interlocking sheets of fiberglass circuit board. The total array consists of 3 by 20×20 unit cells with overall dimensions of 10×100×100 mm.

Split-ring resonators (SRR) are one of the most common elements used to fabricate metamaterials. Split-ring resonators are non-magnetic materials, which are usually fabricated from circuit board material to create metamaterials.

At first a single SRR looked like a ring with small segment removed which results in a "C" shape, on fiberglass, printed circuit board material. In this type of configuration it is actually two concentric bands of non-magnetic conductor material. There is one gap in each band placed 180° relative to each other. The gap in each band gives it the distinctive "C" shape, rather than a totally circular or square shape. Then multiple cells of this double band configuration are fabricated onto circuit board material by an etching technique and lined with copper wire strip arrays are added. After processing, the boards are cut and assembled into an interlocking unit. It is constructed into a periodic array with a large number of SRRs.

There are now a number of different configurations that use the SRR nomenclature.

A periodic array of SRRs was used for the first actual demonstration of a negative index of refraction. For this demonstration, *square shaped SRRs*, with the lined wire configurations, were fabricated into a periodic, arrayed, cell structure. This is the substance of the metamaterial. Then a metamaterial prism was cut from this material. The prism experiment demonstrated a negative index of refraction for the first time in the year 2000; the paper about the demonstration was submitted to the journal Science on January 8, 2001, accepted on February 22, 2001 and published on April 6, 2001.

Just before this prism experiment, Pendry et al. was able to demonstrate that a three-dimensional array of intersecting thin wires could be used to create negative values of  $\epsilon$ . In a later demonstration, a periodic array of copper split-ring resonators could produce an effective negative  $\mu$ . In 2000 Smith et al. were the first to successfully combine the two arrays and produce a LHM which had negative values of  $\epsilon$  and  $\mu$  for a band of frequencies in the GHz range.

The resonance frequency is a key factor when using this periodic arrayed material. At resonance the material delivers an effective magnetic permeability  $\mu$  of enhanced magnitude when interacting (coupling) with the source electromagnetic field (and in this case the incident field). The resonance frequency of the SRR depends on its intended geometrical parameters derived during fabrication.

SRRs were first used to fabricate left-handed metamaterials for the microwave range, and several years later for the terahertz range. By 2007, experimental demonstration of this structure at microwave frequencies has been achieved by many groups. In addition, SRRs have been used for research in acoustic metamaterials. The arrayed SRRs and wires of the first Left-handed metamaterial were melded into alternating layers. This concept and methodology was then applied to (dielectric) materials with optical resonances producing negative effective permittivity for certain frequency intervals resulting in "photonic bandgap frequencies". Another analysis showed Left Handed Material to be fabricated from inhomogeneous constituents, which yet results in a macroscopically homogeneous material. SRRs had been used to focus a signal from a point source, increasing the transmission distance for near field waves. Furthermore, another analysis showed SRRs with a negative index of refraction capable of high-frequency magnetic response, which created an artificial magnetic device composed of non-magnetic materials (dielectric circuit board).

A transmission medium composed of SRRs and wires could indeed be characterized by effective  $\epsilon$  and  $\mu$  whose real parts were both negative over a finite frequency band, as was the real part of the refractive index  $n$ . SRRs also exhibit resonant electric response in addition to their resonant magnetic response. SRRs with wire elements have been constructed from repeated unit cells containing identical elements, such that the resulting medium can be considered homogeneous in the sense that the averaged electromagnetic response is averaged over the structure as a whole. A single SRR (cell) responds to electromagnetic fields in a manner analogous to a magnetic "atom," exhibiting a resonant magnetic dipole response. The original logic behind SRRs specifically, and metamaterials generally was to create a structure, which imitates an arrayed atomic structure only on a much larger scale.

### **Several types of SRR**

In research based in metamaterials, and specifically negative refractive index, there are different types of split-ring resonators. Of the examples mentioned below most all of them have a gap in each ring. In other words, with a double ring structure, each ring has a gap.

There is the *1-D Split-Ring Structure* with two square rings, one inside the other. One set of cited "unit cell" dimensions would be an outer square of 2.62 mm and an inner square of 0.25 mm. 1-D structures such as this are easier to fabricate compared with constructing a rigid 2-D structure.

The *Symmetrical-Ring Structure* is another classic example. Described by the nomenclature these are two rectangular square D type configurations, exactly the same size, laying flat, side by side, in the unit cell. Also these are not concentric. One set of cited dimensions are 2 mm on the shorter side, and 3.12 mm on the longer side. The gaps in each ring face each other, in the unit cell.

The *Omega Structure*, as the nomenclature describes, has an  $\Omega$ -shaped ring structure. There are two of these, standing vertical, side by side, instead of laying flat, in the unit cell. In 2005 these were considered to be a new type of metamaterial. One set of cited dimensions are annular parameters of  $R = 1.4$  mm and  $r = 1$  mm, and the straight edge is 3.33 mm.

Another new metamaterial in 2005 was a coupled "S" shaped structure. There are two vertical "S" shaped structures, standing vertical, side by side, in a unit cell. There is no gap as in the ring structure, however there is a space between the top and middle parts of the S and space between the middle part and bottom part of the S. Furthermore, it still has the properties of having an electric plasma frequency and a magnetic resonant frequency.

In the above section gapped "C" shaped rings have been described. There are also two of these per unit cell, one inside the other – a concentric configuration.

Such media – millimeter-scale split-ring resonators and wires, in a periodic configuration – are known as negative index metamaterials (NIMs), and first applied at microwave frequencies on the order of 10 GHz. Negative values of permeability  $\mu$  and permittivity  $\epsilon$  occurred via the resonant capacitive-inductive response of the split-rings and the effective plasma response of the wire lattice determined by mutual inductance. Negative refraction was demonstrated throughout all angles in two dimensions by direct observation of plane wave refraction through prism-shaped samples (segments) of such assemblies.

## **Magnetic resonances for different SRR parameters and designs**

The magnetic resonance of split-ring resonators (SRR) experimentally and numerically investigated. The dependence of the geometrical parameters on the magnetic resonance frequency of SRR is studied. Further investigation is accomplished concerning the effect of lumped capacitors integrated to the SRR on the magnetic resonance frequency for tunable SRR designs. Different resonator structures are shown to exhibit magnetic resonances at various frequencies depending on the number of rings and splits used in the resonators.

## **Nonlinear properties of split-ring resonators**

In 2008 an overview of the non-linear capabilities of the split-ring resonators was presented. Specifically, the properties of split-ring resonators (SRRs) loaded with high-Q capacitors and nonlinear varactors are theoretically analyzed and experimentally measured. Experimental demonstration shows that the resonance frequency  $f_m$  of the nonlinear SRRs can be tuned by increasing the incident power.

In addition, most of the research in the properties of the SRR had been in the linear regime. However, there has been some research into non-linear capabilities. Specifically, the researchers refer to SRR nonlinear tunability studies. To tune the magnetic responses of the SRRs, extra components or materials need to be introduced into the SRRs. Therefore other research into this area is lightly discussed.

The extra components employed in prior research were: ferroelectric films are added to the substrate of the SRRs, low-doped semiconductors are photodoped within the slits of the SRR, ferrite rods are introduced to ambient the SRR unit cells, and varactors in microwave applications. Furthermore, tunable metamaterials, based on the nonlinear SRRs with varactors, have been tested experimentally in both transmission line form and bulk form.

## **Towards 3D electromagnetic metamaterials in the THz range**

First results of microfabrication of nearly 3D EM3 structures for the THz range

## **NIM configurations utilizing non-SRR structures**

### **Nanoscale cut-wire pairs**

Experimentally obtained and characterized metamaterials based on nanoscale cut-wire pairs and plate pairs. Comparison with theory and subsequent retrieval shows that both options exhibit a frequency range with negative magnetic permeability. In contrast to other reports, however, a negative refractive index is not obtained from the cut-wire pairs or plate pairs alone that we have studied so far (2005).

### **Specialized periodic metallic crosses**

A bulk metamaterial with negative refractive index in the terahertz frequency range is presented and analyzed. The structure is composed of pairs of metallic crosses embedded in benzocyclobutene (BCB). The design is specifically chosen to provide a low-loss, free-standing material which operates under normal incidence and independently of the polarization of the incident radiation. These qualities allow the fabrication of 3D structures by mechanical stacking of multiple thin films.

## **Metamaterial Swiss roll**

**Swiss roll** is a type of optical, electromagnetic metamaterial that has negative refractive index. It is named for its resemblance to the confectionery Swiss roll: it consists of concentric cylinders of insulated metal.

A large array of Swiss rolls proved to be an effective design for a metamaterial lens; near-field imaging with magnetic wires. Pendry's Swiss roll could find applications in magnetic resonance imaging.

## **Controllable magnetic response at optical frequencies**

### **Negative permeability material for red light**

Desired permeability achieved in one wavelength of the visible spectrum at 780 nm.

### **Controllable permeability across visible spectrum**

Coupled nanostrips demonstrate control of magnetic responses across the visible spectrum.

## **Magnetic response at telecommunication and visible frequencies**

At telecommunication or visible frequencies the desired magnetic response, negative permeability ( $\mu_{\text{eff}} < 0$ ) does not occur in natural materials. One stated technological challenge in November 2005 was to achieve  $\mu_{\text{eff}} < 0$  and this would be accomplished with an adapted SRR/wire metamaterial. Prior research had established that the SRR/wire metamaterials were used in the first demonstrations of  $\mu_{\text{eff}} < 0$  at microwave frequencies. By November 2004 magnetic resonance was demonstrated at 100 THz (3  $\mu\text{m}$  wavelength), which is an increase of more than 4 orders of magnitude within four years.

## Chapter- 4

# Acoustic Metamaterials

**Acoustic metamaterials** are artificially fabricated materials designed to control, direct, and manipulate sound in the form of sonic, infrasonic, or ultrasonic waves, as these might occur in gases, liquids, and solids. The hereditary line into acoustic metamaterials follows from theory and research in electromagnetic metamaterials, although the closely related field of auxetics actually *predates* both. Furthermore, with acoustic metamaterials, sonic waves can now be extended to the negative refraction domain.

Control of the various forms of sound waves is mostly accomplished through the bulk modulus  $\beta$ , mass density  $\rho$ , and Chirality. The density and bulk modulus are analogies of the electromagnetic parameters, permittivity and permeability, in electromagnetic metamaterials. Related to this is the mechanics of wave propagation in a lattice structure. Also materials have mass, and intrinsic degrees of stiffness. Together, these form a resonant system, and the mechanical (sonic) resonance may be excited by appropriate sonic frequencies (for example pulses at audio frequencies).

## History of the acoustic metamaterials

Acoustic metamaterials actually began with electromagnetic metamaterials, and the construction of materials to control electromagnetic radiation before that.

Maxwell's equations which predicted the existence of electromagnetic radiation propagating at the speed of light, by James Clerk Maxwell, were made public in 1865. In 1888 Hertz had demonstrated generation of electromagnetic waves, and showed that their properties were similar to those of light.

Before the start of the 20th century, many of the concepts now familiar in microwaves had been developed. The list includes the cylindrical parabolic reflector, dielectric lens, microwave absorbers, the cavity radiator, the radiating iris and the pyramidal electromagnetic horn. Round square and rectangular waveguides were used, with experimental development anticipating by several years Rayleigh's 1896 theoretical solution for waveguide modes. Many microwave components in use were "quasi-optical". Oliver Lodge first introduced the term - quasi-optical. A treatise on microwave optics was published by Righi in 1897.

Hertz had used a wavelength of 66 cm; other post-Hertzian pre-1900 experimenters used wavelengths well into the short cm-wave region, with Bose in Calcutta and Lebedew in Moscow independently performing experiments at wavelengths as short as 5 and 6 millimeters.

Jagadish Chandra Bose used waveguides, horn antennas, dielectric lenses, various polarizers and even semiconductors at frequencies as high as 60 GHz. In 1898 he tried to develop and did experiments with "constructed" twisted elements. These elements exhibited chiral properties. He authored a paper, published by Proceedings Royal Society London on January 1, 1898 "On the Rotation of Plane of Polarisation of Electric Waves by a Twisted Structure".

In the early part of the twentieth century, Karl Ferdinand Lindman studied wave interaction with collections of metallic helices as artificial chiral media (Annalen der Physik, Vol. 63, No. 4, pp. 621–644, 1920.)

W. E. Kock developed materials that had similar characteristics to metamaterials in the late 1940s Winkler (1956), Tinoco and Freeman (1957), W. Pickering 1970's, Several Groups in 1980's and 1990's.

The modern form of metamaterials was originally proposed by Victor G. Veselago, in 1967. Microwave LH Media domain - Negative refraction (electromagnetic) first demonstrated by D. Smith, S. Shultz, and R. Shelby (2000–2001) Anomalous refraction in DNG Media leads to Pendry's perfect lens proposal (evanescent wave reconstruction). Paired layers of metamaterials with negative permittivity and permeability (DNG) and conventional materials (DPS) follow.

In the year 2000 sonic (rubber-silicon coated) crystals in liquid result in the first acoustic metamaterial.

The research on acoustic metamaterials began in the year 2000 with the fabrication and demonstration of sonic crystals in a liquid. This was followed by transposing the behavior of the split-ring resonator to research in acoustic metamaterials. After this double negative parameters (negative bulk modulus  $\beta_{\text{eff}}$  and negative density  $\rho_{\text{eff}}$ ) were produced by this type of medium. Then a group of researchers presented the design and tested results of an ultrasonic metamaterial lens for focusing 60 kHz.

The earlier studies of acoustics in technology, which is called acoustical engineering, are typically concerned with how to reduce unwanted sounds, noise control, how to make useful sounds for the medical diagnosis, sonar, and sound reproduction and how to measure some other physical properties using sound.

Using acoustic metamaterials, the directions of sound through the medium can be controlled, refraction index, so the traditional acoustic technologies extend to controlling the sound wave and even cloak certain matters from acoustic detection.

## Basic principle

Since the acoustic metamaterials are one of the branch of the metamaterials, the basic principle of the acoustic metamaterials is similar to the principle of metamaterials. These metamaterials usually gain their properties from structure rather than composition, using the inclusion of small inhomogeneities to enact effective macroscopic behavior. Similar to metamaterials research, investigating materials with Negative index metamaterials, the negative index acoustic metamaterials became the primary research. Negative refractive index of acoustic materials can be achieved by changing the bulk modulus and mass density.

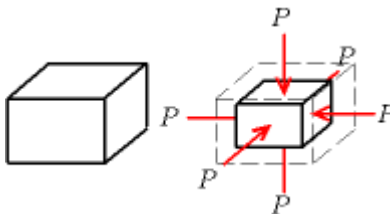
### Bulk modulus and mass density

Below, the bulk modulus  $\beta$  of a substance reflects the substance's resistance to uniform compression. It is defined in relation to the pressure increase needed to cause a given relative decrease in volume.

The term *mass density* of a material, is interchangeable with *density*. The latter is defined as mass per unit volume and is expressed in grams per cubic centimeter ( $\text{g/cm}^3$ ). In all three classic states of matter — gas, liquid, or solid — the density varies with a change in temperature or pressure, and gases are the most susceptible to those changes. The spectrum of densities is wide ranging: from  $10^{15} \text{ g/cm}^3$  for neutron stars,  $1.00 \text{ g/cm}^3$  for water to  $1.2 \times 10^{-3} \text{ g/cm}^3$  for air. Also relevant here are area density which is mass over a (two-dimensional) area, linear density - mass over a one-dimensional line, and relative density, which is a density divided by the density of a reference material, such as water.

For acoustic materials and acoustic metamaterials, both bulk modulus and density are component parameters, which define their refractive index.

### Acoustic metamaterial analogues



Bulk modulus - illustration of uniform compression

Scientific research revealed that acoustic metamaterials have analogues to electromagnetic metamaterials when exhibiting the following characteristics:

In certain frequency bands, the *effective mass density* and *bulk modulus* may become negative. This results in a *negative refractive index*. *Flat slab focusing*, which can result in *super resolution*, is similar to electromagnetic metamaterials. The double negative

parameters are a result of low-frequency resonances. In combination with a well-defined polarization during wave propagation;  $k = |n|\omega$ , is an equation for refractive index as sound waves interact with acoustic metamaterials (below):

$$n^2 = \frac{\rho}{\beta}$$

The inherent parameters of the medium are the mass density  $\rho$ , bulk modulus  $\beta$ , and chirality  $k$ . Chirality, or handedness, determines the polarity of wave propagation (wave vector). Hence within the last equation, Veselago-type solutions ( $n^2 = u^*\epsilon$ ) are possible for wave propagation as the negative or positive state of  $\rho$  and  $\beta$  determine the forward or backward wave propagation.

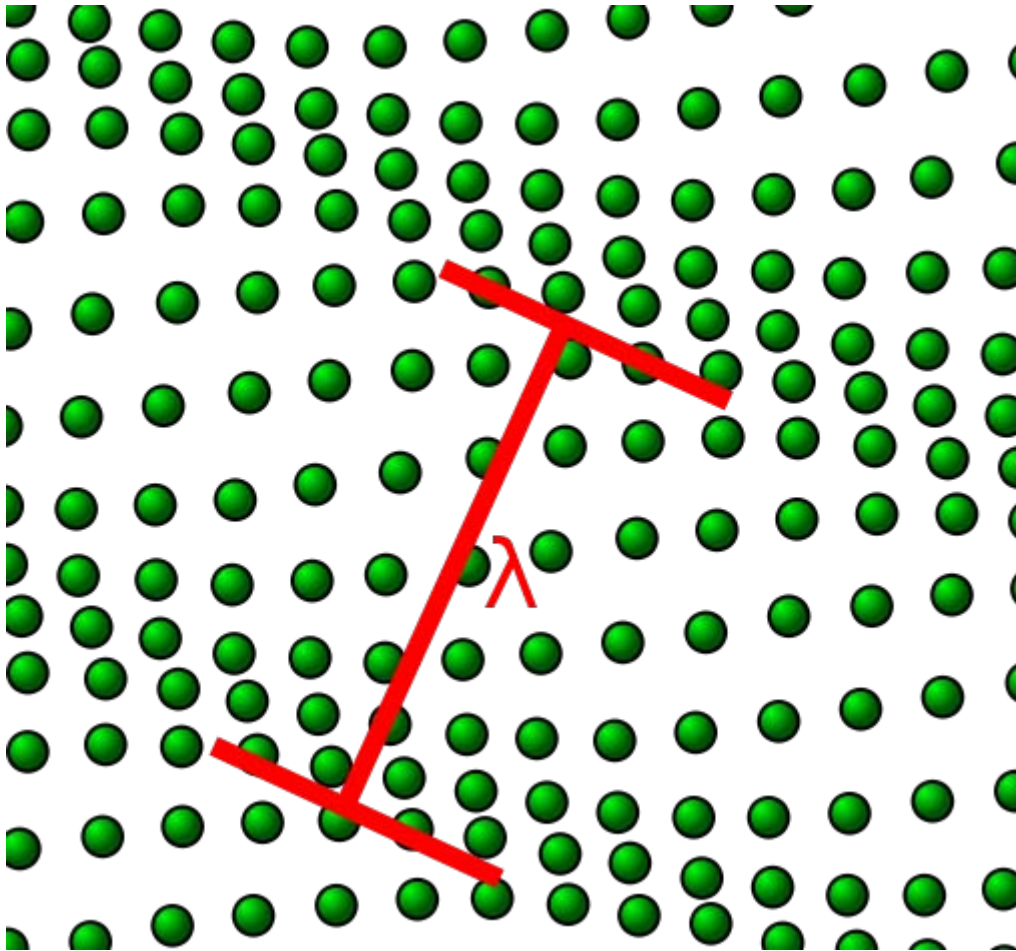
In negative refractive, electromagnetic metamaterials, negative permittivity can be found in natural materials. However, negative permeability has to be intentionally created in the artificial transmission medium. Obtaining a negative refractive index with acoustic materials is different. Neither negative  $\rho$  nor negative  $\beta$  are found in naturally occurring materials; they are derived from the resonant frequencies of an artificially fabricated transmission medium (metamaterial), and such negative values are an anomalous response. Negative  $\rho$  or  $\beta$  means that at certain frequencies the medium expands when experiencing compression (negative modulus), and accelerates to the left when being pushed to the right (negative density).

### **Electromagnetic field vs acoustic field**

The electromagnetic spectrum extends from below frequencies used for modern radio to gamma radiation at the short-wavelength end, covering wavelengths from thousands of kilometers down to a fraction of the size of an atom. That would be wavelengths from  $10^3$  to  $10^{-15}$  kilometers. The long wavelength limit is the size of the universe itself, while it is thought that the short wavelength limit is in the vicinity of the Planck length, although in principle the spectrum is infinite and continuous.

Infrasonic frequencies range from 20 Hz down to 0.001 Hz. Audible frequencies are 20 Hz to 20 kHz. Ultrasonic range is above 20 kHz. Sound requires a medium. Electromagnetics radiation (EM waves) can travel in a vacuum.

## Mechanics of lattice waves



An imaginary demonstration: A hypothetical rigid lattice structure (solid) is composed of  $10^{23}$  atoms. However, in a real solid these particles could just as easily be ions. In a rigid lattice structure, atoms exert pressure, or a force, on each other in order to maintain equilibrium. Atomic forces maintain rigid lattice structure. Most of them, such as the covalent or ionic bonds, are of electric nature. The magnetic force, and the force of gravity are negligible. Because of bonding between atoms, the displacement of one or more atoms from their equilibrium positions will give rise to a set of vibration waves propagating through the lattice. One such wave is shown in the figure to the right. The amplitude of the wave is given by the displacements of the atoms from their equilibrium positions. The wavelength  $\lambda$  is marked.

There is a *minimum possible* wavelength, given by the equilibrium separation  $a$  between atoms. Any wavelength shorter than this can be mapped onto a wavelength longer than  $a$ , due to effects similar to that in aliasing.

## Acoustic metamaterials analysis and experiments

The current research on acoustic metamaterials is based not only on prior experience with electromagnetic metamaterials. The key physics in acoustics are *sound*, *ultrasound* and *infrasound*, which are mechanical waves in gases, liquids, and solids. One objective of the inquiry into the properties of acoustic metamaterials is applications in seismic wave reflection and in vibration control technologies related to earthquakes.

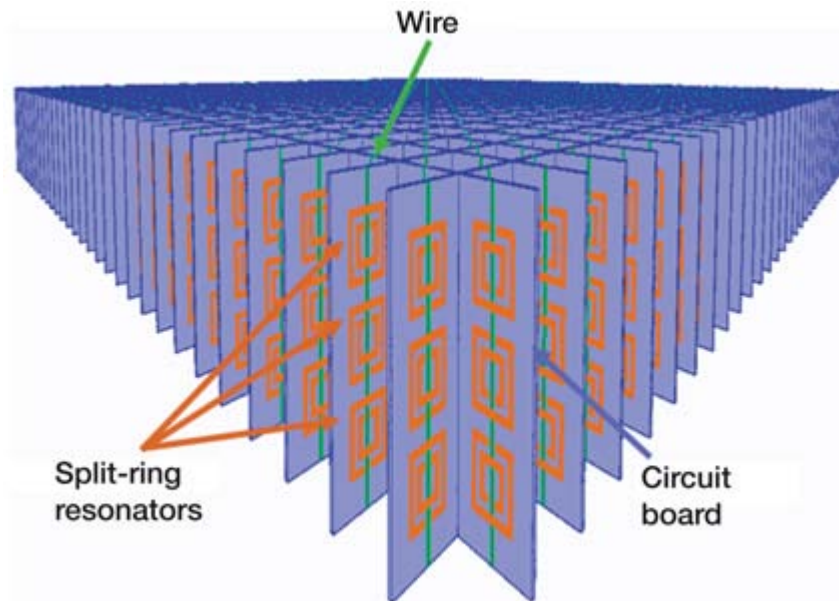
### Sonic crystals

In the year 2000 the research of Liu *et al.* paved the way to acoustic metamaterials through sonic crystals. The latter exhibit spectral gaps two orders of magnitude smaller than the wavelength of sound. The spectral gaps prevent the transmission of waves at prescribed frequencies. The frequency can be tuned to desired parameters by varying the size and geometry of the metamaterial.

The fabricated material consisted of a high-density solid lead ball as the core, one centimeter in size, which was coated with a 2.5-mm layer of rubber silicone. These were arranged in a crystal lattice structure of an  $8 \times 8 \times 8$  cube. The balls were cemented into the cubic structure with an epoxy. Transmission was measured as a function of frequency from 250 to 1600 Hz for effectively a four-layer sonic crystal. A two-centimeter slab absorbed sound that normally would require a much thicker material, at 400 Hz. A drop in amplitude was observed at 400 and 1100 Hz.

The amplitudes of the sound waves entering the surface were compared with the sound waves at the center of the metamaterial structure. The oscillations of the coated spheres absorbed sonic energy, which created the frequency gap; the sound energy is absorbed exponentially as the thickness of the material is increased. The key result here is a negative elastic constant created from resonant frequencies of the material. Its projected applications, with a future expanded frequency range in elastic wave systems, are seismic wave reflection and ultrasonics.

## Split-ring resonators for acoustic metamaterials



Copper split-ring resonators and wires mounted on interlocking sheets of fiberglass circuit board. A split-ring resonator consists of an inner square with a split on one side embedded in an outer square with a split on the other side. The split-ring resonators are on the front and right surfaces of the square grid and the single vertical wires are on the back and left surfaces.

In 2004 split-ring resonators (SRR) became the object of acoustic metamaterial research. Prior research with SRRs fabricated as negative index *electromagnetic* metamaterials was referenced as the progenitor of further research in acoustic metamaterials. An analysis of the frequency band gap characteristics, derived from the inherent limiting properties of artificially created SRRs, paralleled an analysis of sonic crystals. The band gap properties of SSRs were related to sonic crystal band gap properties. Inherent in this inquiry is a description of mechanical properties and problems of continuum mechanics for sonic crystals, as a macroscopically homogeneous substance.

The correlation in bandgap capabilities includes locally resonant elements and elastic moduli which operate in a certain frequency range. Elements which interact and resonate in their respective localized area are embedded throughout the material. In acoustic metamaterials, locally resonant elements would be the interaction of a single 1-cm rubber sphere with the surrounding liquid. The values of the stop band and band gap frequencies can be controlled by choosing the size, types of materials, and the integration of microscopic structures which control the modulation of the frequencies. These materials are then able to shield acoustic signals and attenuate the effects of anti-plane shear waves. By extrapolating these properties to larger scales it could be possible to create seismic wave filters.

According to research prior to this analysis, arrayed metamaterials can create filters or polarizers of either electromagnetic or elastic waves. Here a method is shown which can be applied to two-dimensional stop band and bandgap control with either photonic or sonic structures. Similar to photonic and electromagnetic metamaterial fabrication, a sonic metamaterial is embedded with localized sources of mass density  $\rho$  and the (elastic) bulk modulus  $\beta$  parameters, which are analogous to permittivity and permeability, respectively. The sonic (or phononic) metamaterials are sonic crystals, as in the previous section. These crystals have a solid lead core and a softer, more elastic silicone coating. The sonic crystals had built-in localized resonances due to the coated spheres which resulted in almost flat dispersion curves. Low-frequency bandgaps and localized wave interactions of the coated spheres were analyzed and presented in.

This method can be used to tune bandgaps inherent in the material and, also, create new low-frequency bandgaps. It is also applicable for designing low-frequency phononic crystal waveguides (radio frequency). Doubly periodic square array of SRRs are used to illustrate the methodology.

## Phononic crystal

**Phononic crystals** are synthetic materials that are formed by periodic variation of the acoustic properties of the material (i.e., elasticity and mass). One of the main properties of the phononic crystals is the possibility of having a phononic bandgap. A phononic crystal with phononic bandgap prevents phonons of selected ranges of frequencies from being transmitted through the material.

To obtain the frequency band structure of a phononic crystal, Bloch theory is applied on a single unit cell in the reciprocal lattice space (Brillouin zone). Several numerical methods are available for this problem, e.g., the planewave expansion method, the finite element method, and the finite difference method. A brief survey of numerical methods for calculating the frequency band structure is provided by Hussein (2009)

In order to speed up the calculation of the frequency band structure, the **Reduced Bloch Mode Expansion (RBME)** method can be used. The RBME applies "on top" of any of the primary expansion numerical methods mentioned above. For large unit cell models, the RBME method can reduce the time for computing the band structure by up to two orders of magnitude.

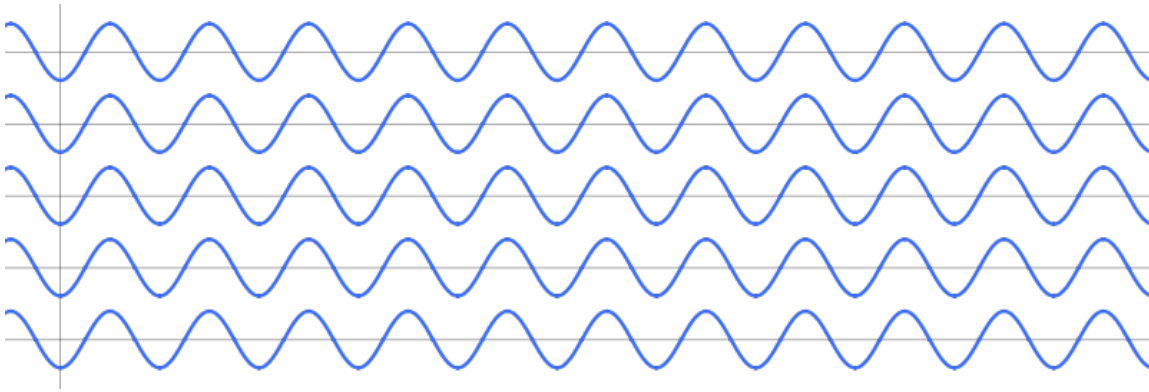
The basis of phononic crystals dates back to Isaac Newton who imagined that sound waves propagated through air in the same way that an elastic wave would propagate along a lattice of point masses connected by springs with an elastic force constant  $E$ . This force constant is identical to the modulus of the material. Of course with phononic crystals of materials with differing modulus the calculations are a little more complicated than this simple model.

Based on Newton's observation we can conclude that a key factor for acoustic band-gap engineering is impedance mismatch between periodic elements comprising the crystal

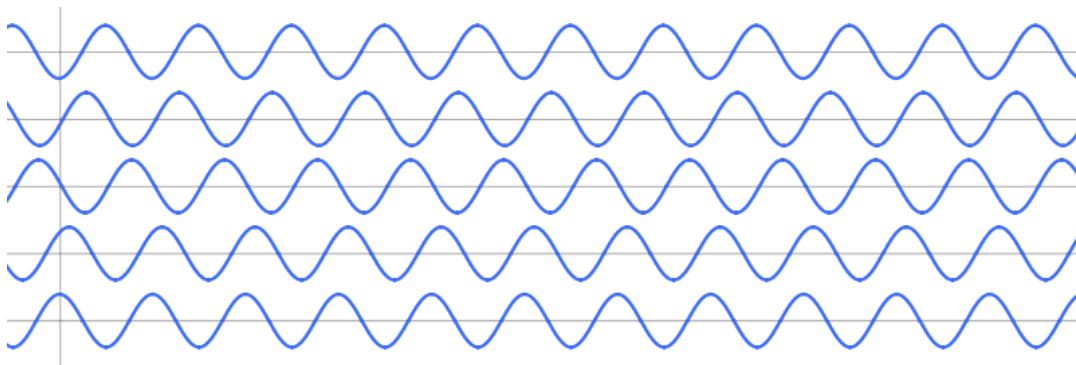
and the surrounding medium. When an advancing wave-front meets a material with very high impedance it will tend to increase its phase velocity through that medium. Likewise, when the advancing wave-front meets a low impedance medium it will slow down. We can exploit this concept with periodic (and handcrafted) arrangements of impedance mismatched elements to affect acoustic waves in the crystal – essentially band-gap engineering.

The position of the band-gap in frequency space for a phononic crystal is controlled by the size and arrangement of the elements comprising the crystal. The width of the band gap is generally related to the difference in the speed of sound (due to impedance differences) through the materials that comprise the composite.

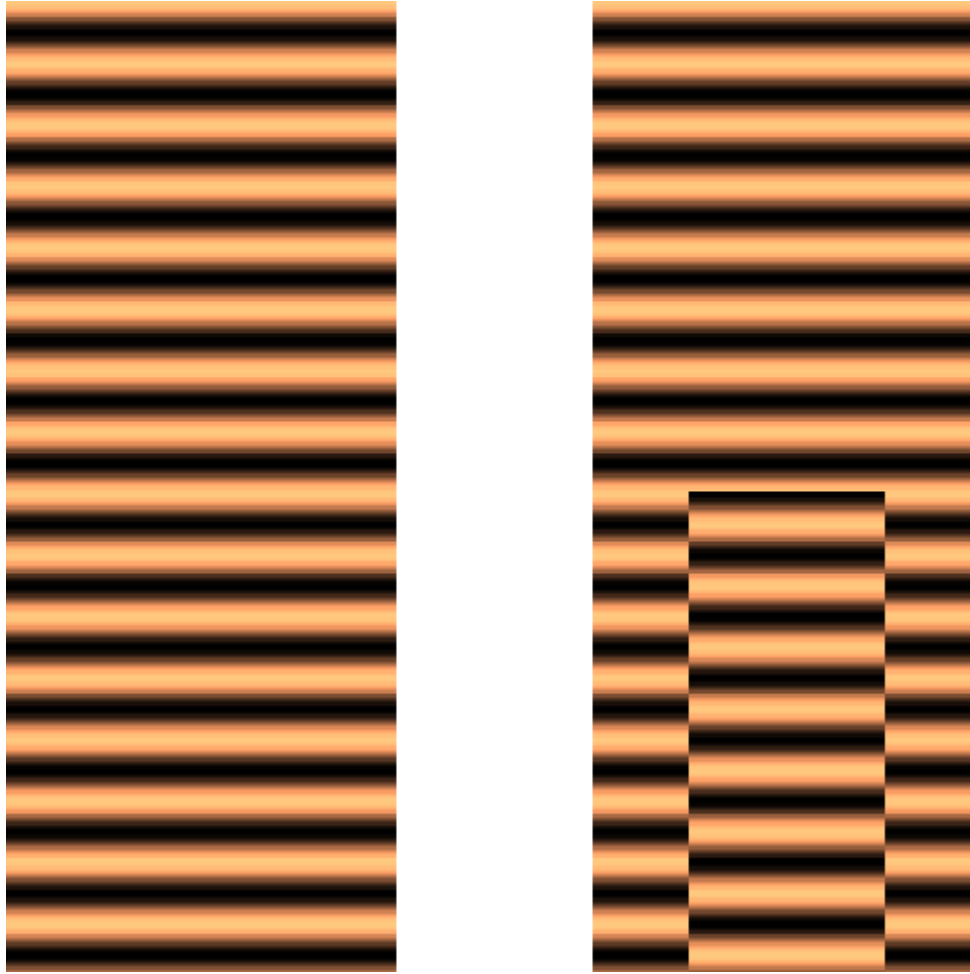
### **Double-negative acoustic metamaterial**



In-phase waves



Out-of-phase waves



Left: the real part of a plane wave moving from top to bottom. Right: the same wave after a central section underwent a phase shift, for example, by passing through metamaterial inhomogeneities of different thickness than the other parts. (The illustration on the right ignores the effect of diffraction whose effect increases over large distances).

The electromagnetic (isotropic) metamaterials have built-in resonance structures that exhibit effective negative permittivity and negative permeability for some frequency ranges. In contrast, it is difficult to build composite acoustic materials with built-in resonances such that the two effective response functions are negative within the capability or range of the transmission medium.

The mass density  $\rho$  and bulk modulus  $\beta$  are position dependent. Using the formulation of a plane wave the wave vector is:

$$\vec{k} = \frac{|n|\omega}{c}.$$

The angular frequency is represented by  $\omega$  and  $c$  is the propagation speed of acoustic signal through the homogeneous medium. With constant density and bulk modulus as

constituents of the medium, the refractive index is expressed as  $n^2 = \rho / \beta$ . In order to develop a propagating (plane) wave through the material, it is necessary for both  $\rho$  and  $\beta$  to be either positive or negative.

When the negative parameters are achieved, the mathematical result of the Poynting vector  $\overleftarrow{s}$  is the opposite direction of the wave vector  $\overrightarrow{k}$ . This requires negativity in bulk modulus and density. Physically, it means that the medium displays an anomalous response at some frequencies such that it expands upon compression (negative bulk modulus) and moves to the left when being pushed to the right (negative density) at the same time.

Natural materials do not have a negative density or a negative bulk modulus, but, negative values are mathematically possible, and can be demonstrated when dispersing soft rubber in a liquid.

Even for composite materials, the effective bulk modulus and density should be normally bounded by the values of the constituents, i.e., the derivation of lower and upper bounds for the elastic moduli of the medium. Intrinsic is the expectation for positive bulk modulus and positive density. For example, dispersing spherical solid particles in a fluid results in the ratio governed by the specific gravity when interacting with the long acoustic wavelength (sound). Mathematically, it can be easily proven that  $\beta_{\text{eff}}$  and  $\rho_{\text{eff}}$  are definitely positive for natural materials. The exception occurs at low resonant frequencies.

As an example, acoustic double negativity is theoretically demonstrated with a composite of soft, silicone rubber spheres suspended in water. In soft rubber, sound travels much slower than through the water. The high velocity contrast of sound speeds between the rubber spheres and the water allows for the transmission of very low monopolar and dipolar frequencies. This is an analogue to analytical solution for the scattering of electromagnetic radiation, or electromagnetic plane wave scattering, by spherical particles - dielectric spheres.

Hence, there is a narrow range of normalized frequency  $0.035 < \omega a / (2\pi c) < 0.04$  where the bulk modulus and negative density are both negative. Here  $a$  is the lattice constant if the spheres are arranged in a face-centered cubic (fcc) lattice;  $\omega$  is frequency and  $c$  is speed of the acoustic signal. The effective bulk modulus and density near the static limit are positive as predicted. The monopolar resonance creates a negative bulk modulus above the normalized frequency at about 0.035 while the dipolar resonance creates a negative density above the normalized frequency at about 0.04.

This behavior is analogous to low-frequency resonances produced in SRRs (electromagnetic metamaterial). The wires and split rings create intrinsic electric dipolar and magnetic dipolar response. With this artificially constructed acoustic metamaterial of rubber spheres and water, only one structure (instead of two) creates the low-frequency resonances to achieve double negativity. With monopolar resonance, the spheres expand, which produces a phase shift between the waves passing through rubber and water. This

creates the negative response. The dipolar resonance creates a negative response such that the frequency of the center of mass of the spheres is out of phase with the wave vector of the sound wave (acoustic signal). If these negative responses are large enough to compensate the background fluid, one can have both negative effective bulk modulus and negative effective density.

Both the mass density and the reciprocal of the bulk modulus are decreasing in magnitude fast enough so that the group velocity becomes negative (double negativity). This gives rise to the desired results of negative refraction. The double negativity is a consequence of resonance and the resulting negative refraction properties.

### **Metamaterial with simultaneously negative bulk modulus and mass density**

In August 2007 a metamaterial was reported which simultaneously possesses a negative bulk modulus and mass density. This metamaterial is a zinc blende structure consisting of one fcc array of bubble-contained-water spheres (BWSs) and another relatively shifted fcc array of rubber-coated-gold spheres (RGSs) in special epoxy.

Negative bulk modulus is achieved through monopolar resonances of the BWS series. Negative mass density is achieved with dipolar resonances of the gold sphere series. Rather than rubber spheres in liquid, this is a solid based material. This is also as yet a realization of simultaneously negative bulk modulus and mass density in a solid based material, which is an important distinction.

### **Double C resonators**

Double C resonator (DCR) is a ring cut in halves. In 2007, proposals have been made for arrays of DCRs and similar negative acoustic metamaterial. Although linear elasticity is mentioned, the problem is defined around shear waves directed at angles to the plane of the cylinders. The DCR was constructed similar to the SRRs in a multiple cell configuration. The DCR has been improved with stiffer material sheets. Each cell consists of a large rigid disk and two thin ligaments. The DCR cell is a tiny oscillator connected by springs. One spring of the oscillator connects to the *mass* and is anchored by the other spring. The LC resonator has specified capacitance and inductance. The limitations are expressed with appropriate mathematical equations. In addition to the intended limitations is that the speed of sound in the matrix is expressed as  $c = \sqrt{\rho/\mu}$  with a matrix of density  $\rho$  and shear modulus  $\mu$ . The resonant frequency is then expressed as  $\sqrt{1/(LC)}$ .

A phononic bandgap occurs in association with the resonance of the split cylinder ring. There is a phononic band gap within a range of *normalized frequencies*. This is when the inclusion moves as a rigid body.

The DCR design produced a suitable band with negative slope in a range of frequencies. This band was obtained by hybridizing the modes of a DCR with the modes of thin stiff bars. Calculations have shown that at these frequencies:

- a beam of sound negatively refracts across a slab of such a medium,
- the phase vector in the medium possesses real and imaginary parts with opposite signs,
- the medium is well impedance-matched with the surrounding medium,
- a flat slab of the metamaterial can image a source across the slab like a Veselago lens,
- the image formed by the flat slab has considerable sub-wavelength image resolution, and
- a double corner of the metamaterial can act as an open resonator for sound.

### **Acoustic metamaterial superlens**

In May 2009 Shu Zhang *et al.* presented the design and test results of an ultrasonic metamaterial lens for focusing 60 kHz (~2 cm wavelength) sound waves under water. The lens is made of sub-wavelength elements and is therefore potentially more compact than phononic lenses that operate in the same frequency range.

High-resolution acoustic imaging techniques are the essential tools for nondestructive testing and medical screening. However, the spatial resolution of the conventional acoustic imaging methods is restricted by the incident wavelength of ultrasound. This is due to the quickly fading evanescent fields which carry the sub-wavelength features of objects.

The lens consists of a network of fluid-filled cavities called Helmholtz resonators that oscillate at certain sonic frequencies. Similar to a network of inductors and capacitors in electromagnetic metamaterial, the arrangement of Helmholtz cavities designed by Zhang *et al.* have a negative dynamic modulus for ultrasound waves. Zhang *et al.* did focus a point source of 60.5 kHz sound to a spot size that is roughly the width of half a wavelength and their design may allow to push the spatial resolution even further. This result is in excellent agreement with the numerical simulation by transmission line model, which derived the effective mass density and compressibility. This metamaterial lens also displays variable focal length at different frequencies.

### **Acoustic diode**

An acoustic diode was introduced in August 2009. An electrical diode allows current to flow in only one direction in a wire; it is an essential electronic device which had no analogues for sound waves. However, the reported design partially fills this role by converting sound to a new frequency and blocking any backwards flow of the original frequency. In practice, it could give designers new flexibility in making ultrasonic sources like those used in medical imaging. The proposed structure combines two components: The first is a sheet of nonlinear acoustic material—one whose sound speed

varies with air pressure. An example of such a material is a collection of grains or beads, which becomes stiffer as it is squeezed. The second component is a filter that allows the doubled frequency to pass through but reflects the original.

## Chapter- 5

# Nonlinear Metamaterials

**Nonlinear metamaterials** are type of periodic, nonlinear, left-handed, artificially fabricated, transmission medium. These are a type of negative index metamaterial where the nonlinearity is available because the microscopic electric field of the inclusions can be larger than the macroscopic electric field of the propagating waves from the electromagnetic (EM) source. This then becomes a useful tool which allows for enhancing the nonlinear behavior of the metamaterial. A dominant nonlinear response, however, can be derived from the hysteresis-type dependence of the material's magnetic permeability on the magnetic component of the incident electromagnetic wave (light) propagating through the material. Furthermore, the hysteresis-type dependence of the magnetic permeability on the field intensity allows changing the material from left to right-handed and back.

Nonlinear media are essential for nonlinear optics. However most optical materials have a relatively weak nonlinear response, meaning that their properties only change by a small amount for large changes in intensity of the electromagnetic field. Nonlinear metamaterials can overcome this limitation, since the local fields of the inclusions in the metamaterial can be much larger than the average value of the field.

## Overview

Metamaterials are engineered microstructured materials. As a microstructured material these share a common description with metallic, polymeric, ceramic and other composite microstructured materials. However, metamaterials may differ in that these are purposely fabricated as a composite, and periodic structure. In other words, on a fundamental level, these are created by many identical, and therefore, repeating, resonant, and scattering elements.

Materials which scatter light or other electromagnetic waves create a general physical process where the different frequencies of light are forced to deviate from a straight trajectory. It is because, physically, the material is non-uniform at one, or more, or many places.

Furthermore, the optical sciences make predictions about the path of light traversing through a material. When light deviates from its predicted (reflected) path, this also is considered scattering. The elements which make up metamaterials are engineered to

scatter light at resonance. Moreover, these resonant scattering elements are purposely designed at a uniform size throughout the material. This uniform size is much smaller than the wavelength of the frequency of light propagating through the material.

Since the repeating, scattering, resonant elements, which make up the engineered material are much smaller than the frequency of propagating light, metamaterials can now, also, be described in terms of macroscopic quantities. This description is simply another way to view metamaterials. And these are electric permittivity,  $\epsilon$  and magnetic permeability,  $\mu$ .

Hence, by designing the individual, geometrically shaped unit of the material, called a cell, as the right kind of composite, it becomes a material with *macroscopic properties that do not occur in nature*.

Of particular interest regarding ***nonlinear metamaterials***, is the artificially induced macroscopic property known as negative refractive index. This effect is created by Negative index metamaterials, which are employed for use as *nonlinear metamaterials*.

## **Non-linear properties of left-handed metamaterials**

Previous studies of left-handed or negative index metamaterials were focused on the linear properties of the medium during wave propagation. In such cases, the view was that magnetic permeability and material permittivity are each non-dependent on the intensity of the electromagnetic field. However, creating tunable structures requires knowledge of non-linear properties where the intensity of the electromagnetic field alters the permittivity, or permeability, or both, which in turn effects the range of transmission spectra or stop band spectra. Hence, the effective permeability is dependent on the macroscopic magnetic field intensity. As the field intensity is varied, switching between its positive and negative values can occur. Consequently, the material can switch from being left-handed to being right-handed, or vice versa.

A composite structure consisting of a square lattice of the periodic arrays of conducting wires and split-ring resonators, produces an enhanced magnetic response. Without the correct magnetic response, it is not possible to produce a left-handed material.

### **Tunable split-ring resonators for nonlinear negative-index metamaterials**

Variable capacitance diodes are incorporated into the split-ring cell producing a dynamic tunable system.

### **Reconfigurable refractive index (infrared)**

Source radiation of near infrared wavelengths are applied to a metamaterial system. The index of refraction can be reconfigured to exhibit negative values, zero, or positive values.

## **SRR microwave nonlinear tunable metamaterial**

Fabrication and experimental studies of the properties of the *first nonlinear tunable metamaterial* operating at microwave frequencies. Such a metamaterial was fabricated by modifying the properties of SRRs and introducing varactor diodes in each SRR element of the composite structure such that the whole structure becomes dynamically tunable by varying the amplitude of the propagating electromagnetic waves. In particular, the power dependent transmission of the left-handed and magnetic metamaterials at higher powers is demonstrated, as was suggested earlier theoretically and selective generation of higher harmonics.

## **SRR microwave nonlinear magnetic metamaterials**

The fabrication and experimental studies of the properties of the *nonlinear tunable magnetic metamaterial* operating at microwave frequencies. Varactor diodes are symmetrically introduced, which results in dynamic tunability for the whole structure. Since the magnetic component of the interaction determines the application, the power dependency is demonstrated. Nonlinearity-dependent enhancement or suppression of the transmission is turns out to be dynamically tunable.

## **SRR microwave nonlinear electric metamaterials**

A new type of nonlinear metamaterials, is proposed and designed, exhibiting a resonant electric response at microwave frequencies. By introducing a varactor diode as a nonlinear element within each resonator, the frequency of the electric mode stop band is shifted by changing the incident power without affecting the magnetic response. These elements could be combined with the previously developed nonlinear magnetic metamaterials in order to create negative index media with a control over both electric and magnetic nonlinearities.

Nonlinear resonators are designed in a similar fashion. A strong nonlinear electric response is obtained.

## **Sub-diffraction limit for non-linear metamaterial lens**

By covering a thin flat nonlinear lens on the sources, the sub-diffraction-limit observation can be achieved by measuring either the near-field distribution or the far-field radiation of the sources at the harmonic frequencies and calculating the IFT to obtain the sub-wavelength imaging. The higher order harmonics are used, the higher resolution is obtained.

## **Non-linear electric metamaterial**

A new type of nonlinear metamaterial is designed, and analyzed with a dominant negative electric response. Introducing nonlinearity into the electric response makes it

tunable while leaving the magnetic response unchanged. A nonlinear NIM containing tunable electric and magnetic elements, which can respond independently is possible.

### **EM field shielding by non-linear metamaterials**

It is well known that over certain frequencies, typical metals can reflect electromagnetic (EM) fields and can thus be used as electromagnetic shielding materials. However, conventional *linear* LHMs cannot be used to shield electromagnetic fields. This is drastically modified when nonlinearity of the magnetic response is taken into account, creating a controllable shielding effect in LHMs, accompanied by a parametric reflection.

### **Meta-dimer metamaterial**

A meta-dimer is composed of two spatially separated SRRs, with the two SRRs identical in each unit cell. The proximity of the SRRs in the dimer results in relatively strong coupling between them. A metamaterial comprising a large number of such metadimers can be utilized as an actively tunable medium at optical wavelengths. If either or both of the SRRs in the meta-dimer become nonlinear, the metamaterial itself acquires nonlinear properties. This can allow for nonlinear behavior, such as tunability in real time. Stereometamaterials are also a type of meta-dimer.

## Chapter- 6

# Photonic Metamaterials

**Photonic metamaterials**, also known as **Optical metamaterials**, are a type of electromagnetic metamaterial, which are designed to interact with optical frequencies which are terahertz (THz), infrared (IR), and eventually, visible wavelengths. As a type of metamaterial, the periodic structures are made up of single units called cells. These single units are much smaller than the wavelength of the radiated source. With photonic metamaterials the radiated source is at optical wavelengths. Furthermore, the subwavelength period distinguishes the photonic metamaterial from photonic band gap or photonic crystal structures. This is because the special optical properties do not arise from photonic bandgaps, but rather from a subwavelength interaction with the light spectrum, which mimics atoms or ions. However, the periodic cells (meta-atoms) are fabricated on a scale that is magnitudes larger than the atom, yet smaller than the radiated wavelength.

Electromagnetic metamaterials in general are designed to operate at different frequencies. For example, prior and current research is in the microwave domain with physical periodic cell structures on the scale of millimeters. Because the optical wavelengths (wavelengths of a few microns) are much shorter than microwave frequencies, photonic metamaterial cell structures are on the scale of nanometers.

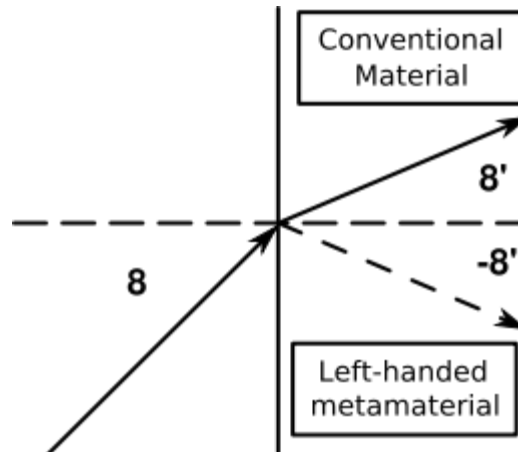
In a naturally occurring, (conventional) material, the response to electric and magnetic fields, and hence to light, is determined by the atoms. As a type of metamaterial, the photonic metamaterial is an artificially engineered structure. Therefore, each periodic cell is designed with specific parameters by which it interacts with the radiated field at optical frequencies. At the same time, however, metamaterials in general, which includes photonic metamaterials, are described as homogeneous materials, or in other words, utilizing an *effective medium model*.

Furthermore, demonstrating artificial magnetism at high frequencies, resulting in strong magnetic coupling, is contrasted with the usual or normal weak magnetic coupling of ordinary materials. This can then be applied to achieving negative index of refraction in the optical range, and developing approaches that show potential for application to optical cloaking. In addition, photonic metamaterials are an emergent tool in transformation optics.

Finally, regarding photonic crystals, the size and periodicity of the scattering elements are on the order of the wavelength rather than subwavelength. A photonic crystal cannot be

described as a homogeneous medium so it is not possible to define values of  $\epsilon$  or  $\mu$ . However, photonic crystal materials are typically composed of insulators and therefore can exhibit very low losses, even at optical frequencies.

## The development of photonic metamaterials



A comparison of refraction in a left-handed metamaterial to that in a normal material

### Artificial composite structures – metamaterials

In tandem with the assemblage of the first metamaterials, came the awareness of possibilities that were once thought not possible before the late 1990s. Nanometer-scale imaging, an opposite refraction phenomenon, and cloaking objects were part of the science fiction genre. These observable, scientific phenomena are possible because structural units of the metamaterials can be tailored in shape, size, and spacing. Their composition, and their form or structure, can be finely adjusted. Inclusions are specifically designed, and then placed at desired locations. Each design alteration, and - or change-up in spacing, creates a new variation in the function of a given metamaterial. As of 2009 these possibilities are occurring in the lab, and some related metamaterial technologies are already in the commercial sector.

A basis for understanding metamaterials in general is the propagation of light in conventional optical materials, such as glass or prisms. Although light consists of an electric field and a magnetic field, ordinary optical materials have a vigorous interaction *only with the electric field*. In comparison, the corresponding faint, magnetic interaction *is essentially nil*. This results in only the most common optics effects. These common optical effects include ordinary refraction with common diffraction limitations in lenses and imaging. In other words, this property limits the ability to control electromagnetic waves, which includes visible light, propagating through these materials. While researching whether or not matter interacts with the magnetic component of light, Victor Veselago (1967) envisioned the possibility of extraordinary refraction, occurring with a negative sign according to Maxwell's equations. According to Veselago, and confirmed

by researchers 30 years later, a refractive index with a negative sign is the result of permittivity,  $\epsilon < 0$  (less than zero) and magnetic permeability,  $\mu < 0$  (also less than zero).

## **Negative permeability and negative refractive index**

Natural materials, such as precious metals, can achieve permittivity values of less than zero ( $\epsilon < 0$ ) up to the visible frequencies. However, at terahertz, infrared, and visible frequencies (optical range), natural materials have a very weak magnetic coupling component, or permeability. In other words, susceptibility to the magnetic component of the radiated light, or electromagnetic wave, can be considered negligible. Nevertheless, producing negative values for permeability ( $\mu < 0$ ) is necessary to produce the negative refractive index of the photonic metamaterial.

Thirty years later an artificial negative value for permeability, was achieved with the first repeating split-ring resonator (SRR) structure. The SRR achieved negative permeability ( $\mu < 0$ ) within a narrow range of frequency. This was then combined with a symmetrically positioned electric conducting post, which created the first actual left-handed material LHM - a type of Metamaterial- operating in the microwave sector. A similarly structured left-handed material, with enhanced capabilities compared to the first, soon followed. This also was demonstrated at microwave frequencies. Although transmission experiments and simulations on these LHMs demonstrated the presence of a left-handed propagation band, the first experimental confirmation of negative index of refraction occurred at a time, shortly after the above; and once again at microwave frequencies.

The LHM is a material, which behaves contrary to the conventional "right-handed" interaction of light found in conventional optical materials. Hence, these are dubbed left-handed materials or negative index materials (NIMs), among other nomenclatures. Simply put, metamaterials, LHMs - or NIMs - have effectively expanded the material response.

To date (March 2010), only artificially fabricated LHMs have the distinction of exhibiting this capability; even when compared to photonic crystals. Photonic crystals, like many other known systems, can exhibit unusual propagation behavior such as reversal of phase and group velocities. But, negative refraction does not occur in these systems, and not yet realistically in Photonic crystals.

Naturally occurring ferromagnetic and antiferromagnetic materials can achieve magnetic resonance, but with significant losses. Furthermore, characteristic of natural materials such as natural magnets, and ferrites, resonance for the electric (coupling) response and magnetic (coupling) response do not occur simultaneously, at the same set of frequencies. These constraints imply that Veselago's theoretical analysis of a material with extraordinary properties might have remained in the background as an intriguing curiosity. However, explorations into the possibility of manufacturing materials which have the enlarged electric and magnetic response began in the mid-1990s. Although earlier research into artificial materials dates back to the 1940s, and even the late 19th

century, advances of the 1990s in fabrication and the computational sciences led to a resurgence in research for these unconventional materials. Furthermore, Victor Veselago's seminal analysis has been cited in over 1500 peer reviewed articles, including a number of books on the subject of artificial materials that have a negative index, and variations thereof.

## Optical frequency metamaterials

Within a only a few years the structures were scaled down for optical frequencies with nano-scale metamaterials. Photonic metamaterial SRRs have now reached scales below 100 nanometers, with special electron beam and nanolithography techniques. One type of nanoscale SRR cell has three very small metallic rods which are physically connected. This is configured into a U type of a shape, which then functions as a nano-inductor. The gap between the tips of the U-shape function as a nano-capacitor. Hence, it is then a nano-LC resonator, with resonance occurring at optical frequencies. These are the actual "inclusions" mentioned in the metamaterial literature, which create local electric and magnetic fields when externally excited. A notable characteristic occurs at optical frequencies; these inclusions are usually ten times smaller than the vacuum wavelength of the light  $c_0$ , at resonance frequency. The fabrication of the inclusions in this way can then be evaluated by using an effective medium approximation.

Finally, *photonic metamaterials* open up a way to overcome the constraints (stated above) set by ordinary materials. The proper design of the inclusions (meta-atoms), which are elementary building blocks, now allow for a magnetic response with sufficient magnitude at optical frequencies. This includes negative permeability,  $\mu < 0$ , despite the fact that these are constructed from non-magnetic materials. Furthermore, analogous to ordinary optical material, such a photonic metamaterial can be treated as an effective medium that is characterized by effective medium parameters  $\epsilon(\omega)$  and  $\mu(\omega)$ , or similarly,  $\epsilon_{\text{eff}}$  and  $\mu_{\text{eff}}$ .

## Effective medium model

An effective (transmission) medium approximation means that the combined overall effect of the inclusions, when reacting to an external excitation, is approximated to evaluate the metamaterial slab (the medium) as "effectively" homogeneous. The slab also has effective parameters, which include effective  $\epsilon$  and  $\mu$ . These are also approximated over the entire medium. Separate inclusions may have different values, but the overall effect results in an approximated effect for each parameter, hence, effective  $\epsilon$ , effective  $\mu$ .

Typically, the metamaterials are fabricated as composite structures created by many identical resonant scattering elements with the size much smaller than the wavelength of the propagating electromagnetic waves. Such micro-structured materials can be described in terms of macroscopic quantities – electric permittivity  $\epsilon$  and magnetic permeability  $\mu$ . By designing the individual unit cells of metamaterials, one may construct composites with effective properties not occurring in nature.

Furthermore, although these materials are artificially constructed they are behaving as "real" materials, because real materials also have a periodic structure, but at atomic scales. Real materials have a refractive index, just like these artificial materials. However, these artificial materials are able to create the overall effect of negative refractive index. So there is no qualitative difference between a metamaterial and a natural dielectric material. There is only a quantitative difference - the unit sizes interacting with light (EM radiation) are magnitudes larger with left-handed metamaterials.

## **The mechanics of optical frequency metamaterials**

Stacking layers is important to achieve the desired results at optical frequencies. However, the surface configuration (non-planar, bulk) of the SRR metamaterial layers normally prevents stacking. Although a single-layer SRR structure can easily be constructed on a dielectric surface, it is relatively difficult to stack these bulk structures due to the tight alignment tolerance requirements. However, a layer by layer stacking technique for SRRs was published in 2007. It uses dielectric spacers to apply a planarization procedure to flatten the SRR layer. As a result it appears that any number of layers can be made this way, including any chosen number of unit cells as well as intentional designing of the spatial arrangements of subsequent layers.

## **Photonic metamaterials: coupling magnetism at optical frequencies**

To be characterized as a left-handed material there is a requirement for negative magnetic permeability  $\mu$ . This was originally achieved in a left-handed medium (metamaterial) at microwave frequencies by using arrays of split-ring resonators, to demonstrate experimental verification of a negative index of refraction. In most natural occurring materials, the magnetically coupled response starts to taper off at frequencies in the gigahertz range, which also means significant magnetism does not occur at optical frequencies. This creates a state where the effective permeability of the material is unity,  $\mu_{\text{eff}} = 1$ . Hence, the magnetic component of a radiated electromagnetic field has virtually no effect on natural occurring materials at optical frequencies.

As metamaterials evolve, a new domain of optical materials has been developed, and magnetic permeability  $\mu_{\text{eff}}$  no longer equals unity for materials at optical frequencies. For metamaterials  $\mu_{\text{eff}} \neq 1$ , and much research and experimentation has been accomplished for permeability less than 0 (negative values);  $\mu_{\text{eff}} < 0$ .

Reviewing the characteristics of predetermined, engineered, periodic structures such as SRRs leads to an understanding of the physics of a periodic metamaterial. Meta-atoms are used to create conditions where a normally weak magnetic effect on materials is now strengthened in the new artificial materials. A meta-atom could be an SRR cell, the arrayed wire component of a YIG tuner, or any other artificial material designed to be periodic, and responsive at a fraction of the radiated wavelength.

In such a design, the meta-atom becomes a larger scale, millimeter or nanometer-sized-magnetic dipole, when compared to the picometer sized atom. A meta-atom creates a

magnetic dipole moment analogous to the magnetic dipole moment of natural atoms. For meta-atom constructed from the precious metal, gold the condition of  $\mu < 0$  can be achieved at telecommunication frequencies but, still not across the range of the visible frequencies. The visible frequency has been elusive because the plasma frequency of any metal is the ultimate limiting condition.

Researchers are earnestly engaged in combining negative "magnetic" permeability  $\mu < 0$  with negative "electric" permittivity  $\epsilon < 0$ , which can occur in each meta-atom when engineered to do so.

In 2006, researchers from various groups agreed to state the following: "Possibly, the real potential of the photonic metamaterials lies in other unexplored areas, for example, in chiral metamaterials or in nonlinear metamaterials. In any case, given today's possibilities regarding the nanofabrication of tailored "atoms," only our own imagination and creativity set the limits."

## **Proposal for metamaterials with optical frequencies response**

By employing a combination of plasmonic and non-plasmonic nanoparticles, lumped circuit element nanocircuits at infrared and optical frequencies appear to be possible. Designing subwavelength lumped circuit element structures at infrared and optical frequencies has special challenges when compared to lower frequency domains. Conventional lumped circuit elements are not available in a conventional way.

The concept and implementation of lumped circuit elements in the microwave and radio frequency (RF) domain for metamaterial design has proved to be effective. These are subwavelength structures. The lumped element concept has allowed for element simplification and circuit modularization. A similar concept applicable to materials that respond at terahertz (THz), infrared (IR), and visible wavelengths can be employed. However these lumped circuit elements must also be smaller than terahertz (THz), infrared (IR), and visible wavelengths. Nanoscale fabrication techniques do exist to accomplish this. Therefore, size reduction as an obstacle, may in time, be overcome.

The response of metals at smaller wavelengths is, however, a more pronounced limitation. Metals such as gold, silver, aluminum, and copper easily conduct currents at RF and microwave frequencies. Hence, these have been more easily integrated as materials employed in these regimes. At optical frequencies characteristics of some noble metals are altered. Rather than normal current flow, plasmonic resonances occur as the real part of the complex permittivity of these metals become negative. Therefore, the main current flow is actually the electric displacement current density  $\partial D / \partial t$ , and can be termed as the "flowing optical current". Solving this problem, then, becomes more than scaling down the element size.

Being smaller than the wavelength, the impedance of the particle becomes dependent several factors. The particle's shape, size, material, along with the optical frequency illumination all contribute to determine the nanoparticle's impedance. The particle's orientation with the optical electric field may also help determine the impedance. The choice of material actually results in the type of impedance the nanoparticle will exhibit. If the material is a conventional silicon dielectric, with real permittivity  $\epsilon_{\text{real}} > 0$  at optical frequencies, the nanoparticle will act as a capacitive impedance or, in other words - nanocapacitor. Conversely, if the material is a noble metal such as gold (Au) or silver (Ag), with a real permittivity less than zero,  $\epsilon_{\text{real}} < 0$ , then it takes on inductive characteristics. Hence, it becomes a nanoinductor. Finally, material loss is represented as a nano-resistor.

## Fabrication techniques

Because microwaves are much longer than terahertz and infrared wavelengths, photonic metamaterials are more difficult to realize. Metamaterials in the microwave domain can be fabricated from circuit board materials. In contrast lithography techniques must be employed to produce the rudimentary elements, nano-resonators, that can create photonic metamaterials. The earlier type of nano-resonators were based on the split-ring resonator in the microwave domain. These can be considered as simplified LC circuits. Inductance is achieved because the ring is split, and capacitance occurs across the gap.

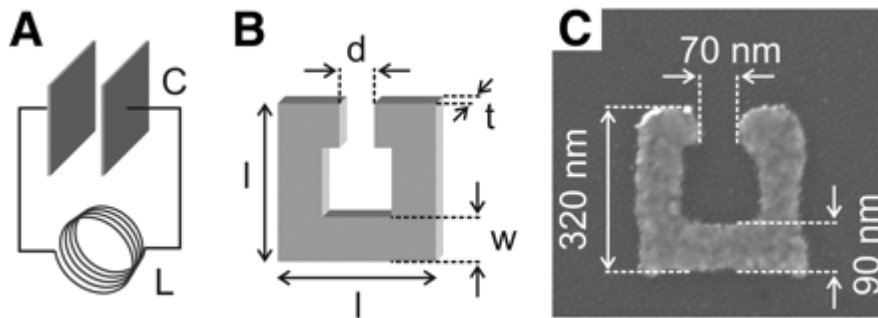


Illustration of the analogy between a conventional LC circuit (A), consisting of an inductance L, a capacitance C, and the single SRRs used here (B). l, length; w, width; d, gap width; t, thickness. (C) An electron micrograph of a typical SRR fabricated by electron beam lithography.

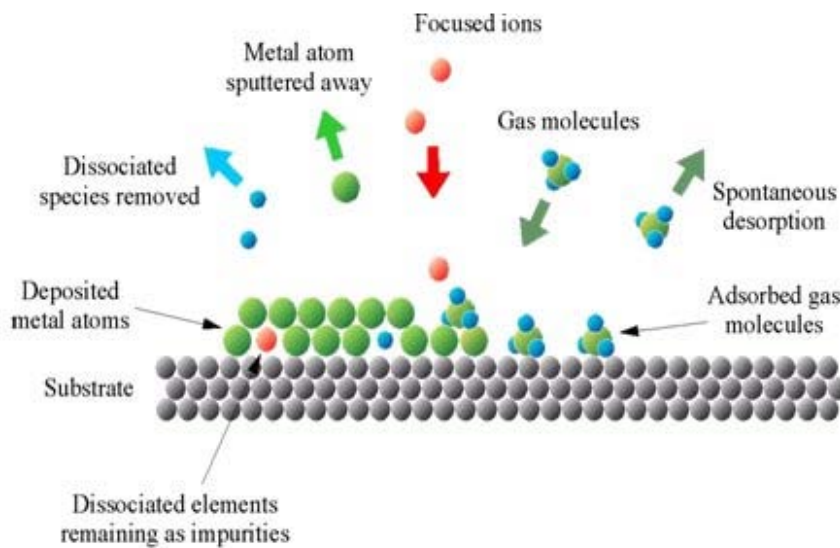
Other types of subwavelength photonic materials soon followed. In one instance, a periodic arrangement of short wires, and in another instance metallic pieces with varied shapes successfully interact at shorter wavelengths. In a different study, rather than the isolated nano-resonator structure, the whole metamaterial can be electrically connected for desired photonic subwavelength result.

In the following sections, some of the fabrication techniques are discussed.

## Electron beam lithography

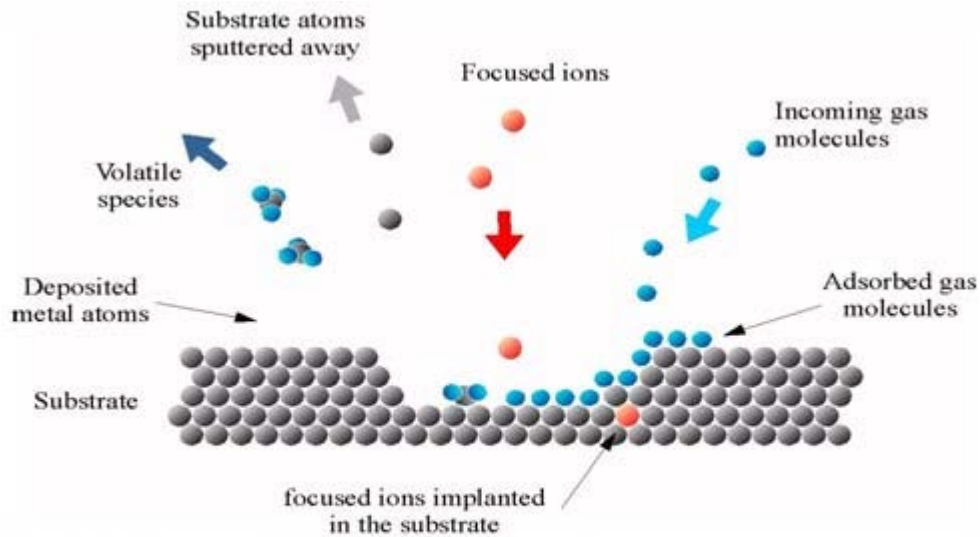
Photonic metamaterials have inclusions which are at the nanometer scale. *Electron beam lithography* is a widely used technique for fabrication of flat and rectangular, planar) nanometer sized-structures. It is a serial technique which is very flexible. Arbitrary two-dimensional patterns are possible scaling down to 10 nm. It is based on exposure to a suitable resist.

## Focused ion beam nanostructuring



1. Adsorption of the precursor molecules on the substrate
2. Ion beam induced dissociation of the gas molecules
3. Deposition of the material atoms and removal of the organic ligands

Gas assisted deposition process



1. Adsorption of the gas molecules on the substrate
2. Interaction of the gas molecules with the substrate  
Formation of volatile and non volatile species
3. Evaporation of volatile species and sputtering of non volatile species

#### Gas assisted FIB etching process

Focused ion beam nanostructuring is a convenient tool for rapid prototyping of photonic metamaterials. The FIB is used as a micro-machining tool, to modify or machine materials at the micro- and nanoscale. FIB micro machining has become a broad field of its own, but nano machining with FIB is a field that still needs developing. The common smallest beam size is around 2.5 to 2.6 nanometers.

Ions are positive, large, heavy and slow, whereas electrons (electron beam lithography) are negative, small, light and fast. The most important consequence of these properties is that ion beams will remove atoms from the substrate and because the beam position, dwell time, and size are so well controlled it can be applied to remove material locally in a highly controlled manner, down to the nanometer scale.

Moreover, unlike an electron microscope, FIB is inherently destructive to the specimen. When the high-energy gallium ions strike the sample, they will sputter atoms from the surface. Gallium atoms will also be implanted into the top few nanometers of the surface, and the surface will be made amorphous.

FIB tools are designed to etch or machine surfaces, an ideal FIB might machine away one atom layer without any disruption of the atoms in the next layer, or any residual disruptions above the surface. Yet currently because of the sputter the machining typically roughens surfaces at the submicrometre length scales.

An FIB can also be used to deposit material via ion beam induced deposition. FIB-assisted chemical vapor deposition occurs when a gas, such as tungsten hexacarbonyl

(W(CO)<sub>6</sub>) is introduced to the vacuum chamber and allowed to chemisorb onto the sample. By scanning an area with the beam, the precursor gas will be decomposed into volatile and non-volatile components; the non-volatile component, such as tungsten, remains on the surface as a deposition. This is useful, as the deposited metal can be used as a sacrificial layer, to protect the underlying sample from the destructive sputtering of the beam. From nanometers to hundred of micrometers in length, tungsten metal deposition allows to put metal lines right where needed. Other materials such as platinum, cobalt, carbon, gold, etc., can also be locally deposited. Gas assisted deposition and FIB etching processes are shown to the right.

## **Interference lithography**

Interference lithography is comparatively inexpensive and is versatile.

## **Tunable metamaterials at optical frequencies**

Photonic metamaterials have become part of the pantheon of tunable and non-linear metamaterials. These are discussed in the Tunable metamaterials and Nonlinear metamaterials articles.

As discussed throughout here, some photonic applications are the purview of nanostructured metamaterials, which exhibit unique physical and optical properties. Areas of active research in optical materials are metamaterials that are capable of negative values for index of refraction (NIMs), and metamaterials that are capable of zero index of refraction (ZIMs). Complicated steps required to fabricate these nano-scale metamaterials have led to the desire for fabricated, tunable structures capable of the prescribed spectral ranges or resonances.

The most commonly applied scheme to achieve these effects is *electro-optical tuning*. Here the change in refractive index is proportional to either the applied electric field, or is proportional to the square modulus of the electric field. These are the Pockels effect and Kerr effect, respectively.

An alternative is to employ a nonlinear optical material as one of the constituents of this system, and depend on the optical field intensity to modify the refractive index, or magnetic parameters.

## **Three-dimensional photonic metamaterials at optical frequencies**

As has been already established, metamaterials are artificial media, and the unit cell of metamaterials is much smaller than the wavelength of light. As of December 2007, the physical characteristics of metamaterials, which include negative permeability and negative refraction, had been limited to demonstrations in two-dimensions. However, a group of researchers at the Physikalisches Institut - Universität Stuttgart perceived that

the practical applications of these physical characteristics require three-dimensional bulk like structures. Up to this time, fabrication techniques were most compatible in the GHz range for microwave applications.

By simply stacking printed circuit boards applications were available at GHz frequencies in the microwave range. This fabrication technique of *metal–dielectric stacks* is successful in this frequency range. However, a stacking technique in the optical (infrared) domain encountered technical problems which limited the number of stacked layers. So, an alternative to the unsuccessful stacking attempt was presented. The selected alternative is the split-ring resonator (SRR) structure. The SRR structure is widely used, and has induced negative values for permeability, for certain frequency ranges. SRR have been used in metamaterials since the 2001 demonstration.

The completed SRR metamaterial layers cannot be stacked, as it is not a flat (or planar) surface. This design prevents stacking. So, the SRR layers were flattened with dielectric spacers.

## **Dyakonov surface waves in photonic metamaterials**

An idea for a type of photonic metamaterial is derived from the birefringent properties of photonic crystals. By utilizing metamaterial anisotropy, resonance conditions at which Dyakonov surface waves exist is met.

Suitable photonic metamaterial structures can support lossless surface waves of the form envisaged by Dyakonov. Surface waves are a special type of waves that are confined at the very boundary between two different media. By their very nature, surface waves are unique tools to explore the properties of material interfaces. This includes not only intrinsic properties but also extrinsic effects, thus making surface waves ideal tools for sensing physical, chemical, and biological agents. They feature genuine physical phenomena as well as prospects for far-reaching applications.

## **Negative-index photonic metamaterial at 780 nm wavelength**

Photonic metamaterials are tailored artificial optical materials composed of sub-wavelength metallic building blocks that can be viewed as nano-scale electronic circuits. These building blocks or “photonic atoms” are densely packed into an effective material such that the operation wavelength ( $\gamma$ ) is ideally much larger than the lattice constant  $a$  for the polarization configuration shown in the metamaterial can be viewed as composed of two sets of sub-circuits or “atoms”: A coil with inductance  $L$  in series with two capacitors with net capacitance  $C$  as an LC circuit, providing a magnetic resonance at the LC resonance frequency. Long metallic wires, acting like a diluted metal below the effective plasma frequency of the arrangement. Negative magnetic permeability and the negative electric permittivity are created, which leads to lead to a negative index of

refraction. Silver was used as constituent material because it is known to introduce significantly lower losses than gold and other noble metals at visible frequencies.

## **Optical negative-index metamaterials**

Describing the recent progress (in 2006) made in creating nanostructured metamaterials with a negative index at optical wavelengths, and discusses some of the devices that could result from these new materials.

## **Experimental demonstration of near-infrared NIMs**

Received 7 March 2005 and published in September of that year was the first fabrication and experimental verification of a transversely structured metal-dielectric-metal multilayer exhibiting a negative refractive index around 2  $\mu\text{m}$ . Both the amplitude and the phase of the transmission and reflection were measured experimentally, and are in good agreement with a rigorous coupled wave analysis.

## **Three-dimensional optical metamaterial**

Here is a 3D optical metamaterial having negative refractive index with a very high figure of merit of 3.5. This metamaterial is made of cascaded 'fishnet' structures, with a negative index existing over a broad spectral range. Moreover, it can readily be probed from free space, making it functional for optical devices. Constructed as a 21-layer fishnet structure with a unit cell parameters of  $a = 5.860 \mu\text{m}$ ,  $b = 5.565 \mu\text{m}$  and  $c = 5.265 \mu\text{m}$ .

## **Negative refraction at 813 nm and 772 nm**

Wavelengths of 813 nm and 772 nm approach the red end of the visible spectrum. A double negative refraction occurs at 813 nm and single negative refraction occurs at 772 nm.

## **Phase-engineered metamaterial structures and devices**

Electromagnetic metamaterials are inherently dispersive: their constitutive parameters (permittivity and permeability) are functions of frequency or, equivalently, their dispersion relation is a nonlinear function of frequency.

Since the invention of the superheterodyne receiver by Edwin Armstrong in 1918 and, later, the development of harmonic signal generators, most radio communication systems have been narrow-band in nature. However, the explosion of needs for high data-rate wireless links is currently producing a paradigmatic shift of radio toward broadband and ultra-wideband spectrum operation. In this context, the unprecedented and tailorable dispersive properties of metamaterials may provide solutions to several new challenges.

While the past decades have focused on magnitude engineering and filter design we predict that the forthcoming decades will experience major interest in phase engineering (where the term "*phase engineering*" is intended to represent both "dispersion and nonlinearity" engineering) along with phase-engineered devices. In this case, metamaterials are expected to play an important role.

## Chapter- 7

# Seismic Metamaterials

**Seismic metamaterials**, are metamaterials which are designed to counteract the adverse effects of seismic waves on artificial structures, which exist on or near the surface of the earth. As of 2009 seismic metamaterials were still in the development stage.

### **The mechanics of seismic waves**

More than a million earthquakes are recorded each year, by a worldwide system of earthquake detection stations. The propagation velocity of the seismic waves depends on density and elasticity of the earthen materials. In other words, the speeds of the seismic waves vary as they travel through different materials in the earth. The two main components of a seismic event are body waves and surface waves. Both of these have different modes of wave propagation.

### **Dissipating ocean surface waves with seismic metamaterials**

Computations showed that seismic waves traveling toward a building, could be directed around the building, leaving the building unscathed, by using *seismic metamaterials*. The very long wavelengths of earthquake waves would be shortened as they interact with the metamaterials; the waves would pass around the building so as to arrive in phase as the earthquake wave proceeded, as if the building was not there. The mathematical models produce the regular pattern provided by Metamaterial cloaking. This method was first understood with electromagnetic cloaking metamaterials - the electromagnetic energy is in effect directed around an object, or hole, and protecting buildings from seismic waves employs this same principle.

Giant polymer-made split ring resonators combined with other metamaterials are designed to couple at the seismic wavelength. Concentric layers of this material would be stacked, each layer separated by an elastic medium. The design that worked is ten layers of six different materials, which can be easily deployed in building foundations. As of 2009, the project is still in the design stage.

### **Electromagnetics cloaking principles for seismic metamaterials**

For seismic metamaterials to protect surface structures, the proposal includes a layered structure of metamaterials, separated by elastic plates in a cylindrical configuration. A

prior simulation showed that it is possible to create concealment from electromagnetic radiation with concentric, alternating layers of electromagnetic metamaterials. That study was in contrast to concealment by inclusions in a split ring resonator designed as an anisotropic metamaterial.

The configuration can be viewed as alternating layers of "homogeneous isotropic dielectric material" A with "homogeneous isotropic dielectric material" B. Each dielectric material is much thinner than the radiated wavelength. As a whole, such structure is an anisotropic medium. The layered dielectric materials surround an "infinite conducting cylinder". The layered dielectric materials radiate outward, in a concentric fashion, and the cylinder is encased in the first layer. The other layers alternate and surround the previous layer all the way to the first layer. Electromagnetic wave scattering was calculated and simulated for the layered (metamaterial) structure and the split-ring resonator anisotropic metamaterial, to show the effectiveness of the layered metamaterial.

### **Acoustic cloaking principles for seismic metamaterials**

The theory and ultimate development for the *seismic metamaterial* is based on coordinate transformations achieved when concealing a small cylindrical object with electromagnetic waves. This was followed by an analysis of acoustic cloaking, and whether or not coordinate transformations could be applied to artificially fabricated acoustic materials.

Applying the concepts used to understand electromagnetic materials to material properties in other systems shows them to be closely analogous. Wave vector, wave impedance, and direction of power flow are universal. By understanding how permittivity and permeability control these components of wave propagation, applicable analogies can be used for other material interactions.

In most instances, applying coordinate transformation to engineered artificial elastic media is not possible. However, there is at least one special case where there is a direct equivalence between electromagnetics and elastodynamics. Furthermore, this case appears practically useful. In two dimensions, isotropic acoustic media and isotropic electromagnetic media are exactly equivalent. Under these conditions, the isotropic characteristic works in anisotropic media as well.

It has been demonstrated mathematically that the 2D Maxwell equations with normal incidence apply to 2D acoustic equations when replacing the electromagnetic parameters with the following acoustic parameters: pressure, vector fluid velocity, fluid mass density and the fluid bulk modulus. The compressional wave solutions used in the electromagnetic cloaking are transferred to material fluidic solutions where fluid motion is parallel to the wavevector. The computations then show that coordinate transformations can be applied to acoustic media when restricted to normal incidence in two dimensions.

Next the electromagnetic cloaking shell is referenced as an exact equivalence for a simulated demonstration of the acoustic cloaking shell. Bulk modulus and mass density determine the spatial dimensions of the cloak, which can bend any incident wave around the center of the shell. In a simulation with perfect conditions, because it is easier to demonstrate the principles involved, there is zero scattering in any direction.

### **The seismic cloak**

The main principles underpinning the protection of structures from seismic waves are then applied to waves of force that travel through the Earth, which is an elastic body. Travelling pressure waves are always generated with longitudinal polarization. This means that the ground is alternately compressed and dilated in the direction of propagation. Travelling shear waves are transverse, or perpendicular to the direction of propagation. One of the effects of the metamaterial is to de-couple these components of the seismic wave. By applying these principles, it is possible to design a cylindrical, seismic metamaterial cloak to remedy the destructive effects of coupled pressure and shear waves that would travel through the same earthen geometrical plane as the structure. The components of the seismic waves should work together to disrupt the elastic earth, on which a building is anchored. However, it can be demonstrated through computation and visual simulation that the waves are in fact dispersed around the location of the building. The frequency range of this capability is shown to have no limitation regarding the radiated frequency. The cloak itself demonstrates no forward or back scattering, hence, the seismic cloak becomes an effective medium.

## Chapter- 8

# Terahertz Metamaterials



Terahertz waves lie at the far end of the infrared band, after the microwave band. In this image, an array of gold structures on top of a semiconductor base. The metamaterial and the semiconductor together form a device that can modulate the intensity of the terahertz radiation, by up to 50 percent when a voltage is applied to the gold structures. The experimental demonstration of the device exceeds the performance of existing electrical terahertz modulators.

**Terahertz metamaterials** are a new class of composite, artificial materials which interact at terahertz (THz) frequencies. The terahertz frequency range used in materials research is usually defined as 0.1 to 10 THz. This bandwidth is also known as the **terahertz gap**.

Terahertz waves are electromagnetic waves with frequencies higher than microwaves but lower than infrared radiation and visible light. They possess many advantages for applications in radio astronomy spectroscopy, non-destructive testing of spacecraft, non-ionizing medical imaging and tumor detection, high resolution close range radar, and security detection of chemicals, biological agents, and weapons. However this frequency region is largely under-utilized and referred to as the “Terahertz Gap” of the electromagnetic spectrum.

Applications of frequencies in the terahertz radiation range hold the promise of efficient advancement in notably important technologies. Currently, a fundamental lack in naturally occurring materials that allow for the desired electromagnetic response has led to constructing new artificial composite materials, termed metamaterials. The metamaterials are based on a lattice structure which mimics crystal structures. However

the lattice structure of this new material consists of rudimentary elements much larger than atoms or single molecules, but is an artificial, rather than a naturally occurring structure. Yet, the interaction achieved is below the dimensions of the terahertz radiation wave. In addition, the desired results are based on the resonant frequency of fabricated fundamental elements. The appeal and usefulness is derived from a resonant response that can be tailored for specific applications, and can be controlled electrically or optically. Or the response can be as a passive material.

## **Terahertz technology**

More broadly the submillimeter-wave energy can be defined 1000–100  $\mu\text{m}$  (300 GHz–3 THz). Beyond 3 THz, and out to 30 micrometer (10 terahertz) wavelengths has been metaphorically termed unclaimed territory where few devices, and perhaps none, exist. The submillimeter, or terahertz band, exists between technologies in traditional microwave and optical domains. Because atmospheric propagation is limited, the commercial sector has passed over this frequency band. However, terahertz technology has been instrumental for high-resolution spectroscopy. Moreover, a rich vein of knowledge has been amassed via submillimeter remote sensing techniques. In particular, interdisciplinary researchers in astrophysics and the earth sciences have mapped thermal emission lines for a wide variety of lightweight molecules. The amount of information obtained is specifically amenable to this particular band of electromagnetic radiation. In fact, the universe is bathed in terahertz energy; most of it going unnoticed and undetected.

## **Terahertz devices**

The development of electromagnetic, artificial-lattice structured materials, termed metamaterials, has led to the realization of phenomena that cannot be obtained with natural materials. This is observed, for example, with a natural glass lens, which interacts with light (the electromagnetic wave) in a way that appears to be one-handed, while light is delivered in a two-handed manner. In other words, light consists of an electric field and magnetic field. The interaction of a conventional lens, or other natural materials, with light is heavily dominated by the interaction with the electric field (one-handed). The magnetic interaction in lens material is essentially nil. This results in common optical limitations such as a diffraction barrier. Moreover, there is a fundamental lack of natural materials that strongly interact with light's magnetic field. Metamaterials, a synthetic composite structure, overcomes this limitation. In addition, the choice of interactions can be invented and re-invented during fabrication, within the laws of physics. Hence, the capabilities of interaction with the electromagnetic spectrum, which is light, are broadened (two-handed).

Development of metamaterials has traversed the electromagnetic spectrum up to terahertz and infrared frequencies, but does not yet include the visible light spectrum. This is because, for example, it is easier to build a structure with larger fundamental elements that can control microwaves. The fundamental elements for terahertz and infrared

frequencies have been progressively scaled to smaller sizes. In the future, visible light will require elements to be scaled even smaller, for capable control by metamaterials.

Along with the ability to now interact at terahertz frequencies is the desire to build, deploy, and integrate THz metamaterial applications universally into society. This is because, as explained above, components and systems with terahertz capabilities will fill a technologically relevant void. Because no known natural materials are available that can accomplish this, artificially constructed materials must now take their place.

Research has begun with first, demonstrating the practical terahertz metamaterial. Moreover, since, many materials do not respond to THz radiation naturally, it is necessary then to build the electromagnetic devices which enable the construction of useful applied technologies operating within this range. These are devices such as directed light sources, lenses, switches, modulators and sensors. This void also includes phase-shifting and beam-steering devices. Real world applications in the THz band are still in infancy.

Moderate progress has been achieved. Terahertz metamaterial devices have been demonstrated in the laboratory as tunable far-infrared filters, optical switching modulators, and absorbers. The recent existence of a terahertz radiating source in general are THz quantum cascade lasers. However, technologies to control and manipulate THz waves are lagging behind other frequency domains of the spectrum of light.

Furthermore, research into technologies which utilize THz frequencies show the capabilities for advanced sensing techniques. In areas where other wavelengths are limited, THz frequencies appear to fill the near future gap for advancements in security, public health, biomedicine, defense, communication, and quality control in manufacturing. This terahertz band has the distinction of being non-invasive and will therefore not disrupt or perturb the structure of the object being radiated. At the same time this frequency band demonstrates capabilities such as passing through and imaging the contents of a plastic container, penetrate a few millimeters of human skin tissue without ill effects, clothing to detect hidden objects on personnel, the detection of chemical and biological agents as novel approaches for counter-terrorism. Terahertz metamaterials, because they interact at the appropriate THz frequencies, seem to be one answer in developing materials which use THz radiation.

Researchers believe that artificial magnetic (paramagnetic) structures, or hybrid structures that combine natural and artificial magnetic materials, can play a key role in terahertz devices. Some THz metamaterial devices are compact cavities, adaptive optics and lenses, tunable mirrors, isolators, and converters.

# Challenges in this field

## Generating THz electromagnetic radiation

Without available terahertz sources, other applications are held back.

Semiconductor devices have become integrated into everyday living. Commercial and scientific applications for generating the appropriate frequency bands of light, or the electromagnetic spectrum, commensurate with the semiconductor application or device are in wide use. Visible and infrared lasers are at the core of information technology, and at the other end of the spectrum, microwave and radio-frequency emitters enable wireless communications.

However, applications for the terahertz regime, previously defined as the terahertz gap of .1 to 10 THz, is an impoverished regime by comparison. Sources for generating the required THz frequencies (or wavelength) exist, but other challenges hinder their usefulness. These laser devices are not compact and therefore lack portability and are not easily integrated into systems. In addition, low-consumption, solid state terahertz sources are lacking. The current devices also have one or more shortcomings of low power output, poor tuning abilities, and may require cryogenic liquids for operation (liquid helium).

This lack of appropriate sources hinders opportunities in spectroscopy, remote sensing, free space communications, and medical imaging.

Potential terahertz frequency applications are being researched globally. Two recently developed technologies, Terahertz time-domain spectroscopy and quantum cascade lasers could possibly be part of a multitude of development platforms worldwide. However, the devices and components necessary to effectively manipulate terahertz radiation require much more development beyond what has been accomplished to date (December 2009).

## Magnetic field interaction

As briefly mentioned above, naturally-occurring materials such as conventional lenses and glass prisms are unable to significantly interact with the magnetic field of light. The significant interaction (permittivity) occurs with the electric field. In natural materials any useful magnetic interaction will taper off in the gigahertz range of frequencies. Compared to interaction with the electric field, the magnetic component is imperceptible when in terahertz, infrared, and visible light. So, a notable step occurred with the invention of a practical metamaterial at microwave frequencies. This is because the rudimentary elements of metamaterials have demonstrated a coupling and inductive response to the magnetic component commensurate to the electric coupling and response. This demonstrated the occurrence of an artificial magnetism, and was later applied to terahertz and infrared electromagnetic wave (or light). In the terahertz and infrared domain, it is a response that has not been discovered in nature.

Moreover, because the metamaterial is artificially fabricated during each step and phase of construction, this gives ability to choose how light, or the terahertz electromagnetic wave, will travel through the material and be transmitted. This *degree of choice* is not possible with conventional materials. The control is also derived from electrical-magnetic coupling and response of rudimentary elements that are smaller than the length of the electromagnetic wave travelling through the assembled metamaterial.

Electromagnetic radiation, which includes light, carries energy and momentum that may be imparted to matter with which it interacts. The radiation and matter have a symbiotic relationship. Radiation does not simply act on a material, nor does it simply act on upon by a given material. Radiation interacts with matter. The magnetic interaction, or induced coupling, of any material can be translated into permeability. The permeability of natural occurring materials is a positive value. A unique ability of metamaterials is to achieve permeability values less than 0 (negative), values not accessible in nature. Negative permeability was first observed at microwave frequencies with the first metamaterials. A few years later negative permeability was demonstrated in the terahertz regime.

There have been reports of some natural magnetic materials that have responded at microwave frequencies. However, the magnetic effects in these materials are typically weak and often exhibit narrow bands, that limits the scope of possible THz devices. It was noted that the realization of magnetism at THz and higher frequencies will substantially affect THz optics and their applications.

This has to do with magnetic coupling at the atomic level. This drawback can be overcome by using metamaterials that mirror atomic magnetic coupling, on a scale magnitudes larger than the atom.

Materials which can couple magnetically are particularly rare at terahertz or optical frequencies.

## **The first THz metamaterials**

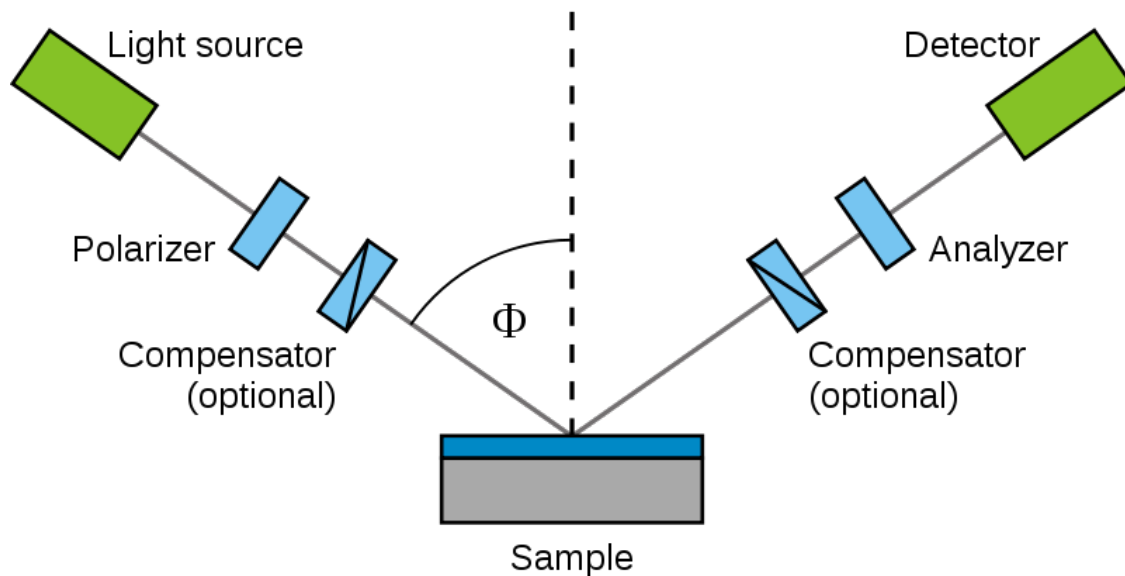
The first terahertz metamaterials able to achieve a desired magnetic response, which included negative values for permeability, were passive materials. Because of this, "tuning" was achieved by fabricating a new material, with slightly altered dimensions to create a new response. However, the notable advance, or practical achievement, is actually demonstrating the manipulation of terahertz radiation with metamaterials.

For the first demonstration, more than one metamaterial structure was fabricated. However, the demonstration showed a range of 0.6 to 1.8 terahertz. The results were believed to also show that the effect can be tuned throughout the terahertz frequency regime by scaling the dimensions of the structure. This was followed by a demonstrations at 6 THz, and 100 THz.

With the first demonstration, scaling of elements, and spacing, allowed for success with the terahertz range of frequencies. As with metamaterials in lower frequency ranges, these elements were non-magnetic materials, but were conducting elements. The design allows a resonance that occurs with the electric and magnetic components simultaneously. And notable is the strong magnetic response of these artificially constructed materials.

For the elements to respond at resonance, at specified frequencies, this is arranged by specifically designing the element. The elements are then placed in a repeating pattern, as is common for metamaterials. In this case, the now combined and arrayed elements, along with attention to spacing, comprise a flat, rectangular, (planar) structured metamaterial. Since it was designed to operate at terahertz frequencies, photolithography is used to etch the elements onto a substrate.

### Magnetic response from metamaterials at 1.8 THz

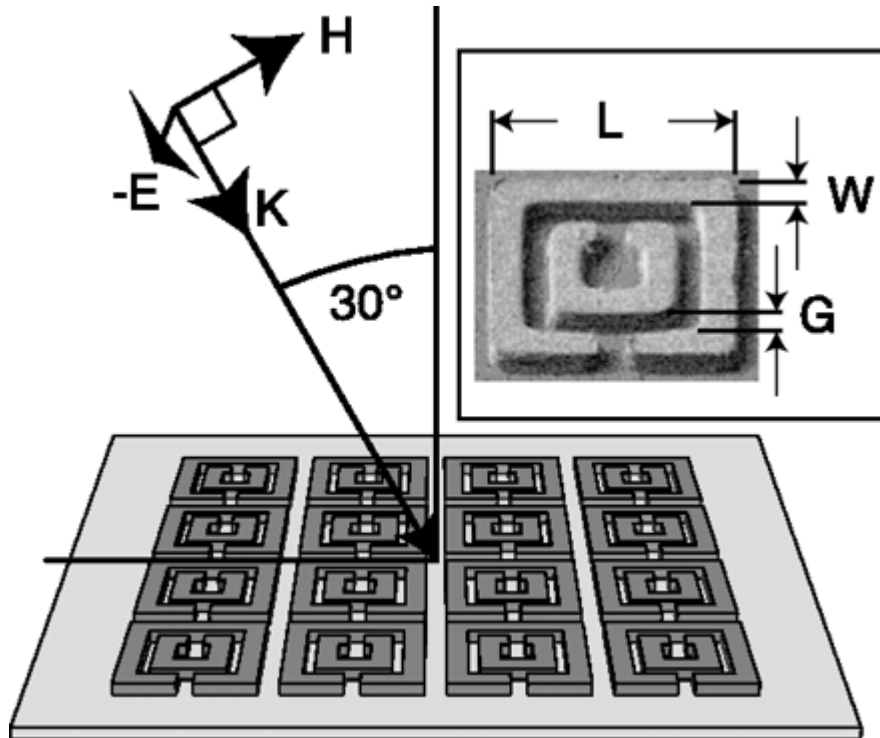


Schematic setup of an ellipsometry experiment

The Split-Ring Resonator (SRR) is a common metamaterial in use for a variety of experiments. Magnetic responses (permeability) at terahertz frequencies can be achieved with a structure composed of non-magnetic elements, such as SRRs, which demonstrate different responses at resonant frequencies and near resonant frequencies. The desired, artificially fabricated, magnetic response is realized over a relatively large bandwidth, and can be tuned throughout the terahertz frequency spectrum. The periodic array allows the material to behave as a medium with an effective magnetic permeability  $\mu_{eff}(\omega)$ , where  $\omega$  is frequency. In other words, at resonance  $\mu_{eff}$  is achieved.

Effective permeability  $\mu_{eff}$  is boosted from the inductance of the rings and the capacitance occurs at the gaps of the split rings. In prior microwave frequency experiments bulk metamaterial is used, such as waveguides to transmit the source of

radiation. In this terahertz experiment *ellipsometry* is applied. In other words, a light source in free space, emits a polarized beam of radiation which is then reflected off the sample. The emitted polarization is intended, and angle of polarization is known. The change in polarization of the radiation reflected off the sample material is then measured. This is used to obtain phase information and the polarization state of the emitted and reflected radiation. This information is then is used to demonstrate the boost in effective magnetic permeability at terahertz frequencies.



Light (THz radiation) strikes the split-ring resonator (SRR) array in the direction of  $\mathbf{K}$ , oriented  $30^\circ$  from the surface normal. For each SRR, the split gap is 2 micrometers. The inset, SRR image, from focused ion beam microscopy imaging. The lattice constant, the corresponding gap between the inner and outer ring ( $G$ ), the width of the metal lines ( $W$ ), the length of the outer ring ( $L$ ) are varied throughout the experiment.

An external magnetic field is applied with the THz radiation. Then the radiation induces a current in the looped wire of the SRR cell. This current then induces a local magnetic field (a vector quantity). The local magnetic field can be understood as a magnetic response. Well below the resonance frequency  $\omega_0$  the local magnetic field increases over time corresponding to increasing frequency. This magnetic response stays in phase with the electric field. Because the SRR cell is actually a non-magnetic material, this local magnetic response is temporary and will retain magnetic characteristics only so long as there is an externally applied magnetic field. Thus the total magnetization will drop to zero when the applied field is removed. In addition, the local magnetic response is actually a fraction of the total magnetic field. This fraction is proportional to the field

strength and this explains the linear dependency. All this has to do with alignments and spins at the atomic level.

As the frequency continues to increase, approaching resonance, the induced currents in the looped wire can no longer keep up with the applied field and the local response begins to lag. Then as the frequency increases above  $\omega_0$ , the induced local field response lags further until it is completely out of phase with the excitation field. This results in a magnetic permeability that is falling below unity, over time - including values less than zero. The linear coupling between the induced local field and the fluctuating applied field is in contrast to the non-linear characteristics of ferromagnetism, hence no permanent magnetic effect is achieved.

Three different SRR samples were compared. The wavelength of the resonant excited field is  $\lambda$  and the material is able to scale  $1/7 \lambda$ . These are the necessary conditions for the metamaterial to become a medium with  $\mu_{eff}$ . The sample was placed inside a vacuum produced inside a compartment. A mercury arc lamp was used as the electromagnetic source, and shined onto the sample, at an angle of  $30^\circ$ . The SRRs are expected to respond magnetically when the magnetic field penetrates the rings (S-polarization) and to exhibit no magnetic response when the magnetic field is parallel to the plane of the SRR (P-polarization). The frequency range of 0.6 THz to 1.8 THz was used for the measurements. The reflectance ratio of S- and P- polarizations was matched with strong magnetic responses of SRRs when the magnetic field penetrates the rings (S-polarization). Three different artificial magnetic structures are designated D1, D2, and D3. D1 strong magnetic response at 1.25 THz, with a ratio of just below 1.5. To show that it is the material that is used to vary the effective permeability, two other samples are used to show that this resonance should scale with dimensions in accordance to Maxwell's equations. Therefore D2 has a strong magnetic response at peaks at 0.95 THz, and the D3 sample peaks at 0.8 THz. This demonstrates the scalability of these magnetic metamaterials throughout the THz range and potentially into optical frequencies. To further demonstrate verification of the results, a mathematical simulation was performed which repeated the demonstration. The results of the simulation were in good agreement with the actual results for materials D1, D2, and D3.

### Magnetic response of metamaterials at 100 terahertz

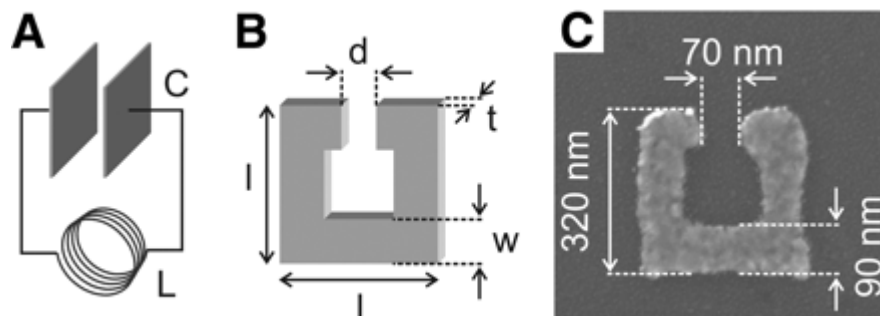


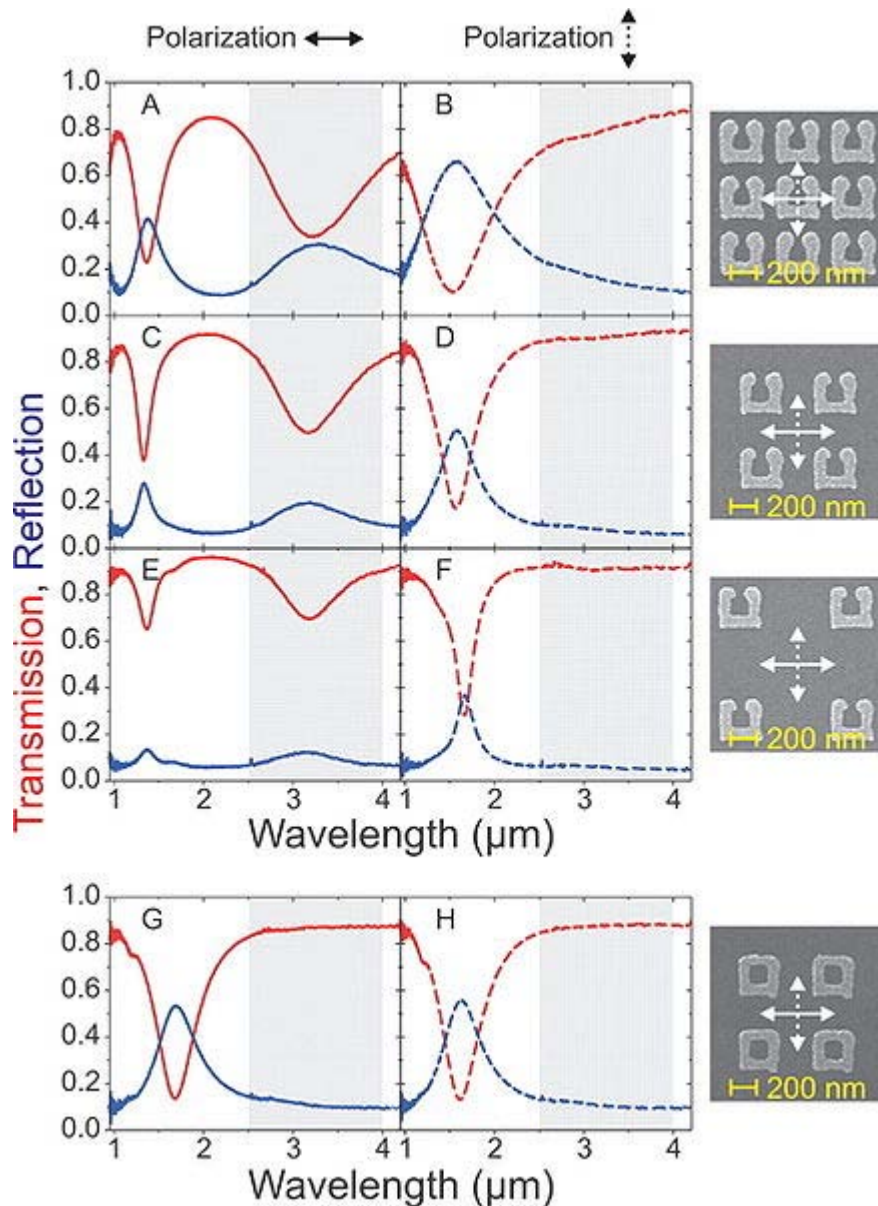
Illustration of the analogy between a conventional LC circuit (A), consisting of an inductance L, a capacitance C, and the single SRRs used here (B). l, length; w, width; d,

gap width;  $t$ , thickness. (C) An electron micrograph of a typical SRR fabricated by electron-beam lithography.

From this analysis and demonstration the electrical susceptibility and magnetic permeability - the parameters of normal materials, are *artificially* expanded. In normal materials, resonances fade away above gigahertz frequencies. Instead, resonances at terahertz frequencies have been effectively demonstrated for metamaterials. This now allows for interesting new effects in linear optics as well as in nonlinear optics. Furthermore, a negative magnetic permeability would allow for negative-index materials at optical frequencies, which seemed totally out of reach just a few years ago.

To fulfill a need to achieve localized magnetic resonant responses for terahertz optical frequencies, an array of single nonmagnetic metallic split rings can be used to implement a magnetic resonance at 100 THz. The split-ring resonator mimicked an LC oscillator which generated waves with frequency  $\omega_{LC} = (LC)^{-1/2}$ .

An LC circuit is a resonant circuit or tuned circuit that consists of an inductor, and a capacitor. When connected together, an electric current can alternate between them at the circuit's resonant frequency. LC circuits are used either for generating signals at a particular frequency, or picking out a signal at a particular frequency from a more complex signal. They are key components in many applications such as oscillators, filters, tuners and frequency mixers.



The radiated transmission is red. The response is graphed in blue. An etched picture of the sample is shown on right-hand side. Polarization configurations are shown on top of the two columns. Resonances of the three lattice constants are shown in the gray area of the graph at about 3- $\mu\text{m}$ . first row (A and B), the lattice constant of the SRRs is  $a = 450$  nm; in the second row (C and D), it is  $a = 600$  nm; and in the third row (E and F), it is  $a = 900$  nm. In the last row (G and H), results for closed-ring resonators with  $a = 600$  nm are shown

To couple an incident light beam to the LC resonance one of two conditions must be met. The first condition is that electric field vector  $\mathbf{E}$  of the incident light source has a component that is normal to the plates of the capacitor. The second condition is the magnetic field vector  $\mathbf{H}$  of the incident light has a component normal to the plane of the coil. When the second condition is met, a localized magnetic field is created which

counteracts the magnetic field of the light source and can result in a negative permeability. Such metamaterials were first realized at frequencies around 10 GHz (3-cm wavelengths) - and could be fabricated on stacked electronic circuit boards. In this case another two orders of magnitude, to 100 THz, had been achieved. This puts visible frequencies for negative refraction index much closer.

The first responses are shown with a lattice constant of  $a = 450$  nm. Additionally, this corresponds to a total number of  $56 \times 56 = 3136$  SRR microstructures. Coupling is controlled through the polarization of the incident light - the interaction of the electric field components with the capacitor and the interaction of the magnetic field components with the inductor. Other lattice constants shown will have a different total number of SRR microstructures.

The LC resonance occurs at  $3 \mu\text{m}$ . Resonant responses occur at lattice constants of 450 nm, 650 nm, and 900 nm. Two distinct resonant responses occur for all three of these lattice constants. Additionally, all three lattice constants are notably smaller than the LC resonant frequency. Coupling to the LC resonance can only occur if there is a component normal from the polarized electric field to the plates of the capacitance. If the electric field is rotated  $90^\circ$  then resonance around the  $3\text{-}\mu\text{m}$  wavelength completely disappears.

Next, closed rings rather than split rings are radiated to compare results. Linear polarization does not occur for either position of the metamaterial. Hence, unlike the split ring resonators, no resonance occurs at  $3\text{-}\mu\text{m}$ . Finally, measurements are performed under an angle of up to  $40^\circ$  with respect to the surface normal, such that the magnetic field vector of the incident light acquires a component normal to the coils. As expected, the  $3\text{-}\mu\text{m}$  resonance persists and does not shift.

Later, in 2005, resonant magnetic nanostructures were fabricated that experimentally exhibited a negative permeability in the mid-infrared range. This was the first practical demonstration to do so. This was seen as an important step toward achieving negative refractive index in the IR range.

### **Negative index of refraction at 200 THz**

The two previous sections discussed a magnetic response at terahertz frequencies, but not a negative index of refraction. These two studies are nevertheless important because a negative magnetic permeability is necessary to achieve negative refraction. In addition, these experiments demonstrated that optical negative index metamaterials are possible because of the acquired magnetic response (permeability). In 2005 experimental observation of a negative refractive index for the optical range, specifically, for the wavelengths close to  $1.5 \mu\text{m}$  (200 THz frequency) was accomplished.

This accomplishment was in agreement with prior theoretical predictions that a layer of pairs of parallel metal nanorods can produce a negative refractive index.

## **Reconfigurable terahertz metamaterials**

Electromagnetic metamaterials show promise to fill the Terahertz gap (0.1 – 10 THz). The terahertz gap is caused by two general shortfalls. First, almost no naturally occurring materials are available for applications which would utilize terahertz frequency sources. Second is the inability to translate the successes with EM metamaterials in the microwave and optical domain, to the terahertz domain.

Moreover, the majority of research has focused on the passive properties of artificial periodic THz transmission, as determined by the patterning of the metamaterial elements e.g., the effects of the size and shape of inclusions, metal film thickness, hole geometry, periodicity, etc. It has been shown that the resonance can also be affected by depositing a dielectric layer on the metal hole arrays and by doping a semiconductor substrate, both of which result in significant shifting of the resonance frequency. However, little work has focused on the "active" manipulation of the extraordinary optical transmission though it is essential to realize many applications.

Answering this need, there are proposals for "active metamaterials" which can proactively control the proportion of transmission and reflection components of the source (EM) radiation. Strategies include illuminating the structure with laser light, varying an external static magnetic field where the current does not vary, and by using an external bias voltage supply (semiconductor controlled). These methods lead to the possibilities of high-sensitive spectroscopy, higher power terahertz generation, short-range secure THz communication, an even more sensitive detection through terahertz capabilities. Furthermore these include the development of techniques for, more sensitive terahertz detection, and more effective control and manipulation of terahertz waves.

### **Surface-plasmon-enhanced terahertz transmission**

In August 2003, measurements of the transmission of terahertz radiation through periodic arrays of holes made in highly doped silicon wafers were reported. The unusual transmission was attributed to the resonant tunneling of surface-plasmon polaritons that can be excited on doped semiconductors at terahertz frequencies.

### **Electronic control of THz transmission properties**

Electronic switching of the extraordinary THz transmission was demonstrated with subwavelength metal hole arrays fabricated on doped semiconductor substrates. The passive resonance properties are mainly determined by the geometry and dimensions of the metal holes as well as the array periodicity. By electronically altering the substrate conductivity via an external voltage bias, switching of the extraordinary THz transmission is accomplished in real time.

## **Hybrid metamaterial modulation of terahertz radiation**

Terahertz modulators based on semiconductor structures often require cryogenic temperatures. This particular modulator is electrically modulated at room temperature. The bandwidth of the hybrid structure is proactively controlled by semiconductor conduction.

Semiconductor-SRR metamaterial-based terahertz electrical modulators will be useful for real-time terahertz imaging, fast sensing and identification, and even in short range secure terahertz communications.

## **High-frequency modulation of terahertz radiation**

In 2008, a metamaterial based modulator for THz radiation, was designed, fabricated and experimentally demonstrated. It was electrically tunable. The metamaterial is constructed with symmetric unit cell structures to ensure the material is not affected by the arbitrary polarizations of a radiated source.

The metamaterial was composed of an array of gold crosses fabricated on top of an n-doped semiconductor (GaAs) layer.

The crossbars were effectively electric dipoles. In the vicinity of the resonance frequency the crossbars create a negative effective permittivity for this metamaterial. Upon reaching negative permittivity, a major fraction of the electromagnetic wave is reflected from the metamaterial surface. The other part is of course transmitted, hence a stop band occurs around the dipole resonance frequency. Here is where the n-doped GaAs layer comes into play. The conductivity of the semiconductor layer is the tuning device for the transmitted part of the EM wave. And the semiconductor layer can be purposely tuned.

## **Adaptive metamaterials (THz)**

With adaptive metamaterials the unit cell's response is reorientation. Adaptive metamaterials offer significant potential to realize novel electromagnetic functionality ranging from thermal detection to reconfigurable electromagnetic radiation absorbers.

## **Reconfigurable terahertz metamaterials**

The first demonstrations of negative refractive index with metamaterials were anisotropic metamaterials. Reconfigurable metamaterials at terahertz frequencies are anisotropic materials where the artificial dipole, which comprises the unit cell, is reoriented when responding to the external EM source field. The split ring resonators are designed in a cantilever configuration, which allows bending out of plane in response to stimulus. A distinctive capability to tune the electric and magnetic response as the split ring resonators reorient within their unit cells.

## **Employing MEM technology**

By combining metamaterial elements - specifically, split ring resonators - with Microelectromechanical systems technology - has enabled the creation of non-planar flexible composites and micromechanically active structures where the orientation of the electromagnetically resonant elements can be precisely controlled with respect to the incident field.

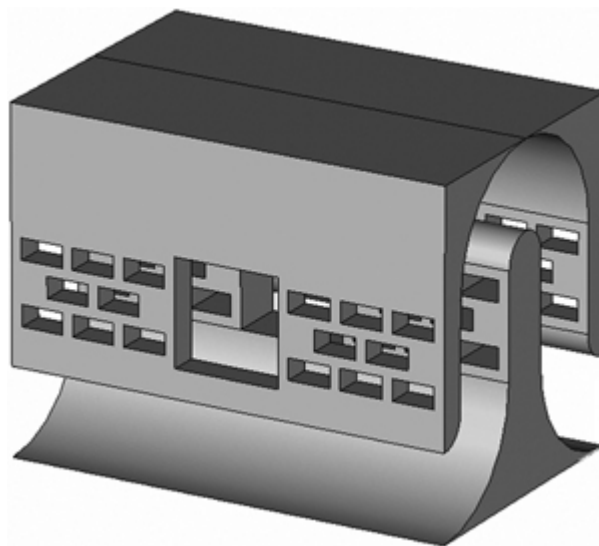
## **Dynamic electric and magnetic metamaterial response at THz frequencies**

The theory, simulation, and demonstration of a dynamic response of metamaterial parameters were shown for the first time with a planar array of split ring resonators (SRRs).

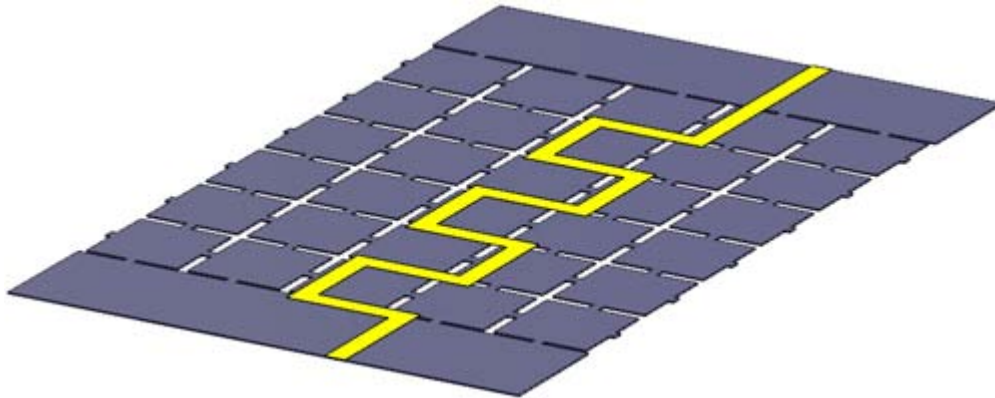
## **Survey of terahertz metamaterial devices**

The current trend of metamaterial research aims for design of nanostructures that are capable of manipulating electromagnetic waves at the visible frequency regime. A metamaterial mimicking the Drude-Lorentz model can be straightforwardly achieved by an array of wire elements into which cuts are periodically introduced. At frequencies above the resonant frequency and below plasma frequency, the permittivity is negative and, because the resonant frequency can be set to virtually any value in a metamaterial, phenomena usually associated with optical frequencies including negative  $\epsilon$  can be reproduced at low frequencies.

## **Novel amplifier designs**



Section of a terahertz, folded-waveguide traveling-wave tube circuit with hole arrays on walls. Image from NASA Glenn Research Center.



Terahertz planar traveling-wave tube circuit with metamaterial embedded in substrate. Image from NASA Glenn Research Center

In the terahertz compact moderate power amplifiers are not available. This results in a region that is underutilized, and the lack of novel amplifiers can be directly attributed as one of the causes.

Research work has involved investigating, creating, and designing light-weight slow-wave vacuum electronics devices based on traveling wave tube amplifiers. These are designs that involve folded waveguide, slow-wave circuits, in which the terahertz wave meanders through a serpentine path while interacting with a linear electron beam. Designs of folded-waveguide traveling-wave tubes are at frequencies of 670, 850, and 1030 GHz. In order to ameliorate the power limitations due to small dimensions and high attenuation, novel planar circuit designs are also being investigated.

In-house work at the NASA Glenn Research Center has investigated the use of metamaterials—engineered materials with unique electromagnetic properties to increase the power and efficiency of terahertz amplification in two types of vacuum electronics slow wave circuits. The first type of circuit has a folded waveguide geometry in which anisotropic dielectrics and holey metamaterials are which consist of arrays of subwavelength holes.

The second type of circuit has a planar geometry with a meander transmission line to carry the electromagnetic wave and a metamaterial structure embedded in the substrate. Computational results are more promising with this circuit. Preliminary results suggest that the metamaterial structure is effective in decreasing the electric field magnitude in the substrate and increasing the magnitude in the region above the meander line, where it can interact with an electron sheet beam. In addition, the planar circuit is less difficult to fabricate and can enable a higher current. More work is needed to investigate other planar geometries, optimize the electric-field/electron-beam interaction, and design focusing magnet geometries for the sheet beam.

## **Novel terahertz sensors**

Device design is quickly becoming a large part of metamaterial research. In the short half decade since its conception, understanding of the physics behind tailored electromagnetic responses in metamaterials has progressed far enough to where application demonstrations are surfacing.

A process is demonstrated for tuning the magnetic resonance frequency of a fixed split-ring resonator array, by way of adding material near the split-ring elements. The sensitivity of the fine tuning suggests possible applications as a sensor device. The resonant frequency responds to silicon nanospheres.

Applying drops of a silicon-nanospheres/ethanol solution to the surface of the sample decreases the magnetic resonance frequency of the split-ring array in incremental steps of 0.03 THz. This fine tuning is done post fabrication and is demonstrated to be reversible. The exhibited sensitivity of the split-ring resonance frequency to the presence of silicon nanospheres also suggests further application possibilities as a sensor device.

## **A metamaterial solid-state terahertz phase modulator**

The terahertz phase modulator uses a voltage-controlled metamaterial of a single unit cell layer. This new device achieves a voltage-controlled linear phase shift of  $\pi/6$  radians at 16 V. Moreover, the causal relation between amplitude switching and phase shifting enables broadband modulation.

## **THz metamaterial IR sensor**

One of the most critical applications of such a filter is to block unwanted radiation from nearby military high-power laser, while still allowing the sensor to conduct necessary battlefield.

## **Biomolecular sensing at THz frequencies**

Recently, it has been proposed in a numerical study to use THz-FSS based on asymmetric split ring resonators as a sensor for detecting biomolecular sample films with a thickness of only 10 nm. Because large biomolecules, e.g. DNA, exhibit a multitude of inherent vibrational modes, terahertz radiation is ideal to excite and probe these modes and to detect DNA by its terahertz properties at a specific binding state. This is a proposal for a rapid processing and reading of up to 100 arrayed gene sensors for diagnostic applications.

## Chapter- 9

# Tunable Metamaterials

A **tunable metamaterial** is a metamaterial with a variable response to an incident electromagnetic wave. This includes remotely controlling how an incident electromagnetic wave (EM wave) interacts with a metamaterial. This means the capability to determine whether the EM wave is transmitted, reflected, or absorbed. In general, the lattice structure of the metamaterial is adjustable in real time, making it possible to reconfigure a metamaterial device during operation. It encompasses developments beyond the bandwidth limitations in left-handed materials by constructing various types of metamaterials.

The ongoing research in this domain includes electromagnetic band gap metamaterials (EBG), also known as photonic band gap (PBG), and negative refractive index material (NIM).

Since natural materials exhibit very weak coupling through the magnetic component of the electromagnetic wave, artificial materials that exhibit a strong magnetic coupling are being researched and fabricated. These artificial materials are known as metamaterials. The first of these were fabricated (in the lab) with an inherent, limited, response to only a narrow frequency band at any given time. Its main purpose was to practically demonstrate metamaterials. The resonant nature of metamaterials results in frequency dispersion and narrow bandwidth operation where the center frequency is fixed by the geometry and dimensions of the rudimentary elements comprising the metamaterial composite. These were followed by demonstrations of metamaterials that were tunable only by changing the geometry and/or position of their components. These have been followed by metamaterials that are tunable in wider frequency ranges along with strategies for varying the frequencies of a single medium (metamaterial). This is in contrast to the fixed frequency metamaterial, which is determined by the imbued parameters during fabrication.

## Tuning strategies for split ring resonators

Metamaterial-based devices could come to include filters, modulators, amplifiers, transistors, and resonators, among others. The usefulness of such a device could be extended tremendously if the metamaterial's response characteristics can be dynamically tuned. Control of the effective electromagnetic parameters of a metamaterial is possible through externally tunable components.

## **Single element control**

Studies have examined the ability to control the response of individual particles using tunable devices such as varactor diodes, semiconductor materials, and barium strontium titanate (BST) thin films.

For example, H. T. Chen, in 2008, were able to fabricate a repeating SRR cell with semiconductor material aligning the gaps. This initial step in metamaterial research expanded the spectral range of operation for a given, specific, metamaterial device. Also this opened the door for implementing new device concepts. The importance of incorporating the semi-conductor material this way is noted because of the higher frequency ranges at which this metamaterial operates. It is suitable at terahertz (THz) and higher frequencies, where the entire metamaterial composite may have more than  $10^4$  unit cells, along with bulk-vertical integration of the tuning elements. Strategies employed for tuning at lower frequencies would not be possible because of the number of unit cells involved. The semiconductor material, such as silicon, is controlled by photoexcitation. This in turn controls, or alters, the effective size of the capacitor and tunes the capacitance. The whole structure is not just semiconductor material. This was termed a 'hybrid', because the semiconductor material was fused with dielectric material; a silicon-on-sapphire (SOS) wafer. Wafers were then stacked - fabricating a whole structure. A. Degiron et al., appear to have used a similar strategy in 2007.

## **Multi-element control**

A multielement tunable magnetic medium was reported by Zhao et al. This structure immersed SRRs in liquid crystals, and achieved a 2% tunable range.

BST-loaded SRRs comprising tunable metamaterial, encapsulates all of the tunability within the SRR circuit.

In a section below, a research team reported a tunable negative index medium using copper wires and ferrite sheets. The negative permeability behavior appears to be dependent on the location and bandwidth of the ferrimagnetic resonance, a break from wholly non-magnetic materials, which produces a notable negative index band. Interestingly, a coil or permanent magnetic is needed to supply the magnetic field bias for tuning.

## **Electrical tuning**

Electrical tuning for tunable metamaterials.

## **Magnetostatic control**

Magnetostatic control for tunable metamaterials.

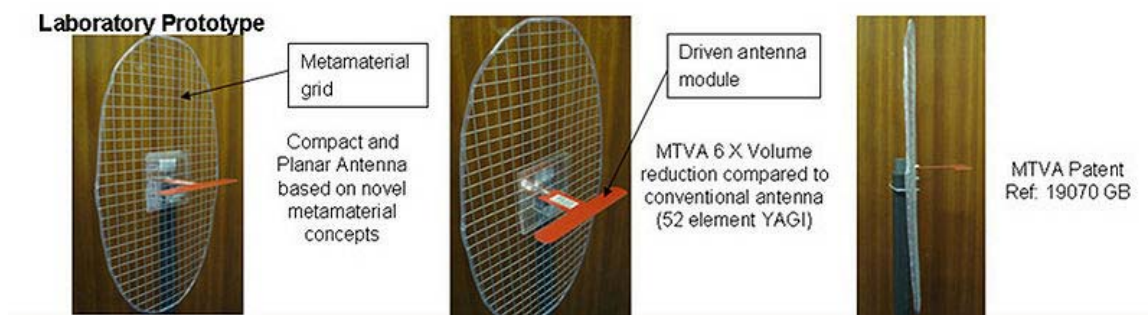
## Optical pumping

Optical pumping for tunable metamaterials.

## Frequency selective surface based metamaterials

**Frequency selective surfaces (FSS)** has become an alternative to the fixed frequency metamaterial where static geometries and spacings of unit cells determine the frequency response of a given metamaterial. Because arrayed unit cells maintain static positions throughout operation, a new set of geometrical shapes and spacings would have to be embedded in a newly fabricated material for each different radiated frequency and response. Instead, FSS based metamaterials allow for optional changes of frequencies in a single medium (metamaterial) rather than a restriction to a fixed frequency response.

Frequency selective surfaces can be fabricated as planar 2-dimensional periodic arrays of metallic elements with specific geometrical shapes, or can be periodic apertures in a metallic screen. The transmission and reflection coefficients for these surfaces are dependent on the frequency of operation and may also depend on the polarization and the angle of the transmitted electromagnetic wave striking the material or angle of incidence. The versatility of these structures are shown when having frequency bands at which a given FSS is completely opaque (stop-bands) and other bands at which the same surface allows wave transmission.



Metamaterial based frequency selective surfaces are employed for researching a metamaterial dipole antenna. This system is constructed with the dipole antenna incorporated into a pair of planar Frequency Selective Surfaces (FSS). The metamaterial FSS and antenna are pictured.

An example of where this alternative is highly advantageous is in deep space or with a satellite or telescope in orbit. The expense of regular space missions to access a single piece of equipment for tuning and maintenance would be prohibitive. Remote tuning, in this case, is advantageous.

FSS was first developed to control the transmission and reflection characteristics of an incident radiation wave. This has resulted in smaller cell size along with increases in bandwidth and the capability to shift frequencies in real time for artificial materials.

This type of structure can be used to create a metamaterial surface with the intended application of artificial magnetic conductors or applications for boundary conditions. Another application is as stop band device for surface wave propagation along the interface. This is because surface waves are created as a consequence of an interface between two media having dissimilar refractive indices. Depending on the application of the system that includes the two media, there may be a need to attenuate surface waves or utilize them.

An FSS based metamaterial employs a (miniature) model of equivalent LC circuitry. At low frequencies the physics of the interactions is essentially defined by the LC model analysis and numerical simulation. This is also known as the static LC model. At higher frequencies the static LC concepts become unavailable. This is due to dependence on phasing and wave polarization. When the FSS is engineered for electromagnetic band gap (EBG) characteristics, the FSS is designed to enlarge its stop band properties in relation to dispersive, surface wave (SW) frequencies (microwave and radio frequencies). Furthermore, as an EBG it is designed to reduce its dependence on the propagating direction of the surface wave traveling across the surface (interface).

### **Artificial magnetic conductors and High impedance surfaces**

A type of FSS based metamaterial has the interchangeable nomenclature *Artificial Magnetic Conductor* (AMC) or *High Impedance Surface* (HIS). The HIS, or AMC, is an artificial, metallic, electromagnetic structure. The structure is designed to be selective in supporting surface wave currents, different from conventional metallic conductors. It has applications for microwave circuits and antennas.

As an antenna ground plane it suppresses the propagation of surface waves, and deployed as an improvement over the flat metal sheet as a ground plane, or reflector. Hence, this strategy tends to upgrade the performance of the selected antenna.

Strong surface waves of sufficient strength, which propagate on the metal ground plane will reach the edge and propagate into free space. This creates a multi-path interference. In contrast the HIS surface suppresses the propagation of surface waves. Furthermore, control of the radio frequency or microwave radiation pattern is efficiently increased, and mutual coupling between antennas is also reduced.

When employing conventional ground planes as the experimental control, the HIS surface exhibits a smoother radiation pattern, an increase in the gain of the main lobe, a decrease in undesirable return radiation, and a decrease in mutual coupling.

### **Description**

An HIS, or AMC, can be described as a type of electromagnetic band gap (EBG) material or a type of synthetic composite that is intentionally structured with a magnetic conductor surface for an allotted, but defined range of frequencies. AMC, or HIS structures often emerge from an engineered periodic dielectric base along with metallization patterns

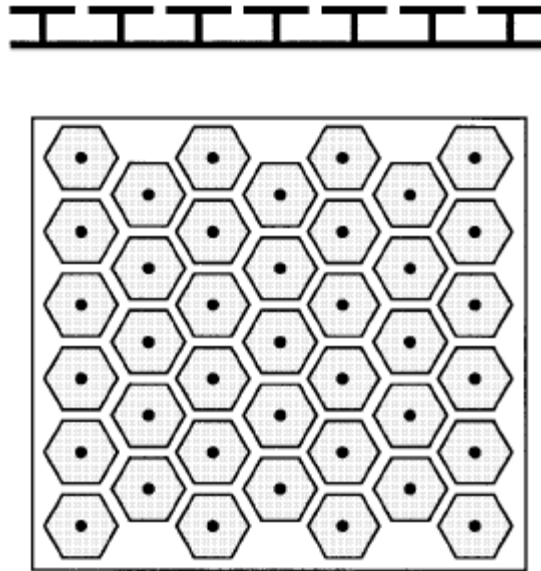
designed for microwave and radio frequencies. The metalization pattern is usually determined by the intended application of the AMC or HIS structure. Furthermore, two inherent notable properties, which cannot be found in natural materials, have led to a significant number of microwave circuit applications.

First, AMC or HIS surfaces are designed to have an allotted set of frequencies over which electromagnetic surface waves and currents will not be allowed to propagate. These materials are then both beneficial and practical as antenna ground planes, small flat signal processing filters, or filters as part of waveguide structures. For example, AMC surfaces as antenna ground planes are able to effectively attenuate undesirable wave fluctuations, or undulations, while producing good radiation patterns. This is because the material can suppress surface wave propagation within the prescribed range of forbidden frequencies.

Second, AMC surfaces have very high surface impedance within a specific frequency range, where the tangential magnetic field is small, even with a large electric field along the surface. Therefore, an AMC surface can have a reflection coefficient of +1.

In addition, the reflection phase of incident light is part of the AMC and HIS tool box. The phase of the reflected electric field has normal incidence to the phase of the radiated electric field at the interface (or the reflecting surface). The variation of the reflection phase is continuous between  $+180^\circ$  to  $-180^\circ$  relative to the frequency. Zero is crossed at one frequency, where resonance occurs. A notable characteristic is that the useful bandwidth of an AMC is generally defined as  $+90^\circ$  to  $-90^\circ$  on either side of the central frequency. Thus, due to this unusual boundary condition, in contrast to the case of a conventional metal ground plane, an AMC surface can function as a new type of ground plane for low-profile wire antennas (wireless communication systems). For example, even though a horizontal wire antenna is extremely close to an AMC surface, the current on the antenna and its image current on the ground plane are in-phase, rather than out-of phase, thereby strengthening the radiation.

## AMC as an FSS band gap



*Top image* - circuit board. The structure consists of a lattice of metal plates, connected to a solid metal sheet by vertical conducting vias. *Bottom image* - Looking down on top of the high-impedance surface, showing a triangular lattice of hexagonal metal plates. The configuration creates a capacitive and inductive surface. It can be utilized as band gap material at prescribed frequencies. It is also designed to enhance antenna operation as a novel periodic material.

Frequency selective surfaces (FSS) materials can be utilized as band gap material in the surface wave domain, at microwave and radio frequency wavelengths. Support of surface waves is a given property of metals. These are propagating electromagnetic waves that are bound to the interface between the metal surface and the air. Surface plasmons occur at optical frequencies, but at microwave frequencies, they are the normal currents that occur on any electrical conductor. At radio frequencies, the fields associated with surface waves can extend thousands of wavelengths into the surrounding space, and they are often best described as surface currents. They can be modeled from the viewpoint of an effective dielectric constant, or an effective surface impedance.

For example, a flat metal sheet always has low surface impedance. However, by incorporating a special texture on a conducting surface, a specially designed geometry, it is possible to engineer a high surface impedance and alter its electromagnetic-radio-frequency properties. The protrusions are arranged in a two dimensional lattice structure, and can be visualized as thumbtacks protruding from the surface.

Because the protrusions are fractionally smaller than the operating wavelength, the structure can be described using an effective medium model, and the electromagnetic properties can be described using lumped-circuit elements (capacitors and inductors).

They behave as a network of parallel resonant LC circuits, which act as a two-dimensional electric filter to block the flow of currents along the sheet.

This structure can then serve as an artificial magnetic conductor (AMC), because of its high surface impedance within a certain frequency range. In addition, as an artificial magnetic conductor it has a forbidden frequency band, over which surface waves and currents cannot propagate. Therefore, AMC surfaces have good radiation patterns without unwanted ripples based on suppressing the surface wave propagation within the band gap frequency range.

The surface impedance is derived from the ratio of the electric field at the surface to the magnetic field at the surface, which extends far into the metal beyond the skin depth. When a texture is applied to the metal surface, the surface impedance is altered, and its surface wave properties are changed. At low frequencies, it is inductive, and supports transverse-magnetic (TM) waves. At high frequencies, it is capacitive, and supports transverse electric (TE) waves. Near the *LC* resonance frequency, the surface impedance is very high. In this region, waves are not bound to the surface. Instead, they radiate into the surrounding space.

A high-impedance surface was fabricated as a printed circuit board. The structure consists of a triangular lattice of hexagonal metal plates, connected to a solid metal sheet by vertical conducting vias.

### **Uniplanar compact photonic-bandgap**

A Uniplanar Compact Photonic-Bandgap (UC-PBG) structure is another form of *Artificial Magnetic Conductor* of which the general characteristics are discussed above. As with all AMC designs its use is advantageous with "low profile" antennas, outperforming conventional antennas of similar configurations. It is a novel, periodic, photonic bandgap (PBG) medium (planar periodic structure) that is designed for microwave integrated circuits. Later developments have achieved millimeter-wave applications. This structure is a two-dimensional square lattice with each element consisting of a metal pad and four connecting branches. Experimental results display a broad stopband, as predicted by finite-difference time-domain (FDTD) simulation.

### **Tunable NIMs using ferrite material**

The YIG film allowed for a continuously tunable negative permeability, which resulted in a tunable frequency range over the higher frequency side of the ferromagnetic resonance of the (YIG). Complementary negative permittivity is achieved using a single periodic array of copper wires. Eight wires were spaced 1 mm apart and a ferromagnetic film of a multi-layered YIG at 400 nm thickness was placed in a K band waveguide. The YIG film was applied to both sides of a gadolinium gallium garnet substrate of 0.5 mm thickness. Ferromagnetic resonance was induced when the external H magnetic field was applied along the X axis.

The external magnetic field was generated with an electromagnet. Pairs of E–H tuners were connected before and after the waveguide containing the NIM composite. The tunability was demonstrated from 18 to 23 GHz. Theoretical analysis, which followed, closely matched the experimental results.

An air gap was built into the structure between the array of copper wires and the YIG. This reduces coupling with the ferrite, YIG material. When negative permeability is achieved across a range of frequencies, the interaction of the ferrite with the wires in close proximity, reduces the net current flow in the wires. This is the same as moving toward positive permittivity. This would be an undesired result as the material would no longer be a NIM. The separation also reduces the effective loss of the dielectric, induced by the interaction of the wire's self-field with permeability. Furthermore, there are two sources of conduction in the copper wire. First, the electric field in a (microwave) waveguide creates a current in the wire. Second, any arbitrary magnetic field created by the ferrite when it moves into a perpendicular configuration induces a current. Additionally, at frequencies where  $\mu$  is negative, the induced microwave magnetic field is opposite to the field excited in a TE<sub>10</sub> mode of propagation in a waveguide. Hence, the induced current is opposite to the current resulting from the electric field in a waveguide.

### **Metamaterial phase shifter**

In aerospace applications (for example) negative index metamaterials are likely candidates for tunable, compact and lightweight *phase shifters*. Because the designated metamaterials can handle the appropriate power levels, have strong dispersion characteristics, and are tunable in the microwave range these show potential to be desirable phase shifters.

The YIG negative index metamaterial is a composite which actually utilizes ferrite material. As a metamaterial, the ferrite produces a resonant, (real) magnetic permeability  $\mu'$  that is large enough to be comparable to the conventional ferrite phase shifter. The advantage of using a ferrite NIM material for phase shifter application is that it allows use of a ferrite in the negative magnetic permeability region near the FMR (ferromagnetic resonance frequency) when is relatively high and still maintains low losses. Near the FMR frequency, the magnitude of  $\mu'$  is larger than that at frequencies away from it. Assuming the loss factor to be about the same for the NIM and the conventional ferrite phase shifter, we would expect a much improved performance using the NIM composite, since the phase shifts would be significantly higher owing to higher differential  $\mu'$ .

## **Liquid crystal tuning for metamaterials**

### **Liquid crystal metamaterial tunable in the near-infrared**

Near-infrared metamaterials can possess a reconfigurable index of refraction from negative through zero to positive values. Reconfigurability is achieved by cladding thin layers of liquid crystal both as a superstrate and a substrate on an established negative-index metamaterial, and adjusting the permittivity of the liquid crystal.

## **Tunability of wire-grid metamaterial immersed into nematic liquid crystal**

Sub-wavelength metal arrays, essentially another form of metamaterial, usually operate in the microwave and optical frequencies. A liquid crystal is both transparent and anisotropic at those frequencies. In addition, a liquid crystal has the inherent properties to be both intrinsically tunable and provide tuning for the metal arrays. This method of tuning a type of metamaterial can be readily used as electrodes for applying switching voltages.

## **Tuning NIMs with liquid crystals**

Areas of active research in optical materials are metamaterials that are capable of negative values for index of refraction (NIMs), and metamaterials that are capable of zero index of refraction (ZIMs). Complicated steps required to fabricate these nano-scale metamaterials have led to the desire for fabricated, tunable structures capable of the prescribed spectral ranges or resonances.

The most commonly applied scheme to achieve these effects is *electro-optical tuning*. Here the change in refractive index is proportional to either the applied electric field, or is proportional to the square modulus of the electric field. These are the Pockels effect and Kerr effect, respectively. However, to achieve these effects electrodes must be built-in during the fabrication process. This introduces problematic complexity into material formation techniques. Another alternative is to employ a nonlinear optical material as one of the constituents of this system, and depend on the optical field intensity to modify the refractive index, or magnetic parameters.

## **Liquid crystal tuning of silicon-on-ring-resonators**

Ring resonators are optical devices designed to show resonance for specific wavelengths. In silicon-on-insulator layered structures, they can be very small, exhibit a high Q factor and have low losses that make them efficient wavelength-filters. The goal is to achieve a tunable refractive index over a larger bandwidth.

## **Structural tunability in metamaterials**

A novel approach is proposed for efficient tuning of the transmission characteristics of metamaterials through a continuous adjustment of the lattice structure, and is confirmed experimentally in the microwave range.

## **Hybrid metamaterial composites**

Metamaterials were originally researched as a passive response material. The passive response was and still is determined by the patterning of the metamaterial elements. In other words, the majority of research has focused on the passive properties of the novel transmission, e.g., the size and shape of the inclusions, the effects of metal film thickness,

hole geometry, periodicity, with passive responses such as a negative electric response, negative index or gradient index etc. In addition, the resonant response can be significantly affected by depositing a dielectric layer on metal hole arrays and by doping a semiconductor substrate. The result is significant shifting of the resonance frequency. However, even these last two methods are part of the passive material research.

Electromagnetic metamaterials can be viewed as structured composites with patterned metallic subwavelength inclusions. As mesoscopic physical systems, these are built starting from the unit cell level. These unit cells are designed to yield prescribed electromagnetic properties. A characteristic of this type of metamaterial is that the individual components have a resonant (coupling) response to the electric, magnetic or both components of the electromagnetic radiation of the source. The EM metamaterial as an artificially designed transmission medium, has so far delivered desired responses at frequencies from the microwave through to the near visible.

The introduction of a natural semiconductor material within or as part of each metamaterial cell results in a new design flexibility. The incorporation, application, and location of semiconductor material is strategically planned so as to be strongly coupled at the resonance frequency of the metamaterial elements. The hybrid metamaterial composite is still a passive material. However, the coupling with the semiconductor material then allows for external stimulus and control of the hybrid system as a whole, which produces alterations in the passive metamaterial response. External excitation is produced in the form, for example, photoconductivity, nonlinearity, or gain in the semiconductor material.

## **Tunable spectral range via electric field control**

Terahertz (THz) metamaterials can show a tunable spectral range, where the magnetic permeability reaches negative values. These values were established both theoretically and experimentally. The demonstrated principle represents a step forward toward a metamaterial with negative refractive index capable of covering continuously a broad range of THz frequencies and opens a path for the active manipulation of millimeter and submillimeter beams.