ISSN (Online) : 2348 - 2001

International Refereed Journal of Reviews and Research
Volume 2 Issue 2 March 2014
International Manuscript ID : 23482001V2I2032014-18
(Approved and Registered with Govt. of India)

ELECTROMAGNETIC METAMATERIALS : AN EFFECTUAL ANALYSIS ON ASSORTED DIMENSIONS

Anuj Agarwal
Department of Physics
Hindu College
Moradabad, U.P., India

ABSTRACT

Smaller-than-the-wavelength structural elements of an electromagnetic metamaterial influence electromagnetic waves that impinge or interact with them. The characteristics of a material must be significantly smaller than the wavelength in order to behave like a homogenous material as correctly defined by an effective refractive index. The characteristics are on the millimetre scale for microwave radiation. A typical microwave frequency metamaterial is an array of electrically conductive components (such as wire loops) with the appropriate inductive and capacitive properties. Split-ring resonators are commonly used in microwave metamaterials. Optical metamaterials are nanometer-scale structures that may be used to alter light. Similarities to subwavelength structured metamaterials are seen in photonic crystals and frequency-specific surfaces such as diffraction gratings, dielectric mirrors, and optical coatings. The fact that their function is derived from diffraction or interference rather than a homogenous substance makes them unique from metamaterials. Photonic crystals, on the other hand, are effective in the visible range of the spectrum because of their material structure. At a wavelength of roughly 560 nm, the centre of the visible spectrum is located (for sunlight). Structures with a diameter of less than 280 nm are more common. Metal surfaces are coated with tiny packets of electrical charge known as surface plasmons, which fluctuate at optical frequencies. Surfaces with high impedance can also be referred to as artificial magnetic conductors (AMC) or frequency selective surfaces (FSS) (HIS). Subwavelength structure is intimately connected to the inductive and capacitive properties of FSS.

Keywords : Electromagnetic Metamaterials, Metamaterials and Key Aspects, Use Cases of Metamaterials

INTRODUCTION

With the use of metamaterials, scientists have been able to produce a wide range of unique features that are impossible to obtain with natural materials. Since metamaterials have grown over the past decade, researchers are now looking for ways to use them in the real world. To further this goal, the capacity to dynamically govern unique reactions displayed by electromagnetic metamaterials would usher in the next revolution of materials. Artificial atoms used in the creation of electromagnetic metamaterials, provide designers unparalleled control over light-matter interactions. As a result of the capacity to receive, adjust and/or produce electromagnetic (EM) waves, several extremely relevant technical products have come into existence, such as cell phones, digital cameras, and computers. EM waves may be controlled by the use of materials, allowing for the development of the above-mentioned technologies. Natural materials, on the other hand, can only provide a tiny percentage of the EM characteristics that are actually feasible. Engineers can create electromagnetic metamaterials (or simply "metamaterials"), artificial materials that allow access to the theoretically possible response [1, 2].

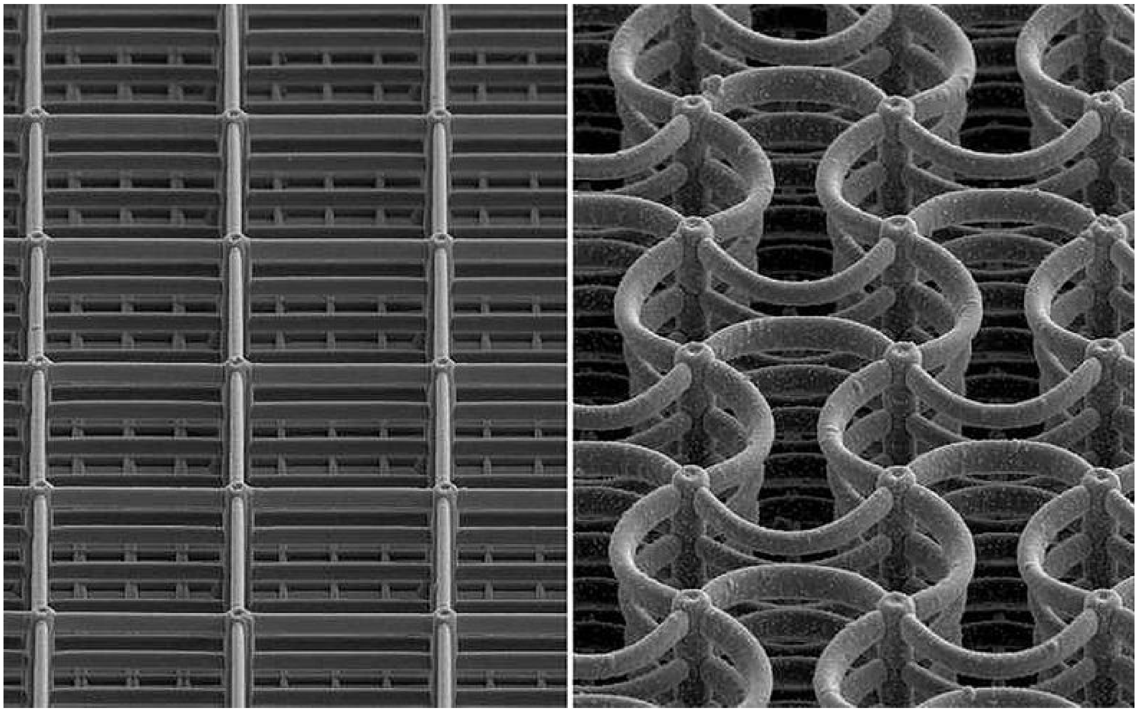

Figure 1 : Metamaterial and Inner Strength

From negative refractive index to superlensing to perfect absorption to cloaking, metamaterials have opened the door to a new generation of designer electromagnetic materials. It is possible to make a macroscopic medium from individual metamaterial components that retains the desired response to electromagnetic waves in a way that is not possible with conventional materials. Rather of their chemical makeup, metamaterials' electric and magnetic responses are derived from the geometry of their unit cells. Because metamaterials are designed from the ground up, they are ideal for creating new types of sophisticated electromagnetic materials [3].

Realizing applications has become increasingly important as metamaterials research has progressed. Exotic electromagnetic responses – some of which are not achievable with natural materials – have been accomplished by metamaterials, but the capacity to change these features in real-time would allow metamaterials to become cutting edge technologies. The advancement of electrical, mechanical, thermal, and optical control is summarised in this work with a view to applications, while future possibilities are also discussed [4].

Because of their capacity to alter the electromagnetic characteristics of metamaterials, electrically tunable metamaterials (ETMs) have attracted considerable attention in recent years. By combining high-performance components from the semiconductor and electronics sectors into metamaterial unit cells, it is now possible to achieve electromagnetic characteristics with real-time, wide bandwidth and high dynamic range. It has already been proven that electromagnetic transduction (ETMs) may be used from radio frequencies (RFs) and microwaves to the infrared range.

Negative refractive index

Negative-index metamaterials (NIM) are characterized by a negative index of refraction. Other terms for NIMs include "left-handed media", "media with a negative refractive index", and "backward-wave media" [5]. NIMs where the negative index of refraction arises from simultaneously negative permittivity and negative permeability are also known as double negative metamaterials or double negative materials (DNG).

Single negative

Single negative (SNG) metamaterials have either negative relative permittivity (εr) or negative relative permeability (μr), but not both. They act as metamaterials when combined with a different, complementary SNG, jointly acting as a DNG. Epsilon negative media (ENG) display a negative εr while μr is positive. Many plasmas exhibit this characteristic. For example, noble metals such as gold or silver are ENG in the infrared and visible spectrums.

Mu-negative media (MNG) display a positive εr and negative μr. Gyrotropic or gyromagnetic materials exhibit this characteristic. A gyrotropic material is one that has been altered by the presence of a quasistatic magnetic field, enabling a magneto-optic effect. A magneto-optic effect is a phenomenon in which an electromagnetic wave propagates through such a medium. In such a material, left- and right-rotating elliptical polarizations can propagate at different speeds. When light is transmitted through a layer of magneto-optic material, the result is called the Faraday effect: the polarization plane can be rotated, forming a Faraday rotator. The results of such a reflection are known as the magneto-optic Kerr effect (not to be confused with the nonlinear Kerr effect). Two gyrotropic materials with reversed rotation directions of the two principal polarizations are called optical isomers [6].

Joining a slab of ENG material and slab of MNG material resulted in properties such as resonances, anomalous tunneling, transparency and zero reflection. Like negative-index materials, SNGs are innately dispersive, so their εr, μr and refraction index n, are a function of frequency.

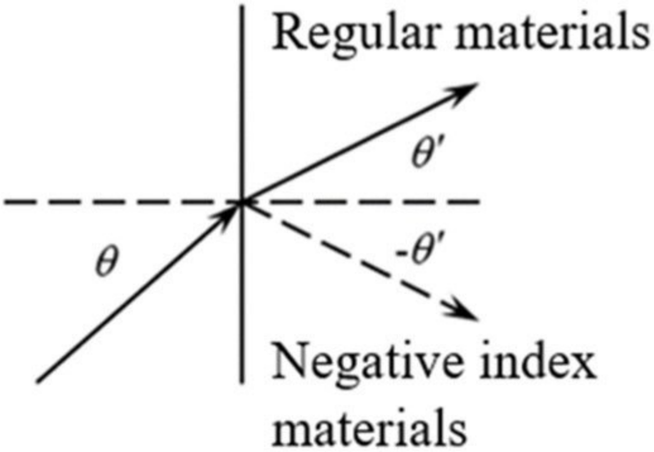

Figure 2 : Negative Index Materials

Hyperbolic

Hyperbolic metamaterials (HMMs) behave as a metal for certain polarization or direction of light propagation and behave as a dielectric for the other due to the negative and positive permittivity tensor components, giving extreme anisotropy [7]. The material's dispersion relation in wavevector space forms a hyperboloid and therefore it is called a hyperbolic metamaterial. The extreme anisotropy of HMMs leads to directional propagation of light within and on the surface. HMMs have showed various potential applications, such as sensing, reflection modulator, imaging, steering of optical signals, enhanced plasmon resonance effects.

Bandgap

Electromagnetic bandgap metamaterials (EBG or EBM) control light propagation. This is accomplished either with photonic crystals (PC) or left-handed materials (LHM). PCs can prohibit light propagation altogether. Both classes can allow light to propagate in specific, designed directions and both can be designed with bandgaps at desired frequencies. The period size of EBGs is an appreciable fraction of the wavelength, creating constructive and destructive interference [8].

PC are distinguished from sub-wavelength structures, such as tunable metamaterials, because the PC derives its properties from its bandgap characteristics. PCs are sized to match the wavelength of light, versus other metamaterials that expose sub-wavelength structure. Furthermore, PCs function by diffracting light. In contrast, metamaterial does not use diffraction.

PCs have periodic inclusions that inhibit wave propagation due to the inclusions' destructive interference from scattering. The photonic bandgap property of PCs makes them the electromagnetic analog of electronic semi-conductor crystals [9].

EBGs have the goal of creating high quality, low loss, periodic, dielectric structures. An EBG affects photons in the same way semiconductor materials affect electrons. PCs are the perfect bandgap material, because they allow no light propagation. Each unit of the prescribed periodic structure acts like one atom, albeit of a much larger size.

EBGs are designed to prevent the propagation of an allocated bandwidth of frequencies, for certain arrival angles and polarizations. Various geometries and structures have been proposed to fabricate EBG's special properties. In practice it is impossible to build a flawless EBG device.

EBGs have been manufactured for frequencies ranging from a few gigahertz (GHz) to a few terahertz (THz), radio, microwave and mid-infrared frequency regions. EBG application developments include a transmission line, woodpiles made of square dielectric bars and several different types of low gain antennas.

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 combine DPS, ENG and MNG properties [10].

Bi-isotropic and bianisotropic

Categorizing metamaterials into double or single negative, or double positive, normally assumes that the metamaterial has independent electric and magnetic responses described by ε and μ. However, in many cases, the electric field causes magnetic polarization, while the magnetic field induces electrical polarization, known as magnetoelectric coupling. Such media are denoted as bi-isotropic. Media that exhibit magnetoelectric coupling and that are anisotropic (which is the case for many metamaterial structures), are referred to as bi-anisotropic.

Four material parameters are intrinsic to magnetoelectric coupling of bi-isotropic media. They are the electric (E) and magnetic (H) field strengths, and electric (D) and magnetic (B) flux densities. These parameters are ε, μ, κ and χ or permittivity, permeability, strength of chirality, and the Tellegen parameter, respectively. In this type of media, material parameters do not vary with changes along a rotated coordinate system of measurements. In this sense they are invariant or scalar.

The intrinsic magnetoelectric parameters, κ and χ, affect the phase of the wave. The effect of the chirality parameter is to split the refractive index. In isotropic media this results in wave propagation only if ε and μ have the same sign. In bi-isotropic media with χ assumed to be zero, and κ a non-zero value, different results appear. Either a backward wave or a forward wave can occur. Alternatively, two forward waves or two backward waves can occur, depending on the strength of the chirality parameter.

Chiral

Handedness of metamaterials is a potential source of confusion as the metamaterial literature includes two conflicting uses of the terms left- and right-handed. The first refers to one of the two circularly polarized waves that are the propagating modes in chiral media. The second relates to the triplet of electric field, magnetic field and Poynting vector that arise in negative refractive index media, which in most cases are not chiral [11].

Generally a chiral and/or bianisotropic electromagnetic response is a consequence of 3D geometrical chirality: 3D-chiral metamaterials are composed by embedding 3D-chiral structures in a host medium and they show chirality-related polarization effects such as optical activity and circular dichroism. The concept of 2D chirality also exists and a planar object is said to be chiral if it cannot be superposed onto its mirror image unless it is lifted from the plane. 2D-chiral metamaterials that are anisotropic and lossy have been observed to exhibit directionally asymmetric transmission (reflection, absorption) of circularly polarized waves due to circular conversion dichrosim.

On the other hand, bianisotropic response can arise from geometrical achiral structures possessing neither 2D nor 3D intrinsic chirality. Plum and colleagues investigated magneto-electric coupling due to extrinsic chirality, where the arrangement of a (achiral) structure together with the radiation wave vector is different from its mirror image, and observed large, tuneable linear optical activity, nonlinear optical activity, specular optical activity and circular conversion dichroism. Rizza et al. suggested 1D chiral metamaterials where the effective chiral tensor is not vanishing if the system is geometrically one-dimensional chiral (the mirror image of the entire structure cannot be superposed onto it by using translations without rotations).

FSS based

Frequency selective surface-based metamaterials block signals in one waveband and pass those at another waveband. They have become an alternative to fixed frequency metamaterials. They allow for optional changes of frequencies in a single medium, rather than the restrictive limitations of a fixed frequency response.

Other types

Elastic : These metamaterials use different parameters to achieve a negative index of refraction in materials that are not electromagnetic. Furthermore, "a new design for elastic metamaterials that can behave either as liquids or solids over a limited frequency range may enable new applications based on the control of acoustic, elastic and seismic waves." They are also called mechanical metamaterials.

Acoustic : Acoustic metamaterials control, direct and manipulate sound in the form of sonic, infrasonic or ultrasonic waves in gases, liquids and solids. As with electromagnetic waves, sonic waves can exhibit negative refraction.

Control of sound waves is mostly accomplished through the bulk modulus β, mass density ρ and chirality. The bulk modulus and density are analogs of 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 audible pulses).

Structural : Structural metamaterials provide properties such as crushability and light weight. Using projection micro-stereolithography, microlattices can be created using forms much like trusses and girders. Materials four orders of magnitude stiffer than conventional aerogel, but with the same density have been created. Such materials can withstand a load of at least 160,000 times their own weight by over-constraining the materials. A ceramic nanotruss metamaterial can be flattened and revert to its original state.

Thermal : Typically materials found in nature, when homogeneous, are thermally isotropic. That is to say, heat passes through them at roughly the same rate in all directions. However, thermal metamaterials are anisotropic usually due to their highly organized internal structure. Composite materials with highly aligned internal particles or structures, such as fibers, are examples of this, for example carbon nanotubes (CNT).

Nonlinear : Metamaterials may be fabricated that include some form of nonlinear media, whose properties change with the power of the incident wave. Nonlinear media are essential for nonlinear optics. Most optical materials have a relatively weak response, meaning that their properties change by only a small amount for large changes in the intensity of the electromagnetic field. The local electromagnetic fields of the inclusions in nonlinear metamaterials can be much larger than the average value of the field. Besides, remarkable nonlinear effects have been predicted and observed if the metamaterial effective dielectric permittivity is very small (epsilon-near-zero media). In addition, exotic properties such as a negative refractive index, create opportunities to tailor the phase matching conditions that must be satisfied in any nonlinear optical structure.

Hall metamaterials : In 2009, Marc Briane and Graeme Milton proved mathematically that one can in principle invert the sign of a 3 materials based composite in 3D made out of only positive or negative sign Hall coefficient materials.

Thermosensors Based on Metamaterials

There are several uses for electromagnetic metamaterials, but temperature sensing is among the most important research and application areas. This is due to the high temperature sensitivity of certain of the substrate materials and/or sub-wavelength structures created. The temperature-sensitive dielectric substrate materials and the sub-wavelength nano/micro mechanical structure with different thermal expansion coefficients will change the resonant frequency/strength under different temperatures, according to the sensing mechanism of resonant-type metamaterial-inspired sensors.

CONCLUSION

Research into metamaterials with unique characteristics has gained a lot of traction in recent years. The described metamaterials have been used in a wide range of technical fields. With narrow resonance lines and strong resonant strength in resonant metamaterials with changeable physical or chemical characteristics, the resonant frequency and strength are largely dependent on meta-atom structure and/or substrate media properties. Consequently, resonant-type metamaterial units or arrays have been used in physical or chemical sensing applications in recent years. We'd like to consolidate recent reports on high-performance metamaterial-inspired sensing applications, particularly temperature sensing applications based on various forms of metamaterials, in this small review to enable researchers in those domains catch up with the newly discovered achievements. In addition, the newly suggested high quality-factor metamaterial units for high-precision sensing applications are explored in terms of sensitivity and resolution by comparing the benefits and drawbacks of numerous traditional metamaterial units. Researchers in the field of metamaterial-inspired sensors can use this brief overview to discover new ways to achieve high-precision sensing.

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