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METAMATERIAL PROPERTIES AND APPLICATIONS

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This paper discusses fundamental properties of metamaterials. It also discuss the recent research activities on metamaterials in various areas such as antenna design, design of high frequency components & devices, microwave engineering etc. The metamaterials are engineered media whose electromagnetic responses are different from those of their constituent components. Here general advantages of metamaterials are pointed out. The main research directions related to metamaterials are discussed.
Keywords: Metamaterials, Permeability, Permittivity

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1. INTRODUCTION

Metamaterials are artificial materials engineered to provide properties which “may not be readily available in nature”. These materials usually gain their properties from structure rather than composition, using the inclusion of small inhomogeneities to enact effective macroscopic behavior. The metamaterials have entered into the main stream of electromagnetics. The essential property in metamaterials is their unusual and desired qualities that appear due to their particular design & structure. In particular composite media electromagnetic waves interact with the inclusions which produce electric & magnetic moments, which in turn affect the macroscopic effective permittivity & permeability of the bulk composite medium. Since metamaterials can be synthesized by embedding artificially fabricated inclusions in a specified host medium. This provides the designer with a large collection of independent parameters such as properties of host materials, size, shape, and compositions of inclusions. All these design parameters can play a major role in getting the final result. In these the shape of the inclusions is one that provides a new possibility for metamaterial processing.

2. METAMATERIAL CLASSIFICATION

The response of a system to the presence of Electromagnetic field is determined by the properties of the materials involved. These properties are described by defining the macroscopic parameters permittivity å and permeability µ of these materials. By using permittivity å and permeability µ the classification of metamaterials as follows, the medium classification can be graphically illustrated as shown in fig. 1.1.

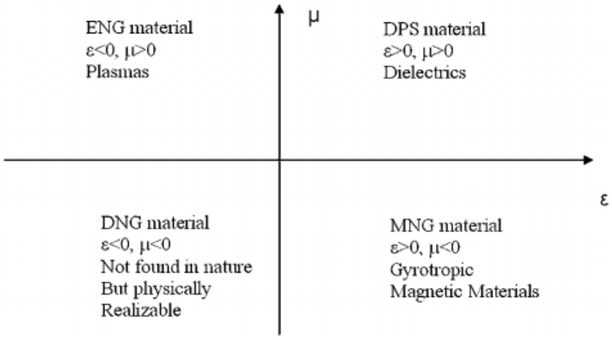

Fig. 1.1: Metamaterial Classification

A medium with both permittivity & permeability greater than zero ($\varepsilon > 0$, $\mu > 0$) are called as double positive (DPS) medium. Most occurring media (e.g. dielectrics) fall under this designation.

A medium with permittivity less than zero & permeability greater than zero ($\varepsilon < 0$, $\mu > 0$) are called as Epsilon negative (ENG) medium. In certain frequency regimes many plasmas exhibit this characteristics.

A medium with both permittivity greater than zero & permeability less than zero ($\varepsilon > 0$, $\mu < 0$) are called as Mu negative (MNG) medium. In certain frequency regimes some gyrotropic material exhibits this characteristic.

A medium with both permittivity & permeability less than zero ($\varepsilon < 0$, $\mu < 0$) are called as Double negative (DNG) medium. This class of materials has only been demonstrated with artificial constructs.

3. TYPES OF METAMATERIALS

The Various types of metamaterials are,

3.1. Electromagnetic Metamaterials.

3.1.1. Negative Refractive index.

3.1.2. Different classes of Electromagnetic Metamaterials.

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3.1.2.1. Double negative metamaterials
3.1.2.2. Single negative metamaterials.
3.1.2.3. Electromagnetic bandgap metamaterials.
3.1.2.4. Double positive medium.
3.1.2.5. Bi-isotropic and bianisotropic metamaterials.
3.1.2.6. Chiral metamaterials.
3.1.3. Slip Ring resonators.
3.2. Terahertz Metamaterials.
3.3. Photonic Metamaterials.
3.4. Tunable Metamaterials.
3.5. Frequency selective surface (FSS) based metamaterials.
3.6. Nonlinear metamaterials.
3.7. Metamaterial Absorber.

3.1. Electromagnetic Metamaterials

Metamaterials have become a new sub discipline within physics and electromagnetism (especially optics and photonics).They are used for optical and microwave applications such as new types of beam steerers, modulators, band-pass filters, lenses, microwave couplers, and antenna radomes. Metamaterials consist of structures. A metamaterial affects electromagnetic waves by having structural features smaller than the wavelength of electromagnetic radiation it interacts with.

3.1.1. Negative Refractive Index

It is the greatest potential of metamaterials 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 ε and permeability μ. However, many metals (such as silver and gold) have negative ε at visible wavelengths. A material having either (but not both) ε or μ negative is opaque to electromagnetic radiation. Although the optical properties of a transparent material are fully specified by the parameters ε and μ, refractive index n is used in practice. Fig 1.2 shows the refraction in left handed metamaterial & conventional material. All known non-metamaterial transparent materials possess positive ε and μ. By convention the positive square root is used for n. However, some engineered metamaterials have $\varepsilon < 0$ and $\mu < 0$. Because the product εμ 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.

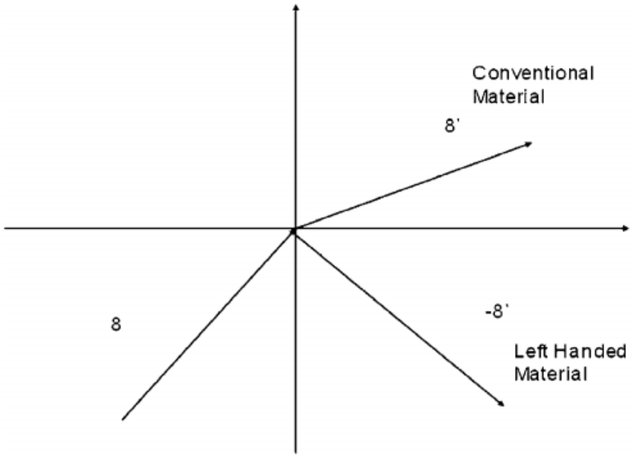

Fig. 1.2: Refraction in Left Handed Metamaterial to that in a Normal Material

3.1.2. Different Classes of Electromagnetic Metamaterials

3.1.2.1. Double Negative Metamaterials

In double negative metamaterials (DNG), both permittivity and permeability are negative resulting in a negative index of refraction. DNGs are also referred to as negative index metamaterials (NIM). Other names for DNGs are "left-handed media", "media with a negative refractive index", and "backward-wave media".

3.1.2.2. 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 DNG metamaterials, SNGs are innately dispersive, so their permittivity å, permeability μ, and refraction index n, will alter with changes in frequency.

3.1.2.3. Electromagnetic Bandgap Metamaterials

Electromagnetic bandgap metamaterials controls 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).

3.1.2.4. 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.

3.1.2.5. Bi-isotropic and Bi-anisotropic 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 å and µ. 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 are exhibit magneto-electric coupling, and which are also anisotropic, are called as bi-anisotropic.

3.1.2.6. Chiral Metamaterials

When a metamaterial is constructed from chiral elements then it is called as chiral metamaterial.

3.1.3. Slip Ring Resonators

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.

3.2. Terahertz Metamaterials

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 wavelengths between 3 mm (EHF band) and 0.03 mm (long-wavelength edge of far-infrared light).

3.3. Photonic Metamaterials

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

3.4. Tunable Metamaterials

A tunable metamaterial is a metamaterial which has the capability to arbitrarily adjust frequency changes in the refractive index.

3.5. Frequency Selective Surface (FSS) based Metamaterials

FSS based metamaterials have become an alternative to the fixed frequency metamaterial.

3.6. 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.

3.7. 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.

4. Applications and Research Areas of Metamaterials

4.1. Metamaterial Antennas

Metamaterial antennas are a class of antennas which use metamaterials to enhance or increase performance of the system. The metamaterials could enhance the radiated power of an antenna. Materials which can attain negative magnetic permeability could possibly allow for properties such as an electrically small antenna size, high directivity, and tunable operational frequency, including an array system. Furthermore, metamaterial based antennas can demonstrate improved efficiency-bandwidth performance.

Metamaterials are manufactured materials that exhibit properties not found in nature. A significant improvement in antenna performance is predicted for a class of metamaterials exhibiting a negative electric permittivity, (ENG), a negative magnetic permeability (MNG), or both (ENG/MNG). Antennas constructed from metamaterials have revolutionary potential of overcoming restrictive efficiency-bandwidth limitations for natural or conventionally constructed electrically small antennas. Metamaterial antennas, if successful, would allow smaller antenna elements that cover a wider frequency range, thus making better use of available space for small platforms or spaces.

Metamaterials employed in the ground planes surrounding antennas offers improved isolation between radio frequency or microwave channels of (multiple-input multiple-output) (MIMO) antenna arrays. Metamaterial, high-impedance ground planes can also be used to improve the radiation efficiency, and axial radio performance of low-profile antennas located close to the ground plane surface. Metamaterials have also been used to increase the beam scanning range by using both the forward and backward waves in leaky wave antennas. Various metamaterial antenna systems can be employed to support surveillance sensors, communication links, navigation systems, command and control systems.

4.2. Superlens

A superlens uses metamaterials to achieve resolution beyond the diffraction limit. The diffraction limit is inherent in conventional optical devices or lenses.

4.3. Clocking Devices

Metamaterials are a basis for attempting to build a practical cloaking device. 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.

4.4. 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.

4.5. 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.

5. CONCLUSION

In this Paper, a short review of history of metamaterials, some of silent features and ideas for metamaterial, various types of metamaterials, various applications of metamaterials has been discussed. Electromagnetic response functions that can offer exciting possibilities of future design of devices & components are reviewed. Some silent properties of metamaterial have been reviewed.

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