Metamaterial and Its Applications: A Review

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Abstract— In recent years, there has been a growing interest in fabricated structures and composite materials that either mimic known material responses or qualitatively have new, physically realizable response functions that do not occur or may not be readily available in nature. During the past ten years, a great interest in the research of metamaterials has been observed. Metamaterials are artificially invented materials that show properties that are not detected in naturally occurring materials. Metamaterials exhibit negative permittivity and/or negative permeability. This paper presents a review of different types of metamaterials, their unique properties, and their advantages.

Keywords: Metamaterials (MTM), Double negative metamaterials (DNG), Negative Index Metamaterials (NIMs), Left-handed Metamaterials (LHM), Split Ring Resonators (SRRs)

I. Introduction

The first attempt to explore the concept of "artificial" materials appears to trace back to the late part of the nineteenth century when in 1898 Jagadis Chunder Bose conducted the first microwave experiment on twisted structures—geometries that were essentially artificial chiral elements by today's terminology [1]. In 1914, Lindman worked on "artificial" chiral media by embedding many randomly oriented small wire helices in a host medium [2]. In 1948, Kock made lightweight microwave lenses by arranging conducting spheres, disks, and strips periodically and effectively tailoring the effective refractive index of the artificial media [3]. The word "Meta" is taken from Greek whose meaning is "beyond". "Metamaterials" have exotic properties beyond naturally occurring materials. These are the materials that extract their properties from their structure rather than the material of which they are composed. The first and one of the most important contributions to this topic was made in 1968 by V. G. Veselago who said that materials with both negative permittivity and negative permeability are theoretically possible [4]. In 1999, John Pendry identified a practical way to make left-handed metamaterials (LHM) that did not follow the conventional right-hand rule [5]. He proposed his design of a periodically arranged Thin-Wire (TW) structure that depicts the negative value of effective permittivity [6]. It was shown that the structure is having a low plasma frequency than the wave in the microwave regime. Because of its low plasma frequency, this structure can produce an effective negative permittivity at microwave frequencies. It was also demonstrated that negative magnetic permeability could be achieved using an array of split-ring resonators [7]. Later then, Smith demonstrated a new LHM that shows simultaneously negative permittivity and permeability and carried out microwave experiments to test its uncommon properties in 2000 [8]. Shelby et al showed negative refraction experimentally for the first time using metamaterials with repeated unit cells of split-ring resonators (SRR) and copper strips [9-10]. Wu et al proposed three structures including symmetrical ring, omega, and S structure for SRRs [11]. Many researchers have worked on metamaterials to extract their potential in various fields. This paper summarizes the history of metamaterials, their classification, advantages, applications, and recent progress.

II. Classification of Metamaterials:

We describe the classification of materials by defining the macroscopic parameters permittivity ε and permeability μ of these materials. Classification of metamaterial graphically illustrated in figure 1.

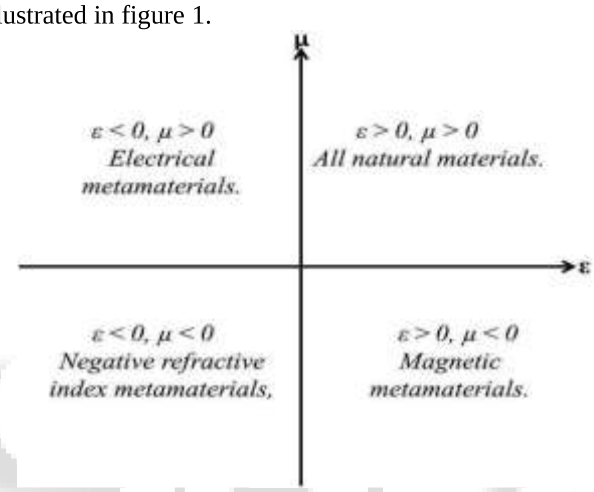

Fig. 1: Classification of Metamaterials

A. First Quadrant

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.

B. Second Quadrant

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

C. Third Quadrant

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

D. Fourth Quadrant

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.
Types of Metamaterials:

1) Electromagnetic Metamaterials

Electromagnetic metamaterials (EM) are materials that have a new sub-section within electromagnetism and physics. EM is used for optical and microwave applications like band-pass filters, lenses, microwave couplers, beam steerers, and antenna radomes. The combination of two SNG layers into one creates another form of DNG metamaterials [10]. To conduct wave reflection experiments, the slab of MNG materials and ENG materials have been joined. Like DNG metamaterials, SNGs change their parameters like refraction index n, permittivity ε, and permeability μ, with a change in frequency due to their dispersive nature. Double negative metamaterials (DNG) are the metamaterials that have both permittivity and permeability are negative with a negative index of refraction. These are also known as negative-index metamaterials (NIM) [12]. Other names for DNGs are left-handed media, media with a negative refractive index, and “backward-wave media [13].

2) Chiral Metamaterials

Chiral media provide another clear example of metamaterial with emergent properties. Chiral media consist of handed elements or handed microstructure [14]. In chiral media, the special geometrical character of the internal structure (antisymmetry or non-symmetry for mirror reflection) creates macroscopic effects that are observed as the rotation of the polarization of the propagating field plane (“optical rotatory power”). This “emergent” rotatory power is due to the magnetoelectric coupling caused by the chiral elements. On the level of constitutive relations that characterize such chiral medium, it is necessary to include cross-coupling terms between the electric and magnetic field excitations and polarization responses.

3) Photonic Metamaterials

Photonic metamaterials are the type of electromagnetic metamaterials designed to interact with optical frequencies is known as Optical metamaterials. Photonic metamaterials radiate the source at optical wavelengths [15]. Furthermore, the sub-wavelength period differentiates the photonic metamaterials from the photonic bandgap structure. This is because the optical properties do not arise from photonic band gaps, rather from a subwavelength interaction with the light spectrum. The metamaterials with the capability of zero indexes of refraction (ZIMs) and negative values for index of refraction (NIMs) are the active area of research in optical materials.

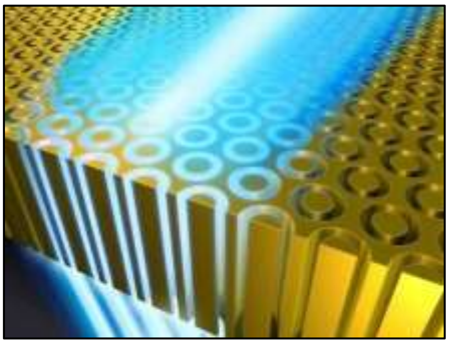

Fig. 2: Photonic Metamaterial

4) Tunable Metamaterials

These are the metamaterials that can randomly change the frequency of a refractive index. An incident electromagnetic wave gives a variable response with these metamaterials. This includes how an incident electromagnetic wave interacts with metamaterials in a remote control. The structure of the tunable metamaterials is changeable in real-time which makes it possible to reconfigure a device during operation [16]. Tuning in the near-infrared range is achieved by varying the permittivity of nematic liquid crystals. The metamaterials can be tuned from negative index values to zero index or positive index values. In addition, negative index values can be increased or decreased.

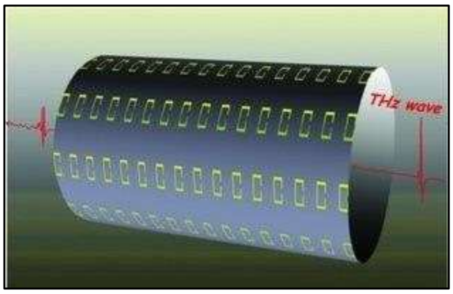

Fig. 3: Tunable Metamaterial

5) Frequency Selective Surface (FSS) based Metamaterials

FSS based metamaterials are the substitute to the fixed frequency metamaterials with static geometry and spacing in the unit cells used to find out the frequency response of a given metamaterial. FSS based metamaterials have the option to change the frequencies in a single medium but in fixed frequency response it is impossible. It was first developed to control the transmission and reflection characteristics of an incident radiation wave. FSS with specific geometrical shapes can be made-up as periodic arrays with elements of two-dimensional planar. FSS based metamaterials have the interchangeable terminology of High Impedance Surface (HIS) or Artificial Magnetic Conductor (AMC). The HIS or AMC has an artificial metallic electromagnetic structure. The designed structures with a selection of supporting surface wave currents are different from conservative metallic conductors

6) Nonlinear Metamaterials

Nonlinear metamaterials are artificial materials in which nonlinearity exists. This is due to the less macroscopic electric field of the electromagnetic source than the microscopic electric field of the inclusions [16]. The material‟s permeability and permittivity describe the response of electromagnetic radiation. It may also be fabricated with some type of nonlinear metamaterials that have properties to change the power of an incident wave.

III. Applications and Research Areas of Metamaterials:

A. *Metamaterial as Antenna*

Metamaterial coatings have been used to enhance the radiation and matching properties of electrically small electric and magnetic dipole antennas. Metamaterial steps up the radiated power. The newest Metamaterial antenna radiate 95% of the input radio signal at 350 MHz Experimental metamaterial antenna are as small as one-fifth of a wavelength. Patch antenna with metamaterial cover has increased directivity. A flat horn antenna with a flat aperture constructed of zero-index metamaterial has the advantage of improved directivity. Zero-index metamaterials can be used to achieve high directivity antennas. Because a signal Propagating in a zero-index metamaterial will stimulate a spatially static field structure that varies in time; the phase at any point in a zero-index metamaterial will have the same constant value once a steady state is reached. The metamaterial can enhance the gain and reduce the return loss of a patch antenna [17].

B. Metamaterial as Absorber

The first Metamaterial based absorber by Landy in 2008 utilizes three layers, two metallic layers, and dielectric and shows a simulated absorptivity of 99% at 11.48 GHz. Experimentally, Landy was able to achieve an absorptivity of 88%. The difference between simulated and measured results was due to fabrication errors [18].

C. Metamaterial as Superlens

Superlens uses metamaterials to go beyond the diffraction limit. It has resolution capabilities that go beyond ordinary microscopes. Conventional optical materials suffer a diffraction limit because only the propagating components are transmitted from a light source. The non-propagating components, the evanescent waves, are not transmitted. One way to improve the resolution is to increase the refractive index but it is limited by the availability of high-index materials. The road to the superlens is its aptitude to significantly enhance and recover the evanescent waves that carry information at very small scales. No lens is yet able to completely reconstitute all the evanescent waves emitted by an object. So the future challenge is to design superlens which can constitute all evanescent waves to get a perfect image [19].

D. Metamaterial as Cloaks

Cloaking can be achieved by the cancellation of the electric and magnetic field generated by an object or by guiding the electromagnet wave around the object. Guiding the wave means transforming the coordinate system in such a way that inside the hollow cloak electromagnetic field will be zero this makes the region inside the shell disappear [20].

E. Metamaterial as Sensor

Metamaterial opens a door for designing sensors with specified sensitivity. Metamaterials provide tools to significantly enhance the sensitivity and resolution of sensors. Metamaterial sensors are used in agriculture, biomedical, etc. In agriculture the sensors are based on resonant material and employ SRR to gain better sensitivity, In biomedical wireless strain sensors are widely used, nested SRR based strain sensors have been developed to enhance the sensitivity[21].

F. Metamaterial as phase compensator

Metamaterial act as a phase compensator, when the wave passes through a (double-positive) DPS slab having positive phase shift while DNG slab has opposite phase shift so when wave exit from a DNG slab the total phase difference is equal to zero [20].

IV. PROGRESS ON METAMATERIAL:

1967- Theoretically proposed by visa logo 1999- First negative mu material by Pendry.
2000- First Metamaterial by smith.
2003- Transmission approach by catalog, Oliner, Eleftheriades.
2005- New structures.
2009- Miniaturized structures for optical fiber.
2015- Metamaterials for media communication.
2017- Metamaterial based satellite antenna.
2018- Space-time coding digital metasurface.
2019- Metamaterials as real-time processor.
2020- Metamaterial in 6G communication

V. FUTURE ASPECTS:

A metamaterial is one of the newest, most dynamic, and exciting areas of science. Scientists achieve what has never been done before with the help of metamaterial. Metamaterials have different properties from materials. Metamaterial first came into public consciousness through the concept of invisible cloaking. Scientists are also making significant progress in honing the properties of materials to create protective shields against radiation and seismic activity. Apart from shielding and absorbing waves, metamaterials can also help us tap off some of the energy these waves carry. The metamaterial can be designed to trap, convert and recycle this energy. With the prospective application in advanced solar batteries and residual radio noise harvesting, metamaterials are in the spotlight of breakthrough greener technologies. With the ability to control the propagation of waves, metamaterials are also enabling scientists to take power and data transfer to the next level. Specific types of waves, such as magneto-inductive waves, existing in the metamaterial, can carry power in a controlled manner. By this phenomenon, scientists are trying to expand wireless charging for cell phones and other electronic devices.

VI. CONCLUSION:

We reviewed here history, concept, classification, and different approaches of the metamaterial. Various applications of metamaterial open the door for exciting possibilities for the future design of devices & components. Metamaterial properties allow for the reduction in size as compared to other materials for the multiband operation and reconfigurability of microwave devices and antennas.

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