USE OF METAMATERIALS IN ANTENNA DESIGN: A REVIEW

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Abstract: Metamaterials are the artificial materials which have the electromagnetics properties that rare or impossible to achieve in nature with artificial structures. Metamaterials have attracted large researchers' interest because of their extra ordinary properties and their suitability for various applications. This paper provides a comprehensive review of the current research activities on metamaterials related to different fields. In this paper a comparative analysis of the metamaterials of the antenna parameters is discussed. The practical challenges for the production of small metamaterial-based antennas are highlighted and the potential ways are also outlined in this paper to solve these problems.

***Index Terms* - Permittivity, Permeability, SSR, DNG.**

I. INTRODUCTION

A metamaterial is a word derived from the Greek word, it is a combination of the words "meta" and "material," in which "meta" means something beyond normal, altered, changed, or something advance. It is an artificial material designed to obtain the physical properties that do not exist in natural materials. The term of metamaterial was given by Rodger M. Walser, University of Texas at Austin, in 1999 [1, 2]. He defined metamaterials as- "Macroscopic composites having a synthetic, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of two or more responses" [2].

Metamaterials (MTM) are the artificial material which have exotic properties of electromagnetic (EM), which does not show in natural material. Metamaterials are also called artificially composite material. It is a wonderful discovery of modern science that has been able to attract researchers. Over the past few decades, work on EM MTM for use in the microwave region has developed a tremendous interest for the researchers [3]. The metamaterial can be of different types i.e., single negative (SNG), double negative (DNG), double positive (DPS). When one of the features such as permittivity (ε) or permeability (μ) is negative then it is entitled SNG materials, when both features are negative it is called DNG metamaterial and when both features are positive it is known as DPS material. Single negative metamaterial also classified into two types i.e., epsilon negative (ENG), mu-negative (MNG) MTM. In 1968 Victor Veselago discovered first type of material having both permeability (μ) and permittivity (ε) negative with different properties as opposed to ordinary natural materials [4]. In 2000, Smith et al. successfully discovered a new composite material with the extra ordinary properties [5] having both permeability (μ) and permittivity (ε) negative, which is referred as left-handed materials. The metamaterials are suited for various applications in the field of communications.

Conventional materials allow the wave propagation in forward-direction only, which is referred as right-hand wave propagation, therefor these materials are known as right-handed materials (RHM), but the metamaterials have this unusual property of supporting backward wave propagation, which is also referred as left-handed or left-handed material propagation (LHM). There is also a modern approach to metamaterial properties such as zero negative refractive index based on Snell's laws and Doppler effect, which are used to represent the transfer of wave propagation from one medium to another [6]. Rays are refracted along the normal of the interface in natural materials, but in LHM, rays will be refracted far from the place where the normal is present. This will result in a focal point being formed within the metamaterials. In general, there are types four kinds of metamaterial structures - S-structure, symmetrical-ring structure, free split-ring structure and omega structure.

II. THE PROPERTIES OF METAMATERIALS

Maxwell's equations describe the electromagnetic behaviour of metamaterials. The propagation of an electromagnetic wave through a material is determined by the electromagnetic property of that material, i.e., dielectric permittivity (ε) and magnetic permeability (μ).

Maxwell’s first equation is

$$\nabla \times E = -j\omega\mu H \tag{1}$$

$$\nabla \times H = j\omega\varepsilon E \tag{2}$$

where E and H are the vectors of electric and magnetic fields strengths, respectively; ε and μ are the material permittivity and permeability; ω is an angular frequency.

In the case of the plane wave propagation, the electric and magnetic fields are represented as:

$$E = E_O e^{(-jkr+j\omega t)} \tag{3}$$

$$H = H_O e^{(-jkr+j\omega t)} \tag{4}$$

To evaluate the properties of materials, a general definition of the Poynting power density vector S, which is subdivided into the time $e^{+j\omega t}$ and the space e^{-jkr} components. The real part of the Poynting vector S, which determines the energy flow, is represented by the following formula:

$$S = \frac{1}{2} E \times H \tag{5}$$

For the plane wave, the electric field E and the magnetic field H are defined by

$$k \times E = \omega\mu H\ ; \tag{6}$$

$$k \times H = -\omega\varepsilon E \tag{7}$$

For the homogeneous medium, ε and μ are simultaneously positive. In this medium, E, H, and k form the right circulate triad of orthogonal vectors. Therefore, it is also defined as the right-handed medium (RHM), where the S, k has the same directions and electromagnetic waves can propagate in them [7].

In that case, the values of ε and μ are negative simultaneously; so, Equations. (6) and (7) can be rewritten as:

$$k \times E = -\omega\, |\mu|\, H\ ; \tag{8}$$

$$k \times H = \omega\, |\varepsilon|\, E \tag{9}$$

For this case, the E, H, and k form left handed triad of orthogonal vectors, which also is defined as the left-hand medium (LHM). In this medium, the Poynting vector S has the opposite direction to the propagation vector *k*, so that it can support backward waves, i.e., the energy and wave fronts travel in opposite directions. Figure 1 depicts triplet models for RHM (a) and LHM (b) materials.

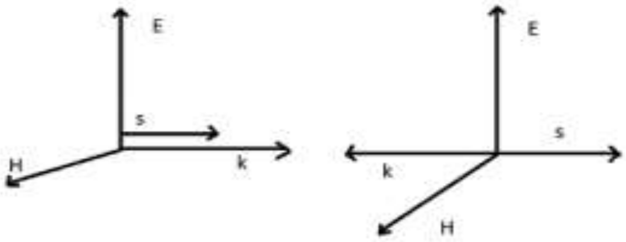

Figure 1. The vectors E, H, k forms the trio for right-handed (a) and left-handed media (b).

III. CLASSIFICATION OF MATERIALS

The materials can be classified depending on the value of permittivity (ε) and permeability (μ).

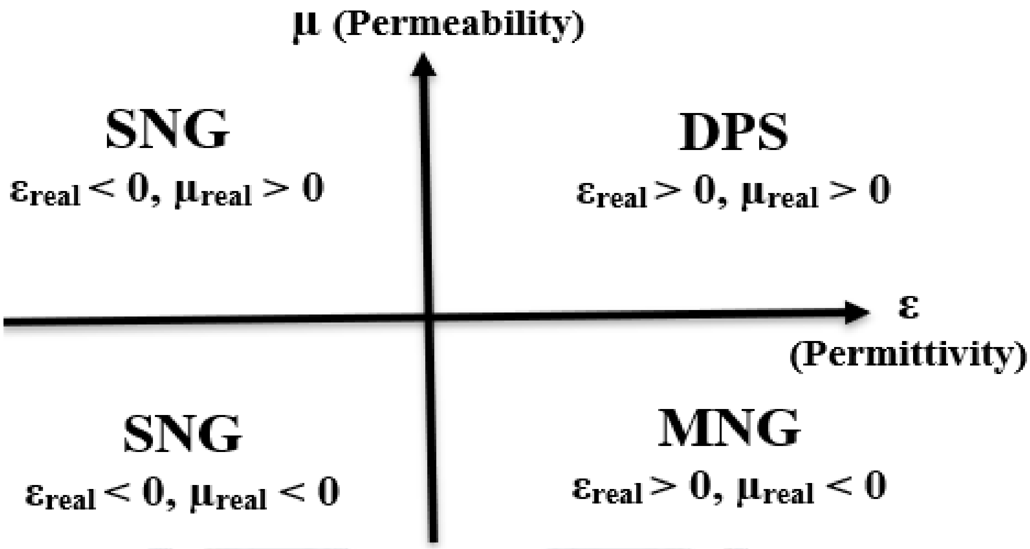

Figure 2: Classification of Metamaterials

The materials are classified into four type as shown in Figure 2 depending on the value of ε and μ which are explained as follows:

3.1. DPS Materials

These materials lie in the first quadrant as shown in Figure 2, having both the parameters ε and μ as positive, therefor these materials are called as Double Positive (DPS) or right-handed materials (RHM). These materials can be found in nature, such as dielectric materials, in which the electromagnetic waves can propagate. Double-positive materials are the ones for which the ε and the μ are positive ($\varepsilon > 0$, $\mu > 0$). These types of materials have positive refractive index, and the waves follow right-hand rule to propagate in the forward-direction [8,9].

3.2. ENG Materials

These materials lie in the second quadrant as shown in Figure 2, the parameters are Epsilon negative (ENG) metamaterials are the materials having negative permittivity and positive permeability ($\varepsilon < 0$, $\mu > 0$), therefore these materials called as epsilon negative (ENG) materials. For example, plasma. These materials produce shunt inductance, and the radiation pattern due to current at these materials. TL unit cell model is constructed using the combination of shunt capacitance and series inductance [8,9].

3.3. DNG Materials

These materials lie in the third quadrant as shown in Figure 2, the double-negative materials (DNG) have negative permeability and negative permittivity and both ε and μ less than zero ($\varepsilon < 0$, $\mu < 0$). These materials can only be artificially realised and are not naturally exist. The DNG materials are also known as the negative refractive index material (NIM). The properties of t DNG were first achieved by combining the thin wire-based ENG structure with SRR-based MNG structure. To get the DNG material from the combination of the ENG and MNG structures, both negative regions of them must coincide and they are also known as LHM metamaterials. The first metamaterial structure metamaterial introduced was split ring resonator (SRR) [8-11].

3.4. MNG Materials

These materials lie in the fourth quadrant as shown in Figure 2. The MNG material with a negative value of permeability and positive value of permittivity ($\varepsilon > 0$, $\mu < 0$) are known as mu-negative materials. For example, gyro-tropic materials such characteristics at specific frequencies [10].

IV. TYPES OF METAMATERIALS

The metamaterials can be classified into Four major types which are as follows.

I. Electromagnetic Metamaterials (EM)
II. Photonic Metamaterials (PM)
III. Acoustic Metamaterials (AM)
IV. Mechanical Metamaterials (MM)

I. Electromagnetic Metamaterials (EM)

Electromagnetic metamaterials (EM) are having the composition of traces and particles in a dielectric matrix; these EM metamaterials have a zero or negative refractive index. Applications like beam stereos, antenna radomes, modulators, lenses, microwave couplers and band-pass filters are widely using these materials. The single-negative metamaterials define electromagnetic MTMs which have either negative permeability or negative permittivity, but not both. The double-negative metamaterial defines backward media define as negative refractive index and both negative permittivity (ε) and negative permeability (μ) [7].

II. Photonic Metamaterial

These types of metamaterials deal with design of optical frequencies using photonic metamaterials. Photonic metamaterial has zero indexes of refraction, and this metamaterial is the current research area in the field of optics [12]. A Photonic metamaterial is an artificially fabricated, subwavelength, periodic structure, designed to interact with optical frequencies. The sub-wavelength period distinguishes the photonic metamaterial from photonic band gap structures.

III. Acoustic Metamaterials

Two or three distinct materials with different mass densities and bulk modulus are made up of acoustic metamaterials; these types of metamaterials have negative effective mass densities and bulk modulus. These are the metamaterials produced artificially to steer, regulate and monitor sound waves in liquid, for solids, for gases. It is possible to specifically control any kind of sound waves by manipulating the bulk modulus and density of mass [13].

IV. Mechanical metamaterial

Mechanical Metamaterials is the artificial composite metamaterial which is consisting of different types of mechanical properties; this metamaterial is having negative Poisson’s ratio, negative elastic modulus, zero shear modulus and frictional properties. This is made up of material with inclusion of secondary materials or a controlled pored structure [14].

V. APPLICATION OF METAMATERIALS

The different applications of metamaterials are as follows:

5.1. Metamaterial as Absorber

A metamaterial absorber [15] is a type of metamaterial structure intended to efficiently absorb electromagnetic radiation such as light. Applications for the metamaterial absorber include emitters, photodetectors, sensors, spatial light modulators, infrared camouflage, wireless communication, and use in solar photovoltaics and thermophotovoltaics. A metamaterial absorber utilizes the effective medium design of metamaterials and the loss components of permittivity and magnetic permeability to create a material that has a high ratio of electromagnetic radiation absorption. Loss is noted in applications of negative refractive index (photonic metamaterials, antenna systems metamaterials) or transformation optics (metamaterial cloaking, celestial mechanics), but is typically undesired in these applications [15] [16].

5.2. Metamaterial as Super-lens

A Super-lens is a lens that goes beyond the diffraction limit using metamaterials structures. The diffraction limit is a characteristic of conventional lenses and microscopes that restricts the fineness of their resolution. 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 super lens is its aptitude to significantly enhance and recover the evanescent waves that carry information at very small scales [17].

5.3. Metamaterial as Cloaks

Metamaterial cloaking is the usage of metamaterials as an invisibility cloak. This is accomplished by manipulating the paths traversed by light through a novel optical material. Metamaterials direct and control the propagation and transmission of specified parts of the light spectrum and demonstrate the potential to render an object seemingly invisible. Metamaterial cloaking, based on transformation optics, describes the process of shielding something from view by controlling electromagnetic radiation. Objects in the defined location are still present, but incident waves are guided around them without being affected by the object itself [18] [19]. Cloaking can be achieved by 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] [21] [22].

5.4. Metamaterial as Sensor

Metamaterial opens a door for designing sensor 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 bio medical wireless strain sensors are widely used, nested SRR based strain sensors have been developed to enhance the sensitivity [23]. the amplification of evanescent wave has been shown to be able to enhance the interaction between wave and mater and then increase the sensitivity of sensors. Planar metamaterials consisting of subwavelength resonators have been proposed for thin dielectric film sensing. To achieve higher sensitivity, the sensor needs to have a sharp resonance in its frequency response and a high concentration of electric field to enable the detection of small changes in dielectric environment [24].

5.5. Metamaterial as Phase Compensator

Metamaterial act as a phase compensator, DNG can provide phase compensation due to their negative index of refraction. This is accomplished by combining a slab of conventional lossless DPS material with a slab of lossless DNG metamaterial.

DPS has a conventional positive index of refraction, while the DNG has a negative refractive index. Both slabs are impedance-matched to the outside region (e.g., free space). The desired monochromatic plane wave is radiated on this configuration. As this wave propagates through the first slab of material a phase difference emerges between the exit and entrance faces. As the wave propagates through the second slab the phase difference is significantly decreased and even compensated for. Therefore, as the wave exits the second slab the total phase difference is equal to zero [21] [25].

5.6. Metamaterials in Antenna Designing

To strengthen the radiation and matching properties of electrically small electric and magnetic dipole antennas, metamaterial coatings have been used. The radiated power is enhanced by metamaterials. 95% of input radio signal at 350 MHz is radiated by the newest Metamaterial antenna, the experimental metamaterial antenna is as small as one fifth of the wavelength. The patch antenna has enhanced directivity with a metamaterial covering. Flat horn antenna with flat aperture constructed of zero index metamaterial has advantage of improved directivity. To achieve high directivity antennas, zero-index metamaterials may be used. Since propagating a signal in a zero-index metamaterial will stimulate a structure of the spatially static field that varies in time, the phase will have the same constant value at every point in a zero-index metamaterial until the steady state is reached. The metamaterial will enhance the gain and minimize the return loss of a patch antenna [26]. The effects of metamaterials over antenna parameters is thoroughly covered and discussed in next section.

VI. EFFECT OF METAMATERIALS OVER ANTENNA PARAMETERS

In literature, many techniques using metamaterials for enhancing antenna parameters such as gain, bandwidth, Directivity, off-side lobe and back lobe bandwidth suppression, efficiency are used by several researchers. The use of metamaterials in antenna design can lead to reduced size, improved gain, increased bandwidth or multiband antenna formation which are explained as follows:

6.1. GAIN

Low gain is a big downside of tiny planar antennas, which must be resolved in order to satisfy max energy in transceiver devices. In addition to using an antenna with an array, the metamaterial is a solution that has recently been used in antenna architecture. In this scenario, the metamaterials used may include artificial magnetic conductors (AMCs) or artificial magnetic materials (AMMs). They are added to the antenna environment in such a way as to Arrange the metamaterial unit cells covering radiated antenna elements [27], or use one or more superstrates above or below the radiated elements [28], or using such as metamaterials as the loading of the antenna [29, 30]. The ability to improve antenna power gain depends on the number of superstrates, the type of unit cell, and distance between the radiation elements to the superstrates.

When the metamaterials are placed on another dielectric layer called superstrate, the unit cells of metamaterials are loaded on a different dielectric with the distance d from the radiation elements to the superstrate. These array unit cells created AMCs or AMMs, which can be loaded in one side or both sides of the superstrate. The power gain of an antenna depends on the number of superstrates, the number of unit cells, and the distance from the radiation elements to the superstrate [31, 32]. The use of metamaterials in antenna architecture as a superstrate has greatly increased the gain obtained, but also the antenna's size and thickness has been increased too.

6.2. SIZE REDUCTION

For the construction of compact antennas, many technological solutions have been used, such as high-permittivity dielectric microstrip antenna substrates, shorting pins, shorting partitions, incorporating certain disturbances into the structure of the antenna, adding fractal geometry, etc. Recently, to decrease the size of the antenna, designers have used metamaterials as a defected ground structure (DGS). The unit cells of the metamaterials have unusual properties at the resonance frequency of the designed antenna; the dimension of these unit cells is equal to the size of the removed parts of the DGS in many designs [33].

6.3. BANDWIDTH ENHANCEMENT

In comparison with the conventional patch antenna, the metamaterial loaded antenna has a high bandwidth. The metamaterials are used as components of the antenna or a superstrate mounted above the radiation surface like the antenna gain enhancement method to achieve this purpose. It is possible to position unit cells of metamaterials on top or under the bottom of the superstrate. The bandwidth of this antenna is dependent on the number of unit cells as well as the radiation surface distance of the superstrate [34] [35] [36] [37].

6.4. MULTIBAND ANTENNA

The metamaterials are also used to design multifrequency-band antennas. Metamaterial unit cells may be used as radiation elements, a part or a loaded part of the antenna's ground plane. Since MTMs at resonant frequencies and unit cell structures of symmetric pairs can support negative refraction indexes. This can be used to design smaller dimensions of multifrequency antennas than traditional ones [38]. To create a multiband antenna, metamaterial can be combined with a conventional or fractal microstrip antenna in which the antenna size is determined by the lowest frequency.

6.5. DIRECTIVITY ENHANCEMENT

DNG material enhances the directive properties of an antenna. Metamaterials have an inherent property that controls the direction of electromagnetic radiation to collect the originating energy in a small angular domain around the normal to the surface.

All these effects of metamaterials on antenna parameters are summarized in table 1

Table 1: Comparative analysis of various metamaterial Based Antenna

Antenna Parameter	Metamaterial Structure	Target Frequency Band	Ref.
Size	CSRR; RCSRR; CSRR; SRR & CRR	6.11GHz; 2.9-5.2GHz; WLAN; WiMAX & WLAN	[33] [39] [40] [41]
Gain	DSSRRP; ZIM; HEXAGONAL CRR; ENZ	WLAN; 10GHz & 11.1GHz; 5.9& 9.9GHz; 1.84-1.88 THz	[27] [31] [42] [43]
Multiband	TSRR; SRR & CSRR; Rectangular CSRR; SEC-SRR	WiMAX, WLAN, ITU; WLAN, ISM, BT, WiMAX; 3.14-3.35 GHz, 5.67-6.3 GHz & 7.58–9.5GHz; S, C and X bands	[38] [44] [45] [46]
Bandwidth Enhancement	CRLH-TL; RECTANGULAR-RING; CRLH-TL; S-shaped	UWB Band 3.2–4.8 GHz 2.73 GHz 5.618–5.9 GHz	[34] [35] [36] [37]

VII. CONCLUSION

The exotic electromagnetic properties of Metamaterials make them an emerging and exciting field for researchers due to their suitability for various applications in different areas of science and technology. In this paper a brief review of metamaterials, their types, various properties, structures, and their advantages have been discussed. The implementation of metamaterials is beneficial in enhancing the antenna parameters like reduction in size, enhancement in gain, directivity, radiation characteristic and bandwidth. The applications of metamaterials for different applications have also been presented in this paper with the aid of literature survey.

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