A REVIEW ON METAMATERIAL ANTENNA FOR WIRELESS COMMUNICATION

Anika Aziz[1]

***Abstract*—** Rapid advancements in wireless technology for mobile devices necessitate large bandwidth, fast data rates, and small form factors. Numerous techniques are proposed to improve the size & performance of the antenna over the last decade. Using metamaterials (MTMs) in antenna design is one such method. MTMs are synthetic structures designed to offer special electromagnetic properties absent from natural materials. Owing to their unusual qualities, metamaterials have attracted a lot of attention and are thought to be a viable way to enhance the functionality and get beyond the constraints of microwave components, particularly antennas. To understand and realize the importance of metamaterial, a detail study of it's structure, unique characteristics and how it interacts with the Electromagnetic wave is required. This paper also summerize the properties of different structural symmetries of metamaterial and their contribution to the antenna performance enhancement. A detail comparison between conventional antenna and metamaterial antenna is also investigated in this survey.

***Keywords*—** *Conventional antenna, Electromagnetic properties*, *Metamaterial (MTM), Performance of antenna Synthetic structure.*

I. INTRODUCTION

FOR the past few decades, the research community has been paying close attention to metamaterials because of their distinctive electromagnetic properties. Dispersing the incoming waves in a certain direction is a crucial function of the metamaterial structures. Often, the frequency band in use dictates the shape of the radiation structure[1]. Artificial structures known as metamaterials has the capacity to display unique and uncommon electromagnetic characteristics, like the ability to achieve negative permittivity and permeability. Owing to their unusual qualities, metamaterials have attracted a lot of attention and are thought to be a viable way to enhance the functionality and get beyond the constraints of microwave components, particularly antennas. It is clear that the antenna design is limited by the properties of the material since its main goal is to ascertain the ideal geometrical shape of conventional materials. Metamaterials are made of standard materials (dielectrics and capacitors) in the microscale, but because of their clever forms, they have entirely distinct macroscopic properties. Metamaterials enable the realisation of negative constitutive parameters in the microwave region, and their subwavelength scale is an additional advantageous characteristic. Consequently, the use of metamaterials into antennas can provide enhanced adaptability and facilitate innovative design approaches. Therefore, it is crucial to research the advantages of metamaterial-inspired antennas and if they can play a significant role in contemporary wireless communications [2].

In this paper, the metamaterial and it's unique features are firstly introduced. This is followed by the categorization, structures and interaction with the electromagnetic waves. After this, an organized Literature Review of the metamaterial antennas is presented. A qualitative comparison between the conventional antenna performance enhancement and that of metamaterial antenna is also presented here. The future potential of metamaterial antennas in wireless communication is discussed in the paper's conclusion.

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II. UNIQUE FEATURES OF METAMATERIAL

A substance having qualities superior to those of a regular material is referred to as a metamaterial (MTM), a combination of the phrases "meta" and "material." It can consist of occasionally created macroscopic composites in two or three dimensions that exhibit peculiar properties ranging from microwave to optical frequencies [3]. Fig 1 shows different MTM structures. Both magnetic permeability (μ) and electric permittivity (ε) are crucial metrics that characterize the characteristics of the material. Furthermore, refractive index,n is an additional significant statistic. For any given material it is defined as follows:

$$n = \sqrt{\mu_r}\, \varepsilon_r, \quad (1)$$

The relative permeabilty and permittivity are denoted by μ_r and ε_r respectively.

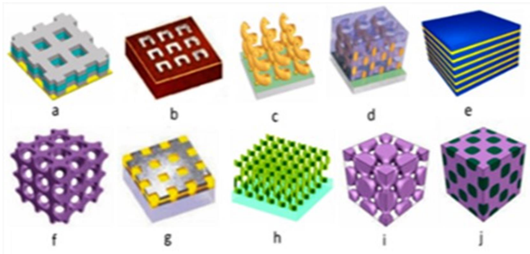


Fig.1. Various meta-atom based metamaterial (MTM) constructions utilising periodic metallic and dielectric element repetition: a.Fishnet NRI MTM b. Chiral MTM c.Chiral MTM (Laser) d. Hyperbolic MTM e. Waveguides MTM f. 3D-SRRs MTM g. NRI MTM (Coaxial) h. Cubic MTM i. Magnetic MTM j. Cubic Lattice MTM [3].

A metamaterial can be constructed by having a negative μ or negative ε or having both of these. These unique characteristics of the metamaterial causes to have it some outstanding properties which is unavailable in conventional materials that include the inverse Doppler effect, perfect lensing, negative refractive index, left-handed behavior,perfect absorption and electromagnetic wave cloaking [3].

To make it useful in practical purposes and utilize it in antenna and other applications, metamaterial unit cells are arranged in array as shown in the following fig2.

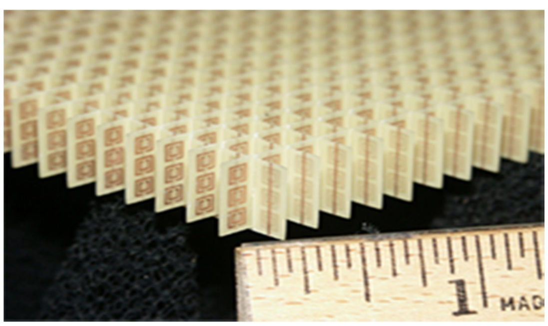


Fig. 2. A 10 mm × 100 mm × 100 mm negative-index Meta material array configuration, which is constructed of 3×20×20 copper Split Ring Resonator unit cells and wires mounted on interlocking sheets of fiberglass circuit board.

III. THE TYPES OF METAMATERIALS

The properties of conventional antennas are improved by the application of a variety of metamaterials, including as mechanical, acoustic, and electromagnetic metamaterials. Conductive particles and traces are put in a dielectric matrix to construct electromagnetic metamaterials with zero or nearly zero permeability, permittivity, and refractive index.

The metamaterials fall into two categories: single negative metamaterials, where the permeability or real component of the permittivity is negative, and double negative metamaterials, which exhibit both negative permeability and permittivity in the frequency of interest. Because of certain characteristics, double negative metamaterials are also known as left-handed materials, negative index materials, or backward wave media. Fig. 3 shows how materials are categorized based on the qualities of the medium. "Right-Handed Material," also known as "Double-Positive Material," is represented by the first quadrant of the picture and has both positive values of ε and μ (DPS). Single-Negative Materials (SNG) are materials that have a single permittivity or permeability value that is less than zero. They are classified as either in the second or fourth quadrant. The third quadrant is occupied by composite materials that have both values of permittivity and permeability less than zero. These materials are also known as "Left-Handed Material" (LHM) or Double-Negative Material (DNG). Materials classified as "epsilon-negative" (ENG) have a permittivity value of less than zero, while materials classified as "mu-negative" (MNG) have a permeability value less than zero. [4]. Russian scientist Veselgo was the first to study the metamaterial's double negative (DNG) feature[5], and Pendry suggested using a DNG metamaterial as a perfect lens for the material's first use. [6].

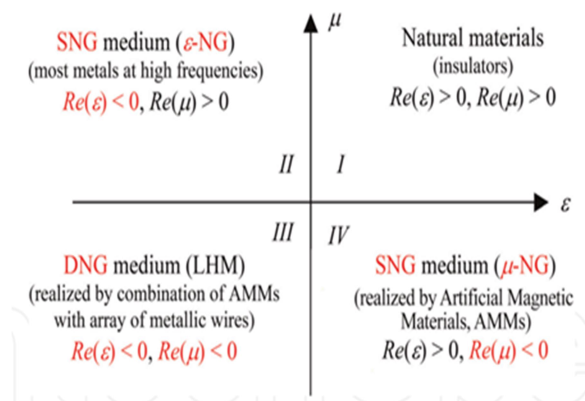


Fig. 3. Different kinds of electromagnetic materials are categorized according to their permeability (μ) and permittivity (ε) properties[4].

IV. CONSTRUCTION OF METAMATERIALS

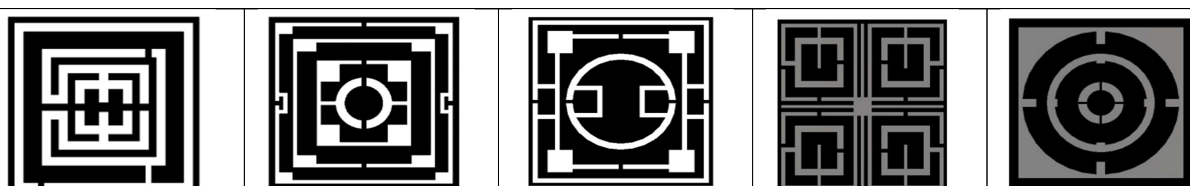
A metamaterial is a macroscopic composite that meets the requirements for an effective medium and has a periodic or non-periodic structure that is smaller than or equal to the sub wavelength. Whereas a non-periodic structure is an inhomogeneous media, a metamaterial with a periodic structure is similar to a homogeneous medium. It can be created at microwave frequencies on a printed circuit board, the characteristics of which are mostly determined by the different fabrication design architectures and different types of substrate materials such as FR-4, F4B, Rogers etc. The ability to explore novel qualities not found in natural materials is provided by the metamaterial's controllable properties through architectural change, suggesting further advantages offered[7].

TABLE 1
DIFFERENT METAMATERIALS WITH DIFFERENT STRUCTURAL SYMMETRIES.

In [4] we can find five types of metamaterials with five different structural symmetries. Table 1 presents the characteristics of these five types of metamaterial structuers used for wireless communication system applications. Fig. 4 illustrates each type of the unit cell of the metamaterial strucuture. The array structure and its functions are discussed in the following “Types of metamaterial antenna” section.

Structural Symmetry	**Compactness**	**Reso-nance**	**Permittivity, Permeability, Refractive index**	**Absorption Q-factor**	**Gain enhancement**	**Mutual coupling**	**Application**
Asymmetrical resonator	*EMR 16.7	at S,C,X band	negative permittivity (2.2~10 GHz)	-	-	Affects the resonance	multiband wireless communications
Single axis symmetric resonator	EMR 15.75	Multiresonances at S, C, X and Ku bands	Negative permittivity, permeability and refract. index are both near zero	Very good absorption properties using a copper back plane	Boost antenna gain & directivity. Higher gain over 2~18 GHz.	-	superstrate for mulitiple application
Two axes symmetric metamaterial	EMR 10.7	resonance at 2.78, 7.7 & 10.16 GHz	Permittivity is negative. Permeability is near zero. refractive Index is near zero.	-	when used as a superstrate, gain is 95%.		Monopole antenna
Mirror symmetric resonator	EMR 7.17	Resonance occurs at C, X, and Ku band	near-zero refractive index and permeability It has ENG property	-	-	excellent cross coupling reductions when an array is formed	frequency selectivity can be achieved for wireless communication systems
Rotating symmetric resonator	-	-	Absorption properties at different frequency	The absorption frequency can be tuned by the metallic stubs.			various application in wireless communication.

* EMR–Effective Medium Ratio: The effective medium ratio (EMR), which is the ratio of the wavelength at the lowest resonance frequency to the metamaterial unit cell length, can be used to determine how compact a metamaterial is. Setting varied splits and ringed linkages at various locations within the metamaterial structure allows for EMR.



Coupled ring split ring resonator based MTM	Inductively tuned split rings resonator based MTM	Gap coupled metamaterial	Mirror symmetric resonator-based metamaterial	Metamaterial absorber’s Front view (resonator)

Fig. 4. The unit cell of each metamaterial structure type

V. Reaction with the ElectroMagnetic (EM) Wave

It is widely acknowledged that constitutive properties in a medium, specifically its electrical permittivity, ε, and magnetic permeability, μ, dictate the response of that medium or substance to external time-varying electromagnetic fields [8].

One method of realizing metamaterials is to symmetrically or nonsymmetrically pattern metallic resonant inclusions on a regular basis in a dielectric or magneto-dielectric material. The reaction and characteristics of the inclusions are the primary reasons why when exposed to an electromagnetic field, the metamaterials alter the new host medium's electromagnetic characteristics. Figure 5 depicts a general view of a potential realisation of a metamaterial structure.

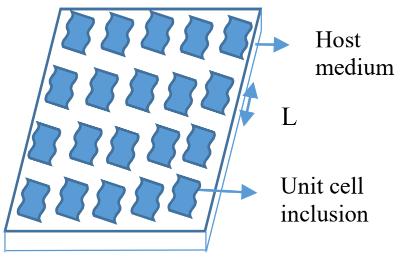


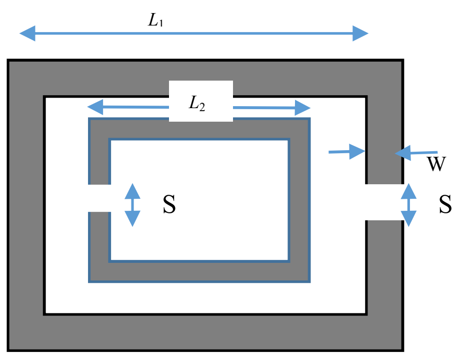
Fig. 5. The composite structure a metamaterial [8]

The constitutive parameters of the metamaterial along with Maxwell's equations can explain the propagation and electromagnetic wave response inside the effective metamaterial medium. In theory, this effective response might be permitted provided the unit cell dimension is small enough—a fraction of an operating wavelength [9]. Refeering to Figure 5 -

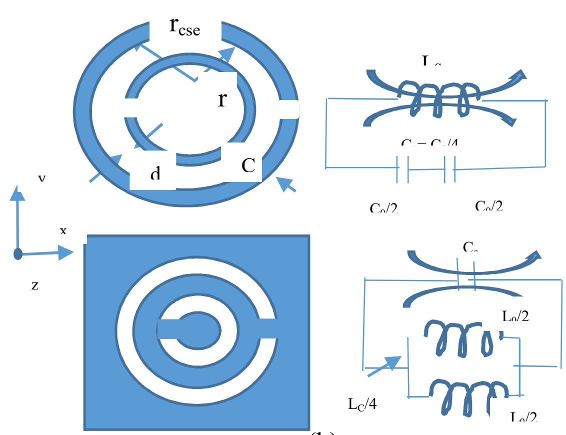
$$L \ll \lambda \tag{2}$$

where λ is the operational wavelength of the incoming electromagnetic field and L is the unit cell dimension. If the aforementioned equation is satisfied, artificial metamaterials can exhibit quasi-static behavior. This enables the qualitative description of the physical behaviour of the artificial materials using an equivalent resonant circuit composed of resistor-inductor-capacitor (RLC) parts.

Split-ring resonator (SRR) is a frequently used and well-liked artificial magnetic material. An electromotive force can be generated within the inclusions by excitation of an external magnetic field perpendicular to the paper plane. This electromotive force causes an effective current to circulate around the inclusions. A generic shape for the effective magnetic permeability is formed upon such excitation. Thus, magnetic permeability might be synthesized in the optical and microwave domains because of the creation of patterned metallic resonant inclusions in a homogenised host material [3]. Similar to this, patterned metallic inclusions can be made to facilitate the engineering of a bulk medium's permittivity. A cubical lattice array of thin rods or wires can actually exhibit negative effective permittivity response at the microwave regime, as proved by Pendry et al [6]. Recently, Falcone et al. [10] described the complementary split-ring resonator (CSRR), a subwavelength resonant planar particle that is illustrated in Figure 4b. It is the SRR's dual counterpart. By substituting apertures for the metallic rings encircling the SRR free-space area and metal plates for the apertures, the planar SRR structure's complementary is created. Complementary SRR rings are the building blocks for tiny microstrip-based bandstop filters. The SRR rings are etched out of the metallic ground screen to achieve them. A quasi-static equivalent circuit model can be used to assess the effective permittivity response of such an inclusion, as seen in the following Fig. 6.



(a)



(b)

Fig. 6: Schematic diagram (a) of a rectangular split-ring resonator (RSRR), (b) a circular split-ring resonator (SRR) and complementary split-ring resonator (CSRR) with the equivalent circuits [11].

Initially, Sir John Pendry and his team proposed [6] that negative permittivity may be realized in the microwave realm with a periodic arrangement of thin metallic wires of diameter α and periodicity p. This structure is the lower-frequency equivalent of plasmas, and it exhibits classic Drude behavior for an incident electric field parallel to the wires, in terms of effective permittivity:

$$\epsilon_{eff}(\omega) = 1 - \frac{\omega_p^2}{\omega(\omega + j\omega_c)}, \quad (3)$$

where ωp is the plasma frequency:

$$\omega_p^2 = \frac{2\pi c^2}{p^2 ln(\frac{p}{\alpha})} \quad (4)$$

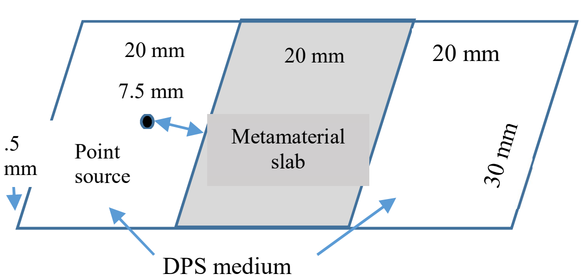
and ωc is the dumping frequency:
The resonance frequency f_0 of the equivalent quasi-static LC circuit of the SRR is-

$$f_0 = \frac{1}{2\pi\sqrt{LC}} \quad (5)$$

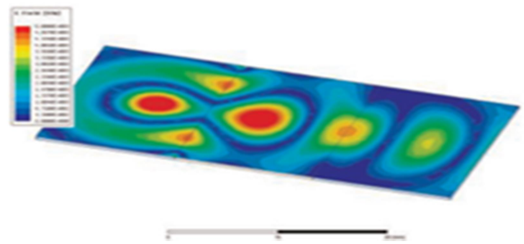
where C is the capacitance between the rings and L is their inductance [13].
Also, their effective permeability is given by:

$$\mu_{eff}(\omega) = 1 - \frac{A\omega^2}{\omega^2 - \omega_m^2 + j\omega\Gamma_m}$$

where A and m are geometric parameter functions and the resonance frequencies are l, g, s, w, and ωm, in Fig 7(b).
Smith and associates talk about the real-world applications and showcases of DNG media in [14]. This was achieved by assembling artificial MNG in the form of SRRs with ENG media in the form of planar metallic strips to construct a substantial bulk structure, both of which were repeated patterns. On a one-dimensional artificial lossless and isotropic metamaterial slab, the behaviour of an electromagnetic field induced by an external plane wave excitation is represented analytically in [8]. Next, we show and analyze the numerical demonstration of electromagnetic wave interaction between artificial DNG, MNG, and ENG metamaterial slabs in two dimensions [10]. An illustration is presented in Fig. 7.



(a)



(b)

Fig. 7. (a) Numerical model shows the electromagnetic wave interaction with the DNG medium and (b) Electric field distribution for the same DNG medium [10].

VI. TYPES OF META MATERIAL ANTENNA

In Table 2 we have done an elaborate literature survey of how the metamaterial antenna has been used in different ways. Prior to that, however, we would like to present an example of a four-by-four array of two-axes symmetric metamaterial, with an overall dimension of forty-one millimeters by forty millimeters, that is utilized as the monopole antenna's superstrate. Figure 8(a) shows the top view of a monopole antenna, and Figure 8(b) shows the bottom view of the antenna. As shown in Figure 8(c), an array of this metamaterial is placed as a superstrate at the ground side of the antenna, 30 mm apart. The monopole antenna has an average gain of 2 dBi and a maximum gain of 2.95 dBi, covering a bandwidth of 2.5 GHz to 4.24 GHz [4].

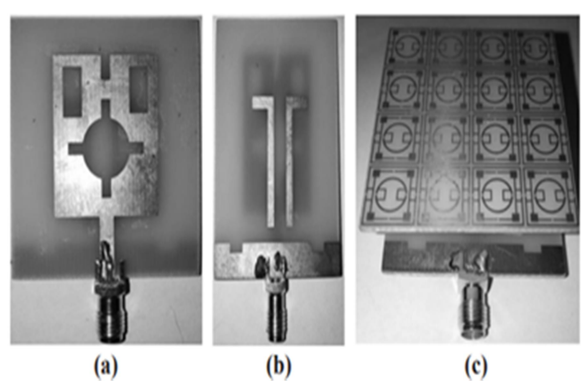


Figure 8. (a) Upper side, (b) lower side and (c) metamaterial array used in the antenna [4].

TABLE 2
Different metamaterial antenna types found in the Literature.

Reference	Antenna type	Composition/ Structure	Performance achieved	Application
Weng et al. [15]	Metamaterial-inspired antenna	copper grids with square lattices on metamaterial substrate	8.2 dB gain at 2.77 GHz	Multiband functions
Li et al. [16]	Planar substrate-rectangular MPA	metamaterial substrate to the conventional antenna	Minimum 200 MHz and maximum 3 GHz BW, comparatively high efficiency and low loss are achieved.	
Zhang et al. [17]	Metamaterial-inspired antenna	near the feed line and on the radiator split-ring slots are used	Ultra wideband antennas with triple band-rejection	
Singh et al. [18]	MPA	Uniplanar compact PBG structure loaded into a coplanar waveguide (CPW) supplied antenna	Enhanced bandwidth	suitable for both local area and wide area wireless network band applications
Joshi et al. [19]	small MPA	MTM structure	BW is 512 MHz at 9.51 GHz	
Singh et al. [20]	Metamaterial-inspired antenna	A New metamaterial structure	The resonant frequency and bandwidth rise as the patch's size decreases.	X band application
Bertin et al. [21]	metamaterial-inspired switch beam antenna	Fabricated antenna	A high bandwidth as much as of 1.1 GHz	telecommunication
Tang et al. [22]	Triband stop (UWB) antenna	SRR structure, filters	large bandwidth coverage 3.03 GHz ~ 11.4 GHz	WLANs and WAN
Nornikman et al. [23]	MPA design	Single Complementary Split-Ring Resonator (SCSRR)	Acceptable return loss, impedance bandwidth, radiation pattern, and resonant frequency	
Ouedraogo et al. [24]	metamaterial-inspired	miniaturization of patch antennas	Improves the BW to an substantial amount	
Chen et al. [25]	metamaterial-based sensing		detection mechanism, sensitive to different types of metamaterials-based sensors.	As sensors & detection mechanism
Patel and Kosta [26]	Square patch antenna, corner curtailed	DNG metamaterial		Wireless network utilization
Wang et al. [27]	composite microstrip patch with metamaterial put in it	The ZRI metamaterial, which can collect electromagnetic beams, is situated 42 mm above a traditional rectangular MPA..	With increased gain, the metamaterial attains zero refraction between 3.51 and 3.57 GHz.	
Dawar et al. [28]	microstrip patch antenna in miniaturized form	72% miniaturization can be achieved with reduced bandwidth		GPS, WLAN, and satellite communication
Rao et al. [29]	Metamaterial is used to increase the coplanar waveguide (CPW) performance which feed the circularly polarized (CP) antenna			Local and Wide Area Networks and satellite applications
A. A. Althuwayb [30]	microstrip patch antenna	utilizing parasitic components and DGS to build a small UWB multiband antenna	five resonance frequencies starting from 0.92 GHz to 7.9 GHz, 80.5% wide BW with DGS.	Used for WLAN/WiMAX, GSM (890–966 MHz) and multiband applications.
Moniruzzaman et al. [31]	The metamaterial used here has split ring resonator (CCI-SRR) structure with cross coupled interlink.	symmetric pattern Epsilon Negative (ENG) with high EMR, near-zero refractive index and negative	this antenna shows enhanced performance for microwave devices in C, X and Ku-bands	Satellite and Radar communication

		permittivity		
Mahfazur Rahman et al. [32]	MTM structure	high EMR as 10.95 has negative permittivity, permittivity, and refractive index	Resonances occurs in between 3.424GHz ~ 16.848GHz.	multi-band wireless communication systems
M.T. Islam et al.[1]		meander-lines-based epsilon negative (ENG) MTM is used. High EMR and NZI are achieved.	The gain of multiband microwave antenna is enhanced.	multiband microwave applications
Hasan Md. Mhedi et al. [33]	A wide band-stop metamaterial	Supports two distinct bands in microwave range. These bands are achieved with extended shielding	shielding undesired electromagnetic radiation.	EMI shielding is used in the C- and X-band
Md. Mhedi Hasan et al [34]	MTM antenna	double negative (DNG) metamaterial (MM)	the antenna gain and directivity are increased by 1.5 and 1.84 dBi respectively	sub-6 GHz 5G antenna
Arshad Karimbu Vallappil et al [35]	MTM antenna	different radiator structures (Triangular-rectangular patches,CSRR) at the top and complete ground plane and a 3x3 cross-slot MTM structure at the bottom are used	60% smaller size than a standard MPA.Gain/BW of 100 MHz/2.6 dBi and700 MHz/2.3dBi, respectively	5G IDAS application

VII. Performances of Metamaterial Antenna Compared to the Conventional Antenna

The three important points on the basis of which the performance of a metamaterial antenna should be compared with conventional antenna are:

A. *Antenna miniaturization*

Minimizing antennas is crucial for reducing the size of wearable, IoT, mobile, and aerial devices, as space constraints prevent the use of big antennas.

Electrically tiny antennas, or ESAs, have garnered a lot of attention because of their small size and low profile, which makes them ideal for a range of applications. Although ESAs satisfy the requirement for small transceivers, their bandwidth and radiation efficiency η are typically compromised. To get around these constraints and improve the radiation characteristics, tiny antennas based on metamaterials were developed. [12]

B. *Gain enhancement*

To increase the signal-to-noise ratio (SNR), lower interference, and increase the range of point-to-point communication systems, gain enhancement of the antenna is essential.

One of the most crucial aspects of an antenna is its gain, particularly for radar systems and fixed point-to-point communications. With a given broadcast power, high gain antennas can increase communication range and exhibit greater resistance to interference. In order to maximise gain, electrically large antennas or antenna arrays with several radiating elements are typically used because an antenna's directivity is a function of its aperture [36]. Additionally, the relationship between antenna size and directivity makes it impossible to use small antennas for a number of applications where a high gain is necessary. It becomes evident how challenging it is to create ultra-compact and high-gain antenna platforms. Consequently, metamaterial superstrates, lenses, and radomes have been introduced as a practical, cost-effective alternative for increasing gain without appreciably changing the antenna's volume in recent years.

Gain enhancement can be achieved through two primary metamaterial-based approaches.:

- Placement of zero-index materials materials as superstrate.
- Deployment of AMC surfaces in close proximity of the radiators.
- positioning metamaterial lenses with a gradient refractive index (GRIN) in front of the antenna.

C. *Isolation*

In order to minimize the coupling that reduces the multi-antenna system's performance, antenna isolation is essential.

The SNG and DNG media provide good isolation and they are a clever, low-profile way to achieve sufficient decoupling. In actuality, they neither significantly change the antenna's characteristics nor make it larger [12].

VIII. USAGE OF META MATERIALS

Metamaterials are also used in monopoles, dipoles, absorbers, microstrip antennas, planar and metallic waveguides, and other structures [37]. Furthermore, a range of tiny microwave components, including filters, phase shifters, and couplers, can be made employing the concepts of composite right- and left-handed transmission lines using forward and backward wave propagation [38]. Because metamaterials can enhance microwave device performance, demand for them is growing daily. Furthermore, low-cost, compact metamaterial development is motivated by state-of-the-art manufacturing technology. In the future, it is reasonable to assume that meta resonator loaded antennas will work towards multifunction, multiband frequency, band notching, and broadband capabilities like 5G or 6G. Because of their special qualities, metamaterials-based antennas provide a fresh way to achieve these objectives. In future metamaterials will be used in the design of the reflector of the anenna with a improved gain, bandwidth and compact size which is suitable for sub-6 GHz 5G applications.

The global market for metamaterials is expected to grow significantly because of its necessity for applications in communication antenna, such as sensors, displays, solar panels, windscreens, radio imaging, medical imaging, radar systems in self-driving cars, acoustics, and radars [39].

IX. CONCLUSION

Metamaterials are a promising solution for improving antenna performance. They possess distinct electromagnetic properties that can be deliberately designed to manipulate and control the movement of electromagnetic waves. By incorporating metamaterial structures into the design of patch antennas, it is feasible to attain support for broad frequency ranges, to provide compact size and enhance the antenna gain, increased efficiency, and stable radiation pattern. This study aims to present a detail survey of the fact how metamaterial anntenas are different from the conventional antennas, what are the improvements and developments of different metamaterial patch antennas considering their structure and performances in course of time and how metamaterials with different structural symmetry can contribute to it. A deep insight into the metamaterial structures and their use in the patch antenna will pave the way for the development of effective use of antenna in future wireless communication.

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