

Tailoring Electromagnetic Wave Behaviour Using Metamaterials: From Fundamental Physics to Modern Applications

Sangeeta Kumari

Research Scholar, Department of ECE, BIT Sindri, Jharkhand University of Technology, Ranchi, Jharkhand, India

ABSTRACT: Day by Day researchers are developing new techniques to enhance antenna parameters. 5G uses spectrum in LTE frequency range and also in mm wave band, which greatly enhances the amount of Band Width. Maxwells equations deals with the behaviors of EM wave in any medium. And metamaterials deal with unconventional wave manipulation inside the medium. Material characteristics, permeability and permittivity can be controlled artificially. As electric flux density depends on electric field as well as on polarization vector P. So in metamaterial current distribution can be controlled in 2D and 3D structures periodically, or able to control polarization behaviors. There is simultaneous improvement of radiating and scattering performance by loading metamaterial in microstrip patch antenna. There are three loading manner, superstrate loading, coplanar loading and cavity ground loading techniques. In this paper, improvement in polarization property of antenna is discussed by loading metamaterial dielectric.

I. INTRODUCTION

Metamaterials are engineered/manmade which are designed by engineers. The emergence of metamaterials has drastically changed the world of electronic applications. This artificial material could have potential to bring technological changes in every field of engineering, with the potential to bring transformational changes. A material whose properties solely depends on their structure rather than its composition are metamaterial. So by changing the composition of material it enable us to manipulate the permittivity and permeability of material for optimizing the radiating properties of antenna and thereby increasing its gain and efficiency. Recently, due to the greater demand of metamaterial because of its behavior there has been more interest in both experimental and theoretical studies. Many properties and potential applications of left-handed material have been explored and analyzed theoretically and experimentally [1]. Metamaterial (MM), defined by Walser in 2001 [9], is a combination of two terms, “meta” and “material,” meta means beyond and material means wide range of substances, including metals plastics, ceramics, fabric and more. Metamaterials are actually three-dimensional or two-dimensional periodically designed macroscopic composites that display excellent properties extending from microwave to optical frequencies and finds wide range of its application in mechanical, electrical and electronics field. The properties unavailable in conventional materials include the inverse Doppler effect, negative refractive index, perfect lensing, left-handed behavior, electromagnetic wave cloaking, and perfect absorption [2-5]. Metamaterial antennas actually increases the performance of electrically small antennas used for 5G, 6G, Wi-Fi are a type of antennas which uses metamaterials to increase the performance parameters like gain, efficiency and directivity of electrically small antenna systems[1]. The purpose of these small compact antennas is to radiate electromagnetic energy into free space. However, this class of antennas are engineered artificially with metamaterial which are structured in periodic form to produce unusual electromagnetic as well as physical properties. So antenna system incorporating metamaterial enhance radiated power. Recently the choice for designing antenna system which can be assembled to very small space is metamaterial as these antennas radiate 95 percent of input radio signal. As theoretically the standard antenna needs to be at least half the wavelength of the input signal to operate efficiently. Metamaterial permits the size of antenna to be smaller and in contrast experimentally it covers wider frequency range. At 300 MHz, for instance, an antenna would need to be half a meter long. In contrast, experimental metamaterial antennas are as small as one-fiftieth of a wavelength, and could have further decreases in size and uses space for space-constrained cases. So, this smaller antenna regrouped into array to enhance the gain of radiating antennas. Furthermore, metamaterials negative refractive index focuses electromagnetic radiation by a flat lens antennas incorporated with metamaterials [7].

The uses of metamaterial in antenna can improve characteristics like

- (i) Gain
- (ii) Directivity
- (iii) Band Width

And simultaneously add new features l

1.1 THE LEFT-HANDED METAMATERIALS

Metamaterials are the homogeneous artificial structure [8] that are artificially arranged into periodic structures to to give electromagnetic property not find naturally. Lattice constants of the periodic structure in Metamaterial are much smaller than the electromagnetic waves. So the metamaterial provides unique electromagnetic property never occurring with naturally occurring materials. The electromagnetic property of material solely depends on the four maxwells equation. The electrical and magnetic behavior of electromagnetic wave characterizes permittivity and permeability respectively. The four possible combinations of permittivity and permeability are shown in fig.1

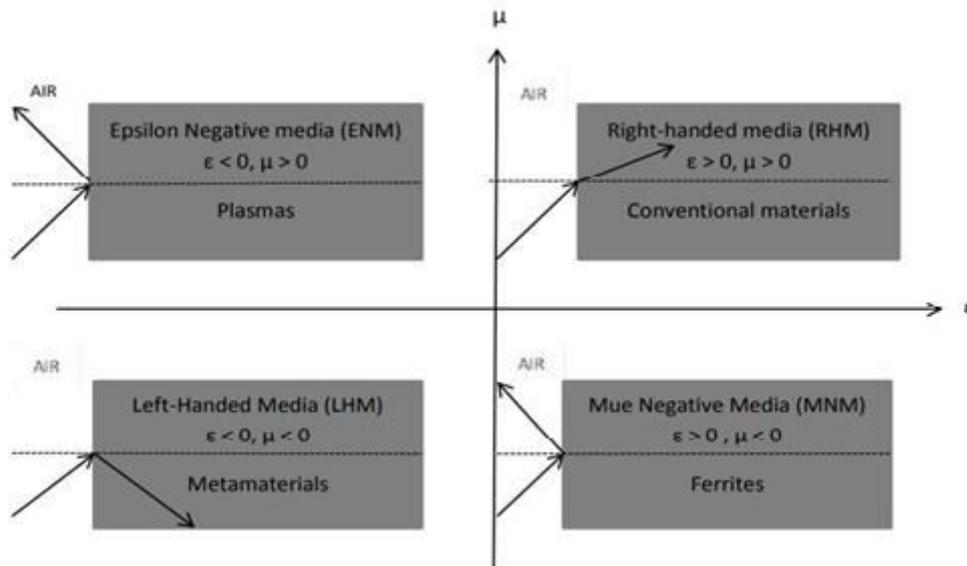


Figure 1. Possible Combination

The materials are classified into four types as shown in fig 1 depending on the value of ϵ and μ which are explained as follows:

As shown in the fig 1, when the electromagnetic wave incident from air to plasmas and ferrites it gets reflected so the wave attenuates. But we know for conventional materials positive refraction takes place and for metamaterial negative refraction takes place respectively [9]. As in the above fig.1 materials that reside in quadrant 1 ,2 ,3 is known to exist naturally, however naturally occurring materials having both the permeability and permittivity have not discovered yet. In 1967 Victor Veselago speculated about the existence of such double negative materials in his paper entitled “The electrodynamics of substances with simultaneously negative permittivity and negative permeability”. Vassalage discussed the unique phenomena occurring for an electromagnetic wave in a double negative material.

Backward Waves: Since the electromagnetic waves in DNG material form a Left-Handed triad, and the double negative index material are generally referred as LH materials. In the case of LH materials the power flows away from the source (group velocity is positive) while its phase front travels towards the source (phase velocity is negative) [10].so the Left Handed materials supports backward wave i.e. waves are antiparallel having opposite group and phase velocities.

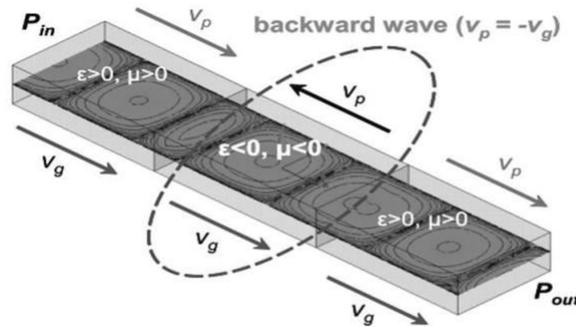


Figure 2. Backward wave in LH materials

Negative Refractive Index- Metamaterials are artificial material which exhibit negative permittivity, negative permeability and negative refractive index, [11] which is not found in readily available materials. Metamaterials have negative refractive index that is a reversal of Snell’s law, hence called as negative index materials. Due to negative refractive index, the group and phase velocities of electromagnetic wave appear in opposite direction such that the direction of propagation is reversed with respect to the energy flow direction. Negative μ_r and ϵ_r occur in nature, but not simultaneously [12]. negative refraction can be achieved when both μ_r

$$\begin{aligned}
 n &= \sqrt{(-\epsilon_r)(-\mu_r)} \\
 &= \sqrt{\epsilon_r(e^{-j\pi})\mu_r(e^{-j\pi})} \\
 &= \sqrt{\epsilon_r\mu_r}(e^{-j\pi})^{1/2}(e^{-j\pi})^{1/2} \\
 &= \sqrt{\epsilon_r\mu_r}(e^{-j\pi/2}e^{-j\pi/2}) \\
 &= -1\sqrt{\epsilon_r\mu_r} < 0 \dots \dots \dots (i)
 \end{aligned}$$

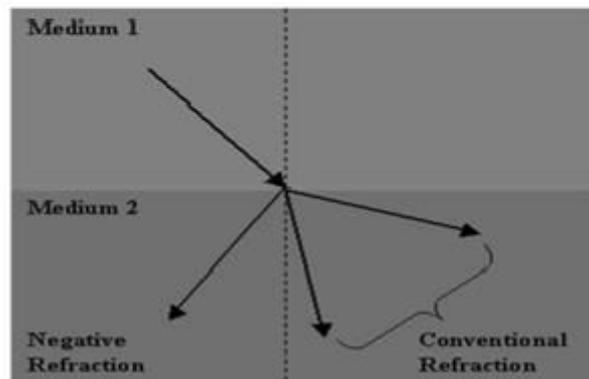


Figure 3.

HOW ARE LH MATERIALS REALIZED?

Early metamaterials relied on a combination of Split-ring resonators (SSRs) and conducting wires or ports. SSRs are used to obtain desired relative permeability μ_r and cut off frequencies [12]. Conducting posts are polarized by the electric field, generating the desired relative permittivity, ϵ_r for all frequencies below a certain cut-off frequency. As shown in Fig. 4(a) all thin wires have same radius “r” and are separated by a distance “a” from each other.



Figure.4(a) SRR

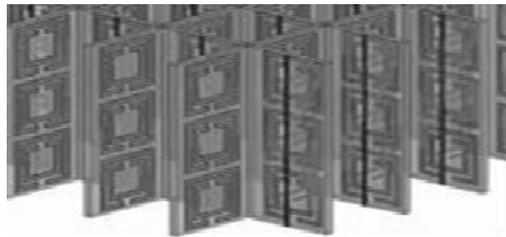


Figure.4(b) metal wire arrays of SRR and metal wire to form a metamaterial.

In his paper [13], Vesalage also stated that although LH materials do not exist in nature, they can be artificially constructed. Veselago concluded that the realization of a LH Metamaterial will be possible with the discovery or construction of an isotropic negative μ material. When Veselago published his paper, materials with $\mu < 0$ were not known to exist. For 30 years, Veselago's paper and its theory was not investigated any further. Interest in Veselago's paper and LH materials began to materialize when Professor Pendry, at Imperial College demonstrated the first non-ferrite negative μ Metamaterial based on split ring resonators (SRRs) in 1998. Pendry's SRR was the corner stone of the first bulk LH Metamaterial realization by a group at University of California, San Diego (UCSD) in 2000. The UCSD's LH Metamaterial was based on combining a SRR (negative μ) with a metal wire (negative ϵ).

II. DESIGN UNITS

The Transmission Line Approach CRLH Unit Cell

The CRLH unit cell [14] is equivalent to the combination of series capacitors and shunt inductors respectively represented via (cylindrical metal generally perfect electric conductor and a microstrip gaps and this is used to realize metamaterial and is called transmission line approach to realize metamaterials. Metamaterial realized using unit cell is called transmission line approach. The transmission line approach to design a metamaterial is made by shunt inductance and series capacitance. The via is used to short the ground plane and the patch and behaves like shunt inductor and series capacitors and can be formed by the gap created by the patches and the ground plane.

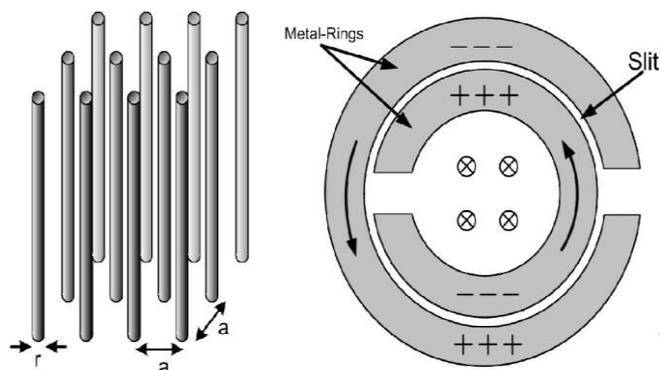


Figure 5. Slit and thin wires ring in a circular split ring resonator

VESELAGO AND NEGATIVE INDEX

All transparent or translucent materials that we know possess positive refractive index i.e., a refractive index that is greater than zero. However, there is no any naturally occurring material which has negative refractive index. This was first invented by Victor Veselago a Russian Physicist. In the year 1968 Veselago published the behavior of electromagnetic waves with the material having negative permeability and negative permittivity. These are the commonly used parameters to describe the behavior of polarization of material in presence of electromagnetic waves. Maxwell's equations relate the permittivity and the permeability to the refractive index. There are four maxwells equations

$$\nabla \times E = -j\omega\mu H \text{ -----(1)}$$

$$\nabla \times H = j\omega\varepsilon E \text{ ----- (2)}$$

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. The sign of the index is usually taken as positive. However, Veselago showed that if a medium has both negative permittivity and negative permeability, this convention must be reversed: we must choose the negative sign of the square root.

As per the above equations refractive index is negative, the velocity of the wave is given by c/n where c is the speed of light in vaccum and n is the refractive index. This negative refractive index shows the wave reverse its direction and travels backward towards the source [15].as in case of propagation of waves energy is incident on the material from left and the energy in the material from the left, the energy in the material should likewise travel to the right away from the interface. The ratio c/n is called the phase velocity and determines how the peaks(zeros) of a wave pass a given point in a time. The group, energy, signal and front velocities differ from the phase velocity.

III. TYPES OF METAMATERIALS

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

- 1.Electromagnetic Metamaterials (EM)
2. Photonic Metamaterials (PM)
3. Acoustic Metamaterials (AM)
4. Mechanical Metamaterials (MM)

IV. CONCLUSION

During the literature survey, it has been observed that metamaterial has great potential in different areas of engineering. It offers wide angle scanning and excellent beam performance. It offers electrically controlled polarization. Metamaterial antenna design has five times smaller design with wider bandwidth. It does not require active phase shifters or amplifiers unlike traditional phased array antenna. It consumes very low power. So various design and analysis of metamaterial designed structures like filters, absorber, antenna and it finds various applications in microwave and different areas of engineering.

Metamaterial is a category of engineered artificial material composed of subwavelength inclusions with rationally designed shapes, sizes and composition.

The vast need of data with respect to smart phone users has attracted scientists and engineers from both academia and industry to design hardware at 28 GHz and beyond for future 5G wireless systems.

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AUTHOR'S BIOGRAPHY



Sangeeta Kumari received her degree in Electronics & Communication Engineering from Magadh University, Bodhgaya. M.E Degree in Electrical Engineering from BIT Sindri, Dhanbad. Presently pursuing PhD degree in Electronics & Communication Engineering from BIT Sindri under Jharkhand University of Technology, Ranchi. She is currently working as Assistant Professor (Contract) in the Department of ECE, BIT Sindri, Dhanbad. She has teaching experience of 19 years.



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