METAMATERIAL BASED PATCH ANTENNA FOR SATELLITE COMMUNICATION

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ABSTRACT

From the past few years, the research and development in the field of metamaterial is on its peak. Metamaterials are artificial materials designed to have the properties which are not observed in naturally occurring materials. Metamaterials exhibits negative permittivity and negative permeability as well. They are engineered materials with unique properties that go beyond what nature provides us. This paper presents a review of metamaterials and the different forms of it, their own unique properties and advantages. This paper also presents the design of electrically small metamaterial antenna (ESMA). The proposed antenna is designed to operate at a frequency of 2.46 GHz which is a versatile option for various short-range wireless communication applications where cost-effectiveness, moderate penetration, and ease of use are priorities. It is also Used for S-band satellite radio, mobile satellite services, and some data transmission. The proposed design is suitable for applications where size is a critical factor, such as in small satellite communication systems. The proposed design can be easily scaled to other frequency bands with appropriate parameter tuning. Finally, the proposed design is validated through measurement results, which show good agreement with the simulation results

Keywords- Metamaterials (MML), Electrically Small Metamaterial Antenna (ESMA), negative-index material (NIM).

INTRODUCTION

The word “Metamaterial” is an amalgamation of “meta” and “material”, Meta is a Greek word which betokens something beyond, altered, transmuted or something advance. Metamaterials are incipient unreal matters with the eccentric EM properties that are not found in natural occurring materials. Betokens metamaterials are the artificial structures designed to have properties not obtainable in nature. The natural materials have positive electrical permittivity, magnetic permeability, and index of refraction whereas metamaterials have negative values for these parameters. With these metamaterials new kind of the microwave component/devices and miniaturized antennas can be created for defense industries and wireless communication. The metamaterials are first observed and theoretically proposed by the Russian physicist Victor Veselago in 1968. These are the materials that extract their properties from their structure rather than the material of which they are composed of. These materials have negative value of electrical permittivity as well as electrical permeability due to which the metamaterials have been termed as negative index materials (NIM) or double negative (DNG) media or left-handed materials (LHM) or backward wave (BW) media- having all these parameters negative. Negative magnetic permeability could be achieved using an array of split-ring resonators (SSR). 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. Shelby et al showed negative refraction experimentally for the first time using a metamaterial with repeated unit cells of split ring resonators (SRR) and copper strips. Wu et al proposed three structures including symmetrical ring, omega and S structure for SRRs. Many researchers have worked on metamaterials to extract their potential in various fields. This paper summarizes history of metamaterials, its classification, advantages and applications.

Classification Of Metamaterials According to Their Physical Properties

The properties of the material define the electromagnetic properties associated with it. These properties define the macroscopic parameters permittivity ε and permeability μ of materials. On the basis of permittivity ε and permeability μ Maintaining the Integrity of the Specifications

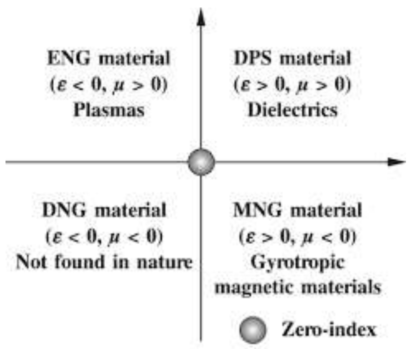

Fig1: Quadrants for properties of materials

A. **Double Positive (DPS) Material**: The materials which have both permittivity & permeability greater than zero (ε > 0, μ > 0) are called as double positive (DPS) materials. Most occurring media (e.g. dielectrics) fall under this designation.
B. **Epsilon Negative (ENG) Material**: If a material has permittivity less than zero and permeability greater than zero (ε < 0, μ > 0) it is called as epsilon negative (ENG) material. In certain frequency regimes, many plasmas exhibit these characteristics.
C. **Mu Negative (MNG)Material:** If a material has permittivity greater than zero & permeability less than zero (ε > 0, μ < 0) it is called as mu negative (MNG) material. In certain frequency regimes, some gyro tropic material exhibits these characteristics.
D. **Double Negative (DNG) Material:** If a material has permittivity & permeability less than zero (ε < 0, μ < 0) it is termed as double negative (DNG) material. This class of materials can only been produced artificially.

I. **What Can be Achieved**

A. Improvement in gain of patch antenna: The surface waves are the modes of propagation supported by a grounded substrate. In antennas, the surface waves are spread out in a cylindrical fashion around the excitation point. Their field amplitudes decrease with the distance (inversely proportional to square root of the distance). The surface wave excitation occurs on all the substrate-based antennas. In microstrip antennas, TE as well as TM waves are generated, in which both the electric and magnetic field exists but in a different fashion. This results into a loss and the reduction of gain. Metamaterials have simultaneous negative permittivity and permeability due to which they are capable of absorbing the surface waves and minimizes the leakage of radiation

$$\%BW = \frac{A \times h}{\lambda_o \sqrt{\epsilon_r}} \sqrt{\frac{W}{L}} \qquad (1)$$

B. Improvement in bandwidth of patch antenna: The bandwidth (BW) of patch antenna is given by the BW is directly proportional to the height of dielectric substrate and inversely proportional to the square root of the dielectric constant, keeping L and W of patch constant, A is already a constant, ℨ0 will remain same for given f0. Thus, to increase bandwidth, the dielectric should have more height and a lesser permittivity. By adding a metamaterial cover to the patch antenna, the height increases and the permittivity also gets reduced, and so the bandwidth increases.

C. Improvement in directivity of patch antenna: The directivity is the figure of merit of an antenna. It measures the power intensity of an antenna that radiates in the direction of its strongest emission versus the power density of an isotropic radiator. When Left-Handed Materials (LHM) is used as substrates in patch antennas, it acts like a lens which is almost same or thinner than the waves it focuses. Thus, the radiant energy emanated by the patch antenna is focused and concentrated in one particular direction due to which there is an improvement in the directivity.

D. Miniaturization i.e. reduction of size of patch antenna: The metamaterial loading is an ideal approach in which a metamaterial unit cell or array is placed very close to the patch due to which there is a very strong magnetic coupling between the two surfaces. The electric field is also introduced in it. After loading, the antenna becomes resonant at a lower frequency and so, it becomes electrically small. It is known as Electrically Small Antenna (ESA)

What Can be Applications

Patch antennas with metamaterials can find applications in various fields, thanks to their unique properties and capabilities. Metamaterials are engineered materials designed to have properties not found in nature, and they can be used to enhance the performance of patch antennas in several ways. Here are some applications of patch antennas using metamaterials:

Miniaturization: Metamaterials can be used to reduce the size of patch antennas while maintaining their resonant frequency. This is particularly useful in applications where space constraints are a concern, such as in mobile devices and compact communication systems.

Improved bandwidth: Metamaterials can help expand the operating bandwidth of patch antennas. By integrating metamaterial structures, it's possible to achieve broader frequency coverage, which is advantageous in applications where multiple frequencies need to be supported.

Enhanced gain and directivity: Metamaterials can be designed to boost the gain and directivity of patch antennas. This can be crucial in long-range communication systems, such as satellite communication or radar, where signal strength and coverage are essential.

Beam steering: Metamaterial-based patch antennas can be engineered to enable beam steering. This is especially valuable in phased-array antennas used in radar and communication systems. By controlling the phase of the electromagnetic waves through metamaterials, the antenna's beam direction can be adjusted without physically repositioning the antenna.

Cloaking and low-profile applications: Metamaterials can be used to design patch antennas that are almost invisible or low-profile. In applications where aesthetics and concealment are important, like in military or architectural contexts, metamaterials can help create antennas that blend seamlessly into their surroundings.

Polarization control: Metamaterials can be employed to control the polarization properties of patch antennas, allowing for dual-polarization or circular-polarization configurations. This is valuable in applications such as satellite communication and wireless networks.

Gain enhancement in low-permittivity substrates: Patch antennas typically have limited gain when placed on low-permittivity substrates, but metamaterials can be used to enhance the gain under such conditions. This can be advantageous in applications where low-loss dielectric materials are preferred.
Reduced mutual coupling: In antenna arrays, the proximity of individual antennas can lead to mutual coupling, which can degrade the overall system performance. Metamaterial-based techniques can mitigate this issue by isolating adjacent antennas and reducing interference.

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Frequency reconfigurability: Metamaterial-based patch antennas can be designed to change their resonant frequency dynamically. This reconfigurability is valuable in software-defined radio systems and adaptive communication networks.

Cross-polarization suppression: Metamaterial structures can be used to suppress unwanted cross-polarization radiation in patch antennas, leading to improved performance and reduced interference in polarized communication systems.

LITERATURE REVIEW

Metamaterials are composite media that can be engineered to exhibit unique electromagnetic properties. Metamaterials allow extreme control over optical fields, enabling effects such as negative refraction to be realized and have properties not found in naturally occurring substances. These materials are designed at the micro- or nano-scale, with structures and arrangements that give them unique and often counterintuitive properties. Metamaterials can be composed of various materials, such as metals, ceramics, polymers, or composites.

The distinctive feature of metamaterials is that their properties are determined by their structure rather than their composition. This allows researchers to manipulate and control properties like electromagnetic behaviour, sound propagation, and thermal conductivity in ways that were previously not possible with conventional materials. Metamaterials have led to the development of numerous groundbreaking applications, including: Electromagnetic Cloaking, Energy Harvesting and Absorption, Medical imaging, Microwave and Antenna Engineering. Metamaterials often challenge conventional material properties and have opened new possibilities in engineering and science. Metamaterials are used in antennas to increase performance of miniaturized antenna systems. The metamaterials antennas are used to increase the gain of an antenna because it has a unique band gap features and periodic structures. In small conventional antennas the most of the wavelength reflects the signal back to the source. But in the metamaterial antenna, they have the structure that stores and re-radiates energy which makes its size small and behaves as larger antenna.

a) The core concept of metamaterial design is to craft materials by using artificially designed and fabricated structural units to achieve the desired properties and functionalities. the classification of metamaterials was introduced by Veselago based on its effect of permittivity (ε) and permeability (μ) of a homogeneous material.

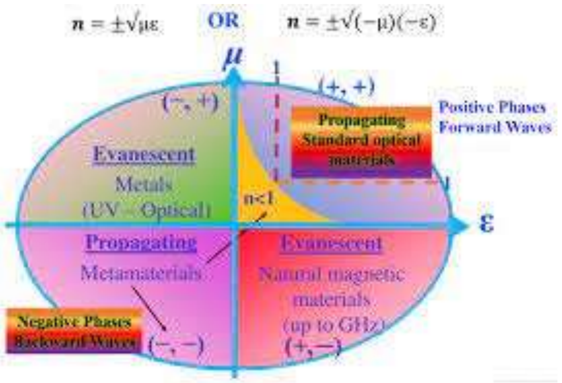

Fig2: Metamaterial's classification based on their permittivity (ε) and permeability (μ).

Metamaterials and functional material development strategies are focused on the structures of the matter itself, which has led to unconventional and unique electromagnetic properties through the manipulation of light—and in a more general picture the electromagnetic waves—in widespread manner. Metamaterial's nanostructures have precise shape, geometry, size, direction and arrangement.

b) **Electromagnetic Metamaterials**: Electromagnetic metamaterials (EM) are the materials which 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 randoms.

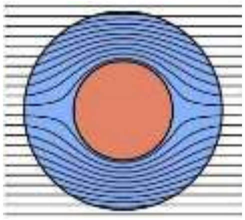

Fig 3: Electromagnetic metamaterials

c) Role Of Metamaterials in Patch Antenna

Many exotic applications of the metamaterials exist. Many researchers are endeavouring to amend the accomplishment of microwave, wireless communications, microelectronics, and optical scheme utilizing these incipient metamaterials. By utilizing metamaterials, the radiated power of the antenna could be enhanced.

The main features of metamaterial like negative permittivity and permeability can be exploited for making electrically small, highly directive, and reconfigurable antennas. These antennas also demonstrate the improved efficiency, bandwidth performance and ameliorate the beam scanning range of antenna arrays. These antennas also support navigation systems, communication links, surveillance sensors and command & control systems. Light emanating is rejected and controlled by wide angles, for aerospace applications using nano-composites utilizing metamaterial technology.

Thin film technology advanced with metamaterial nano-composites is utilized to amplify the solar cell efficiency by amassing light from wide angles and by absorbing it over the spectrum of interest. The Extraordinary properties of MTMs and their latent applications in cloaking expeditiously drew attention from agencies like DARPA & NATO. Immensely colossal scale metamaterials with customized electromagnetic properties have been used for shipboard applications too.

METHODOLOGY

For designing the metamaterial inspired patch antenna, the tool used is ANSYS HFSS for simulation and designing.

Fig4: Journey from Square patch antenna to metamaterial inspired patch antenna

Square patch Antenna and Metamaterial inspired patch Antenna

A square patch antenna with an FR4 substrate and a lumped port feed is a common design for various wireless communication applications operating in the 2.4 GHz Industrial, satellite (s-band), Scientific, and Medical (ISM) band.

Components

A. Square Patch Antenna

1. Made of a conductive material like copper or gold.
2. The size of the patch determines the resonant frequency of the antenna. For 2.4 GHz operation on FR4 substrate, the patch size needs to be calculated based on the dielectric constant of FR4

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(typically around 4.4).

3. Online calculators and design tools can be used to determine the optimal patch size for the desired frequency.
4. Here, in this project, I have taken (28 mm (about 1.1 in) * 28mm) of height 1.6 mm.

B. FR4 Substrate:

5. FR4 (Flame Retardant 4) is a common choice for microwave circuits due to its low cost, ease of fabrication, and moderate dielectric constant.
6. The thickness of the substrate also affects the resonant frequency and radiation pattern. Here it is of 1.6mm thick.
7. Standard FR4 thicknesses are readily available, and the choice depends on the desired antenna characteristics.
8. The dimension of the substrate is of (48mm*48mm*1.6mm)

C. Lumped Port Feed

1. A simple and widely used feeding technique for microstrip antennas.
2. A coaxial cable or microstrip line feeds the antenna at a specific point on the patch.
3. The location of the feed point (typically centered or offset from the center) plays a crucial role in impedance matching and radiation pattern.
4. In this project it is applied at the centre having 18 mm on y-axis.

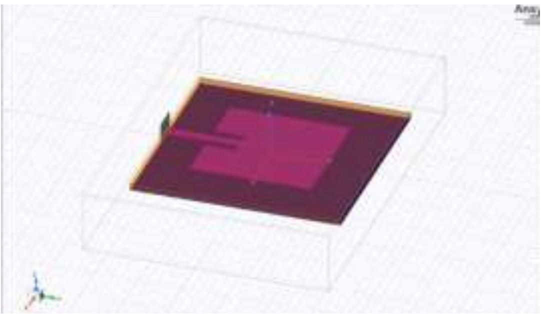

Figure 5: Square patch antenna

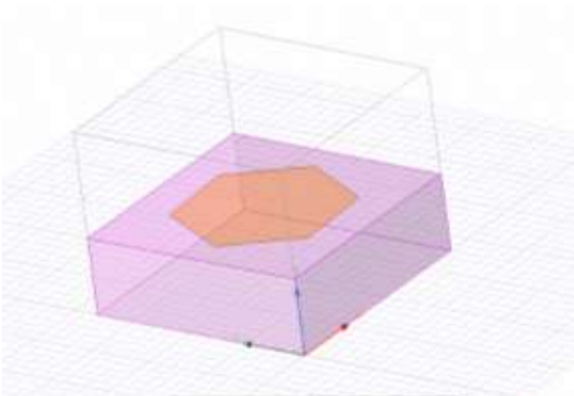

Figure 6: hexagonal unit cell

Design Consideration

A) **Impedance Matching:** The impedance of the antenna (typically around 50 ohms for most applications) needs to be matched to the impedance of the transmission line (usually 50 ohms) to ensure efficient power transfer. This can be achieved by adjusting the feed point location or adding matching elements like inductors or capacitors.

B) **Bandwidth:** Square patch antennas inherently have a narrow bandwidth. Techniques like adding slots or using a thicker substrate can be employed to improve bandwidth if needed for the specific application.

a. Here, in the project the bandwidth is 69MHz.

C) **Radiation Pattern:** The square patch antenna typically radiates in the plane of the substrate with a broadside pattern (maximum radiation perpendicular to the substrate). The feed point location and patch modifications can be used to fine-tune the radiation pattern for specific requirements.

(a) (b)

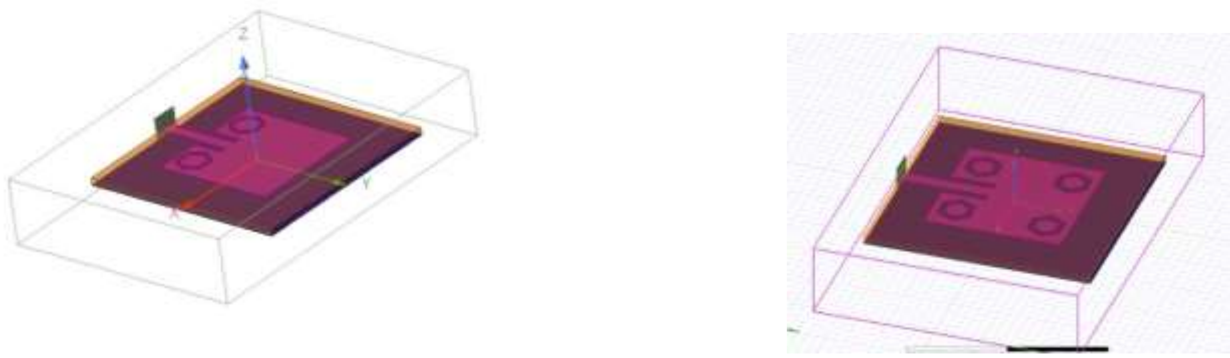

Figure 7: Metamaterial inspired square patch antenna (a) 2 hexagons (b) 4 hexagons shape.

Applications:

Square patch antennas designed for 2.4 GHz with FR4 substrate and lumped port feed find applications in various wireless communication systems, including:

A) Wi-Fi devices (IEEE 802.11b/g/n)
B) Bluetooth communication
C) Zigbee devices
D) RFID (Radio Frequency Identification) systems
E) Industrial wireless control systems

RESULTS

The HFSS simulation of our antenna at different stages to reach the final output has been shown above.

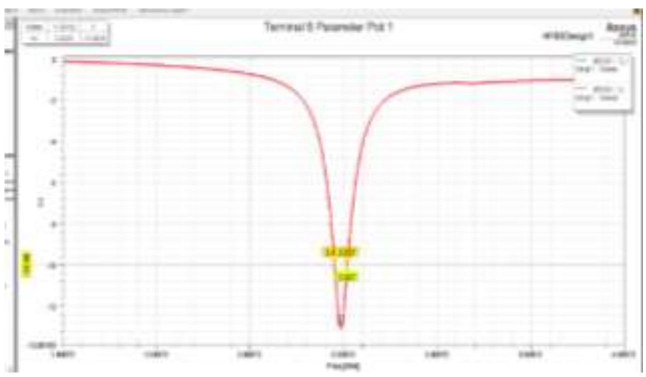

figure 8: S parameter of square patch antenna. It is clear from the above figure that the resonant frequency is 2.49 GHz

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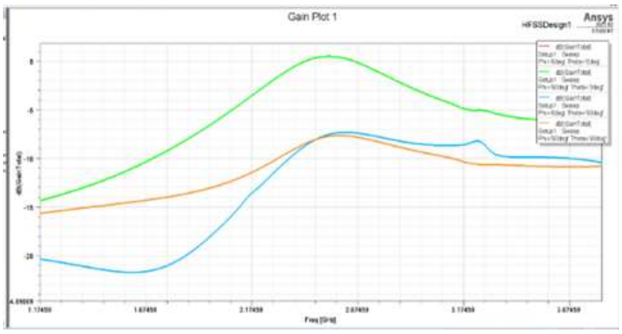

figure 9: gain plot of square patch antenna . It is clear from the above graph that at frequency = 2.4ghz , gain is 0.6 db.

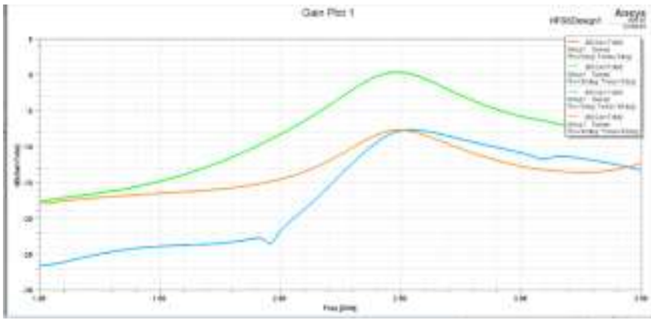

figure 10: s parameter graph for metamaterial inspired square patch antenna having frequency = 2.46ghz and having bandwidth of 69 mhz . The sharpness of the graph is due to the impedance matching

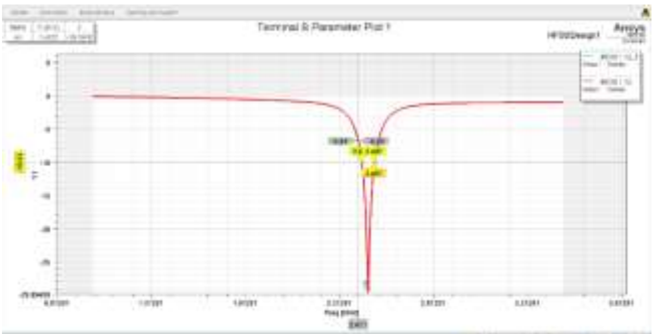

figure 11: gain plot for metamaterial inspired square patch antenna. Here at resonant frequency, gain is 0.7 db.

Figure 12: Freq vs gain plot of hexagonal unit cell

Comparison between square patch antenna and metamaterial inspired square patch antenna

Design	**S11 (Y)**	**Gain**
Square Patch Antenna	-13	0.61dB
Metamaterial inspired square antenna	-29	0.70 dB

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