Metamaterial Based Patch Antenna forWireless Communication: A Review

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***Abstract*— This decisive evaluation discusses the review of use of metamaterial (MTM) in microstrip patch antenna design. The extensive properties of metamaterial have been used to enhance the antenna performance in terms of gain, bandwidth, directivity and size reduction. The electromagnetic properties of metamaterial have attracted a lot of attention in the scientific community. Metamaterial is an artificial material having negative permeability and or negative permittivity. MTM is a kind of material whose properties cannot be obtained from natural materials. These incomparable electromagnetic properties make MTM popular and accepted by the engineers, researchers in antenna. It is possible to reduce the size of a patch antenna while maintaining acceptable bandwidth and power levels using metamaterials. In this review paper, we first overview the metamaterial, its types and then the application of metamaterial in Microstrip patch antennas over the last 13-15 years.**

***Index Terms*— Patch Antenna, Superstrate, Metamaterial, SRR, CSRR**

I. INTRODUCTION

Wireless communication research has been inspired by the advent of new technologies and the exponential increase in subscriber demand. The antenna community serves an important role in this regard. Since the antenna is the most critical component of a wireless network, it must be carefully designed and deployed. The ever domain of communicational inventionshave seen are evolution with pagers to mobile phones and wire lines to wire fewer ways [1,2]. The discovery of antenna's multiband nature was one of the first revolutions in the development of antennas. Antennas such as a monopole, dipole, DRA, patch, and PIFA are among the many types used to support multifunctional wireless systems [3, 4]. Multiband antennas boost wireless quality and application coverage on a single device because each portion is active for a distinct band. Multiband antennas cover numerous applications and are small, affordable, and high-speed [5-7].

Metamaterials have been increasingly popular in recent years as a means of creating tiny resonant multiband antennas. Metamaterials have many properties, and many of these features are related to significant parts of antenna design. The employment of metamaterialsin the antenna allows for small size and multiband nature. Metamaterials are artificially designed materials with properties different from the naturally occurring materials. Electric permittivity (ε) and magnetic permeability (μ) are the two basic parameters which describethe electromagnetic property of a material or medium. Permittivity describes how a materialis affected when it is placed in electric field. And permeability describes how a material is affected in presence of magnetic field. Metamaterials may have either negative permittivity or permeability or both may be negative simultaneously. Metamaterial is an arrangement of periodic structures of unit cells in which the average size of a unit cell should be much smaller[1] than the impulsive wavelength of the light.

i.e., $a \ll \lambda$

Metamaterials are a desirable option for the design of multiband antennas due to the ability to customize ε and μ. Metamaterials' zero- index feature allows the fabrication of compact, highly efficient antennas with better gain and directivity, improving performance above traditional material-loaded antennas [8-10].

The application of metamaterial design-based antennas is the main topic of discussion in this paper. Patch antennas are currently seeing widespread adoption across a variety of microwave and wireless network applications. The use of metamaterials helps improve a variety of properties and deal with the issues of antennas, including miniaturizing the substrate's size, reducing the size of the main radiator, increasing the efficiency of radiation, controlling the bandwidth, and supporting multi-band operation.

II. METAMATERIAL

Metamaterial substrate were first studied in the early 20th century. In 1967, a Russian physicist the name Victor V. described materials with a negative index of refraction and claimed that such materials could permit light to pass through them [8]. He demonstrated the anti- parallel nature of the wave propagation and vector direction of the Poynting vector. This is the reverse of how waves travel through materials that are naturally occurring. John showed that it is possible to create metamaterial practically [9]. A negative refractive index is one of the most distinguishing characteristics of a metamaterial, which is a type of man-made substance with electromagnetic properties that do not occur in nature and its properties as shown in Fig. 1[13].

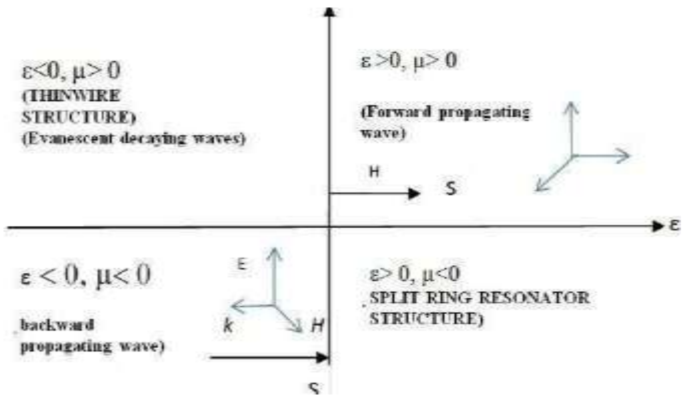

Fig. 1: Metamaterial properties for practical applications

BASIC MATHEMATICAL EQUATIONS

Taking into consideration the differential equations of Maxwell's first order,

$$\nabla \times E = -j\omega\mu H \qquad (1)$$

$$\nabla \times H = -j\omega\mu E \qquad (2)$$

Where ω represents angular frequency of EM-wave in freespace.The E and H fields for planar EM-wave can be expressed as follows

$$E = E_o e^{(-jk.r+j\omega t)} \qquad (3)$$

$$H = H_o e^{(-jk.r+j\omega t)} \qquad (4)$$

Here K representers wave vector and Equal. (1) and (2) can be expressed as follows:

$$H = H_o e^{(-jk.r+j\omega t)} \qquad (5)$$

$$k \times H = -\omega\varepsilon E \qquad (6)$$

E,H and k formaright-handed orthogonal system when ε and μ are both positive[16]. In this medium, there will be wave propagation in the forward direction. In the case where both εand μ take on simultaneously negative values, equations (5) and (6) can be rewritten as follows:

$$k \times E = -\omega|\mu|H \qquad (7)$$

$$k \times H = \omega|\varepsilon|E \qquad (8)$$

The vectors E, H, and k form an orthogonal left-handed system, and the real part of the PoyntingVector determines energy flow as follows (9):

$$S = 1/2\ E \times H^* \qquad (9)$$

Changes in permittivity and permeability do not influence the direction of energy flow, hence group velocity is positive for both left-and right-handed systems and Index refractive as given in (10):

$$n = \pm\sqrt{\varepsilon\mu} \qquad (10)$$

And Equation (11) shows the phase velocity

$$V_p = c/n \qquad (11)$$

c is light's vacuum velocity and for right-handed systems, both n and phase velocity must be a positive value. As a result, energy and wave propagate ahead in the same direction. The phase velocity is negative in a left-handed system because is negative. As a result, energy will flow in the opposite direction from the wave, causing it to travel backward. In non- uniform waveguides, it is not uncommon for backward waves to manifest themselves. Fig. 2 shows the left and right-handed systems [17-19].

(a) (b)

Fig. 2. (a) Left-hand system (b) Right-hand system [13]

DIFFERENT METAMATERIAL STRUCTURE

Circular-shape geometry

The split causes the structure to resonate at higher frequencies and increases its capacitance. The strong capacitance between the two concentric rings allows current to flow. SRRs respond to an alternating electromagnetic field by electrically shrinking. Electromagnetic solver calculations demonstrate that broadcast parallel to the SRR plane generates a dip in transmission close magnetic resonance when the applied magnetic field is orthogonal to the SRR plane. Figure 3 shows the geometry of a circular SRR with current flowing through the rings, where r is the inner ring's internal radius, g is the SRR split dimension, w is each ring's width, and d is the distance between the two concentric rings. Changing the ring parameters (ro, s, w) in Fig. 3 changes the SRRs' resonance frequency [20- 23].

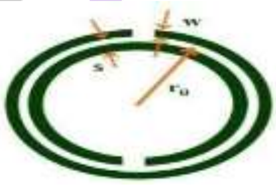

Fig. 3: Geometry of circular shape SRR [23]

Square-shape geometry

A single cell SRR is two open loops printed on a microwave dielectric circuit board. Both the metal rings and loops have a little gap between them, giving them a 'C' shape as opposed to a square form. Splitting both rings add capacitance. Due to the splits, the current in the rings doesn't find a closed passage; nonetheless, it still flows due to the gap between the two concentric rings. Due to ring splits, the structure may sustain larger resonant wavelengths. The back strip generates electric resonance and designs an LHM unit cell. Fig. 4 shows an LHM unit cell encased in a waveguide to achieve resonance [21-24**].**

Fig. 4: Square-shaped unit cell of SRR [24]

OMEGA-SHAPED GEOMETRY

The omega-shaped structure metamaterial is shown in Fig. 5 and it shows that two erect, side-by-side rings in the unit cell, not lying flat. Two particles, a circular ring and a wire strip, comprise the omega structure. Because of its ideal conducting shape and increased performance, an omega structure was chosen for the metamaterial substrate and antenna [23, 24].

Fig. 5: A unit cell of Omega structure [23]

S-SHAPED GEOMETRY

When looking at a unit cell, we see two vertical S-shaped structures, with some space between the top and the middle and the middle and bottom of the 'S.' However, the ring structure does not have any space, as illustrated in Fig. 6. There is also a magnetic resonance frequency, as well as an electric plasma frequency. Traces that create the S-pattern produce inductance, while the S-patterns on the top and bottom layers offer capacitance. Due to the lack of overlap between the top and bottom layers, the negative permeability response is modest in this scenario. However, this SRR's inductance gives only a mild negative permittivity response [23-25].

Fig. 6: A unit cell of 'S'-shaped geometry [23]

D-SHAPED GEOMETRY

D-shaped design consists of two rectangular square D types lying horizontally, face to face, with in the unit cell. Rings are stacked and non-concentric structures. The metamaterial substrate has a symmetrical ring construction because it performs better than alternative patterns. Inductance and capacitance of the symmetrical-ring structure are mostly owing to the two rings on top, while the coupling between one of the rings on the top layer is responsible for the latter. Additional capacitance is provided by the split in both rings. Fig. 7 depicts the effect of the back-side strip, which is similar to the effect of the SRR structure's strip [23,25-27].

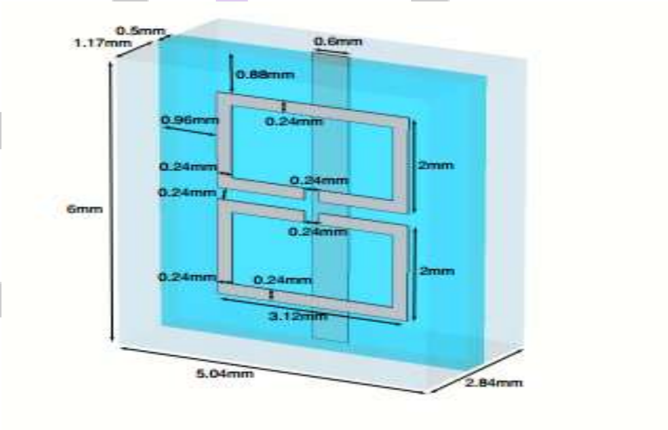

Fig. 7: A single unit cell of the Symmetrical-ring geometry [41]

CSRR

The SRR-loaded structures exhibited a limited ability to respond, because of the inadequate coupling between the conductor and SRR structure. Because of this, in [28] a new design with improved coupling is presented and it is named a complementary split-ring resonator (CSRR) as shown in Fig. 8. It is possible to create the complement of a flat metallic structure by removing all metal parts and replacing them with apertures and metal plates. With infinitely thin and perfectly conducting metal, the apertures behave as perfect magnetism.

(a)

(b)

Fig. 8: Geometry of (a) SRR and (b) CSRR [24, 25]

III. ANALYSIS OF METAMATERIAL BASED ANTENNAS

Antenna designers have taken a keen interest in metamaterials because of their unique properties. They have been used widely in antenna applications to provide more bandwidth, increased gain, and smaller size. Metamaterials have been used in a variety of ways to enhance antenna performance over the last ten years. Metamaterial-based antennas improve performance.

Metamaterial has been employed in antenna design in a variety of ways by antenna designers to achieve various goals [30-32]. Loading metamaterials in antenna design can be done in many different ways:

1. μ-negative metamaterial loading
2. LH-TL metamaterial loading
3. CSRR loaded ground plane
4. Partial metamaterial loading
5. Metamaterial as substrate
6. Metamaterial as superstrate

Metamaterial is used for gaining the antenna's performance by presenting it numerous portions of the antenna. There is a significant boost in gain with the introduction of left handed metamaterials in the circular patch antenna examined in [33]. An ESRR-encased microstrip patch antenna on FR4 dielectric substrate has been studied in [34].
The effectiveness and radiation properties of the device are being studied. The results of the experiments support both the improvement of antenna characteristics and their duction in size caused by the material. In [35], tiny strip patch antennas with complementary split-ring resonators were designed, in this study; the author examined the effects of the planned frequency and size reduction on complementary split- ring resonators. The antenna's size is reduced by 49% by using complementary split-ring resonators, according to the author.

IV. Applications of Metamaterial in the Antenna

Antennas made from metamaterials have a wide range of uses, including the following [40- 44]:

Small antenna: Miniaturization is the current trend in technology, and the desire for more sturdy and compact designs is on the rise as a result. The power emitted can be increased by using a DNG material electrically tiny antenna and as a result, it is used in handheld devices and other electronics.Compact antenna: High impedance surfaces or artificial magnetic conductors (AMC) are utilized to create small antennas because they cause in-phase reflections that are difficult to avoid. The radiation effectiveness of patch antennas can be improved by using high impedance surfaces.

High gain antennas: The low permittivity of some materials in certain frequency ranges is common in metamaterials. As a result, this low permittivity value and the correspondingly low refractive index can be considered to be close to zero. High-gain antennas can benefit from this feature.

Civil applications: Mobile phones and other civil electronic equipment can benefit from the frequency-selective transmission and reflection capabilities of metamaterials.Antenna arrays: Individual antenna radiation properties are studied in metamaterials in order to better optimize and decouple antenna arrays for steered imaging applications. This is due to metamaterials' ability to manipulate electromagnetic wave propagation.

V. Review

In this section, brief review of various metamaterial based microstrip patch antennas has been presented.
Design of square slotted microstrip patch antenna in loaded and unloaded conditions metamaterial SRRs have been directly connected to the microstrip patch antenna to obtain the broadband performance and also obtained dual bands at two frequency 5.07 GHz and 6.55 GHz respectively. This antenna is suitable for Wi-Fi, WLAN applications. The electrical size of the antenna at lower resonant frequency is $0.338\lambda \times 0.169\,\lambda$ [8].

A low-cost metamaterial embedded wearable rectangular microstrip patch antenna using polyester substrate for WLAN applications resonates at 5.10GHz with a bandwidth and gain of 97MHz and 4.92 dBi, respectively have been reported [9]. The slots are cut in the rectangular microstrip patch to make the antenna compact as compared to the conventional rectangular microstrip patch antenna (without slots), small portion of the proposed antenna (with slots) gets bent due to the body movements. A metamaterial square SRR is embedded inside the slot hence; unwanted bending effects on the resonant frequency and impedance matching (S11) of antenna have been reduced.

A geo-textile material that is polypropylene based metamaterial loaded wearable T-shaped microstrip patch antenna for public safety band applications have been presented [11]. In loading condition, the antenna resonates at 4.97 GHz with a bandwidth and gain of 50 MHz and 6.40 dBi respectively.

Titos Kokkinos and Alexandros P. Feresidis proposed work on the design and experimental characterization of sub wavelength, superdirective, end fire antenna arrays operating in the 2.45-GHz band [12]. Microstrip-fed, low-profile folded monopoles are designed using metamaterial the proposed method eliminates the need for tunable feeding networks or additional insulators between the radiating elements. In particular, metamaterial-inspired, microstrip-fed, low-profile folded monopoles (LPFM), which exhibit im-proved coupling performance as compared to conventional monopoles and are much more robust. The parasitic array remains matched at 6 dB over a bandwidth of 25 MHz around 2.475 GHz, while its directivity was measured to be7.6dBi, and its radiation efficiency 24%.

VI. Comparison gain, bandwidth and size of few of antennas which uses metamaterial

Table-I Comparative study of different Metamaterial loaded microstrip patch antenna

Refer ence No.	Year of publi cat ion	Author	Title	Configuration of Antenna	Gain	Bandwidth	Size
8	2011	J.G.Joshi , Shyam S. Pattnaik, and S.Devi	Metamaterial Loaded Square Slotted Dual Band Microstrip Patch Antenna	Metamaterial loaded square slotted dual band microstrip patch antenna	5 dBi at 5.07 GHz 4.5 dBi at 6.55 GHz	118 MHz at 5.07 GHz 171 MHz at 6.55 GHz	0.338λ × 0.169 λ
9	2012	J.G.Joshi, Shyam S. Pattnaik, and S.Devi	Metamaterial Embedded Wearable Rectangular Microstrip Patch Antenna.	Metamaterial embedded wearable rectangular microstrip patch antenna	4.95 dBi at 5.10 GHz	97MHz at 5.10GHz	0.254λ × 0.5λ
11	2013	J.G. Joshi, Shyam S. Pattnaik, and S. Devi	Geo-textile Based Metamaterial Loaded Wearable Microstrip Patch Antenna	Geo-textile based metamaterial loaded wearable microstrip patch antenna	6.38 dBi at 4.97 GHz	50 MHz	0.369 λ × 0.369 λ.
12	2012	Titos Kokkino s and Alexandr os P. Feresidis	Electrically Small Superdirective Endfire Arrays of Metamaterial-Inspired Low-Profile Monopoles	Electrically small super directive endfire arrays of metamaterial-inspired low-profile monopoles	Gains of array 1.7,1.6 and1.4 dBi	35 MHz around 2.48 GHz 30 MHz around 2.475 GHz. 25 MHz around 2.475 GHz	λ/11 × λ/7 × λ/12

Table-I define the comparative study of gain, bandwidth and size of different metamaterial based antenna reported in different Research work

VII. Conclusion

In this paper brief review of metamaterial loaded microstrip patch antenna have been presented. Metamaterial enhances gain, bandwidth and reduces the size of microstrip patch antennas. The trade-off between size and performance is resolved by using metamaterial in antenna design. It also helps to obtain the multi-band performance with considerable gain and bandwidth. It also provides good impedance matching at lower frequencies. Antenna designers can easily develop the portable antennas for different portable devices using metamaterial to cater the need of present RF and mobile communication devices.

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