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Metamaterials and Their Applications in Patch Antenna: A Review

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Abstract

Metamaterial is the arrangement of "artificial" elements in a periodic manner providing unusual electromagnetic properties. This unusual property has made it an area of interest for last few decades. It has wide applications in antennas. Gain, directivity, bandwidth, efficiency, and many other parameters of microstrip patch antenna can be improved using metamaterials. In this review paper, we first overview the metamaterials, its types and then the application of metamaterials in Microstrip patch antennas over the last 13-15 years.

Keywords: *Metamaterial, SRR (split ring resonator), superstrate, microstrip patch antenna*

1. Introduction

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 describe the electromagnetic property of a material or medium. Permittivity describes how a material is 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., $a \ll \lambda$

Metamaterial was first introduced by Victor Veselago [2] in 1967 after the Second World War. He showed that wave propagation in metamaterial is in opposite direction than the naturally occurring materials. John Pendry [1] discovered a realistic way to design a material in which right handed rule is not applied. In this material, group velocity is antiparallel in direction to its phase velocity. Materials with negative permittivity such as ferroelectrics were available in nature but materials with negative permeability did not exist in nature.

Pendry showed that the negative permittivity could be achieved by aligning metallic wires along the direction of a wave whereas negative permeability by placing split ring with its axis along the direction of propagation of wave.

The existance of backward waves was discovered before 1967 by Schuster [3], Pocklington [4], and Malyuzhinets [5]. Materials with negative refractive index were also discovered before Veselago [2] by D.V. Sivukhin [6], V.E. Pafomov [7], and R. A. Silin [8]. In last few decades, the research is going on this area as it has applications in various fields such as electromagnetics, microwaves [9], antennas, optics, mechanics, acoustics [10], *etc*.

In this review paper, the basic properties of metamaterials and its types are studied . The challenges in the designing of patch antenna are presented and then

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using theoretical concepts, it is explained how these designing issues can be sorted out using metamaterials. The work done by various researchers in this area is presented.

2. Basic Properties of Metamaterial

Consider the Maxwell's first order differential equations,

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

$$\nabla \times \boldsymbol{H} = -j\omega\mu \boldsymbol{E} \quad (2)$$

where ω is the angular frequency.

For plane-wave electric and magnetic fields like

$$\boldsymbol{E} = \boldsymbol{E}_0 e^{(-j\boldsymbol{k}\cdot\boldsymbol{r}+j\omega t)} \quad (3)$$

$$\boldsymbol{H} = \boldsymbol{H}_0 e^{(-j\boldsymbol{k}\cdot\boldsymbol{r}+j\omega t)} \quad (4)$$

where **k** is a wave vector, the equations (1) and (2) will become

$$\boldsymbol{k} \times \ \boldsymbol{E} = \omega\mu\boldsymbol{H} \quad (5)$$

$$\boldsymbol{k} \times \ \boldsymbol{H} = -\omega\varepsilon\, \boldsymbol{E} \quad (6)$$

For simultaneous positive values of ε and μ, the vectors E, H and **k** make a right handed orthogonal system[11]. There will be forward wave propagation in this medium.

For simultaneous negative values of ε and μ, equations (5) and (6) can be rewritten as

$$\boldsymbol{k} \times \ \boldsymbol{E} = -\omega|\mu|\boldsymbol{H} \quad (7)$$

$$\boldsymbol{k} \times \boldsymbol{H} = \omega|\varepsilon|\boldsymbol{E} \quad (8)$$

And the vectors E, H and **k** make a left-handed orthogonal system.

Energy flow is determined by the real part of the Poynting Vector.

$$S = \frac{1}{2}\, \boldsymbol{E} \times \boldsymbol{H}^*$$

For simultaneous change of sign of permittivity and permeability, the direction of energy flow is not affected, therefore, the group velocity will be positive for both left-handed and right-handed system. Refractive index is given as

$$n = \pm\sqrt{\varepsilon\mu}$$

And phase velocity is given as

$$v_p = \frac{c}{n}$$

where c is the velocity of light in vaccum.

For right handed system, n is positive, thus the phase velocity will be positive. Therefore, energy and wave will travel in same direction resulting in forward wave propagation.

For left-handed system, n is negative, thus the phase velocity is negative. Hence the direction of energy flow and the wave will be opposite resulting in backward wave propagation [12]. Backward waves may commonly appear in non-uniform waveguides [13, 14]. Figure 1 shows the right-handed system and left-handed system in left and right respectively.

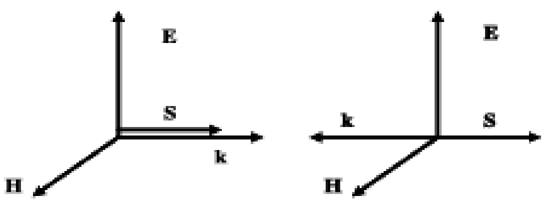


Figure 1. Left: Right Handed System and Right: Left Handed System [11]

3. Types of Metamaterial

Here, the metamaterials are classified on the basis of permittivity and permeability as shown in Figure 2.

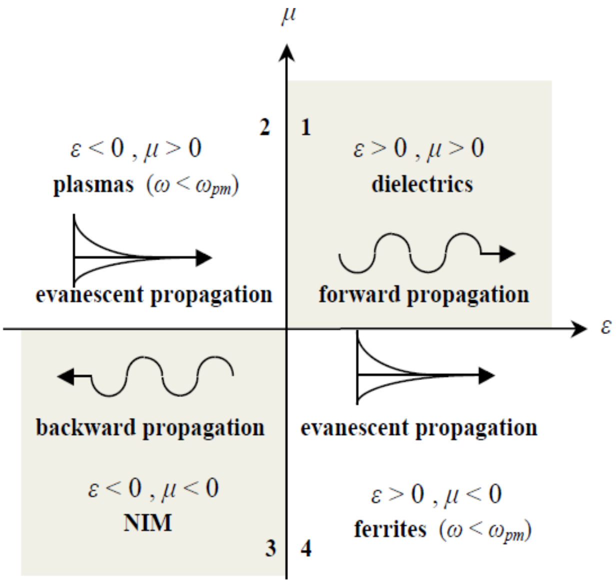


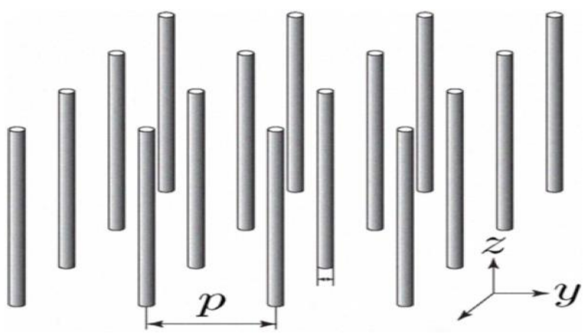
Figure 2. Classification of Metamaterial on the Basis of Permittivity and Permeability

In Figure 2, Quadrant 1 represents the materials with simultaneously positive value of permittivity and permeability both. It covers mostly dielectric materials. Quadrant 2 represents the materials with negative permittivity below plasma frequency and positive permeability. It covers metals [15-18], ferroelectric materials, and extrinsic semiconductors. Quadrant 3 represents the materials with simultaneously negative value of permittivity and permeability both. No such material is found in nature. Quadrant 4 represents the materials with negative permeability below plasma frequency and positive permittivity. It includes ferrite materials.

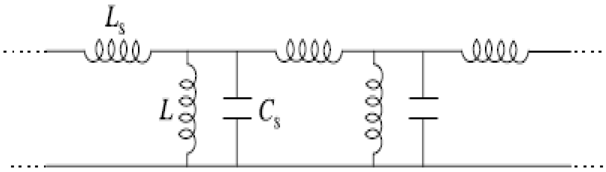
3.1. Artificial Dielectrics

Artificial dielectrics are the structures having negative permittivity but positive permeability.

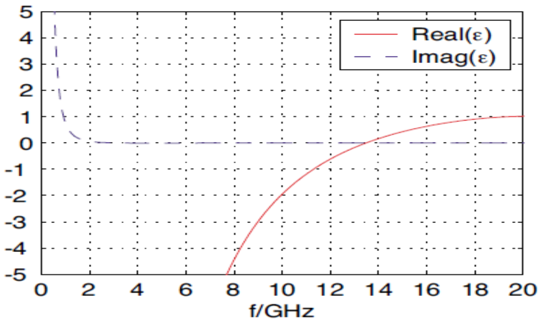
An array of cylinders displays negative permittivity below plasma frequency. Figure 3 shows an array of cylinders, its equivalent circuit and its permittivity.



(a) An Array of Cylinders



(b) Equivalent circuit

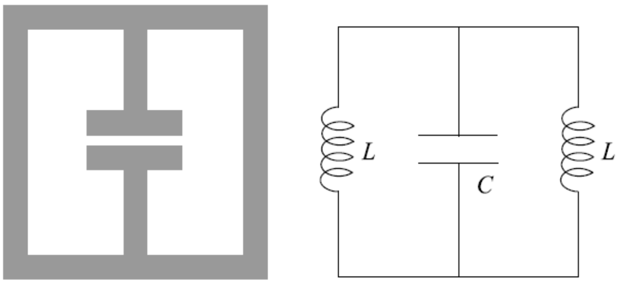


(c) Relative Permittivity Versus Frequency

Figure 3. An Array of Cylinders, its Equivalent Circuit, and its Relative Permittivity [1]

where p is the distance between the axis of cylinders.

Electric coupled field resonator [11] also demonstrates negative permittivity. Figure 4 shows the Electric coupled field resonator and its equivalent structure.



(a) (b)

Figure 4. (a) Electric Coupled Field Resonator (b) Equivalent Structure [11]

Effective permittivity [19] still obeys the Drude-Lorentz law and is given as

$$\varepsilon_{eff} = 1 - \frac{\omega_{p.eff}^2}{\omega(\omega + i\gamma_{eff})}$$

where ωp.eff is the effective plasma frequency and γeff is the effective damping factor.

These are given as

$$\omega_{p.eff}^2 = \frac{2\pi c^2}{d^2 \ln\left(\frac{p}{r}\right)}$$

and

$$\gamma_{eff} = 0.1\omega_{p.eff}$$

3.2. Artificial Magnetics

Artificial magnetics are the structures having negative permeability but positive permittivity.

Artificial magnetics exhibits negative permeability below plasma frequency. Figure 5 shows the simple view of split ring and split rings placed in stack.

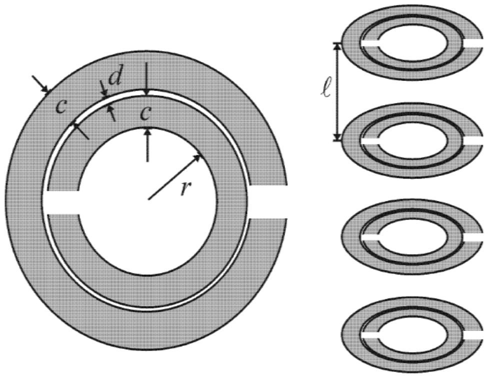


Figure 5. Left: Simple View of Split Ring and Right: Split Rings in Stack [1]

Figure 6 shows the relative permeability of the split rings placed in stack.

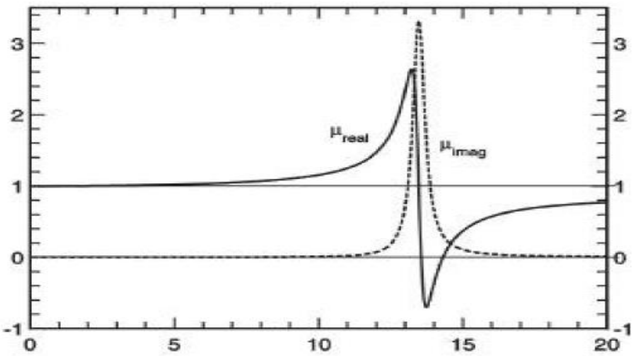


Figure 6. Relative Permeability Versus Frequency [1]

where l is the lattice spacing.

Effective permeability [19] is given as

$$\mu_{eff} = 1 - \frac{F\omega^2}{\omega^2 - \omega_0^2 + i\Gamma\omega}$$

where F represents the filling ratio of split ring resonator.

$$F = \frac{\pi r^2}{l^2}$$

ω_0 is the resonance frequency and is given as

$$\omega_0 = \sqrt{\frac{3lc^2}{\pi^2 r^3}}$$

and Γ represents the damping term which is given as

$$\Gamma = \frac{2}{r\sigma\mu_0}$$

Split ring resonators(SRR) can also be classified as edge coupled SRR(EC-SRR) and broad coupled SRR(BC-SRR).

In EC-SRR, two concentric metallic split rings are printed on a dielectric substrate[11]. When a time varying magnetic field is applied to it externally along the z-direction, the electric current starts flowing from one ring to another through the slots between them by the force of the cuts on each ring. The slots between the rings acts as distributed capacitance. The EC-SRR and its equivalent circuit is shown in Figure 7.

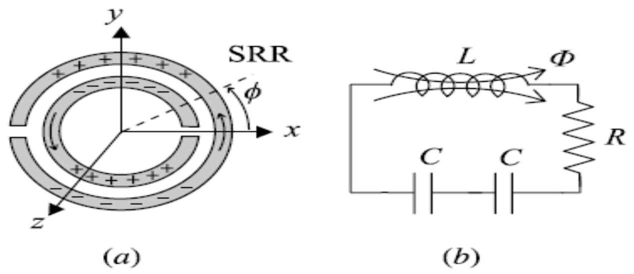


Figure 7. (a) EC-SRR (b) Equivalent Circuit [11]

where L is the self-inductance of EC-SRR.

In BC-SRR, both metallic rings are printed on the both sides of the dielectric substrate. Since the charge distribution in it does not form a net electric dipole, therefore, it is non-bianisotropic. Thus it eliminates EC-SRR bianisotropy. It has smaller electrical size than EC-SRR. Equivalent circuit of BC-SRR is same as that of EC-SRR. The BC-SRR is shown in Figure 8.

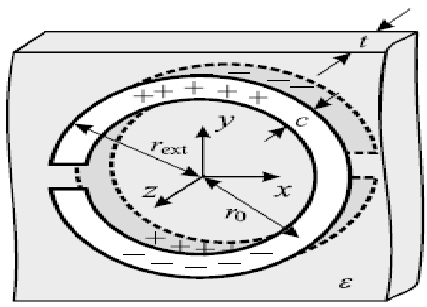


Figure 8. Schematic Diagram of BC-SRR [11]

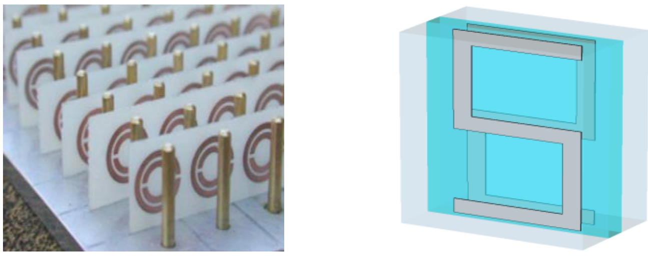
3.3. Negative-Index Material

Refractive index of an electromagnetic responsive material mainly depends on its permittivity and permeability as shown below

$$n = \pm\sqrt{\varepsilon\mu}$$

When either ε or μ is negative, then refractive index will be purely imaginary resulting in evanescent waves. When both the parameters are positive, the refractive index is positive and thus results in forward wave propagation. When both the parameters are negative, the refractive index will be negative resulting in backward wave propagation. The materials with simultaneous negative permittivity and permeability are called Negative-index materials (NIM). These are also called left handed materials.

The combination of alternating layers of thin metallic wires and circular split rings, Omega shaped [20], S shaped structures [20], Double H shaped [21] structures *etc.* exhibits negative index of refraction. Figure 9 shows the combination of alternating layers of thin metallic wires and circular split rings, and S shaped structure.



(a) (b)

Figure 9. (a) Combination of Alternating Layers of Thin Metallic Wires and Circular Split Rings (b) S Shaped Structure [20]

Figure 10 shows the omega shaped structure and Double H shaped structure.

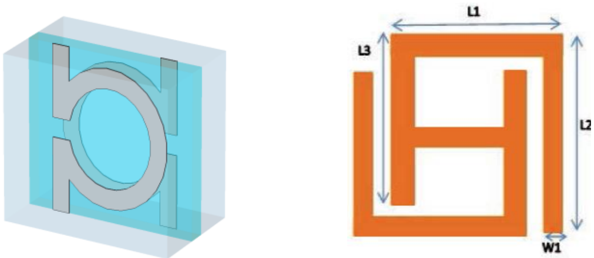


Figure 10. (a) Omega Shaped Structure [20] (b) Double H Shaped Structure [21]

3.4. Chiral Materials

Chiral material is comprised of particles whose mirror images cannot be superimposed. It is different from electromagnetic metamaterials in which both ε and μ are required to be negative for achieving negative index of refraction. But in chiral materials, either ε or μ or both are not required to be negative. We can achieve negative refraction in chiral materials by having strong chirality.

For chiral material, refractive index is

$$n = \sqrt{\varepsilon\mu} \pm \kappa$$

where κ is chirality parameter. It defines the cross coupling effect between the electric field and magnetic field when going through chiral material. Because of its chiral asymmetry property, it reacts different for left circularly polarized and right polarized waves [22]. Figure 11 shows the materials having chiral property.

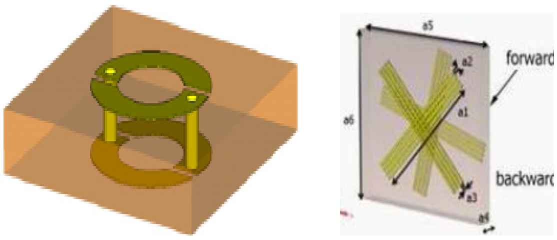


Figure 11. Chiral Materials

3.5. Cloaking

Metamaterials are used for making invisible cloak. Metamaterial controls the propagation such that it can bend light around the object. If the light is not reaching at the object, we can't see the object and it becomes invisible to us. The incident waves are guided around the object and it is still present in its location but we can't see it. The incident rays recover their original path at the other end.

Figure 12 shows the examples of cloaking.

Figure 12. Cloaking Effects

4. Applications in Patch Antenna

There are various issues while we design a patch antenna such as - compactness in size, gain improvement, directivity enhancement, increased bandwidth, suppressed sidelobes or backlobes. Metamaterials are being used for improving the performance of conventional patch antennas.

4.1. Directivity and Gain Enhancement

Effective permittivity can be expressed as

$$\epsilon_{eff} = 1 - \omega_p / \omega^2$$

where ω_p and ω are the plasma frequency and the frequency of the electromagnetic wave respectively.

When resonant frequency is equal to plasma frequency, the effective permittivity will be zero.

$$If\ \omega = \omega_p \quad then \quad \epsilon_{eff} = 0$$
$$n = \sqrt{\epsilon_{eff}\ \mu_{eff}} = 0$$

Thus when operating at the plasma frequency, there will be zero index of refraction.

Directivity and gain can be increased by using metamaterial as antenna substrate.

If a source is embedded in a substrate with zero index of refraction, then according to Snell's law, the exiting ray from substrate will be very close normal to the surface. Then, all the refracted rays will be in almost the same direction around the normal. Therefore, the closer the operating frequency is to the plasma frequency, the better directivity can be achieved.

Enoch *et al.*, had used metamaterial as substrate [23]. The layers of copper grids seperated by foam were used as metamaterial. This metamaterial possessed the plasma frequency at about 14.5 GHz. Monopole antenna fed by a coaxial cable was used as a source of excitation and the emitting part of the monopole was approximately centerd at the center of the metamaterial substrate. A ground plane was added to substrate. It had the best directivity at 14.65 GHz.

Since the metamaterial has a plasma frequency at about 14.5 GHz, the index of refraction is close to zero at this frequency. According to Snell's law, the refracted ray from the metamaterial will be very close to the normal of it. Hence he obtained the best directivity at 14.65 GHz.

I. Wu. *et al.*, used the same technique for obtaining high directivity [24] as used in [23]. He used the dipole antenna as source of emission instead of monopole antenna [23].

The dipole antenna was embedded in metamaterial substrates. The periodic structures of rods, or of both rods and rings were used as metamaterial. Ground planes were not used there. He used the different methodology and the process of analysis than [23]. He placed method for farfield radiation was used.

Y. G. Ma *et al.*, represented that the directivity of an EM emission could be more improved by embedding the source in an anisotropic metamaterial with either effective permittivity or effective permeability nearly zero [25].

The difference between this [25] and the technique of Enoch *et al.*, [23] lies in the problem of impedance mismatch between the ε-near-zero (ENZ) matrix and surrounding air. The metamaterial used was anisotropic with effective permittivity near zero, allowing it to match the surrounding media at the proper polarizations. By using the anisotropic slab, the emitted wave received in surrounding air exhibits the characteristics of plane wave same as the straight wavefront parallel to the interface shows when it is propagating along ± x axis [26]. It was shown that the high directivity can be supported by this anisotropic matrix.

R. Khajeh Mohammad Lou *et al.*, used two types of metamaterial superstrates [27] to increase directivity, gain and bandwidth. Directivity enhancement was based on zero index refraction phenomenon. The radiation energy of patch antenna is concentrated near zero index refraction. The S coupled and Double split rings were used as metamaterial superstrates.

Using 5×7 array of the coupled S-shaped structures, the near zero refractive index was observed in the frequency range of 13.5-17.5 GHz. Hence the radiated energy will be concentrated in this frequency range and directivity will be maximaum. A 6×7 array of Double split ring structures near zero refractive index was also used.

The metamaterial superstrate layer was placed about one third of the operating wavelength, *i.e.*, λ/3 above ground plane to increase the gain.

Bimal Garg, *et al.*, presented a "Pentagonal Rings" shaped metamaterial cover [28] to enhance the gain and directivity of microstrip patch antenna. The designed metamaterial has negative values for both effective permittivity and permeability. The metamaterial cover was placed at a height of 3.2 mm from the ground plane. As left handed metamaterial has the property of focusing radiations of antenna [29, 30], the directivity had been increased about 2.019 dB and the gain had improved.

H. Attia, *et al.*, represented magneto-dielectric superstrates [31] to improve gain of microstrip antenna array. The gain was improved without any substantial increase in antenna size. The superstrate was designed of SRR unit cells. The effective permittivity and permeability both were positive for this superstate material. A 4×1 antenna array was used with magneto dielectric superstrate to achieve gain enhancement of about 3.5 dB. The gain enhancement depended on the distance between the patches and superstrates. This technique is better than the techniques which used EBG based superstrates [32, 33] as it resulted low antenna profile.

Le-Wei Li, *et al.*, used the completely different approach [34] to enhance the bandwidth and gain of a conventional patch antenna. He applied the planer metamaterial patterned structures directly on the upper patch and bottom ground of the substrate. Periodically distributed isolated microtriangles gaps were designed on the upper patch and the periodically distributed cross strip gaps were designed on the bottom ground plane. A capacitive-inductive equivalent circuit was formed by the coupling of upper patch and bottom ground plane. Thus, a backward wave was induced which travelled along the plane of patch. Therefore, the radiation along the patch direction was enhanced which in turn increased the bandwidth and gain.

Osama M. Haraz, *et al.*, presented the two different techniques for gain and directivity enhancement [35]. In first technique, the metallic ground was suspended underneath the monopole antenna. Gain of the monopole antenna could be increased by controlling the dimensions of suspended ground. Using appropriate dimensions, it could work as a reflector and produce a unidirectional broadside radiation patterns. Gain was increased about 3 dB using suspended ground as compared to that of conventional antenna. There was also a shift of resonance frequencies towards lower frequencies, so it had also become compact.

In second technique, a metamaterial superstrate with metallic printed strips was used to increase the gain and directivity. A metamaterial superstrate with metallic printed strips on its lower side was placed above the monopole antenna at a distance about 11 mm above the ground. Gain enhancement about 3 dB was achieved by adding superstrate.

Zhongqing Wang, *et al.*, designed a left-handed metamaterial cover [36] to enhance the gain and directivity of antenna. This left handed metamaterial cover was designed with a microstrip line, two symmetrical triangular split ring resonators printed on the substrate. There were also two gaps cut on the metal ground plane which made it DGS. This left handed metamaterial cover has negative permittivity and permeability in various frequency bands. When the left-handed metamaterial cover was placed above the antenna, the gain and directivity of antenna was increased and resonant frequencies were shifted towards lower side.

4.2. Size Reduction

Mohmoud Abdalla, *et al.*, presented a compact and triple band metamaterial [37] antenna for all WiMAX applicatins. The antenna was designed using a monopole rectangular patch antenna with CPW feed and two metamaterial LH transmission line cells. These two metamaterial LH transmission line cells were loaded on the monopole rectangular patch antenna. Each unit cell was formed of inductive slot and interdigital capacitor. Each cell could be designed separately to resonate at different frequency so that it can introduce two different antenna bands. The monopole patch antenna contributes to obtain the third band.

The designed antenna has 66% size reduction as compared to conventional antenna at lower band (2.4GHz), whereas 50% size reduction at 3.5 GHz and 25% at 5.5 GHz is also achieved.

Yuchu He, *et al.*, presented a compact metamaterial-inspired circular monopole antenna [38]. The circular patch antenna design was based on the design in [39]. In the circular patch, an arced T-shaped slot was cut out. The designed antenna was covering the 2.3 GHz band with 220 MHz bandwidth. For achieving the wideband, the circular shape was exalted by the design in [40].

R. Pandeeswari, *et al.*, presented a compact sized antenna [41] by loading it with square shaped multi split ring resonator (MSRR). MSRR with four rings was used and it has negative permeability. Rectangular patch of size 0.5mm×5mm×1.6mm is used and MSRR was placed close to it. When patch was excited, then according to Faraday's law of electromagnetic induction, the e.m.f. is induced in the rings and it caused flow of current in it. Thus, the resonant frequency shifts to lower side. It was shifted at 8.51 GHz when MSRR was placed at a distance of 0.25mm from patch whereas it was 17.89 GHz before MSRR loading. Thus the resonant frequency was reduced by 52% by using MSRR.

Surbhi Dwivedi, *et al.*, proposed metamaterial inspired patch antenna [42] for size reduction. The rod and split ring resonator was used as metamaterial. The substrate dimensions were varied for optimization. Size reduction was obtained up to 36.7 %. Bandwidth was also increased by 12.43% by using metamaterial. Multiband operation was obtained by using slotted and chopped patch antenna.

Jaegeun Ha, *et al.*, presented a compact and wideband patch antenna [43]. Patch antenna was loaded with planer metamaterial. The unit cell of the metamaterial was comprised of an interdigital capacitor and a complementary split ring resonator slot to have CRLH properties. The interdigital capacitor inserted in the patch provides series capacitance. The SRR slot etched on the ground plane provided shunt admittance. The series capacitance increased on increasing the interdigital finger length. It caused decrease in the half wavelength resonance frequency, thus the size of the antenna had been reduced by 55%.

The increase in the interdigital finger length also generates TM_{10} mode in addition. This TM_{10} mode can be combined with normal TM_{11} mode to achieve a wideband.

Wanquan Cao, *et al.,* proposed a compact patch antenna [44] with CSRR loaded on ground. This antenna was used for beam steering.

Saimoom Ferdous, *et al.,* proposed a method to obtain reduced size with multiband operation for conventional antenna [45]. Size reduction is obtained by loading Mu negative metamaterial as a substrate in circular microstrip patch antenna. Triple band operationed by loading it with epsilon negative metamaterial.

Filiberto Bilotti, *et al.,* proposed a compact circular patch antenna [46] loaded with metamaterial. in his previous work, he assumed the metamaterial as an ideal isotropic material. Here he presented the same structure with its cavity model analysis to optimize the position and orientation of the unit cell structures. The metamaterials unit cells were embedded underneath the patch. These metamaterials used were mu negative metamaterials. The patch was designed to resonate at 0.5 GHz using the formulas given in [47]. Magnetic field was very high between metamaterial and dielectric whereas it was zero at the centre of the patch. After SRR inclusions, antenna resonates at 0.565 GHz with electrically small dimensions of the patch.

He also proposed [48] again miniaturized patch antenna with mu negative loading. A theoretical analysis of magnetic field distribution underneath the patch is done. This helps to find out the position, arrangement and alignment of magnetic unit cell underneath the patch.

4.3. Bandwidth Enhancement

Marco A. Antoniades, *et al.,* presented a printed monopole antenna loaded with metamaterial to achieve broadband dual mode operation [49]. The metamaterial used was negative refractive index transmission line. The metamaterial loading was adjusted to support even mode current at 5.5 GHz which transforms the antenna into short folded monopole. At 3.55 GHz, the ground plane radiates due to in phase current along its top edges. The ground plane radiates a dipole mode orthogonal to folded monopole mode, thus resulting a wideband of 4.06 GHz.

Merih Palandoken, *et al.,* presented a compact broadband microstrip antenna [50] loaded with left-handed metamaterial and dipole. The proposed antenna consists of six unit cells of negative refractive index metamaterials fashioned in 2×3 antenna array, and a dipole. The impedance of antenna was matched with a stepped impedance transformer. It was also matched with rectangular slot cut in the truncated ground plane. The phase compensation and the coupled LH resonance properties resulted into its broad bandwidth (63 %) over the band 1.3-2.5 GHz.

Lang Wang, *et al.,* presented a series fed array of rectangular microstrip metamaterial patches [51]. This series fed array of metamaterial patches enhanced the bandwidth and gain of the antenna. The feedline connecting the metamaterial patches was off-centered. The shunt fed array [34, 52-54] was also used for providing bandwidth but it has large dimensions.

In [28], Bandwidth can be improved by using two metamaterial superstrate layers. The gap between the first layer and second layer is from $\lambda/3$ to $\lambda/2$.

4.4. Efficiency Improvement

In [28, 31] efficiency is improved.

In [49], Very high Efficiency about 90 % is also achieved.

In [44], Efficiency is improved and it is more than 80 %.

In [43], Efficiency has been improved very much. It is 96%.

7. Conclusion

In this review paper, the metamaterial and its types on the basis of permittivity and permeability have been studied. Metamaterials has many applications in patch antennas. It can improve the gain, bandwidth, directivity, and the efficiency of the antenna. It can reduce the size, sidelobes, and the backlobes of the antenna. The applications of the metamaterial to improve gain, directivity, size, bandwidth, and efficiency of the patch antenna has also been studied.

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