Metamaterial-Inspired Antennas : A Review

Ankita Sharma, Ranu Yadav, Ankit Agarwal, S.K Bhatnagar
Department of Electronics and Communication Engineering, Swami Keshvanand Institute of Technology, Management and Gramothan, Jaipur-302017 (INDIA)
Email- ankii.sharma18@gmail.com

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Abstract:In this review paper, distinctive properties of metamaterial, prominently negative refractive index materials are presented. Metamaterials are macroscopic composites that have three dimensional periodic structures which are artificial (man-made) for an optimized combination, not readily accessible in nature. Metamaterial shows unexpected properties such as negative permittivity and negative permeability simultaneously that leads to negative refractive index which supports backward waves. Metamaterial in antennas are used to enhance dual-band and multi-band characteristics along with antenna size reduction, increase in bandwidth and radiator efficiency. They are classifying into a variety of category such as antenna based on metaresonators, metasurfaces, and metamaterial loadings. The main aim of the research work is to deal with topic in broad way, and to review the state of art progress in the field of metamaterial-inspired antennas.

Keywords: Metamaterials, Metamaterial-Inspired Antennas, Metaresonators, Metasurfaces, Negative Refractive Index Materials, and Metamaterial Loadings.

1. INTRODUCTION

Through the last decades, there have been significant progresses in Wireless Technology that demands the accessibility of efficient devices, that to be function at high data-rates and at low signal powers [1], [2]. In 1898 J.C. Bose conducted microwave experiment on twisted structures that represented the possibility of existence of artificial material. . Later, in 1967 Veselago theoretically investigated negative refractive index (NRI) materials with unique phenomena for electromagnetic wave in a double negative material [3]. After 30 years, an array of split-ring resonators (SRR) and artificial wired medium to build a real medium that shows the negative refractive index properties in the microwave band was used by Pendry in 1996 [4]. The word was first coined by Rodger M. Walser (2001) who gave the following definition:

"Metamaterials are artificial periodic structures with lattice constants that are much smaller than the wavelength of the incident radiation. Therefore providing negative refractive index characteristics" [5].

While in 2004 by smith, first metamaterial had realized [6]. After that, metamaterial gained popularity in the research field and large number of scientists studied similar structures like omega-shaped structures, double SRR, single SRR, CSRR, H-shaped structure, S-shaped structure, U-shaped structure, V-shaped structure, and spiral shaped resonators.

Metamaterial inspired antennas are well known for their small physical size, broad bandwidth, low cost and good efficiency [7]. This paper reviews the most recent progress in the development of metamaterial inspired small antennas. The following four categories are:

- CRLH-based or dispersion engineered resonant antennas. On the basis of engineered dispersion curves (k–β diagram), a variety of antennas with negative-order modes and zeroth-order resonators are present [8]–[9].
- Miniature antennas based on metamaterial loadings, such as epsilon/mu-negative materials [10], high permeability shells, and the magnetic photonic crystals (MPC). The metamaterial-inspired near-field resonant antennas are also included [11].
- Metaresonator antennas [12]-[13], mainly for antennas based on complementary split-ring resonators (CSRRs) and split-ring resonators (SRRs).
- Antennas loaded with metasurfaces [14]–[15], such as electromagnetic band gap (EBG),patch-type reactive impedance surface (RIS) or mushroom structures as they are able to miniaturize antenna size, reduce the surface waves with the improvement in radiation characteristics.

2. THEORY OF METAMATERIALS

In the Greek word, Meta means beyond/after/above/superior, as they exhibit properties beyond the properties of readily available materials [16]. Metamaterials supports high degree of miniaturization as structural cell size of them is one-fourth of the guided wavelength which is stated as:

$$P<\lambda_g/4$$

Where, P=structural average cell size
λ_g=guided wavelength

Metamaterial can be characterized by using Maxwell equations [16].Maxwell's equations shows this relationship as:

$$n= \pm \mu\varepsilon$$

3. CLASSIFICATION AND PROPERTIES

Materials can be classified on the basis of ε and μ in four quadrants as shown in Figure 1.

When a wave incident from air to conventional materials, it gets positive refraction along with wave propagation while in case of metamaterials, it gets negative refraction along with wave propagation. Moreover, when wave gets incident from air to plasmas and ferrites, it gets reflected along with attenuation. In quadrant 2 and 4 there is single negative region that impede the signal. In quadrant 1, most of the material exhibits their behaviors and have positive permeability and permittivity. Moreover, in quadrant 3, metamaterial exist that are not readily available in nature and exhibit negative permeability and permittivity simultaneously due to which refractive index in snell's law is negative [17].

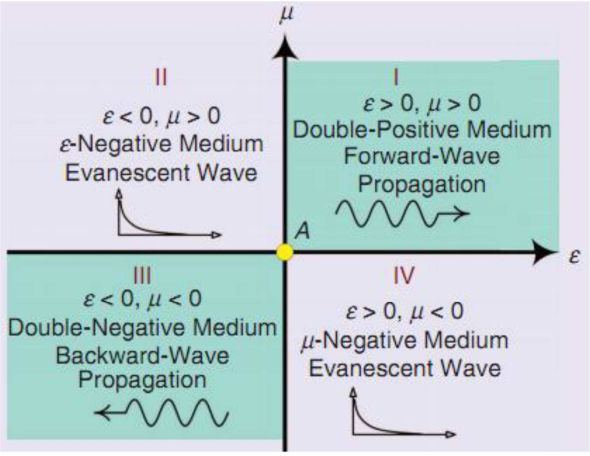


Figure 1 : Permittivity-permeability (ε-μ) diagram which shows the material classifications [17]

Furthermore, for conventional material, the refracted waves are expanding away after entering and exiting the medium as shown in Figure 2. While for left-handed materials, the waves are refracted so as to produce a focus inside the material and then outside as shown in Figure 3.

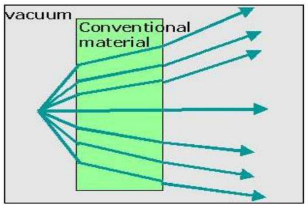


Figure 2 : Refracted rays [17]

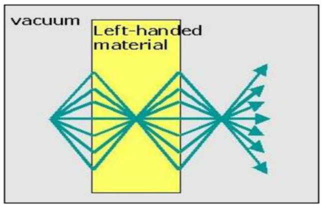


Figure 3 : Refracted rays [17]

4. REALIZATION OF METAMATERIALS

4.1 Negative ε

The metamaterial used as a metallic mesh of thin wires for obtaining negative value of ε. The effective permittivity can be expressed as:

$$\varepsilon_{p} = 1 - \omega^{2}_{p}/\omega^{2}$$

Where,
ω_p = plasma frequency
ω= frequency of the propagating electromagnetic wave

4.2 Negative μ

A split ring resonator is constructed with two concentric metallic rings, with a gap of 1800 apart in each ring. The gap between inner and outer ring acts as a capacitor while the rings themselves act as an inductor, resulting in an LC resonant circuit. Split-Ring Resonators (SRRs) are arranged periodically in form of its array.

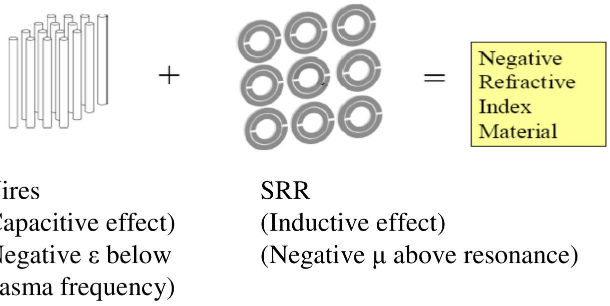
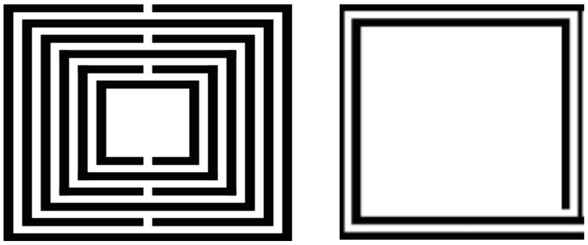


Figure 1.4, Combination of thin wires and SRR

5. APPLICATIONS

5.1 Metamaterials in Sensors

In designing of sensors, metamaterial draws a significant role and are widely used in agriculture, biomedical etc as they enhance the performance by increasing resolution capability, sensitivity and overall efficiency. Sensors employed in agriculture are used with resonant material, SRR for achieving reasonable gain with good sensitivity [18]. While, the biomedical wireless strain sensors which is broadly used, employs SRR form on strain sensors to enhance specified sensitivity. Figure 5, given below shows unit cells of metamaterial structure that are used for sensors.



(a) Multiple SRR (b) Spiral Resonators

Figure 5 : Unit cells of metamaterial structure which are used for the sensor [18]

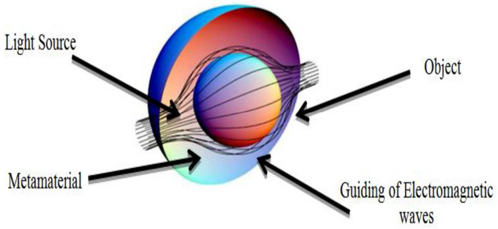


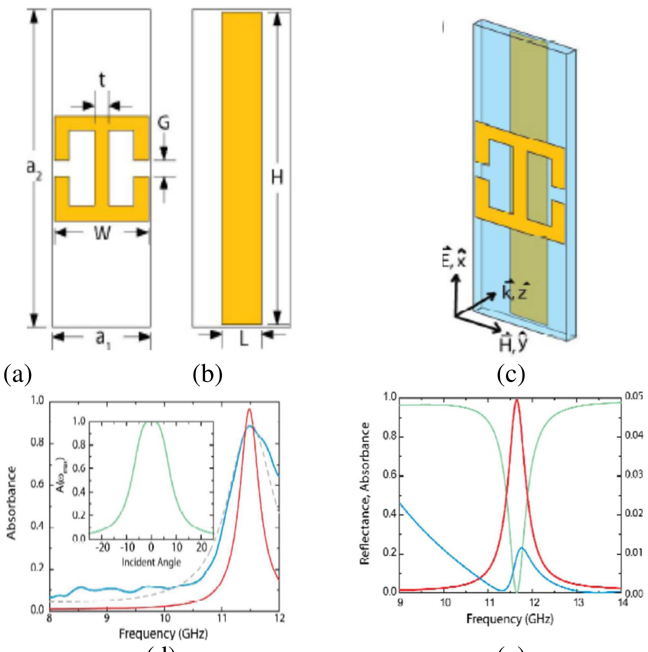
Figure 6 : Cloaking [19]

5.2 Metamaterials in cloaking Devices

Metamaterial as cloaking devices are depends on logic of coordinate transformation and are form of material having negative index [19]. The cloak makes the changes in direction of microwave beam inside a masked (targeted) object, with minimum distortion, by making it invisible in appearance. These devices neighboring the targeted object to cloaked with a shell that result in travelling of light around it as shown in Figure 6.

5.3 Metamaterials in cloaking Devices

The most interesting research area which is gradually rising and gaining popularity is metamaterial as absorber. Figure 7 shows firstly designed metamaterial inspired absorber that makes use of three layers, out of which two comprises of metallic layers and the remaining is of dielectric and when they are simulated, they are absorptive with 99% at 11.48 GHz [20].



(a) (b) (c)

(d) (e)

Figure 7 : (a), (b) & (c) The unit cell is shown with its component (d) Results after fabrication (e) Results after simulation [20].

5.4 Metamaterials in Antenna Superstrate

The challenge for next generation is to fulfill the demands of satellites for telecommunication that are used in multiple beam antennas. Metamaterials works as resonant structures that acknowledge transmission and reception of EM waves in particular frequency band and in particular direction. On conventional antenna the metamaterial superstrates can be apply to alter the polarization state of antenna and also to increase both the impedance and directivity bandwidth in microstrip antenna [21], [22]. The major benefit with metamaterial as superstrate is to control direction of transmitted data that allows us to propose directive antennas with higher gain and also to sustain the low-profile benefit of antennas.

5.5 Metamaterials in Antenna Radome

Antenna Radomes are cover to shield the antenna from disturbances such as rainfall, heavy wind, aerodynamic haul, etc. Radomes are mostly used in antennas (SATCOM), antennas in aircrafts and missiles, vehicular antennas, antenna towers for cell phone, and antenna as parabolic reflectors, with further applications in microwave communication to cover up antennas [23]. Metamaterials are broadly used to properly design antenna radomes. To obtain preferred parameters of composite material, metamaterial structures of any shape are implanted in dielectric medium that can be attuned easily. The recent research areas are focused on designing of metamaterial radomes, having relative permeability and permittivity approximately to 1[24].

6. CONCLUSION

Metamaterials and their antenna applications are expected to be very interesting in field of research and innovation. Recent progresses of metamaterial-inspired antennas are discussed in this review paper. In metamaterials, left-handed materials (or material with negative refractive index) draw a significant role in microwaves and also gaining popularity. The properties and characteristics of metamaterials allow reduction in size, increment in gain and overall efficiency when compared with other materials for multiband operation in antennas and also in microwave devices in terms of reconfigurability.

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5.6Metamaterial based antennas

Refere-nce Number	Title	ε_r	Size	State of Art	Frequency Range	Parameter
[26]	Dual Band Metamaterial Antenna For LTE/Bluetooth/WiMax System.	4.4	42*32 (mm^2)	An antenna with radiating patch and slotted ground plane along with metamaterial structure added near the Feed line on the substrate.	Frequency Band: 2.67-3.40 GHz and 3.61-3.67 GHz.	Gains: 0.15-3.81 dB and 3.47-3.75dB.
[27]	Metamaterial Based Miniaturized Dual Band Antenna	4.4	60*60 (mm^2)	An array of 2D structure of Moore Split Ring Resonators (MSRRs) based on magneto dielectric material placed right under the patch.	1.8 GHz and 3.5 GHz	Impedance band: 2% and 4% respectively. A miniaturization of 40% and 60% are achieved in radiating patch and ground plane respectively.
[28]	Hybrid Mode Wideband Patch Antenna Loaded With A Planar Metamaterial Unit Cell.	4.4	40*35 (mm^2)	A patch with an interdigital capacitor is on the top side and a CSRR slot is etched on the bottom side as a ground plane.	3.8 GHz.	Gain: 3.8dBi Efficiency: 96%
[29]	Broadband Microstrip Antenna With Left-handed Metamaterials	4.4	55*14 (mm^2)	The antenna is composed of six unit cells of left-handed metamaterial (LHM) and a dipole element.	2.5 GHz	Maximum gain of -1dB. Broad Impedance bandwidth of 63% over the band of 1.3–2.5 GHz at 2.5 GHz.
[30]	Microstrip Patch Antenna Loaded With Metamaterials For Multiband Applications.	4.4	40*50 (mm^2)	Closed C- shaped slot has been used to miniaturize both mushroom type EBG structures and microstrip antenna. This EBG structures used as substrate of patch antenna results in multiband operation.	Frequency Bands are 2.45GHz, 4.7GHz, 5.3GHz, and 6.1 GHz.	Gain (db): 7.75, 6.16, 4.24, 7.33, and 5.2 respectively.

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