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Metamaterial Inspired Antennas : Reviews and Future Challenges

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Abstract

Metamaterials have gained popularity in the field of antenna research due to their unusual properties that are not readily found in naturally existing materials. Artificial structures known as "metamaterials" have the capability to reveal unusual and exotic electromagnetic properties, such as the realisation of negative permittivity and permeability.Due to their unique characteristics, metamaterials can be used to overcome the disadvantages of conventional microstrip antennas and provide a larger bandwidth, reduction in size of the antenna, better return loss, and improvement in gain, directivity, and SAR with an acceptable amount of input power. Hence, metamaterial structures are commonly loaded on or near the patch, embedded in the substrate, loaded or etched from the ground plane, or placed as a superstrate layer for enhancing bandwidth , gain and reducing the size of conventional patch antennas. The aim of this paper is to review and discuss the latest research on metamaterial inspired antennas for wireless and biomedical applications.

Keywords: Metamaterial, SRR, CSRR, Performance Enhancement.

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1. Introduction

Antennas provide the wireless transmission and reception of electromagnetic signals and play an essential role in modern telecommunications and biomedical applications. Antenna miniaturisation is of great importance for shrinking the dimensions of mobile, airborne, wearable and IoT devices, where space limitations prohibit the usage of large antennas, while metamaterial-based small antennas are also envisioned for usage in wireless communication and biomedical applications.

1.1. Metamaterials

A metamaterial is a word derived from the Greek word, it is a combination of the words "meta" and "material," in which "meta" means something beyond normal, altered, changed, or something advance. Metamaterials are artificially designed materials with properties different from the naturally occurring materials.Metamaterial was first introduced by Victor Veselago [1] in 1967 after the Second World War. It is an arrangement of periodic structures of unit cells in which the average size of a unit cell should be much smaller[2] than the impulsive wavelength of the light. i.e., $a \ll \lambda$.

Ref	Evolution of metamaterial concepts
[1]	Realized that Maxwell's equations of electromagnetism will result in a negative refractive index (n) when electrical permittivity (Ɛ) and magnetic permeability(μ) are both having less than zero values.
[2]	In (1998) described a photonic structure as metamaterial composed of an array of split-ring resonator and mesh wire. This new structure confirms the property of negative epsilon ε and unwraps the new opportunity in gigahertz (GHz) devices
[3]	Found a composite system consists of a periodic group of interspaced conducting nonmagnetic SRR and continuous wires, which forms "left-handed medium." The split-ring resonator (SRR) structure lowers the resonant frequency significantly. It

	has been also observed that "left-handed medium" inverts the phenomenon like Doppler's effect and Snell's law.

1.2. Metamaterials Classification Based on their Properties

Metamaterials are classified on the basis of permittivity and permeability as shown in Figure 1.

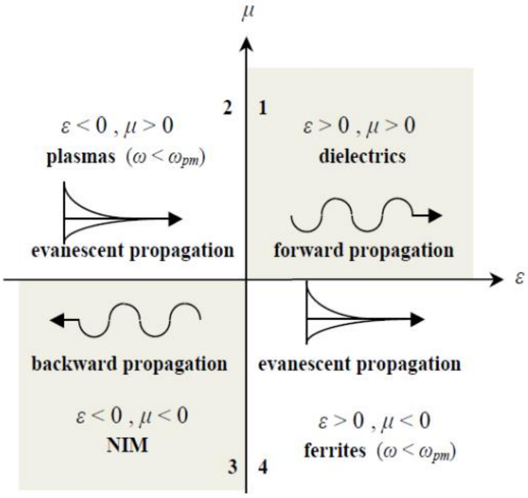

Figure 1. Classification of Metamaterial on the basis of Permittivity(ϵ) and Permeability(μ)

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.

Table.1. Wave Propagation Characteristics of metamaterials

S.No	Quadrant	Permitivity & Permeability	Medium	Materials	Wave propagation
1.	I	ϵ and μ both are positive	DPS (Double Positive) or RHM(Right Handed Medium)	Dielectric Materials, found in nature	n is positive, thus the phase velocity will be positive. Energy and wave will travel in same direction resulting in forward wave propagation.
2.	II	ϵ negative and μ positive	ENG (Epsilon Negative Medium)	Metals , ferroelectric materials, and extrinsic semiconductors.	Non propagating evanescent waves
3.	III	ϵ and μ both are negative	DNG or Left-Handed Medium	Not found in nature	n is negative, thus the phase velocity is negative. Direction of energy flow and the wave will be opposite resulting in backward wave propagation.
4.	IV	ϵ positive and μ negative	MNG (μ negative)	Materials with negative permeability below plasma frequency and positive permittivity i.e) Ferrite materials	Non propagating evanescent waves

Currently,two basic types of structures are being used for designing the most metamaterials: a dense of array of thin wires (the electrical dipoles) and an array of split ring resonators (SRRs) (the magnetic loops).

1.3. ENG Metamaterials

The ENG metamaterial uses the metallic mesh of thin wires,for obtaining negative value of ϵ. The wire can be made of copper,aluminium,silver, or gold, they are arranged periodically as shown in figure 2 .These parallel metal wires,which exhibit high – pass behaviour for an incoming plane wave,whose electric field is parallel to the wires.[4]

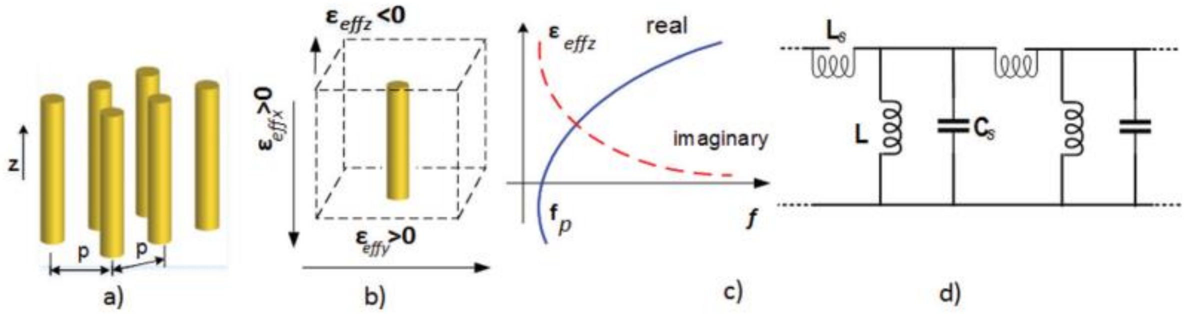

Figure.2. An array of thin conducting wires (a), unit cell (b), plots of the effective permittivity of an array of wires (c), and its equivalent circuit (d).

1.4. Mu-negative (MNG) Metamaterial

As the mu-negative (MNG) material, the most popular structure has been using is split ring resonators (SRRs). A unit cell of the SRR is composed of two concentric metallic rings (can be circle or square) and separated by a gap d (see Figure 3). Each ring has a narrow slot, and they are spaced 180 degree apart on each side. The gap between inner and outer ring acts as a capacitor, while the rings themselves act as an inductors.[4]Therefore, the combination of the two rings acts as an LC resonance circuit. Since the SRR has a lower wavelength than its size due to its quasi-static resonant nature, it may be utilized to create tiny antennas. **(Jones 23)**

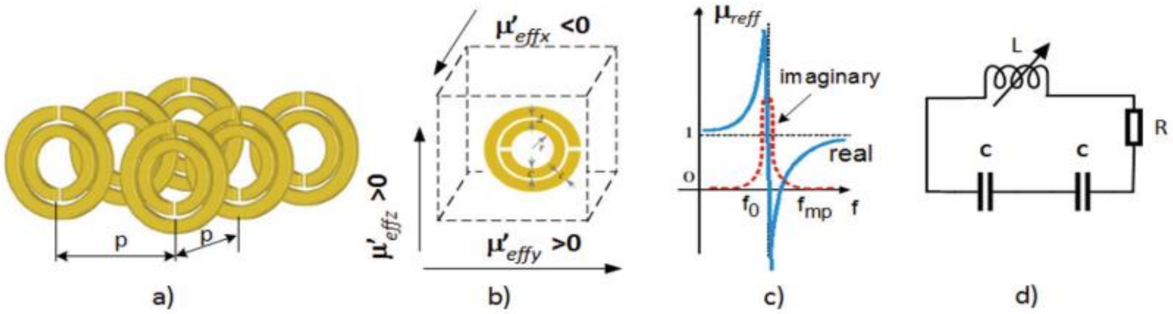

Figure. 3. An array of SRRs (a), SRR unit cell (b), the effective permeability of SRR array (c), and equivalent circuit (d).

1.5. Double-Negative (DNG) Metamaterial

The DNG metamaterial is also known as the negative refractive index material (NIM). The properties of the metamaterials DNG were first achieved by combining the thin wire-based ENG structure with SRR-based MNG structure (Figure 4 a) [4]. This combination satisfies the requirement of $\varepsilon < 0$ from a wire/rodded medium (as an artificial dielectric) and $\mu < 0$ from a split ring resonator (SRR). The first structure was constructed from the combination of planar SRRs etched on a thin dielectric layer and metallic rods (Figure 4 b). In addition, to take advantage of the two sides of the dielectric layers, two-dimensional metamaterials have been designed by engraving the SRR on one side of the dielectric layer and planar strips on the other [3] (Figure 4 c).

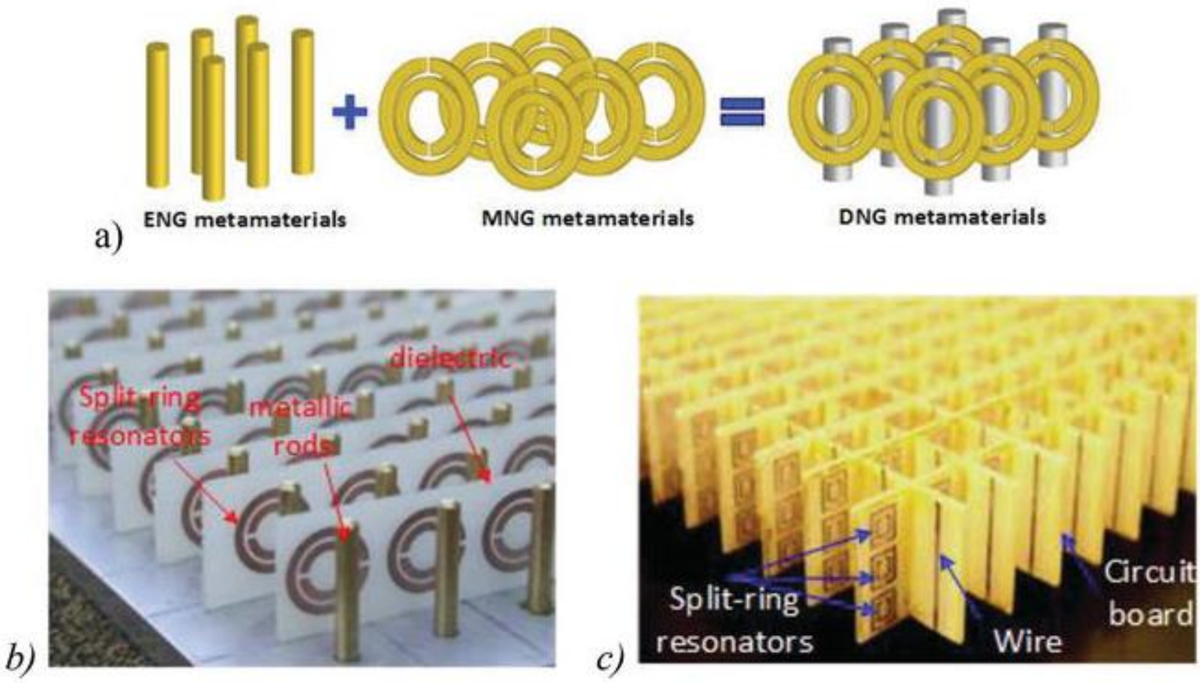

Figure.4. a) Combination of thin wires and SRR to form DNG metamaterials, b) & c) Examples of realizations of DNG metamaterials.

2. Literature Review

Ref.	Metamaterial Antenna Design	Major Findings
Weng et al. [5] (2008])	Conventional substrate is replaced by metamaterial substrate which is composed of copper grids (5x5 cells) with square lattices. Size: 45X45 mm^2	Achieves multiband at 2.77 GHz, 8.2 dB gain
Li et al. [6] (2008)	Planar metamaterial patterned substrate inspired rectangular MPA.	Bandwidth is broadened from 200 MHz to 3 GHz along with higher efficiency and lower loss.
Zhang et al. [7] (2008)	Multiple notches have been achieved by embedding split-ring slots on radiator and SRR structure near feed line.	Ultrawideband antennas with triple band-rejection characteristics.
Singh et al. [8] (2010)	Coplanar Waveguide (CPW) fed antenna loaded with uniplanar compact PBG structure.	Bandwidth is enhanced in addition to a gain of 6.45 dBi. Suitable for WiMAX and WLAN band applications.
Joshi et al. [9] (2010)	Electrically small MPA design loaded with metamaterial configuration.	Increased gain of 3.21 dBi and directivity of 7.8 dBi. 512 MHz impedance bandwidth at a resonant frequency of 9.51 GHz

Bertin et al. [10] (2011)	Metamaterial inspired switch beam antenna comprises electrically short monopole as radiators stand vertically at four corners of the grounded square board.	Extensive bandwidth of 1.1 GHz. Telecommunication applications
Tang et al. [11] (2011)	Triband stop (UWB) antenna equipped with split-ring resonator (SRR) structures	Covers a large bandwidth from 3.03 GHz to 11.4 GHz along with triband notches. Prototype exhibits the omnidirectional radiation performance.
Nornikman et al. [12] (2012)	MPA design inspired with a Single Complementary Split-Ring Resonator (SCSRR) structure. Four different structures of SCSRR are integrated in the microstrip patch antenna.	Improved the antenna characteristic return loss, radiation pattern, impedance bandwidth, and resonant frequency.
Ouedraogo et al. [13] (2012)	Suggested approach comprises of a single layer of CSRR, which significantly reduces the overall area of a conventional patch antenna.	Miniaturization of patch antennas, Bandwidths of the antennas with reduced area up to 1/4, 1/9, and 1/16 of a conventional antenna have been found to be 1.2%, 0.81%, and 0.4%, respectively, in contrast to 1.3 percent for the traditional antenna. The respective efficiencies of the proposed antenna are 8.7%, 49.8%, and 28.1% percent, respectively
Kumar et al. [14] (2012)	CPW fed metamaterial antenna encumbered with CSRR structure.	Frequency ranges from 2.482 to 2.984 GHz, allowing it to be employed in WLAN applications
Patel and Kosta [15] (2013)	Double Negative Group (DNG) metamaterial loaded corner curtailed square patch antenna for wireless network utilisation.	Gain 10 times more that obtained in conventional antenna maximum bandwidth of about 1.44 GHz and three operating bands which makes antenna suitable for UHF and L-band applications
Gupta and Mumcu [16] (2013)	Proposed a small size, multiple CSRR structures are incorporated under patch which causes the 90^{o} rotationally symmetric antenna. Antenna is miniaturized by vertical inductive pin loaded truncated ground plane.	Radiation efficiency of 75% at 2.24 GHz
Patel and Kosta [17] (2014)	Compact circular MPA encumbered with CSRR structure.	Seven operating frequencies along with maximum bandwidth of 259 MHz. C and X-band applications

Islam et al. [18] (2015)	Metamaterial antenna	UWB characteristics 114 percent bandwidth 3.4–12.5 GHz ,VSWR< 2 , Gain of 5.16 dBi at 10.15 GHz
Dawar et al. [19] (2015)	Antenna comprises a two-segment labyrinth-Capacitive Loaded Strip (CLS) metamaterial embedded on a substrate.	Antenna exhibits miniaturization about 72% along with reduction in bandwidth. GPS, WLAN, and satellite communication
Rajeshkumar and Raghavan [20]	Triband SRR loaded microstrip line fed antenna , PIN diodes are used in outer split rings for achieving reconfigurability between WiMAX and WLAN frequencies.	Impedance bandwidth of 186%, 4.3%, and 40.3% along with omnidirectional radiation pattern in H-plane. WLAN and WiMAX applications.
Zhu et al. [21] (2015)	Electrically small antenna loaded with metamaterial. Triangular Electromagnetic Resonator (TER) is added to the antenna and fed by CPW. Complementary TER which enhances the bandwidth and shows omnidirectional radiation pattern.	Three bands (1.78–1.84) GHz, (2.34–3.86) GHz, and (5.75–5.87) GHz. WLAN and WiMAX spectrum applications are compatible with both antennas.
Rahimi et al. [22] (2016)	SRR-based metamaterial in a slot loaded microstrip patch antenna.	Gain of 2–3.5 dBi and an efficiency of above 90%,
Alam et al. [23] (2016)	Metamaterial (MTM) unit cell	Gain of 4.06 dB and is a triple band. DCS 1800, Bluetooth, WiMAX, and WLAN applications in both lower and upper bands
Gao et al. [24] (2016)	MPA composed of permeability negative metamaterial (MTM) dual layer symmetry single-ring resonator pair (D-SSRRP) implanted on both sides of the dielectric layer	Increased the gain up to 2.2 dB and decreased HPBW around 20^o. Designed antenna operates at 5.2 GHz and 6.2 GHz and can be used for WLAN applications
Singla and Rajput [25] (2016)	Design of compact dual-band metamaterial-inspired prototyped using single CSRR structures. Different SCSRR structures such as circular, triangular, square, hexagonal, and octagonal are investigated.	Miniaturization upto 76.2% and can be used for GPS, PCS, WCDMA, and WiFi applications. attains two bands due to inclusion of SCSRR structure and chamfered hexagonal patch.
Muzeeb et al [26] (2016)	Epsilon Negative Group (ENG) metamaterial loaded monopole antenna for quadruple applications	Gain up to 3.03 dBi than traditional antenna
Rajkumar and KIran [27] (2016)	Modified TSRR loaded metamaterial multiband antenna.	Compact size of 25.7 mm × 23.2 mm with height of 1.6 mm. Fractional bandwidths of 9.28 %, 74.37 % and 5.34 %, respectively.

		Suitable for WLAN, WiMAX, and ITU band application
Ameen et al. [28] (2017)	Metamaterial antenna is built of two Composite Right / Left Handed Transmission Line (CRLH-TL) unit cells and a circularly polarized double hexagonal split-ring resonator (SRR).	Triple-band characteristics at 2.61 GHz, 4.12 GHz, and 6.24 GHz, with an impedance bandwidth of 6.54 %, 6.61 %, and 34.20 % respectively. Appropriate for use with WiMAX and WLAN.
Yadav et al. [29] (2017)	Circular MSA is equipped with a CSRR and a microstrip feed line with an S-shaped slot. Antenna has 3 notches at 3.5 GHz, 5.5 GHz, and 7.5 GHz.	Suitable for X-band (72.5–8.4 GHz) satellite communication.
Rajkumar and KIran [30] (2017)	Metamaterial-inspired compact open SRR MPA for multiband applications. Use of open split rings as the radiating element in this design results in a compression of 52.83 % and 38.83% respectively, as compared to a ring of the same dimensions and an SRR antenna.	2.8 GHz, which covers WLAN applications operating at 2.4/5.2/5.8 GHz, 5.5 GHz WiMAX, and 7.4 GHz X-band.
Arora et al. [31] (2017)	Inspired by metamaterials for enhancing the effectiveness of patch antennas.	Bandwidth of 780 MHz and gain of 12.1 dBi which makes it possible for antenna to be used for WiMAX band applications.
Nuthakki et al. [32] (2017)	Monopole planar antenna encumbered with metamaterial unit cell. Four unique unit cells have been proposed which follows CRLH-TL properties and results in four open-ended metamaterial antennas, respectively.	Enhanced bandwidth of 104%, 103%, 104%, and 103% along with gain of 4.2 dBi, 4.5 dBi, Omnidirectional radiation pattern and enhanced efficiency, suitable for ultrawideband applications.3.5 dBi, and 4.4 dBi
Geetha Priyadharshini,[33] (2017)	The LHM structure used is a single unit cell, which is a combination of a Hexagonal Split Ring Resonator (H-SRR) and a Capacitive Loaded Strip (CLS). The incorporation of a 9 × 9 array LHM structure with a single Rectangular patch Antenna, enhanced the Antenna's performance characteristics.	Increasing gain with a value of 6.53 dB and directivity of 8.129 dBi. Bandwidth of the proposed antenna is measured to be 4.65%.
Md Rafiqul Islam et al [34] (2017)	An array of five split ring resonators (SRRs) unit cells is inserted under the rectangular patch. The LHM unit cell structure consists of two rectangular split ring resonator (SRR) and thin wire (TW). The rings are printed on the substrate. The substrate is a FR4 substrate. The length of the outer ring is L1 = 7.4mm, and the inner ring is L2 = 5.4mm. The gap	Mobile GSM and WiMax application. The metamaterial antenna achieved results with major size reduction of 45%, better bandwidth and better returns loss if it is compared to the pair of slots antenna.

	between the rings W1 = W2 = 0.5mm and a small brick is inserted in the centre of the inner ring. The cut in both rings is G1 = 1.6mm.	The return loss in the FR4 antenna at 1.8 GHz is -22.5 dB. Using metamaterial the return loss has improved to -25 dB at 2.4 GHz and -23.5 dB at 1.8 GHz.
Saravanan et al. [35] (2018)	Metamaterial inspired superstrate MPA. Square patch antenna as radiating structure and a single layer symmetrical phi-shaped slotted metamaterial superstrate.	Exhibits reflection coefficient of -28.64 dB along with improved gain of 7.94 dBi
Rao et al. [36] (2018)	Metamaterial-enhanced Coplanar Waveguide (CPW) fed circularly polarized (CP) antenna. An SRR structure is integrated into the feed line, resulting in an increase in bandwidth. CSRR slot is inserted over the antenna's ground plane, enabling the antenna to attain notch	WLAN, WiMAX, and satellite applications.
Mengjun et al. [37] (2018)	When the Metamaterial Structure is placed between the antenna and the human's forearm, the antenna gain is increased by 9.3 and 5.37 dB, and the radiation efficiency is increased by 48.4% and 35.7%, at 2.45 and 5.8 GHz, respectively	The specific absorption rate is decreased by more than 70%, considering the limitations imposed by FCC & ICNIRP.
Labidi and Choubani [38] (2018)	Three TZ-shaped metamaterial unit cells on Rogers RT-5880 substrate, forming metasurface . Enhancement of performances of loop antenna by using negative index metamaterial (NIM).	Miniaturization of loaded-loop antenna. Bandwidth nearly 15% about the resonant frequency of 1 Terahertz High gain around 5.39 dBi ,directivity of 5.71 dBi. Inclusion of metasurface enhances the radiation efficiency up to 93%.
Shankar Bhattacharjee et al. [39] 2018	The antenna comprises three sections: central circular radiating monopole section, a pair of asymmetric arc-shaped slots, and an embedded asymmetric CSRR section. The antenna measures 70.4 mm^3 (16 × 16 × 0.275). Inner and outer radius of the CSRR has dimensions of 2.8 and 3.5 mm Gap of the inner ring is 0.5 × 0.4 mm^2, outer one is 0.5 × 0.5 mm^2, respectively.	Designed for body implantable applications. Electrical dimension of only $0.42\lambda \times 0.42\lambda \times 0.0072\lambda$ at 2.3 GHz resonating frequency. Fractional bandwidth of 93.5% (1.35–3.5 GHz) is achieved with the low-profile antenna.
Chaturvedi and Raghvan [40] (2019)	Microstrip-fed MPA encumbered with metamaterial (MTM) structure. SRR is integrated into a patch antenna, producing a resonance frequency of 2.72	According to the observed data, the antenna has a fractional bandwidth of 19.4 percent and a gain of 1.86 dBi.

	GHz. Additionally, a 0.19 × 0.03 mm^2 stub is incorporated within the SRR structure, extending the surface current channel and shifting the resonance frequency from 2.72 gigahertz to 2.63 gigahertz. Additionally, by covering the space with denim jeans material, the resonance frequency is reduced to 2.45 GHz.	Appropriate for WBAN applications.
N. Sharma and S. S. Bhatia [41] (2019)	Printed monopole antenna with band stop characteristics employing CSRR slot. Centred frequencies at 5.4 GHz and 7.4 GHz.	Maximum gain of 4.89 dBi with negative value of gain at rejected frequencies
M. Elhabchi et al. [42] (2019)	Dual-band notched enabled ultrawideband (UWD) elliptical slotted metamaterial-inspired antenna. The antenna is loaded with a dual SRR metamaterial as a defected ground plane slot (DGS) and a single SRR metamaterial as a stub on the pinnacle edge of patch.	By controlling the dimensions of metamaterial structures and slots, bandwidth of rejected bands can be adjusted. Metamaterial structures help in avoiding the interference with the unwanted WLAN band (5–6 GHz) as well as the X-band satellite communication system (7.25 to 8.39 GHz).
Hasan et al. [43] (2019)	Wireless quad-band antenna inspired by SRR-constrained metamaterials that is electrically compact size of 30 mm × 31 mm. It will have two unit cells of metamaterial that will be aligned with one another.	Overall band width of 200 MHz (between 2.40 and 2.60 GHz) and 390 MHz (between 3.40 and 3.79 GHz), making it appropriate for Bluetooth (2.40 to 2.485 GHz), Wi-Fi (2.4 GHz), WLAN (2.40 to 2.49 GHz and 3.65 to 3.69 GHz), and WiMAX (3.40 to 3.79 GHz) applications. Additionally, the antenna has an average gain of 1.50 dBi, a maximum value of 2.25 dBi, and a minimum gain of 0.88 dBi.
Luo et al. [44] (2020)	An elliptical radiator and a rectangular ground plane with six rejections in the WiMAX band (2.96–3.33 GHz and 3.73–3.8 GHz) via the use of elliptical-shaped ESRR and round-shaped RSRR, the INSAT band (4.43–4.53 GHz), WLAN band (5.37–5.57 GHz), and C-band (7.02–7.30 GHz and 7.56–8.06 GHz).	Unique low profile monopole UWB antenna with six band notches.
Alotaibi and	Novel ultra wideband planar radiator with multiband notch. Each notch is	With three rejected bands, a nearly 10 GHz

Alotaibi [45] (2020)	accomplished by incorporating a C-shaped slot into the radiating patch, a U-shaped slot into the microstrip line, and an L-shaped slot into the ground plane.	operational band is obtained (2.08GHz–12 GHz) (3.28–3.91 GHz, 4.9–7.15 GHz, and 9.21–10.94 GHz). It also has an omnidirectional emission pattern, reducing interference from technologies such as WiMAX, WLAN, and X-band applications.
Althuwayb [46] (2021)	Substrate-Integrated Waveguide (SIW) technology to improve the radiation gain and efficiency of a metamaterial (MTM)-inspired planar antenna for sub-6 GHz wireless communication systems. MTM unit cells with series interdigital-capacitor and short circuited spiral stub make up the antenna. Operating frequency range of 1.8 GHz from 3.0 to 4.8 GHz.	Antenna's performance is improved by inserting a column of metallic connectors between the MTM unit cells. Antenna's size is unaffected by this procedure. Antenna's average gain as well as efficiency after SIW was 5.8 dBi and 78 %, respectively, representing a 2 dBi and 21% improvement throughout 3–4.8 GHz.
Christydass and Gunavathi [47] (2021)	6 evolution small octa-band rectangular microstrip patch antenna. Multiband operations are enabled via CSRR, SRR, FR-4 dielectric substrate and C-shaped slots, which are required for all multipurpose communication systems.	8 resonances at 2.25 GHz, 3.86 GHz, 6.94 GHz, 7.48 GHz, and 9.47 GHz, and a reasonable gain in all operational bands. All resonant bands have efficiency above 65%.
Ahmed M Tamim et al. [48] 2021	Electrically small antenna inspired by a metamaterial structure which creates an impact by achieving a multi-band property that can be applied for different microwave applications.	The initial length of the antenna was $0.61\lambda_0$ x $0.58\ \lambda_0$ x $0.12\ \lambda_0$; however, after embedding metamaterial, 58% reduction was achieved and the size of the electrical length of the reduced antenna becomes $0.254\ \lambda_0$x $0.207\ \lambda_0$ x $0.013\ \lambda_0$, where λ_0 denotes free space wavelength. Highest measured gain of 4.79 dB
Mohamed El Atrash et al [49] (2021)	π-section composite right/left-handed (CRLH) Operates at 2.45 GHz ISM band Physical size : 25 mm × 25 mm, gain of 2.34 dBi, and a total efficiency of 87% in free space. 2 × 2 artificial magnetic conductor (AMC) array was placed in-between the antenna and the human body to maintain resonance at 2.45 GHz under body loading conditions.	CRLH: Realized Gain: 2.34 dBi, Total efficiency of 87% in free space In free space, the low-profile integrated design exhibited a gain of 7.63 dBi (enhancement of 5.29 dBi) and total efficiency of 96.4%. The integrated design achieved a gain and total efficiency enhancements by 14.88 dBi and

	Suitable for WBAN and wearable applications.	72.4%, respectively, as well as, lower specific absorption rate (SAR) levels
Preet Kaur et al. [50] (2022)	A rectangular microstrip patch antenna is taken as a reference antenna, which resonates at a frequency of 5.2 GHz and has an impedance bandwidth of 70 MHz. To improve the bandwidth of the patch antenna, firstly the Split Ring Resonator (SRR) is designed according to the reference patch antenna. The optimized SRR metamaterial is placed in between the patch and ground plane of the proposed antenna.	The -10dB impedance bandwidth of the metamaterial-embedded proposed antenna is 1.63-4.88 GHz and has an average gain of 4.5 dB
Mehaboob et al. [51] (2022)	Antenna consists of two microstrip lines with the slits in between them and both the shapes are made like a C-shape by forming the gaps at opposite sides of each ring. The substrate for unit cell of meta-material is polyester which has width and length of 10 mm.	At 2.4 GHz, gain of 5.2 dB , Return loss of −29 dB. As a result of its negative electromagnetic characteristics, MTM structures are thought to have good radiating effects. Hexagonal shape of MTM had more advantages than the circular, square shape.
Jones et al. [52] (2023)	Tree-shaped metamaterial-loaded microstrip antenna. Size:$15 \times 16 \times 1.6$ mm^3 microstrip antenna. Two X-shaped slots are added to achieve the characteristics needed for WIMAX applications at 5.5 GHz. Split-Ring Resonator is added to the structure to increase its bandwidth. It runs for WLAN applications with a center frequency of 5.8 GHz.	Measured impedance bandwidth is 45.39% with SRR and 53.48% without SRR, respectively.
Ritesh et al. [53] (2023)	Designed antenna has slots with Quasi CSRR (Complementary Split Ring Resonator) and SRR (Split Ring Resonator) cell, respectively. A metamaterial-inspired multiband antenna with a size of $32 \times 22 \times 1.6$ mm^3 is designed on FR4 dielectric material. The antenna has electrical dimension of $0.2581\,\lambda \times 0.1775\,\lambda \times 0.0129\,\lambda$ ($32 \times 22 \times 1.6$ mm^3), at a lower resonant frequency of 2.42 GHz. By the implementation of the proposed Frequency Selective Surface (FSS) with design, antenna gain is improved for the resonant bands.	Antenna achieves octa-band resonant modes for IoT and wireless applications S-band WLAN, bottom C-band WAIC, WLAN, bottom X-band, superior X-band, bottom Ku-band, superior Ku-band and bottom K band with optimized radiation properties.

Sujatha Priyadharshini et al [54] (2023)	Patch antenna employs arc shaped patch and concentric circle shaped patch achieves ultra-wideband operation. Two-layer antenna configuration consists of metamaterial super-substrate. Metamaterial structure is obtained through the arrangement of the proposed unit cell in 5 X 5 order. Metamaterial exhibits near Zero refractive index for wide range of frequency.	Three wideband operation ranging from 3.06 to 4.72 GHz(B.W of 42%), 4.94-6.19 GHz (B.W of 22 %) and 6.50-10.56 GHz(B.W of 47.5%). Super-substrate provides significant gain enhancement by 181% when the maximum gain reaches 6.2 dBi and X-band frequency. Used for X-band operations such as satellite communication,military , and medical monitoring.

3. Metamaterials in Antenna Design

3.1. Directivity and Gain enhancement

One of the main shortcomings of conventional patch antennas is their lower gain. When metamaterial structures are present, the resonant frequency changes to match the plasma frequency, resulting in zero permittivity or permeability and, consequently, zero refractive index. Snell's law states that all radiated energy leaving the substrate will be directed perpendicular to the plane, and all reflected energy will point in the same direction. This results in high gain and directivity.

The Double Negative Group (DNG) metamaterial loaded corner curtailed square patch antenna was reported in [15] for use in wireless networks. The gain is improved by the addition of DNG metamaterial ten times more than it is with a regular antenna. The HFSS simulation software examines the intended antenna.The prototype antenna has three operational bands and a maximum bandwidth of around 1.44 GHz, making it appropriate for use in UHF and L-band applications.

The high gain can be found by using metamaterial as unit cells of PBG around the radiating patch. Metamaterial substrates [31,33,40 & 43] embedded in the conventional patch antenna help in getting better gain of antenna. Gain of conventional MPA can also be enhanced with using electromagnetic band gap (EBG) structures.Metamaterial-inspired SRR and CSRR [43,45] are also effective in recuperating the gain of antenna. Miniaturisation of conventional MPA can be achieved through loading the metamaterial structures. Metamaterial loaded patch antenna produces subwavelength at resonant modes of the conventional patch antenna. SRRs and CSRRs [5- 54] are most commonly used for size reduction of patch antenna without deforming the antenna performance parameters. The two segmented labyrinth-capacitive loaded strip (CLS) [33] metamaterial is a novel way of reducing the size of antenna.

By using metamaterial as a superstrate, antenna size can also be reduced by improving other antenna parameters. The extensive literature review shows that researchers have made high-gain antennas with the aid of metamaterial structures [5-54]. The metasurface placed at the rear end of the antennas acts as a reflector surface. The electromagnetic waves reflected from the metasurface constructively interfere with the propagation waves of the antenna and ultimately result in a high gain response. In addition, metasurfaces also act as lumped inductive and capacitive surfaces which show great response in terms of antenna bandwidth as well as gain.

3.2. Size Reduction

Patch antennas can be made smaller using a method that was inspired by metamaterials, according to [24 & 25]. The suggested method only uses one layer of CSRR, which considerably reduces the total size of a patch antenna [13]. According to research, the bandwidths of the antennas with reduced area up to 1/4, 1/9, and 1/16 of a conventional antenna were determined to be 1.2 percent, 0.81 percent, and 0.4 percent, respectively, as opposed to 1.3 percent for the traditional antenna. The proposed antenna has relative efficiencies of 8.7%, 49.8%, and 28.1 percent. By making the antennas, the simulated results have been confirmed, and the findings are in good agreement with the outcomes of the measurements.

A compact version of antenna was reported in [27] of a modified TSRR loaded metamaterial multiband antenna. By adding a modified TSRR construction, the suggested antenna achieves a compact dimension of 25.7 mm 23.2 mm with a height of 1.6 mm. The recommended antenna is simulated by the HFSS simulator, and manufacturing of the desired antenna has verified the simulation results. The proposed antenna reaches fractional bandwidths of 9.28 percent, 74.37 percent, and 5.34 percent, making it perfect for WLAN, WiMAX, and ITU band applications. The measured results closely match the predicted results.

3.3. Bandwidth Enhancement

Wideband antennas are highly required for 5G and future 6G wireless communication which strongly supports the biomedical telemetry applications. By literature review numerous approaches are used to increase the bandwidth of antennas;like inserting via ports, parasitic patch loading, slot etching, band gap constructions, and stub insertions are some common strategies used by researchers and academics. But usage of metamaterials have proven good enhancement in bandwidth[6,8,15,50 & 81]. While using metamaterial principles can increase bandwidth, it also makes antennas more complex and larger overall. [74]

The microstrip patch antennas loaded with metamaterial are reported to have enhanced bandwidths of 150% and 169%, respectively.[40].

Compact-size antennas are loaded with a single-layer metamaterial to increase the bandwidth was reported in literature review. Additionally, metamaterials can be utilized to increase an antenna’s bandwidth and provide multiband properties.In ultrawideband antennas, there is need to alter out the existing narrow bands such as WiMAX, WLAN, and X-band. Metamaterial-inspired structures, for example, SRRs and CSRRs in addition to defected ground structures can be embedded either on radiator or near the feed line to achieve desired frequency notching.

3.4. Efficiency Improvement

Antennas with high radiation efficiency allow more power to be transmitted from the source to the receiver. This allows more power efficiency and more utility of the energy. This parameter is of major consideration for ultra-low-power applications where the energy is a vital consideration. Metamaterials have been utilized for improving the radiation efficiency of antennas as per the reported literature [5-54].

As per literature review, an implementation of two microstrip lines of zero-order resonator (ZOR) antennas with different heights over the ground plane is demonstrated. The improved ZOR antenna exhibits a far more efficient output of 75% compared to the 10% value of the reference antenna. Monopole antennas loaded with metamaterial for radiation efficiency are reported in [5–54]. In [65], a compact antenna with dimensions of 35 mm × 32 mm is presented. Compared with a conventional single band microstrip patch radiator, the radiator size of this antenna is only 8.5% at 2.5 GHz, 17% at 3.5 GHz, and 37% at 5.5 GHz. In addition, the radiation efficiency of the antenna is also pronounced with integration of the metamaterial. Similar work is reported in [83], in which the researchers propose a novel graphene-based plasmonic patch antenna over a metamaterial substrate. The antenna is able to operate in the terahertz spectrum and comprehensive investigation of its radiation efficiency is also presented. The substrate has an anisotropic nature which causes divergence in the fields. Even though this impeding factor is in place, the functionality of the presented antenna has merit since the radiation efficiency is calculated at 16.6%. This numerical value is about four times larger than that of a usual antenna without the metamaterial.

Ultra-wide band technology has its merits as it can be utilized in low-power application over short distances. Antennas with good radiation efficiency operating in the UWB spectrum have been a topic of research. In [53], a metamaterial structure based on a frequency-selective surface (FSS) cell is proposed to improve the radiation characteristics of the antenna. The antenna has dimensions of 45 mm × 45 mm, and is integrated near an ultra-wide band (UWB) antenna to enhance its performance. The presented work shows polarization mode independency (transverse electric (TE) and transverse magnetic (TM)). With extensive simulations, it is observed that the radiation efficiency of the antenna is enhanced with the FSS filter at a close distance from the radiator. With improvement in the efficiency, the antenna gain is also improved to 3.22 dBi. These performances make the antenna a potential choice for high radiation efficiency applications. A substrate-integrated metamaterial-based leaky wave antenna is proposed to advance radiation bandwidth.

3.5 SAR improvement

In WBAN, the close proximity of human body poses significant challenges to the wearable antennas and vice-versa.The impact of electromagnetic radiations on human body and the reduced efficiency of the antenna due to electromagnetic immersion in body tissue, fragmentation of radiation pattern, impedance variations and frequency detuning.

These factors call for special attention during antenna design for wearable devices. Developers should focus on structural deformation, accuracy and precision in antenna fabrication methods and size during wearable antenna design.

The Federal Communication Commission (FCC) introduced Specific Absorption Rate (SAR) limits for wireless devices to ensure acceptable radiations level in human body. The SAR limit is set to 1.6 W/kg averaged over 1g of actual tissue, while the limit is set to 2W/kg averaged over 10g of actual tissue by the Council of European Union. SAR is a parameter that is used to measure the rate at which RF (radiofrequency) energy is absorbed by human tissues. SAR values ensure that any wearable device or wireless smart gadget does not exceed the maximum permissible exposure levels. By using metamaterial structure ,the specific absorption rate is decreased by more than 70%, considering the limitations imposed by FCC & ICNIRP as reported in [37 & 49].

3.6 Multiband Operation

Multiband antennas have gained more popularity due to the requirement to combine various functions (several communication systems operation) on a single device. A**s**,MTMs can support negative refraction indexes at resonant frequencies and unit cell structures of symmetric pairs. This can be used to design multifrequency antennas with smaller dimensions than traditional one.

Various techniques can be employed to achieve multiple bands such as triangular electromagnetic resonator (TER) [74], different single CSRR structures (circular, triangular, square, hexagonal, and octagonal) , and metamaterial unit cells in the patch antenna . CSRRs and SRRs [5-54] can be used for obtaining enhanced bandwidth without increasing the overall size of antennas.

Various techniques employed for multiband operation: Multiband property is archived with different shaped strips, such as the C- and L-shapes, the Y-shape, and the rhombus shape. In some other designs, multiband property is archived by etching different slots, such as the U-shape , the F-shape , and the T-shape slots. Recently, meta- materials have been investigated for antenna miniaturization and enabling multiband operation. Different kinds of split-ring resonators (SRRs) are used in antenna designs [5-83]. Among these designs, SRRs were used as radiating elements to surround the radiating elements , or were printed on the ground plane side of the radiating elements.

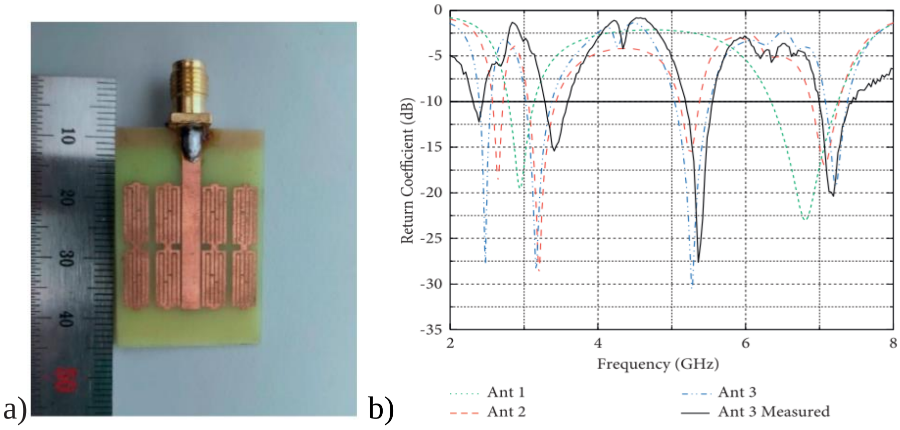

Figure.5. Interdigital LHM antenna a), S11 results at 2.49 GHz, 3.22 GHz, 5.23 GHz, and 7.15 GHz. b) Return loss Charactistics

The proposed antenna has a compact size of 36mm × 24mm × 1mm (0.27λ × 0.18λ × 0.008λ) and is printed on an FR4 substrate with a tangent loss of 0.02. A conventional printed monopole is assumed as the primary antenna. Later, a 4 × 2 array of interdigital LHM is applied to surround the monopole. This LHM is verified with negative perme- ability and permittivity from 2.75 GHz to 3.75 GHz. The proposed antenna works at 2.40–2.55 GHz, 3.02–3.38 GHz, 5.04–5.52 GHz, and 7.08–7.38 GHz.

The loop antenna design follows the Hilbert curve. The proposed antenna includes three Hilbert loops: loop-2 fits inside the empty area of loop-1, and loop-3 fits inside loop-2. The interconnections between two loops are optimized to get good impedance matching, bandwidth, and circular polarization. The connected three loops of antenna increases the overall electrical length hence, provides miniaturization along with the multi-band behavior.

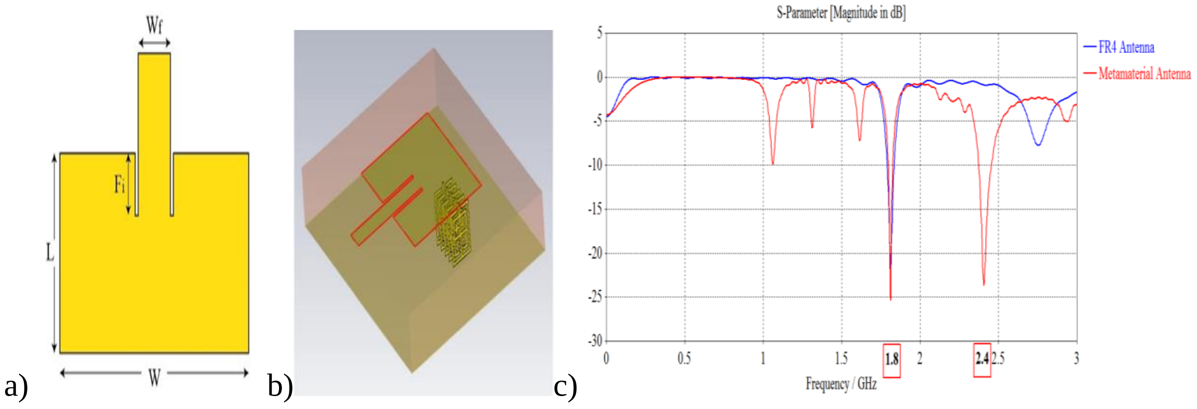

Figure.6. a) Conventional Microstip patch antenna b) With Metamaterial SRRs under the patch c) Dual band characteristics at 1.8 GHz and 2.4 GHz

4. Future Scope and Challenges

With the further advancement in metamaterials, it has potential or future possibilities to achieve high data transfer rate and make it suitable for 5G or 6G communications. The sixth-generation (6G) radio wave communication systems are predicted to be life changing, progressing from “connected things” to “connected intelligence,” with much more stringent performance expectations including very high data rates, very high energy efficiency, massive low latency control, very broad frequency bands, ubiquitous uninterrupted global network coverage, and connected intelligence, in comparison to previous generations of radio wave communication systems. To satisfy the aforementioned demands, artificial intelligence (AI) is a viable technology for next-generation networks. For the design and optimization of 6G with high-level intelligence, AI has been used as a new paradigm, which greatly depends on the novelty in the antenna design.Metamaterial provides a promising solution for this.

More specifically, we require methods for boosting the ESAs' bandwidth and enhancing their radiation effectiveness. Wideband, small, and energy-efficient antennas will be crucial parts of the next generation of wireless communication systems.

The use of artificial magnetic conductor (AMC) surfaces and near-zero refractive index (NZRI) superstrates are required for futuristic antenna design.This is because of the capacity of NZRI superstrates to concentrate electromagnetic energy and the role of AMC as a reflecting surface. Also the metamaterial-inspired gradient-index (GRIN) lenses can increase gain over a broad bandwidth.. Superstrates and beam-steerable antenna integration, however, needs more research.

The highly challenging task is to decouple the radiation from antennas in antenna array design thechniques for MIMO applications.The metamaterial decoupler is inserted between the adjacent radiating parts to achieve this suppression of undesirable coupling in arrays.Another future challenges is the design the electricall small antennas.

5. 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. From scientific research shows that the application of metamaterials in the antenna design can enhance gain, directivity, size, bandwidth, and efficiency . Depending on the design purpose of the antenna, the choice of structure and method of application of metamaterials varies.

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