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A recent survey on zeroth-order resonant (ZOR) antennas

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Abstract

Metamaterials have shown an enormous amount of success in the field of engineering as well as in physics and finds applications in various domains. One such important application of metamaterials i.e., Zeroth Order Resonator (ZOR) antennas is discussed in this article. Metamaterials are manmade materials having properties not found in nature occurring materials i.e., simultaneously negative permittivity (ε) and permeability (μ) over certain range of frequency. Due to these unique properties, metamaterials are used in various antennas to enhance the bandwidth, gain, polarization, radiation patterns etc. The omnidirection radiation pattern is obtained by using ZOR antennas, which is one of the important applications of Composite Right/Left-Handed Transmission Line (CRLH-TL). CRLH-TL uses the properties of metamaterial having exotic properties. This article presents a brief introduction to metamaterials followed by detailed discussion about CRLH-TL and various ZOR Antennas along with their properties. Eventually the applications and radiation patterns have also been studied in this report which will give the researchers an analysis of the research that has already been published.

Keywords Metamaterials · Zeroth Order Resonator · Permittivity · Permeability · Omnidirectional · Composite Right Left Handed Transmission line

1 Introduction

Metamaterials are defined as artificial materials that exhibit unusual but very useful and powerful properties. These are materials which has been engineered to have properties that is not found in nature but gain these properties from structures rather than the composition. Being one of the most extraordinary materials, the metamaterial has become a huge interest for physicists and engineers all around the world. Since the first practical demonstration of negative permittivity [1] and permeability [2] by Pendry et al., the metamaterials have entered into the field of electromagnetics, photonics, etc., having found applications in cloaking [3], antennas [4], cross-polarizers [5], super-lens [6], absorbers [7] and many more. Depending on effective values of permittivity and magnetic permeability, the materials can be classified as Epsilon-Negative (ENG) material [8], Double-Negative (DNG) material [9], Mu-Negative (MNG) material [9] and Double-Positive (DPS) material [10]. Artificial materials have been fabricated using DNG, ENG, MNG and DPS materials.

Resonating wires affect the electric response of the medium while designing metamaterials. The resonating wires give the material negative permittivity. The resonating loops give the material negative permeability. The most common approach for designing metamaterials is to merge structure of negative permittivity with structure of negative permeability. The discovery of negative-refractive index materials dates long back to 1940s when Winston E. Kock developed a material that had similar characteristics to that of a metamaterial. Later Russian Physicist, Victor Veselago, explained about how the properties of a metamaterial can be achieved by reversing the characteristics of a material. Whilst John Pendry suggested for the first time the practical approach for making the metamaterial a reality.

During the last decade, various comprehensive surveys have been published on metamaterial antennas [11–15]. The literature surveys were based upon the size of antennas,

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types of antennas and so on. This survey focuses on various features and applications on Zeroth-Order (ZOR) Antennas, a Composite Right/Left-Handed (CRLH) based resonant antennas. In this survey, we have done a comprehensive literature survey of ZOR antennas based on the classification of miniature antennas. The key features that we have included in this survey are as follows: -

(i). A short review of metamaterial antennas and its classifications.
(ii). Comprehensive literature review of zeroth-order resonant based antennas based on types of miniature antennas like ENG, MNG, etc.
(iii). The literature review also deals with the radiation patterns and the applications of the ZOR antennas which will help researchers to design an optimal structure and obtain a better bandwidth.
(iv). This paper will also help the researchers in the concerned field to analyze and effectively implement a technique in terms of radiation features, particular application, etc.

The outline of the paper is given below. Section 2 presents the basic concepts of metamaterial antennas and its classification. A short description of Zeroth-Order Resonant Antennas (ZOR) is given in Sect. 3. Section 4 presents the radiation patterns corresponding to the applications for each in brief. In Sect. 5, state-of-the-art of various ZOR antennas are presented. A few limitations are discussed in Sect. 5. Finally, we conclude our work in Sect. 6.

2 Metamaterial antennas and its classification

Metamaterial antennas are those antennas that uses metamaterials to increase the performance of electrically small antenna. Like any other antennas, metamaterial antennas can step-up a system's radiation power. These antennas are small but behave as if it were larger than its original size. These antennas have become a part of widely used applications that have been very useful. A metamaterial antenna tends to re-radiate energy because of its novel geometry and is one of the features that makes this material exotic for the scientists to use. These materials take minute antennas as their basis as they cover a wider frequency range and make use of lesser available space. These antennas help in attaining higher gain with the help of materials containing radiating elements.

The metamaterial antennas are often classified into various categories. Several authors have classified the metamaterial antennas. Figure 1 presents the various classification of metamaterial antennas. In this report, we have classified the metamaterial antennas into four categories:

(i). Classification based on CRLH-based Antennas.
(ii). Classification based on Miniature Antennas.
(iii). Classification based on Metaresonator Antennas.
(iv). Classification based on Metasurface Antennas.

2.1 Classification based on CRLH-based antennas

CRLH-based metamaterial antennas are based on transmission line (TL) theory with reference to the parametric circuits. These include antennas that has (i) negative-order resonance, (ii) zeroth-order resonance (ZOR) and (iii) positive-order resonance.

These antennas have been hugely accepted around the world and is a powerful tool for designing and understanding metamaterials. The multiband feature can be achievable using multiple resonances.

(i) *Negative-Order Resonance*: The unique nature of negative order resonance helps in achieving a higher efficiency along with a much smaller antenna size. It is similar to that of a half-wavelength resonator in a simulated electric field distribution plot as observed in x–y plane of a substrate.
(ii) *Zeroth-Order Resonance (ZOR)*: Due to the unique nature of zeroth-order mode, the size of the resonator does not depend on its physical length but only on the amount of reactance provided by its unit cells.
(iii) *Positive-Order Resonance*: The positive-resonant mode is extremely related to a half-wavelength resonator as well.

2.2 Classification based on miniature antennas

Electrically small antennas are achieved by (i) ENG, (ii) MNG, (iii) High-Mu Shells, (iv) near-field resonant parasitic (NFRP) elements [16–18] and (v) magnetic photonic crystals [19, 20]. These antennas have been provided as an alternative to those antennas which had issues with the size and radiation performance.

(i). ENG or Epsilon-Negative: Materials possessing negative permittivity (ε) are known to be Epsilon-Negative. Antennas having these properties are known as Epsilon-Negative Antennas.
(ii). MNG or Mu-Negative Antenna: Materials possessing negative permeability (μ) are known to be Mu-Negative. Antennas having these properties are known as Mu-Negative Antennas.
(iii). NFRP or Near-Field Resonant Parasitic elements: Research involving low-loss materials with negative permittivity or high magnetic permeability can be approximated using NFRP elements, as also known as High-Mu Shells.

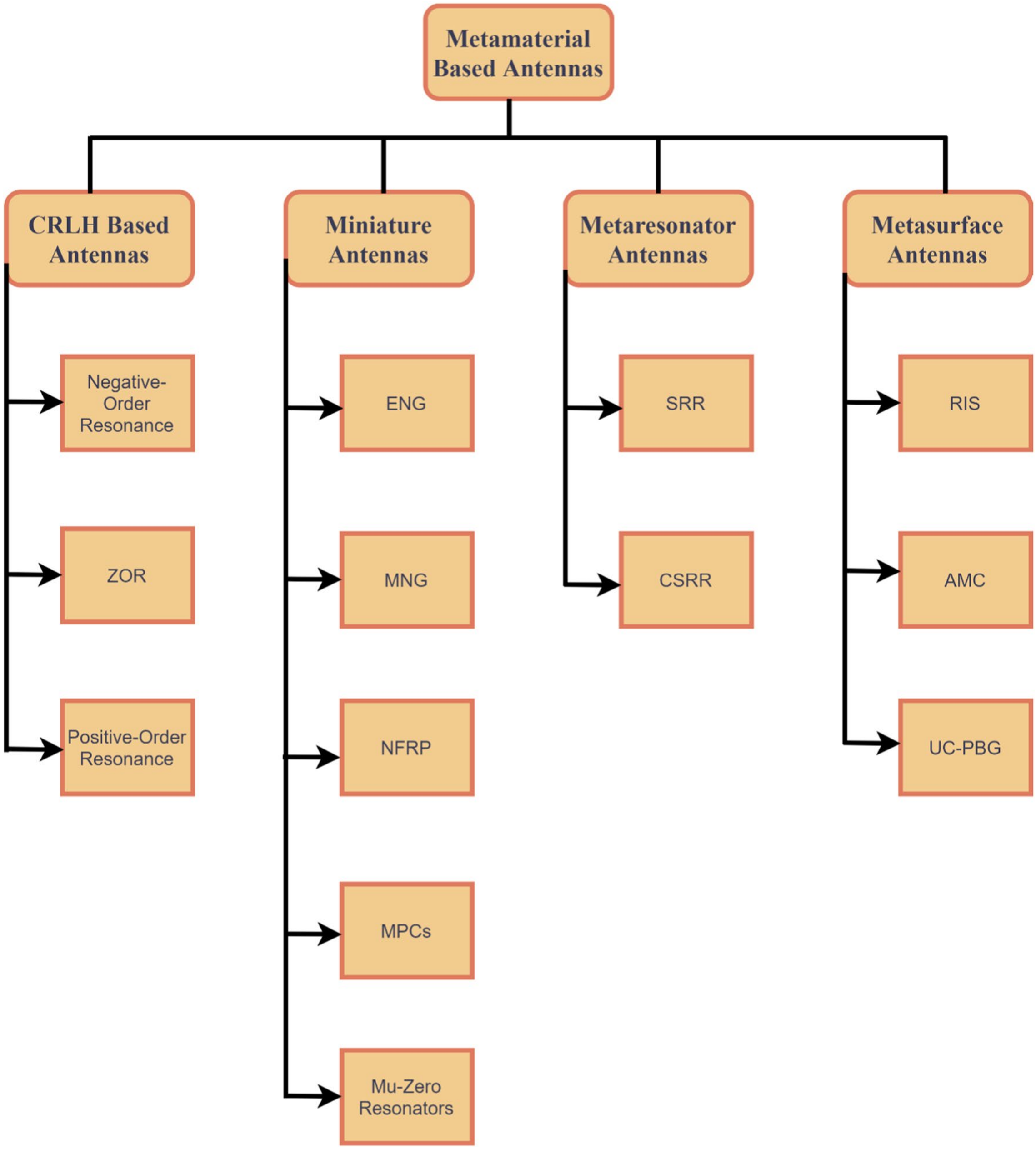


Fig. 1 Classification of metamaterial based antennas

(iv). MPC or Magnetic Photonic Crystals: The small antennas make use of MPC materials which generates slow group velocity modes to produce a satisfactory and acceptable bandwidth.
(v). Mu-Zero Resonators: The realization of Mu-Zero resonance antennas has been done using mu-negative transmission line loadings. These antennas are treated to be equivalent to the ENG antennas.

2.3 Classification based on metaresonator antennas

Antennas based on metaresonators are (i) Split-Ring Resonators (SRR) [21] and (ii) Complementary Split-Ring Resonators (CSRR) [22] -based metaresonator antennas. SRR has been used to synthesize metamaterials as it is considered to be a resonant magnetic dipole. The CSRR has been proven to work as that of an electric dipole.

(i). *Split-Ring Resonators (SRR)*: The split-ring resonators consists of a desired geometrical engineered structure with a gap in between them so as to obtain a desired magnetic permeability. An artificial magnetism is therefore achieved in this case even if metal used for the construction is non-magnetic.
(ii). *Complementary Split-Ring Resonators (CSRR)*: The complementary split-ring resonators are the modified version of the conventional SRRs.

2.4 Classification based on metasurface antennas

Metasurfaces are those materials that are engineered to orchestrate the dispersion properties of surface waves. These being a subfield of metamaterials have also found a wide variety of applications in antennas [23–26]. These are low-profile, less-lossy and easier to fabricate. There are various types of metasurfaces such as (i) RIS composed by metallic patches [27, 28], (ii) AMC or artificial magnetic conductor [24], (iii) UC-PBG or uniplanar compact photonic band gap [26, 29].

(i). *RIS*: The RIS composed by metallic patches not only helps in miniaturizing the size of antennas but also remarkably strengthens the features of both the bandwidth and radiation.
(ii). *AMC (Artificial Magnetic Conductor) or EBG structures*: These are low-profile high-gain antenna. These structure helps in creating uniform radiation which results into high-gain antenna.
(iii). *UC-PBG (Uniplanar Compact-Photonic Band Gap)*

3 Zeroth-order resonator (ZOR) antennas

Zeroth order resonating (ZOR) antenna is based upon zeroth order resonator concepts. The ZOR is basically a composite right/left-handed transmission line (CRLH TL) structure whose resonance frequency is independent of width and length of patch and the height of substrate because of the infinite wavelength. These structures have a uniform vertical electric field towards the ground plane due to which the ZOR antenna has the magnetic loop current along the open sided wall. The survey shows the literature review of a few ZOR antennas with the proposed structure and its applications.

The novelty of metamaterial ZOR antennas has led to a number of applications such as in microwaves, space communications, portable ground-penetrating radars, space vehicle navigation, airplanes and many others. With the help of double-negative (DNG), epsilon-negative (ENG), mu-negative (MNG) materials, ZOR antennas have shown quite fantastic results along with its compact size and better radiation patterns.

4 Radiation patterns of ZOR antennas

The radiation pattern of antennas implies to the graphical representation of the angular or directional dependence of strength of radio waves from an antenna. It is the variation of the power radiated by an antenna as a function of the direction away from the antenna. The electromagnetic radiation patterns are visualized as various shapes like donuts or toroidal or others. The electromagnetic radiations are useful for the calculation of antenna gain of the proposed structure (Table 1).

4.1 Omnidirectional radiation pattern

These radiation patterns can be produced by the simplest of the antennas consisting of one or two straight conductors on a common axis. One can achieve a higher antenna gain with an omnidirectional radiation as the power radiated is maximum in horizontal directions. These radiations can be of two types that is low-gain and higher-gain. The common applications of omnidirectional radiations are the wireless communication systems (Fig. 2).

4.2 Omnidirectional circularly polarized radiation

These radiation patterns are generated when two antennas are excited with the use of equally distributed power and

Table 1 Applications of ZOR antennas corresponding to radiation patterns

Sl. no.	Radiations patterns	Applications
1	Omnidirectional	Wireless Communications (GSM, UMTS, LTE, WLAN, WiMAX), etc
2	Omnidirectional circularly Polarized	Indoor wireless communication, personal mobile systems, etc
3	Dipole	Medical Implantable Communication Service, radiation applications, etc
4	Slot-Like	Navigation Radar, etc
5	Far-Field	Wireless ECG Monitoring devices, etc
6	Unidirectional	Mobile medical microwave imaging, short range communications, etc
7	Conical-Beam	Wireless and mobile communication systems

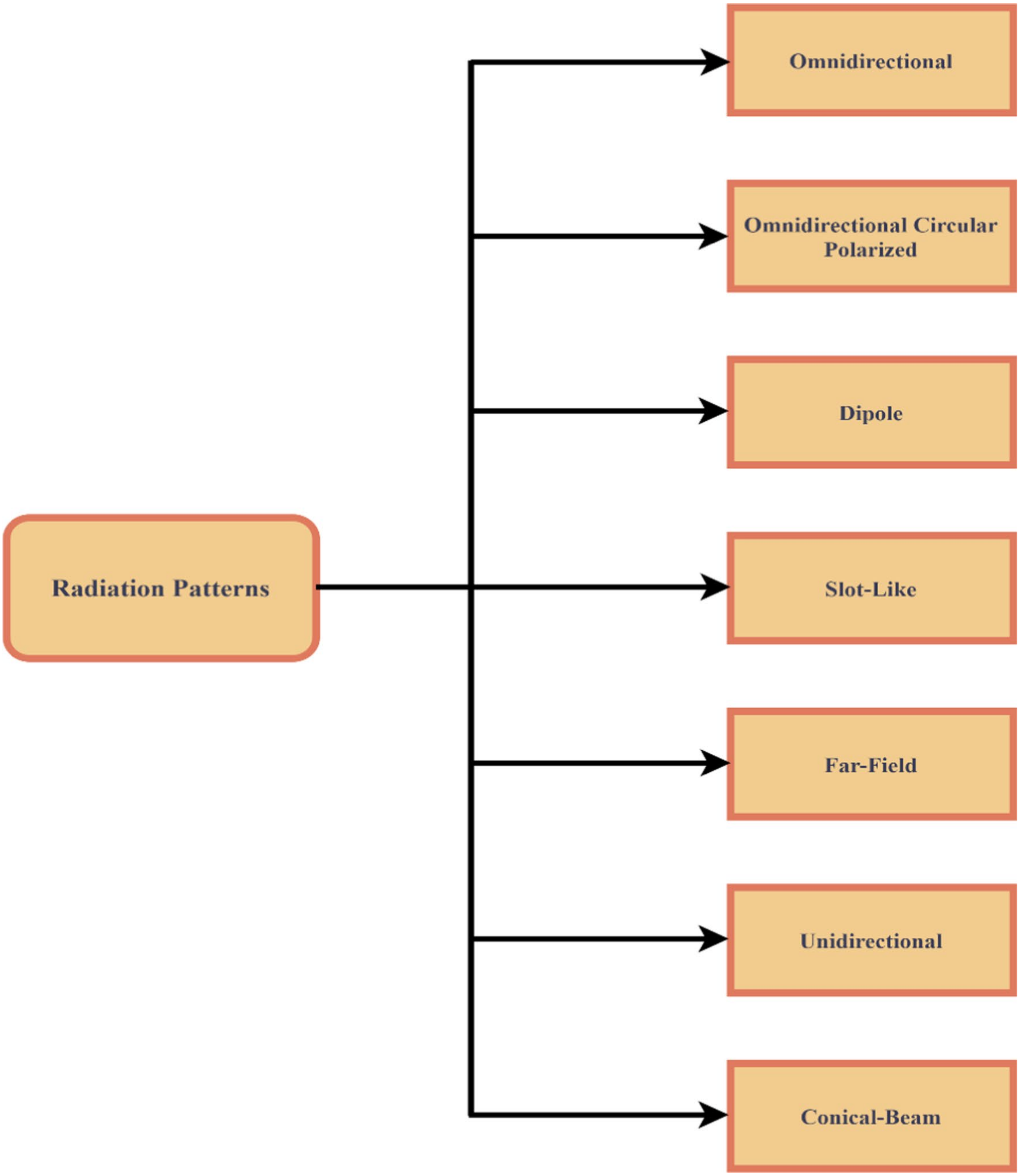


Fig. 2 Radiation patterns of ZOR antennas

has a phase difference of 90 degrees. Microstrip feed networks are generally used to connect the two antennas. The common applications of omnidirectional circularly polarized radiations are indoor wireless communication systems and personal mobile systems.

4.3 Dipole-like radiation pattern

The dipole is omnidirectional in the plane which is perpendicular to the wire axis together with the radiation that falls to zero on the axis. The antennas gain is equivalent to the directive gain for a half-wave dipole. Further enhancements in dipole radiation can be achieved with more substantial directivity. The common applications for this radiation patterns are medical implantable devices and radiation applications.

Slot-like radiation pattern: The slot-like radiation pattern is omnidirectional in the horizontal plane perpendicular to the antenna but narrow in the vertical plane. The applications of slot-like radiation antennas are navigation radar.

4.4 Far-field radiation pattern

This radiation pattern has a uniform wave pattern, but the field strength decreases with increase of the distance between the source and the point. The applications of these radiations are wireless ECG monitoring devices.

4.5 Unidirectional radiation pattern

These radiations are achieved when two similar characteristics modes are combined with a phase difference of 90 degrees. To obtain this radiation, it is not necessary to obtain antennas with complex geometries. The applications of these radiation patterns are short range communication systems.

4.6 Conical-beam radiation pattern

These radiation patterns are achievable by torus knots. Researchers are giving efforts to achieve this radiation pattern as these are applied in microwave applications and is essentially helpful.

5 State-of-the-art

This section contains the resent works of the researchers on different types of Zeroth-Order Resonant (ZOR) antennas. This section is further subdivided into various subsections. Sections 5.1, 5.2, 5.3, 5.4 and 5.5 deals with ENG ZOR, CRLH-TL, MNG ZOR, CPW-fed ZOR and a few other ZORs respectively.

5.1 Epsilon-negative (ENG) ZOR antennas

In this section, we have discussed various recent state-of-the-art epsilon-negative based antennas.

Park et al. [30] shows the zeroth-order resonant antennas with 3-stage epsilon-negative (ENG) and double negative (DNG) ZORs had the same zeroth-order resonance frequencies and the radiation characteristics. These antennas became limited to shunt inductance.

Kim et al. [31] proposed a compact structure that was brilliant for digital video broadcasting-handheld (DVB-H) applications.

Park et al. [32] proposed a mushroom structure with curved branches so as to omnidirectional radiation. The circularly polarized (CP) antenna has found various applications in wireless communications.

Kwon et al. [33] proposed a ZOR antenna that could be implantable in a human body. It has a compact size, low specific absorption rate and tolerant performance which could be easily implanted in a human body.

Park et al. [34] proposed a dual band CP antenna using zeroth-order and first-order resonance structure. A left-hand CP (LHCP) and right-hand CP (RHCP) has been obtained in the two modes, ZOR (lower-band) and first-order resonance (FOR) (upper-band). These structures could be used for modern wireless communications.

Majedi et al. [35] proposed a coplanar stripline (CPS) structure based on ENG TL. These find applications in guided wave and radiation applications.

Niu et al. [36] proposed a bandwidth extension technique of a ZOR and FOR using ENG-TL theory. This structure has additional features such as miniaturized size, extended bandwidth and high efficiency. These find applications in modern wireless communication systems.

Adhithya et al. [37] proposed a triple-band ZOR ENG antenna that had used two series pseudo-open termination (P-OT) unit cells. This structure could work in C-band applications majorly focused on microwave satellites and Wi-Fi (Table 2).

5.2 Composite right/left-handed transmission line (CRLH TL) antennas

In this section, we have discussed various recent state-of-the-art Composite Right/Left-Handed Transmission Line (CRLH TL) Antennas.

Li et al. [38] proposed a structure that was relatively smaller in size and had better selectivity, added symmetrical responses & manageable bandwidth.

Ji et al. [39] proposed a structure that could be used to plan novel wideband metamaterial (MTM) antennas and a few other microwave components for mobile handset applications.

Jung et al. [40] proposed a structure based on coplanar waveguide technology (CPW) that was free of deformation of the substrate which led to robustness of the antenna.

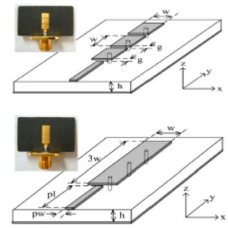
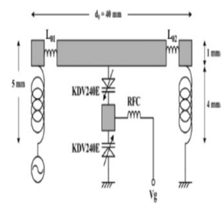
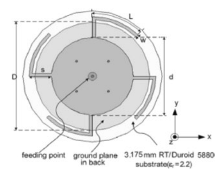
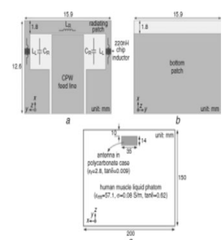
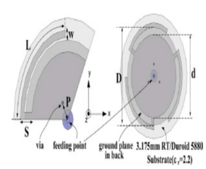
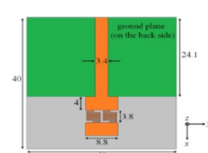
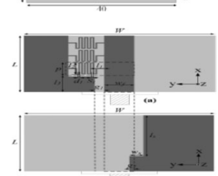
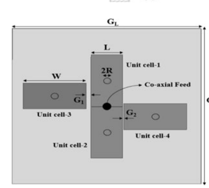
Jang et al. [41] proposed a bandpass filter (BPF) for a ultra-high frequency band which was further miniaturized using MTM ZOR so that its performance could be enhanced. This drives the development of smaller equipment.

Jang et al. [42] proposed a low- and a high- radiation ZOR so as to govern the effectiveness of modelling a resonant 1-D MTM based antenna. These find applications in microwave as well as in other frequency bands.

Xu et al. [43] 2-D proposed a composite right/left-handed transmission line (CRLH-TL) that consists of complementary spilt-ring resonators (CSRRs) along with capacitive gaps in series. These antennas find applications in multifunctional wireless communication systems.

Chiu et al. [44] proposed an unbalanced CRLH-TL which would authorize concurrent excitation of the ZOR series,

Table 2 Summary of recent state-of-the-art of Epsilon Negative (ENG) ZOR Antennas

Ref. no.	Purpose	Geometry	Simulated results	Proposed structure
[30]	Studied good accord of Bloch and Floquet theory with that of full-wave simulation	FR4 substrate: Dielectric constant = 2.2 Size of cells: x = 3.5 mm, y = 7, 10.5, 14 mm resp. Size of antenna = 3.5 × 7 × 1.57 mm	Frequency = 9.8, 10, 10.2, 10.4 GHz Gain = 3.37, 4.63, 5, 5.55 dBi Gain variation = 2.22, 3.49, 3.08, 4.05 dBi	
[31]	Studied an antenna that governs a digital video broadcasting-handheld band application	FR-4 substrate: dielectric constant = 4.4 thickness = 1 mm Size of antenna = 40 mm x 5 mm x 5 mm	Gain = 4 dB more than reference gain	
[32]	Studied the pattern to obtain omnidirectional radiation and vertical polarization	FR4 substrate Dielectric constant = 2.2	Frequency = 8 MHz Average axial ratio = 1.83 dB	
[33]	Studied an implantable ZOR	FR4 substrate Thickness = 1.6 mm Dimension s = 15.9 × 12.9 × 1.6 mm Liquid phantom = 200 × 400 × 150 mm	Frequency = 9 MHz SAR value = 1.54 W/kg Source power = 11.8 mW	
[34]	Studied LHCP and RHCP in ZOR and FOR modes	RT/Duroid 5880 substrate Dielectric constant = 2.2	Frequency at ZOR = 10 MHz and 9 MHz Frequency at FOR = 33 MHz and 38 MHz	
[35]	Studied a compact antenna using ENG-TL for different ground size	Taconic RF-35 substrate Thickness = 1.524 mm Dielectric constant = 3.5 Size of antenna = 40 × 40 mm^2	Frequency = 2.75, 2.71, 2.69 GHz Gain = 2.74, 2.77, 3.01 GHz	
[36]	Studied bandwidth extension characteristics	F4B-2 substrate Dielectric constant = 2.65 Thickness = 1.6 mm	Frequency = 1.77 to 3.57 GHz	
[37]	Studied a triple-band ZOR using P-OT unit cells	RT Duroid 5880 substrate Dielectric constant = 2.2 Thickness = 1.57 mm	Frequency = 5.95 GHz, 6.26 GHz, 6.91 GHz Gain = 2.19 dBi, 1.39 dBi, 1.14 dBi	

which would be determined by series inductance and periodical capacitance, along with shunt resonances, which could be determined by shunt capacitance and loaded shunt inductance.

Li et al. [45] proposed a dual-band omnidirectional CP structure using CRLH-TL. This structure is designed for unmanned aerial vehicle transmission of images.

Li et al. [46] proposed a dual-band ZOR structure using CRLH-TL to obtain a compact multiband antenna design for a smart mobile phone. This structure particularly finds applications in antenna covering GSM850/900 and DCS1800/PCS1900/UTMS and also in other wireless communication terminals.

Sam et al. [47] proposed a frequency reconfigurable substrate integrated waveguide-digital capacitor (SIW-IDC) antenna. This finds applications in low-cost printed circuits board (PCB) so as to make ultra-high-speed digital applications.

Kim et al. [48] proposed a CRLH structure without using any via-holes. This structure could be integrated within the ECG sensor device and further be placed on human body phantom by reducing severe radiation efficiency during wireless electrocardiogram (ECG).

Yang et al. [49] proposed a reconfigurable antenna based CRLH-TL and had been fed by asymmetric coplanar strip (ACPS). The antenna could work on single-bands as well as on dual-bands. All these find applications on UMTS, ISM, WiMAX, WLAN (Table 3).

5.3 Mu-negative (MNG) ZOR antennas

In this section, we have discussed various recent state-of-the-art Mu-Negative (MNG) ZOR Antennas.

Lee et al. [50] proposed a mu-negative (MNG) ZOR which would improve radiation efficiency with the help of current cancellation in between the conductor strip of antenna.

Wei et al. [51] proposed a structure based on MNG-TL. The antenna is a horizontal polarized omnidirectional planar loop antenna. These find applications in wireless local area network (WLAN) and in MIMO antennas.

Rezaeieh et al. [52] proposed a wideband and unidirectional structure that showed an enhanced and stable gain. The structure was loaded with MNG cells. These structure finds applications for mobile medical microwave imaging and few others in short range communications.

Chen et al. [53] proposed a dual-band CP structure with the help of etching dumbbell-shaped slots on ZOR and FOR modes. These find applications in wireless communications (Table 4).

5.4 Coplanar waveguide (CPW)-fed ZOR antennas

In this section, we have discussed various recent state-of-the-art Coplanar Waveguide (CPW)-Fed ZOR Antennas.

Jang et al. [54] proposed and analyzed a structure of a CPW-fed ZOR antenna which has a reduced size, higher efficiency, easy manufacturing and an extended bandwidth and can be widely used in microwave circuits and various applications of antenna.

Lai et al. [55] proposed a compact ZOR structure which constituted inductor-loaded (IL) and capacitor-loaded (CL) CPWs. These could predict the reflection coefficients of the inputs for the proposed antenna and exhibited a higher radiation efficiency.

Hong-Min Lee [56] proposed a compact CPW-fed ZOR with a modified ground plane. This structure improves efficiency along with reduction of frequency of the antenna.

Chen et al. [57] proposed a single-layer asymmetric CPW (ACPW) structure based on low profile ZOR antennas. These have been widely used in microwave circuit and antenna designs because of anti-parallelism phase, zero propagation constant and group velocities.

Wang et al. [58] proposed a CPW-fed structure for bandwidth extension based on CRLH-TL. The good radiation and wide bandwidth characteristics made this structure suitable for GSM/UMTS/LTE/WLAN communication systems.

Chi et al. [59] proposed a compact and bandwidth-enhanced ZOR antenna. Also, CPW was used to develop a via-less uniplanar antenna.

Li et al. [60] proposed a multiband monopole antenna based on CPW. This structure had satisfactory omni-directional radiation patterns. These find applications in modern communication systems.

Sharma et al. [61] proposed a structure based on CPW-fed MTM along with backed ground plane. This structure provided extended bandwidth and a miniaturized size. These find applications in LTE, WLAN and WiMAX.

Lee et al. [62] proposed a structure based on ACPW along with a modified ground plane based on CRLH-TL.

Jang et al. [63] proposed a structure based on ZOR using stretchable micromesh that could provide a high degree of freedom with an added benefit of semi-transparency. These find applications in flexible and stretchable wearable devices (Table 5).

5.5 A few other ZOR antennas

In this section, we have discussed various recent state-of-the-art a few other ZOR Antennas.

Lee et al. [64] proposed a novel antenna which constituted a zeroth-order resonance (ZOR) whose frequency is independent of physical length. The absolute gain was found to

Table 3 Summary of recent state-of-the-art of composite right/left-handed transmission line (CRLH TL) antennas

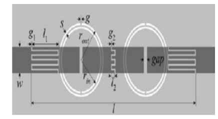
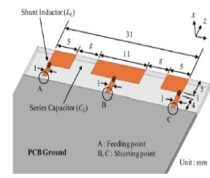
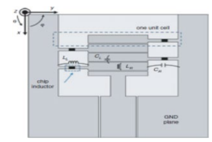
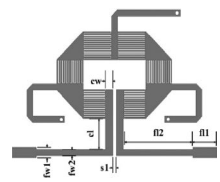
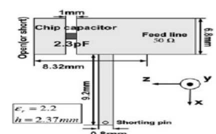
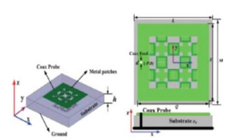
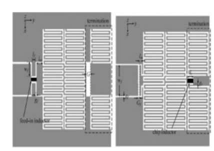
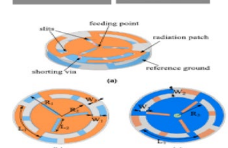
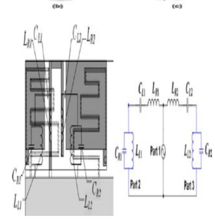
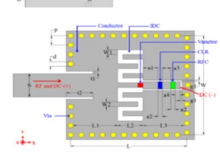
Ref. no.	Purpose	Geometry	Simulated results	Proposed structure
[38]	Studied the method to obtain the resonant frequency	FR4 Substrate = 1.5 mm Dielectric constant = 2.65	Frequency = 1.93 GHz Insertion loss = 1.7 dB	
[39]	Studied an antenna which could extend the bandwidth of metamaterial antennas	Gap = 5 mm PCB size = 40 × 100 × 0.8 mm^3 Ground size = 40 × 90 × 0.8 mm^3	Gain = 1.05 to 3.35 dBi Efficiency = 41.5% to 66.6%	
[40]	Studied the independence of substrate using ZOR	Different curvatures D = 30, 50, 70 mm and a flat surface	Frequency = 2.45 GHz Peak gains = 0.89, 0.69, 1.13, 1.39 dBi	
[41]	Studied the improvisation to isolate from other wireless communication bands	Non periodic MTM ZOR filter with L_c = 1.2 nH, C_c = 2.6 pF	Frequency = 900 MHz Loss < 1 dB	
[42]	Studied ZOR to have a compact size and wider bandwidth	Teflon TLY-5 substrate Permittivity = 2.2 Height = 2.37 mm	Frequency = 9.59 GHz Gain = 5.9 dBi	
[43]	Studied a 2-D resonant CRLH TL	2 × 2 CRLH array and two RH section patches	Frequency = 4.5 GHz Gain = 2.6 dBi	
[44]	Studied an unbalanced CRLH-TL	Duroid 5880 Dielectric constant = 2.2 Size of antenna = 0.14 λ_0 × 0.16 λ_0	Frequency = 2.4 and 3.0 GHz Peak gain = 1.47 dBi and 1.71 dBi	
[45]	Studied a dual band omnidirectional ZOR	Dielectric substrate height = 3.175 mm Permittivity = 2.2	Frequency = 2.4 GHz and 5.8 GHz Gain = 1.75 dBi and 1.73 dBi	
[46]	Studied a dual-band antenna for smart mobile phones	FR4 substrate Size = 122 × 60 × 1 mm^3 Dielectric constant = 4.4 Size of antenna = 12 × 25 mm^2	Frequency = 5.4 GHz	
[47]	Studied an antenna for designing low-cost PCBs	Roger/Duroid 5880 substrate	Frequency = 4.13 GHz to 4.50 GHz	

Table 3 (continued)

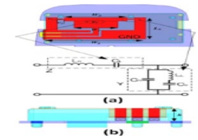
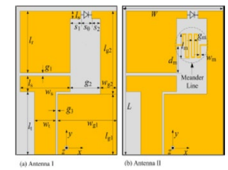
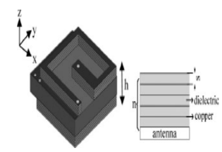
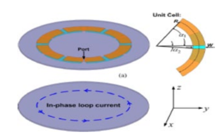
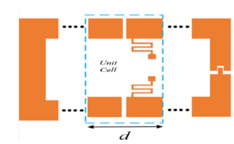
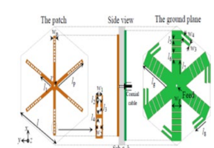
Ref. no.	Purpose	Geometry	Simulated results	Proposed structure
[48]	Studied an antenna for wireless ECG sensors	PCB substrate Permittivity = 2.2 Thickness = 0.5 mm	Frequency = 2.4 GHz	
[49]	Studied a reconfigurable antenna	RO4350B substrate Dielectric constant = 3.48 Thickness = 0.762 mm	Single band frequency = 2.08–2.54 GHz Dual-band = 1.65–1.84 GHz and 5.35–6.40 GHz	

Table 4 Summary of recent state-of-the-art of Mu-Negative (MNG) ZOR Antennas

Ref. no.	Purpose	Geometry	Simulated Results	Proposed Structure
[50]	Studied to improve the efficiency of radiation in ZOR	FR4 substrate Dielectric constant = 2.2 Thickness = 1.57 mm	Bandwidth = 3 dB Efficiency = 18.66%	
[51]	Studied horizontal polarization of MNG-TL antenna	Teflon substrate Dielectric constant = 2.65	Frequency = 2.4 GHz Gain = 6.5 to 7.9 dBi	
[52]	Studied a wideband and unidirectional ZOR	FR4 substrate Thickness = 0.8 mm	Frequency = 0.76 to 1.07 GHz Peak gain = 4.5 dBi	
[53]	Studied an etched dumbbell-shaped dual-band CP antenna	Hexagonal FR4-epoxy substrate Dielectric constant = 4.4 Height = 3.2 mm	Frequency: ZOR = 2.31 to 2.46 GHz FOR = 3.32 to 3.6 GHz	

be 2.6 dBi and the gain variation was 1.5 dBi along with an operation frequency of 7.9 GHz.

Ji et al. [65] proposed a structure that could be sued for handheld wireless mobile systems. The antenna was made by using double negative (DNG) ZOR and was initiated for GSM850/1800/1900, WCDMA, and WiBro operations.

Ko et al. [66] proposed a hybrid ZOR structure so as to obtain a broad beamwidth. The modes used are TM_{010} and ZOR modes. The proposed has benefits of a smaller size, a single layered-structure and a simple mushroom structure.

Yang et al. [67] proposed a compact, via-free and bisected ZOR structure that had been based on bisected interdigital capacitor-loaded TL (B-CL-TL). This structure showed improvised bandwidth and better radiation efficiency.

Kang et al. [68] proposed a structure for null compensation which is rectangular in shape. To compensate the nulls, the electric- and magnetic- loop current was made to be orthogonal to each other. This structure had features like reduced space and low profile.

Ko et al. [69] proposed a folded mushroom ZOR structure which resulted into a wider bandwidth. To obtain the same, frequency of TM_{010} was down-shifted so that the mushroom structure of the ZOR mode could be folded without adding any additional feature.

Table 5 Summary of recent state-of-the-art of Coplanar Waveguide (CPW)-Fed ZOR Antennas

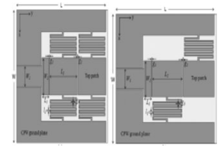
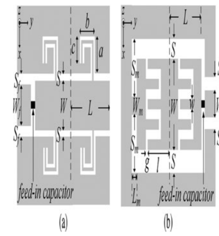
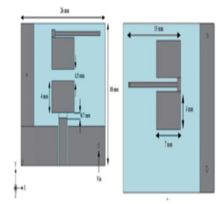
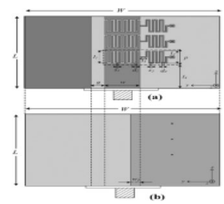
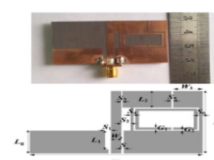
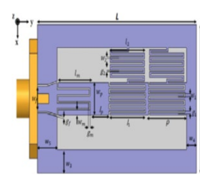
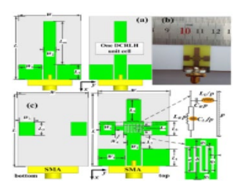
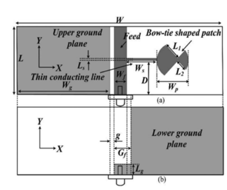
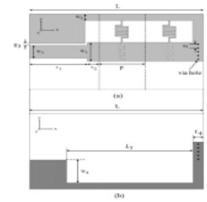
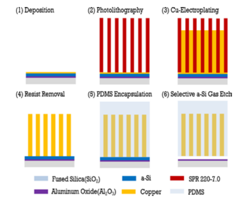
Ref. no.	Purpose	Geometry	Simulated Results	Proposed Structure
[54]	Studied CPW ZOR to reduce the size of antenna	FR4 substrate Dielectric constant = 2.2 Thickness = 1.6 mm	Frequency of symmetric antenna = 2.03 GHz Asymmetric = 1.5 GHz	
[55]	Studied the prediction of reflection coefficients of the inputs of ZOR	FR4 substrate Thickness = 1.6 mm Dielectric constant = 4.4 Size of antenna = 12.8 × 16 × 1.6 mm	Frequency = 2.5 GHz Peak gain = 1.1 dBi	
[56]	Studied the improvisation of efficiency in ZOR	FR4 substrate: Length = 4 mm Thickness = 0.8 mm Permittivity = 4.4 Antenna = 26 × 18 mm^2	Frequency = 2.3 GHz Peak gain = 2.3 dBi	
[57]	Studied a low-profile ZOR based on ACPW	RT/Duroid 5880 substrate Dielectric constant = 2.2 Area f radiation = 28 × 50 × 1.57 mm^3	Frequency = 1.94 GHz Peak gain = 2.3 dBi	
[58]	Studied a CPW-fed to achieve bandwidth extension	F4B-2 substrate Dielectric constant = 2.65 Thickness = 1.5 mm	Frequency = 240 MHz to 840 MHz Gain = 4.13 dB	
[59]	Studied bandwidth enhancement of ZOR	RT/Duroid 5880 substrate Thickness = 1.57 mm Dielectric constant = 2.2	Frequency = 2.16 GHz Gain = 1.62 dBi	
[60]	Studied a CPW-fed multiband monopole antenna	Epoxy resin bonded fiber substrate Permittivity = 4.3 Thickness = 1.5 mm	Frequency = 5.71 GHz	
[61]	Studied a CPW with backed ground	FR4 epoxy substrate Dielectric constant = 4.4 Thickness = 1.6 mm	Frequency = 2.4 GHz Gain = 1.5 dB	

Table 5 (continued)

Ref. no.	Purpose	Geometry	Simulated Results	Proposed Structure
[62]	Studied an ACPW with modified ground plane	Rogers RT/Duroid 5880 substrate Dielectric constant = 2.2 Thickness = 1.57 mm	Frequency = 2.69 GHz to 9.15 GHz	
[63]	Studied a stretchable micromesh ZOR	Tortuous Cu micromesh/PDMS substrate Dielectric constant = 2.8 Thickness = 4.7 µm	Frequency = 2.92 GHz Gain = -0.02 dBi	

Peng et al. [70] proposed a EZR (epsilon-zero resonance)—MZR (mu-zero resonance) resonator for a CP antenna. This structure has a low profile ZOR feature and high design efficiency.

Mehdipour et al. [71] proposed a structure of a low-profile monopole antenna which had ZOR and CSRR features. These find applications in vehicular wireless applications and general wireless communications.

Sharma et al. [72] proposed a structure of dual-band characteristics. The structure consisted of series gap, racial stub and meander line inductor. These find applications in GPS, WiMAX and WLAN.

Dai et al. [73] proposed a dual-band microstrip structure that could create horizontal magnetic loop current o the patch that generally led to low-profile at a low frequency band.

Wu et al. [74] proposed a rectangular mushroom-like structure to design a dual-band wireless-systems. This structure could be used for WLAN applications and was also suitable for wireless handheld devices.

Chang et al. [75] proposed a zeroth-order self-oscillating active integrated antenna (AIA) which had been integrated by a pair of ZORs with a cross-coupled pair. This could operate at UHF radio-frequency identification (RFID) band.

Peng et al. [76] proposed a structure that comprised of EZR-MZR resonator and had been used to design quasi-isotropic antenna. This structure had high efficiency and was electrically small in size. These find applications with different RFID frequency.

Ragazzo et al. [77] proposed a novel electromagnetic visible imaging (EMVI) which was used to visualize and quantify the amplitude of a magnetic or electric field. These find applications in civil or defense applications.

Panda et al. [78] proposed a highly efficient RF coil for achieving ultra-high magnetic field systems. This structure had a high performance eight-channel dipole-based RF coil for 10.5 T MRI system. These find applications in clinical high-quality imaging.

Luo et al. [79] proposed a programmable ZOR along with the configuration of a employed active element PIN diodes. This structure needs less than 1 V of supplying voltage which is remarkably lower than all other elements such as MEMS or Varactors.

Sun et al. [80] proposed a microstrip patch of hybrid mode technology and had been used to design 2-D wide angle scanning planar phased array. This structure had a simple structure, a low-profile and convenient fabrication (Table 6).

6 Limitations and challenges of zeroth-order resonance (ZOR) antennas

The basic features anticipated of an electrically small antennas are low radiation resistance and high reactance. The fundamental limitations of an electrically small antennas are the bandwidth, quality factor and operating frequencies. In the last two decades, various works has been contributed to the field of Metamaterial ZOR antennas. But still, there are various limitations and challenges in the

Table 6 Summary of recent state-of-the-art of a few other ZOR Antennas

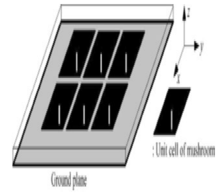
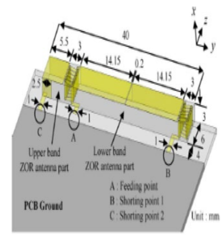
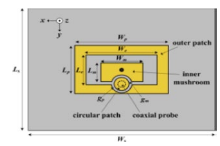
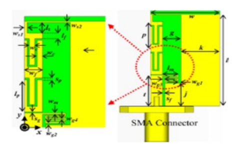
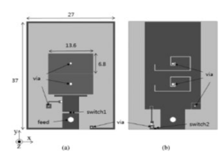
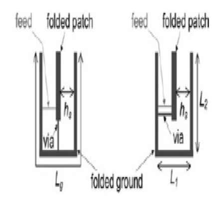
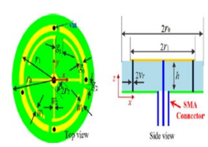
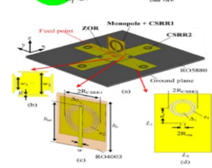
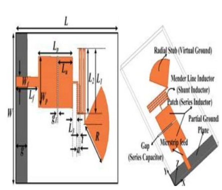
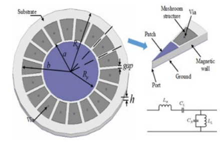
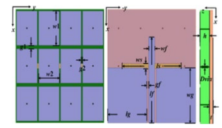
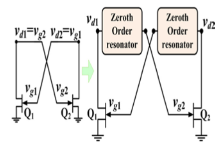
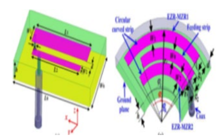
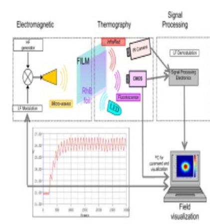
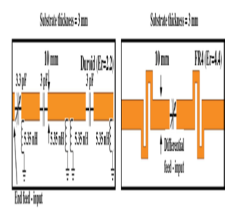
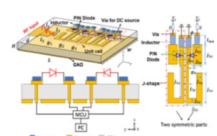
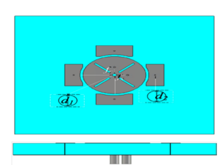
Ref. no.	Purpose	Geometry	Simulated Results	Proposed Structure
[64]	Studied a low-profile radiation antenna omnidirectionally	Gap = 0.2 mm Wire diameter: 0.3 mm, Patch = 4.8 mm × 4.8 mm Antenna = 22 mm*22 mm	Frequency = 7.9 GHz Absolute Gain = 2.6 dBi Gain Variation = 1.5 dBi	
[65]	Studied a compact multiband antenna	Size of PCB = 50 mm × 100 mm × 0.8 mm PCB ground = 50 mm × 90 mm Distance of antenna from PCB = 4 mm	Lower band, gain = 1.14 to 2.53 dBi, efficiency = 53% Upper band, gain = 0.07 to 2.35 dBi, efficiency = 51%	
[66]	Studied a hybrid ZOR patch antenna	RT/Duroid 5880 Dielectric constant = 2.2 Height = 3.175 mm	Frequency = 5.74 GHz	
[67]	Studied a B-CL-TL ZOR antenna	FR4 dielectric board Thickness = 1.6 mm	Frequency = 2.21 GHz Gain = 1.4 dBi	
[68]	Studied a dual antenna for null compensation	RT/Duroid 5880 Dielectric constant = 2.2 Thickness = 1.57 mm	Frequency = 2.3 GHz Gain = 4.3 dBi	
[69]	Studied a folded mushroom ZOR	Patch width = 10 mm Ground width = 14 mm Substrate dielectric constant = 1	Gains = 3.32 and 3.41 dBi	
[70]	Studied a omnidirectional CP antennas based on EZR-MZR	Diameter = 57 mm Height = 4 mm	Frequency = 1.5444 GHz	
[71]	Studied a monopole antenna	RO5880 substrate Dielectric constant = 2.2 Thickness = 1.57 mm	Frequency = 800 MHz to 6 GHz Gain = 23 dB	
[72]	Studied a MTM dual-band antenna	FR4 epoxy substrate Dielectric constant = 4.4 Thickness = 1.6 mm	Peak gain = 1.82 dB and 2.15 dB	

Table 6 (continued)

Ref. no.	Purpose	Geometry	Simulated Results	Proposed Structure
[73]	Studied a dual-band ZOR that had monopolar patch	Substrate thickness = 1.5 mm Dielectric constant = 2.65	Frequency = 4.01, 5.24, 5.94 GHz Gain = 5.8 to 8 dBi	
[74]	Studied a rectangular mushroom-like structure	FR4 substrate Dielectric constant = 4.4	Frequency = 2.37 to 3.09 GHz and 4.7 to 5.88 GHz	
[75]	Studied a AIA ZOR	Rogers 4003C substrate Dielectric constant = 3.55 Thickness = 1.52 mm	Frequency = 0.92 GHz Gai = 0.3 dBi	
[76]	Studied an electrically small EZR-MZR antenna	Substrate dielectric constant = 2.2 Height = 6 mm	Frequency = 1.5 GHz Gain = 3.58 dB	
[77]	Studied a EMVI method which was used to propose thermooptic imaging sensor	RhB-epoxy fluorescent film = 20 µm Kapton-graphite = 30 µm Thick FLEX film = 25 µm	EMVI heating profiles = 33 to 39 dBm (2 to 8 W)	
[78]	Studied a ZOR for 10.5 T MRI system	Rogers RT/Duroid 5880 substrate Dielectric constant = 2.2 Thickness = 3 mm	SAR value = 3.2 W/kg at 447 MHz	
[79]	Studied a programmable ZOR	FR4 substrate Dielectric constant = 4.3	Frequency = 5.26 GHz	
[80]	Studied a 2-D wide angle scanning planar phased array	Substrate Dielectric constant = 2.3 Thickness = 1.5 mm	Frequency = 446 GHz	

development of ZOR antennas. In this section, the various limitations and challenges of ZOR antennas are discussed.

The quality factor of a resonator is not yet reduced which can enhance bandwidth of a ZOR antenna prototype. Many structures still need to work on the narrow bandwidth issues as they are unable to meet practical demands due to not so good operating frequencies. Narrow bandwidth channels work on small amounts of data and those antennas which has lower speed. There is a loss of energy which gets created by the unbalanced currents on the ground plane and sheath of the coaxial cable. A triple-band ZOR antenna does not have very good fractional bandwidths.

7 Conclusions and future scope

In this report, we have presented a brief overview of Zeroth-Order Resonant (ZOR) Antennas. Along with it, we have also presented a detailed classification of metamaterial antennas which has been performed by various researchers. Further, the report presents the various radiation patterns alongside the applications of ZOR antennas. Finally, we have presented the state-of-the-art ZOR antenna approaches by different researchers followed by limitations and challenges of the existing proposed structures [81].

Based on the extensive discussion in the previous sections, it has been found that an electrically small antenna works best as they have the lowest radiation resistance and the highest reactance. In a single structure it is very difficult to address these issues. A researcher can further work on these for developing a structure to address these issues. With a proper designed structure of the interdigital capacitor, the Q-factor of a resonator can be reduced. A researcher can work on the Q-factor so as to enhance bandwidth of an antenna. Due to narrow bandwidth issues, it is impossible to reach practical demands. The researchers can work on operating frequencies to fix this issue. Specific Absorption Rate (SAR) value in M-ZOR coils shows a loss of energy. The researchers can reduce the SAR value by embedding capacitors and make a planar circuit board.

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