Review of Metasurfaces Through Unit Cell Design and Numerical Extraction of Parameters and Their Applications in Antennas

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ABSTRACT
A thorough review of metasurfaces (2D planar counterpart of metamaterials) based on electromagnetic (EM) classification i.e., ε-negative (ENG), µ-negative (MNG), and double-negative (DNG) materials is presented in this paper. The concept of left-handedness in metasurfaces which comprise of ENG, MNG, and DNG is demonstrated through basic Maxwell’s equations. This concept is then explained by designing unit cells of each category along with numerical extractions of parameters through Kramers-Kronig rule (for ENG) and Nicholson-Ross-Weir (NRW for MNG and DNG), thereby verifying unit cell designs. This helps the reader to have complete insight regarding the design, simulation, and mathematical verification of ENG, MNG, and DNG-based metasurfaces used in antenna applications for gain enhancement, absorbers to reduce radar cross-section and beam forming. Moreover, the paper also provides a thorough review of the state-of-the-art research based on these metasurfaces in antenna applications delineated above. A comparison of the state of the art is drawn at the end of this review.

INDEX TERMS
Metamaterials, negative refractive index materials, metasurface antennas, lens, gain enhancement, beam forming, and beam scanning.

I. INTRODUCTION
In 1999, the word “Metamaterial” was first coined by Walser who interpreted metamaterials as the fabricated 3-dimensional periodic structures synthesized to produce materials having exotic properties, which are not occupied by the materials present in nature [1]. Afterward, it was then appeared in the literature in 2000 [2]. Generally, metamaterials are the periodic arrangement of man-made structures having a size much smaller than the operating wavelength.

On the other hand, metasurfaces are the 2D correspondents of metamaterials. This type of ultra-thin and 2D structure serves to mitigate undesirable losses and strong dispersions in wave-propagation and is suitable for easy fabrication of micro and nano-structures [3].

The classification of metamaterials is based on the constitutive parameter values i.e., double-positive (DPS) in which both µ and ε are positive, ε-negative (ENG) µ-negative (MNG), and double negative (DNG) [4], [5], [6], [7]. Among these categories, dielectrics, magnetic materials, and plasmas are materials that exist in nature with DPS, MNG, and ENG values, respectively. But a DNG material does not exist in nature and has been engineered for production [8]. In this regard, Veselago published the first study on the properties of materials with negative permittivity and permeability simultaneously in [9]. Since then, this technology has been experimentally demonstrated in different forms for many applications with unique modifications. The initial DNG structure which was based on a 3D cylindrical Split-Ring-Resonator for DNG media and an array of metallic cylinders for ENG media was originally developed by Pendry et al., in [14]. However, the proposed structure wasn’t applicable for 2D planar structures and exhibited non-isotropic properties (showing null magnetic response in other directions) including the flow of current that occurs along the length of the cylinders which is undesirable [88]. Therefore, the need for periodic and packed array structures emerged replacing cylindrical structures to prevent continuous
mathematically by parameter extraction. The state-of-the-art each classification and verifying these through simulation and classifications of metasurfaces by designing the unit cell of a comprehensive overview about the basic electromagnetic [87], and perfect absorbers [88], [89], [90], [98], lens applications [80], [81], [82], [83], [84], [85], [86], [87], and directivity enhancement [72], [73], [74], [75], [95], [96], and DNG), metasurface antennas are being catered for gain MTs antennas [76], [77], [78], [79]. Moreover, based on the size miniaturization and wide bandwidth miniaturized applications in gain enhancement along with size miniaturization [72], [73], [74], [75] and wide bandwidth miniaturized MTS antennas [76], [77], [78], [79]. Moreover, based on the electromagnetic classification properties (i.e., ENG, MNG and DNG), metasurface antennas are being catered for gain and directivity enhancement [72], [73], [74], [75], [95], [96], [98], lens applications [80], [81], [82], [83], [84], [85], [86], [87], and perfect absorbers [88], [89], [90].

The objective of this paper is to provide the readers with a comprehensive overview about the basic electromagnetic classifications of metasurfaces by designing the unit cell of each classification and verifying these through simulation and mathematically by parameter extraction. The state-of-the-art research will be reviewed based on the classification and their potential applications.

The paper is organized as follows, metasurfaces are classified based on $\varepsilon$ and $\mu$ values in Section I. For each classification, the metasurface based unit cell is designed, simulated, and numerical extraction of the parameters is carried out in Section II to give readers a comprehensive understanding of the designing process and parameters extraction of metasurfaces. Afterward, the state-of-the-art is discussed based on classified metasurfaces and their potential applications, especially in antenna designs in Section III. In the end, the conclusion and recommendations are provided in Section IV.

II. CLASSIFICATION OF META SURFACES

As discussed above, electromagnetic properties of materials are classified based on constitutive parameters i.e., permittivity ($\varepsilon$) and permeability ($\mu$), which produce ENG, MNG, and DNG materials [4], [5], [6], [7]. The relationship between the refractive index 'n' and the constituent parameters $\varepsilon$ and $\mu$ is given by the formula in [5]:

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

As shown in Fig.1, the electromagnetic metamaterials/metasurfaces are classified based on the values of $\varepsilon$ and $\mu$ in different quadrants.

![FIGURE 1. The classification of electromagnetic metamaterials/metasurfaces [5] @ IntechOp.](image)

Fig. 1 demonstrates that in quadrant I, both $\varepsilon$ and $\mu$ are positive forming a double-positive structure (DPS) or right-handed medium (RHM) which are easily found in nature such as dielectric materials in which EM waves can propagate. While in quadrant II, $\varepsilon$ is negative and $\mu$ is positive, composing ENG i.e., epsilon negative medium which has properties like electric plasma. On the other hand, in quadrant III, both $\varepsilon$ and $\mu$ are negative giving a double negative (DNG) or left-handed medium (LHM) which are not found in nature. The quadrant IV contains negative $\mu$ and positive $\varepsilon$, representing mu-negative (MNG) media, such as ferrite materials. From Fig.1, it is evident that waves can propagate in two media
lying in regions I and III, while the non-propagating evanescent waves are found in regions II and IV. The ambiguity of how these waves travel backward in a left-handed medium is cleared well by Maxwell’s equations. For this purpose, consider the fundamental equations as given in [5].

$$\nabla \times \vec{E} = -j\omega \mu \vec{H} - \vec{M}_s$$  \hspace{1cm} (2a)

$$\nabla \times \vec{H} = j\omega \varepsilon \vec{E} + \vec{J}_s$$  \hspace{1cm} (2b)

where $\vec{E}$ and $\vec{H}$ are electric and magnetic field vectors, while $\vec{M}_s$ is the magnetic current density and $\vec{J}_s$ is the electric current density. Considering a plane wave, the electric ($\vec{E}$) and magnetic ($\vec{H}$) field vectors are represented as:

$$\vec{E} = \vec{E}_0 e^{-j\vec{\beta} \cdot \vec{a}}$$  \hspace{1cm} (3)

$$\vec{H} = \vec{H}_0 / \eta e^{-j\vec{\beta} \cdot \vec{a}}$$  \hspace{1cm} (4)

where $\vec{\beta}$ is wave propagation constant and $\vec{a}$ is the decay constant, while $\eta$ is the intrinsic impedance.

Now the information about the medium can be directly obtained by substituting the relations (3) and (4) into (1) and (2) respectively. For simplicity, consider source-free regions where $\vec{M}_s = \vec{J}_s = 0$. Hence, after differentiation the response for the right-handed medium (where $\varepsilon, \mu > 0$) is as follows:

$$\vec{\beta} \times \vec{E} = +\omega |\mu| \vec{H}$$  \hspace{1cm} (5a)

$$\vec{\beta} \times \vec{H} = -\omega |\varepsilon| \vec{E}$$  \hspace{1cm} (5b)

On the other hand, for the case of a left-handed medium (where $\varepsilon, \mu < 0$), therefore the left-handed triplet would be as follow:

$$\vec{\beta} \times \vec{E} = -\omega |\mu| \vec{H}$$  \hspace{1cm} (6a)

$$\vec{\beta} \times \vec{H} = +\omega |\varepsilon| \vec{E}$$  \hspace{1cm} (6b)

The magnitudes of $\varepsilon$ and $\mu$ are used to cater for the sign convention in the third quadrant. The relations in (5) and (6) form right-handed and left-handed triplets ($\vec{E}, \vec{H}, \vec{\beta}$), where $\vec{\beta}$ is the phase constant or wavenumber i.e., $k = \frac{\omega}{\varepsilon_0} = \beta$.

Fig. 2 shows the response of right-handed and left-handed triplets in terms of pointing vector $S$, which determines energy flow response in terms of $\vec{E}$ and $\vec{H}$ vectors as follow:

$$S = \frac{1}{2} \vec{E} \times \vec{H}$$  \hspace{1cm} (7)

As the frequency is always positive, hence the response of phase velocity $v_p$ determines that either the medium is right-handed or left-handed, by the following relation:

$$v_p = \frac{\omega}{\beta} \text{ (where } \vec{\beta} = \beta / |\beta|)$$  \hspace{1cm} (8)

Relation (8) shows that, for right-handed medium, relation (5) is in-phase with phase velocity which is dependent on phase response $\beta$, while for the left-handed medium, relation (6) is out of phase with phase velocity. Hence $\beta$ is the factor to decide the response for both mediums i.e.,

$$\beta > 0, \quad v_p > 0 \quad \text{--- for RH - medium}$$

$$\beta < 0, \quad v_p < 0 \quad \text{--- for LH - medium}$$

This antiparallel phase response can be better demonstrated by the generic phase lag and lead concept of a wave. Fig. 3(a) shows that the phase of wave 5 lags behind the phase of wave 1 with respect to time, thus the progression of the wave in a forward direction with a lagging (or positive) phase response establishes a right-handed medium. As both $\beta$ and $v_p$ is positive in this case, therefore according to the relation (8), both are parallel to each other. On the other hand, Fig. 3(b) shows that the phase of wave 5 leads the phase of wave 1 with respect to time, and develops a left-handed medium as the wave moves in a forward direction with a leading (or negative) phase response, as making $v_p$ negative also, according to relation (8). Thus, the wave is traveling in the forward direction with negation phase velocity, producing an anti-parallel phase response. This notion is demonstrated in Fig.3 [6].

The combined effect of a group of waves traveling in the forward direction is demonstrated in Fig.4, by the parallel and antiparallel phases between phase velocity $v_p$ and group velocity $v_g$ (envelope), for right-handed and left-handed medium respectively.

This concludes that for left-handed medium, phase velocity $v_p$ is anti-parallel to group velocity $v_g$ with phase advance of propagating wave. Moreover, in terms of wave number $k_n$ i.e.,

$$\beta = k_n = nk_0 = n \frac{\omega}{c}$$  \hspace{1cm} (9)

where

$$n = \pm \sqrt{\varepsilon \mu}$$  \hspace{1cm} (10)

The LH-medium contains $\beta < 0, n$ is must less than 0 forming a negative refractive index with properties having negative $\varepsilon_r$ and $\mu_r$ [6]. Based on these classifications, the next section demonstrates the ENG, MNG, and DNG effect through unit cell design simulations along with the verification of results.

![FIG. 2. Right-handed medium (a), Left-handed medium (b) [5] @ IntechOpen.](image_url)

| Parameters | Value (mm) |
|------------|------------|
| R          | 3.375      |
| Sw         | 4.65       |
| H, Hs      | 7          |
| W, L       | 7          |
| Ws         | 2.5        |

TABLE 1. Parameters of ENG unit cell.
through mathematical extraction of the parameters. This is done so that the readers may be provided with the basic information regarding the unit cell design and parametric extraction both using simulation and mathematics in the single platform. This will further help the readers to understand the state of the art which is presented in Section III.

III. ILLUSTRATING THE CLASSIFICATION BY DESIGNING UNIT CELLS

A. ENG BASED METASURFACE

It is demonstrated in the literature that ENG metamaterial is produced by using the metallic mesh of thin cylindrical wires for obtaining a negative value of $\varepsilon$ [7]. However, this thin cylindrical wire-media is not being applicable for 2D metasurface structures. Therefore, a new unit cell is designed to get negative epsilon value at the desired resonance frequency (6.2 GHz) to produce a 2D ENG metasurface. The designed unit cell structure is depicted in Fig.5, and its parameters are given in Table 1. It should be noted here that any other resonance frequency may be selected for unit cell design. For illustration purposes, the authors are using 6.2 GHz.
The designed structure contains a circular patch having radius $R$ with a square slot of dimension $d \times d$, and an Alumina substrate ($\varepsilon = 9.9$ and $\tan \delta = 0.0001$). If we consider an array of this unit cell, then below a cut-off frequency of the array there is no propagation, and an electromagnetic wave will experience total reflection. This behavior is similar to the propagation of the electromagnetic waves in plasma. If a lattice constant ‘a’ (i.e., the distance between unit cells) is much smaller than a wavelength ($a \ll \lambda$), the array structure can be thought of as a continuous plasma like material described by an effective permeability $\mu_{eff}$ in [7] as:

$$\mu_{eff} = 1 - \frac{f_p^2}{f^2}$$  

(11)

where $f_p$ the plasma frequency and $f$ is the resonant frequency. To design a unit cell at a resonance frequency of 6.2 GHz, the condition $f_p > f$ must be fulfilled to keep permittivity negative. The equation relating $f_p$ and design
where \( a \) is the lattice constant and \( r \) is the radius of a circle. In the proposed design, the radius is 3.375 mm, while the lattice constant \( a \) should be 7 mm to get \( f_p > f \).

The cell is designed using a CST simulator to achieve desired results. The boundary conditions i.e., PEC and PMC are defined in the y- and z- directions respectively, as shown in Fig.6.

\[
\omega_p^2 = \frac{2\pi c_0^2}{a^2 \ln(a/r)}
\]  

### TABLE 3. Parameters of DNG unit cell.

| Parameters | Size (mm) | Parameters | Size (mm) |
|------------|-----------|------------|-----------|
| \( r_1 \)  | 1.8       | \( g \)    | 0.165     |
| \( r_2 \)  | 2.4       | \( d \)    | 0.2       |
| \( c \)    | 0.4       | \( W, L, L_s \) | 6         |
| \( W_s \)  | 2.35      | \( S \)    | 0.375     |

### FIGURE 11. Unit cell’s geometry. (a) Front-, (b) Back-, (c) Side-view.

### FIGURE 12. CST Model of DNG unit cell.

### FIGURE 13. DNG-based Unit Cell. (a) S-parameters, (b) \( \varepsilon \) and \( \mu \) results.

### FIGURE 14. (a) Image currents due to PEC (b) and due to AMC (c) Theoretical model of antenna located above AMC loaded metasurface [1] @IEEE.
1) RESULTS AND DISCUSSION

Fig. 7 shows the simulated S-parameters, \( \varepsilon \), and \( \mu \) results. The designed unit cell exhibits ENG properties with a negative \( \varepsilon \) value and positive \( \mu \) value at the resonance frequency. Now to verify these characteristics, Kramers-Kronig relations [92] are utilized to extract the effective relative permittivity (\( \varepsilon_{\text{eff}} \)), and permeability (\( \mu_{\text{eff}} \)) with the following relations:

\[
\begin{align*}
\varepsilon_{\text{eff}} &= \pm \sqrt{\frac{(1 + S_{11})^2 + S_{21}^2}{(1 - S_{11})^2 - S_{21}^2}} \\
R_{01} &= \frac{\varepsilon_{\text{eff}} + 1}{\varepsilon_{\text{eff}} - 1} \\
e^{i\omega k_d d_{\text{eff}}} &= \frac{S_{21}}{1 - S_{11} R_{01}} \\
n_{\text{eff}} &= \frac{1}{k_{0d} d_{\text{eff}}} \ln(|e^{i\omega k_d d_{\text{eff}}}|) \\
e_{\text{eff}} &= \frac{n_{\text{eff}}}{z_{\text{eff}}} & \mu_{\text{eff}} &= n_{\text{eff}} z_{\text{eff}}
\end{align*}
\]

Where \( m \) is an integer denoting the branch index of a complex logarithm, i.e., \( m=0,1,2,... \), (keep it zero for the initial branch), \( d_{\text{eff}} \) is the thickness of the unit cell, \( k_0 \) is the wavenumber. Using the equations (13)- (17), the calculated values of \( \varepsilon \) and \( \mu \) comes out as, \( -59.46 \) and \( 79.1 \) respectively, which are close to simulated results, i.e., \( -57.06 \) and \( 40.73 \).

B. MNG BASED METASURFACES

For the mu-negative (MNG) structure, the split ring cylindrical model is presented in [14]. But due to its non-isotropic behavior and flow of current along the length of the cylinder, the design was modified as a disc-like SRR suitable for planar applications [18], [19], [20], [21], [22], [23]. In this section, a unit cell of the SRR consisting of two concentric metallic rings, separated by a gap \( g \) is designed. The structure is designed using Rogers RT 5870 substrate (\( \varepsilon = 2.33 \) and \( \tan \delta = 0.0012 \)). The geometry of the unit cell and its designed model in CST are shown in Fig.8 and Fig.9, respectively. While all the parameters are mentioned in Table 2.

To design SRR at the desired frequency, the following relation is used [93]:

\[
f_0 = \frac{1}{2\pi \sqrt{LC}}
\]

The inductance of the ring can be calculated using the following relation [93]:

\[
L = \mu_0 R_m \left( \ln \left( \frac{8R_m}{t + c} \right) - 0.5 \right)
\]

where \( R_m = r_1 + c/2, t \) is the thickness of copper, \( c \) is the width of circular rings, and \( \mu_0 \) is free space permeability.

In this model, the total capacitance is the sum of gap capacitance \( C_{\text{gap}} \) and surface capacitance \( C_{\text{sur}} \). Now to find \( C_{\text{gap}} \), and \( C_{\text{sur}} \) following equations will be used [93]:

\[
C_{\text{gap}} = \varepsilon_0 \frac{ct}{g} + \frac{2\pi}{\ln\left(\frac{2.4c}{g}\right)}
\]

\[
C_{\text{sur}} = \frac{2\varepsilon_0}{\pi} n_1 \ln \frac{4r_1}{g}
\]

where \( g \) is the cut slots of circular rings.

After getting the values of \( C_{\text{gap}} \) and \( C_{\text{sur}} \), the split ring resonator can be designed at the desired resonance frequency by relation (18). For this model, the boundary conditions i.e., PEC and PMC are applied in the x- and z- directions respectively.
1) RESULTS AND DISCUSSION

After simulating the unit cell in the CST microwave studio, the desired results fully satisfy the mu-negative characteristics. The unit cell has negative $\mu$ and positive $\varepsilon$ values at the resonant frequency. The simulated results are shown in Fig. 10.

To verify the negative $\mu$ and positive $\varepsilon$ values mathematically, the Nicolson Rose Weir (NRW) method [94] is used. The procedure utilized by NRW method is deduced from the following equations:

$$X = \frac{S_{21}^2 - S_{11}^2 + 1}{2S_{11}}$$  \hspace{1cm} (22)

The reflection coefficient is:

$$\Gamma = X \pm \sqrt{X^2 + 1}$$  \hspace{1cm} (23)

The transmission coefficient will $T$ be:

$$T = \frac{S_{11} + S_{21} - \Gamma}{1 - (S_{11} + S_{21})\Gamma}$$  \hspace{1cm} (24)

$$\frac{1}{\lambda^2} = -\left[\frac{1}{2\pi L} \ln(1/T)\right]^2$$  \hspace{1cm} (25)

The permeability is given as:

$$\mu_r = \frac{1 + \Gamma}{\pi (1 - \Gamma) \sqrt{1/\lambda_0^2 - 1/\lambda^2}}$$  \hspace{1cm} (26)
The permittivity is given as:

$$\varepsilon_r = \frac{\lambda_0^2}{\mu_r} \left[ \frac{1}{\lambda_c^2} - \frac{1}{2\pi L} \ln(1/T) \right]$$  \hspace{1cm} (27)

where $\lambda_0$ and $\lambda_c$ are free-space and cut-off wavelengths respectively, while $L$ is the sample’s length. Using the above equations, the calculated values from NRW method for $\varepsilon$ and $\mu$ are $-7.88$ and $2.13$ respectively, thus verifying the simulations.

C. DNG BASED METASURFACES

The study on DNG property was first theorized in [9], and first practically demonstrated in [14]. To that end, a design was presented to achieve DNG characteristics by combining the thin wire-based ENG structure with the SRR-based MNG structure [15]. This combination satisfies the requirement of $\varepsilon < 0$ from a wire/rodmed medium and $\mu < 0$ from a split ring resonator (SRR). In this paper, the same methodology is adopted and the unit cell which was designed for MNG material is considered with an edition of thin metallic wire at the backside of the substrate to fulfill the requirement of $\varepsilon < 0$, and few changes are made in design parameters to design DNG based metasurface. The geometry of the proposed unit cell is shown in Fig. 11. While Fig.12, shows the designed model in CST, and Table 3 provides parameter values of DNG based unit cell.

1) RESULTS AND DISCUSSION

The simulated results show that the desired DNG characteristics of the proposed design with negative $\mu$ and $\varepsilon$ values are achieved, that is $-3.01$ and $-0.7$ respectively.
To verify the negative $\mu$ and $\varepsilon$ values numerically, the NRW method [94] is again considered to calculate $\mu$ and $\varepsilon$ values from the S-parameters, which come out as $-4.36$ and $-5.1$ respectively.

The metasurfaces are used in the literature to design antennas to achieve improved performance in terms of gain, bandwidth, beam steering, scanning, polarization, etc. The state-of-the-art vis-à-vis uses of different metasurfaces for improving antenna performance are discussed.

IV. STATE OF THE ART

A. GAIN AND DIRECTIVITY ENHANCEMENT

The gain enhancement of an antenna is related to other properties including improved radiation characteristics, high directivity, reduced surface waves, and back radiations [95]. According to Snell’s law, when the refractive index of a material is negative (e.g., DNG materials), the waves converge twice, and the source image is created at two points which leads to an increase in the directivity and gain consequently [5], [6]. Considering the initial designing approach, a superstrate structure surrounded by the arrays of artificial magnetic conductors (AMCs) is placed above (or below) the radiating patch to enhance the antenna’s gain, because when a metamaterial layer is used as a superstrate for a patch antenna it can increase both directivity and gain of the antenna [96]. Here it is important to mention that metamaterials are employed in antennas as artificial magnetic conductors (AMCs),
because in AMCs, conductive current and the image current are in-phase, rather than out of phase. This implies that the reflection phase from AMC and PEC (perfect electric conductor) for a normal incident plane wave is equal to $0^\circ$ and $180^\circ$ respectively. And when these AMCs are incorporated into antennas, the structure act as a high-impedance surface (HIS) [1]. The scheme is shown in Fig. 14.

Adopting this concept, the Fabry-Pérot cavity model in [96] provides a high gain antenna of 14.1 dBi. In [96], the model was conceptualized by a metamaterial superstrate structure containing planar DNG metamaterials having a negative refractive index placed above the radiating patch resulting in 11.2 dBi of gain at 2.3 GHz frequency. The whole scheme is shown in Fig. 15.

Considering more significant gain enhancement led to antenna design in [97] as shown in Fig. 16. The design contains more than one metamaterial-based superstrate layer above radiating patch to provide a strong guiding medium to the radiations which contributes to the significant gain enhancement of 17.1 dBi at 9.4 GHz.

Although the above-mentioned designs are good for increasing antenna’s gain at the cost of increasing the size and thickness of antennas. Hence, these are not suitable for low-profile planar structures. Therefore, the prototypes in [72] and [73] and in [74] and [75] for 5G communications were reported to achieve high-gain antennas with miniaturized size. The proposed antenna in [72] has an octagon structure, metasurface with two-stacking layers, and ground plane. The excitation is done through a microstrip line and a slot etched on a ground plane. This design provides the maximum gain of 11.8 dBi over the variation of 1.7 dBi in the frequency range of 4.48 GHz-6.0 GHz, and 9.7 dBi with the variation of 1.5 dBi over the frequency range of 6.0 GHz-7.8 GHz. The antenna geometry and results are shown in Fig. 17.
In technological innovation over time, this notion of gain enhancement was penetrated into 5G communications with a more low-profile design without an air gap between substrates, as illustrated in [74]. In [74], a metasurface containing square rings is stacked directly above a slotted radiating patch having truncated corners (for circular polarization) without air gap making the prototype low-profile for planar structures as shown in Fig.18. In this proposed scheme, metasurface act as high impedance surface, which supports in phase reflections i.e., at a resonance frequency of 27 GHz (this is the radiating patch frequency), the phase reflection of 0°, and ±90° from metasurface resulted in a wideband antenna of 24 – 34.1 GHz frequency with a maximum gain of 11 dBi and reduced size of 12 × 12 × 1.02 mm³.

Further research investigation into this strategy led to the latest antenna design reported in [75], with an even smaller size having just a single substrate layer containing a radiating patch surrounded by a metasurface lattice of periodic patches. The configuration was being used to design an antenna having wide-bandwidth, single metasurface layer, low profile, circularly polarized characteristics, suitable for 5G mm-wave systems, and MIMO applications as shown in Fig.19. The antenna provides a high gain of 11 dBi over the wideband frequency range of 24.5 - 31 GHz, with a size of 12 × 12 × 0.51 mm³.

Similarly, for a lower frequency range, i.e., near 6 GHz, one of the noticeable works was presented in [98] for gain and bandwidth improvement. The proposed antenna in [98] consists of a patch antenna with a cross-slot for circular polarization and a simple square patch metasurface that excites multiple-resonances to improve the antenna’s axial ratio up to 33.25% (5.64-7.89 GHz), along with gain and bandwidth up to 12.17 dBi and 65.06 % respectively, as shown in Fig.20.

**B. LENS METASURFACES**

Metamaterials owing negative refractive index properties are widely used as flat lens antennas which focus electromagnetic waves to increase directivity and gain. This unique feature amplifies and centralizes the evanescent and propagating ways in the materials which possess negative refractive index (NRI) [47]. For understating, Fig.21 presents the concept of lens metamaterial. Metamaterials act as transmit-array-focused lenses, to focus the waves at a single point in the forward direction. While metamaterials can also focus the rays in a backward direction through a reflect-array-focused lens.

Conventionally, for long-haul microwave communications, phase shifters were used as lens antennas for beam scanning objectives, which makes the design large, complex, and power-hungry for high data rate requirements. In the compensation, researchers came up with a new approach of lens metasurface antennas, which not only perform beam scanning operations more efficiently as compared to phased arrays system but also kept the design miniaturized and less power consumption. Hence, these metasurfaces-based lens antennas are highly applicable for collimating broadband microwaves both at transmit and reflect mode, beam steering, gain enhancement, radar cross-section reduction, broadband spectrum for 5G communication, and spatial beam forming for 5G and sub-6 GHz massive MIMO multi-beam systems.
As evident from Fig. 21, that metasurface-based lens performance can be categorized in two ways i.e., transmit-array focused lens and reflect-array focused lens based on classified EM properties. There is a third category as well, which comprises the lens antennas performing both transmission and reflection functions simultaneously. All these categories are discussed below.

1) TRANSMITTER METASURFACE LENS ANTENNAS

To focus the incident EM waves transmitted from the horn feed antenna, metasurface-based lens antennas re-transmit the waves as the plane waves after the phase adjustment by phase shifter elements (i.e., unit cells). In [80] an ultra-thin, tri-layered metasurface-based planar lens contains 22 split rings resonators to collimate microwave beams in transmission mode at 9 GHz frequency with a gain of 17 dBi. Here the split ring resonator metasurface is sandwiched between metal grating which is perpendicularly oriented as shown in Fig. 22. This resonator supports forward and backward cross- and co-polarized waves generating a highly focused transmissive beam with a gain of 17 dBi over the phase variation from 0 to 2.5π.

On the other hand, in [81] the dual-band transmissive gradient metasurface-based lens antenna for two operating bands i.e., C- and X-bands is presented. The model was designed to have a four-layer structure with the same structures at layers 1 and 4 and another same structure at layers 2 and 3 (naming it ABBA system) to obtain highly
focused transmitted waves at both frequencies. After illuminating from different polarizers, gradient metasurface (GMS) operates at $f_1$ and $f_2$ with phase distributions of $\varphi_{xx}$ and $\varphi_{yy}$ respectively as:

$$\varphi_{xx} = k_1 \left( \sqrt{F^2 + x^2 + y^2} - F \right)$$

$$\varphi_{yy} = k_2 \left( \sqrt{F^2 + x^2 + y^2} - F \right)$$

The general schematic diagram of GMS is shown in Fig.23.

For the proposed design, under the different polarizers, GMS combines the incident waves of two lenses having the same focal length $F$ at the frequencies $f_1$ and $f_2$. There are two notable features of this design, first one is the two operating modes are highly isolated from each other due to the perpendicular EM modes, and secondly, as EM waves are not interacting with each other, hence, the proposed antenna work efficiently at two operating bands resulting in highly directive beams of gain 18.7 dBi and 23 dBi for $f_1$ and $f_2$ respectively. The whole topology is shown in Fig.24.

In [82], the authors came up with a unique model to cater certain problems related to multi-beam lens antennas in microwave bands including small prototype size, low profile with no air gaps between substrate layers, wide bandwidth, dual-polarization, and low side-lobe levels (SLLs). Hence, it produced a novel prototype to provide a 5-layered metasurface-based reflectionless, wide bandwidth i.e., 1.71-2.2 GHz, multibeam (i.e., beams at $0^\circ$ and $\pm 30^\circ$), polarization-free lens antenna, with $\pm 45^\circ$ polarizer as the feeding antenna having the gain ranging from 10-13.5 dBi within $\pm 30^\circ$ coverage span. The results were verified for the beams at $0^\circ$ and $30^\circ$. The schematics and results are shown in Fig.25.

2) REFLECTOR METASURFACE LENS ANTENNAS

As metasurface-based lens antennas focus the beams on transmissive mode, likewise, reflector metasurface lenses focus...
the beams on reflective mode. In reflector lenses, the ground is a must to prevent backward radiations. This methodology is best demonstrated by [83], in which a metasurface-based ultra-thin reflect-arrays lens is designed to perform beam collimation in reflected mode at 30° off-axis from the center to avoid interference issues with the feed antenna offering 27.5 dBi high gain at 11.8 GHz operating frequency. Moreover, the resonators that are employed in this prototype cover a phase range of 360°. The complete topology is shown in Fig. 26.

The same idea [84] also presents the reflect-array lens, but it is designed to administer a multi-spectral beam deflection and collimation at two different operating frequencies. In this design, the metasurface is composed of two-layered metallic patterns of different resonators, backed by a ground plane, i.e., the top layer contains a cross-line structure for developing phase response of reflected wave from 0° to 180°, while the bottom layer contains I-shaped patterns of topological morphing to devise gradient-phase distribution. Hence, reflected waves are being controlled freely, after being fed by the linear polarizer, and the model deflects the beams for the K-, X-, and Ku bands. Therefore, the design is capable to reduce radar cross-section efficiently. The schematics are shown in Fig. 27.

3) TRANSMIT AND REFLECT METASURFACE ANTENNAS

By combining the effects of DNG and MNG/ENG properties with the help of designed unit cells, a metasurface lens antenna can be devised which can transmit and reflect the incident waves. Therefore, the design proposed in [85] is analogous to this concept. In [85], a new bifunctional metasurface lens antenna was proposed to transmit and reflect incident waves (from the Vivaldi antenna feed source) simultaneously, by focusing x-polarized and y-polarized incident waves at the reflection and transmission side respectively, keeping focal length unchanged. This means that for the transmit array, the feed antenna is y-polarized and for the reflect array the feed antenna is rotated 90°, making it x-polarized. In addition, due to the rotation of the feed antenna, the reflect array can divert the beam at 147.5°, to prevent feed antenna blockage. The design consists of a 4-layered unit cell to cover a 360° phase span, with different geometry of cells for transmission and reflection purposes, as shown in Fig. 28. The antenna yields two highly directive beams for E//y (transmit-array) with the gain of 21.4 dBi and E//x (reflect-array) with the gain of 20 dBi at 10 GHz. The antenna’s configuration and results are shown in Fig. 28.

Another very important trait of lens metasurface is the application for beam-scanning antenna used in 5G massive MIMO systems, demonstrated in [86]. It consists of a thin planar metasurface-based lens antenna containing two substrate layers with an air-gap having array of discrete unit cells for a phase shift to realize the multi-beam spatial beam-steering over the range of −27° to +27°. The feeding network consists of a stacked-patch, seven-element substrate integrated waveguide (SIW) antenna structure, which transmits and receives EM waves at the operating band of 28 GHz, backed by metal ground for the suppression of back-radiations as shown in Fig. 29. The prototype was designed by considering and properly addressing the three key challenges associated with the planar lens structures i.e., the gain and radiation efficiency should be high, minimum thickness of the structure, and the proper positioning of the focal arc, as it ensures the high gain throughout the scanning range. Hence, a suitable prototype for 5G massive MIMO systems having a high gain of 24.2 dBi, and beam-steering of ±27° range with stable radiations over the range of 26-29 GHz is proposed.

Adopting the same designing approach, the new metasurface lens antenna in [87] was designed to perform beam-steering for massive MIMO and multi-beam at the sub-6 GHz band (or 5G mm-wave band). The design is presented with some changes in the structure as compared to [86], like
the metasurface-based lens now composed of three substrate layers containing array unit cells to modify the phase of the incident and reflected waves as shown in Fig. 30. Moreover, the lens antenna is fed by stacked patch planar, $8 \times 8$ array structure to produce 64 dual-polarized beams, suggested for full dimension massive MIMO at 5G mm-wave band. Hence, the antenna with the desired characteristics of beam-steering within the range of $\pm 25^\circ$, producing a maximum gain of 22.4 dBi over the operating of 5.17-6.10 GHz is realized in [87].
FIGURE 29. Configuration of the proposed antenna. (a) Top and perspective view of Jerusalem Cross (JC) unit cells for phase shifting, (b) Side-view of the metasurface lens loaded SIW fed elements, (c) Measured result of beam scanning at 28 GHz by the antenna, (d) Simulated and measured results of gain and aperture efficiency [86] @IEEE.

FIGURE 30. Architecture of proposed antenna. (a) Phase-shift Elements, (b) Configuration of lens and feeding structure, (c) Gain of proposed lens antenna feeding at different ports, (d) Fabricated prototype of the structure [87] @IEEE.
As it can be inferred, above mentioned beam scanning metasurfaces can’t be incorporated for planar structures due to the large size and huge air gap between substrate layers. Hence, a novel topology was devised in [99], in which beam-scanning approach was conceptualized through a planar metasurface-based lens antenna. The prototype yields distinguishable results with $\pm 60^\circ$ beam-steering range, along with 22.2% impedance bandwidth and 21dBi gain of 8 $\times$ 8 array structure as shown in Fig. 31.

4) ABSORBER METASURFACES
The absorber antennas are highly demandable to avoid detection from radars. As it is stated before that by combining an ENG slab with an MNG slab, a perfect absorber antenna was designed and reported in [88] as shown in Fig. 32. The model consists of two resonators i.e., electric ring resonator to provide coupling and a metallic wire to provide magnetic coupling. Both resonators couple electric and magnetic fields separately to absorb incident waves completely, as the absorbance rate is unity. The antenna works at the operating frequency of 11.5 GHz.

The wideband absorbers are more in demand as compared to a single band. Therefore, [89] proposes an ultra-wideband
FIGURE 33. Topology of absorber metasurface proposed. (a) Unit cell configuration, (b) top and (c) bottom view of metasurface, (d) Simulated and measured results of proposed absorber, (e) at different polarization angles, (f) for incident waves in TE mode, (g) for incident waves in TM mode [89] @IEEE.

metasurface-based absorber to meet the requirement. In [89], the absorber consists of two metasurfaces with different unit cell geometry in the upper and lower layers, with an air-gap between the layers. The model comprises three layers, where the upper layer contains unit cells having the geometry of the four complementary circular sectors to abate its coupling with the lower frequency metasurface. While the lower layer contains unit cells having the geometry of four symmetric circular sectors to diminish angle sensitivity and polarization, and the middle layer is with an air gap. To realize the broadband metasurface four chip resistors incorporate both unit cells. The performance of the proposed absorber was examined under normal and oblique incident angles, which shows that the absorber yields more than 90% absorbance in the range of 3.78-15.63 GHz for normal incident waves. While for oblique angles, it yields more than 80% absorbance under the transvers-electric (TE) mode with the strength of incident angle is as low as 40%, and the transverse-magnetic (TM) mode with strength of incident angle is as low as 50%. Hence, the model provides polarization insensitive absorber as shown in Fig 33.

As evident that the absorber metasurfaces are the perfect candidate for radar cross section reduction (RCSR), therefore, the model in [90] devised the hybrid-metasurface for mono-static and bi-static RCSR, which consists of anisotropic-frequency-selective-absorber i.e., AFS absorber and polarization-rotation-reflective-surface i.e., PR reflective surface. The co-polarized wave is absorbed by this AFS absorber, while the cross-polarized wave passes. Now the PR reflective surface, which is placed beneath the AFS absorber, a cross-polarized wave will be reflected with 90° rotation and then it is absorbed by the AFS absorber. As the incident waves are being absorbed rather than deflected to other directions, both mono-static and bi-static RCSR is achieved in the frequency band ranging from 6 GHz to 8 GHz. The proposed configuration and results are shown in Fig. 34.

V. ANALYSIS ON THE EM-BASED CLASSIFIED METASURFACES

The analysis on the investigated research work described in this paper is presented in Table 4. As such the reported metasurface-based antennas in [72], [73], [74], and [75] were designed to achieve high gain with small size. Among these [74], [75] designs are designed for 5G communications with high gain and small size. The models proposed in [96] and [98] reveal that gain is enhanced by placing metasurface incorporated resonators in front (or on top) of radiating patch to direct the beams after passing through the structure. The gain achieved by [98] is much larger than that in [96] but at the cost of the antenna’s size. The comparison between [74] and [75] reveals that the latter model is more suitable for low profile, a high gain antenna having just one substrate layer to ease the fabrication process as well. The examined antennas in [80], [81], [82], [83], [84], and [85] comprehend the concept of lens metasurfaces to design compact, high gain, and broad-band transmit and reflect antennas for beam-focusing. The presented metasurface antennas in [80], [81] behave as a transmit-array lens, which collimated the beam in the forward direction, but both designs didn’t focus the waves at the specific point after passing through the metasurface. Similarly, the design in [82] also operates as
FIGURE 34. Geometry of absorber antenna proposed. (a) Unit cell for AFS absorber; (b) Unit cell for PR reflective surface, (c) Working methodology of proposed model (d) Reflection coefficients of metasurface for TE- (e) and TM-polarized incident wave, (f) The schematic results for mono-static RCSR of the antenna of x- polarized and (g) y-polarized incident wave [90] @IEEE.
TABLE 4. Analysis of the performance based on antenna types.

| Sr. no. | Antenna Type                              | EM Classification | Application                      | Size (mm³) | BW (GHz) | Max. Gain (dBI) |
|---------|-------------------------------------------|-------------------|----------------------------------|------------|----------|-----------------|
| [72]    | Multiple Superstrate MTS Antenna          | DNG               | Gain Enhancement + Wideband      | 102x102x8  | 4.48-7.87 | 6-7.87 11.8      | 9.7  |
| [74]    | Stack-packed MTS Antenna                  | DNG               | High Gain + Wideband + Low profile | 12x12x1.02 | 24-34.1   | 11               |
| [75]    | Single layered, MIMO MTS antenna          | DNG               | High Gain + Wideband + Low profile | 12x12x0.51 | 24-34.1   | 11               |
| [80]    | Lens MTS Antenna                          | MNG/ENG           | Beams focusing + Gain Enhancement | Not mentioned | 7-10   | 17               |
| [81]    | Dualband Transmitted Lens MTS Antenna     | MNG/ENG           | Beams focusing + Gain Enhancement | Not mentioned | 6.5 & 10.5 | 18.7 & 23       |
| [82]    | Broadband Transmitted Lens MTS Antenna    | MNG/ENG           | Multi-beam splitter lens         | Not mentioned | 1.71-2.2 | 10-13.5          |
| [83]    | Reflective Lens MTS                       | DNG               | Gain Enhancement                 | 440x440x60 | 11.8      | 27.5             |
| [84]    | Dual-band Reflective MTS                  | DNG               | RCSR                            | 7.4x11.2x1.6 | 11 & 25 | Not mentioned |
| [85]    | Transmit+Reflect array lens MTS           | DNG + ENG/MNG     | EM waves controller              | 20x20x6    | 10       | 21.4 (Tx) 20 (Rx) |
| [86]    | Transmit+Reflect array lens MTS           | DNG + ENG/MNG     | Multi-beam phase shifter from ±27° for 5G | 101.2x101.2 x50.6 | 28 | 24.2          |
| [87]    | Transmit+Reflect array lens MTS           | DNG + ENG/MNG     | Multi-beam phase shifter from ±27° for 5G mm-wave | 50x50x25 | 5.17-6.10 | 22.4          |
| [88]    | MTS based Wireless Communication Prototype | ENG/MNG           | MTS performs the function of phase-shifting for beamforming from 0°-60° | 37x37x1   | 2.3 & 28.5 | 21.7 & 19.1 |
| [89]    | Electronically Steered MTS Antenna        | ENG/MNG           | Steers the beam in two directions i.e., azimuth (±50°) and elevation (±70°) | 229x120x3.5 | 9-10.7 | 9.86            |
| [90]    | LC-Based Reflect-array MTS                | DNG + ENG/MNG     | Scan the beam with the range of ±40° for 6G | 20x20x0.087 | 108 | Not mentioned |
| [96]    | Superstrate MTS Antenna                   | DNG               | Gain Enhancement                 | 262x262x73 | 2.3   | 11.2             |
| [98]    | Multiple Superstrate MTS Antenna          | DNG               | Gain Enhancement                 | 40x28.7x41.47 | 9.4-12 | 17.1             |
| [99]    | MTS based Beam scanning array             | ENG               | Scanning range of the beams is ±60° for sub-6GHz | 196x196x3.8x61 | 4.8-6 | 21               |

Contrarily, [83] and [84] act as reflect-array lens antennas to deflect and collimate the beam in a backward direction operating at single and multi-band frequencies. The need to attain both transmitted and reflected beam collimation from the single model is achieved by [85], [86], [87], but these are...
complex designs, thus imposing difficulties in fabrications due to the multi-layered structure. The next regime is the absorber metasurfaces [90], [91], [92], which absorb all the incident waves either at a single operating frequency [90] or at a wide operating band [91], [92]. These designs are suitable candidates for radar cross-section reduction as well.

VI. CONCLUSION

In this paper, based on the electromagnetic classifications, a comprehensive overview with the help of designed metasurfaces unit cells, showing unique characteristics as \( \varepsilon \)-negative (ENG), \( \mu \)-negative (MNG), and double negative (DNG) materials is demonstrated. First, the basic concept of materials with negative refractive index is demonstrated through Maxwell’s equations. Then this concept is idealized by the unit cells to classify the material properties based on \( \varepsilon \)-negative, \( \mu \)-negative, and double-negative parametric values. After that, the simulated results are further verified with the help of mathematical relations i.e., the Kramers-Kron and Nicolson Rose Weir (NRW) method. Moreover, state-of-the-art designs are discussed to highlight the utilization of classified metasurfaces for attaining the high gain metasurface-based antennas, lens metasurfaces for highly directive collimated beam antennas with compact antenna size both in transmitted (forward) and reflected (backward) modes and absorber antennas to reduce radar cross-section. A comparison of the state-of-the-art design is drawn to facilitate readers’ understanding. In addition, based on the review, following recommendations are made: metasurfaces can be used for tackling the problem of circular polarization bandwidth enhancements, for providing beam scanning in millimeter wave band vis-à-vis 1-D or 2-D leaky wave antennas, and absorber antennas for tackling the problem of circular polarization bandwidth enhancements, for providing beam scanning in microwave and millimeter wave bands.

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