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Metamaterial Absorber: A Review

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Abstract: ***Due to their compact dimensions, minimal profile, and straightforward manufacturability, Metamaterial Absorbers have largely taken the place of conventional absorbers. These sub-wavelength unit cells, constituting the metamaterial, have been engineered to serve various purposes, encompassing tasks such as diminishing radar cross-section (RCS), displaying insensitivity to polarization, functioning as gas sensors, and enabling cloaking effects, among other applications. This comprehensive review encompasses an exploration of multiple applications for metamaterial absorbers. Several factors, including the dielectric constant's magnitude, the configuration involving resonant patches in a hybrid arrangement, and the gap between the dielectric substrate and metallic ground, collectively influence absorptive qualities, bandwidth, and the count of resonant bands.***

Keywords: Metamaterial, Absorber, Polarization, RCS, Cloaking, Gas Sensor.

1. Introduction

Our world depends heavily on communication and exchange of the information using wireless mode. With the development of IOT devices, wireless communication has undergone a major development that causes Electromagnetic (EM) wave interference and pollutes the environment. This is going to be a serious threat to humankind. To overcome this issue, many researchers have proposed absorbers in the world of wireless communication.

An absorber refers to a solid material designed for the purpose of absorbing a portion of the energy carried by an incoming electromagnetic waves i.e., it can neither transmit nor reflect the incident EM waves. Some of the conventional absorbers are Janumann, Dallenbach and Salisbury absorbers [1-4], They are bulky in size, complex in design and are not suitable for practical applications like sensors, solar cells & stealth technology to lower or block Radar signals etc. To design small and simple absorbers, researchers have shifted towards metamaterial absorbers (MMA). These materials have drawn a lot of attention due to their high absorption, thin layers, and low density. Metamaterial will absorb an incident EM wave, which will eventually be converted to heat.

Artificial Electromagnetic media having sub-wavelength scale structures are known as Metamaterial.They exhibit unnatural properties like negative permittivity & permeability at the resonant frequency, possess the left-handed behavior, perfect lensing, negative refractive index, inverse Doppler effect, electromagnetic wave cloaking, and perfect absorption., Electromagnetic wave cloaking and perfect absorption, among other characteristics. Thirty years after Victor Veselago [5] theoretically proposed metamaterial, In 1999 J.B Pendry et al[6], have implemented these materials comprising SRR and thin wires.

Metamaterial absorbers have found diverse applications, such as in solar cells, sensors, and thermal imaging, where they can be engineered to possess properties like multiband capability, broadband absorption, polarization sensitivity, and adjustability. Despite previous progress, creating metamaterial absorbers that efficiently exhibit multiple absorption bands remains challenging. The absorption characteristics arise from precisely managed and tunable effects produced by modulating the coupling between patches within the metamaterial structure, aligned with the resonance frequency of the electromagnetic wave.

2. Existence of Metamaterials

The Helmholtz equations [7] or simply wave equations were derived using Maxwell's laws on Electromagnetic time harmonic waves propagating in a lossy medium with permittivity (ε), permeability (μ) and conductivity (σ) are

$$\nabla^2 E - \gamma^2 E = 0 \tag{1}$$
$$\nabla^2 H - \gamma^2 H = 0 \tag{2}$$

Presume a plane monochromatic wave propagating in the z-direction with electric and magnetic fields propagating in the x and y directions respectively. Then the corresponding electric field can be expressed as

$$E = E_x(z) a_x \tag{3}$$

Whereas magnetic field is expressed as

$$H = H_y(z) a_y \tag{4}$$

Substituting Eq. 3 with Eq. 1, the solution of the wave equation is expressed as

$$E_x(z) = E_0 e^{\gamma z} + E_0 e^{-\gamma z} \tag{5}$$

Where$\gamma = \alpha + j\beta$, is a complex number. α is attenuation constant and β is propagation constant.

The above equation can also be expressed as

$$E(z,t) = E_0 e^{-\alpha z} Cos(\omega t - kz) a_x \tag{6}$$

Similarly, the magnetic field in the y direction is given as

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$$H(z,t) = H_0 e^{-\alpha z} Cos(\omega t - kz) a_y \qquad (6)$$

The characteristics impedance or intrinsic impedance of the medium is expressed as

$$\eta = \frac{E_0}{H_0}$$

For lossless medium, conductivity is zero and both the Electric field and magnetic field are in phase. Then the velocity of the wave can be expressed as

$$\upsilon = \frac{1}{\sqrt{\mu\varepsilon}}$$

Based on the equation provided, it can be inferred that the propagation of an electromagnetic wave is influenced by the permittivity and permeability of a medium. In materials with ferrous properties, both these factors assume positive values. Consequently, the wave vector (k) and the Poynting vector (p) align in the same direction, leading to the classification of these materials as right-handed. However, if both permittivity and permeability turn negative, the wave vector and Poynting vector take opposite directions, resulting in the categorization of these materials as left-handed or metamaterials. This specific class of materials is deliberately engineered to exhibit negative permittivity and negative permeability at a targeted resonant frequency.

Metamaterials are artificially created large-scale structures designed with a periodic arrangement to achieve specific functionalities that aren't attainable using natural materials alone, The concept of materials with negative refractive indices was initially proposed bt Victor Veselago, and later, J.B. Pendry. Successfully realized these materials after numerous attempts.

3. Analysis of Metamaterial Absorber (MMA)

Metamaterial absorbers (MMA) represent materials designed to capture the energy of incident particles. When creating an absorber, it becomes imperative to confine the electromagnetic signal within the structure of the metamaterial. The degree of absorption is defined by the expression, $A(\omega) = 1 - ||S_{11}||^2 - ||S_{21}||^2$ with S_{11} and S_{21} denoting complex reflection and transmission coefficients, respectively. To enhance absorptivity, it's desirable to minimize the transmission coefficient, achieved through the introduction of a metallic ground plane. This modification results in a simplified absorption expression, $A(\omega) = 1 - ||S_{11}||^2$Effective absorption hinges on a strong impedance match between the metamaterial absorber and its surroundings. The effective impedance of the MMA is contingent on the permittivity and permeability, expressed as

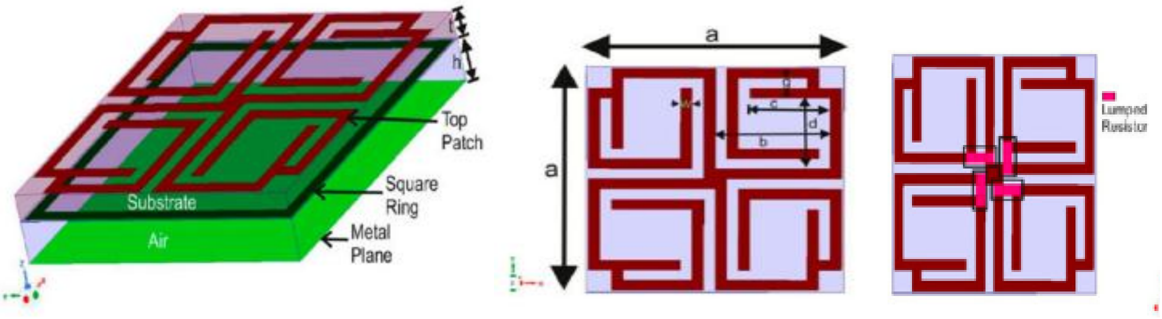
$$Z(\omega) = \sqrt{\frac{\mu(\omega)}{\varepsilon(\omega)}} = \sqrt{\frac{\mu_0\mu_r(\omega)}{\varepsilon_0\varepsilon_r(\omega)}} = \sqrt{\mu_0/\varepsilon_0}\sqrt{\frac{\mu_r(\omega)}{\varepsilon_r(\omega)}}$$

$$\varepsilon_r = \frac{2}{jkd} * \frac{(1-V_1)}{(1+V_1)}$$

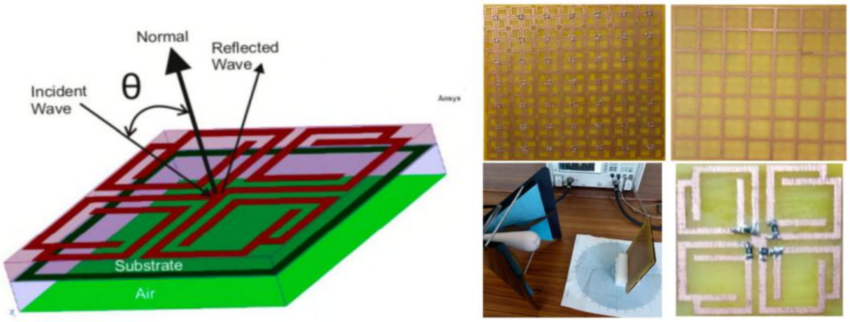
$$\mu_r = \frac{2}{jkd} * \frac{(1-V_2)}{(1+V_2)}$$

Where $V_1 = S_{21} + S_{11}$, $V_2 = S_{21} - S_{11}$ and d=substrate thickness.

Refractive Index is given as $n_r = \sqrt{\mu_r(\omega)\varepsilon_r(\omega)}$. The real component of the normalized impedance should closely approach unity, and the reactive component should effectively diminish towards zero at the frequency corresponding to peak absorption in an ideal MMA scenario. A highly thin metasurface absorber was introduced in reference [8]. The inherent fourfold symmetry of its unit cell imparts insensitivity to both TE and TM polarizations. Augmented absorption in the lower frequency band was achieved using lumped resistors. Impressive absorptivity figures of 95%, 99%, 97%, and 94% were attained at central frequencies of 1.6 GHz, 5 GHz, 7.5 GHz, and 10.2 GHz, respectively. To optimize absorptivity, an air gap measuring 2.5 mm was introduced beneath the FR4 glass epoxy dielectric substrate, complemented by a metal backing. The upper layer of the metamaterial unit cell was fashioned in a modified swastika symbol configuration, incorporating additional stubs. These unit cells, arranged in a 7x7 array, were systematically positioned to form a two-dimensional planar Metasurface. This innovative absorber remains unaffected by both TE and TM polarization over a wide angular range spanning from 0° to 90° and even 90° to 180°. With applications ranging from reducing radar cross-section for stealth purposes to enhancing isolation in electromagnetic interference scenarios, as well as contributing to RF energy harvesting systems, this Metasurface boasts a multitude of practical uses.



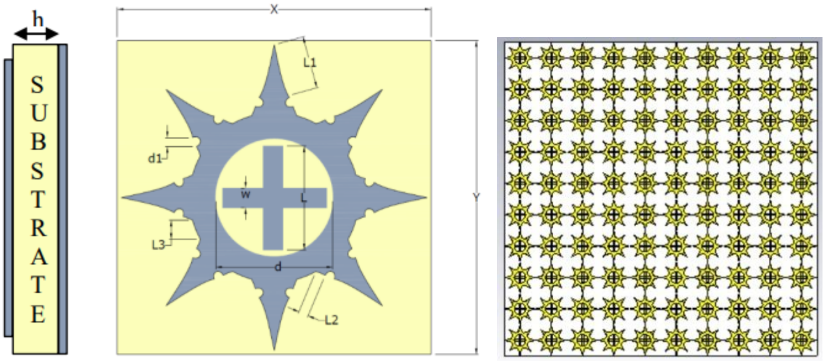
(a) (b) (c)



(d) (e)

Figure1. (a) Schematic of absorber unit cell structure (b) Top view of the unit cell (b) Top view with lumped parameters (d) Incident and Reflected EM waves (e) Fabricated prototype and Testing of Metamaterial absorber.

In their work [9], Mohamed Edries et al. introduced a metamaterial absorber featuring a sun fractal structure, strategically designed to achieve Radar cross-section reduction across three distinct frequency bands. Notably, absorption peaks of 97%, 91.6%, and 93.3% were attained at frequencies of 2.2 GHz, 5.9 GHz, and 6.8 GHz, respectively. The distinctive sharp edges characterizing the proposed fractal sun shape facilitated the highest absorption rate at the lowest frequency. This absorber's configuration holds potential for diverse applications spanning medical, military, and electromagnetic protection contexts. To create a 2D Metasurface, a configuration encompassing a 10 × 10 array of the proposed metamaterial unit cells was employed.



(a) (b)

Figure 2: Proposed Unite cell structure (a) Side and Top view (b) Proposed 10×10 MMA

Zeyan Ali and colleagues [10] introduced a Metasurface absorber utilizing a slow-wave mechanism. In this design, each metamaterial unit cell comprises a Jerusalem Cross structure on one side of the dielectric substrate, with metal on the opposite side. Notably, no supplementary absorbent materials were integrated into the unit cell, aimed at minimizing production costs. The achievement of dual-frequency absorption was realized through the coupling of two unit cells possessing distinct sizes, resonating at frequencies of 5.61 GHz and 7.565 GHz. This specific slow wave metasurface absorber effectively captures and delays electromagnetic waves, introducing a delay time ranging from 0.3 to 0.4 nanoseconds.

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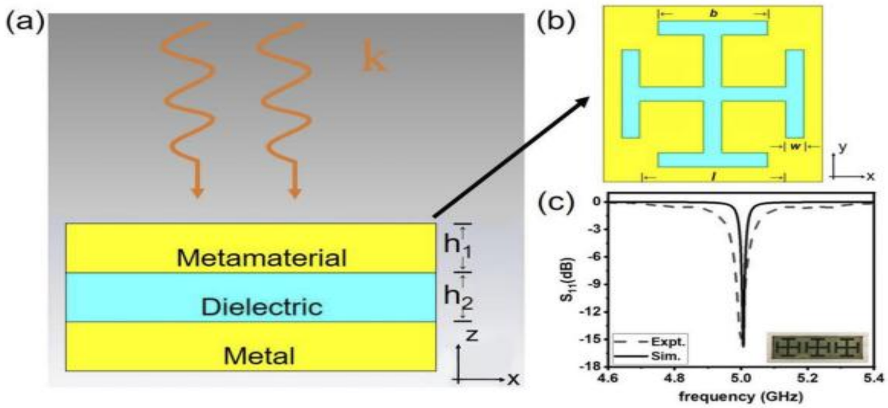
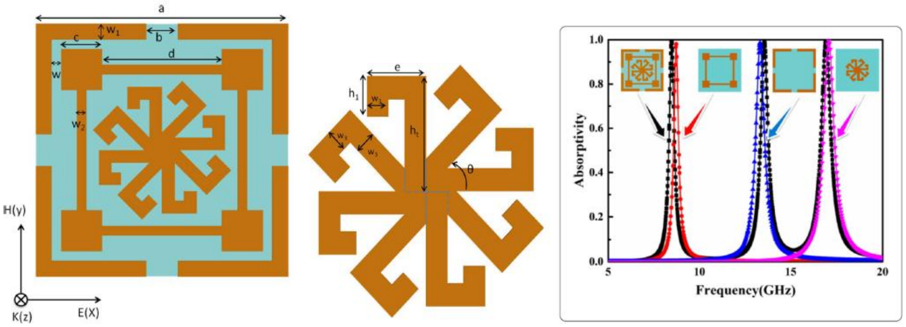


Figure 3: Proposed Metasurface Absorber (a) Side view (b) Top Layer of metamaterial unit cell (c) S11 of proposed unit cell structure.

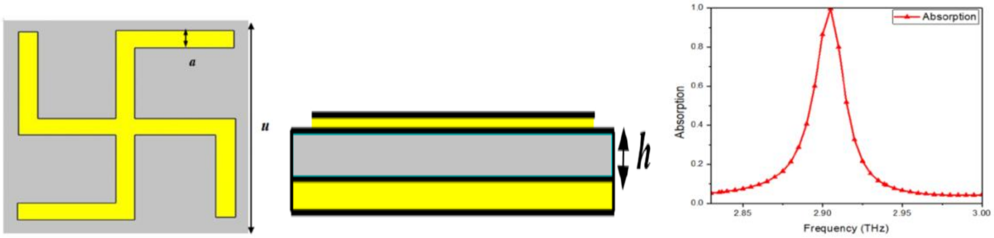
In their research [11], Guangshang Deng and collaborators presented an ultrathin tri-band metamaterial absorber that demonstrated impressive absorption rates of 99.9%, 99.5%, and 99.9% at frequencies of 8.5 GHz, 13.5 GHz, and 17 GHz, respectively. The symmetrical design of this metamaterial absorber ensures its absorption remains unswayed by diverse polarization angles. To create a prototype, a flexible dielectric substrate, specifically a flexible polyimide film, was employed, yielding a 20x30 unit cell configuration. The metamaterial absorber exhibits a three-layer structure encompassing a resonance layer, dielectric layer, and metallic ground layer. The unit cell itself is composed of a resonant structure achieved through the combination of a Single Split Ring (SSR) and a Modified Ring Resonator (MRR).



(a) (b) (c)

Figure 4: Proposed Metasurface Absorber (a) Top Layer of meta material unit cell (b) Layout of eight 7-shaped resonance structures (c) Absorptivity vs Frequency of proposed unit cell structure

Sagnik Banerjee and colleagues [12] introduced the concept of Single Negative Metamaterials, featuring a resonating layer in the shape of a swastika on one side of a dielectric substrate, complemented by a metallic ground, forming the unit cell of the metamaterial absorber. Gallium Arsenide was employed as the dielectric substrate material. This arrangement endowed the metamaterial unit cells with negative permeability and positive permittivity at the intended resonant frequency. Remarkably, this structure achieved an absorption rate of 99.65% at 2.095 THz, accompanied by a sensitivity of 2.12 THz/RIU and 106 figures of merit. The proposed absorber configuration holds potential as a gas sensor, proficient in detecting the presence of harmful gases within a designated area. A successful application was demonstrated in the detection of chloroform within a specific environment.



(a) (b) (c)

Figure 5: Unit Cell Structure of Terahertz Metamaterial Absorber (a) Top View (b) Side View (c) Absorption spectrum of proposed unit cell

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A novel and effective approach for mitigating the Radar Cross Section (RCS) [13] of a microstrip patch antenna was successfully realized through the implementation of an innovative hybrid metamaterial structure. This hybrid arrangement involves the amalgamation of split square and ring-shaped metamaterial unit cells, systematically organized in a chessboard pattern. The proposed antenna configuration demonstrated a wideband performance across the frequency bands of 2 GHz to 4.4 GHz, 7.8 GHz to 9.1 GHz, and 14.3 GHz to 18 GHz. The reference antenna, featuring dimensions of 80x80 mm on the top layer, was supplemented with the hybrid metamaterial unit cell structure. Notably, to achieve a low RCS for the antenna, radiation was conducted at a frequency of 4.2 GHz.

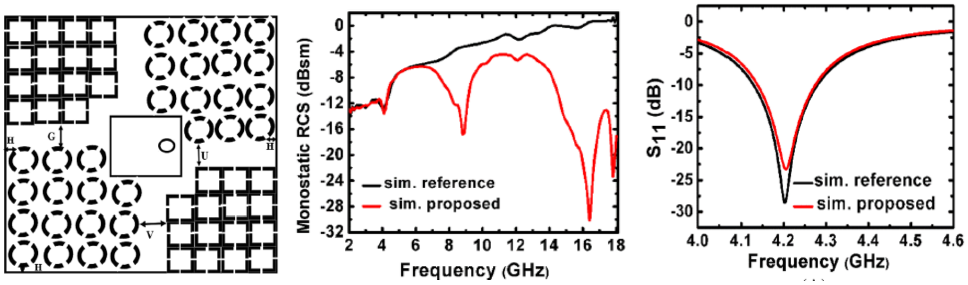

Figure 6: Proposed Metasurface Absorber (a) Side view (b) Top Layer of metamaterial unit cell (c) S11 of proposed unit cell structure.

A Metasurface absorber designed for energy harvesting, operating based on the principle of destructive interference through phase cancellation, was put forward [14]. The approach involved achieving a symmetrical geometry with four-fold symmetry by arranging four L-shaped resonant unit cells. This particular unit cell configuration induced destructive interference of electromagnetic waves emanating from the diagonal element at the resonant frequency. When utilized in reflection mode, the proposed metamaterial absorber exhibited resonant currents that nullified each other, resulting in a metasurface that is radiative and produces minimal backscattering. Utilizing a dissipative substrate, a remarkable absorption rate of up to 90% was achieved. This Metasurface absorber is particularly well-suited for RF Energy Harvesting at 2.25 GHz. To materialize this concept, a 5x5 metasurface array was fabricated on Rogers's 4003 substrate.

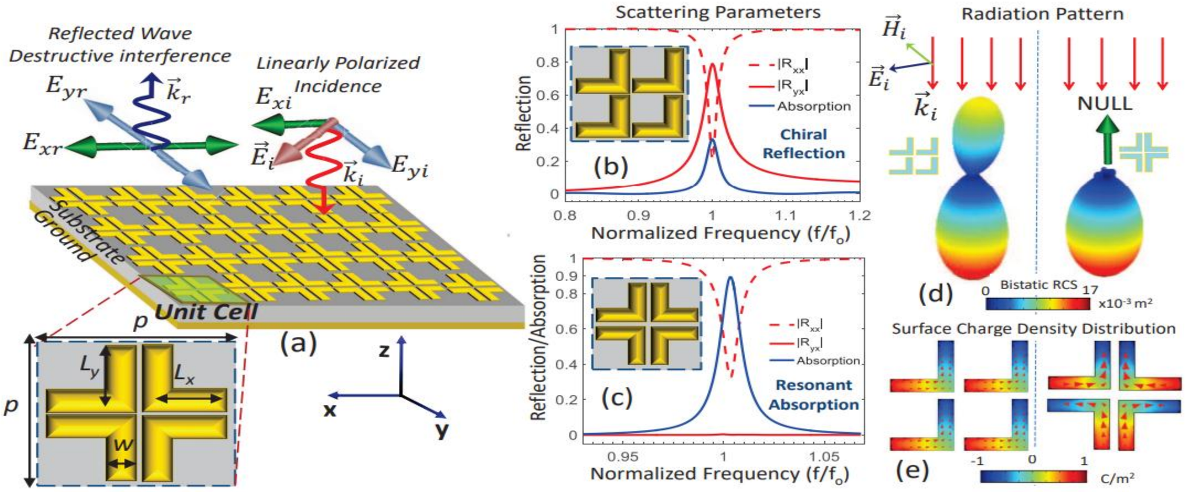

Figure 7: (a) Schematic of an interference-based metamaterial absorber. (b) Simulated response in terms of co-and cross-polarized components of reflected fields. (c) Suppression of both the co-and cross-polarized components for the rotated quadruple-L metasurface. (d) The radiation pattern for a single unit cell at resonant frequency. (e)Time-harmonic surface charge density

An ultra-wideband metamaterial (MTM) absorber is established using a metallic square spiral configuration, characterized by its ultrathin nature [15]. To extract the lumped components of the equivalent circuit, a proposed method grounded in the least squares approach is employed. This approach, being straightforward and effective, aligns well with electromagnetic simulations, showcasing reliable agreement. The unit cell of this proposed structure features a square spiral situated on an FR-4 substrate and positioned in front of a conductive plate. Experimental measurements corroborate the absorptivity exceeding 90% within the frequency range of 11.4 to 20.0 GHz, encompassing the Ku-band and accommodating both transverse magnetic (TM) and transverse electric (TE) polarizations.

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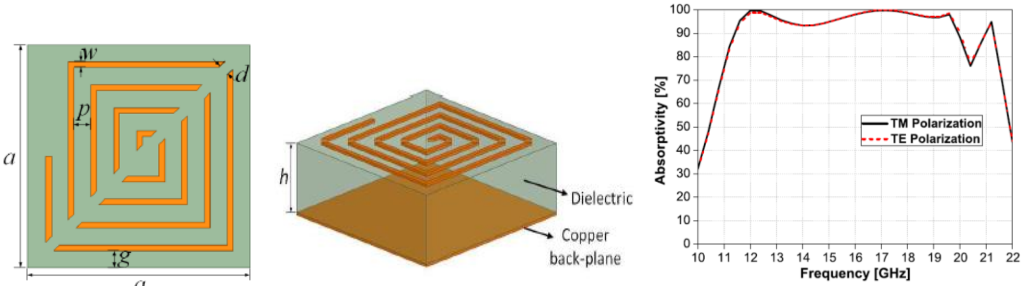

(a) (b) (c)

Figure 8: Proposed Metasurface Absorber Unit Cell (a) Top View (b) Perspective View (c) Simulate absorption of the proposed absorber for both TE & TM Polarizations.

Table 1: Comparison of study carried on the selected research associated with MMA

Ref.	Unit Cell Dimension (mm^2)	Lower absorption peak (GHz)	Absorption rate at lowest frequency (%)	No absorption bands	Absorption frequencies (GHz)	The air gap between the substrate and metallic Ground	Verification of metamaterial property
[8]	22.4 × 22.4	1.6	95	4	1.6/5/7.5/10.2	Yes	Yes
[9]	40 × 40	2.20	97	3	2.20/5.90/6.80	No	Yes
[10]	10 × 10	5.61	-	2	5.61/7.565	No	No
[11]	8 × 8	8.5	99.9	3	8.5/13.5/17	No	No
[12]	0.1 × 0.1	2905	99.65	1	2905	No	Yes
[13]	9.5 × 9.5	4.0	-	4	4.0/8.7/16.4/17.7	No	Yes
[14]	20 × 20	2.25	90	1	2.25	Yes	No
[15]	3.65 × 3.65	12.2	99	Wideband	11.4 to 20	No	Yes

From table: 1, A brief review was carried out on the selected research associated with Metamaterial Absorber. From the literature, all the proposed structures are Insensitive to polarization. An absorptivity of more than 90% was achieved in all the proposed literature.

4. Conclusion

A brief review of metamaterial absorbers has been carried out in this paper. Some selective research associated with metamaterial absorbers and their applications has been focused on. These structures are made for ultra-thin, ultra-wideband applications. The multiple-layered metamaterial absorber is made up of metallic ground and patches with various patterns that are separated by the dielectric constant. To increase the bandwidth, an air gap was added between the dielectric substrate and metallic ground. The proposed structures have numerous uses, including the lowering of radar cross sections, stealth applications, improved isolation in EMI applications, RF energy harvesting systems, medical, military and electromagnetic protection, detection of gas leaks, and slowing down EM waves, among others.

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