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From Narrowband to Wideband: A Review of Metamaterial Absorber Design and Development

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Abstract

Metamaterial absorbers (MMAs) have appeared as innovative structures capable of effectively manipulating electromagnetic (EM) waves beyond the capabilities of natural materials. This review provides a comprehensive summary of narrowband and wideband MMAs, discussing their design strategies, working principles, and application-specific configurations. This study intends to point out current growths that enable high absorption performance, polarization insensitivity, angular stability, and frequency selectivity. A variety of unit cell structures, resonator shapes, and material selections are explored to realize their roles in achieving desired absorption features. The review categorizes MMAs based on their absorption bandwidth, structural parameters and performance metrics such as quality factor, sensitivity and frequency tunability. Methods like impedance matching, resonant mode coupling and equivalent circuit modeling are investigated to enlighten the physical mechanism of absorption. Crucial applications in wireless communication, radar cross-section reduction, energy harvesting, biomedical and environmental sensing are also discussed. Meanwhile, comparisons among current designs are presented in tabular form to back future designers in choosing ultimate MMA configurations. The paper concludes by summarizing the design challenges and providing visions into emerging trends and potential future guidelines in MMA technology.

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1. Introduction

Metamaterial absorbers (MMAs) have gained significant attention in recent years for their ability to control and manipulate electromagnetic (EM) waves in ways that natural materials cannot achieve (Cui *et al.*, 2010). These materials are composed of sub-wavelength structures, arranged periodically to exhibit distinctive properties such as negative permittivity and permeability. This enables MMAs to efficiently absorb electromagnetic radiation by interacting with the incident electric and magnetic fields. Unlike traditional absorbers, MMAs can be designed to operate at specific frequencies or across a broad range of frequencies, offering exceptional versatility in various technological applications, including telecommunications (Munuwar *et al.*, 2016; Ali *et al.*, 2016; Masri *et al.*, 2010; Duangtang *et al.*, 2014; Mi *et al.*, 2013), radar systems (Ziolkowski *et al.*, 2018; Lin *et al.*, 2012; Bulu *et al.*, 2005) stealth technologies (Islam *et al.*, 2020; Kundtz *et al.*, 2010; Moniruzzaman *et al.*, 2020; Ma *et al.*, 2010; Cheng *et al.*, 2016) sensing devices (Cong *et al.*, 2015; Bhattari *et al.*, 2015) and super-lenses (Lipworth *et al.*, 2014; Fang *et al.*, 2005; Hexa *et al.*, 2018; Aydin *et al.*, 2007; Nafe *et al.*, 2015).

The vital mechanism of MMAs lies in matching their impedance with free space. Most absorbers achieve this by designing unit cells with metallic resonators, dielectric substrates, and sometimes ground plates to reduce the reflection of incident EM waves (McKinzie *et al.*, 2014; Al-Bawri *et al.*, 2025; Choi *et al.*, 2014; Li *et al.*, 2020). This principle has been widely implemented in metamaterial designs to achieve near-perfect absorption by tailoring resonator geometry, material properties, and substrate configurations. For example, split-ring resonators (SRRs) and complementary split-ring resonators (CSRRs) effectively couple the electric and magnetic fields to match free-space impedance (Sudhendra *et al.*, 2013). Ground planes are also employed to ensure zero transmission, enabling efficient energy dissipation within the structure (Venneri *et al.*, 2018; Kim *et al.*, 2015; Venneri *et al.*, 2018). This type of design guarantees that the maximum amount of EM energy is absorbed instead of being reflected or transmitted. In resonators, circulating currents induce both electric and magnetic dipoles, which convert incident energy into heat and dissipate it within the structure. This interaction between electric and magnetic resonances creates strong absorption characteristics, which can be tuned to a desired frequency range by altering the geometric and material parameters of the unit cells.

MMAs are typically categorized into narrowband and wideband absorbers, each tailored for specific applications. Narrowband MMAs are optimized for selective frequency absorption, making them particularly effective for wireless communication, sensing, and radar cross-section (RCS) reduction. For instance, narrowband absorbers have been employed to reduce the specific absorption rate (SAR) in 5G mobile devices, thereby enhancing user-safety by absorbing excess EM energy. Another design has been developed for Wi-Fi applications, offering effective shielding against interference at 2.4 GHz and 5 GHz

In contrast, wideband MMAs are designed to operate across broader frequency ranges, making them suitable for advanced applications such as stealth technology, radar systems, and multi-band wireless communication (Yoo *et al.*, 2015; Chaurasiya *et al.*, 2016; Baskey *et al.*, 2013; Chen *et al.*, 2012; Hossain *et al.*, 2021). These absorbers employ multi-resonant structures, lumped resistors (Cheng *et al.*, 2012; Zhang *et al.*, 2018; Chaurasiya *et al.*, 2015; Mol *et al.*, 2017), or lossy dielectric materials (Jia *et al.*, 2018; Kaur *et al.*, 2018; Rabbani *et al.*, 2024; Noginov *et al.*, 2011) to broaden the absorption bandwidth. For example, certain designs achieve wideband absorption by exciting multiple resonant modes, providing outstanding absorption across continuous frequency ranges. This feature particularly critical in modern defense systems, where reducing radar detectability across a wide spectrum significantly improves stealth performance.

One of the key challenges in designing MMAs is balancing between absorption rate, bandwidth, and angular stability. Narrowband absorbers require precise geometry to achieve near-perfect absorption at target frequencies, ensuring polarization and angular stability. This aspect is critical in real-world applications, where the incident angle of EM waves can vary significantly. Certain designs demonstrate consistent high absorption even at oblique angles up to 60° or beyond, improving their suitability for dynamic operational environments. On the contrary, wideband MMAs face challenges in maintaining high absorption across large frequency ranges while keeping the structure compact and lightweight. This has been addressed by utilizing multi-resonant unit cells or incorporating resistive elements to extend the absorption spectrum.

Current developments in metamaterial absorber (MMA) designs have significantly prolonged their applicability across diverse frequency domains and use cases. For instance, a triple-band MMA designed for terahertz (THz) sensing applications showed high figure-of-merit (FOM) values and sensitivity for gas detection by altering the refractive index, achieving absorption peaks near 99.9% with outstanding Q-factors and polarization independence, making it a strong candidate for environmental and biochemical sensing (Nipun *et al.*, 2025; Kabir *et al.*, 2025; Moniruzzaman *et al.*, 2025). In the microwave realm, another study proposed a condensed Ka-band MMA with near-unity triple-band absorption and wide-angle stability, adjusted for satellite and radar applications (Hasan *et al.*, 2025). Likewise, a multi-resonant MMA covering 26–35 GHz showcased effective shielding against electromagnetic interference (EMI) with robust performance under diverse polarizations (Nipun *et al.*, 2025). Addressing mobile communication demands, a dual-band absorber aiming GSM and 5G bands (1.8 GHz and 3.5 GHz) attained absorption rates above 98%, high shielding effectiveness, and angular stability, tested through both simulation and experimental validation (Hasan *et al.*, 2024). For optical and infrared applications, an ultra-thin, broadband, polarization-insensitive MMA was engineered using aluminum nitride and nickel layers, covering a wide spectral range from visible to shortwave IR, showing over 90% absorption and admirable thermal and angular stability—ideal for applications in IR detection and solar energy harvesting. These emerging designs demonstrate the evolving versatility of MMAs, offering enhanced sensing, shielding, and absorption performance across a wide spectrum.

In this review, the current advancements in narrowband and wideband MMAs are explored, focusing on their design strategies, material choices, and key applications. The selection of literature for this review was conducted through a systematic approach to ensure relevance, quality and comprehensiveness. Peer-reviewed journal articles and high-impact conference papers published between 2017 to 2025 were prioritized. The included studies specifically focus on the design, development and application of metamaterial absorbers in both narrowband and wideband regimes. Focus was placed on works that demonstrated experimental validation, unique structural configurations, performance analysis such as absorptivity, Q-factor, FOM and practical applications for example sensing, EMI shielding, radar cross-section reduction and wireless communication. To retrieve the literature, databases such as IEEE Xplore, ScienceDirect, SpringerLink and Wiley were used. Additionally, recent state-of-the-art works were incorporated to show current advancement in the MMA field.

2. Discussion on Metamaterial Absorber

MM absorbers work based on the fundamental principle of controlling the interaction of electromagnetic waves. Unlike traditional absorbers, MMAs are engineered with unit cells that demonstrate tailored responses at definite electromagnetic frequencies. These unit cells are typically composed of metallic resonators, like split-ring resonators (SRRs), and dielectric substrates (Koschny *et al.*, 2005), which interact with both the electric and magnetic components of incident EM waves (Smith *et al.*, 2005). By carefully planning the geometric properties and selecting materials for the unit cells, MMAs can achieve almost perfect absorption by ensuring minimal reflection and zero transmission of the incident wave.

Study shows, a perfect matched layers is the foundation of absorption of a metamaterial absorber. The effective impedance of a perfect absorber is a function of its electric permittivity (ε) and the magnetic permeability (μ). The effective impedance Z of an absorber can be measured by (Lim *et al.*, 2016; Wu *et al.*, 2016):

$$Z = \sqrt{\frac{\mu}{\varepsilon}} = \sqrt{\frac{(1+R)^2 - T^2}{(1-R)^2 - T^2}} \qquad (1)$$

It is a known fact that the summation of absorption (A), reflection (R) and transmission (T) is equal to unity. But the absorber has a metal background which does not allow signal to pass through; as a result, the T becomes zero. So, the equation for absorption can be re-written as:

$$A = 1 - R \qquad (2)$$

Since $R = S_{11}^2$, then equation (2) becomes

$$A = 1 - S_{11}^2 \qquad (3)$$

Where S_{11}^2 is the reflected power.

The absorption phenomenon of the MMA reveals that its lightweight, cost-effectiveness and frequency flexibility rely on the design principles of conventional metamaterials.

3. Building blocks of Metamaterial Absorber

Novel designs for narrow band have incorporated various materials and configurations, including the application of FR4 and Rogers 5880 substrates. These substrates offer promising dielectric properties, allowing the structure of compact and thin absorbers. The geometrical modifications, such as circular, rectangular or other extra ordinary shape resonators (Rahman *et al.*, 2025; Cheng *et al.*, 2017; Xu *et al.*, 2017; Tung *et al.*, 2017; Nguyen *et al.*, 2017; Yoo *et al.*, 2015; Hasan *et al.*, 2017; Smith *et al.*, 2000) increases the absorption performance while ensuring angular stability. These MMAs demonstrate outstanding benefits, such as Specific Absorption Rate (SAR) reduction (Kendry *et al.*, 2000; Shelby *et al.*, 2001; Liao *et al.*, 2011) and insensitivity to polarization and incident angles, which are vital for next-generation wireless devices. Many researchers have proven that adjusting the dimensions and layout of resonators (Amiri *et al.*, 2019; Costa *et al.*, 2013; Gu *et al.*, 2010; Karaaslan *et al.*, 2017) can lead to improved absorption efficiency and bandwidth (Bakir *et al.*, 2018; Wang *et al.*, 2016; Gunduz *et al.*, 2016; Zhang *et al.*, 2017; Ren *et al.*, 2020; Yi *et al.*, 2019; Hossain *et al.*, 2018; (Huang *et al.*, 2019; Aalizadeh *et al.*, 2018). Numerical simulations and comparable circuit modeling (Hoa *et al.*, 2019; Fernez *et al.*, 2018; Laroche *et al.*, 2006; Ni *et al.*, 2016) are the key technique to modify designs and predict expected outcomes, allowing effective incorporation into mobile devices and other applications.

The sharp, selective absorption peaks of narrowband MMAs (Edries *et al.*, 2021) have been largely used in applications such as sensing and stealth technology. The design of these absorbers generally includes resonators (Rahman *et al.*, 2023) tuned to specific resonant frequencies.

(Edries *et al.*, 2021) introduced a triple-band MMA based on a crossed sun fractal structure as depicted in Figure 1, showing absorption tops at 2.2 GHz, 5.9 GHz, and 6.8 GHz, with ultimate values of 97%, 91.6%, and 93.3%, respectively. The compact FR-4 substrate ($40 \times 40 \times 1.6$ mm^3) features strong edges, broadening the performance through superior field confinement. The mechanism is evaluated through equivalent circuit modeling, backing its applications in electromagnetic protection and military uses. The authors point up the structure's skinny in nature and ease of integration into existing systems, making it a potential candidate for numerous practical applications in defense and commercial sectors.

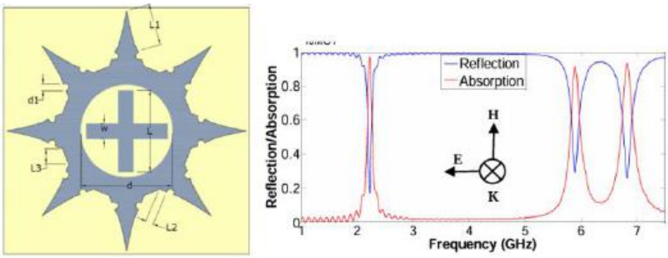

Figure1: MMA Structure and Result

(Moniruzzaman *et al.*, 2021) presented a simple MMA showing in the Figure 2, having dimension of 20 × 20 × 1.6 mm^{3}designed for Wi-Fi frequencies at 2.4 GHz and 5 GHz, achieving maximum absorption rates of 99.2% and 99.9%, respectively. The design incorporates tuning metallic stubs to facilitate frequency adjustments. The angular stability of the MMA is commendable, maintaining effective performance up to 60°, while exhibiting minimal cross-polarization effects, which are crucial for multi-user environments. The results demonstrate good agreement with simulations, affirming its effectiveness in wireless communication applications and wave shielding. Additionally, the research discusses potential implications for enhancing signal strength and quality in congested urban settings.

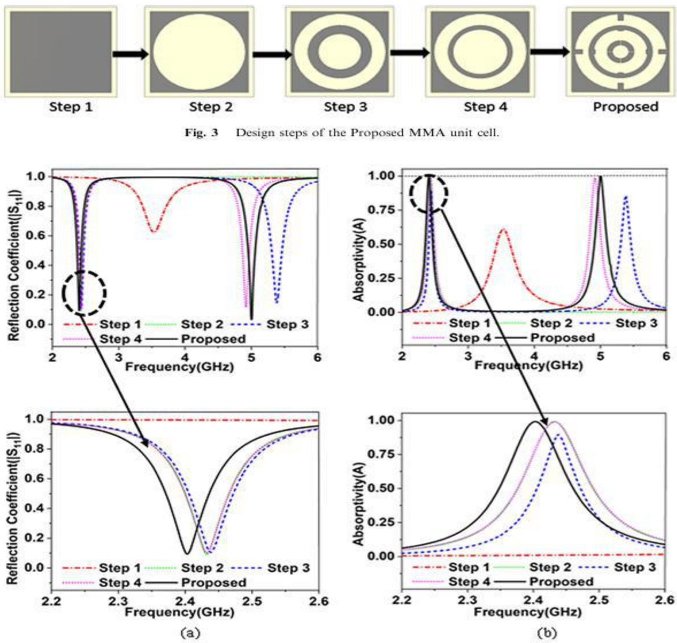

Figure 2: MMA designing stages with the results of Reflection and Absorption

(Rahman et *al.*, 2023) introduced a unique metamaterial structure exhibiting four resonances at S, X, and Ku bands visible in Figure 3, showcasing a significant advancement in multi-band absorbers. The design features an electrical dimension of 8 × 8 × 1.57 mm^3 on a Rogers (RT5880) substrate, known for its excellent dielectric properties. The arrangement of quartiles and H-shaped modifiers enhances resonance characteristics, resulting in high absorption efficiency. The prototype measurements closely match simulations, reinforcing the effectiveness of the design. This MMA is proposed for multi-band wireless communication, which is essential for devices operating across different frequency bands, enhancing their functionality and adaptability.

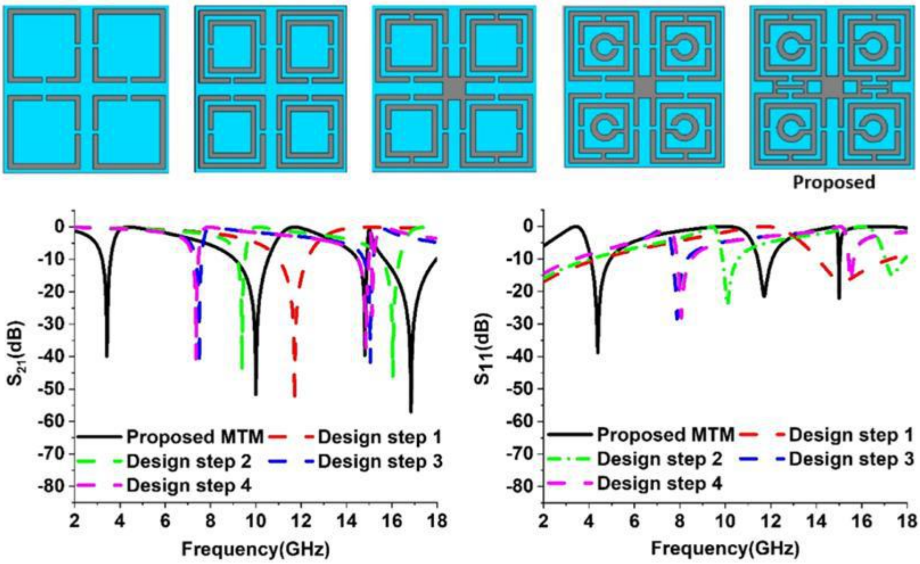

Figure 3: MMA designing evaluation and results

(Hasan *et al*.,2023) research introduced a dual-band MA based on a symmetric plus-shape resonator and the dimension of the unit cell is 16 × 16 × 1.6 mm^3 as in Figure 4, achieving remarkable absorption peaks of 99.04% and 99.90% at 12.32 GHz and 16.00 GHz, respectively. The substrate of the proposed MMA is FR4 material, which provides mechanical stability and good dielectric properties. Notably, the absorber shows near-unity absorption for TE and TM modes, even at angles up to 90°, demonstrating its robust design against variations in wave incidence. The design's rotational symmetry contributes to its polarization insensitivity, making it suitable for Ku band applications, where polarization diversity is common in communication systems.

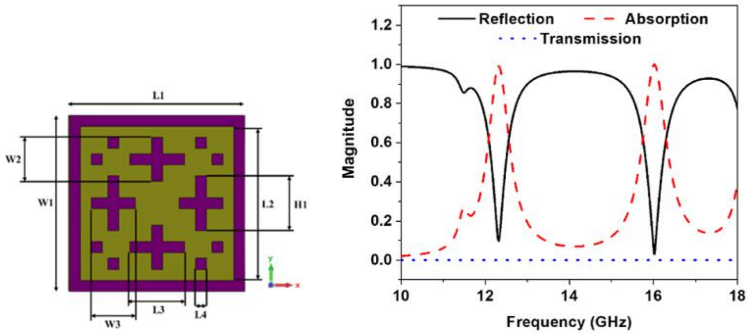

Figure 4: MMA and result

(Rabbani *et al*., 2024) described a new MMA achieving highest absorption at 3.26 GHz, 11.6 GHz, and 17.13 GHz visible in Figure 5, with the unit cell constructed on an FR4 substrate. The design features circular copper rings combined with dumbbell-shaped structures, maintaining peak absorption rates of approximately 93.8%, 96.47%, and 99.95% across frequencies, respectively. The high-quality (Q) factors indicate insensitivity to incident and polarization angles, vital for stable performance in dynamic environments. Simulation results align closely with measurements, validating the design's use in miniaturized microwave devices. The authors discuss the potential for this MMA in applications such as radar systems and satellite communications, where precise absorption characteristics are critical.

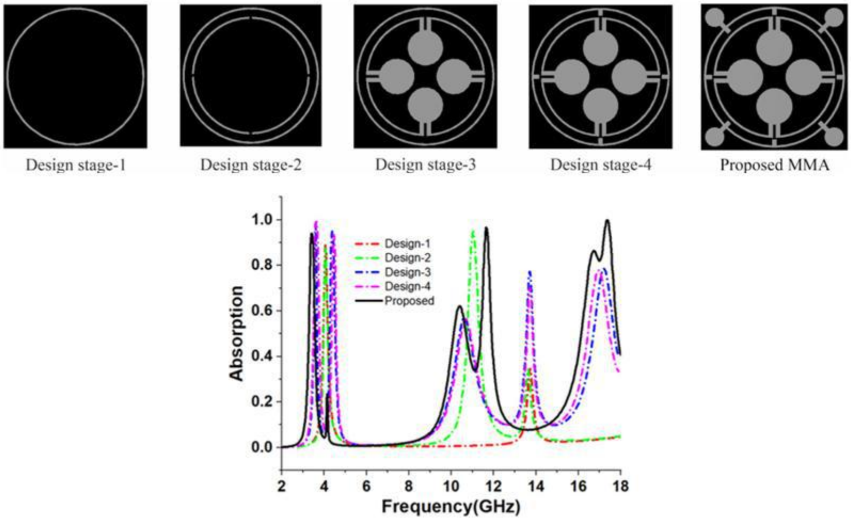

Figure 5: Designing stages and the results

(Sudarsan *et al.*, 2024) showed in Figure 6, an ultrathin MMA with a three-band response is investigated in this study. The structure, featuring copper layers on an FR4 substrate having dimension of 10 × 10 × 0.8 mm^3, achieves absorption rates of 99.9%, 85%, and 95% at frequencies of 15.29 GHz, 8.59 GHz, and 6.09 GHz, respectively. The design maintains performance under various angles and polarizations, with simulation results validating its application in bio-sensing technologies. The potential to integrate this MMA into portable devices for health monitoring and diagnostic applications is discussed, showcasing the MMA's versatility and significance in the evolving field of biomedical sensing.

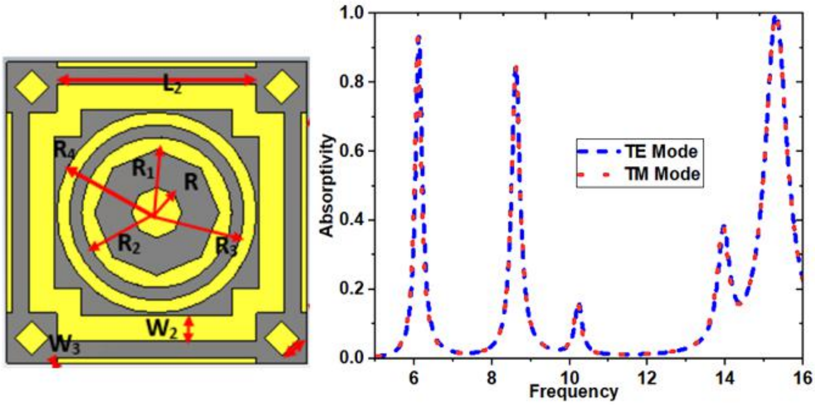

Figure 6: MMA and result

(Chowdhury *et al.*, 2024) presented a triple band MMA targeting enhanced sensing applications as showing in Figure 7, achieving noteworthy absorption at 2.46 GHz, 6.25 GHz, and 12.45 GHz. With a compact design of 18 × 18 × 1.6 mm^3, it exhibits up to 99.99% absorption. The design was certified through numerical simulations and experimental methods, showcasing high sensitivity in sensing applications, particularly in detecting changes in food color in water mixtures. This capability opens avenues for environmental monitoring and food safety applications, highlighting the MMA's role in critical real-world applications.

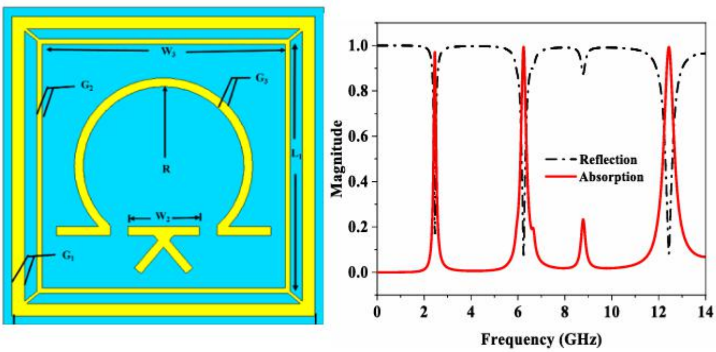

Figure 7: MMA and result

(Nipun *et al.*, 2024) presented MMA demonstrates resonances at 3.5 GHz and 13 GHz, with peak absorptions of 92.7% and 99.99%, correspondingly. Utilizing an FR4 substrate and circular rings in its design, the absorber is compact at 12 × 12 × 1.6 mm^3 as depicted in Figure 8. It shows insensitivity to polarization and incident angles up to 60°, confirming its robust performance in real-world conditions. The equivalent circuit model corroborates the findings through simulations, while the prototype measurement results closely align with simulations, indicating its suitability in wireless communication systems. This research also highlights the design's potential for integration into low-profile antennas, expanding its practical applications in modern telecommunications.

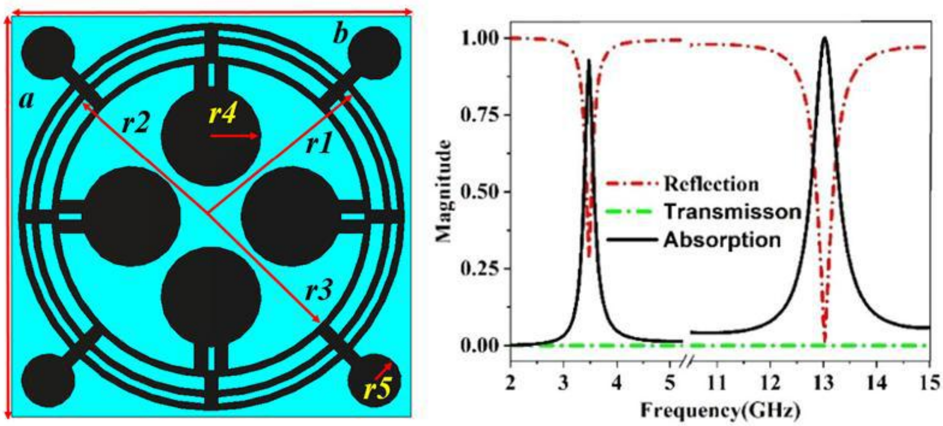

Figure 8: MMA and result

On the other side, wideband MMAs are obtained to operate across a wide-ranging frequency spectrum, making them resourceful for applications like radar cross-section reduction and electromagnetic wave shielding. The development of wideband absorbers has focused on attaining strong absorption execution over several GHz. Using of multiple resonant elements with tactical geometrical arrangements and by including lumped elements like resistors, engineers successfully designed wide absorption bandwidths and angle-independent performance. For example, the use of circular-sector unit cells with resistors and complex engagements of metallic patches enhances the absorbers performance range and efficacy (Saadeldin *et al.*, 2023).

Materials like FR4 for low frequency and Rogers RT5880 for high frequency play a crucial role in the design of wideband near perfect absorbers with effective absorption efficiency. Regardless of these progresses, encounters are there, embracing fabrication tolerances and the balance between bandwidth and thickness. Current investigation intends to refer these issues by exploring new materials and design approaches. Wideband absorbers plan to cover a larger frequency range, making them more resourceful in applications like radar-absorbing materials and broadband communication.

(Nguyen *et al.,* 2021) introduced a broad bandwidth showing in Figure 9, and larger incidence angle MM absorber using a hybrid unit cell and the measurement of the unit cell is 17.6 × 17.6 × 0.8 mm^3. Balanced unit cells maintain great absorption across every polarization angles. A rotary unit cell achieves extraordinary absorption under oblique incidence for both TE and TM modes. To improve the bandwidth, a hybrid unit cell with four rounded sectors is introduced, resonating at 10.38 GHz and 10.55 GHz. The proximity of these frequencies results in increased bandwidth. The suggested design is justified through full-wave simulations and measurements, showing simulated absorption exceeding 91% around 10.45 GHz at angles of incidence up to 70° for both polarizations. Measured absorption at this frequency approaches 96.5% under normal incidence, maintaining above 90% in TE mode and above 94% in TM mode as the angle of incidence varies. The determined90% absorption bandwidth is 1.95% from 10.1 to 10.2 GHz and 10.4 to 10.5 GHz up to 70° in the TE mode, and 3.39% from 10.15 to 10.5 GHz at the same angle in the TM mode.

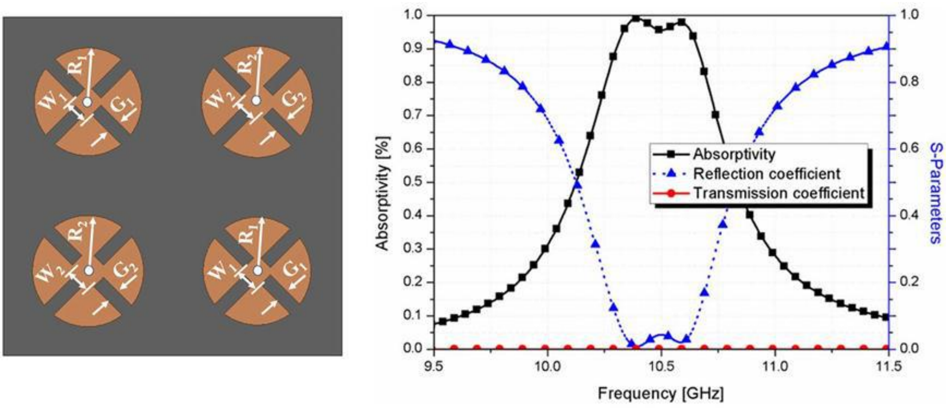

Figure 9: MMA and result

(Sharma *et al.,* 2019) addressed the challenges in achieving broad absorption bandwidth for single-layer metamaterial absorbers showing Figure 10. It investigates a frequency-selective surface (FSS) single-substrate layer with the dimension 8 × 8 × 2 mm^3, broadband metamaterial absorber in the range of 8–18 GHz through theoretical, experimental, and simulation approaches. Simulations identify optimal substrate dielectric thicknesses, FSS thicknesses, and dimensions, leading to a fabricated prototype that closely matches simulation results. The fabricated absorber, with a thickness of 2.0 mm, achieves a minimum reflection coefficient of −29.0 dB at 12.2 GHz, resulting in a −10 dB absorption bandwidth of 7.5 GHz (from 8.5 to 16 GHz). Effective complex electromagnetic parameters are extracted, highlighting key features of miniaturization, single-substrate design, simple geometry, and wide bandwidth for practical electromagnetic applications.

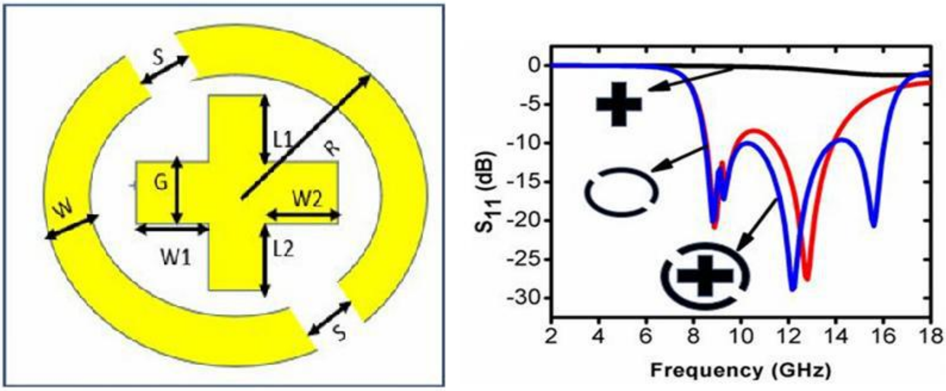

Figure 10: MMA and result

(Chen *et al.*, 2021) presented a broadband microwave metamaterial absorber showing in Figure 11, with a relative absorption bandwidth of 127.3% and an actual dimension is 20 × 20 × 17 mm^3. Characteristic modes theory guides the design, leading to excellent performance with a wider bandwidth and fewer modes compared to existing MMAs. Characteristic modes analysis (CMA) reveals a wideband modal significance (MS) greater than 0.707, indicating that the MMA achieves wideband absorption by exciting only one mode from 1.38 GHz to 6.44 GHz. Surface current distributions confirm successful mode excitation, while the input impedance showcases a wideband match characteristic with free space. The prototype, fabricated and measured, demonstrates a great absorption rate exceeding 90% in the scale from 1.44 to 6.32 GHz. This study establishes CMA as an effective design method for metamaterial absorbers. In this design the author used 130Ω resistances.

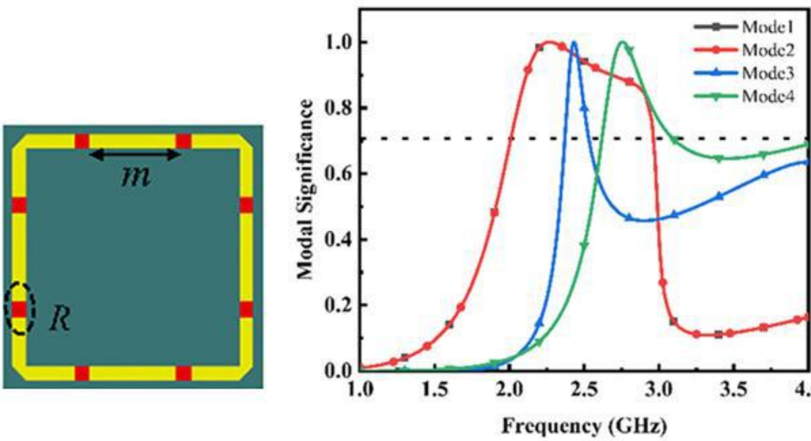

Figure 11: MMA and result

(Nguyen *et al.*, 2021) reported a wide-band and polarization insensitive metamaterial absorber based on a symmetrical structure with surface mount resistors valued 240Ω. The design showed in Figure 12, involves of a periodic array of a top metal symmetry resonator loaded with four lumped resistors, detached by an FR-4 dielectric substrate with a dimension of $9.7 \times 9.7 \times 2.5$ mm^3 from a continuous metal ground plane. Measurements confirm good agreement with simulation results, showing polarization-insensitive behavior across a frequency range from 8 to 18 GHz, covering the entire X- and Ku-bands with an absorption exceeding 80% at incident angles up to 40° for both transverse electric (TE) and transverse magnetic (TM) polarizations. Compared to existing broadband absorbers utilizing lumped resistors, this absorber exhibits superior compactness, structural simplicity, and high relative absorption bandwidth, making it promising for X- and Ku-band applications.

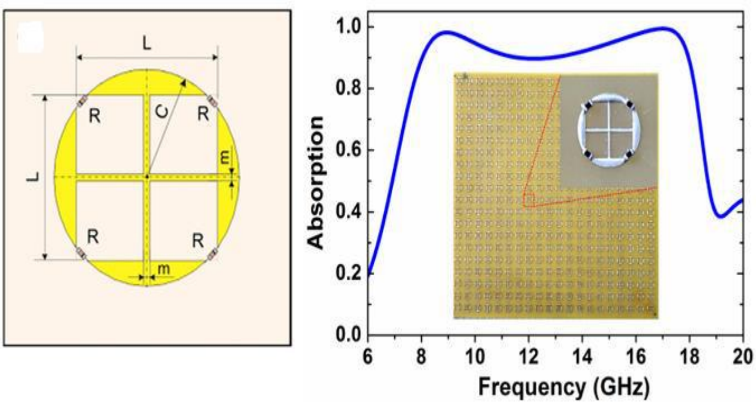

Figure 12: MMA and result

(Ly *et al.*, 2022) introduced a wideband, ultra-thin, wide-angle, and polarization-insensitive MMA utilizing a solo-layer resistive frequency-selective surface (FSS) displayed in Figure 13. Simulated result indicates that the absorption rate exceeds 90% in the frequency range of 24.1–42.6 GHz, achieving a relative absorption bandwidth of 55.47%. With a dimension of $8.5 \times 8.5 \times 1.2$ mm^3, the design achieves values of 0.088 and 0.156 for the lowest and highest frequencies, respectively. The power loss density analysis elucidates the absorption mechanism, indicating the critical role of the resistive film layer in achieving wideband absorption. The design also showcases effective absorption for oblique incidence across a wide angle, maintaining polarization insensitivity.

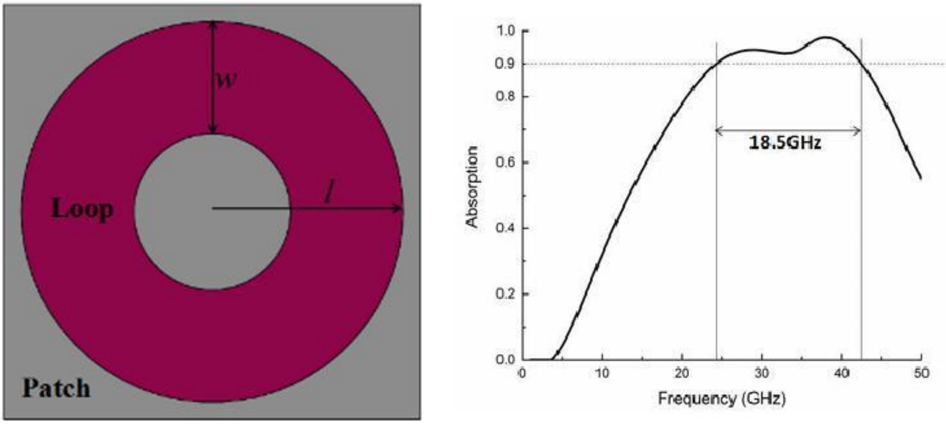

Figure 13: MMA and result

(Zheng *et al.*, 2023) proposed a high-performance electromagnetic-wave metamaterial absorber suitable for 5G technology, exhibiting absorption exceeding 99% at a tailored frequency range of 28 GHz visible in Figure 14. The design maintains this high performance under both transverse-electric and transverse-magnetic polarizations when electromagnetic waves are incident normally, with absorption rates above 97% even at incident angles up to 45°. The absorber's flexibility and simple production process make it ideal for mass manufacturing. The minimal meta-structure dimension is 4.4 ×4.4 mm^2, allowing for a cost-effective solution. Additionally, the research highlights alternative high-performance metamaterial absorber tailored for a bandwidth centered at 77 GHz, relevant to self-driving cars, achieved with minor adjustments to the original design.

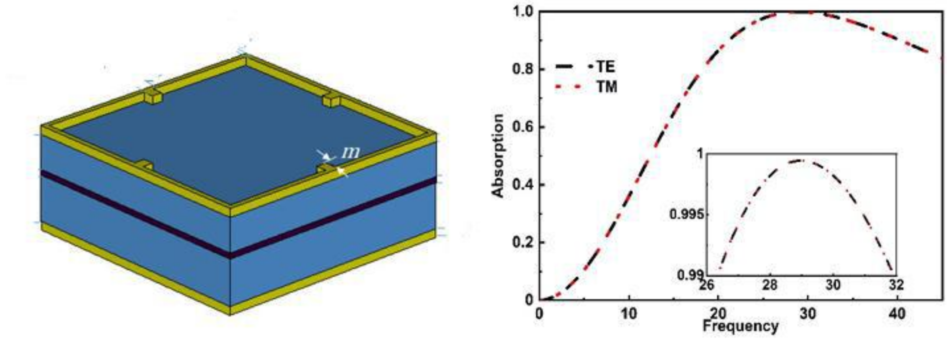

Figure 14: MMA and result

(Saadeldin *et al.*, 2023) analyzed an ultra-thin and broadband metamaterial absorber loaded with four lumped resistors shown in Figure 15. The design aims to enhance absorption by simultaneously lowering reflection and transmission coefficients. A continuous metallic ground achieves zero transmission, while impedance matching with free space (Z = Z0 or μr = εr) reduces reflection. The structure achieves both electric and magnetic resonances, resulting in perfect absorption. The finite element method simulates and analyzes the absorber, demonstrating over 90% absorptions across a broad frequency range (14.35–29.18 GHz) for both TE and TM polarizations. The proposed design maintains excessive absorption via incident angle variations from 0° to 50°, indicating its prospective applications in communications, stealth, and imaging fields. The value of resistance used in this design is 240Ω. The suggested dimension is 10 × 10 × 3.25 mm^3.

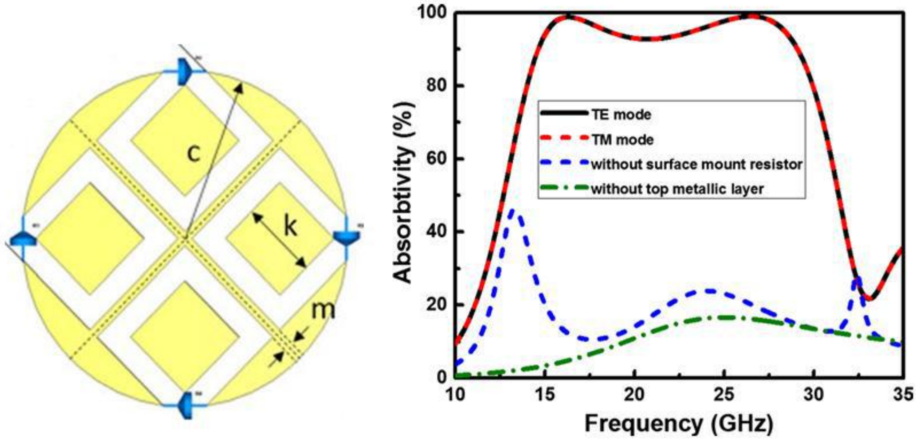

Figure 15: MMA and result

(Saadeldin *et al.*, 2023) proposed and analyzed a wideband visible in Figure 16, ultrathin metamaterial absorber specifically designed for Ku-band applications. The reported absorber achieves nearly perfect absorptivity above 90% across the entire Ku band (12–20 GHz) at normal incidence for both TE and TM polarizations, facilitated by simultaneous electric and magnetic resonances. The effective permittivity and permeability are designed to achieve impedance matching with free space, resulting in the absorption of incident energy. Additionally, the structure demonstrates good absorption response (above 80%) under oblique incidence (from 0 to 50°), indicating its suitability for diverse Ku-band applications. The dimension of the proposed structure is 3.7 × 3.7 × 2.5 mm^3.

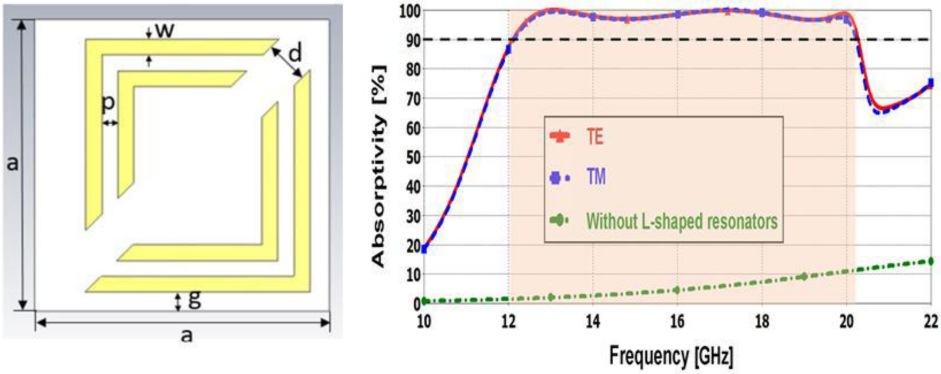

Figure 16: MMA and result

(Shukla *et al.*, 2024) presented a microwave MM absorber described in Figure 17, which is independent of angle and designed with two circular hexagons connected through merged resistors value of 350Ω. Established on a FR4 dielectric substrate dimension is 31.5 × 31.5 × 3.2 mm^3, the absorber exhibits a wide absorption bandwidth from 2.8 to 10.42 GHz with absorptivity above 90%, covering the S, C, and X bands. Current and electric field distributions are explored at two peak frequencies (3.66 GHz and 9.54 GHz) with maximum absorptivity of 99.99% and 99.44%, respectively. The structure undergoes testing under varying polarization angles using anechoic chamber methods with horn antennas and VNA. Results show close agreement between tested and simulated values, demonstrating the absorber's potential application in defense for radar cross-section (RCS) reduction.

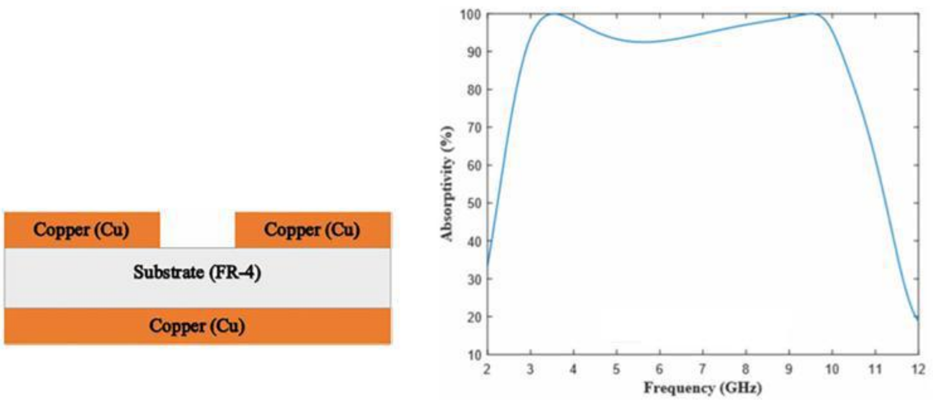

Figure 17: Graphical representation of MMA and result

A comprehensive analysis has been studied based on peak absorption percentages of the reviewed paper. The chart showcasing values predominantly above 90%, with many achieving near-unity absorption. Most absorbers function excellently across GHz frequencies, demonstrating the usefulness of various geometrical and material revolutions. This analysis highlights the ongoing trend of improving MMAs for frequency-selective absorption and vital for applications like sensing, EMI shielding, and radar cross-section reduction. The chart is given below:

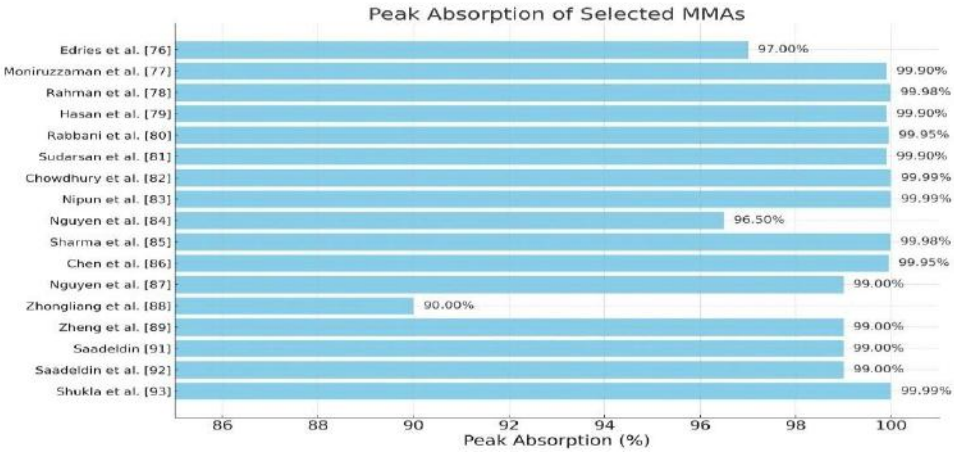

Figure 18: Peak Absorption chart

A pie chart is also realized to illustrate the application categories of the selected metamaterial absorbers. From the chart it is visible that wireless communication and EMI shielding account for the largest portion, comprising approximately 38% of the studied absorbers, reflecting the growing demand for signal clarity and interference reduction. Where Radar and stealth technologies follow at 24%, driven by military and aerospace needs. Meanwhile, sensing applications, including gas and biosensing make up 19%, showing their relevance in health and environmental monitoring. Energy harvesting and medical/thermal uses together contribute 14%, while solar and optical absorption holds a 5% share, showcasing potential in renewable energy and photonic applications. The pie chart is depicted in the following figure:

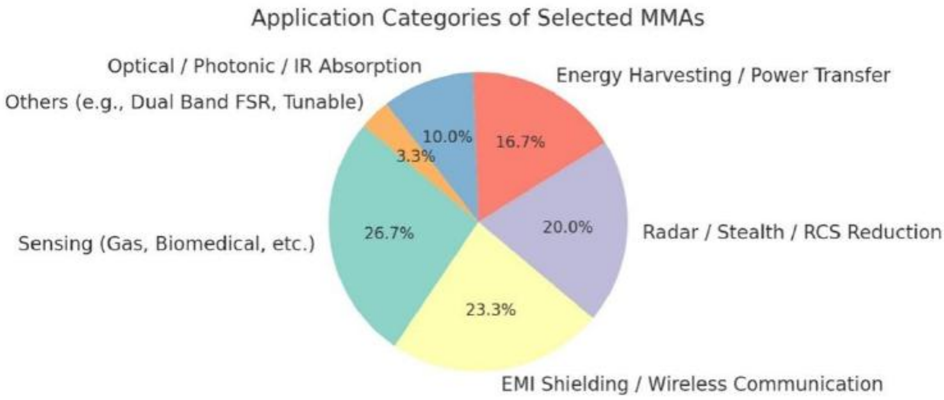

Figure 19: Pie chart illustrating the application categories

Over the years, wide-ranging investigation has been conducted on MMAs, leading to diverse range of designs with varying performance features. In narrowband absorbers, many studies have focused on achieving sharp, frequency-selective absorption using resonant constructions like split-ring resonators and homocentric rings on common substrate such as FR-4 and Rogers 5880. These absorbers, functioning across S, X and Ku bands, often demonstrate strong polarization insensitivity and high Q-factors, making them suitable for applications such as SAR reduction, Wi-Fi shielding and biosensing. For example, structures developed by M. Moniruzzaman and M. S. Hasan showed exceptional angular stability and dual-band absorption and high absorption across multiple frequency ranges. Also M.M.K. Nipun proposes THz narrowband MMA for sensing applications. In contrast, wideband MMAs employ techniques like multi-resonator unit cells, surface-mount resistors and conductive coupling strategies to enlarge absorption bandwidth. These absorbers are commonly designed for RCS reduction, EMI shielding and wireless power transfer. Especially, works by H. Chen and T.K.T. Nguyen emphasized high absorption across broad GHz ranges with polarization and angle insensitivity. Meanwhile M.K. Nipun proposed an MMA for ultrawide band MMA for visible and infrared Spectrum. Furthermore, recent developments involving resistive films, hybrid meta-surfaces and characteristic mode analysis have further improved the bandwidth and structural compactness. Collectively, these studies illustrate the evolution of MMAs from narrowband application specific designs to wideband multifunctional architectures, showing the field's rapid progression and growing application potential.

4. Design Suggestions for Narrowband and Wideband Absorbers

4.1 Narrowband Absorbers

Narrowband MMAs are typically designed to operate at a single frequency or within a very limited frequency range. These absorbers are often used for applications such as sensing, imaging, and specific communication systems (Munk *et al.*, 2005) where high precision is required. The following key design principles are critical for narrowband MMAs:

High-Q Resonators: Resonators with a high-quality factor (Q-factor) guarantee sharp, narrow absorption peaks at the desired frequency. Split-ring resonators (SRR) (Landy *et al.*, 2008; Dayal *et al.*, 2013) are commonly used to achieve narrowband absorption.

Material Selection: For narrowband absorbers, the selection of dielectric substrate (Hokmabadi *et al.*, 2014; Pang *et al.*, 2017; Song *et al.*, 2017; Hajizadegan *et al.*, 2013; Kim *et al.*, 2016) should spotlight low dielectric losses to reduce energy dissipation outside the resonant frequency. Common materials include FR-4 and Rogers 5880.

Tunable Absorbers: Tunable metamaterial absorbers (Zhang *et al.*, 2014; Huang *et al.*, 2018; Ling *et al.*, 2015; Kaur *et al.*, 2019; Munaga *et al.*, 2015; Ghosh *et* *al.*, 2015), which can vigorously change their absorption frequency, can be achieved by combining active components such as diodes or graphene layers. This tunability can be particularly useful for sensing applications.

4.2 Wideband Absorbers

Wideband absorbers are designed to cover a broad range of frequencies, which makes them ideal for applications like radar-absorbing materials and electromagnetic interference shielding. Design strategies for wideband MMAs include:

Multi-resonant Structures: A blend of resonators tuned to different frequencies can be employed to attain broadband absorption. This method allows for multiple absorption peaks, which mutually cover a wide frequency range (Shelby *et al.*, 2001; Cheng *et al.*, 2016; Bhatarai *et al.*, 2015).

Gradient Index Metamaterials: Gradient-index metamaterials progressively transition from one impedance to another, allowing for better impedance matching across a wide range of frequencies. This design strategy is highly effective in extending the bandwidth of MMAs (Aydin *et al.*, 2007; Singh *et al.*, 2018).

Dielectric Layer Thickness: Increasing the thickness of the dielectric substrate supports to broaden the absorption bandwidth. However, the trade-off is the increased overall size of the absorber. Optimizing thickness is a key trade-off in wideband MMA design (Liu *et al.*, 2018; Nipun *et al.*, 2025).

The Table 1 summarizing diverse methods used to improve the practicality of metamaterial absorbers (MMA) based on different parameters such as design strategy, materials, and operating frequency, along with their advantages and improvements:

Table 1 summarization of different MMA

Functions	Description	Advantages	Observed Improvement	Reference
Angular Stability	Incorporating tuning stubs or specific geometry to maintain performance at different angles.	Effective performance at wide incident angles	Maintains absorption up to 60° incidence angles	(Rabbani *et al.*, 2024)
Multiband Resonance	Utilizing structures like concentric rings, H-shaped modifiers, or	High absorption across multiple	Enhanced functionality for multi-band wireless and	(Sudarsan *et al.*, 2024)

	fractal geometries for multiple bands.	frequency bands	radar applications	
Compact Unit Cell Design	Miniaturized designs with high efficiency in small form factors.	Space-saving, low-profile designs	Compact cells without compromising absorption performance	(Chen *et al.*, 2021)
Use of Lumped Resistors	Incorporating resistors in the design to broaden bandwidth and increase absorption.	Wideband and polarization-insensitive behavior	Achieves high absorption across a wide frequency range (e.g., X- and Ku-bands)	(Chowdhury *et al.*, 2023)
Frequency Selective Surface (FSS)	Using FSS layers with specific geometries to filter and absorb specific frequencies.	Targeted absorption at desired frequency ranges	Enhanced broadband absorption covering multiple GHz ranges	(Ly *et al.*, 2022)
Hybrid Unit Cell	Combination of multiple geometric resonators to broaden absorption bandwidth.	Increases overall bandwidth and multi-angle efficiency	Wider absorption bandwidth, improved efficiency at oblique angles	(Nguyen *et al.*, 2021)
Circuit Model-Based Design	Designing based on equivalent circuit models to match impedance with free space.	Ensures minimal reflection and near-perfect absorption	Validated designs closely matching simulation and measured results	(Chen *et al.*, 2016)
Multilayered Structures	Stacking multiple layers of metamaterials to enhance broadband absorption.	Broader absorption range and improved impedance matching	Near-unity absorption over a broader frequency range, suitable for stealth and radar applications	(Saadeldin *et al.*, 2023)
Dielectric Material Optimization	Selection of low-loss, high-performance substrates like Rogers or FR4.	Improved dielectric properties and minimal energy loss	Increased efficiency in energy absorption, reduced losses,	(Chowdhury *et al.*, 2024)

			and better angular response	
Surface Current Manipulation	Designing for optimal surface current distribution across the MMA.	Improved mode excitation and resonance	Achieves consistent absorption by optimizing current distribution at different frequency bands	(Zheng *et al.*, 2023)
Impedance Matching with Free Space	Tuning the effective impedance to match that of free space.	Near-perfect absorption with minimal reflection	Enhanced absorption at normal and oblique incidences for both TE and TM polarizations	(Bulu *et al.*, 2005)

Existing MMA designs face notable limitations, including sensitivity to fabrication tolerances and reduced absorption at oblique angles. Realizing both broader bandwidth and compact thickness remains challenging. Material losses and environmental instability further disturb the performance. Considering these challenges, future research on the development of robust, compact, and multifunctional MMAs that maintain performance across varying angles, polarizations, and operational conditions are needed. Incorporating machine learning-based optimization strategies, can enable intelligent absorber designs with real-time adaptability. Moreover, integrating multiple functionalities—such as sensing, shielding, and energy harvesting—within a single absorber structure will pave the way for next-generation smart electromagnetic devices.

5. Conclusion

Metamaterial absorbers (MMAs) are highly versatile devices that play significant roles in a wide range of applications, from wireless communication systems to electromagnetic interference (EMI) shielding and radar-absorbing materials (RAM) to sensing. This review has explored the design strategies and principles for both narrowband and wideband absorbers, each tailored to their specific applications. Narrowband MMAs are designed for accurate, single or multiple frequency absorption, making them ideal for sensing, imaging, and specific communication systems. Their effectiveness is based on high quality resonators and careful selection of materials to ensure minimal energy loss and sharp absorption peaks. The use of tunable components can extend their flexibility, making them appropriate for precision-targeted applications. On the other hand, wideband MMAs are structured to cover broad frequency ranges, using multi-resonant structures, gradient-index metamaterials, and optimized dielectric thickness to achieve their broad absorption capabilities. These absorbers are crucial in applications requiring widespread frequency coverage, such as radar systems, EMI shielding, and environmental sensing. In designing both types of absorbers, the trade-off between compactness and performance remains a critical factor. Narrowband absorbers emphasize precision, while wideband designs focus on expanded frequency ranges. By selecting appropriate resonator structures, substrate materials, and employing innovative design techniques, MMAs can be optimized for both narrowband and wideband applications, sensing technologies, and electromagnetic shielding. The continued evolution of MMAs, driven by improved material science and resonator design, promises further advancements in performance across various industries.

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Conflict of interest

The authors affirm that there are no conflicts of interest associated with the publication of this work. They have followed ethical guidelines and addressed various issues; including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and and/or submission, and redundancy. The authors have thoroughly observed and complied with ethical standards throughout the research and writing process.

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