SYNTHESIS AND SINTERING 6 (2026) 12–25

Available online at www.synsint.com

Synthesis and Sintering

ISSN 2564-0186 (Print), **ISSN** 2564-0194 (Online)

Review article

A review of circuit analog absorbers: material synthesis, processing strategies, and electromagnetic applications

Alireza Bayat [a,*], **Reza Mirzakhani** [a], **Pouria Dianati Souha** [b]

[a] *Faculty of Technical and Engineering, Electrical Engineering-Telecommunication, Imam Khomeini International University, Qazvin, Iran*
[b] *Department of Aeronautical Engineering, Faculty of Aviation and Space Science, University of Kyrenia, Kyrenia, Mersin 10, Turkey*

ABSTRACT

Circuit analog absorbers (CAAs) represent a class of engineered functional materials designed for efficient electromagnetic wave attenuation through impedance matching and resonance-based mechanisms. While traditionally analyzed using electromagnetic circuit models, their practical realization critically depends on material synthesis strategies, microstructural engineering, and controlled fabrication processes. This review presents a comprehensive overview of CAAs from both electromagnetic and materials science perspectives, covering the evolution from classical absorber configurations to modern frequency selective surface (FSS) and metamaterial-based designs. Particular emphasis is placed on the synthesis of conductive and resistive materials, including carbon-based polymer composites, nanoparticle-derived metallic films, and multifunctional hybrid systems. The role of additive manufacturing, multilayer lamination, thermal consolidation, and low-temperature sintering in controlling electrical conductivity, dielectric response, and surface impedance is critically analyzed. Processing–structure–property relationships governing broadband absorption, polarization stability, and angular performance are discussed in the context of thermodynamic and kinetic phenomena including percolation network formation, polymer curing reactions, and nanoparticle sintering mechanisms. By integrating synthesis science with electromagnetic modeling, this review highlights how advanced fabrication routes and material engineering enable the development of thin, broadband, and mechanically robust absorbers suitable for radar cross-section reduction, electromagnetic interference shielding, and next-generation communication systems. The presented analysis provides a synthesis-oriented framework for future research on high-performance absorber materials and advanced sintering-driven fabrication strategies.

KEYWORDS

Circuit analog absorbers
Frequency selective surfaces (FSS)
Metamaterial absorbers
Material synthesis
Additive manufacturing
Electromagnetic wave absorption

1. Introduction

The concept of circuit analog absorbers (CAAs) has been a significant development in electromagnetic wave absorption since the mid-20th century, building upon foundational works like the Salisbury screen and Jaumann absorber [1]. Refer to Figs. 1 & 2; these early structures used layers of resistive sheets separated by dielectric spacers to absorb incidentelectromagnetic waves effectively. Circuit analog absorbers, however, advanced this concept by integrating frequency selective surfaces (FSS) and resistive elements to mimic the behavior of an equivalent electrical circuit, allowing for more controlled and efficient absorption across a wide range of frequencies [2].

Initially, CAAs were primarily employed for radar cross-section (RCS) reduction, especially in military applications where reducing the radar

---

* Corresponding author. *E-mail address:* abaiat@eng.ikiu.ac.ir (A. Bayat)

Received 13 February 2026; Received in revised form 14 March 2026; Accepted 14 March 2026.

https://doi.org/10.53063/synsint.2026.61330

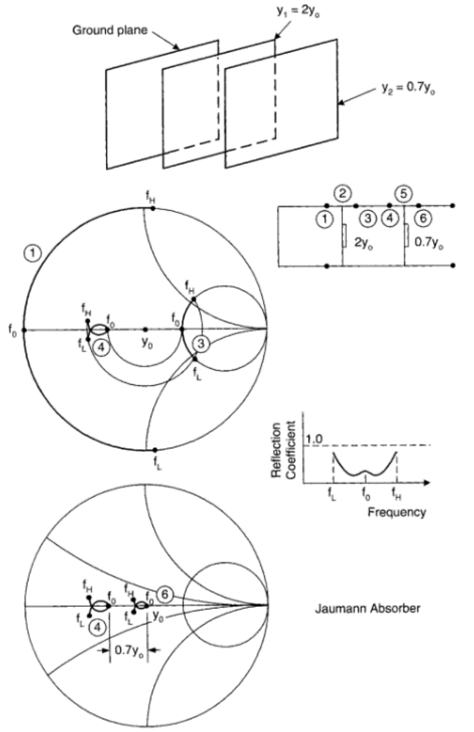

Fig. 1. Jaumann absorber, smith chart, reflection co-efficient and equivalent circuit [3].

signature of aircraft and other vehicles was crucial for stealth technology [4]. Over time, the development of computational tools and material sciences has enabled researchers to optimize the design of CAAs, leading to a new generation of thin, broadband absorbers with applications in both military and civilian sectors [5].

In recent years, the design of CAAs, where depicted in Fig. 3, has seen several important trends. One of the primary focuses has been on enhancing bandwidth without significantly increasing the thickness of the absorber. Researchers have explored the use of multi-layered structures with resistive FSS and metamaterials to create ultrathin wideband absorbers [6]. These absorbers can maintain high absorption rates while keeping a low profile, making them suitable for integration

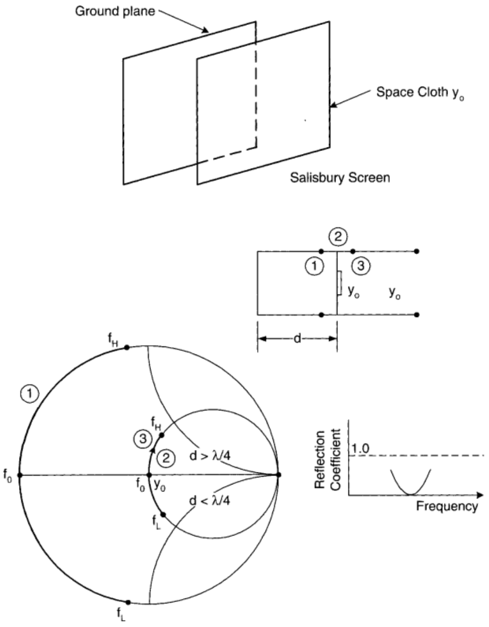

Fig. 2. Salisbury screen, smith chart, reflection co-efficient and equivalent circuit [3].

into stealth technology and other compact systems [7]. Moreover, the advent of reconfigurable absorbers has allowed for dynamic switching between absorption and reflection modes, providing new capabilities for antenna systems and smart skins in aerospace applications [8].

Furthermore, the development of polarization-independent and wide-angle CAAs has addressed the limitations of traditional absorbers that are typically dependent on the angle of incidence and polarization of the incoming wave [9]. This has expanded the use of CAAs in scenarios where the orientation and polarization of signals cannot be easily controlled, such as telecommunication systems and electromagnetic interference (EMI) shielding in complex environments [10].

Today, CAAs are widely used not only in military stealth applications but also in a variety of fields. Telecommunications companies are employing CAAs to improve the efficiency of antenna systems by absorbing unwanted signals and reducing interference [11]. Similarly, EMI shielding for electronic devices is becoming increasingly reliant on the use of CAAs to protect sensitive equipment from electromagnetic noise [12]. Additionally, researchers are exploring the use of CAAs in smart surfaces and next-generation aircraft skins, where they serve both structural and electromagnetic functions [13].

Despite the extensive body of review literature on electromagnetic absorbers and circuit analog absorbers (CAAs), most existing studies primarily focus on electromagnetic design methodologies, equivalent circuit modeling, and application-oriented performance metrics. In contrast, this review provides a distinct and comprehensive perspective by systematically integrating materials synthesis, fabrication routes, and processing–structure–property relationships into the analysis of CAA performance. Particular emphasis is placed on the role of conductive material synthesis, additive manufacturing techniques, multilayer processing, and sintering-driven mechanisms in governing absorber behavior. Furthermore, this work highlights the thermodynamic and kinetic aspects of conductive network formation and microstructural evolution, which are often overlooked in conventional reviews. By bridging electromagnetic theory with materials processing science, this review offers a unified framework that enables more realistic and scalable design of high-performance absorbers, thereby addressing a critical gap in the current literature.

2. Literature search and selection criteria

The methodology employed for identifying and selecting studies in this review involved a systematic approach to ensure comprehensive coverage of the literature on circuit analog absorbers (CAAs) and their applications. The strategy includes the following key steps:

- **Databases and search engines:** The following academic databases and search engines were utilized to gather relevant studies:

–IEEE explore: A primary resource for publications related to electromagnetic absorbers, antennas, and related fields.

–Google Scholar: A broad search engine used to access peer-reviewed articles, conference papers, theses, and patents.

–Web of Science: For citation analysis and retrieval of high-impact papers.

–Scopus: For multidisciplinary research and to track developments across different fields such as telecommunications, material science, and electromagnetic research.

–ScienceDirect: To gather studies on the material sciences aspects of CAAs.

–Wiley Online Library: For accessing research on innovative designs and theoretical advancements in electromagnetic absorbers.

- **Search terms:** The search was conducted using combinations of the following keywords to retrieve a wide array of studies on CAAs:

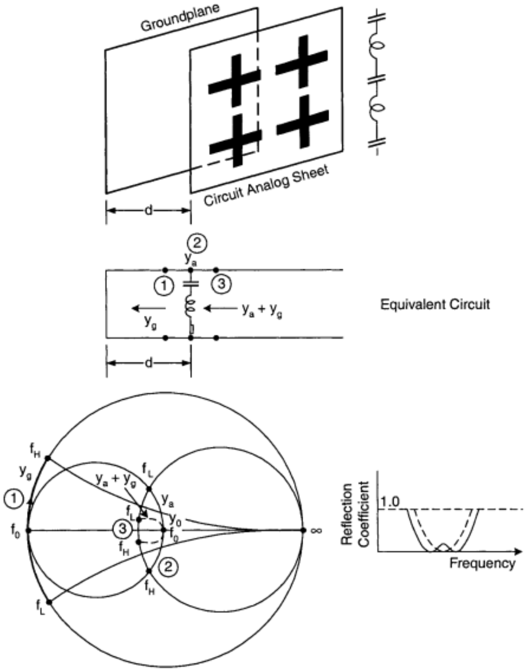

Fig. 3. The simple circuit analog absorber, reflection co-efficient, smith chart and equivalent circuit [3].

–Circuit analog absorber
–Electromagnetic absorber
–Frequency selective surface (FSS)
–Wideband absorber
–Reconfigurable absorber
–Radar cross-section (RCS) reduction
–Metamaterial absorber
–Polarization-independent absorber
–Electromagnetic interference (EMI) shielding

Boolean operators (and, or) were employed to combine these terms and maximize the scope of the search. For example, combinations like "circuit analog absorber and frequency selective surface" or "circuit analog absorber and radar cross-section reduction" were used to capture relevant literature.

- **Inclusion criteria**: The inclusion criteria ensured that the review captured the most relevant and recent advancements in CAAs. The criteria were:

–Timeframe: Articles published from 2007 onwards were considered, focusing on the last two decades of developments. This time range includes the most impactful and current research on modern CAAs.

–Language: Only studies published in English were included.

–Publication type: Peer-reviewed journal articles, conference papers, patents, and reputable technical reports were considered.

–Relevance: The study must focus on the design, development, optimization, or application of CAAs. General studies on electromagnetic absorbers were excluded unless they explicitly discussed CAAs or FSS-based designs.

- **Selection process**: Initially, the search yielded a large set of papers. After performing the initial search, titles and abstracts were screened for relevance to the topic. Studies that appeared to fit the inclusion criteria were then read in full to assess their suitability for the review. Papers that provided key insights into the historical evolution, current trends, and application areas of CAAs were retained. Additionally, citation tracking was employed to find seminal papers frequently referenced by other researchers in the field.

By using this methodical search strategy, the review ensures a broad yet focused analysis of circuit analog absorbers, synthesizing key developments, trends, and applications in the field.

3. Basic principles of circuit analog absorbers

Circuit analog absorbers (CAAs) are artificial materials designed to absorb electromagnetic (EM) waves effectively, combining electromagnetic theory, transmission lines, and resonance-based absorption mechanisms. Electromagnetic waves consist of oscillating electric and magnetic fields that propagate through space. When EM waves encounter a material, they can be reflected, transmitted, or absorbed, depending on the material's impedance, permittivity, and permeability. The governing principles of wave propagation are derived from Maxwell's equations, which describe how electric and magnetic fields interact with matter and propagate in different media [14]. Impedance matching is crucial to minimizing reflection and maximizing absorption. The impedance of a material is the ratio of electric to magnetic field strengths. Absorption occurs when the impedance of the absorber is matched to the impedance of the surrounding medium (air, typically 377 ohms). This ensures minimal reflection at the interface and maximizes wave penetration into the absorber, where dissipation occurs [15]. CAAs utilize the principle of resonance to absorb EM energy. These absorbers consist of periodic conductive elements (such as resistive sheets or metallic patches) that resonate at particular frequencies. At resonance, electromagnetic energy is trapped and localized, which enhances absorption efficiency by concentrating the fields in the absorbing medium [16]. As shown on Fig. 4, the capacitance values of 4 different elements as a function of the element size with respect to the lattice periodicity.

LC resonators: A common approach is to model CAAs as networks of inductive (L) and capacitive (C) elements, forming LC resonators. These elements resonate when the incident wave's frequency matches the natural frequency of the circuit. The resulting current causes energy dissipation via resistive losses, primarily through heat. This resonance-based model is well-supported by circuit theory and is extensively used in CAAs design [17]. Once EM energy enters the absorber, it must be dissipated to avoid reflection. This dissipation occurs through ohmic losses in resistive materials, where the absorbed EM energy is converted into heat via Joule heating. The resistive materials in the absorber play a critical role in this process, converting the electromagnetic energy into thermal energy efficiently [18].

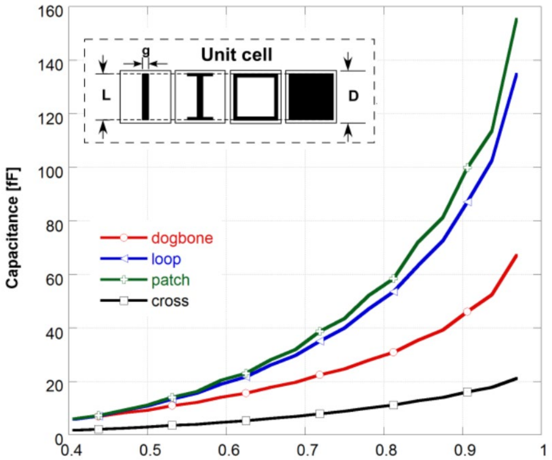

Fig. 4. Capacitance values of 4 different elements as a function of the element size with respect to the lattice periodicity [18].

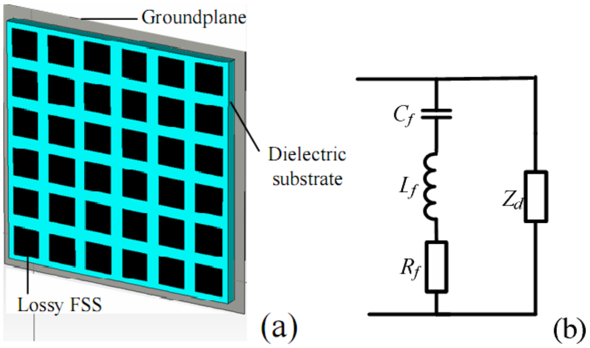

Fig. 5. a) Three-dimensional sketch of the conventional FSS absorber and b) its equivalent circuit [27].

Dielectric and magnetic losses: Absorption can also be enhanced by materials with complex permittivity and permeability, leading to dielectric and magnetic losses. These losses occur due to polarization mechanisms in dielectrics and domain realignment in magnetic materials, contributing to overall absorption [3].

CAAs are often analyzed through equivalent circuit models, representing the absorber as a network of resistors, capacitors, and inductors. These models provide a way to calculate the surface impedance, which should ideally match the free-space impedance for maximum absorption efficiency. By adjusting the values of these lumped elements, the surface impedance of the absorber can be fine-tuned to optimize absorption [19].

Surface impedance: The surface impedance of CAAs must be carefully controlled to minimize the reflection coefficient. This impedance can be engineered by designing specific patterns or structures in the absorbing material. The ability to tune surface impedance is a fundamental principle in creating effective CAAs, as discussed in Ref. [20].

Achieving broadband absorption is a common goal in CAA design, especially for applications like radar-absorbing materials (RAM). Techniques to extend the absorption bandwidth include:

Multi-layer structures: Stacking layers with different resonant frequencies allows for effective absorption across a wider frequency range [21].

Gradual impedance transition: Gradually varying the impedance across layers or surfaces of the absorber ensures better broadband performance by reducing reflections over a larger frequency spectrum [22].

Distributed resonance structures: Using multiple resonators with slightly varying resonance frequencies allows absorption to occur over a broader range of frequencies [23].

3.1. Equivalent circuit model

The basic unit of a CAA can be modeled as a series, as shown in Fig. 5 or parallel RLC resonator, as shown in Fig. 6. In the series configuration, the impedance of each unit cell is given by:

$$Z_{unit}(j\omega) = R + j(\omega L - \frac{1}{\omega c}) \qquad (1)$$

where R is the resistance, L is the inductance, C is the capacitance and $\omega=2\pi f$ is the angular frequency of the incident wave.

At the resonant frequency f_0, the inductive reactance cancels the capacitive reactance:

$$\omega_0 L = \frac{1}{\omega_0 C} \rightarrow f_0 = \frac{1}{2\pi\sqrt{LC}} \qquad (2)$$

At resonance, the impedance becomes purely resistive:

$$Z_{unit}(j\omega_0)=R \qquad (3)$$

This ensures that the surface impedance of the absorber matches the impedance of free space Z_0=377 Ω, minimizing reflection [18, 24–27].

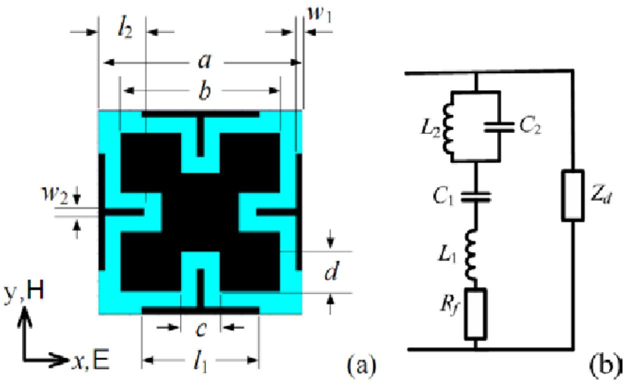

Fig. 6. a) Schematic structure of the designed FSS and b) its corresponding circuit model [27].

3.2. Reflection and absorption coefficients

The reflection coefficient Γ of the CAA is derived using the surface impedance of the absorber Z_{abs} and the impedance of free space Z_0. The reflection coefficient is given by:

$$\Gamma = \frac{Z_{abs} - Z_0}{Z_{abs} + Z_0} \tag{4}$$

For maximum absorption, Γ should be minimized, which occurs when $Z_{abs}=Z_0$. The absorption coefficient A(f), assuming no transmission (backing the absorber with a conducting plate), can be expressed as:

$$A(f) = 1 - \left|\Gamma(f)\right|^2 \tag{5}$$

Substituting the expression for Γ, the absorption becomes:

$$A(f) = 1 - \left(\frac{Z_{abs} - Z_0}{Z_{abs} + Z_0}\right)^2 \tag{6}$$

At resonance, where $Z_{abs}=Z_0$, the absorption reaches its maximum value of 1, meaning that all the incident power is absorbed and no power is reflected [18, 24–27].

3.3. Impedance matching and broadband absorption

The goal of broadband absorption is to maintain $Z_{abs}\approx Z_0$ over a range of frequencies. This can be achieved by designing a surface with multiple resonant circuits, each tuned to a different frequency. For each resonant element, the impedance near the resonance can be approximated by:

$$Z_{abs}(f) = R + j(\omega L - \frac{1}{\omega C}) \tag{7}$$

By varying the values of L, C, and R for different unit cells, the surface impedance can be engineered to match free space impedance across a wide frequency band, resulting in broadband absorption [18, 24–27].

3.4. Advanced numerical simulations

Numerical methods such as the finite difference time domain (FDTD) and method of moments (MoM) are commonly employed to simulate the interaction between the incident wave and the CAA. These methods account for the periodic structure of the absorber, complex material properties, and the effects of neighboring cells.

The electromagnetic field distribution, surface currents, and scattering parameters can be computed using these methods. Additionally, optimization techniques, such as genetic algorithms (GA) and particle swarm optimization (PSO), can be applied to fine-tune the design of CAAs for optimal performance across multiple frequency bands [18, 24–27].

4. Comparative analysis of circuit analog absorbers: advancements and methodologies

Circuit analog absorbers (CAAs) have gained significant attention in recent years due to their potential in mitigating electromagnetic interference (EMI) and improving radar stealth. This article aims to compare and contrast recent advances in the design, material selection, and fabrication techniques for CAAs. Through this comparative analysis, we highlight key findings from multiple studies, focusing on

Table 1. Comparative results.

Reference	Frequency range (GHz)	Size (mm)	Thickness (mm)	Number of layers
[1]	4–40 GHz	20–50 mm	1–3 mm	Multiple layers
[2]	5–25 GHz	10–30 mm	1 mm	Single layer
[5]	2–18 GHz	35 mm	1.8 mm	Quasi-single layer
[7]	1–40 GHz	25–50 mm	2–4 mm	Multiple layers
[11]	2–18 GHz	20–35 mm	1.8 mm	Single layer
[12]	5–30 GHz	15–35 mm	1–2 mm	Double layer
[13]	4–18 GHz	10–40 mm	2 mm	Double layer
[28]	2–18 GHz	10–25 mm	1–2 mm	Double layer
[29]	8–12 GHz (X-band)	20 mm	1.5 mm	Single layer
[30]	5–15 GHz	20–30 mm	1.2 mm	Single layer
[31]	Optical frequencies	N/A	N/A	Multiple layers
[32]	1–40 GHz	15–45 mm	1.5 mm	Single layer
[33]	5–25 GHz	20–35 mm	2 mm	Single layer
[34]	8–12 GHz (X-band)	30 mm	3 mm	Single layer
[35]	10–20 GHz	25 mm	1.5 mm	Single layer
[36]	8–12 GHz (X-band)	15 mm	1.5 mm	Single layer
[37]	3–18 GHz	20–40 mm	1–3 mm	Multiple layers
[38]	8–12 GHz (X-band)	15 mm	1–2 mm	Single and double layer
[39]	5–20 GHz	20–35 mm	1.5 mm	Single layer
[40]	4–24 GHz	20–40 mm	2 mm	Single layer
[41]	2–25 GHz	20 mm	3.35 mm	Single layer

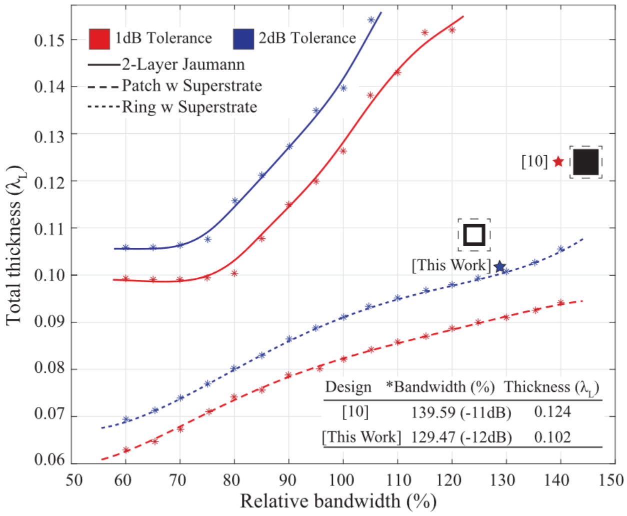

Fig. 7. Optimized bandwidth-thickness curves for single-FSS-layer CA absorbers and 2-layer Jaumann prototype with reserved fabrication tolerances [35].

design optimization, bandwidth enhancement, material characteristics, and practical applications. The comparative Table is provided about the 21 previously work on CAA as shown in the Table 1.

While the studies summarized in Table 1 demonstrate significant progress in bandwidth enhancement and thickness reduction, a critical comparison reveals several important trades-offs. Multilayer designs generally achieve broader bandwidth (e.g., 1–40 GHz range), but at the cost of increased fabrication complexity, higher material usage, and potential interlayer mismatch issues. In contrast, single-layer absorbers offer simpler fabrication and lower weight but often suffer from narrower bandwidth and reduced angular stability. Additionally, although many works report high absorption under normal incidence, fewer studies rigorously evaluate performance under oblique incidence, which is crucial for practical applications. This indicates that reported performance metrics are not always directly comparable and may overestimate real-world effectiveness.

4.1. Design techniques

The design of CAAs has seen a transformation, with a shift towards more advanced computational techniques and the adoption of new methodologies such as deep learning. For instance, Xiong et al. [42] introduced a divide-and-conquer deep learning approach for designing plasmonic stack metamaterials. This method greatly reduced design prediction error, emphasizing precision and real-time capabilities. Similarly, Lv et al. [35] proposed a semi-analytical design method for frequency selective surfaces (FSS) that efficiently optimizes bandwidth-thickness configurations. The mentioned result is shown in Fig. 7. These computational methods significantly enhance the speed and accuracy of CAA design. On the other hand, traditional genetic algorithm-based approaches [12] still offer a powerful tool for optimizing square-loop arrays in absorbers. However, these methods, while efficient, are gradually being complemented or replaced by more dynamic machine learning models.

Although recent approaches such as deep learning-based design [42] significantly improve prediction speed and accuracy, their practical implementation remains limited by the availability of high-quality training datasets and fabrication constraints. In contrast, traditional optimization methods such as genetic algorithms [12] are computationally more intensive but offer greater transparency and physical interpretability. Therefore, while machine learning approaches show strong potential, their current advantage lies primarily in design acceleration rather than fundamentally improving absorber physics.

4.2. Bandwidth and frequency response

Many studies focused on improving the operational bandwidth of CAAs. For instance, Yao et al. [32] achieved a remarkable 137.1% fractional bandwidth, providing a high level of absorption under normal incidence. Refer to Fig. 8, Chen et al. [28] expanded the operational bandwidth even further, using a double-layer resistor-loaded square-loop array, achieving an operating bandwidth ratio of 1:8.78 with excellent reflectivity performance under normal incidence. Additionally, Saikia et al. [30] combined capacitive and circuit analog absorbers, resulting in a thin broadband microwave absorber with optimized thickness and improved absorption performance. This hybrid design represents an innovative way to tackle the thickness constraints often found in traditional CAAs.

Although several studies report extremely wide fractional bandwidths (e.g., >100%), these results are often achieved under idealized conditions, such as normal incidence and controlled laboratory environments. In practical scenarios, bandwidth performance is strongly affected by fabrication tolerances, material inhomogeneity, and environmental factors. Therefore, direct comparison between reported bandwidth values should be approached with caution, and more standardized evaluation criteria are needed in future studies.

4.3. Material selection and fabrication

Material choice plays a critical role in the efficiency of CAAs. In this regard, additive manufacturing techniques are being explored as a solution for creating absorbers with complex material compositions. Prince et al. [34] demonstrated the use of polylactic acid (PLA)-based materials for fabricating CAAs through additive manufacturing, as

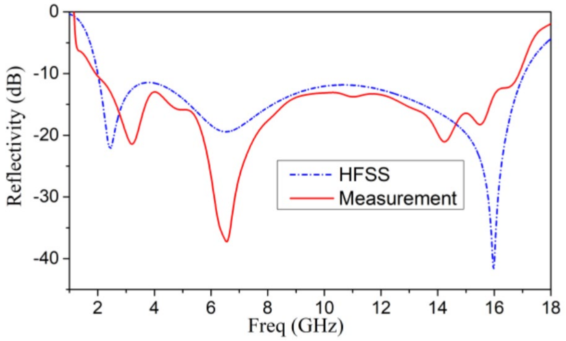

Fig. 8. Simulated and measured reflectivity of the modified design under the dashed chart depicts the simulated result, and the solid line depicts the measurement.

shown in Fig. 9. This method allowed the integration of different materials into a single structure, offering more flexibility in absorber design. Additionally, carbon-fiber-reinforced polymer (CFRP) materials are gaining traction due to their high strength-to-weight ratio and electromagnetic properties. Riley et al. [36] and O'Donnell and Narayanan [43] investigated the use of unidirectional CFRP laminas in CAAs, with a focus on impact damage characterization. They found that even minor mechanical damage can adversely affect the microwave reflection coefficient, underscoring the need for damage-resistant designs.

Despite the growing interest in advanced materials such as CFRP and additively manufactured polymers, their adoption introduces new challenges. For example, CFRP-based absorbers provide excellent mechanical strength but exhibit anisotropic electromagnetic behavior, which may limit polarization-independent performance. Similarly, additive manufacturing offers design flexibility but often introduces porosity and surface roughness, leading to deviations from predicted electromagnetic responses. Compared to conventional fabrication methods such as photolithography or etched FSS structures, these emerging techniques require further optimization to achieve consistent and reproducible performance.

4.4. Durability and practical applications

The practical application of CAAs, particularly in radar stealth and EMI shielding, requires durability under mechanical stresses. O'Donnell and Narayanan [43] focused on the impact damage that can occur in CFRP-based CAAs. They highlighted the need for damage-resistant designs, as even small defects in these materials can compromise their electromagnetic effectiveness. Refer to Fig. 10, in contrast, traditional designs using resistive square-loop arrays [12] or frequency selective surfaces [43] provide excellent performance under normal conditions but are not optimized for mechanical durability. This indicates a trade-off between mechanical robustness and electromagnetic performance, depending on the absorber's intended application.

4.5. Absorber designs and structures

Similarities: Many of the studies share a common objective of designing broadband and polarization-insensitive CAAs. For example, the works by Zhou et al. [44] and Shukoor et al. [45] propose broadband absorbers using double-ring and square-loop structures, respectively.

Most studies utilize lumped resistors or resistive materials to achieve wideband absorption, such as in Ghosh et al. [46] and Meng et al. [47].

Differences: Multilayer and single-layer absorber configurations exhibit different advantages and limitations. Multilayer absorbers generally provide broader bandwidth and enhanced multi-frequency performance due to multiple resonant interfaces and improved impedance matching. For example, Zhang et al. [48] presents a double-layer FSS absorber with improved dual-band broadband absorption characteristics. In contrast, single-layer absorber designs offer reduced thickness and fabrication simplicity. Studies such as Ref. [49]

Fig. 9. Schematic of the RS (left) and CH (right) absorbers, including a side view (center). A thin, perfect electric conductor ground plane was placed on the rear face of the substrate (right edge of the side view) for simulation purposes. The black, gray, and light blue materials are graphite PLA, the substrate (solid PLA), and free space, respectively [34].

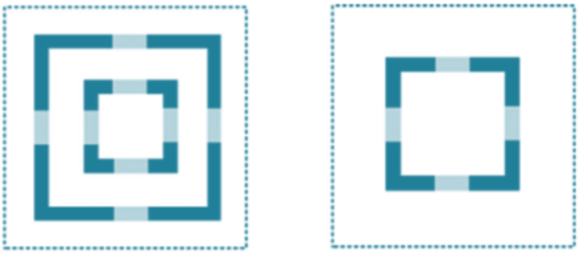

Fig. 10. Perspective views of the 4 × 4 unit cell multilayered absorber. In contrast, traditional designs using resistive square-loop arrays [12].

demonstrate compact single-layer metamaterial absorbers capable of achieving multiple resonances through polarization conversion and geometric optimization.

Similarly, metamaterial-based absorbers often achieve ultrathin profiles and superior absorption efficiency compared to traditional frequency selective surface (FSS) absorbers. For instance, Refs. [50] and [51] concepts to realize broadband and ultrathin absorber structures. In contrast, conventional FSS-based absorbers, such as [48], provide simpler fabrication and lower design complexity but may require thicker multilayer configurations to achieve comparable broadband performance.

The comparative analysis of recent literature on CAAs reveals substantial progress in both design and material innovation. Machine learning techniques such as deep learning are becoming more prominent, significantly improving the precision and speed of CAA designs. At the same time, innovations in material science, including the use of CFRP and PLA-based absorbers, are allowing for more flexible and durable designs. However, challenges remain, particularly in balancing the electromagnetic performance with mechanical robustness.

Overall, the literature reveals a clear gap between electromagnetic design optimization and materials realization. While many studies focus on improving absorber performance through geometric or circuit-based approaches, fewer works systematically address how synthesis methods, processing conditions, and microstructural variations influence the final electromagnetic response. This lack of integration limits the scalability and reproducibility of many proposed designs. Consequently, future research should emphasize a more holistic approach that combines electromagnetic modeling with materials synthesis and processing control.

5. Applications of circuit analog absorbers

CAAs are used in various applications, including radar-absorbing materials (RAM), electromagnetic interference (EMI) shielding, and stealth technology. Their ability to absorb EM waves at specific frequencies makes them ideal for controlling unwanted reflections in these contexts. Further research is therefore needed to develop optimized designs that effectively integrate advanced materials and intelligent design approaches while maintaining structural integrity under practical operating conditions.

CAAs are heavily utilized in stealth technology to reduce the radar cross-section (RCS) of military assets like aircraft and ships. They absorb incoming radar waves and diminish reflected signals, thus reducing the object’s detectability to radar systems. In stealth applications, CAAs are optimized to work over a broad frequency range and different angles of incidence. Thin, lightweight CAAs are often combined with frequency selective surfaces (FSS) or Artificial Magnetic Conductors (AMC) to enhance broadband absorption [25, 52, 53].

CAAs are essential in antenna designs to manage impedance matching and reduce reflected waves, ensuring efficient transmission and reception. They are also employed to reduce mutual coupling between closely spaced antennas, which is particularly useful in array systems and multiple-input, multiple-output (MIMO) systems. By incorporating CAAs into antenna systems, interference can be minimized, which improves signal quality and system performance [54, 55].

CAAs play a crucial role in electromagnetic compatibility (EMC) by shielding electronic devices and systems from electromagnetic interference (EMI). In environments where multiple electronic systems are operating, CAAs absorb stray electromagnetic energy and prevent it from coupling with sensitive components, thus maintaining system integrity. They are used in applications like communication systems, military electronics, and automotive electronics to ensure devices meet EMC regulations.

CAAs are used in microwave systems to absorb unwanted reflections and resonances, improving overall signal quality. They are critical in components like microwave cavities, waveguides, and in radar systems where reflection control is essential for signal fidelity. These absorbers can be designed to cover wide frequency bands, making them useful in both civilian and military radar systems, microwave circuits, and electromagnetic testing chambers [1, 24, 56].

CAAs are effective in minimizing multipath interference in wireless communication systems. Multipath interference occurs when signals are reflected off surfaces like walls or other objects and arrive at the receiver out of phase, degrading signal quality. By absorbing these reflected signals, CAAs help improve the clarity and reliability of wireless communication systems, including cellular networks and Wi-Fi systems [57].

In the aerospace industry, CAAs are applied to satellites and spacecraft to absorb electromagnetic waves, managing reflections that could interfere with sensitive communication systems. Additionally, they play a role in managing thermal emissions by controlling the absorption of infrared energy. This is crucial for maintaining the thermal balance of spacecraft and ensuring the reliability of satellite communication systems.

While the preceding sections have focused on the electromagnetic principles, equivalent circuit modeling, and design methodologies of circuit analog absorbers (CAAs), it is important to recognize that the practical realization of these designs is inherently dependent on material selection and fabrication processes. The impedance characteristics, resonance behavior, and absorption performance predicted by theoretical models can only be achieved when the underlying materials are synthesized and processed with precise control over their electrical and microstructural properties. In particular, factors such as conductive network formation, layer uniformity, interfacial bonding, and fabrication-induced defects play a critical role in determining the actual absorber response. Therefore, to bridge the gap between theoretical design and practical implementation, the following section discusses the key aspects of material synthesis, processing techniques, and sintering mechanisms that govern the performance of CAAs.

6. Material synthesis, processing, and sintering aspects of circuit analog absorbers

Although circuit analog absorbers (CAAs) are often analyzed from an electromagnetic and equivalent circuit perspective, their practical realization fundamentally depends on materials synthesis, microstructural engineering, and controlled fabrication routes. The absorber performance is intrinsically governed by processing–structure–property relationships, where electrical conductivity, dielectric response, layer uniformity, and interfacial integrity are determined by synthesis parameters. This section reviews the key material systems, fabrication approaches, and sintering mechanisms relevant to modern CAA development.

6.1. Synthesis of conductive and resistive materials

The electromagnetic functionality of CAAs relies on precisely engineered resistive and conductive layers, typically implemented through metallic films, carbon-based composites, conductive polymers, or hybrid nanostructured materials. The synthesis route directly determines sheet resistance, surface impedance, and broadband absorption behavior.

6.1.1. Carbon-based composite systems

Carbon-based fillers such as carbon black, graphene nanoplatelets, graphite flakes, and carbon nanotubes are frequently incorporated into polymer matrices to achieve tunable electrical conductivity. In carbon-fiber-reinforced polymer (CFRP) systems, as investigated in Refs. [36, 38], the electrical properties are controlled by fiber orientation, volume fraction, and interfacial bonding.

The electrical conductivity of such composites is governed by percolation theory. Below a critical filler loading threshold, the composite behaves as a dielectric. Once the percolation threshold is exceeded, conductive pathways form through filler–filler contact, leading to a sharp increase in conductivity. The percolation threshold depends on:

- Filler aspect ratio
- Dispersion homogeneity
- Interfacial compatibility
- Processing-induced agglomeration

From a thermodynamic standpoint, filler dispersion stability is controlled by the interfacial energy between the polymer matrix and conductive particles. Poor dispersion leads to clustering, increasing impedance variability, and degrading absorber performance. Therefore, surface functionalization and controlled mixing processes are essential to ensure uniform conductive network formation.

Quantitatively, the electrical conductivity (σ) of conductive polymer composites near the percolation threshold follows a power-law relationship given by:

$$\sigma \propto (\varphi - \varphi\_c)^t \qquad (8)$$

where φ is the filler volume fraction, φ_c is the percolation threshold, and t is the critical exponent (typically ranging from 1.6 to 3 depending on filler morphology). For carbon-based systems such as carbon black or graphene composites, φ_c typically lies between 0.5–5 vol%, depending on dispersion quality and aspect ratio. For instance, high-aspect-ratio fillers such as carbon nanotubes can reduce the percolation

Table 2. Comparison of reported circuit analog absorbers (CAAs) based on designed approach, bandwidth, material, fabrication method and durability of structure. The table highlights the relationship between design strategy, materials processing, and absorber performance across different studies.

Study	Design approach	Bandwidth	Material	Fabrication method	Durability focus
[29]	Double-layer, resistor-loaded square-loop arrays	High (1:8.78)	Not specified	Traditional	Not covered
[30]	Hybrid capacitive and circuit analog absorbers	Medium	Not specified	Traditional	Not covered
[32]	Wide-angle, polarization-independent design	137.1%	Not specified	Traditional	Not covered
[32]	Carbon-fiber-reinforced polymer (CFRP)	Medium	CFRP	Traditional	Impact damage characterization
[34]	Additive manufacturing of PLA-based absorbers	Medium	PLA-based	Additive manufacturing	Not covered
[36]	CFRP laminas in CAAs	Medium	CFRP	Traditional	Impact damage
[42]	Deep learning for plasmonic stack metamaterials	Medium (plasmonic stack metamaterials)	Various	Divide-and-conquer deep learning	Not covered
[43]	Semi-analytical design for FSS absorbers	Medium to high	FSS layers	Semi-analytical	Not covered
[58]	X-band PCAAs	Medium	Not specified	Traditional	High fabrication precision needed
[59]	Comparative analysis of CA and CC-based broadband absorbers	Medium	Not specified	Traditional	Not covered

threshold below 1 vol%, enabling lightweight absorbers with tunable sheet resistance in the range of 10–10^3 Ω, which is suitable for impedance matching in CAAs.

6.1.2. Metallic and nanoparticle-based resistive films

Many CAAs employ patterned metallic layers or resistor-loaded frequency selective surfaces (FSS), such as square-loop arrays [12, 29]. These layers are typically fabricated using:

- Screen printing of conductive inks
- Photolithographic etching
- Inkjet printing
- Vacuum deposition

For nanoparticle-based inks (e.g., silver or copper nanoparticles), electrical conductivity depends on particle sintering behavior. After deposition, thermal treatment promotes:

- Solvent evaporation
- Particle rearrangement
- Neck formation between nanoparticles
- Grain growth and densification

The densification of nanoparticle-based conductive films during sintering is governed by diffusion-driven mechanisms, including surface diffusion, grain boundary diffusion, and volume diffusion. The characteristic sintering time can be approximated by:

$$t \propto (r / D\gamma\Omega kT) \tag{9}$$

where r is the particle radius, D is the diffusion coefficient, γ is the surface energy, Ω is the atomic volume, and T is the temperature. Due to their high surface-to-volume ratio, metallic nanoparticles (e.g., Ag or Cu) can sinter at relatively low temperatures (typically 150–300 °C), forming conductive networks with resistivities approaching 2–5 times that of bulk metals. This low-temperature sintering behavior is particularly advantageous for flexible and polymer-based CAAs, where high-temperature processing is not feasible.

6.2. Additive manufacturing and layer-by-layer processing

Additive manufacturing has emerged as a promising synthesis route for CAAs, particularly for complex geometries and multifunctional structures. PLA-based absorbers fabricated through fused deposition modeling (FDM) [34] demonstrate how processing parameters influence electromagnetic properties.

Key process variables include:

- Extrusion temperature
- Layer height
- Print speed
- Raster orientation
- Filler loading concentration

These parameters affect:

- Interlayer adhesion
- Porosity distribution
- Surface roughness
- Effective dielectric constant
- Electrical continuity

From a kinetic perspective, polymer extrusion involves viscoelastic flow and solidification dynamics. Cooling rate influences crystallinity and internal stress, which may alter dielectric properties. Moreover, porosity introduced during printing modifies effective permittivity and permeability through Maxwell–Garnett mixing effects.

Additive manufacturing enables graded impedance structures, where spatially varying filler concentration or geometry produces gradual impedance transitions, enhancing broadband absorption without significantly increasing thickness.

The sintering process reduces contact resistance and stabilizes sheet impedance. The kinetics of nanoparticle sintering are temperature-dependent and may occur at relatively low temperatures due to high surface energy and nanoscale diffusion effects. Controlled sintering is therefore essential for achieving reproducible absorber performance.

6.3. Multilayer lamination and thermal consolidation

Many broadband CAAs are realized as multilayer structures inspired by classical absorbers such as the Jaumann absorber and the Salisbury screen. In modern implementations, multilayer stacking involves controlled lamination processes.

- Typical consolidation techniques include:
- Hot pressing
- Vacuum bagging
- Autoclave curing
- Epoxy crosslinking
- Thermoplastic fusion bonding

The mechanical and electromagnetic performance of multilayer CAAs strongly depends on interfacial bonding quality. Poor adhesion can introduce air gaps, which alter effective impedance and shift resonance frequency. Thermal curing kinetics of polymer matrices determine crosslink density, which affects dielectric constant and thermal stability.

In metal-backed absorbers, conductive ground planes are often fabricated using foil lamination or sputtered metallic films. When conductive pastes are used, low-temperature sintering promotes densification and electrical continuity. Diffusion-driven neck formation between particles reduces resistivity and stabilizes reflection loss across frequency bands.

6.4. Processing–structure–property relationships

The electromagnetic response of CAAs cannot be separated from their microstructural characteristics. Processing parameters directly influence:

- Filler dispersion
- Grain size (in metallic films)
- Porosity level
- Layer thickness uniformity
- Surface roughness
- Interface integrity

These structural features determine effective permittivity (ε_eff) and permeability (μ_eff), which govern surface impedance matching with free space (Z_0 = 377 Ω). Even small deviations in sheet resistance or dielectric thickness can shift the resonance frequency and reduce absorption bandwidth.

For example:

- Increased porosity lowers effective permittivity, shifting resonance toward higher frequencies.
- Improved nanoparticle sintering reduces sheet resistance, potentially leading to overmatching and increased reflection.
- Anisotropic fiber alignment in CFRP introduces polarization-dependent absorption.

Thus, absorber optimization must integrate electromagnetic modeling with controlled materials synthesis. A purely circuit-based design approach is insufficient without understanding how processing-induced microstructure affects impedance.

From a practical design perspective, optimal absorption is typically achieved when the sheet resistance of the resistive layer approaches the free-space impedance ($Z_0 \approx 377\ \Omega$). In many reported CAAs, effective absorption (>90%) is obtained when the sheet resistance is tuned within the range of 100–500 Ω, depending on the operating frequency and multilayer configuration. Deviations from this range due to poor dispersion, incomplete sintering, or thickness variation can significantly increase reflection losses and shift resonance frequency.

6.5. Thermodynamic and kinetic considerations

From a materials science perspective, CAA fabrication involves several thermodynamic and kinetic phenomena:

- Percolation-driven conductive network formation
- Controlled by filler concentration and dispersion thermodynamics.
- Polymer curing reactions
- Governed by reaction kinetics and crosslinking mechanisms, affecting dielectric stability
- Nanoparticle sintering kinetics
- Influenced by surface diffusion, grain boundary diffusion, and temperature profiles
- Thermal expansion mismatch

Interfacial stress between metallic and polymeric layers may impact long-term durability.

Understanding these mechanisms enables rational design of absorbers with stable performance under thermal cycling, mechanical stress, and environmental exposure.

6.6. Emerging synthesis strategies

Recent trends in absorber fabrication include:

- Hybrid metamaterial–polymer composites
- Gradient impedance structures via compositional grading
- Transparent conductive films for optically transparent CAAs
- Multifunctional composites combining structural load-bearing and electromagnetic absorption

The integration of nano-engineered fillers, controlled low-temperature sintering, and advanced additive manufacturing will likely define the next generation of CAAs. Future research should focus on coupling thermodynamic modeling, microstructural characterization, and electromagnetic simulation to achieve predictive absorber design.

7. Conclusions

Circuit Analog Absorbers (CAAs) have evolved from classical resonant electromagnetic structures into advanced engineered materials whose performance is governed by both electromagnetic design and materials processing. While impedance matching and equivalent circuit models remain fundamental, absorber efficiency, bandwidth, and angular stability are strongly influenced by material composition, conductive network formation, and microstructural control.

This review highlights that modern CAAs are realized using diverse material systems, including carbon-based composites, nanoparticle-derived conductive films, frequency selective surface (FSS) laminates, and hybrid metamaterial structures. Their performance is closely linked to processing–structure–property relationships, where parameters such as filler dispersion, percolation behavior, sintering kinetics, and interfacial bonding determine effective permittivity, permeability, and surface impedance.

Advanced fabrication techniques—such as additive manufacturing, multilayer lamination, and low-temperature sintering—have enabled the development of ultrathin, broadband, and polarization-independent absorbers. These approaches provide improved control over microstructure and reproducibility, bridging the gap between theoretical design and practical implementation.

CAAs continue to play a critical role in applications, including radar cross-section (RCS) reduction, electromagnetic interference (EMI) shielding, antenna systems, and next-generation communication technologies. Their capabilities are further enhanced through the integration of FSS and metamaterial concepts, enabling improved performance in complex electromagnetic environments.

Future research should focus on synthesis-driven design strategies, including nano-engineered conductive fillers, reconfigurable and adaptive materials, wide-angle and polarization-independent structures, and integration with emerging technologies such as 5G, IoT, and autonomous systems. Additionally, the development of multifunctional materials combining structural and electromagnetic properties remains a promising direction.

In summary, CAAs should be viewed as multifunctional materials systems whose performance depends on the integration of materials synthesis, processing, and electromagnetic design. Continued advances in this multidisciplinary framework will drive the next generation of high-performance absorber technologies.

CRediT authorship contribution statement

Alireza Bayat: Supervision, Writing – review & editing, Project administration.

Reza Mirzakhani: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft.

Pouria Dianati Souha: Validation, Writing – review & editing, Visualization.

Data availability

The data underlying this article will be shared on reasonable request to the corresponding author.

Declaration of competing interest

The authors declare no competing interests.

Funding and acknowledgment

The authors received no specific funding for this work.

References

[1] B.A. Munk, P. Munk, J. Pryor, On Designing Jaumann and Circuit Analog Absorbers (CA Absorbers) for Oblique Angle of Incidence, IEEE Trans. Antennas Propag. 55 (2007) 186–193. https://doi.org/10.1109/TAP.2006.888395.

[2] S. Ghosh, S. Bhattacharyya, K.V. Srivastava, Design and analysis of a broadband single layer circuit analog absorber, 46th European

Microwave Conference (EuMC). 2016 (2016) 584–587. https://doi.org/10.1109/EuMC.2016.7824410.

[3] B.A. Munk, Frequency Selective Surfaces: Theory and Design, Wiley. (2005). https://doi.org/10.1002/0471723770.

[4] M. Chen, X. Zhu, H. Lei, D. Fang, Z. Zhang, Optimal Design of Broadband Radar Absorbing Sandwich Structure with Circuit Analog Absorber Core, Int. J. Appl. Mech. 07 (2015) 1550020. https://doi.org/10.1142/S1758825115500209.

[5] Z. Yao, S. Xiao, Z. Jiang, L. Yan, B.Z. Wang, On the Design of Ultrawideband Circuit Analog Absorber Based on Quasi-Single-Layer FSS, IEEE Antennas Wirel. Propag. Lett. 19 (2020) 591–595. https://doi.org/10.1109/LAWP.2020.2972919.

[6] N. Liu, J. Li, X. Sheng, H. Fu, An equivalent circuit model based design method for wideband absorber using resistive FSS, Phys. Scr. 99 (2024) 095548. https://doi.org/10.1088/1402-4896/ad6f4b.

[7] J.W. Yu, Y. Cai, X.Q. Lin, X. Wang, Perforated Multilayer Ultrawideband Absorber Based on Circuit Analog Absorber With Optimal Air Spaces, IEEE Antennas Wirel. Propag. Lett. 19 (2020) 34–38. https://doi.org/10.1109/LAWP.2019.2951845.

[8] J. Sun, Q. Li, X. Fang, A Novel Reconfigurable Absorber/Radiator Based on SEMC Antenna, IEEE International Conference on Computational Electromagnetics (ICCEM). 2024 (2024) 15–17. https://doi.org/10.1109/ICCEM60619.2024.10559043.

[9] S. Ghosh, K.V. Srivastava, A Polarization-Independent Broadband Multilayer Switchable Absorber Using Active Frequency Selective Surface, IEEE Antennas Wirel. Propag. Lett. 16 (2017) 3147–3150. https://doi.org/10.1109/LAWP.2017.2766100.

[10] K.H. Murali Naik, A.K. Singh, D. Rama Krishna, Ultrathin wideband low profile circuit analog metamaterial absorber, Microw. Opt. Technol. Lett. 66 (2024) e34247. https://doi.org/10.1002/mop.34247.

[11] Z. Ma, C. Jiang, W. Cao, J. Li, X. Huang, An Ultrawideband and High-Absorption Circuit-Analog Absorber With Incident Angle-Insensitive Performance, IEEE Trans. Antennas Propag. 70 (2022) 9376–9384. https://doi.org/10.1109/TAP.2022.3177490.

[12] Y. Han, W. Che, C. Christopoulos, Y. Xiong, Y. Chang, A fast and efficient design method for circuit analog absorbers consisting of resistive square-loop arrays, IEEE Trans. Electromagn. Compat. 58 (2016) 747–757. https://doi.org/10.1109/TEMC.2016.2524553.

[13] V. Inbavalli, V. Sakthivel, C. Venkatesh, S.K. TR, Design of Broadband Circuit Analog Absorber With Optimal Thickness for Stable Angular Response in C, X, Ku, and K Bands, IEEE Trans. Electromagn. Compat. 65 (2023) 2065–2069. https://doi.org/10.1109/TEMC.2023.3298816.

[14] J.D. Jackson, Classical electrodynamics, John Wiley & Sons. (2021). https://doi.org/10.1119/1.19136.

[15] D.M. Pozar, Microwave engineering: theory and techniques, John Wiley & Sons, Singapore. (2021).

[16] T. Sergei, Analytical Modeling in Applied Electromagnetics, Artech. (2003).

[17] R.F. Harrington, Field Computation by Moment Methods, Wiley. (1993). https://doi.org/10.1007/978-3-642-50319-1_10.

[18] F. Costa, A. Monorchio, G. Manara, An Overview of Equivalent Circuit Modeling Techniques of Frequency Selective Surfaces and Metasurfaces, Appl. Comput. Electromagn. Soc. J. (2014) 960–976. https://doi.org/10.1002/ecjb.20162.

[19] J.D. Kraus, D.A. Fleisch, Electromagnetics: With Applications, WCB/McGraw-Hill. (1999). https://doi.org/10.1002/9781394283491.ch2.

[20] A. Alù, N. Engheta, Achieving transparency with plasmonic and metamaterial coatings, Phys. Rev. E. 72 (2005) 016623. https://doi.org/10.1103/PhysRevE.72.016623.

[21] H.A. Wheeler, Transmission-Line Properties of a Strip on a Dielectric Sheet on a Plane, IEEE Trans. Microw. Theory Tech. 25 (1977) 631–647. https://doi.org/10.1109/TMTT.1977.1129179.

[22] L. Zhang, S. Liu, T. Cui, Theory and application of coding metamaterials, Chin. Opt. 10 (2017) 1–12. https://doi.org/10.3788/CO.20171001.0001.

[23] N.I. Landy, S. Sajuyigbe, J.J. Mock, D.R. Smith, W.J. Padilla, Perfect metamaterial absorber, Phys. Rev. Lett. 100 (2008) 207402. https://doi.org/10.1103/PhysRevLett.100.207402.

[24] R.L. Fante, M.T. McCormack, Reflection properties of the Salisbury screen, IEEE Trans. Antennas Propag. 36 (1988) 1443–1454. https://doi.org/10.1109/8.8632.

[25] M. Paquay, J.C. Iriarte, I. Ederra, R. Gonzalo, P.d. Maagt, Thin AMC Structure for Radar Cross-Section Reduction, IEEE Trans. Antennas Propag. 55 (2007) 3630–3638. https://doi.org/10.1109/TAP.2007.910306.

[26] F. Costa, S. Genovesi, A. Monorchio, On the Bandwidth of High-Impedance Frequency Selective Surfaces, IEEE Antennas Wirel. Propag. Lett. 8 (2009) 1341–1344. https://doi.org/10.1109/LAWP.2009.2038346.

[27] L. Sun, H. Cheng, Y. Zhou, J. Wang, Broadband metamaterial absorber based on coupling resistive frequency selective surface, Opt. Express. 20 (2012) 4675–4680. https://doi.org/10.1364/OE.20.004675.

[28] J. Chen, Y. Shang, C. Liao, Double-Layer Circuit Analog Absorbers Based on Resistor-Loaded Square-Loop Arrays, IEEE Antennas Wirel. Propag. Lett. 17 (2018) 591–595. https://doi.org/10.1109/LAWP.2018.2805333.

[29] A.P. Sohrab, Z. Atlasbaf, A circuit analog absorber with optimum thickness and response in X-band, IEEE Antennas Wirel. Propag. Lett. 12 (2013) 276–279. https://doi.org/10.1109/LAWP.2013.2248073.

[30] M. Saikia, K.V. Srivastava, Design of Thin Broadband Microwave Absorber using Combination of Capacitive and Circuit Analog Absorbers, IEEE Indian Conference on Antennas and Propagation (InCAP). 2018 (2018) 1–4. https://doi.org/10.1109/INCAP.2018.8770777.

[31] A. Monti, A. Alù, A. Toscano, F. Bilotti, The design of optical circuit-analog absorbers through electrically small nanoparticles, Photonics. 6 (2019) 26. https://doi.org/10.1038/s41598-025-99904-x.

[32] Z. Yao, S. Xiao, Y. Li, B.-Z. Wang, Wide-angle, ultra-wideband, polarization-independent circuit analog absorbers, IEEE Trans. Antennas Propag. 70 (2022) 7276–7281. https://doi.org/10.1109/TAP.2022.3149594.

[33] Q. Guo, J. Su, Z. Li, Design of circuit analog absorber using characteristic mode analysis, IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP). (2020) 1–3. https://doi.org/10.1109/IMWS-AMP49156.2020.9199671.

[34] T.J. Prince, E.J. Riley, S.W. Miller, Additive Manufacturing of PLA-Based Microwave Circuit-Analog Absorbers, IEEE Trans. Electromagn. Compat. 63 (2021) 1341–1346. https://doi.org/10.1109/TEMC.2020.3044014.

[35] X. Lv, S.J. Chen, A. Galehdar, W. Withayachumnankul, C. Fumeaux, Fast semi-analytical design for single-FSS-layer circuit-analog absorbers, IEEE Open J. Antennas Propag. 1 (2020) 483–492. https://doi.org/10.1109/TAP.2020.2983756.

[36] E.J. Riley, E.H. Lenzing, R.M. Narayanan, Application of unidirectional carbon-fiber-reinforced-polymer laminas in circuit-analog absorbers, IEEE Trans. Electromagn. Compat. 60 (2018) 1743–1751. https://doi.org/10.1109/TEMC.2017.2781142.

[37] A.K. Zadeh, A. Karlsson, Capacitive circuit method for fast and efficient design of wideband radar absorbers, IEEE Trans. Antennas Propag. 57 (2009) 2307–2314. https://doi.org/10.1109/TAP.2009.2024490.

[38] E.J. Riley, E.H. Lenzing, R.M. Narayanan, X-band circuit-analog absorbers using unidirectional carbon fiber, IEEE Antennas Wirel. Propag. Lett. 17 (2018) 1060–1063. https://doi.org/10.1109/LAWP.2018.2831909.

[39] Y. Shang, Z. Shen, S. Xiao, On the design of single-layer circuit analog absorber using double-square-loop array, IEEE Trans. Antennas Propag. 61 (2013) 6022–6029. https://doi.org/10.22061/jecei.2018.790.

[40] A.A. Ovhal, A. Parameswaran, D. Kundu, H.S. Sonalikar, Design of a wide-band circuit analog absorber using modified square loop loaded with lumped resistors, IEEE Wireless Antenna and Microwave Symposium (WAMS). 2022 (2022) 1–4. https://doi.org/10.1109/WAMS54719.

[41] R. Mirzakhani, A. Bayat, Novel Design of Optically Transparent Circuit Analog Absorber by Modifying of exponentially tapered edge of element to achieve wider Bandwidth, AUT J. Model. Simul. 56 (2024) 55–68. https://doi.org/10.22060/miscj.2024.22964.5353.

[42] J. Xiong, J. Shen, Y. Gao, Real-Time On-Demand Design of Circuit-Analog Plasmonic Stack Metamaterials by Divide-and-Conquer Deep Learning, Laser Photonics Rev. 17 (2023) 2100738. https://doi.org/10.1002/lpor.202100738.

[43] J.C. O'Donnell, R.M. Narayanan, Impact damage characterization for varying areal-weight unidirectional carbon fiber-reinforced polymer circuit-analog absorbers, Compos. B: Eng. 202 (2020) 108427. https://doi.org/10.1016/j.compositesb.2020.108427.

[44] Q. Zhou, P. Liu, M. Fu, G. Chen, P. Li, Design of a broadband circuit analog absorber based on double rings structure, IEEE 17th International Conference on Communication Technology (ICCT). 2017 (2017) 382–385. https://doi.org/10.1109/ICCT.2017.8359666.

[45] M.A. Shukoor, S. Dey, S.K. Koul, A Novel Broadband Polarization Insensitive Circuit Analog Absorber (CAA) for Radar Cross Section (RCS) Reduction Applications at X. and Ku-Bands, IEEE Indian Conference on Antennas and Propagation (InCAP). 2021 (2021) 665–668. https://doi.org/10.1109/InCAP52216.2021.9726277.

[46] S. Ghosh, S. Bhattacharyya, D. Chaurasiya, K.V. Srivastava, A broadband polarization-insensitive circuit analog absorber using lumped resistors, IEEE Applied Electromagnetics Conference (AEMC). 2015 (2015) 1–2. https://doi.org/10.1109/AEMC.2015.7509244.

[47] Z. Meng, D. Liu, Y. Pang, J. Wang, Y. Jia, et al., Multispectral Hierarchical Metamaterials with Broadband Microwave Absorption, Gradient Infrared Emissivity, and High Visible Transparency, Adv. Mater. Technol. 10 (2024) 2400835. https://doi.org/10.1002/admt.202400835.

[48] W. Zhang, X. Wang, K. Yang, A dual-band broadband absorber using frequency selective surface for satellite antenna, Sci. Rep. 14 (2024) 28311. https://doi.org/10.1038/s41598-024-79804-2.

[49] B.-X. Wang, Y. He, P. Lou, N. Xu, X. Wang, et al., Multiple-band terahertz metamaterial absorber using multiple separated sections of metallic rectangular patch, Front. Phys. 8 (2020) 308. https://doi.org/10.3389/fphy.2020.00308.

[50] H. Xiao, R. Qin, M. Lv, C. Wang, Highly transparent broadband and polarization-insensitive absorber based on metasurface, Appl. Sci. 10 (2020) 9125. https://doi.org/10.3390/app10249125.

[51] A.E. Assal, H. Breiss, R. Benzerga, A. Sharaiha, A. Jrad, A. Harmouch, Toward an ultra-wideband hybrid metamaterial based microwave absorber, Micromachines. 11 (2020) 930. https://doi.org/10.3390/mi11100930.

[52] S. Narayan, J. Sreeja, V.V. Surya, B. Sangeetha, R.U. Nair, Radar Absorbing Structures Using Frequency Selective Surfaces: Trends and Perspectives, J. Electronic Mater. 49 (2020) 1728–1741. https://doi.org/10.1007/s11664-019-07911-2.

[53] H. Singh, R.M. Jha, Active Radar Cross Section Reduction: Theory and Applications, Cambridge: Cambridge University Press. (2015). https://doi.org/10.1017/CBO9781316136171.

[54] M. Ramkumar, C. Sudhendra, K. Rao, A novel low RCS microstrip antenna array using thin and wideband radar absorbing structure based on embedded passives resistors, Prog. Electromagn. Res. C. 68 (2016) 153–161. https://doi.org/10.2528/PIERC16080506.

[55] Y. Fu, T. Shen, J. Dou, Mutual Coupling Reduction of a Multiple-Input Multiple-Output Antenna Using an Absorber Wall and a Combline Filter for V2X Communication, Sensors. 23 (2023) 6355. https://doi.org/10.3390/s23146355.

[56] W. Tang, Z. Shen, Simple design of thin and wideband circuit analogue absorber, Electron. Lett. 43 (2007) 689–691. https://doi.org/10.1049/el:20070956.

[57] D.J. Kern, D.H. Werner, A genetic algorithm approach to the design of ultra-thin electromagnetic bandgap absorbers, Microw. Opt. Technol. Lett. 38 (2003) 61–64. https://doi.org/10.1002/mop.10971.

[58] H.T. Chou, J.W. Liu, T. Chang, Y.S. Chang, A Design of Perodic Circuit Analog Absorber at X-band and its Fabrication Discrepancy Analysis, IEEE International Symposium on Radio-Frequency Integration Technology (RFIT). 2021 (2021) 1–3. https://doi.org/10.1109/RFIT52905.2021.9565252.

[59] G. Singh, S. Ghosh, A Comparative Analysis between Circuit Analog and Capacitive Circuit based Broadband Absorbers, National Conference on Communications (NCC). 2020 (2020) 1–5. https://doi.org/10.1109/NCC48643.2020.9056000.