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Review Article

Metamaterial absorbers: Comparative analysis of fabrication techniques and emerging trends

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The metamaterial absorbers have been artificially designed structures that have controlled and have manipulated electromagnetic waves across different frequency regimes, which have been important in stealth technology, EMI shielding, sensing, and energy harvesting. In particular, the efficiency and reliability of such absorbers have had a close dependence on fabrication methods used to fabricate these absorbers. This review has given an orderly exploration of some recent developments in the fabrication techniques of metamaterial absorbers, grouped into four major classes: Top Down, printing-based, mold-assisted, and laser-based approaches. Each technique has been qualitatively compared based on resolution, manufacturing cost, scalability, substrate compatibility, structural complexity, duration of fabrication, frequency suitability, and absorption efficiency. A general comparison has summarized the advantages and limitations of each technique. The review also has outlined emerging trends that could shape the next generation of high-performance metamaterial absorbers.

Keywords: Fabrication techniques, Metamaterial absorbers, Top-down processes

1 Introduction

Metamaterials are artificial structures engineered to exhibit electromagnetic properties that are not typically found in natural materials, such as negative permittivity and permeability[1]. Among their diverse applications, metamaterial absorbers have gained particular attention for their ability to efficiently suppress the reflection of incident electromagnetic waves across a broad frequency range[2,3]. These absorbers are widely used in applications such as radar stealth, electromagnetic interference (EMI) shielding, sensing, and energy harvesting[4–6]. A typical metamaterial absorber consists of a patterned resonator layer, a dielectric substrate, and a ground plane. The absorber's performance—such as its absorption bandwidth, peak absorption, and angular stability—strongly depends on the design of its unit cell and the precision with which it is fabricated[7]. As operating frequencies increase into the microwave, terahertz, and optical regimes, the demand for tighter structural tolerances and more complex geometries also grows. Fabrication plays an important role in determining the effectiveness of metamaterial absorbers. Conventional fabrication techniques like photolithography and electron beam lithography have been extensively used due to their ability to achieve high-resolution patterning[8,9]. However, these methods are limited by high equipment costs, long processing times, and restrictions on substrate types, making them less suitable for flexible or large-area applications. In response to these limitations, alternative fabrication techniques have been developed. Printing-based methods, such as inkjet and screen printing, have gained popularity for their low cost, flexibility, and compatibility with a wide range of substrates[10,11]. These techniques allow rapid prototyping and scalable manufacturing but are often limited in resolution. Mold assisted techniques like nanoimprint lithography and hot embossing offer a compromise between resolution and scalability, enabling efficient replication of fine features, especially on polymer substrates[12]. Laser-based techniques, including laser direct writing and laser ablation, offer maskless, contact-free patterning that is well-suited for fast iteration and customizable designs[13].

Despite the availability of numerous fabrication methods, selecting an appropriate technique remains a challenge, as it involves balancing multiple

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parameters such as resolution, cost, scalability, material compatibility, and absorber performance. While some reviews have addressed metamaterial absorber designs or their applications, there is still a lack of consolidated literature focused specifically on the fabrication techniques used to realize these structures and their comparative evaluation.

This review aims to fill that gap by systematically categorizing and analysing the major fabrication methods employed for metamaterial absorbers. It discusses recent advancements in each technique, compares them across key performance indicators, and provides insights to guide researchers and engineers in selecting suitable fabrication approaches for specific use cases.

2 Materials and Methods

The fabrication of metamaterial absorbers operating in the various frequency range requires a balance between performance, material compatibility, fabrication precision, and production scalability. Based on their operational characteristics and material requirements, the fabrication techniques for microwave metamaterial absorbers can be classified into four major categories: top-down lithographic techniques, printing-based techniques, mold assisted techniques, and laser-based techniques.

2.1 Top-down lithographic techniques

Top-down techniques such as photolithography and soft lithography are capable of producing high-resolution patterns essential for defining subwavelength unit cells[14,15]. These methods are particularly useful when the design requires precise feature sizes and alignment on rigid substrates like FR4, Rogers, or silicon. While electron beam lithography (EBL) is commonly used for higher-frequency metamaterials, standard photolithography and soft lithography are better suited for microwave frequencies due to lower cost and sufficient resolution[16]. These techniques are best chosen when high precision and batch reproducibility are required, such as in filter-integrated metamaterial absorbers or experimental validations of complex unit cell geometries.

2.2 Printing-based techniques

Printing-based techniques, including screen printing, inkjet printing, and aerosol jet printing, are widely employed in the fabrication of microwave absorbers due to their simplicity, low cost, and suitability for flexible substrates[17,18]. Screen printing is extensively used for mass production and for printing on substrates like textiles, flexible polymers, and FR4[19].Inkjet printing allows high-resolution digital patterning with minimal material waste, making it ideal for research and low-volume production. These techniques are typically selected when the application involves large-area absorbers, wearable EM shields, or lightweight structural integration[20].

2.3 Moldassisted techniques

Mold assisted techniques, such as hot embossing and casting, are suitable for fabricating microwave absorbers with 3D structural features or for embedding patterns into composite matrices. These methods are particularly effective for creating structured dielectric layers or embedding conductive patterns within bulk materials. Hot embossing allows the replication of surface patterns onto thermoplastic substrates[21], while casting is useful for forming composite absorbers using bio-based or polymer-filled materials. These methods are generally chosen when low-cost bulk production and structural durability are required, especially in automotive or aerospace applications.

2.4 Laser based techniques

Laser-based techniques, including laser ablation and laser direct writing, enable maskless, direct fabrication of microwave absorbers with customizable geometries[22]. These methods offer moderate resolution and fast prototyping capabilities on a wide range of substrates including flexible films, metals, and dielectrics[23]. Laser processing is often selected for rapid design iteration, prototyping, or when working with unconventional substrates where contact-based methods are unsuitable. It is particularly advantageous in the fabrication of test samples, curved surface absorbers, or patterns requiring post-fabrication tuning.

3 Results and Discussion

3.1 Top-down lithographic techniques

3.1.1 Photolithography

Photolithography is a widely used top-down microfabrication technique for patterning the resonant elements of metamaterial absorbers with high precision. It is particularly suitable for defining fine metallic features required in microwave and terahertz absorbers. A representative demonstration is provided by Wang *et al.*[24], who fabricated a tripleband metamaterial absorber using a photolithographic process on a flexible polyethylene terephthalate (PET) substrate. As illustrated in Fig. 1a of their paper, the process begins with spin-coating a layer of positive photoresist onto an aluminium-coated PET film. The substrate is then exposed to UV light through a photomask that defines the desired resonator geometry. After development, the exposed regions of aluminium are selectively removed via wet chemical etching, followed by the removal of the residual photoresist to reveal the patterned resonator structure. Finally, a ground plane is formed by depositing an aluminium layer on the backside of the PET film. Photolithography was chosen in this work due to its ability to accurately reproduce complex geometries with microscale precision, which is crucial for achieving multi-band and narrow-band absorption characteristics. It also offers high repeatability, low edge roughness, and compatibility with a wide range of substrates, including flexible materials like PET[25]. Furthermore, it is one of the most mature and scalable processes in microfabrication, enabling high-throughput production with consistent performance across batches[26]. The final fabricated absorber using photolithography is shown in Fig. 1b.

3.1.2 Electron beam lithography

Electron-beam lithography (EBL) is a maskless top-down nanofabrication technique that uses a highly focused electron beam to directly write patterns on an electron-sensitive resist. The process begins with spin-coating a thin film of resist, commonly polymethyl methacrylate (PMMA), onto the chosen substrate. A computer-controlled electron beam then exposes the desired pattern with nanometre precision, after which the exposed regions of the resist are developed to create a patterned mask. This is followed by metal deposition, typically involving gold or other conductive films, and a subsequent lift-off process that leaves behind the desired resonator structures. In some cases, an additional metallic ground plane is deposited on the backside of the substrate to complete the absorber structure. The complete flow of the process is shown in Fig. 2a and the final fabricated absorber using EBL process is shown in the Fig. 2b. EBL is particularly valuable in the fabrication of terahertz (THz) metamaterial absorbers due to its capability to achieve sub-micron resolution, enabling accurate realization of the fine structural details required for resonance tuning at high frequencies. For instance, Wang *et al.*[27] demonstrated a broadband metamaterial absorber in the THz regime using EBL to define the top resonator patterns, followed by deposition and lift-off. Their work highlights the ability of EBL to achieve high fidelity and structural uniformity, which are essential for stable broadband absorption characteristics. Similarly, H Tao *et al.*[28] employed EBL to fabricate polarization-independent metamaterial absorbers operating in the THz range, emphasizing the flexibility of the technique in realizing complex geometries. Despite its advantages, EBL is limited by low throughput since the serial nature of electron beam exposure makes it time-consuming and costly for large-area devices. Consequently, its primary utility lies in prototyping, proof-of-concept demonstrations, and high-frequency device research rather than large-scale manufacturing. Nonetheless, its unmatched resolution and patterning flexibility ensure that EBL continues to be a widely adopted technique in the development of next-generation THz metamaterial absorbers.

3.1.3 Thin film deposition

Thin-film deposition techniques play a crucial role in the fabrication of metamaterial absorbers, particularly for forming the metallic resonators and ground planes that are integral to absorber

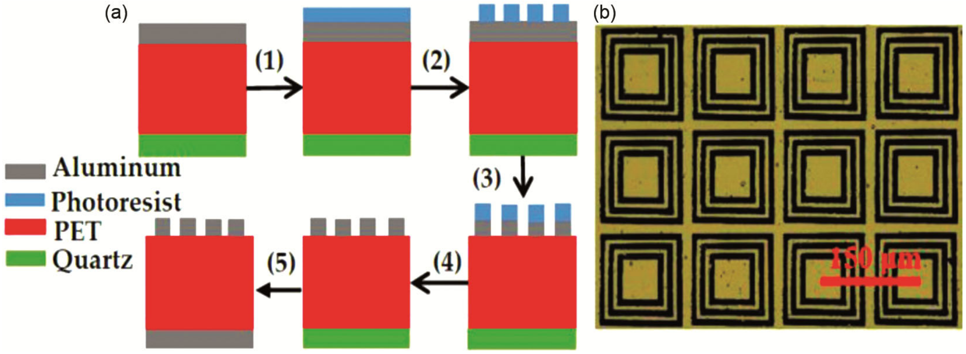

Fig. 1 — Photolithography for fabrication(a) Process flow diagram and (b)Fabricated absorber[24].

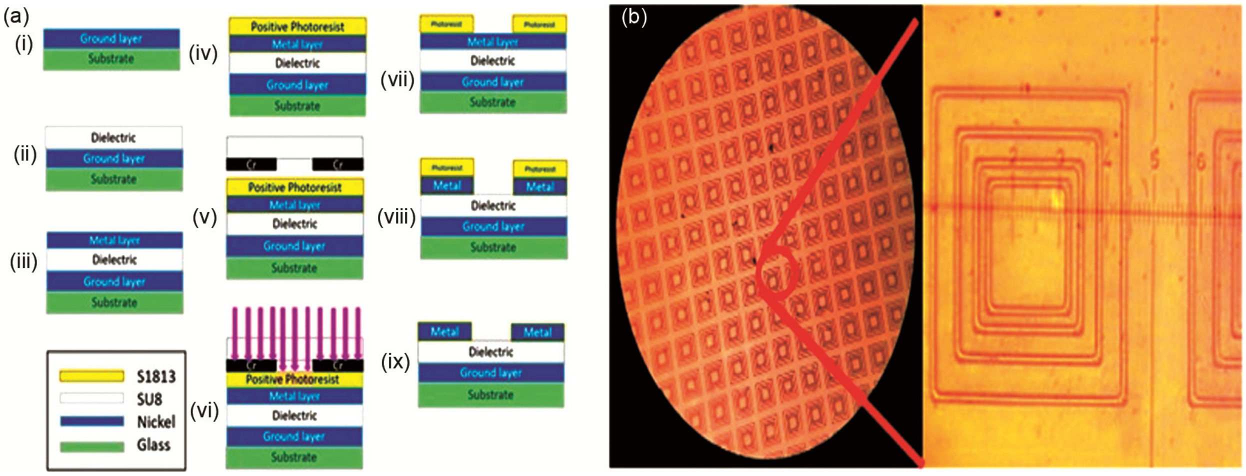

Fig. 2 — Electron beam lithography (a) Process flow and steps of the EBL process (b) Fabricated sample[29].

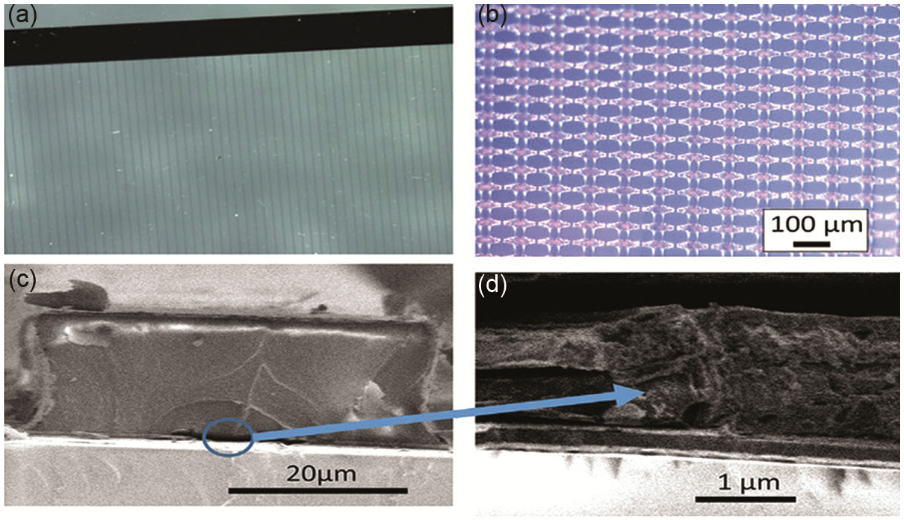

Fig. 3 — Schematic of the thin film deposition process (a) High temperature deposition (500 °C) of BST, (b) 3-D optical microscope picture of the vertical part of the metallic split rings, (c) SEM cross section image of a metamaterial surface unit cell and (d) enlarged area of the device showing BST film between two electrodes. Reproduce under the license 6107380395895[32].

performance. Common approaches include physical vapor deposition (PVD) methods such as thermal evaporation and sputtering, as well as chemical vapor deposition (CVD) for dielectric or conductive films. In a typical process, a thin metallic layer (e.g., gold, aluminium, or chromium) is deposited onto a dielectric substrate, which may later be patterned using photolithography or electron-beam lithography to define resonant structures. In addition, sputtering or evaporation is often used to create the bottom metallic ground plane, while CVD can be employed for conformal coating of dielectric layers that improve impedance matching. For example, Pitchappa *et al.*[30] demonstrated a tunable terahertz metamaterial absorber by depositing a gold layer onto a Si/SiO_2 substrate via electron-beam evaporation, followed by lithographic definition of resonant patterns. Thin-film deposition offers advantages of uniformity, reproducibility, and compatibility with nanoscale patterning techniques, enabling multilayer or stacked absorber designs[31]. As shown in Fig. 3, Shreiber *et al.* demonstrated the fabrication of a tunable THz metamaterial device based on a $Ba_{0.6}Sr_{0.4}Ti_{O3}$ (BST) thin film. The process involved deposition of the BST layer onto aMgO substrate using RF magnetron sputtering at 500 °C. A metallic ground plane and electrodes were then patterned, followed by the definition of split-ring resonator (SRR) arrays on top of the film. This structure allowed external biasing of the BST layer, enabling dynamic tuning of the resonant frequency in the THz regime[32].

However, challenges such as adhesion between metal and substrate, surface roughness, and residual stresses must be carefully managed to ensure stable absorber performance [33]. Overall, thin-film deposition serves as a versatile and indispensable step in constructing high-performance metamaterial absorbers, especially in the terahertz and optical frequency ranges.

3.1.4 Etching

Etching is an essential top-down fabrication process used to selectively remove material and define the fine resonant patterns of metamaterial absorbers. It is generally employed after thin-film deposition and lithographic patterning, where the unprotected regions of the metallic or dielectric layer are removed to create the desired structure. Etching can be broadly classified into wet chemical etching and dry etching. Wet etching involves immersing the substrate in chemical solutions such as ferric chloride or hydrochloric acid to dissolve the exposed metallic regions, offering simplicity and cost-effectiveness but often leading to undercutting and reduced resolution. Dry etching techniques, including reactive ion etching (RIE) and plasma etching, provide higher anisotropy and better control over feature sizes at the micro- and nanoscale, making them particularly suitable for terahertz and optical metamaterial absorbers[34]. To better illustrate its role, Fig. 4 shows a representative fabrication process flow for a terahertz metamaterial absorber, where photolithography is used to define the resonator pattern, followed by reactive ion etching to transfer the features onto the substrate [35]. This schematic highlights how etching enables the precise removal of unwanted material, thereby ensuring accurate resonator geometries essential for broadband absorption performance. Cong *et al.*[36] demonstrated a broadband terahertz metamaterial absorber fabricated on a silicon substrate, where inductive square-loop resonators were patterned via photolithography followed by reactive ion etching to achieve sharp feature definition in the structure. Similarly, Chen *et al.*[37] employed ion-beam etching to define metallic split-ring resonators with sub-100 nm precision, achieving strong absorption in the near-infrared regime. Etching thus plays a critical role in transferring high-resolution patterns onto absorber substrates, ensuring accuracy in resonator geometry and reliable performance across wide frequency ranges.

3.2 Printing based techniques

3.2.1 Screen printing technique

Printing-based fabrication methods have recently emerged as promising alternatives to conventional lithography and etching approaches for the development of metamaterial absorbers. Unlike top-down techniques, which rely on subtractive processes, printing techniques are additive in nature, directly depositing functional inks or pastes onto substrates to define the resonant elements. Screen printing is one of the oldest and most reliable printing techniques, and it has gained significant attention for the fabrication of microwave metamaterial absorbers. The process involves transferring a conductive or resistive ink

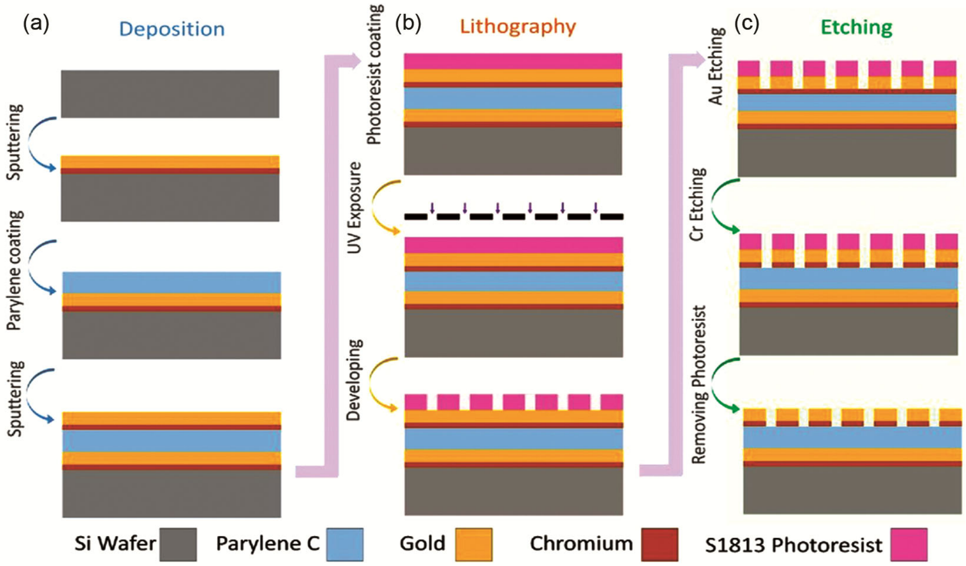

Fig. 4 — Fabrication process flow of a terahertz metamaterial absorber, showing sequential steps of thin-film (a) Deposition, (b) Photolithography and (C) Reactive ion etching[35].

through a patterned mesh stencil (screen) onto a substrate, with a squeegee used to control the deposition thickness and uniformity as shown in Fig. 5. By selecting appropriate mesh size, ink viscosity, and printing parameters, it is possible to achieve precise patterns with layer thicknesses ranging from micrometers to tens of micrometers. This makes screen printing particularly suitable for the deposition of carbon-based, graphene, or metallic inks on substrates such as FR4, PET, and flexible polymers[19].

A key advantage of screen printing is in its ability to deposit relatively thick conductive or resistive layers in a single pass, which is often required for broadband and tunable absorber designs. Moreover, the technique is highly scalable for large-area fabrication and does not require complex equipment, making it cost-effective compared to lithography-based approaches. Screen printing becomes especially advantageous when rapid prototyping or large-area absorber fabrication is required, or when flexible/conformal devices are desired for integration into wearable systems, stealth coatings, or curved platforms [38]. Unlike electron-beam lithography or photolithography, which provide nanoscale resolution but are limited by high cost, vacuum processing, and small substrate sizes, screen printing offers a low-cost and scalable route that is compatible with a variety of substrates and does not require cleanroom facilities (39).For example, Singh and Gupta[39] demonstrated a wideband microwave metamaterial absorber fabricated by screen printing resistive ink patterns on a flexible substrate backed with a copper ground plane. The absorber achieved a fractional bandwidth of ~86.2% covering the X and Ku bands, while maintaining mechanical flexibility. Similarly, Huang *et al.*[40] reported a graphene-based absorber fabricated by printing graphene nanoflakes onto a silicone substrate, achieving more than 90% absorption across the 8–18 GHz range and conformal adaptability to curved surfaces. More recently, Li *et al.*[41] demonstrated a flexible broadband absorber based on conductive graphene ink screen-printed on a polyimide substrate, achieving strong absorption from 7.9–18 GHz under both flat and wrapped configurations.

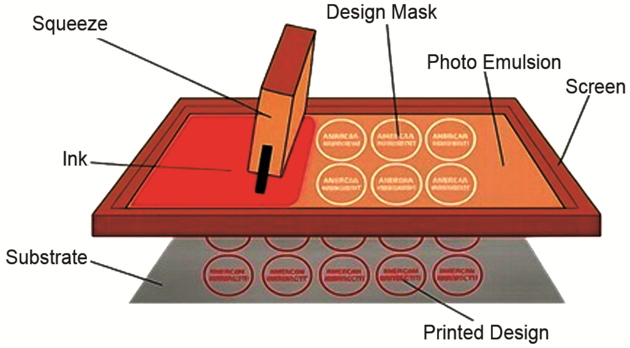

Fig. 5 — Schematic illustration of the screen-printing transferring pattern on the substrate.

Despite its promise, several challenges remain in adopting screen printing for high-performance absorber fabrication. First, the resolution of screen printing (typically >50 μm) is lower than that of advanced lithographic techniques, which limits its applicability for high-frequency terahertz or optical metamaterials requiring sub-micrometer features. Second, the uniformity and reproducibility of printed layers depend strongly on ink rheology, stencil quality, and process control, which can lead to variability in electrical properties and device performance. Third, adhesion of printed layers on flexible substrates can be problematic under repeated mechanical bending, and the long-term environmental stability of printed graphene or carbon inks remains an active research area[40,41]. Nevertheless, with advances in conductive/resistive ink formulations and hybrid approaches combining printing with other patterning methods, screen printing is expected to play a key role in enabling low-cost, scalable, and flexible metamaterial absorbers for real-world applications.

3.2.2 Inkjet printing

Inkjet printing is a versatile and cost-effective additive manufacturing technique that enables the direct deposition of functional inks on a wide range of substrates with high precision. This method relies on the controlled ejection of ink droplets through nozzles, allowing the fabrication of complex patterns without the need for masks or multiple processing steps. For metamaterial absorbers, conductive inks such as silver nanoparticle ink, graphene-based ink, or carbon-based ink are typically used to print the resonator patterns directly on flexible or rigid substrates[42–44]. Compared to traditional lithography, inkjet printing offers advantages such as maskless fabrication, low material wastage, scalability, and compatibility with flexible electronics. Furthermore, it enables rapid prototyping of absorber designs, making it attractive for broadband and tunable metamaterial absorbers[45]. Yet, challenges include limitations in line resolution, ink spreading on porous substrates, and the need for post-processing such as sintering to enhance conductivity. Despite these issues, inkjet printing is emerging as a promising method for producing lightweight, conformal, and low-cost metamaterial absorbers suitable for real-world applications. Jeong *et al.*, fabricated an optically transparent metamaterial absorber fabricated on a PET substrate using silver nanoparticle ink via inkjet printing can be seen in Fig. 6.

The microscopic image shown in Fig. 6 clearly shows the breadth of the printed conductive lines, which typically fall in the range of tens of micrometres depending on the ink droplet size, substrate wetting, and printing parameters. In this case, the deposited silver nanoparticle ink forms uniform, continuous traces on the PET substrate with minimal spreading, indicating good ink–substrate compatibility and optimized rheological properties. Their work demonstrated strong absorption along with flexibility and transparency, highlighting the potential of this method for next-generation absorber designs[46].

3.2.3 3D printing

3D printing, also referred as additive manufacturing, has recently emerged as a powerful technique for fabricating metamaterial absorbers with complex geometries and multi-material integration. Unlike traditional methods that rely on planar lithography or masking, 3D printing enables direct layer-by-layer construction of absorber structures with tailored designs, including gradient index profiles, Layered architecture, and conformal shapes[47,48]. This capability is particularly advantageous for broadband and multi-band absorbers, where structural design plays an important role in achieving wide absorption spectra. A representative example is shown in Fig. 7, where a honeycomb-inspired absorber was fabricated using polylactic acid (PLA) through 3D printing, combined with resistive films applied by silk-screen printing, and integrated on a metallic backplane.

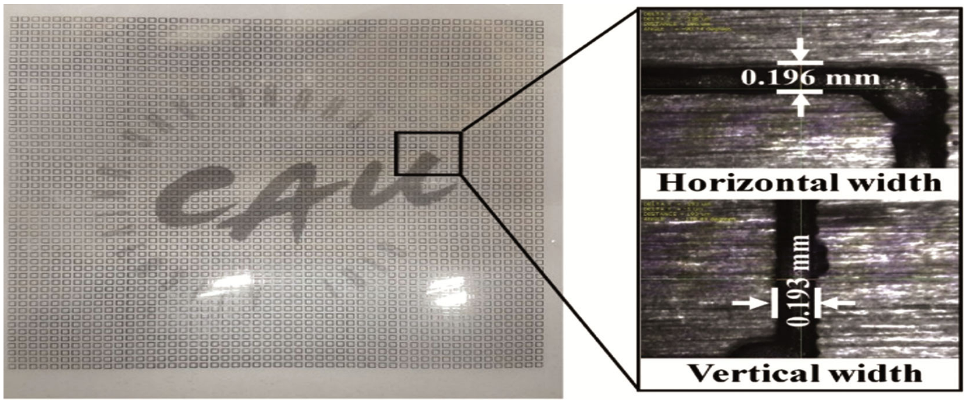

Fig. 6 — Optically transparent absorber fabricated on a PET sheet using inkjet printing[46].

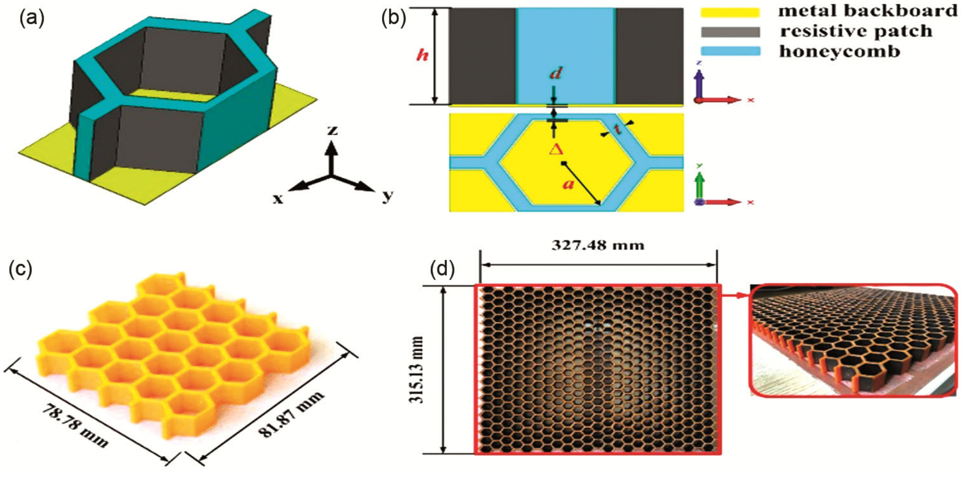

Fig. 7 — Metamaterial absorber using 3D printing (a) Design overview, (b) Design parameters, (c) 3D-printed honeycomb structure using PLA and (d) Fabricated absorber[49].

Experimental results demonstrated that the 3D-printed honeycomb absorber achieved greater than 90% absorptivity across an ultra-wide frequency band of 3.53–24.00 GHz, with stable performance for transverse magnetic (TM) waves up to an incidence angle of 70°[49].

There are several approaches for 3D printing metamaterial absorbers, including fused deposition modelling (FDM), stereolithography (SLA), and selective laser sintering (SLS)[50,51]. Thermoplastic filaments such as polylactic acid (PLA) or acrylonitrile butadiene styrene (ABS) can be incorporated with conductive fillers like carbon nanotubes or graphene to create functional composites[52]. Alternatively, high-resolution SLA allows the realization of microstructure patterns with superior dimensional accuracy, which is critical for high-frequency (millimetre-wave and terahertz) absorbers. Moreover, 3D printing is compatible with lightweight polymer substrates, enabling large-area production and conformal integration onto non-planar surfaces, a feature highly desirable for stealth and EMI shielding applications[53].While offering great potential, it still has challenges remain. The resolution of conventional FDM is still limited for sub-millimetre features required in high-frequency regimes, and conductive inks or doped filaments often require additional post-processing to achieve adequate conductivity. Furthermore, material costs can be significant when scaling up to industrial production[54]. The ability of 3D printing to fabricate customizable, lightweight, and multifunctional absorbers positions it as a disruptive technique that bridges laboratory prototyping and real-world deployment of next-generation metamaterial absorbers.

3.3 Mold-assisted approaches

3.3.1 Soft lithography / Nanoimprint lithography

Mold assisted fabrication approaches are based on the use of a pre-patterned mold or stamp to replicate micro- and nanostructures onto a substrate. These methods are attractive because they can generate large-area periodic patterns with good uniformity at relatively low cost, making them more scalable than conventional lithography techniques[55,56]. Since the mold can be reused, they also reduce processing time and material waste, which is an important consideration for practical absorber production[57].Soft lithography, particularly nanoimprint lithography (NIL), is one of the most widely studied mold-assisted techniques. It allows the transfer of patterns from an elastomeric or rigid mold to a thin polymer layer by applying pressure and curing. The most commonly used material for soft molds is polydimethylsiloxane (PDMS), which is flexible, inexpensive, and capable of replicating fine features[58]. NIL can achieve sub-100 nm resolution and is especially useful for fabricating metamaterial absorbers at optical and terahertz frequencies, where high precision is essential[59,60]. An example of nanoimprint lithography process using a paper is shown in Fig. 8. The process begins with spin-coating of an imprint resist on top of a multilayer stack (SiO_2/ITO/a-GaP), followed by stamping with an inverted imprint mold to transfer the nanoscale features. Subsequent reactive ion etching and wet etching steps define the patterned absorber geometry.

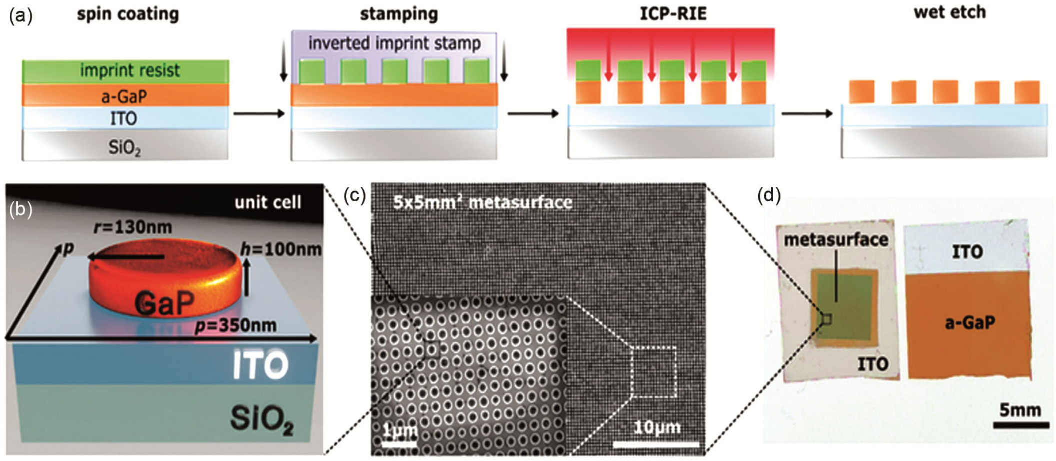

Fig. 8 — Fabrication of a metasurface absorber using nanoimprint lithography, (a) Schematic illustration of the fabrication sequence: spin-coating, stamping, ICP-RIE, and wet etching, (b) Unit cell design of GaP nanostructures on an ITO/SiO_2 substrate, (c) SEM image of the fabricated metasurface array and (d) Optical photograph of the final 5×5 mm^2 absorber sample. Adapted from[61].

The resulting metasurface consists of periodic a-GaP nanostructures integrated on a transparent ITO substrate. This approach demonstrates how soft lithography enables large-area, high-resolution patterning while remaining compatible with optoelectronic materials [61].

A key advantage of NIL is its ability to replicate patterns over large areas is a simple process, which makes it faster and less costly compared to methods such as electron beam lithography. It also works well with a variety of substrates, including flexible films and curved surfaces, that opens opportunities for conformal absorbers in stealth and wearable technologies[62,63]. However, the durability of molds, defect transfer, and alignment in multilayer structures remain as technical hurdles. To address these issues, researchers have combined NIL with thin film deposition and etching, which improves the robustness of the final structure[64]. Despite these challenges, NIL is considered one of the most practical and scalable methods for high-resolution fabrication of metamaterial absorbers.

3.3.2 Replica molding

Replica molding is another mold-assisted technique that has been widely used for fabricating micro- and nanostructures. In this process, a patterned master mold is first prepared using a high-resolution method such as photolithography or electron beam lithography, and then a liquid precursor such as polydimethylsiloxane (PDMS) is cast against it. Once cured, the polymer retains the negative of the master pattern and can be used either as a functional device itself or as a secondary mold for further replication[65,66]. For metamaterial absorbers, replica molding provides a simple and low-cost route to reproduce complex periodic structures over large areas. Its flexibility allows for replication on curved or flexible substrates, which is particularly valuable for conformal absorbers used in stealth coatings and wearable electronics[67]. Compared to nanoimprint lithography, replica molding does not require high-pressure imprinting equipment, making it more accessible for rapid prototyping[68]. As shown in Fig. 9, Han *et al.* demonstrated an ultrawide meta-film replication process for large-area microwave absorbers. The fabrication begins with precision machining of a metallic master mold containing the desired unit cell pattern (double-square loops). A UV-curable resin is then applied and pressed against a soft mold to replicate the fine features onto a flexible film. The imprinted patterns are subsequently filled with conductive carbon ink using a blade coating process, followed by lamination with a thermoplastic polyurethane (TPU) substrate and a metallic backplane. This replica molding process enables the production of highly reliable and consistent feature replication. The resulting flexible meta-films exhibited strong absorption in the X-band, with near-unity absorption centered around 12 GHz and a wide operational bandwidth[69].

However, the mechanical softness of PDMS and similar elastomers can lead to deformation or feature collapse when replicating very fine nanostructures, which limits the resolution achievable for terahertz or optical absorbers[70]. In addition, the long-term durability of molds and the possibility of introducing defects during peeling or alignment are practical concerns. Despite these limitations, replica molding remains a highly versatile method because of its simplicity, reusability, and adaptability to unconventional substrates. It continues to be a popular approach for developing experimental metamaterial absorber prototypes.

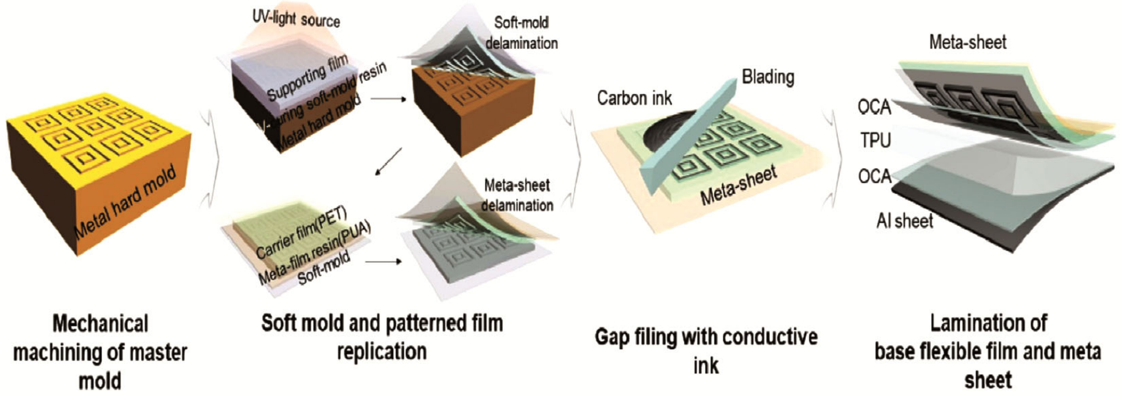

Fig. 9 — Schematic representation of replica molding fabrication[69].

3.3.3 Hot embossing

Hot embossing is a thermomechanical replication technique in which a rigid stamp or mold is pressed into a thermoplastic substrate at elevated temperature and pressure. Once the polymer is softened, the mold patterns are transferred into its surface, and the structure is fixed by cooling under pressure before the mold is released[71]. This approach enables the replication of micro- and nanoscale features with high fidelity and has been used extensively for optical and electromagnetic device fabrication[72].

For metamaterial absorbers, hot embossing offers an efficient way to produce periodic structures with good dimensional stability and uniformity over relatively large areas. Since it has rigid molds, it can achieve higher resolution and structural robustness compared to soft replica moulding, making it better suited for absorbers operating at higher frequencies. The process is also compatible with a wide range of thermoplastic polymers, which can be doped with conductive or dielectric fillers to enhance absorber performance[73]. A schematic of the hot embossing process is presented in Fig. 10, where the square-shaped unit cell design on the copper mold is replicated onto a PET substrate using hot embossing. In this, the copper mold and PET sheet are placed between two pre-heated metallic plates. Under elevated temperature, the PET softens, and the application of pressure allows the mold features to be precisely transferred onto the polymer surface. After cooling, the PET retains the embossed microstructures[74].

The main limitations of hot embossing are the need for high temperature and pressure, which restricts its compatibility with certain flexible substrates, and the relatively slow cycle times compared to other scalable techniques such as roll-to-roll nanoimprinting[75]. In addition, mold fabrication requires precision machining or lithography, which increases the initial cost. Despite these drawbacks, hot embossing remains an attractive method for prototyping and medium-scale production, where its ability to combine structural precision with repeatability is particularly valuable[76,77].

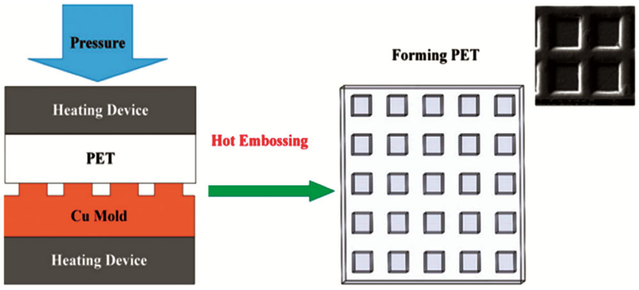

Fig. 10 — Process flow of hot embossing: transfer of periodic features from Cu mold onto PET substrate[74].

3.4 Laser enabled techniques

3.4.1 Laser direct writing

Laser-assisted fabrication has become an important route for developing metamaterial absorbers because it allows direct patterning of materials without the need for masks or complex processing steps. By focusing a laser beam onto a surface, precise heating, melting, or removal of material can be achieved, which makes it possible to create absorber patterns with fine resolution. Laser direct writing (LDW) is one of the most widely adopted laser-assisted methods for fabricating metamaterial absorbers. In this process, a highly focused laser beam is scanned across the substrate to directly form the desired absorber geometry. Since no masks or molds are required, LDW provides exceptional flexibility in prototyping complex or customized designs. The resolution typically ranges from the microscale down to sub-micrometre features, depending on the laser wavelength, pulse duration, and focusing optics used[78,79]. A laser direct writing technique is used to pattern a $Ge_2Sb_2Te_5$ (GST) alloy thin film deposited on a sapphire substrate, as shown in Fig. 11(a). A tightly focused beam micromachine ablates material to define an array of periodic squares (or holes), achieving high spatial resolution without masks. The processed structure exhibits uniform periodicity in both the plane and depth profiles, as seen in Fig. 11(d)[80].

A major advantage of LDW is its capability to work with diverse materials, such as conductive films, polymers, and composites, making it suitable for absorber designs across different frequency ranges. Additionally, the process is relatively fast compared to conventional lithography and allows rapid design iteration, which is useful in research and development environments. However, its scalability for large-area manufacturing remains limited, and the cost of high-precision laser systems can be significant[81,82]. Recent studies have shown that LDW can be used to pattern thin films, and even flexible substrates for microwave and terahertz absorbers, offering tunability and compact device integration[83]. These strengths make LDW a promising choice for rapid prototyping of next-generation absorbers.

3.4.2 Laser ablation

Laser ablation is another widely used technique for fabricating metamaterial absorbers, relying on the controlled removal of material from a substrate when it is exposed to high-energy laser pulses. Unlike laser direct writing, which primarily involves surface modification or selective curing, ablation physically removes material to generate patterns with high precision. This makes it particularly useful for producing intricate absorber geometries that require clean edges and well-defined dimensions[84,85]. The resolution of laser ablation depends strongly on the laser wavelength, pulse energy, and interaction time with the substrate. Short-pulse and ultraviolet lasers are often preferred since they can minimize the heat-affected zone and prevent thermal damage to the surrounding material[86]. The ability to create features down to the micrometre scale makes ablation suitable for absorbers operating from microwave to terahertz frequencies.

One of the advantages of this approach is its mask-free nature, which reduces fabrication complexity and time. Moreover, ablation can be applied to metals, ceramics, and polymer composites, broadening its compatibility with different absorber designs. However, limitations include slower throughput for large-area fabrication and the potential for surface roughness or redeposition of ablated debris, which can affect absorber performance if not properly managed[87,88]. In Fig. 12(a) the process flow of the laser ablation is shown in which we can see the metal coated FR4 sheets used to make the design pattern in which a mask plate is used to guide the laser that removes the material from the surface of the substrate and make the design patterns. The final fabricated absorber using laser ablation process can be seen in Fig. 12(b)[89].

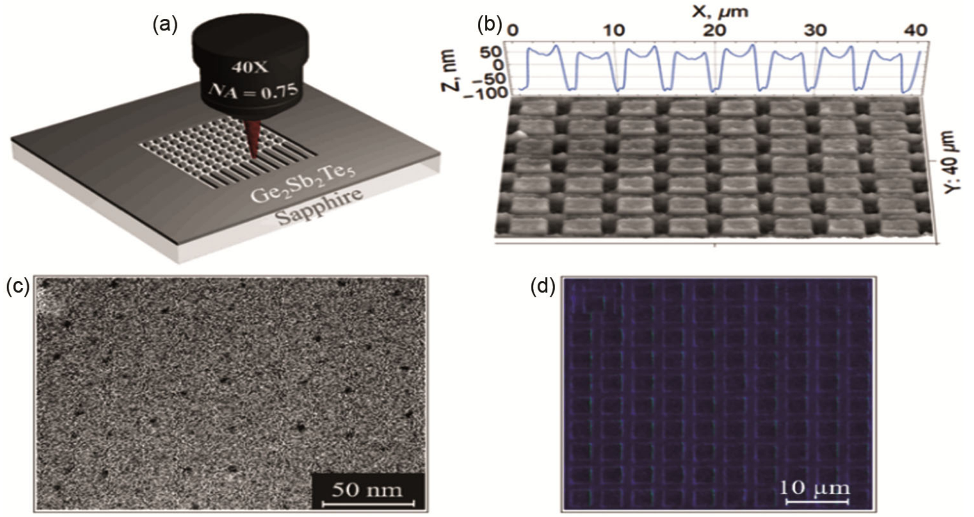

Fig. 11 — (a) Schematic illustration of the laser inscribing process of a 150 nm GST film through direct laser writing technique, (b) AFM image of the fabricated sample, (c) TEM image of the deposited GST film and (d) Optical microscope photograph of the fabricated Sample. Reproduce with permission[80] under license number 6106430828638.

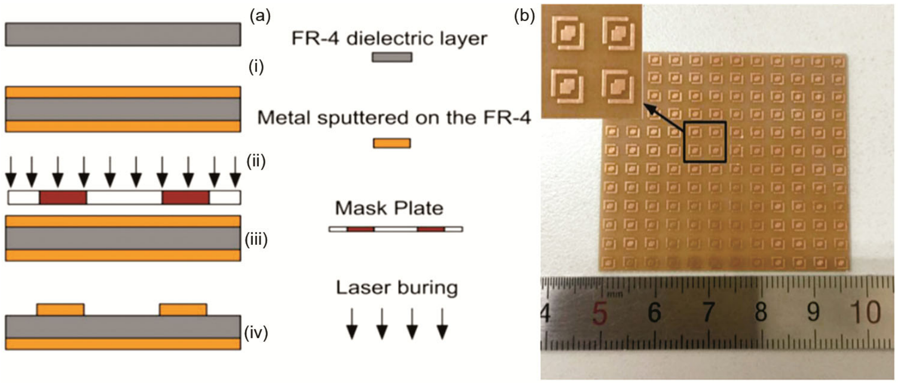

Fig. 12 — Laser ablation for fabrication (a) Process flow chart of Laser ablation and (b) Fabricated prototype of the proposed ultra-broadband absorber[89].

3.5 Comparative analysis

The development of metamaterial absorbers relies heavily on the choice of fabrication technique, as this directly influences performance, scalability, and practical deployment. Each method offers distinct advantages in terms of resolution, cost, scalability and substrate compatibility. For example, photolithography and electron beam lithography remain the gold standards for high-resolution structures but are limited by high costs and low scalability. On the other hand, printing-based and mold-assisted approaches enable large-area and flexible device production, though with reduced resolution. Laser-based methods provide a balance between precision and adaptability, making them suitable for both prototyping and specialized applications.

A comparison of the most widely used fabrication techniques is summarized in Table 1, highlighting their key features.

3.6 Emerging techniques and future outlook

The progress of metamaterial absorbers is linked to the advancement of fabrication strategies. While significant developments have been made, challenges such as high production cost, limited scalability, structural imperfections, and environmental concerns continue to restrict their widespread adoption. Recent research indicates a shift toward innovative approaches that not only overcome these limitations but also open new opportunities for absorbers in next-generation technologies.

3.6.1 Hybrid fabrication approaches

A promising direction involves hybrid fabrication, where two or more techniques are combined to get their individual strengths. For instance, nanoscale lithography can be employed for high-precision patterning, followed by large-area printing to reduce cost and enhance scalability. Such multi-step strategies enable an advance absorber design that cover wide frequency ranges and exhibit multi-band performance[107–109]. This balance between resolution and manufacturability is critical for applications requiring both fine structural detail and large-area deployment.

3.6.2 Eco friendly and flexible materials

Sustainability and adaptability are becoming key factors in absorber design. The use of biodegradable polymers, natural fibers, and recyclable composites provides a pathway toward environment friendly absorbers without sacrificing electromagnetic performance[110,111]. At the same time, flexible and stretchable substrates such as PET, polyimide, and

Table 1 — Fabrication techniques comparison table based on their abilities, scalability and production cost.

Technique	Resolution	Substrate Compatibility	Structural Complexity	Scalability	Cost	references
Photolithography	High (µm scale)	Rigid wafers, some polymers	High	Limited (lab-scale)	High	(90,91)
Electron Beam Lithography (EBL)	Very high (nm scale)	Rigid wafers	Very High	Poor (slow, costly)	Very High	(92,93)
Thin-Film Deposition	High (nm–µm)	Metals, oxides, semiconductors	High	Limited	High	(94,95)
Etching	High (µm–nm)	Silicon, glass, polymers	High	Moderate	Moderate–High	(96,97)
Screen Printing	Moderate (50–200 µm)	Polymers, foams, flexible films	Moderate	Excellent (scalable)	Low	(98,99)
Inkjet Printing	Moderate (20–50 µm)	Polymers, paper, flexible films	Moderate	High	Low–Moderate	(100)
3D Printing	Moderate (tens of µm)	Polymers, composites	High	High (scalable)	Moderate	(101,102)
Soft Lithography	High (sub-µm possible)	Elastomers, polymers, composites	High	Moderate	Moderate	(103)
Nanoimprint Lithography	Very high (sub-100 nm)	Polymers, resists	Very High	Moderate	Moderate–High	(104)
Laser Direct Writing	High (µm scale)	Metals, ceramics, polymers	High	Moderate	Moderate–High	(105)
Laser Ablation	High (µm scale)	Metals, polymers, ceramics	High	Moderate	Moderate	(106)

elastomers, coupled with conductive inks, are being integrated into designs for wearable electronics, conformal sensors, and adaptive shielding systems[112,113]. These material choices not only improve user comfort and system integration but also align with global efforts toward greener technologies.

3.6.3 AI driven design and fabrication

Artificial intelligence (AI) and machine learning (ML) are transforming the design-to-fabrication pipeline of metamaterial absorbers. Data-driven models can predict absorption spectra, optimize geometrical parameters, and even anticipate deviations caused by fabrication tolerances. This integration reduces reliance on time-intensive simulations and trial-and-error experimentation. When combined with automated printing or digital fabrication, AI-driven strategies promise rapid prototyping of absorbers that are highly customized for specific operational environments[114–116].

3.6.4 Industrial scalability and integrations

Bridging the gap between laboratory prototypes and industrial applications requires fabrication methods that ensure repeatability, and compatibility with existing manufacturing lines. Roll-to-roll printing, scalable nanoimprint lithography, and advanced 3D printing techniques are emerging as practical solutions to achieve mass production without compromising performance[117,118]. These approaches are expected to enable absorbers that are not only high-performing but also cost-effective, positioning them for deployment in communication systems, automotive platforms, and consumer electronics.

3.6.5 Future applications

In defence, advanced stealth systems demand ultra-thin, broadband, and angle-insensitive absorbers capable of maintaining performance under varying incident angles. Meeting these requirements increasingly relies on nanoimprint lithography and thin-film deposition methods, which allow precise control of feature dimensions while maintaining conformal integration on complex platforms. In civilian domains, the rapid growth of 5G/6G communication networks and IoT platforms has intensified the need for compact, conformal, and flexible absorbers that can function as effective EMI shielding layers, ensuring electromagnetic compatibility in densely integrated circuits. To achieve this, fabrication strategies such as screen printing with conductive inks, roll-to-roll printing on flexible substrates, and additive manufacturing have emerged as cost-effective and scalable solutions for large-area deployment. Beyond communication technologies, metamaterial absorbers are increasingly explored for energy-related applications, where their strong resonant confinement is utilized to harvest ambient RF signals and enhance the efficiency of wireless power transfer systems. Here, 3D printing combined with hybrid lithography enables the realization of multi-band structures optimized for maximum energy capture, thereby supporting the development of self-powered sensors and battery-free IoT nodes. Furthermore, in biomedical and healthcare sectors, high-Q absorbers operating in the microwave and terahertz regimes are being investigated as highly sensitive diagnostic tools, enabling non-invasive monitoring of physiological parameters and detection of disease biomarkers with enhanced accuracy. Such applications benefit from soft lithography, laser-assisted printing, and flexible substrate processing, which together facilitate portable, lightweight, and biocompatible sensing platforms. Collectively, these developments highlight how tailored fabrication strategies will play a decisive role in bridging performance demands with manufacturability for next-generation defence, communication, energy, and healthcare technologies[119–121].

4 Conclusion

The advancement of metamaterial absorbers is intrinsically tied to the evolution of fabrication strategies. This review has highlighted how conventional top-down methods remain indispensable for achieving sub-micron resolution, while printing-based and mold-assisted techniques enable scalable and flexible device production. Laser-assisted approaches, in turn, provide rapid prototyping capabilities and adaptability across diverse substrates. A comparative analysis shows that no single method is universally optimal; rather, the choice depends on balancing resolution, scalability, cost, and substrate compatibility. Emerging trends point toward hybrid fabrication schemes, eco-friendly and flexible materials, and AI-assisted design workflows that can accelerate the transition of absorbers from laboratory prototypes to industrial applications. The use of sustainable materials and scalable processes is expected to be particularly influential in expanding their role in defence, communication, energy harvesting, and biomedical sensing. By aligning fabrication precision with application-specific requirements, next-generation absorbers can deliver high performance while remaining cost-effective and environmentally responsible. This convergence of materials innovation, processdevelopment, and digital design tools will ultimately define the future landscape of metamaterial absorber technologies.

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References

1 Pendry J B, Phys Rev Lett, 85 (2000) 3966.
2 Landy N I, Sajuyigbe S, Mock J J, Smith D R & Padilla W J, *Phys Rev Lett*, 100 (2008) 207402.
3 Watts C M, Liu X & Padilla W J, *Adv Mater*, 24 (2012) 98.
4 Liu X, Starr T, Starr A F & Padilla W J, *Phys Rev Lett*, 104 (2010) 207403.
5 Grant J, Ma Y, Saha S, Khalid A & Cumming D R S, *Opt Lett*, 36 (2011) 3476.
6 Gu J, Singh R, Liu X, Zhang X, Ma Y, Zhang S et al., *Nat Commun*, 3 (2012) 1151.
7 Tao H, Bingham C M, Strikwerda A C, Pilon D, Shrekenhamer D, Landy N I et al., *Phys Rev B*, 78 (2008) 241103.
8 Smith D R, Padilla W J, Vier D C, Nemat-Nasser S C & Schultz S, *Phys Rev Lett*, 84 (2000) 4184.
9 Liu Y & Zhang X, *Chem Soc Rev*, 40 (2011) 2494.
10 Yin Z, Huang Y, Bu N, Wang X &Xiong Y, *Chin Sci Bull*, 55 (2010) 3383.
11 Feng Y, Liang M, Zhao X & You R, *Microsyst Nanoeng*, 11 (2025) 14.
12 Chou S Y, Krauss P R & Renstrom P J, *J Vac Sci Technol B*, 14 (1996) 4129.
13 Pinheiro T, Morais M, Silvestre S, Carlos E, Coelho J, Almeida H V et al., *Adv Mater*, 36 (2024) 2402014.
14 Xia Y &Whitesides G M, *Angew ChemInt Ed*, 37 (1998) 550.
15 Rogers J A & Nuzzo R G, *Mater Today*, 8 (2005) 50.
16 Chou S Y, Krauss P R & Renstrom P J, *J Vac Sci Technol B*, 14 (1996) 4129.
17 Chung J Y, Nolte A J & Stafford C M, *Adv Mater*, 23 (2011) 349.
18 Singh M, Haverinen H M, Dhagat P & Jabbour G E, *Adv Mater*, 22 (2010) 673.
19 Jeong H & Lim S, *Sensors*, 17 (2017) 1175.
20 Lee D, Kim H K & Lim S, *Microw Opt Technol Lett*, 59 (2017) 1424.
21 Guo L J, *Adv Mater*, 19 (2007) 495.
22 Ding M, Liu Y, Lu X & Tang W, *Materials*, 12 (2019) 3700.
23 Malinauskas M, Žukauskas A, Hasegawa S, Hayasaki Y, Mizeikis V, Buividas R et al., *Light Sci Appl*, 5 (2016) e16133.
24 Wang J, Lang T, Hong Z, Xiao M & Yu J, *Nanomaterials*, 11 (2021) 1110.
25 Wakatsuchi H, Sievenpiper D F & Christopoulos C, *IEEE Electromagn Compat Mag*, 5 (2016) 76.
26 Soukoulis C M & Wegener M, *Nat Photonics*, 5 (2011) 523.
27 Wang D, Xu K D, Luo S, Cui Y, Zhang L, Liao Z et al., *Opt Express*, 31 (2023) 5940.
28 Tao H, Bingham C M, Pilon D, Fan K, Strikwerda A C, Shrekenhamer D et al., *J Phys D Appl Phys*, 43 (2010) 225102.
29 Alipour Z, Mirzaei S I & Fardmanesh M, *Eng Proc*, 58 (2023) 92.
30 Pitchappa P, Ho C P, Qian Y, Dhakar L, Singh N & Lee C, *Sci Rep*, 5 (2015) 11678.
31 Liu N, Mesch M, Weiss T, Hentschel M & Giessen H, *Nano Lett*, 10 (2010) 2342.
32 Shreiber D, Zhou W, Dang G, Taysing-Lara M, Metcalfe G & Ngo E et al., *Thin Solid Films*, 660 (2018) 282.
33 Ghaderi M, Karimi E, Ayerden N P & Wolffenbuttel R F, *Proc Eurosensors*, 1 (2017) 328.
34 Madou M J, Fundamentals of Microfabrication (CRC Press, Boca Raton), ISBN: 9781482274004, 2018.
35 Wang B, Ma R, Wang P, Tsujita W, Sadamoto K & Sawa Y et al., *Proc SPIE*, 10531 (2018) 49.
36 Cong L, Tan S, Yahiaoui R, Yan F, Zhang W & Singh R, *Appl Phys Lett*, 106 (2015) 031107.
37 Chen H T, Taylor A J & Yu N, *Rep Prog Phys*, 79 (2016) 076401.
38 He P, Cao J, Ding H, Liu C, Neilson J & Li Z et al., *ACS Appl Mater Interfaces*, 11 (2019) 32225.
39 Singh A & Gupta N, *IEEE Trans Electromagn Compat*, 64 (2022) 1321.
40 Huang X, Pan K & Hu Z, *Sci Rep*, 6 (2016) 38197.
41 Long L V, Khiem N S, Tung B S, Tung N T, Giang T T& Son P T et al., *Photonics*, 8 (2021) 440.
42 Alamán J, Alicante R, Peña J & Sánchez-Somolinos C, *Materials*, 9 (2016) 910.
43 Kawase T, Moriya S, Nakamura K, Inoue K & Aoki T, *Ext Abstr SSDM*, (2010) A-6-1.
44 Perelaer J, de Gans B J & Schubert U S, *Adv Mater*, 18 (2006) 2101.
45 Tentzeris M M & Nauroze A, *Wiley Encycl Electr Electron Eng*, (2017) 1.
46 Jeong H, Tentzeris M M& Lim S, *Materials*, 12 (2019) 3406.
47 Soukoulis C M & Wegener M, *Nat Photonics*, 5 (2011) 523.
48 Singh H, Tuffaha M, Tripathi S, Öztürk A B, Dave H & Dhanka M et al., *Adv Drug Deliv Rev*, 224 (2025) 115636.
49 Jiang W, Yan L, Ma H, Fan Y, Wang J & Feng M et al., *Sci Rep*, 8 (2018) 4817.
50 Hasanov S, Alkunte S, Rajeshirke M, Gupta A & Huseynov O et al., *Preprints*, (2021) 2021110277.
51 Tumbleston J R, Shirvanyants D, Ermoshkin N, Janusziewicz R, Johnson A R & Kelly D et al., *Science*, 347 (2015) 1349.
52 Osswald T A, Jack D & Thompson M S, *Polym Compos*, 43 (2022) 3496.
53 Yang Z, Liang Q, Duan Y, Li Z, Chen T & Li D, *Proc Int Congr Artif Mater Novel Wave Phenom*, (2020) 207.
54 Babu S S, Love L, Dehoff R, Peter W, Watkins T R & Pannala S, *MRS Bull*, 40 (2015) 1154.
55 Xia Y & Whitesides G M, *Annu Rev Mater Sci*, 28 (1998) 153.
56 Guo L J, *Adv Mater*, 19 (2007) 495.
57 Verschuuren M & Sprang H V, *MRS Proc*, 1002 (2007) N03-05.
58 Chou S Y, Krauss P R & Renstrom P J, *Science*, 272 (1996) 85.
59 Huang Z, Droulias S, Koschny T & Soukoulis C M, *Opt Express*, 22 (2014) 28596.

60 Tao H, Strikwerda A C, Liu M, Mondia J P, Ekmekci E & Fan K et al., *Appl Phys Lett*, 97 (2010) 261909.

61 Hüttenhofer L, Golibrzuch M, Bienek O, Wendisch F J, Lin R & Becherer M et al., *Adv Energy Mater*, 11 (2021) 2102877.

62 Chen L, Ruan Y, Luo S S, Ye F J & Cui H Y, *Micromachines*, 11 (2020) 1032.

63 Wang Y, Yang H, Wu J, Yang Y, Jin J & Geng X et al., *Nanoscale*, 15 (2023) 16144.

64 Park Y, Kim J, Yang Y, Oh D K, Kang H & Kim H et al., *Adv Sci*, 12 (2025) 2409371.

65 Xia Y, Kim E, Zhao X M, Rogers J A, Prentiss M & Whitesides G M, *Science*, 273 (1996) 347.

66 Rogers J A & Nuzzo R G, *Mater Today*, 8 (2005) 50.

67 Ok J G, Youn H S, Kwak M K, Lee K T, Shin Y J & Guo L J et al., *Appl Phys Lett*, 101 (2012) 223102.

68 Joannopoulos J D, Winn J N & Johnson S G, Photonic Crystals: Molding the Flow of Light (Princeton University Press, Princeton), 2nd Edn, ISBN: 9781400828241, 2011.

69 Han J S, Park H, Jeong J Y, Jung J, Gwak E J & Jeon E C et al., *Opt Express*, 30 (2022) 29760.

70 Gates B D, Xu Q, Stewart M, Ryan D, Willson C G & Whitesides G M, *Chem Rev*, 105 (2005) 1171.

71 Schift H, *J Vac Sci Technol B*, 26 (2008) 458.

72 Guo L J, *J Phys D Appl Phys*, 37 (2004) R123.

73 Peng L, Deng Y, Yi P & Lai X, *J Micromech Microeng*, 24 (2014) 013001.

74 Yang H, Hao J, Wang H & Ding M, *Materials*, 16 (2023) 5079.

75 Greenwald A, Ryu J, Liu Y, Biswas R, Ok J & Youn H et al., *MRS Proc*, 1412 (2012) FF01-04.

76 Chen Y, *Appl Phys A*, 121 (2015) 451.

77 Li Q, Li K, Lv J, Tao L & Gong F, *Micromachines*, 15 (2024) 1307.

78 Wang S, Zhou Z, Li B, Wang C & Liu Q, *Mater Today Nano*, 16 (2021) 100142.

79 Zhu H, Wu B, Gao M, Ren F, Qin W & Juodkazis S et al., *Small Sci*, 2 (2022) 2200038.

80 Bochek D V, Samusev K B, Yavsin D A, Zhukov M V, Limonov M F &Rybin M V et al., *Opt Laser Technol*, 141 (2021) 107124.

81 Xu H, Cheng J, Huang Q, Luo M, Li D & Zhu D et al., *Opt Lett*, 49 (2024) 89.

82 Chen C, Liu Y, Jiang Z Y, Shen C, Zhang Y & Zhong F et al., *Opt Express*, 30 (2022) 13391.

83 Suo Y, Zhang L, Li Y, Wu Y, Zhang J & Wen Q, *Micromachines*, 13 (2022) 686.

84 Kim H, Melinger J S, Khachatrian A, Charipar N A & Piqué A, *Opt Lett*, 35 (2010) 4039.

85 Kim B, Nam H K, Watanabe S, Park S, Kim Y & Kim Y J et al., *Int J Precis EngManuf Green Technol*, 8 (2021) 771.

86 Jamaatisomarin F, Chen R, Hosseini-Zavareh S & Lei S, *J Manuf Mater Process*, 7 (2023) 94.

87 Lin L, Huo J, Zou G, Liu L, Jeurgens L P H & Zhou Y N, *J Phys Chem C*, 124 (2020) 1178.

88 Tancin R J, Özdoğru B, Sunderlin N, Weddle P J, Usseglio-Viretta F L E & Boone D R et al., *EES Batter*, (2025) D5EB00149H.

89 Xin W, Binzhen Z, Wanjun W, Junlin W & Junping D, *IEEE Photonics J*, 9 (2017) 1.

90 Fruncillo S, Su X, Liu H & Wong L S, *ACS Sens*, 6 (2021) 2002.

91 Xia Y, Luo X, Shen W, Pan M, Wei T & Yao X et al., *J Energy Storage*, 131 (2025) 115862.

92 Zhu C, Ekinci H, Pan A & Cui B, *Microsyst Nanoeng*, 10 (2024) 52.

93 Constancias C, Landis S, Manakli S, Martin L, Pain L & Rio D, *Lithography*, (2013) 101.

94 Abegunde O O, Akinlabi E T, Oladijo O P, Akinlabi S & Ude A U et al., *AIMS Mater Sci*, 6 (2019) 174.

95 Hossain M I & Mansour S, *Cogent Eng*, 10 (2023) 2179467.

96 Sockmen , Stranz A, Fundling S, Wehmann H H, Bandalo V & Bora A et al., *J MicromechMicroeng*, 19 (2009) 105005.

97 Racka-Szmidt K, Stonio B, Żelazko J, Filipiak M & Sochacki M, *Materials*, 15 (2021) 123.

98 Rubio J C & Bolduc M, *Electron Mater*, 6 (2025) 7.

99 Cao T, Yang Z, Zhang H & Wang Y, *Heliyon*, 10 (2024) e30163.

100 Beedasy V & Smith P J, *Materials*, 13 (2020) 704.

101 Park S, Shou W, Makatura L, Matusik W & Fu K, *Matter*, 5 (2022) 43.

102 Ma T, Zhang Y, Ruan K, Guo H, He M & Shi X et al., *InfoMat*, 6 (2024) e12568.

103 Karimian T, Lanzerstorfer P & Weghuber J, *Mater Today Bio*, 32 (2025) 101672.

104 Unno N & Mäkelä T, *Nanomaterials*, 13 (2023) 2031.

105 Zhang B, Yan W & Chen F, *Adv Photonics*, 7 (2025) 034002.

106 Ma R, Zhang X, Sutherland D, Bochenkov V & Deng S, *Int J Extreme Manuf*, 6 (2024) 062004.

107 Greenwald A, Ryu J, Liu Y, Biswas R, Ok J &Youn H et al., *MRS Proc*, 1412 (2012) FF01-04.

108 Sadeqi A, RezaeiNejad H, Owyeung R E & Sonkusale S, *MicrosystNanoeng*, 5 (2019) 16.

109 Samir A, Ashour F H, Hakim A A A & Bassyouni M, *npj Mater Degrad*, 6 (2022) 68.

110 Thyavihalli Girijappa Y G, Mavinkere Rangappa S, Parameswaranpillai J & Siengchin S, *Front Mater*, 6 (2019) 226.

111 Long L V, Khiem N S, Tung B S, Tung N T, Giang T T & Son P T et al., *Photonics*, 8 (2021) 440.

112 Li M, Jiang Z, Shao H, Shao G, Xu B & Jiang J et al., *Compos Part A ApplSciManuf*, 200 (2026) 109282.

113 Soni M &Misra S, *ACS Appl Opt Mater*, 1 (2023) 1679.

114 Shahsavaripour A, Badiei M H, Kalhor A & Yousefi L, *Sci Rep*, 15 (2025) 9426.

115 Yang G, Xiao Q, Zhang Z, Yu Z, Wang X & Lu Q, *I Science*, 28 (2025) 111995.

116 Li X, Cui T, Zhuang S, Qian W, Lin L & Su W et al., *Opt Express*, 31 (2023) 9224.

117 Peng J, Wang S, Liang B, Wen Q, Sun C & Li K et al., *Virtual Phys Prototyp*, 19 (2024) e2378937.

118 Zhao C, Jia M, Zhang N, Meng S & Tian Y, *Sci Rep*, 15 (2025) 29093.

119 Moniruzzaman M, Larguech S, Mobarak M, Jizat N M, Alharbi S S& Islam M T et al., *Sci Rep*, 15 (2025) 12292.

120 Fowler C, Silva S, Thapa G & Zhou J, *Opt Mater Express*, 12 (2022) 1242.

121 Miah A, Al Zafir S, Hasnain M, Das J, Haque S M A & Wahed A, *PLOS One*, 20 (2025) e0328077.