# Recent Developments in Active Metamaterials and their Practical Applications

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**Article History**

Received: Feb. 18, 2025

Revised: Jun. 21, 2025

Accepted: Jul. 04, 2025

## Abstract

Mechanical metamaterials are specially designed materials that exhibit unconventional mechanical properties due to their precisely designed microarchitectures and inherent material characteristics. Recent developments have made it possible to create active, tunable, and reconfigurable metamaterials, which provide dynamic control over electromagnetic behavior and offer significant advantages over conventional static systems. In this paper, tuning mechanisms such as circuit-based, geometric, material-driven, and active control mechanisms are comprehensively discussed. It extends to their application in a number of devices, including antennas, filters, imaging devices, and sensors. Although these technologies have a great deal of promise, challenges exist, specifically with respect to fabrication complexity and limited tunability. Continuous breakthroughs in materials science and device engineering will be essential to developing these metamaterials from concepts in the lab to practical, real-world applications. The main contribution of this review is to give a systematic overview of the most recent tuning mechanisms for active metamaterials, while also highlighting the integration of artificial intelligence as a transformative approach for future design and optimization.

***Keywords***- Active tunable metamaterials, reconfigurable materials, tuning processes, electromagnetic characteristics, antennas.

## I. INTRODUCTION

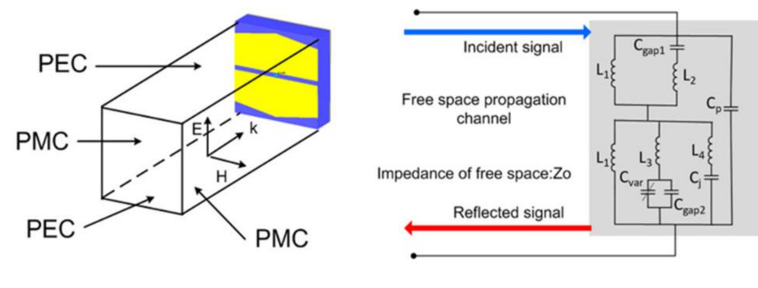
Metamaterials are artificial structures that behave in ways not usually found in natural materials [1] , especially in how they interact with electromagnetic waves. Effects like negative refraction and superlensing have been made possible through their use. Due to the real-time manipulation of wave propagation that they allow, exciting opportunities have been opened up in areas such as wireless communication and medical imaging [2–4].

Particularly, the majority of devices termed "metamaterial-based" are not built on the collective qualities of the metamaterial itself, but instead on the dynamics of individual resonant components. Although such configurations are not metamaterials in the strict sense of the above term, they do share a design philosophy, particularly for programmable or tunable devices. In much of the research, Structures centered around elements like split-ring resonators (SRRs) are often found to interact closely with transmission lines or antenna systems [5],[6]. Conventional metamaterials have a key drawback: their static character limits their application in many dynamic environments. To overcome this, allowing real-time changes in their electromagnetic characteristics during operation, tuned and reconfigurable metamaterials help to avoid this limit [7],[8]. These adjustments can be made utilizing a variety of tuning strategies [9], including geometric, material, and circuit-based. The performance of the metamaterial will change depending on the unit cell design or the material properties, enabling it to be adaptive to different environmental conditions. Numerous mechanisms have been studied to achieve metamaterial tunability. The paper presents an overview in narrative form of the recent advancements in reconfigurable and tunable metamaterials with emphasis on the basic tuning principles, real-world implementations, and potential applications in communications, sensing, imaging, and energy. The most representative contributions were selected on the basis of technical influence, innovation, and applicability. The review aims to provide a comprehensive yet focused synthesis of diverse approaches, including circuit-based, material-based, and geometric tuning strategies, while also highlighting emerging trends such as AI-assisted metamaterial design and hybrid reconfigurable structures. This work is intended to serve both as a reference for current researchers and a guide for future investigations in the field. It is important to distinguish between true metamaterials, which derive their unique electromagnetic behavior from the collective response of subwavelength periodic structures, and metamaterial-inspired devices, which may rely primarily on the behavior of individual resonant components rather than a bulk effective medium response. While both share similar design philosophies, especially in the context of tunable or programmable functionalities, the latter do not necessarily exhibit the homogenized material parameters (such as negative permittivity or permeability) characteristic of conventional metamaterials. This clarification has been incorporated early in the revised Introduction to better guide the reader's understanding of the terminology used throughout the manuscript. Three fundamental tuning categories—material tuning, geometric tuning, and circuit tuning—help classify these techniques [10], [11].

## II. MECHANISMS APPLIED IN TUNING

Several methods have been investigated to attain metamaterial tunability. There are three main groups to classify these techniques: circuit tuning, geometric tuning, and material tuning.

*A*. Circuit Tuning is the alteration of the equivalent circuit of a unit cell by changing capacitance, inductance, or resistance. The typical approach is varactors—voltage-regulated capacitors capable of modulating the resonance frequency of the metamaterial [12], [13].
Other methods, such as MEMS-based switches or PIN diodes, allow dynamic reconfiguration by altering the unit cell impedance [14]. MEMS (Micro-Electro-Mechanical Systems) tuning mechanisms operate by physically altering the position or geometry of sub-components such as cantilevers or capacitive plates through electrostatic actuation. These structural variations cause variations of effective inductance or capacitance at the unit cell level, thereby changing the resonant frequency and matching the wave propagation properties. MEMS-based metamaterials are particularly favorable for high-frequency applications due to their mechanical precision and miniaturization. For instance, a novel Intelligent Reflecting Surface (IRS) structure was proposed for future 6G communication systems and included multiple tuning approaches such as circuit-based, geometric, and material-based. Specifically, based on the saw-tooth-shaped unit cell as shown in Figure 1, achieving a phase deviation of up to 340° was presented to highlight the superiority of geometric tuning in dynamic beam steering and phase modulation [15].




(a) Unit-cell with Floque Boundary. (b) Equivalent Circuit Model (ECM).

Figure 1 The unit-cell sawtooth and Equivalent Circuit Model (ECM)[15].

*B*. In metamaterials, Geometric Tuning is the physical modification of the resonant element forms or placements. One can accomplish this by stretching the substrate, moving conducting sections using microelectromechanical system (MEMS) actuators, or tilting resonant structures. These modifications could cause the material's electromagnetic properties to change noticeably regarding resonance frequency and scattering behavior. Figure 2 illustrates a typical configuration of a parallel plate capacitor used for electrostatic actuation, as presented in [16].

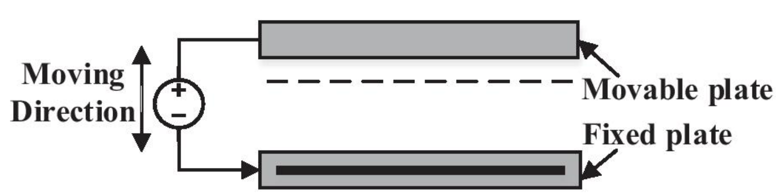



Figure 2 Schematic of Parallel Plate Capacitor for Electrostatic Actuation [16].

*C*. Material Tuning is the process of varying the material properties of the unit cell, that is, its permittivity, permeability, or conductivity. Liquid crystals, phase-change materials , and ferroelectric films help control the electromagnetic response [17]. Liquid crystals (LCs), for example, exhibit anisotropic dielectric properties that can be reoriented using external electric fields. When integrated into the unit cell of a metamaterial, the reorientation of LC molecules changes the effective permittivity of the surrounding medium. This dielectric modulation allows for dynamic tuning of resonance frequency, absorption bandwidth, and polarization behavior. Such tunability makes LC-based metamaterials particularly promising for applications in terahertz modulators, tunable lenses, and beam-steering devices. Unlike conventional biasing schemes, the configuration in Figure 3 utilizes a compact network with two transistors and an internal capacitor to dynamically tune. The voltage applied across $C_{LC}$ dictates the αLC [17].

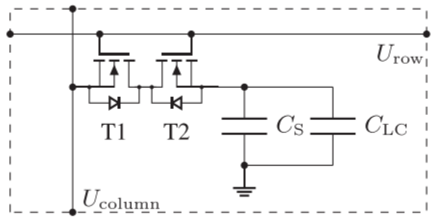



Figure 3 The proposed unit cell's biasing network has two transistors (T1 and T2) and an internal capacitor ($C_S$)[17].

In addition to individual tuning strategies, recent developments have demonstrated the effectiveness of hybrid tuning mechanisms, which combine two or more approaches—such as circuit-based modulation, material-property tuning, and geometric reconfiguration—within a single metamaterial design. These hybrid systems enable multifunctional control, broaden the tuning range, and improve adaptability for real-time applications. For instance, electrically triggered hybrid metamaterials integrating phase-change materials and plasmonic elements have shown tunable absorption, reflection, and transmission behaviors across a wide spectrum [18]. Figure 4 illustrates a hybrid tunable metamaterial design that integrates a plasmonic metal layer and a phase-change material ($VO_2$) within a multilayered structure, enabling electrically triggered resonance tuning [18].

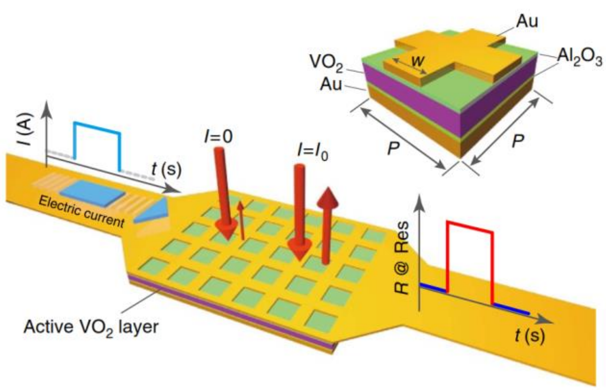



Figure 4 Schematic of a Hybrid Metamaterial Absorber with $VO_2$ Phase-Change Layer [18]

Among the three mechanisms, circuit-based tuning offers the fastest response due to electronic control but suffers from increased power consumption and heat dissipation. Geometric tuning, while passive and power-efficient, is often limited by mechanical fatigue and slower switching speed. Material tuning enables broad spectral adaptability; however, it is constrained by complex biasing schemes and environmental sensitivity. Hybrid mechanisms combining two or more approaches are being explored to overcome individual drawbacks but add significant fabrication complexity.

## III. IMPLEMENTING TUNABLE METAMATERIALS

Particularly in communication, imaging, and sensing, tunable metamaterials have been investigated for several uses. Elective electromagnetic responses are perfect for flexible and adaptive devices as one can dynamically adjust them.

*A.* The design of reconfigurable antennas and filters is one of the primary uses of tunable metamaterials. Dynamic frequency adjustment of these devices helps to enable more compact designs and bandwidth flexibility by allowing their running frequencies to change. From wireless communication systems to radar and satellite communication [19], tuned filters and antennas are used in many fields. Figure 5 illustrates the mechanical displacement of the membrane modifies the resonant frequency of the high-impedance surface, allowing dynamic electromagnetic response control [20].

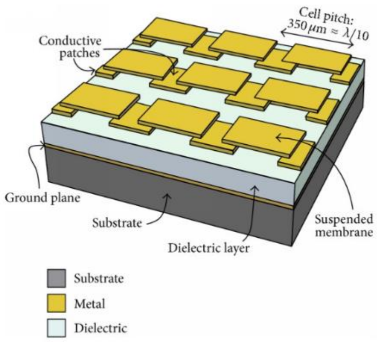



Figure 5 Reconfigurable metamaterial with suspended conductive membrane [20].

*B.* Tunable metamaterials can enhance the performance of imaging devices, such as those used in terahertz and microwave frequencies. The functionality of devices such as lenses, modulators, and switches can be optimized for specific imaging processes by adjusting the resonance frequency of the metamaterial. In Figure 6 schematic representation of a dynamically tunable metamaterial structure, presumably employing varactor diodes (red arrows) for dynamic tuning. This is ideally suited to demonstrate how electrical biasing can modify the resonance characteristics of the metamaterial for terahertz or microwave applications [21].

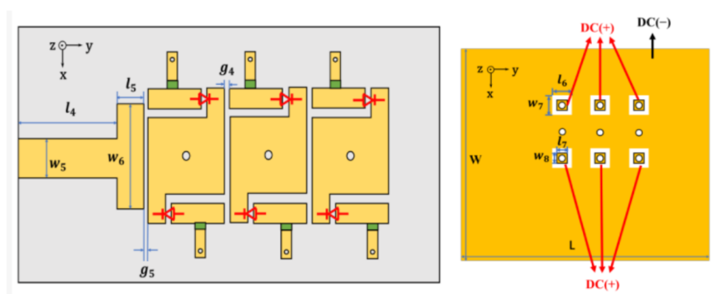



Figure 6 Electrically tunable metamaterial unit cell1 [21].

*C.* Tuning a metamaterial's material properties helps one create cloaking devices that might make objects invisible to particular frequencies. In military and security settings, when the objective is to reduce radar or other electromagnetic sensor detection, this use is very pertinent. For instance, a mechanical metamaterial cloak, a mechanical metamaterial device that can redirect or absorb mechanical waves such as sound or vibration, can be controlled dynamically to achieve tunable invisibility characteristics. As shown in Figure 7 (a), the performance of the elastic cloak is controlled by external magnetic fields to adjust cloaking behavior. This behavior is modeled using a Magnetoactive Mechanical Metamaterial (MAMM), which consists of an asymmetric lattice embedded with grounded springs that respond to magnetic stimulation. The corresponding mass-spring model is depicted in Figure 7 (b) and illustrates the magneto-mechanical response of the MAMM under varying field conditions [22].

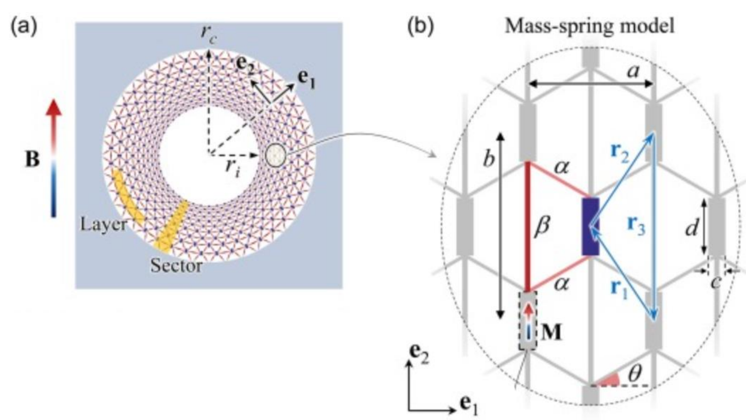



Figure 7 Magnetoactive Mechanical Metamaterial for Tunable Elastic Cloaking [22].

*D.* Tunable metamaterials have also been shown to be highly promising for chemical and biological sensing [23], and in other uses. By embedding liquid crystals or phase-change materials, metamaterials can be made to react to external environmental stimuli, creating very sensitive and versatile sensors. The schematic in Figure 8 represents the reversible phase shift in GST between amorphous and crystalline states [24].

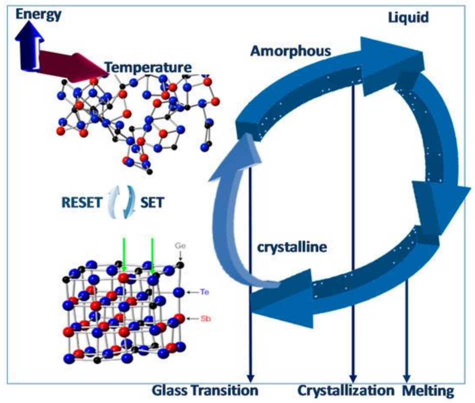


Figure 8 Reversible Phase Transition in GST [24].

*E*. Energy Harvesting and Solar Cells: Applications of tuned metamaterials also abound in solar cell technologies. These materials can raise energy conversion efficiency by modifying the absorption properties of the material in reaction to environmental changes. Illustration of a high-temperature solar energy system uses a selective metamaterial absorber for selective absorption of solar radiation, minimizing thermal emission and optimizing thermal efficiency, with high absorption in the solar spectrum range [25]. As shown in Figure 9, a selective metamaterial absorber design can enhance solar energy harvesting by optimizing absorption while minimizing thermal emission [25].

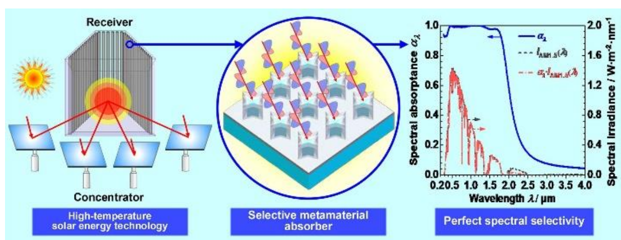


Figure 9 Selective metamaterial absorber for solar thermal energy [25].

In communication systems, tunable metamaterials promise miniaturized, adaptable components. Yet, the inclusion of active elements often reduces long-term reliability. For example, varactor-tuned antennas offer agility in spectrum use but become unstable at mmWave frequencies due to parasitic capacitance. Likewise, imaging systems benefit from dynamic focusing yet require extensive calibration for stability, particularly with temperature-dependent tunable materials. Among the tuning methods discussed, circuit tuning excels in terms of adaptability and speed but is hindered by power hunger and thermal drift. Despite being low power and mechanically robust, geometric tuning faces mechanical fatigue and slow response. Material tuning offers broad spectral range versatility but is limited by environmental sensitivity and complex fabrication procedures. Hybridization can, in theory, offset single-mode limitations, but integration complexity and prohibitive cost remain obstacles. Future research must tailor hybrid systems to every application, carefully trading off performance, reliability, and manufacturability.

## IV. CHALLENGES AND FUTURE APPLICATIONS FOR TUNABLE METAMATERIALS

Applications in various fields, including imaging, sensing, and telecommunications, increasingly depend on the development of highly tailored metamaterials. However, the realization of these materials for practical applications faces several critical challenges.

Among the most significant challenges are their complexity and high production cost. Integrating active elements—such as MEMS devices, PIN diodes, and varactors—into metamaterial structures substantially increases fabrication difficulty and cost [26]. Furthermore, maintaining long-term stability and reliability of these components remains a major issue, particularly as many designs experience performance degradation at higher frequencies [27].

The speed and range of tunability also remain key limitations. Although current tunable metamaterials can adjust their electromagnetic characteristics to some extent, their response speed to external stimuli is often limited [28]. Moreover, the material properties in use today constrain the achievable tuning range, thus hindering their suitability for highly dynamic environments. To overcome these limitations, it is crucial to develop novel materials—such as phase-change materials, low-loss two-dimensional (2D) materials, or responsive polymers—that offer broader and faster dynamic control. Exploring multiphysical tuning mechanisms (e.g., thermal, electrical, optical) may further extend system adaptability [29].

Scalability represents another significant challenge. While small-scale prototypes have shown promising results, transitioning to commercial and industrial applications requires overcoming substantial manufacturing precision and materials challenges [30]. Research into scalable nanofabrication techniques, roll-to-roll processing, and self-assembly methods will be instrumental in addressing these barriers. These advancements are necessary to enable mass production without compromising material fidelity or performance, making these technologies viable for large-scale deployment.

Addressing these challenges demands strong interdisciplinary collaboration. Advances in materials science, nanotechnology, and electrical engineering must converge to develop and optimize tunable metamaterials [31]. Furthermore, the incorporation of artificial intelligence (AI) and machine learning (ML) into prototyping and design introduces advanced tools to facilitate discovery and optimization [32]. For instance, deep-learning algorithms such as convolutional neural networks (CNNs) can discover complex relations between a metamaterial's geometry and electromagnetic response. These trained models can proceed to develop optimized designs rapidly without the need for time-consuming full-wave simulations [33],[34]. This approach drastically accelerates the discovery of new configurations for cloaking, filters, and sensing. Furthermore, AI-enabled rapid prototyping and customization can simplify the design process and support innovation in application-specific metamaterials.

Future research should prioritize several key areas. First, scalable and cost-effective fabrication techniques, particularly at micro- and nanoscale levels, must be developed to support large-scale production. Second, the response time of tuning mechanisms needs improvement through faster actuation materials or hybrid control strategies. Third, integrating tunable metamaterials with flexible and wearable platforms opens new possibilities in biomedical sensing and on-body communication [35]. Additionally, expanding the use of AI in inverse design and real-time control, with a focus on explainable AI and robust training datasets, will further enhance design efficiency. Finally, rigorous experimental validation of AI-designed structures in real-world scenarios is essential to bridge the gap between simulations and practical implementations.

Although colossal strides have been achieved, there are still numerous research areas to be addressed. Systematic investigations of long-term performance under combined electromagnetic, mechanical, and heat loads are still unavailable. Tunable metamaterial integration with wearable and flexible systems is still not fully developed, which makes them difficult to be utilized in biomedical applications and on-body communications. To overcome these limitations, future research should target the creation of durable hybrid designs, adaptive low-loss materials, and advanced real-time control architectures. A concerted effort in material creation, large-scale manufacturing, and intelligent design paradigms must be overcome current limitations. By bridging these critical research gaps, the metamaterials community will be well-placed to realize larger sets of applications and optimize the performance and versatility of future electromagnetic systems.

Table I. compares several technologies that include passive metamaterials, metasurfaces, and reconfigurable antennas [36-39]. The parameters being compared are flexibility, power consumption, bandwidth, manufacturing complexity, cost, and field of application. The comparison highlights the constraints and limitations of the various approaches, with a focus on power requirements, fabrication complexity, and cost for active metamaterials.

TABLE I. COMPARISON OF METAMATERIAL TECHNOLOGIES BY KEY FEATURES

| Feature | Active Metamaterials | Passive Metamaterials | Metasurfaces | Reconfigurable Antennas |
|---|---|---|---|---|
| **Power Consumption** | High (due to active components) | Low (no external power required) | Low (depends on passive elements) | Moderate (depends on active components) |
| **Bandwidth** | Narrow around resonant frequencies, but compensates loss | Can improve bandwidth but limited at lower frequencies | Can improve bandwidth by controlling wave propagation | Variable; depends on reconfiguration mechanism |
| **Flexibility** | High (dynamic reconfiguration) | Low (static design) | High (adaptable to specific applications) | High (dynamic reconfiguration for different modes) |
| **Manufacturing Complexity** | High (requires active circuits and precise design) | Moderate (requires complex resonant structures) | High (requires precise fabrication of metasurfaces) | Moderate to High (depends on integration complexity) |
| **Applications** | WPT, Microwave Energy Harvesting, Metamaterial Arrays | Antennas, Impedance Matching, Radiation Enhancement | Miniaturized antennas, IoT, Sensing, Energy Harvesting | 5G/6G Networks, Cognitive Radios, Wireless Sensors |
| **Cost** | High (due to active components and complexity) | Moderate (low power, simple designs) | High (due to fabrication complexity) | Moderate (higher for reconfigurable systems) |

The comparative analysis depicted in Table I has a distinct pattern: while active metamaterials offer superior dynamism and reconfigurability, they are laden with high manufacturing complexity and fabrication expenses. Such a compromise strongly restricts their realization in large-scale applications in cost-conscious consumer technologies. Conversely, metasurfaces come forward as an economic alternative for such applications due to their relatively lower expenses despite their limited dynamic tuning range.

Furthermore, Table II presents a fine-grained comparison of performance and appropriateness in relation to major operational measures and a thorough discussion of the advantages and disadvantages of various tuning strategies.

TABLE II. COMPARISON OF TUNING MECHANISMS IN ACTIVE METAMATERIALS

| Feature / Criterion | Circuit Tuning | Geometric Tuning | Material Tuning |
|---|---|---|---|
| **Speed of Response** | Fast (electronic switching) | Moderate to slow (mechanical motion) | Moderate (depends on material type) |
| **Power Consumption** | High (active biasing required) | Low (passive or mechanical input) | Moderate |
| **Fabrication Complexity** | High (needs active elements) | Medium (needs actuators) | High (requires functional materials) |
| **Stability & Repeatability** | Variable (thermal/electrical drift) | High (mechanical reliability) | Sensitive to environmental factors |
| **Scalability** | Moderate | Limited (harder at micro scale) | Poor to moderate |
| **Cost** | High | Medium | High |
| **Example Applications** | IRS, programmable antennas | Tunable lenses, MEMS surfaces | Cloaking, adaptive optics |
| **Notable Limitation** | Parasitic effects, thermal noise | Fatigue, slow reconfiguration | Hysteresis, environmental sensitivity |

## III. CONCLUSION

Programmable and tunable metamaterials represent a rapidly evolving branch of science with immense application potential across upcoming technologies. The current review has emphasized breakthrough developments in tunable mechanisms—ranging from geometric reconfiguration, material phase changes, to circuit-level control—that enable dynamic control over electromagnetic wave behavior. Such functionalities bring forth new vistas of adaptive communications, real-time imaging, precision sensing, and energy harvesting efficiency. In spite of the impressive progress, challenges remain regarding fabrication complexity, response time, integration with existing platforms, and scalability at large scales. Conquering these limits will necessitate multidisciplinary solutions that combine materials science, electrical engineering, and nanofabrication. Finally, tunable and programmable metamaterials have the potential to change the design environment for future adaptive systems by introducing novel physical features. The proposed future work includes the development of scalable fabrication methods, improvements in tuning speed and efficiency, integration with flexible and wearable platforms, and the application of artificial intelligence and machine learning techniques for the optimization of metamaterial design.

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