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Recent advances of stretchable soft antennas: material, structure and integration

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Stretchable soft antennas represent a transformative class of devices that seamlessly integrate wireless communication into deformable and dynamic platforms. Enabled by advances in functional materials and structural engineering, these antennas can withstand large mechanical deformations while maintaining stable electromagnetic performance – unlocking new possibilities in wearable electronics, soft robotics, and implantable biomedical systems. This review systematically surveys recent progress in conductive material choices – from traditional metals and liquid metal to nanocomposites and hybrid architectures – and examines how structural strategies such as serpentine layouts, kirigami patterns, and out-of-plane designs redistribute strain to preserve antenna performance under repeated deformation. We also discuss emerging fabrication techniques and applications in wireless health monitoring, soft robotic systems, and energy harvesting. Finally, we highlight key challenges, including improving environmental stability, achieving seamless multi-module integration, and unraveling the coupling mechanisms between mechanical deformation and electromagnetic behavior. This review offers a materials and structure driven framework for the rational design of stretchable soft antennas with robust wireless functionality.

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1. Introduction

Since the advent of metallic antennas in the late 19th century, antenna technology has undergone significant evolution. Early antennas were large, rigid structures primarily made from metals such as copper or aluminum, typically with simple linear or rod-like geometries designed for radio transmission.[1] While these early designs were effective within their context, their structural inflexibility posed limitations as the demand for more versatile, compact, and integrated communication systems grew.

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Over time, antenna technologies advanced with a focus on miniaturization, integration, and adaptation to diverse modern applications in mobile networks, satellite communication, and the internet of things (IoT).[2,3] Despite their continued dominance in wireless communication, traditional rigid antennas remain fundamentally constrained by their lack of mechanical compliance, which limits their utility in emerging fields where dynamic deformation is intrinsic to the application.[4]

The proliferation of fifth-generation (5G) networks,[5,6] the IoT,[7] wearable health monitoring systems,[8–12] and soft robotics[13–15] has further highlighted the need for antennas capable of maintaining stable performance under mechanical deformation. These emerging applications demand antennas that can seamlessly integrate with dynamic surfaces and curved geometries—contexts where conventional rigid antennas fail to provide adequate performance.[16–19]

In response to these challenges, stretchable soft antennas have emerged as a promising solution. These antennas are specifically engineered to maintain stable electromagnetic properties while withstanding mechanical strains such as stretching, bending, and twisting.[20–22] Their ability to conform to non-planar surfaces and endure repeated deformations without degradation opens new possibilities for applications in flexible electronics,[23–25] epidermal sensors,[26–28] and body-integrated wireless communication systems.[29–32]

The realization of these mechanically adaptive antennas hinges on advancements in both material science and structural engineering.[33,34] In particular, the selection of conductive materials and soft substrates is critical to ensuring both electrical efficiency and mechanical resilience.[35,36] Conductive materials must not only offer high electrical conductivity but also exhibit the requisite deformability and durability to sustain performance under dynamic stress. Recent innovations have explored a variety of materials, including thin metal films,[9,37] liquid metals,[38–40] silver nanowires,[16,41] graphene,[42] and MXenes,[43] which are often embedded within elastomeric substrates such as polydimethylsiloxane (PDMS) or Ecoflex.[44,45] These material combinations provide the necessary mechanical robustness while preserving radiative efficiency.

Equally essential to the success of stretchable soft antennas is the design of their structures.[46] The structural configuration governs how antennas deform while maintaining functional stability, and strategies such as serpentine,[47,48] fractal,[49] origami,[14] kirigami,[50] and three-dimensional architecture[51,52] allow for the accommodation of large mechanical strains without compromising electromagnetic performance. In parallel, scalable fabrication techniques such as printing, 3D printing, laser patterning, and soft lithography enable the precise and reproducible production of these complex geometries.[25,29,44,53]

This review aims to provide a comprehensive examination of the recent advancements in stretchable soft antennas technology. We begin by discussing material strategies for the conductive and substrate layers, followed by an exploration of structural design principles and their corresponding fabrication approaches. Finally, we explore the integration of multifunctional capabilities, including sensing, actuation, and energy harvesting, highlighting the role of stretchable soft antennas as foundational components in next-generation adaptive electronic systems.

2. Material selection

A typical stretchable soft antenna consists of two principal components: a conductive material that forms the radiating element and a substrate material that provides mechanical

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support while allowing for deformation. The conductive material ensures reliable signal transmission, while the substrate must impart the necessary mechanical flexibility and durability to withstand dynamic strains. The overall performance of stretchable soft antennas is highly contingent upon the properties of both these layers. In this section, we examine the materials used for the conductive and substrate layers, offering a comparative analysis to highlight their respective strengths and trade-offs.

2.1 Conductive materials

The conductive material in stretchable soft antennas plays a critical role in determining signal transmission efficiency and overall device performance. It forms the radiating element that generates and receives electromagnetic waves; thus, its electrical conductivity directly impacts antenna gain, radiation efficiency, and bandwidth. To maintain signal fidelity in dynamic and deformable environments, the material must not only possess high conductivity but also exhibit mechanical compliance—tolerating bending, stretching, and twisting without degradation of electrical properties (Table 1).

Traditional bulk metals such as gold, silver, and copper are commonly employed in high-performance applications due to their superior electrical properties. Gold, for instance, has an electrical conductivity of approximately 4.1×10^7 S m^{-1}, silver 6.2×10^7 S m^{-1}, and copper 5.8×10^7 S m^{-1}.[54] These metals are typically patterned into thin-film antenna structures using conventional microfabrication techniques such as photolithography, electron-beam evaporation, sputtering, or thermal evaporation, followed by lift-off or etching processes. While those methods allow precise control over film thickness and geometry, these techniques require costly facilities and are not easily scalable. Moreover, metal films on soft substrates often suffer from poor adhesion and mechanical failure under strain. Continuous flat metal films can only tolerate $<2\%$ strain before cracking or losing conductivity.[55,56] To address this constraint, advanced design strategies, such as serpentine or fractal geometries, are often incorporated to preserve flexibility while maintaining electrical conductivity. These approaches are discussed in detail in the structural design and fabrication section. Alternatively, metallic nanowires (NWs), particularly silver nanowires (AgNWs), are used to fabricate deformable antennas *via* spray-coating or vacuum filtration to create a percolated network.[57] Notably, wavy networks of silver nanowires have been employed to fabricate optically transparent radio-frequency antennas with reversible stretchability of up to 40%, demonstrating the potential of NW-based systems in deformable antennas.[58,59]

Liquid metals, such as eutectic gallium–indium (EGaIn), offer significant advantages in terms of stretchability and electrical conductivity. EGaIn, for example, exhibits a conductivity of approximately 3.46×10^6 S m^{-1} and its ability to undergo large deformations (up to 300%) without compromising electrical performance makes it an ideal candidate for applications involving continuous deformation.[17,60] Liquid metal antennas are typically fabricated by injecting EGaIn into microchannels patterned in elastomeric substrates such as PDMS or silicone.[17,18] Such designs enable reconfigurable or stretch-tunable antennas. However, challenges such as oxidation and integration with PCBs require encapsulation strategies and surface treatment to maintain long-term reliability.

Conductive polymers, including poly(3,4ethylenedioxythiophene) polystyrene sulfonate (PEDOT:PSS) and polyaniline, provide a lightweight and flexible alternative to metals. These materials can be processed into thin films and exhibit electrical conductivities ranging from 5 to 1500 S m^{-1},[61] which is generally lower than that of metals. These materials are often deposited by printing, spin-coating, or drop-casting onto soft substrates to form the antenna pattern. Although their electrical performance is lower than that of metals, conductive polymers provide superior conformability and can endure repeated deformations, making them ideal for applications where flexibility is prioritized.[62]

Low-dimensional materials, such as graphene, carbon nanotubes (CNT), metallic niobium diselenide ($NbSe_2$), and MXenes, represent a promising class of conductive materials due to their outstanding electrical properties and mechanical resilience;[43,63,64] graphene, with a conductivity of approximately 4.3×10^3 S cm^{-1},[65] and MXenes, exhibiting electrical conductivity values as high as 1.5×10^4 S cm^{-1},[66] with excellent flexibility and stretchability. These materials can be directly patterned onto substrates *via* spray coating or 3D printing, or alternatively fabricated as freestanding films through vacuum filtration followed by transfer onto soft substrates. This versatility in processing, combined with their high intrinsic conductivity and stretchability, enable them to retain high performance even under continuous mechanical deformation, making them indispensable in the design of future soft and wearable communication systems.[43,66,67]

The selection of conductive materials plays a pivotal role in determining not only the electromagnetic performance of stretchable antennas but also their mechanical robustness, biocompatibility, and integration compatibility. While the previous sections have outlined individual material categories and their typical properties, a comparative overview is essential to clarify the trade-offs involved in practical implementation. To this end, we present a performance-based analysis of five representative material classes—liquid metals, metallic nanomaterials, conductive polymers, conductive inks, and two-dimensional (2D) materials—benchmarked against five critical metrics: electrical conductivity, stretchability, processability, durability, and biocompatibility (Fig. 1).

Liquid metals exhibit exceptional deformability and maintain stable conductivity under large strains; however, their high surface tension and limited biocompatibility necessitate careful encapsulation strategies. Metallic nanomaterials, such as silver nanowires, combine high conductivity with scalable printing compatibility, yet are prone to fracture or delamination under cyclic loading. Conductive polymers offer inherent softness and biocompatibility but are often constrained by moderate conductivity and environmental instability. Conductive inks are well suited for low-cost, large-area fabrication–particularly on textile substrates–though they generally suffer from limited stretchability and mechanical endurance.

Table 1 Conductive materials used in stretchable soft antennas

Material type	Conductive material	Electrical properties	Strain (%)	Cycle number	Ref.
Liquid metal	EGaIn	3.4×10^6 S m^{-1}	86	NA	10
		2.8×10^6 S m^{-1}	48	NA	68
		0.0456 Ω sq^{-1}	10	NA	69
		3.46×10^6 S m^{-1}	200	1000	70
		8.1×10^5 S m^{-1}	300	100	71
		3.46×10^6 S m^{-1}	50	NA	13
		2.3×10^6 S m^{-1}	60	NA	72
		3.46×10^6 S m^{-1}	20	NA	73
		3.46×10^6 S m^{-1}	72	NA	74
		29.4×10^{-6} Ω cm	50	NA	75
		29.4×10^{-6} Ω cm	120	100	17
	EGaIn & copper	3.46×10^7 S m^{-1}	NA	NA	76
	GaInSn	3.46×10^6 S m^{-1}	30	NA	77
		3.46×10^6 S m^{-1}	300	NA	60
		3.46×10^6 S m^{-1}	40	NA	78
Metal	Copper	5.8×10^7 S m^{-1}	100	5000	50
		5.8×10^7 S m^{-1}	70	100	79
		5.8×10^7 S m^{-1}	30	NA	80
		5.96×10^7 S m^{-1}	40	NA	81
		5.8×10^7 S m^{-1}	30	NA	82
	CuNWs	6319 μΩ cm	30	500	83
	CuO NPs	3.7×10^4 S cm^{-1}	20	1000	84
	Au/Ni	1×10^7 S m^{-1}	20	NA	85
	AgNFs	5×10^7 S m^{-1}	100	3000	41
	AgAu	8.5×10^5 S m^{-1}	35	NA	86
	Ag flakes	1.837×10^6 S m^{-1}	50	NA	87
	Ag NW	3.8 Ω sq^{-1}	40	300	58
	Silver particle	7.5×10^{-5} Ω cm	30	NA	88
	Pt	70–6400 Ω cm	50	500	14
	Metallic microcoils	7.8 mΩ cm	50	NA	89
	Silver-plated knitted textile	1.14×10^3 S m^{-1}	100	100	90
	Multifilament silver plated thread	500 ± 100 Ω m	80	100	91
Elastic conductive composites	Ag-PDMS	6.58×10^6 S m^{-1}	20	NA	6
		1.19×10^5 S m^{-1}	80	NA	92
		1000 S cm^{-1}	15	NA	93
	Ag/PU-PEI	4000 S cm^{-1}	50	NA	94
	Smart polymer nanocomposite	1.59–6.58×10^6 S m^{-1}	10	400	5
	OSCs	80–90 Ω m	70	50	95
	Steel wool-based elastic conductive composites	170 S m^{-1}	80	150	96
	ECC	5×10^{-4} Ω cm	100	800	97
		10^{-4} Ω cm	40	NA	98
	ECA	1.6×10^{-4} Ω cm	20	NA	99
	SWCNTs/PANI	1.35 Ω sq^{-1}	20	700	63
Ink	AgNWs-PBS85	0.002 Ω cm	35	NA	100
	Silver conductive ink	18 Ω sq^{-1}	35	NA	101
	Silver ink polysiloxane composite	10–70 S cm^{-1}	20	NA	20
	Silver–polymer composite ink	0.4×10^6 S m^{-1}	20	NA	102
	Silver ink	849 S cm^{-1}	110	NA	103
		8.49×10^4 S m^{-1}	100	1000	104
	PE 873	214.53 mΩ sq^{-1}	25	NA	105
	Shieldex Kiel +30-based LHP	1.08895×10^5 S m^{-1}	25	NA	106
Nanomaterials	CNT-Ag	1×10^5 S m^{-1}	10	1000	7
	Ag/laser-induced graphene	1.2 ± 0.06 Ω sq^{-1}	15	NA	107
	Graphene	1300–170 Ω sq^{-1}	30	NA	108
	MXene-SWNT	2.9×10^5 S m^{-1}	150	500	43
	GNF-RGO	4.47×10^4 S m^{-1}	40	NA	42

Note: the table above contains three key parameters for the electrical properties of a material: electrical conductivity (S m^{-1}); electrical resistivity (Ω cm); sheet resistance (Ω sq^{-1}).

Among these, 2D materials–especially MXenes–offer a well-balanced combination of high conductivity, mechanical flexibility, and processability. Although MXenes are inherently susceptible to oxidation, recent advances in surface passivation and encapsulation have substantially improved their ambient stability, enabling their integration into stretchable electronic platforms. This balance positions them as promising candidates for applications requiring both reliable electrical performance and mechanical adaptability. Ultimately, achieving high-performance stretchable antenna systems requires careful optimization of these material trade-offs to meet the functional demands of specific applications.

2.2 Substrate materials

Substrate materials serve as the mechanical backbone of stretchable soft antennas, ensuring structural integrity while accommodating repeated deformation. Beyond mechanical

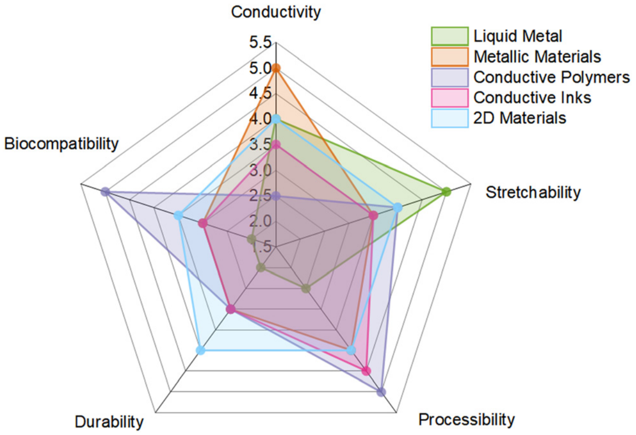

Fig. 1 Performance benchmarking of stretchable conductive materials. Radar chart comparing five representative classes of conductive materials—metallic materials, conductive inks, conductive polymers, liquid metals, and two-dimensional (2D) materials—across five key performance metrics: conductivity, stretchability, processability, durability, and biocompatibility. Each axis is scored from 1 to 5, with higher values indicating relatively better performance within this evaluation framework. The chart provides a comparative visual guide for material selection in stretchable and wearable electronic systems. Note: to quantitatively evaluate the multifunctional performance of these material categories, we established a five-dimensional scoring system covering conductivity, stretchability, processibility, durability, and biocompatibility. Each metric was assigned a score from 1 (low) to 5 (high) based on reported trends and representative performances in the literature. Metallic materials received the highest score in conductivity (score = 5), due to their excellent and stable electrical performance under standard operating conditions. Liquid metals achieved the highest score in stretchability (score = 5), reflecting their intrinsic molecular flexibility and ability to maintain conductivity under large strain. Conductive polymers scored highest in processibility (score = 5), due to their compatibility with scalable fabrication techniques such as screen and inkjet printing. In terms of durability, defined as electrical stability under cyclic strain, 2D materials performed relatively well (score = 4), although advances in composites and encapsulation strategies are gradually closing the gap for other materials. Biocompatibility was rated highest for conductive polymers (score = 5), particularly those specifically engineered for skin-contact applications. This scoring framework is intended as a general reference for material screening, though actual performance may vary depending on material formulation, processing methods, and application contexts.

support, substrates play a pivotal role in determining the electrical performance of antennas through their dielectric properties – most notably, the dielectric constant (ε), which governs impedance matching, bandwidth, and radiation efficiency. A higher ε enhances electric field confinement and unit capacitance, typically lowering the resonant frequency and narrowing the bandwidth, which may cause impedance mismatches. Conversely, a lower ε generally improves radiation efficiency and broadens the operational bandwidth. Consequently, substrates with moderate dielectric constants (approximately 2.5–4.0) are commonly preferred to achieve a balanced trade-off between antenna miniaturization and communication performance. In this section, we review commonly employed stretchable substrates, highlighting both their mechanical characteristics and dielectric behavior (Table 2).

Elastic fabrics are widely employed in wearable antennas due to their light weight, breathability, and ability to conform to non-planar surfaces, such as the human body.[109] These textile substrates generally exhibit low dielectric constants in the range of 1.2–1.7,[110–112] which minimizes electromagnetic energy absorption and promotes efficient radiation. Despite their advantageous mechanical properties, the hygroscopic nature of textiles poses a significant challenge: moisture uptake alters both their mechanical stiffness and dielectric properties.[113] In addition, surface roughness and porosity can affect the uniformity and adhesion of conductive materials, influencing the antenna's impedance and stability.[109] These factors must be carefully considered during the design and characterization of wearable antenna systems to ensure robust and reliable operation under real-world conditions.

Silicone elastomers such as polydimethylsiloxane (PDMS) and Ecoflex offer exceptional stretchability, up to 200% for PDMS and 1000% for Ecoflex, biocompatibility, and low modulus, making them ideal candidates for skin-integrated and biomedical applications.[114,115] With dielectric constants generally ranging from 2.6 to 3.4[116,117] these materials strike a practical balance between electrical insulation and impedance tunability.

Polyimide (PI), particularly in the form of commercially available films such as Kapton, offers a compelling combination of mechanical durability, thermal stability, and favorable dielectric properties. PI substrates typically exhibit a dielectric constant of approximately 2.5–3.5, enabling stable electrical performance across a wide frequency range.[118] PI films can achieve high stretchability (up to 100%) through structural design innovations, such as the incorporation of kirigami patterns or composite approaches.[50] These modifications enable PI-based substrates to retain their mechanical integrity and electrical performance under large deformations, making them suitable for advanced flexible electronic applications.

Thermoplastic polyurethane (TPU) represents another class of mechanically robust and easily processable substrates.[84,119,120] These materials typically exhibit higher dielectric constants, in the range of 2.4–4.2, which can aid in confining electromagnetic fields but may also introduce increased dielectric loss and impedance mismatch. Notably, their high fatigue resistance under repeated loading makes them well-suited for long-term operation in dynamic environments.[121]

To enable stable and efficient antenna performance under deformation, substrate materials must exhibit a balanced combination of moderate ε and low dielectric loss ($\tan\delta$), ensuring both electrical functionality and mechanical compliance. The $\tan\delta$ quantifies energy dissipation within the substrate, with higher values leading to signal attenuation, heat generation, and potential reliability concerns. To facilitate material selection, we provide a comparative overview of representative substrates based on their dielectric parameters (Fig. 2). Textile-based materials (*e.g.*, PET fabrics) offer ultralow ε (1.2–1.7) and minimal loss, supporting broadband wearable systems, though their hygroscopicity and surface roughness can compromise integration. Silicone elastomers (*e.g.*, PDMS, Ecoflex) combine moderate ε (2.6–3.4), low $\tan\delta$ (<0.04), and high stretchability, rendering them well-suited for skin-conformal and biomedical applications. Slightly stiffer substrates like polyimide (PI) maintain excellent thermal stability and dielectric uniformity,

Table 2 Soft substrates and their properties for stretchable soft antennas

Substrate	Dielectric constant	Dielectric loss	Thickness	Strain (%)	Cycle number	Ref.
Ecoflex	3.05	0.017	1.5 mm	10	NA	122
	3.125	0.01	1.5 mm	25	500	19
	2.2	NA	1.57 mm	15	NA	107
	3.03	0.01	1. 7 mm	15	200	123
	2.5	0.01	1.45 mm	72	NA	74
	2.1	NA	NA	50	NA	75
	2.8	0.02	2 mm	100	100	90
	1.8	NA	1.6 mm	300	100	71
	3.125	0.01	1.5 mm	15	200	46
	2.5–3.0	NA	150 μm	50	NA	13
VHB	3.2	0.03	1 mm	100	1000	103 and 104
PDMS	2.7	NA	1.25 mm	20	NA	85
	2.74	0.057	2 mm	20	NA	6
	2.7	0.01	2 mm	25	NA	106
	3	NA	4.5 mm	40	NA	124
	2.67–3.00	0.01–0.05	1.1 mm	NA	NA	76
	2.67	NA	90 μm	50	500	14
	2.67	NA	0.2 mm	35	NA	125
	2.63	0.076	2 mm	35	NA	101
	3	NA	3 mm	20	NA	20
	2.8	NA	1.1 mm	20	NA	73
	3	0.014	1.35 mm	30	NA	80
	2.8	0.02	100 μm	40	NA	81
	2.5–3.0	0.01–0.05	NA	40	300	58
	2.8	0.02	1 mm	15	NA	126
	4.5	0.02	NA	20	NA	127
	2.8	NA	1.5 mm	100	5000	50
PI	2.55	NA	12 μm	70	100	79
	2.55	NA	NA	30	NA	82
Fabric	1.4	NA	300 μm	30	2000	128
TPU	2.48	0.0783	0.19 mm	20	NA	129
	4.12	NA	3.1 mm	30	NA	88
	2.85	0.09	NA	15	300	119
DEE (dielectro-elastic elastomer)	5	0.0074	700 μm	30	1000	130
PAAm (hydrogel)	79	NA	7 mm	48	NA	68
Silicone elastomer	2.8	0.02	0.5 mm	30	NA	108
Dragon skin	1.8	NA	0.4 mm	30	NA	131
Solaris	2.5–3.3	0.2–0.5	0.2–2 mm	32	NA	132
EVA copolymer	2.8–3.2	0.002	0.2 mm	25	NA	133
Textile&PE773	1.7	0.012	0.5 mm	25	NA	105
SEBS	2.3	0.07	2 mm	40	NA	134
Rubber/PVA	3.6	0.06	NA	40	NA	42
TC5005	2.8–3.1	NA	5 mm	300	NA	60

favoring high-frequency circuit embedding. For applications requiring repeated actuation or large strain—such as soft robotics—thermoplastic elastomers (TPU, SEBS, rubber/PVA) offer high fatigue resistance, moderate-to-high ε (2.4–4.2), and acceptable loss ($\sim$0.04–0.08). Highly stretchable adhesives such as VHB and Solaris also deliver functional ε with extreme deformability, enabling use in dielectric elastomer actuators (DEAs) and reconfigurable systems. While hydrogels like PAAm exhibit an ultrahigh ε ($\sim$79), their substantial dielectric loss ($\sim$0.3) restricts their suitability in low-loss or high-frequency communication settings. Collectively, these considerations underscore that rational substrate selection—balancing dielectric behavior, mechanical resilience, and environmental stability—is pivotal for the design of next-generation stretchable antenna systems.

3. Structural design and fabrication

For materials that inherently lack stretchability and are prone to cracking or delamination under mechanical deformation, structural design offers a compelling strategy to overcome these limitations. By geometrically reconfiguring intrinsically rigid conductors, such as bulk metals or certain nanomaterials, it becomes possible to impart macroscale stretchability without compromising electrical functionality. Structural strategies are typically classified into two principal categories: 2D structural engineering, which operates within the plane of the material, and 3D structural engineering, which introduces out-of-plane topologies to accommodate more complex deformation modes. Each category is coupled with specific fabrication techniques designed to preserve or enhance the mechanical–electrical coupling essential for stretchable soft antenna applications.

3.1 2D structural engineering

2D structural engineering focuses on in-plane geometric modifications to enhance the deformability of materials without affecting their electrical properties. These strategies are particularly effective for materials that lack intrinsic stretchability.

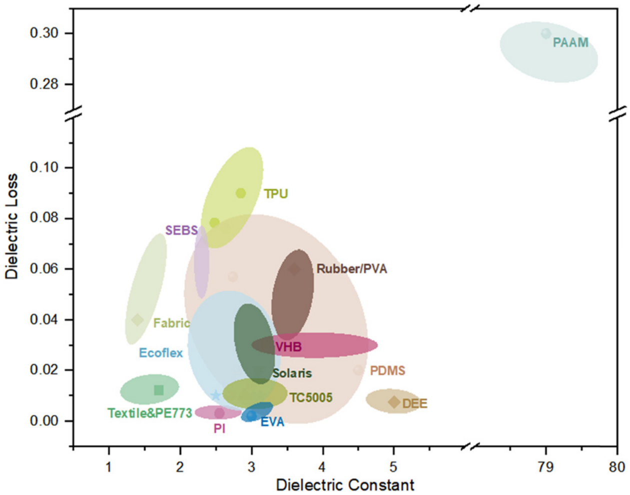

Fig. 2 Dielectric properties of stretchable substrate materials. Comparative mapping of representative stretchable substrates based on their dielectric constant (ε) and dielectric loss ($\tan\delta$). Elastomeric materials such as PDMS, TPU, Ecoflex, and VHB exhibit moderate dielectric constants ($\varepsilon \approx 2$–4) coupled with low dielectric loss, making them well-suited for stretchable, low-loss electronic applications. In contrast, hydrogels like PAAM show significantly higher dielectric constants ($\varepsilon \sim 80$) alongside markedly increased dielectric loss ($\sim$0.30), which may restrict their use in radio-frequency systems where low energy dissipation is critical. Ellipses delineate the approximate performance regions characteristic of each material class. (Data adapted from Table 2.)

Serpentine configurations, characterized by curved geometries such as meandered or zigzag paths, have proven effective in enhancing stretchability by distributing mechanical strain along non-linear trajectories. This design strategy is widely adopted for metallic films, which inherently lack stretchability, enabling their integration into soft and deformable systems without compromising electrical continuity. High-resolution fabrication methods such as laser cutting and photolithography are employed to pattern these structures with precision, ensuring mechanical compliance while preserving antenna functionality. For instance, a radio-frequency dipole antenna fabricated from a 30 μm-thick copper foil, patterned into unit cells comprising three serpentine cycles *via* laser milling, demonstrated a resonant frequency shift from 1.24 GHz at 0% strain to 1.08 GHz under 45% uniaxial elongation (Fig. 3a and b).[135] Similarly, a multilayered stack antenna incorporating laser-patterned serpentine aluminum films achieved reversible stretching up to 30% strain while operating at 13.56 MHz, maintaining stable performance over 3000 cycles at 5% strain and 1000 cycles at 10% strain (Fig. 3c and d).[136] Furthermore, a silver-plated knitted textile embedded in an Ecoflex matrix and patterned with serpentine rectangular meshes exhibited linear downshifts in resonant frequency from 3.45 GHz to 2.75 GHz as the antenna was stretched from 0% to 100%, demonstrating excellent compliance and consistent electromagnetic response under large strain deformation (Fig. 3e and f).[90]

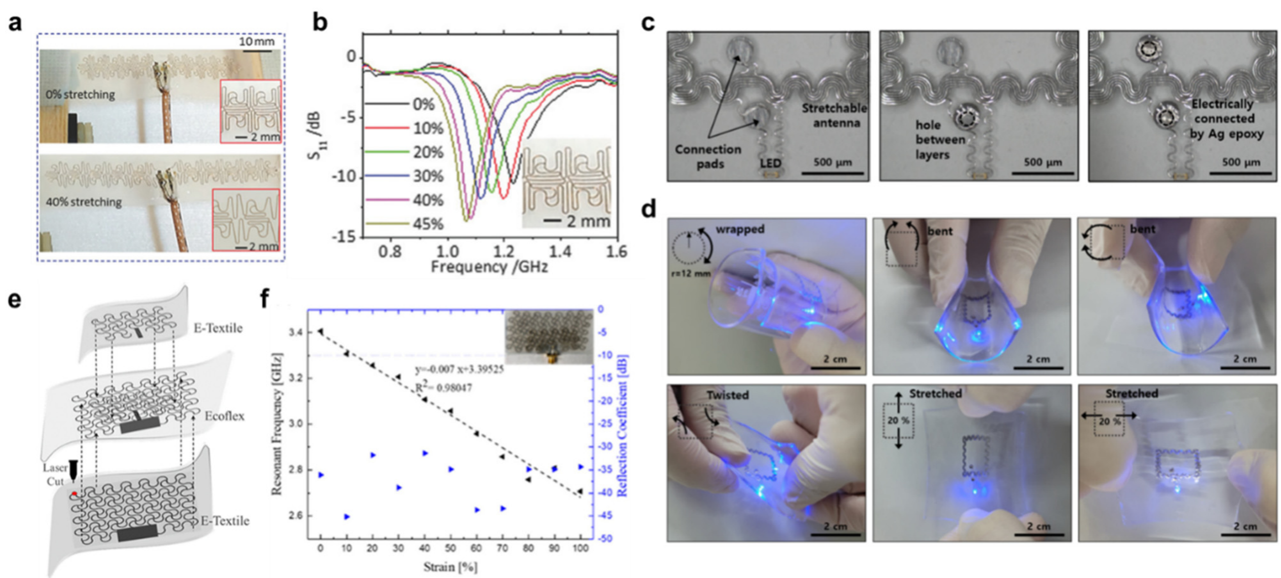

Fig. 3 (a) Optical images of antennas integrated onto elastomer substrates under various applied tensile strains. SMA connectors are soldered at the antenna feed points for radiofrequency (RF) characterization. Reproduced from ref. 135 with permission from Wiley-VCH GmbH, copyright 2016. (b) Measured S_{11} return loss spectra of antennas comprising unit cells with three serpentine cycles, recorded under increasing levels of tensile strain.[135] Reproduced from ref. 135 with permission from Wiley-VCH GmbH, copyright 2016. (c) Microscopy images illustrating the multilayer antenna fabrication process, including *via* formation using a micro-punching tool for vertical interconnections. Reproduced from ref. 136 with permission from MDPI, copyright 2022. (d) Demonstration of mechanical compliance, showing the stretchable and bendable performance of optoelectronic devices integrated with the multilayered antenna.[136] Reproduced from ref. 136 with permission from MDPI, copyright 2022. (e) Schematic illustration of the textile-based microstrip antenna design, with both the patch and ground plane engineered using meshed rectangular serpentine units. Reproduced from ref. 90 with permission from American Chemical Society, copyright 2021. (f) Evolution of resonant frequency and S_{11} parameters as a function of uniaxial strain up to 100%, demonstrating the antenna's strain-dependent tunability.[90] Reproduced from ref. 90 with permission from American Chemical Society, copyright 2021.

Additionally, horseshoe and spiral geometries provide further compliance, leveraging rotational freedom and arc curvature to accommodate stretching. Spiral-shaped copper antennas were reported to tolerate up to 15% uniaxial strain, with stretch-induced frequency shifts depending on the arc angle and periodicity of the horseshoe elements (Fig. 4a–f).[19,123] These shapes allow more uniform deformation and can be systematically optimized through parametric coupling of mechanics and electromagnetics.

Collectively, these 2D geometric strategies—serpentine, mesh, horseshoe, and spiral—serve as effective tools for enabling stretchability in otherwise brittle conductors. When combined with scalable and precise fabrication techniques such as laser cutting, photolithography, and 3D printing, they form a versatile platform for designing stretchable soft antennas with reliable mechanical and radiofrequency performance under large strains.

Beyond geometric engineering, emerging low-dimensional materials with intrinsically high electrical conductivity have demonstrated remarkable potential for enhancing stretchability through the formation of crumpled or wrinkled structures (Fig. 4g–i).[43,137–139] Such stretchable conductors represent promising candidates for next-generation deformable antenna systems. For instance, an ultrastretchable conductor was fabricated by depositing a crumple-textured composite coating of two-dimensional $Ti_3C_2T_X$ MXene nanosheets and single-walled carbon nanotubes (SWNTs) onto a latex substrate. This hybrid structure was employed to construct a high-performance dipole

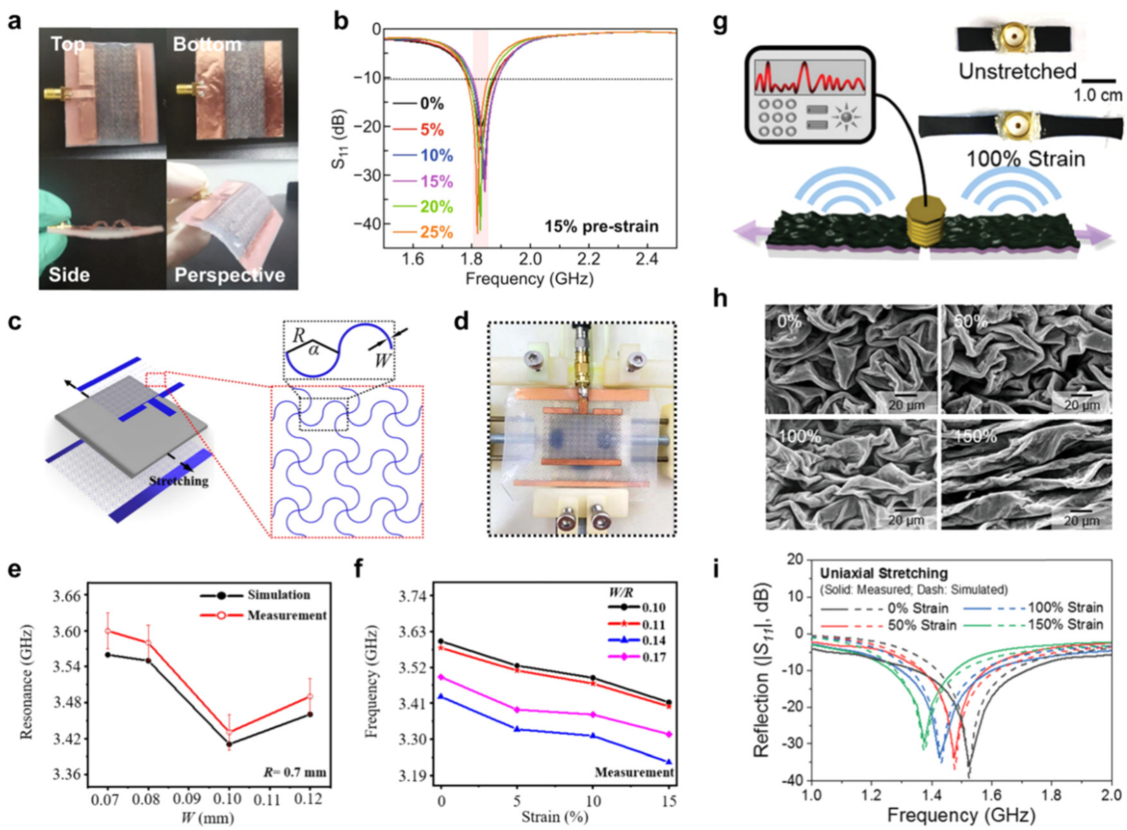

Fig. 4 (a) Optical images of a hierarchically structured microstrip antenna featuring a double-arched patch geometry, fabricated by applying a pre-strain of 15%. Reproduced from ref. 19 with permission from Nature Publishing Group, copyright 2021. (b) Mechanical and electromagnetic performance of the antenna shown in an under applied tensile strain, demonstrating its strain-insensitive characteristics.[19] Reproduced from ref. 19 with permission from Nature Publishing Group, copyright 2021. (c) Definition of geometric parameters used in the serpentine mesh structure, enabling controlled mechanical compliance and tunable electromagnetic behavior. Reproduced from ref. 123 with permission from Elsevier Ltd, copyright 2021. (d) Optical images of the fabricated stretchable microstrip antenna under relaxed and stretched states. Reproduced from ref. 123 with permission from Elsevier Ltd, copyright 2021. (e) Comparison between simulated (black) and measured (red) resonance frequencies for antennas with varying patch widths, highlighting the impact of geometry on resonant behavior. Reproduced from ref. 123 with permission from Elsevier Ltd, copyright 2021. (f) Experimentally measured resonance frequencies for antennas with different meshed architectures subjected to tensile strain ranging from 0% to 15%, illustrating structure-dependent frequency stability.[123] Reproduced from ref. 123 with permission from Elsevier Ltd, copyright 2021. (g) Schematic and digital images of a stretchable dipole antenna based on a hybrid single-walled carbon nanotube (SWCNT)–MXene conductive film, shown under various strain levels. Reproduced from ref. 43 with permission from Wiley-VCH GmbH, copyright 2019. (h) Scanning electron microscopy (SEM) images of the SWCNT–MXene coating on the antenna wing subjected to different degrees of uniaxial strain, revealing the evolution of the microstructure during deformation. Reproduced from ref. 43 with permission from Wiley-VCH GmbH, copyright 2019. (i) Simulated and measured $|S_{11}|$ parameters and corresponding resonant frequencies of the SWCNT–MXene antenna under different strains, demonstrating robust RF performance under mechanical loading.[43] Reproduced from ref. 43 with permission from Wiley-VCH GmbH, copyright 2019.

antenna capable of enduring uniaxial strains up to 150% while maintaining reflected power below 0.1%. As the strain increased from 0% to 150%, the antenna's resonant frequency exhibited a linear shift from 1.575 to 1.375 GHz. Remarkably, during fatigue testing, the SWNT-MXene antenna maintained excellent stability, with nearly unchanged reflection coefficients ($|S_{11}| \approx -33$ dB at 1.425 GHz) over 500 cycles under 100% uniaxial strain.[43] Such stretchable conductors, combining scalable fabrication, mechanical compliance, and stable performance, have considerable promise for scalable deployment in next-generation stretchable soft antenna systems.

3.2 3D structural engineering

While two-dimensional (2D) structural strategies enhance in-plane stretchability, accommodating complex deformation modes—particularly those involving out-of-plane displacement—necessitates the implementation of three-dimensional (3D) structural configurations. These 3D architectures significantly improve mechanical resilience and enable dynamic, reversible shape reconfiguration under various mechanical stimuli.

For instance, a 3D antenna featuring a spiral hemispherical geometry demonstrated reversible stretchability up to 30%, with less than 1% shift in resonant frequency after 100 cycles

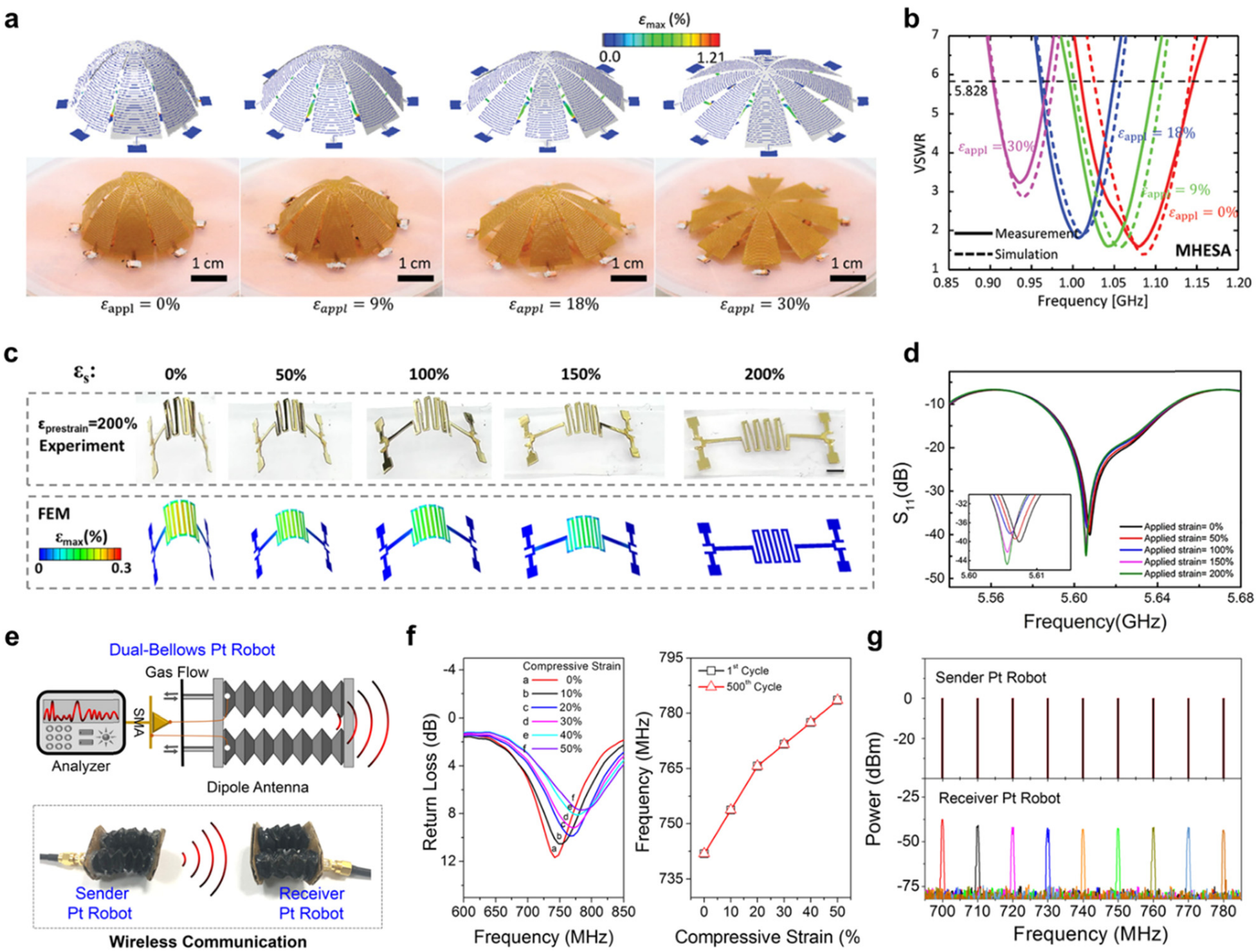

Fig. 5 (a) Optical images (bottom) and finite element analysis (FEA) results (top) of the meanderline-based hemispherical electrically small antenna (MHESA) under equal-biaxial tensile strains of 0%, 9%, 18%, and 30%. Reproduced from ref. 82 with permission from Wiley-VCH GmbH, copyright 2018. (b) Voltage standing wave ratio (VSWR) characteristics of the MHESA under different levels of applied strain. The VSWR reflects the impedance matching with the transmission line; values approaching 1 indicate near-ideal matching.[82] Reproduced from ref. 82 with permission from Wiley-VCH GmbH, copyright 2018. (c) Optical images (top) and FEA results (bottom) of the 3D Au/PI serpentine-like antenna under various tensile strains (scale bar, 1 mm). Reproduced from ref. 140 with permission from Nature Publishing Group, copyright 2017. (d) S_{11} parameters of the 3D serpentine-like antenna under different applied substrate strains.[140] Reproduced from ref. 140 with permission from Nature Publishing Group, copyright 2017. (e) Schematic illustration of a dual-bellows Pt robot functioning as a reconfigurable dipole antenna, and photographs of the sending (left) and receiving (right) Pt robots. Reproduced from ref. 14 with permission from The American Association for the Advancement of Science, copyright 2019. (f) Left: Return loss of the reconfigurable dipole antenna under compressive strains ranging from 0% to 50%. Right: Resonant frequencies as a function of compressive strain before and after 500 cycles of robotic actuation. Reproduced from ref. 14 with permission from The American Association for the Advancement of Science, copyright 2019. (g) Pulse signals sent by the Pt sender robot were successfully received by the Pt receiver robot. The frequencies of the transmitted and received signals were identical.[14] Reproduced from ref. 14 with permission from The American Association for the Advancement of Science, copyright 2019.

of compression and release, attributed to its mechanically resilient design (Fig. 5a and b).[82] Similarly, antennas incorporating buckled serpentine geometries exhibited exceptional frequency stability, with resonant frequency deviations below 1% under tensile strains reaching 200% (Fig. 5c and d).[140] A dipole antenna utilizing a conductive Pt–elastomer origami structure showed a resonant frequency increase from 741.8 to 783.5 MHz as compressive strain increased from 0% to 50%. This strain-dependent frequency response remained consistent over 500 cycles of robotic actuation, enabling robust wireless tracking of the actuation status in dual-bellows Pt robots (Fig. 5e–g).[14] Furthermore, the integration of Kirigami-inspired designs into 3D assembled structures provides mechanical decoupling between radiating elements and the deformable substrate. This strain isolation mechanism effectively suppresses frequency variation under complex deformation modes—including bending, stretching, compression, and random dynamic perturbations—and supports stable operation under 100% strain for over 5000 mechanical cycles with negligible frequency drift.[50]

Despite the functional benefits of various structural strategies, each presents inherent trade-offs in practical engineering applications. To systematically visualize the performance trade-offs across different structures, Fig. 6a presents a radar chart comparing eight representative architectures along three key dimensions: strain tolerance, fabrication complexity, and mechanical robustness. The results reveal distinct performance distributions, reflecting inherent design compromises between deformability, manufacturability, and structural stability. Serpentine and spiral structures offer simple geometries and are compatible with scalable fabrication techniques, making them suitable for basic flexible devices. However, they may experience mechanical fatigue and resonant frequency drift under prolonged cyclic loading. Mesh architecture provides isotropic compliance and uniform stress distribution but often rely on high-resolution microfabrication, which increases process complexity. Kirigami and origami-inspired designs exhibit excellent compliance and reconfigurability under large deformation, yet are constrained by intricate patterning, limited reproducibility, and mechanical weakness at hinge regions. Buckled structures, typically formed through prestrain-release techniques, enable out-of-plane deformation and stress delocalization, offering high mechanical robustness under large strains. In contrast, wrinkled architectures, often realized in nanomaterial-based conductive films, deliver ultrahigh stretchability and low fabrication complexity, although their long-term stability under cyclic strain may be compromised by interfacial delamination or fatigue. This comparative visualization offers an intuitive and quantitative framework to support application-specific structural selection and multi-objective design optimization in flexible and wearable electronic systems.

3.3 Deformation–electromagnetic coupling and compensation strategies

Mechanical deformations—including stretching, bending, and compression—can alter an antenna's geometry, current distribution, and dielectric environment, leading to shifts in resonant frequency, radiation pattern, and polarization. This phenomenon, known as deformation–electromagnetic (EM) coupling, presents a critical challenge to maintaining stable EM performance in stretchable antenna systems under dynamic conditions. As evidenced in previous examples, such coupling is a recurring issue across various designs. (Fig. 6b) summarizes reported strain-induced frequency shifts (Δf) across diverse antenna types. Even moderate strains frequently cause resonant frequency variations exceeding 20%, highlighting the sensitivity of these systems to mechanical inputs and the need for strategies that decouple mechanical strain from electromagnetic response.

Geometric distortions often underlie these effects. For instance, transverse stretching of a circular patch antenna induces ellipticity due to the Poisson effect, altering its effective electrical length and thus its resonant frequency. Analytical models indicate that frequency increases as the minor axis

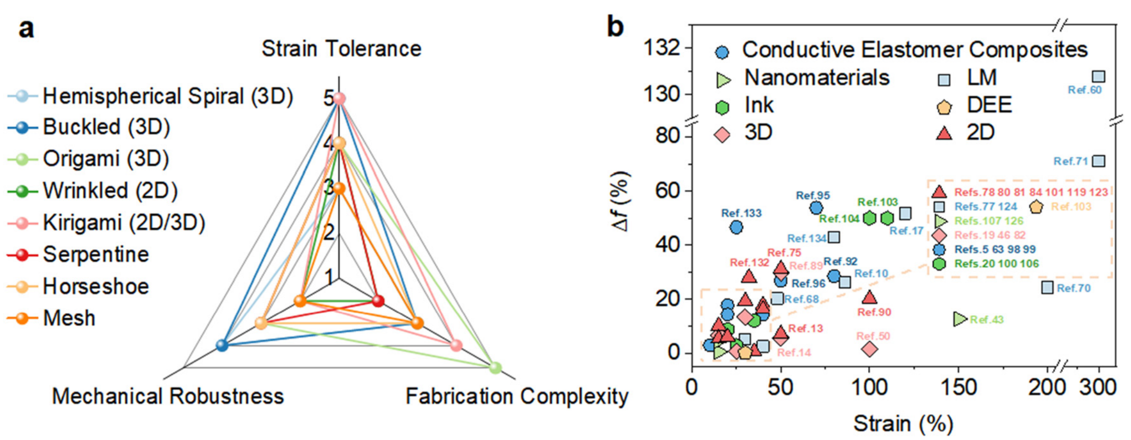

Fig. 6 Electromechanical trade-offs in structural designs for stretchable antennas. (a) Radar chart comparing representative structural designs---serpentine, horseshoe, mesh, kirigami, wrinkled, origami, buckled, and hemispherical spiral—based on three engineering metrics: strain tolerance, mechanical robustness, and fabrication complexity. (b) Summary of reported strain-induced frequency shifts (Δf) *versus* applied strain across various stretchable antenna types, categorized by material and structural strategies, including conductive elastomer composites, nanomaterials, liquid metals (LM), dielectric elastomer elastomers (DEE), and 2D/3D architectures.

contracts and decreases with elongation along the major axis. To mitigate such changes, structural design strategies aim to stabilize the current path and preserve electrical dimensions. Serpentine and arch-shaped layouts distribute local strain and minimize current path elongation. Slotting techniques, such as lateral slot insertion in circular patches, have been shown to redirect surface currents and suppress frequency drift. For example, Yang *et al.* achieved a strain-insensitive antenna ($<0.8\%$ frequency variation) under 58.8% elongation by introducing lateral slots to compensate for transverse deformation.[141]

Material-based compensation provides an additional control layer. Dielectrics with strain-dependent permittivity, such as nanoparticle-doped elastomers, dynamically adjust capacitance under mechanical loading. Kim *et al.* demonstrated that incorporating high-permittivity ceramic nanoparticles into elastomeric substrates suppressed frequency downshifts during stretching by reducing dielectric constant. Similarly, auxetic structures, which exhibit negative Poisson's ratios, expand laterally under tension, offsetting geometric changes and enhancing dimensional stability.[130]

Multiphysics simulation plays a central role in evaluating and optimizing such strain-resilient designs. Antennas are initially modeled using EM solvers (*e.g.*, CST, HFSS) to establish baseline performance. Mechanical deformation is then simulated using finite element platforms (*e.g.*, COMSOL) under defined strain conditions. Deformed geometries are subsequently re-imported into EM solvers to assess changes in scattering parameters, radiation patterns, and polarization. This iterative workflow, often informed by electrical length theory, enables optimization toward frequency-stable operation.[141] Final validation typically involves *in situ* measurements using vector network analyzers during mechanical actuation.

This integrated approach—linking geometry, materials, and simulation—forms the foundation for developing stretchable antennas with consistent EM performance under deformation. As wearable systems and soft robotics continue to evolve, coupling-aware design frameworks will be essential for enabling reliable, multifunctional wireless interfaces.

4. Functional integration

The advancement of stretchable soft antennas has transcended their traditional role in wireless communication, evolving into multifunctional platforms capable of environmental sensing, physiological monitoring, and energy harvesting. This integration is pivotal for the development of autonomous, compact systems in next-generation wearables and soft robotics.

For example, a textile-based stretchable microstrip antenna has been demonstrated with intrinsic strain sensing, allowing for simultaneous wireless communication and mechanical deformation monitoring. This integration offers a powerful solution for wearable devices that require real-time data transmission and monitoring of mechanical deformations.[90] Fractal-inspired designs, such as Hilbert patterns embedded in antenna patches and ground planes, offer up to $\sim$40% stretchability with a maximum gain of 2.95 dB at 2.5 GHz. Their resonant frequency shifts linearly with strain, allowing for wireless joint motion detection using RF receivers (Fig. 7a and b).[142] P. X. Si *et al.* developed a passive, flexible patch antenna system incorporating structurally decoupled modules to achieve simultaneous angle sensing and energy harvesting. Notably, this battery-free system maintains stable radio frequency signal output under dynamic bending and conformal skin contact, illustrating its strong potential for low-power, on-skin wireless interaction platforms.[143] Furthermore, near-field communication (NFC) coil antennas fabricated through a strain-free embroidery technique demonstrate high deformation resilience, maintaining stable inductance, resonant frequency under up to 50% elongation and 16 mm bending radius. These embroidered coils were integrated into a battery-free, energy-harvesting body sensor network. The complete system delivers stable power and wireless body temperature monitoring under mechanical deformation (Fig. 7c).[144]

These demonstrations underscore the growing potential of stretchable antennas as multifunctional nodes within wearable electronic systems. However, realizing system-level integration requires more than optimizing the antenna's intrinsic performance—it necessitates the seamless incorporation of sensing, power management, and communication modules onto a mechanically compliant platform. This level of functional integration is essential for enabling closed-loop, multimodal systems capable of real-time interaction.[41] Yet, it introduces significant technical challenges due to fundamental mismatches in material properties, electromagnetic characteristics, and mechanical deformation behavior among constituent components.

For example, although conductor materials such as silver nanofibers, MXene, and liquid metals offer excellent electromagnetic performance, they are susceptible to conductive pathway degradation under repeated stretching, leading to compromised interconnect reliability. Additionally, the elastic modulus mismatch between soft substrates (*e.g.*, PDMS, PU, Ecoflex) and rigid modules can generate interfacial stress concentrations, resulting in delamination or signal distortion. To address these issues, researchers have developed strategies such as modular layout partitioning, soft encapsulation, and mechanical stress-buffer layers to improve system-level mechanical conformity. A notable example is the MXene/SWNT composite system reported by Li *et al.*, which integrates antenna and EMI shielding functionalities while maintaining stable conductivity under strains up to 800%.[43] Engineered wrinkling and plasma surface treatment further enhance electromagnetic compatibility and mechanical robustness.

Beyond mechanical matching, electromagnetic bottlenecks—including electromagnetic interference (EMI) and near-field coupling—pose additional constraints in densely integrated platforms. These issues become particularly pronounced when multiple RF modules, such as NFC, Bluetooth, or power coils, are co-located, leading to parasitic interactions that distort the antenna's radiation pattern and impedance matching.[53] Current approaches to mitigate these effects include the use of low-

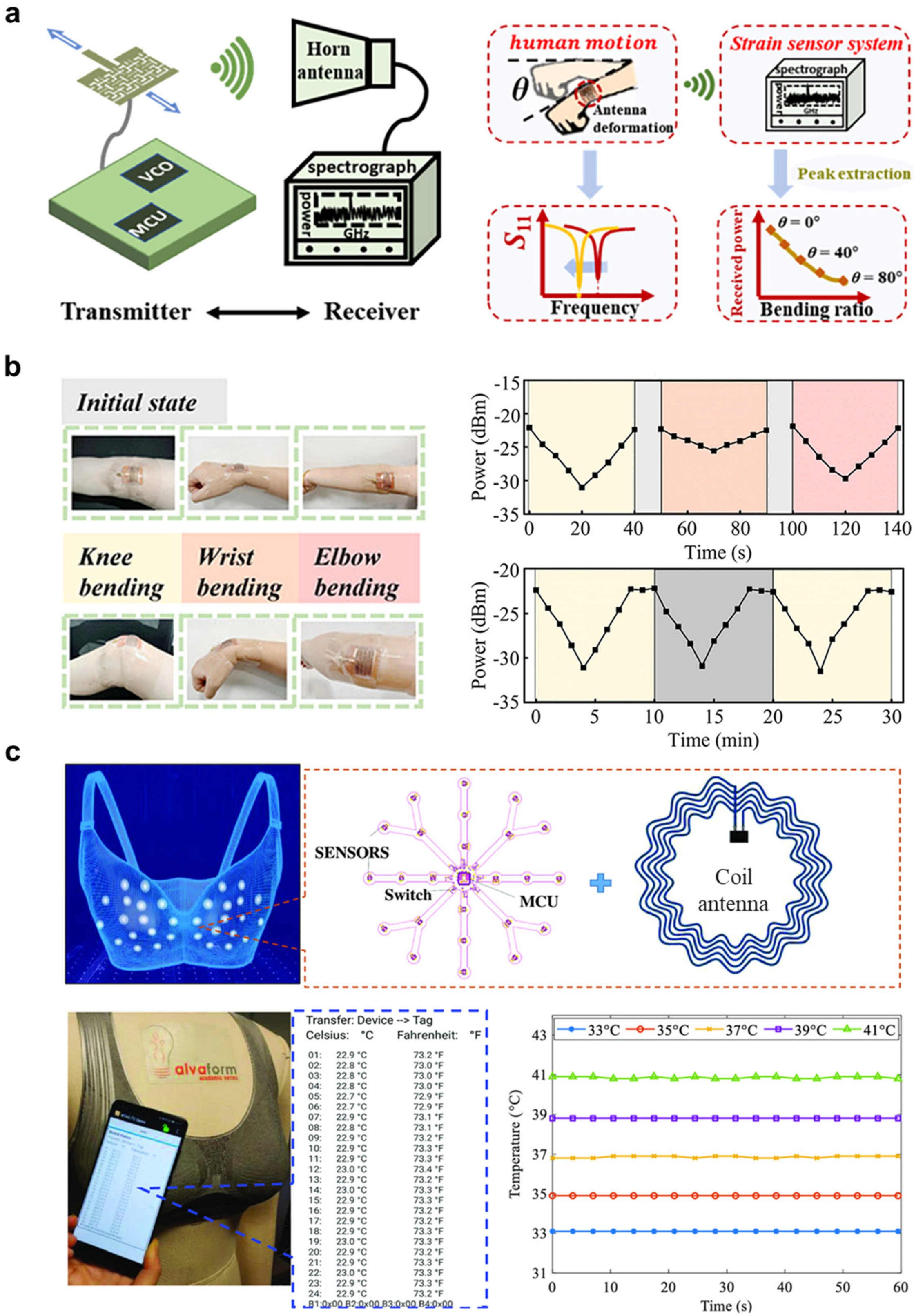

Fig. 7 (a) Schematic of the wireless strain sensing system and the working principle of the stretchable microstrip antenna for human joint monitoring. Reproduced from ref. 142 with permission from American Chemical Society, copyright 2023. (b) Monitoring of human joint states using the wireless strain sensing system. Photographs of three representative joints (knee, wrist, and elbow). Received power variations for each joint at four bending angles (20°, 40°, 60°, and 80°), recorded at 5 s intervals. Background colors correspond to the joints shown in the photographs. Received power variation for knee bending at different angles (20°, 40°, 60°, and 80°) recorded at 1 min intervals (bottom-right panel).[142] Reproduced from ref. 142 with permission from American Chemical Society, copyright 2023. (c) Exploded-view and schematic illustration of the temperature monitoring bra for NFC communication and temperature data acquisition *via* an android-based application (photograph shown). Fluctuation of the sensed temperature under controlled conditions at 33, 35, 37, 39, and 41 °C.[144] Reproduced from ref. 144 with permission from Wiley-VCH GmbH, copyright 2019.

permittivity isolation layers, frequency detuning techniques, and magnetic shielding structures. For instance, Zhu *et al.* developed a multifunctional soft system on Ecoflex incorporating a broadband antenna, rectifier, laser-induced graphene (LIG) sensor, and microcontroller. Their dual-resonant antenna structure mitigates frequency drift, while a slotted ground plane design reduces SAR and enhances radiation directivity.[107]

In wearable contexts, the proximity of antennas to the human body further complicates system design due to strong electromagnetic coupling with biological tissue. This can elevate the specific absorption rate (SAR) and degrade radiation efficiency. According to international standards (*e.g.*, IEEE C95.1, ICNIRP), SAR averaged over 1 gram of tissue must remain below 1.6 W kg^{-1} for safe operation.[145] Yet, the high permittivity of biological tissue can lead to enhanced near-field coupling, increased SAR, and frequency detuning.[146] To address this, structural shielding (*e.g.*, metal reflectors, slotted ground planes) and dielectric isolation using low-permittivity elastomers (*e.g.*, PDMS, Ecoflex) have been employed.[147] These strategies reduce electromagnetic leakage toward the body while stabilizing the antenna's operating frequency and radiation profile.[148] Among various design topologies, planar inverted-F antennas (PIFAs) are particularly favored in wearable systems due to their integrated ground plane, which ensures low SAR and stable front-to-back (F/B) ratios. Advanced implementations incorporating reflector and spacer layers have successfully reduced 1 g SAR to below 0.2 W kg^{-1} without sacrificing impedance matching.[132,145]

Together, these system-level strategies underscore the central role of soft antennas as not only electromagnetic radiators but also core integrative elements in multifunctional stretchable electronics. By addressing mechanical, electrical, and electromagnetic compatibility simultaneously, such designs pave the way for fully autonomous, skin-like platforms capable of real-time communication, adaptive sensing, and seamless operation under continuous deformation—laying the foundation for intelligent wearable interfaces and untethered soft robotic systems.

5. Discussion

Stretchable soft antennas have evolved from conceptual frameworks into functional systems capable of maintaining stable electromagnetic performance under significant mechanical deformation. This advancement is largely driven by innovations in both material selection and structural design. Deformable conductors—including liquid metals (*e.g.*, eutectic gallium–indium alloys), MXenes (*e.g.*, $Ti_3C_2T_X$), silver nanowires, and graphene-based materials—have demonstrated high conductivity while preserving mechanical compliance when embedded in elastomeric substrates such as PDMS, Ecoflex, or polyurethane. These composites enable repeatable stretching, bending, and twisting without compromising radiative efficiency. Structural design approaches, such as serpentine interconnects, fractal geometries, and out-of-plane architectures (*e.g.*, kirigami or 3D buckled layouts), decouple mechanical strain from electrical discontinuity by redistributing stress across engineered geometries. These strategies are essential for preserving impedance matching, gain, and resonance frequency during dynamic use, which are critical metrics in antenna engineering.

Beyond their primary role in wireless transmission, stretchable soft antennas are increasingly being engineered with multifunctional capabilities. By coupling strain-sensitive geometries with antenna circuits, recent prototypes have demonstrated real-time deformation sensing, body temperature monitoring, and wireless energy harvesting – features particularly relevant for wearable health monitoring and untethered soft robotic systems. Scalable fabrication technologies – including screen printing, 3D direct ink writing, laser ablation, and embroidery – have enabled high-resolution patterning on soft substrates, supporting mass production and system-level integration.

Nevertheless, significant challenges remain. Long-term environmental and biocompatibility stability, and low-loss integration with sensing, power, and communication modules demand further research. In particular, the dynamic coupling between strain-induced geometric changes and electromagnetic field distribution is not yet fully characterized, especially in anisotropic or multilayered architectures.

From a translational perspective, one major barrier lies in the scalability and reproducibility of existing fabrication techniques. Methods such as lithographic patterning, laser machining, or transfer printing often fall short in throughput, yield, and robustness for industrial-scale manufacturing. Moreover, achieving spatially uniform mechanical–electromagnetic performance across large-area devices is complicated by inherent material heterogeneity and process variability. Ensuring long-term mechanical durability and electromagnetic stability under continuous deformation cycles is another pressing concern—especially for applications in wearable and robotic platforms. Integration challenges with conventional electronics packaging and system-level assembly must also be overcome to enable commercialization.

Future directions may involve the development of roll-to-roll manufacturing processes for stretchable conductive composites, scalable printing techniques for automated structural patterning, and standardized testing protocols to benchmark durability, performance consistency, and user safety. The convergence of materials innovation, structural mechanics, and scalable manufacturing approaches will be key to translating laboratory-scale prototypes into viable industrial products. As these interdisciplinary challenges are progressively resolved, stretchable soft antennas will be central to the realization of seamless, low-profile wireless interfaces between soft machines, the human body, and the digital environment.

Conflicts of interest

Authors declare no competing interests.

Data availability

No primary research results, software or code have been included and no new data were generated or analysed as part of this review.

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References

1 C. A. Balanis, The Evolution of Antenna Technology:History, Dipoles, and Loops, *IEEE Antennas Propag. Mag.*, 2024, **66**(3), 42–51.
2 L. Zhu, W. Ma and R. Zhang, Movable Antennas for Wireless Communication: Opportunities and Challenges, *IEEE Commun. Mag.*, 2024, **62**(6), 114–120.
3 T. Tandel and S. Trapasiya, Reconfigurable Antenna for Wireless Communication: Recent Developments, Challenges and Future, *Wireless Pers. Commun.*, 2023, **133**(2), 725–768.
4 M. Zhang, G. Xu and R. Gao, Reconfigurable Antennas for Wireless Communication: Design Mechanism, State of the Art, Challenges, and Future Perspectives, *Int. J. Antennas Propag.*, 2024, **2024**(1), 3046393.
5 S. M. Salleh, M. F. Ain, Z. Ahmad, I. S. Z. Abidin and C. M. N. C. Isa, Development of Stretchable and Bendable Polymer Wearable Antenna for 5G Applications, *eXPRESS Polym. Lett.*, 2022, **16**(12), 1267–1279.
6 S. M. Salleh, M. F. Ain, Z. Ahmad, I. S. Z. Abidin, L. Y. Seng and M. N. Osman, Stretchable and Bendable Polydimethylsiloxane- Silver Composite Antenna on PDMS/Air Gap Substrate for 5G Wearable Applications, *IEEE Access*, 2023, **11**, 133623–133639.
7 H. Xu, W. Zheng, Y. Yuan, D. Xu, Y. Qin, N. Zhao, Q. Duan, Y. Jin, Y. Wang, W. Wang, Y. Lu and L. Gao, Flexible Gas-Permeable and Resilient Bowtie Antenna for Tensile Strain and Temperature Sensing, *IEEE Internet Things J.*, 2022, **9**(22), 23215–23223.
8 L. Y. Chen, B. C. K. Tee, A. L. Chortos, G. Schwartz, V. Tse, D. J. Lipomi, H. S. P. Wong, M. V. McConnell and Z. Bao, Continuous Wireless Pressure Monitoring and Mapping With Ultra-small Passive Sensors for Health Monitoring and Critical Care, *Nat. Commun.*, 2014, **5**, 5028.
9 W. Dang, L. Manjakkal, W. T. Navaraj, L. Lorenzelli, V. Vinciguerra and R. Dahiya, Stretchable Wireless System for Sweat PH Monitoring, *Biosens. Bioelectron.*, 2018, **107**, 192–202.
10 A. Rice and A. Kiourti, A Liquid-Metal-Based, Stretchable Inductive Loop Sensor for Muscle Atrophy, *IEEE Antennas Wireless Propag. Lett.*, 2024, **23**(1), 424–428.
11 S. I. Park, D. S. Brenner, G. Shin, C. D. Morgan, B. A. Copits, H. U. Chung, M. Y. Pullen, K. N. Noh, S. Davidson, S. J. Oh, J. Yoon, K.-I. Jang, V. K. Samineni, M. Norman, J. G. Grajales-Reyes, S. K. Vogt, S. S. Sundaram, K. M. Wilson, J. S. Ha, R. Xu, T. Pan, T.-I. Kim, Y. Huang, M. C. Montana, J. P. Golden, M. R. Bruchas, R. W. Gereau and J. A. Rogers, Soft, Stretchable, Fully Implantable Miniaturized Optoelectronic Systems for Wireless Optogenetics, *Nat. Biotechnol.*, 2015, **33**(12), 1280–1286.
12 J. Kim, J. Park, Y.-G. Park, E. Cha, M. Ku, H. S. An, K.-P. Lee, M.-I. Huh, J. Kim, T.-S. Kim, D. W. Kim, H. K. Kim and J.-U. Park, A Soft and Transparent Contact Lens for The Wireless Quantitative Monitoring of Intraocular Pressure, *Nat. Biomed. Eng.*, 2021, **5**(7), 772–782.
13 L. Teng, K. Pan, M. P. Nemitz, R. Song, Z. Hu and A. A. Stokes, Soft Radio-Frequency Identification Sensors: Wireless Long-Range Strain Sensors Using Radio-Frequency Identification, *Soft Rob.*, 2019, **6**(1), 82–94.
14 H. Yang, B. S. Yeow, Z. Li, K. Li, T.-H. Chang, L. Jing, Y. Li, J. S. Ho, H. Ren and P.-Y. Chen, Multifunctional Metallic Backbones for Origami Robotics With Strain Sensing and Wireless Communication Capabilities, *Sci. Robot.*, 2019, **4**(33), eaax7020.
15 M. Baumgartner, F. Hartmann, M. Drack, D. Preninger, D. Wirthl, R. Gerstmayr, L. Lehner, G. Mao, R. Pruckner, S. Demchyshyn, L. Reiter, M. Strobel, T. Stockinger, D. Schiller, S. Kimeswenger, F. Greibich, G. Buchberger, E. Bradt, S. Hild, S. Bauer and M. Kaltenbrunner, Resilient Yet Entirely Degradable Gelatin-Based Biogels for Soft Robots and Electronics, *Nat. Mater.*, 2020, **19**(10), 1102–1109.
16 D. R. Agrawal, Y. Tanabe, D. Weng, A. Ma, S. Hsu, S.-Y. Liao, Z. Zhen, Z.-Y. Zhu, C. Sun, Z. Dong, F. Yang, H. F. Tse, A. S. Y. Poon and J. S. Ho, Conformal Phased Surfaces for Wireless Powering of Bioelectronic Microdevices, *Nat. Biomed. Eng.*, 2017, **1**(3), 0043.
17 M. Kubo, X. Li, C. Kim, M. Hashimoto, B. J. Wiley, D. Ham and G. M. Whitesides, Stretchable Microfluidic Radiofrequency Antennas, *Adv. Mater.*, 2010, **22**(25), 2749–2752.
18 J.-H. So, J. Thelen, A. Qusba, G. J. Hayes, G. Lazzi and M. D. Dickey, Reversibly Deformable and Mechanically Tunable Fluidic Antennas, *Adv. Funct. Mater.*, 2009, **19**(22), 3632–3637.
19 J. Zhu, S. Zhang, N. Yi, C. Song, D. Qiu, Z. Hu, B. Li, C. Xing, H. Yang, Q. Wang and H. Cheng, Strain-Insensitive Hierarchically Structured Stretchable Microstrip Antennas for Robust Wireless Communication, *Nano-Micro Lett.*, 2021, **13**(1), 108.
20 M. R. Ramli, S. Ibrahim, Z. Ahmad, I. S. Z. Abidin and M. F. Ain, Stretchable Conductive Ink Based on Polysiloxane-Silver Composite and Its Application as a Frequency Reconfigurable Patch Antenna for Wearable Electronics, *ACS Appl. Mater. Interfaces*, 2019, **11**(31), 28033–28042.
21 Z. Liu, F. Wan, L. Mou, M. J. de Andrade, D. Qian, R. Wang, S. Yin, K. Li, H. Chen, B. An, Z. Hu, H. Wang, M. Zhu, S. Fang and Z. Liu, A General Approach for Buckled Bulk Composites by Combined Biaxial Stretch and Layer-by-Layer Deposition and Their Electrical and Electromagnetic Applications, *Adv. Electron. Mater.*, 2019, **5**(4), 1800817.
22 S. H. Kim, G. W. Baek, J. Yoon, S. Seo, J. Park, D. Hahm, J. H. Chang, D. Seong, H. Seo, S. Oh, K. Kim, H. Jung, Y. Oh, H. W. Baac, B. Alimkhanuly, W. K. Bae, S. Lee,

M. Lee, J. Kwak, J.-H. Park and D. Son, A Bioinspired Stretchable Sensory-Neuromorphic System, *Adv. Mater.*, 2021, **33**(44), 2104690.

23 S. Xu, Y. Zhang, L. Jia, K. E. Mathewson, K.-I. Jang, J. Kim, H. Fu, X. Huang, P. Chava, R. Wang, S. Bhole, L. Wang, Y. J. Na, Y. Guan, M. Flavin, Z. Han, Y. Huang and J. A. Rogers, Soft Microfluidic Assemblies of Sensors, Circuits, and Radios for the Skin, *Science*, 2014, **344**(6179), 70–74.

24 Y. H. Jung, J.-Y. Yoo, A. Vazquez-Guardado, J.-H. Kim, J.-T. Kim, H. Luan, M. Park, J. Lim, H.-S. Shin, C.-J. Su, R. Schloen, J. Trueb, R. Avila, J.-K. Chang, D. S. Yang, Y. Park, H. Ryu, H.-J. Yoon, G. Lee, H. Jeong, J. U. Kim, A. Akhtar, J. Cornman, T.-I. Kim, Y. Huang and J. A. Rogers, A Wireless Haptic Interface for Programmable Patterns of Touch Across Large Areas of the Skin, *Nat. Electron.*, 2022, **5**(6), 374–385.

25 H. Song, H. Shin, H. Seo, W. Park, B. J. Joo, J. Kim, J. Kim, H. K. Kim, J. Kim and J.-U. Park, Wireless Non-Invasive Monitoring of Cholesterol Using a Smart Contact Lens, *Adv. Sci.*, 2022, **9**(28), 2203597.

26 Y. Liu, C. Yiu, Z. Song, Y. Huang, K. Yao, T. Wong, J. Zhou, L. Zhao, X. Huang, S. K. Nejad, M. Wu, D. Li, J. He, X. Guo, J. Yu, X. Feng, Z. Xie and X. Yu, Electronic skin as wireless human-machine interfaces for robotic VR, *Sci. Adv.*, 2022, **8**(2), eabl6700.

27 Y. Kim, J. M. Suh, J. Shin, Y. Liu, H. Yeon, K. Qiao, H. S. Kum, C. Kim, H. E. Lee, C. Choi, H. Kim, D. Lee, J. Lee, J.-H. Kang, B.-I. Park, S. Kang, J. Kim, S. Kim, J. A. Perozek, K. Wang, Y. Park, K. Kishen, L. Kong, T. Palacios, J. Park, M.-C. Park, H.-J. Kim, Y. S. Lee, K. Lee, S.-H. Bae, W. Kong, J. Han and J. Kim, Chip-less Wireless Electronic Skins by Remote Epitaxial Freestanding Compound Semiconductors, *Science*, 2022, **377**(6608), 859–869.

28 X. Yu, Z. Xie, Y. Yu, J. Lee, A. Vazquez-Guardado, H. Luan, J. Ruben, X. Ning, A. Akhtar, D. Li, B. Ji, Y. Liu, R. Sun, J. Cao, Q. Huo, Y. Zhong, C. Lee, S. Kim, P. Gutruf, C. Zhang, Y. Xue, Q. Guo, A. Chempakasseril, P. Tian, W. Lu, J. Jeong, Y. Yu, J. Cornman, C. Tan, B. Kirn, K. Lee, X. Feng, Y. Huang and J. A. Rogers, Skin-integrated Wireless Haptic Interfaces for Virtual and Augmented Reality, *Nature*, 2019, **575**(7783), 473–479.

29 X. Zhu, K. Wu, X. Xie, S. W. Anderson and X. Zhang, A Robust Near-field Body Area Network Based on Coaxially-shielded Textile Metamaterial, *Nat. Commun.*, 2024, **15**(1), 6589.

30 K. N. Noh, S. I. Park, R. Qazi, Z. Zou, A. D. Mickle, J. G. Grajales-Reyes, K.-I. Jang, R. W. Gereau, J. Xiao, J. A. Rogers and J.-W. Jeong, Miniaturized, Battery-Free Optofluidic Systems with Potential for Wireless Pharmacology and Optogenetics, *Small*, 2018, **14**(4), 1702479.

31 S. Niu, N. Matsuhisa, L. Beker, J. Li, S. Wang, J. Wang, Y. Jiang, X. Yan, Y. Yun, W. Burnetts, A. S. Y. Poon, J. B. H. Tok, X. Chen and Z. Bao, A Wireless Body Area Sensor Network Based on Stretchable Passive Tags, *Nat. Electron.*, 2019, **2**(8), 361–368.

32 Y. S. Choi, H. Jeong, R. T. Yin, R. Avila, A. Pfenniger, J. Yoo, J. Y. Lee, A. Tzavelis, Y. J. Lee, S. W. Chen, H. S. Knight, S. Kim, H.-Y. Ahn, G. Wickerson, A. Vazquez-Guardado, E. Higbee-Dempsey, B. A. Russo, M. A. Napolitano, T. J. Holleran, L. A. Razzak, A. N. Miniovich, G. Lee, B. Geist, B. Kim, S. Han, J. A. Brennan, K. Aras, S. S. Kwak, J. Kim, E. A. Waters, X. Yang, A. Burrell, K. S. Chun, C. Liu, C. Wu, A. Y. Rwei, A. N. Spann, A. Banks, D. Johnson, Z. J. Zhang, C. R. Haney, S. H. Jin, A. V. Sahakian, Y. Huang, G. D. Trachiotis, B. P. Knight, R. K. Arora, I. R. Efimov and J. A. Rogers, A Transient, Closed-loop Network of Wireless, Body-integrated Devices for Autonomous Electrotherapy, *Science*, 2022, **376**(6596), 1006–1012.

33 S. Cheng and Z. Wu, A Microfluidic, Reversibly Stretchable, Large-Area Wireless Strain Sensor, *Adv. Funct. Mater.*, 2011, **21**(12), 2282–2290.

34 N. Matsuhisa, S. Niu, S. J. K. O'Neill, J. Kang, Y. Ochiai, T. Katsumata, H.-C. Wu, M. Ashizawa, G.-J. N. Wang, D. Zhong, X. Wang, X. Gong, R. Ning, H. Gong, I. You, Y. Zheng, Z. Zhang, J. B. H. Tok, X. Chen and Z. Bao, High-frequency and Intrinsically Stretchable Polymer Diodes, *Nature*, 2021, **600**(7888), 246–252.

35 M. Park, J. Im, M. Shin, Y. Min, J. Park, H. Cho, S. Park, M.-B. Shim, S. Jeon, D.-Y. Chung, J. Bae, J. Park, U. Jeong and K. Kim, Highly Stretchable Electric Circuits from a Composite Material of Silver Nanoparticles and Elastomeric Fibres, *Nat. Nanotechnol.*, 2012, **7**(12), 803–809.

36 M. D. Bartlett, A. Fassler, N. Kazem, E. J. Markvicka, P. Mandal and C. Majidi, Stretchable, High-k Dielectric Elastomers through Liquid-Metal Inclusions, *Adv. Mater.*, 2016, **28**(19), 3726–3731.

37 J. Zhu, Z. Hu, S. Zhang, X. Zhang, H. Zhou, C. Xing, H. Guo, D. Qiu, H. Yang, C. Song and H. Cheng, Stretchable 3D Wideband Dipole Antennas from Mechanical Assembly for On-Body Communication, *ACS Appl. Mater. Interfaces*, 2022, **14**(10), 12855–12862.

38 S. Cheng, Z. Wu, P. Hallbjorner, K. Hjort and A. Rydberg, Foldable and Stretchable Liquid Metal Planar Inverted Cone Antenna, *IEEE Trans. Antennas Propag.*, 2009, **57**(12), 3765–3771.

39 Z. Wu, K. Hjort and S. H. Jeong, Microfluidic Stretchable Radio-Frequency Devices, *Proc. IEEE*, 2015, **103**(7), 1211–1225.

40 R. Lin, H.-J. Kim, S. Achavananthadith, Z. Xiong, J. K. W. Lee, Y. L. Kong and J. S. Ho, Digitally-embroidered Liquid Metal Electronic Textiles for Wearable Wireless systems, *Nat. Commun.*, 2022, **13**(1), 2190.

41 Y. Zhang, Z. Huo, X. Wang, X. Han, W. Wu, B. Wan, H. Wang, J. Zhai, J. Tao, C. Pan and Z. L. Wang, High Precision Epidermal Radio Frequency Antenna *via* Nanofiber Network for Wireless Stretchable Multifunction Electronics, *Nat. Commun.*, 2020, **11**(1), 5629.

42 M. Smith, Y. S. Choi, C. Boughey and S. Kar-Narayan, Self-Reinforcing Graphene Coatings on 3D Printed Elastomers for Flexible Radio Frequency Antennas and Strain Sensors, *Flexible Printed Electron.*, 2017, **2**(3), 035001.

43 Y. Li, X. Tian, S.-P. Gao, L. Jing, K. Li, H. Yang, F. Fu, J. Y. Lee, Y.-X. Guo, J. S. Ho and P.-Y. Chen, Reversible Crumpling of 2D Titanium Carbide (MXene) Nanocoatings for Stretchable Electromagnetic Shielding and Wearable Wireless Communication, *Adv. Funct. Mater.*, 2020, **30**(5), 1907451.
44 K. Yamagishi, T. Ching, N. Chian, M. Tan, W. Zhou, S. Y. Huang and M. Hashimoto, Flexible and Stretchable Liquid-Metal Microfluidic Electronics Using Directly Printed 3D Microchannel Networks, *Adv. Funct. Mater.*, 2024, **34**(31), 2311219.
45 Z. Li, T. Le, Z. Wu, Y. Yao, L. Li, M. Tentzeris, K.-S. Moon and C. P. Wong, Rational Design of a Printable, Highly Conductive Silicone-based Electrically Conductive Adhesive for Stretchable Radio-Frequency Antennas, *Adv. Funct. Mater.*, 2015, **25**(3), 464–470.
46 J. Zhu, J. J. Fox, N. Yi and H. Cheng, Structural Design for Stretchable Microstrip Antennas, *ACS Appl. Mater. Interfaces*, 2019, **11**(9), 8867–8877.
47 S. Zhang, J. Zhu, Y. Zhang, Z. Chen, C. Song, J. Li, N. Yi, D. Qiu, K. Guo, C. Zhang, T. Pan, Y. Lin, H. Zhou, H. Long, H. Yang and H. Cheng, Standalone Stretchable RF Systems Based on Asymmetric 3D Microstrip Antennas With on-body Wireless Communication and Energy Harvesting, *Nano Energy*, 2022, **96**, 107069.
48 Y. Huang, W. Dong, T. Huang, Y. Wang, L. Xiao, Y. Su and Z. Yin, Self-similar Design for Stretchable Wireless LC Strain Sensors, *Sens. Actuators, A*, 2015, **224**, 36–42.
49 J. A. Fan, W.-H. Yeo, Y. Su, Y. Hattori, W. Lee, S.-Y. Jung, Y. Zhang, Z. Liu, H. Cheng, L. Falgout, M. Bajema, T. Coleman, D. Gregoire, R. J. Larsen, Y. Huang and J. A. Rogers, Fractal Design Concepts for Stretchable Electronics, *Nat. Commun.*, 2014, **5**, 3266.
50 Z. Wang, H. Wang, F. Liu, Y. Kang, Y. Chen and X. Feng, 3D Kirigami Antennas with Robust Frequency for Stretchable Wireless Communication, *Extreme Mech. Lett.*, 2022, **56**, 101841.
51 M. Jobs, K. Hjort, A. Rydberg and Z. Wu, A Tunable Spherical Cap Microfluidic Electrically Small Antenna, *Small*, 2013, **9**(19), 3230–3234.
52 Z. Huang, Y. Hao, Y. Li, H. Hu, C. Wang, A. Nomoto, T. Pan, Y. Gu, Y. Chen, T. Zhang, W. Li, Y. Lei, N. Kim, C. Wang, L. Zhang, J. W. Ward, A. Maralani, X. Li, M. F. Durstock, A. Pisano, Y. Lin and S. Xu, Three-dimensional Integrated Stretchable Electronics, *Nat. Electron.*, 2018, **1**(8), 473–480.
53 A. Hajiaghajani, A. H. A. Zargari, M. Dautta, A. Jimenez, F. Kurdahi and P. Tseng, Textile-integrated Metamaterials for Near-field Multibody Area Networks, *Nat. Electron.*, 2021, **4**(11), 808–817.
54 S. G. Hassan and E. J. Mohammad, Study of The Skin Depth in Different Metallic Atoms, *Mater. Today: Proc.*, 2020, **42**(5), 2749–2751.
55 S. P. Lacour, S. Wagner, Z. Y. Huang and Z. Suo, Stretchable Gold Conductors on Elastomeric Substrates, *Appl. Phys. Lett.*, 2003, **82**(15), 2404–2406.
56 N. Lu, X. Wang, Z. Suo and J. Vlassak, Metal Films on Polymer Substrates Stretched Beyond 50%, *Appl. Phys. Lett.*, 2007, **91**(22), 221909.
57 J. B. Pyo, B. S. Kim, H. Park, T. A. Kim, C. M. Koo, J. Lee, J. G. Son, S.-S. Lee and J. H. Park, Floating Compression of Ag Nanowire Networks for Effective Strain Release of Stretchable Transparent Electrodes, *Nanoscale*, 2015, **7**(39), 16434–16441.
58 B. S. Kim, K.-Y. Shin, J. B. Pyo, J. Lee, J. G. Son, S.-S. Lee and J. H. Park, Reversibly Stretchable, Optically Transparent Radio-Frequency Antennas Based on Wavy Ag Nanowire Networks, *ACS Appl. Mater. Interfaces*, 2016, **8**(4), 2582–2590.
59 T. Rai, P. Dantes, B. Bahreyni and W. S. Kim, A Stretchable RF Antenna With Silver Nanowires, *IEEE Electron Device Lett.*, 2013, **34**(4), 544–546.
60 S. J. Mazlouman, X. J. Jiang, A. Mahanfar, C. Menon and R. G. Vaughan, A Reconfigurable Patch Antenna Using Liquid Metal Embedded in a Silicone Substrate, *IEEE Trans. Antennas Propag.*, 2011, **59**(12), 4406–4412.
61 W. S. Wong and A. Salleo, *Flexible Electronics: Materials and Applications*, Springer Nature, Springer Science & Business Media, LLC, 233 Spring Street, New York, NY 10013, USA, 2009.
62 S. J. Chen, C. Fumeaux, P. Talemi, B. Chivers and R. Shepherd, IEEE, 17th International Symposium on Antenna Technology and Applied Electromagnetics Montreal, CANADA, 2016.
63 X. Guo, Y. Huang, C. Wu, L. Mao, Y. Wang, Z. Xie, C. Liu and Y. Zhang, Flexible and Reversibly Deformable Radio-Frequency Antenna Based on Stretchable SWCNTs/PANI/Lycra Conductive Fabric, *Smart Mater. Struct.*, 2017, **26**(10), 105036.
64 G. S. Gund, M. G. Jung, K.-Y. Shin and H. S. Park, Two-Dimensional Metallic Niobium Diselenide for Sub-micrometer-Thin Antennas in Wireless Communication Systems, *ACS Nano*, 2019, **13**(12), 14114–14121.
65 T. Leng, X. Huang, K. Chang, J. Chen, M. A. Abdalla and Z. Hu, Graphene Nanoflakes Printed Flexible Meandered-Line Dipole Antenna on Paper Substrate for Low-Cost RFID and Sensing Applications, *IEEE Antennas Wireless Propag. Lett.*, 2016, **15**, 1565–1568.
66 M. Han, Y. Liu, R. Rakhmanov, C. Israel, M. A. S. Tajin, G. Friedman, V. Volman, A. Hoorfar, K. R. Dandekar and Y. Gogotsi, Solution-Processed Ti3C2Tx MXene Antennas for Radio-Frequency Communication, *Adv. Mater.*, 2021, **33**(1), 2003225.
67 W. Zhao, H. Ni, C. Ding, L. Liu, Q. Fu, F. Lin, F. Tian, P. Yang, S. Liu, W. He, X. Wang, W. Huang and Q. Zhao, 2D Titanium Carbide Printed Flexible Ultrawideband Monopole Antenna for Wireless Communications, *Nat. Commun.*, 2023, **14**(1), 278.
68 P. Zhao, T. Chen, J. Si, H. Shi and X. Hou, Fabrication of a Flexible Stretchable Hydrogel-based Antenna Using a Femtosecond Laser for Miniaturization, *Opt. Express*, 2023, **31**(20), 32704–32716.
69 P. Qin, Q. Wang, P. Zhang, G. Huang, Q. Li, B. Liu, L. Li, L. Gui, J. Liu and Z. Deng, A Highly Transparent Flexible

Antenna Based on Liquid Metal Mesh Film, *Int. J. RF Microwave Comput. Aided Eng.*, 2023, **2023**(1), 6369944.

70 K. Yamagishi, W. Zhou, T. Ching, S. Y. Huang and M. Hashimoto, Ultra-Deformable and Tissue-Adhesive Liquid Metal Antennas with High Wireless Powering Efficiency, *Adv. Mater.*, 2021, **33**(26), 2008062.

71 B. Yao, X. Xu, Q. Zhang, H. Yu, H. Li, L. Ren, S. Perini, M. Lanagan, Q. Wang and H. Wang, Highly Stretchable and Mechanically Tunable Antennas Based on Three-dimensional Liquid Metal Network, *Mater. Lett.*, 2020, **270**, 127727.

72 Y. Liu, M. Yu, L. Xu, Y. Li and T. T. Ye, Characterizations and Optimization Techniques of Embroidered RFID Antenna for Wearable Applications, *IEEE J. Radio Freq. Identif.*, 2020, **4**(1), 38–45.

73 W. Chen, Y. Li, R. Li, A. V.-Y. Thean and Y.-X. Guo, Bendable and Stretchable Microfluidic Liquid Metal-Based Filter, *IEEE Microwave Wireless Compon. Lett.*, 2018, **28**(3), 203–205.

74 P. Liu, S. Yang, A. Jain, Q. Wang, H. Jiang, J. Song, T. Koschny, C. M. Soukoulis and L. Dong, Tunable Meta-atom Using Liquid Metal Embedded in Stretchable Polymer, *J. Appl. Phys.*, 2015, **118**(1), 014504.

75 Y. Huang, Y. Wang, L. Xiao, H. Liu, W. Dong and Z. Yin, Microfluidic Serpentine Antennas with Designed Mechanical Tunability, *Lab Chip*, 2014, **14**(21), 4205–4212.

76 M. D. Perez, S. H. Jeong, S. Raman, D. Nowinski, Z. Wu, S. M. S. Redzwan, J. Velander, Z. Peng, K. Hjort and R. Augustine, Head-compliant Microstrip Split Ring Resonator for Non-invasive Healing Monitoring After Craniosynostosis-based Surgery, *Healthcare Technol. Lett.*, 2020, **7**(1), 29–34.

77 Y. R. Jeong, J. Kim, Z. Xie, Y. Xue, S. M. Won, G. Lee, S. W. Jin, S. Y. Hong, X. Feng, Y. Huang, J. A. Rogers and J. S. Ha, A Skin-attachable, Stretchable Integrated System Based on Liquid GaInSn for Wireless Human Motion Monitoring with Multi-site Sensing Capabilities, *NPG Asia Mater.*, 2017, **9**, e443.

78 S. Cheng, A. Rydberg, K. Hjort and Z. Wu, Liquid Metal Stretchable Unbalanced Loop Antenna, *Appl. Phys. Lett.*, 2009, **94**(14), 144103.

79 F. Liu, X. Cheng, F. Zhang, Y. Chen, H. Song, Y. Huang and Y. Zhang, Design and Assembly of Reconfigurable 3D Radio-Frequency Antennas Based on Mechanically Triggered Switches, *Adv. Electron. Mater.*, 2019, **5**(6), 1900256.

80 T. Chang, Y. Tanabe, C. C. Wojcik, A. C. Barksdale, S. Doshay, Z. Dong, H. Liu, M. Zhang, Y. Chen, Y. Su, T. H. Lee, J. S. Ho and J. A. Fan, A General Strategy for Stretchable Microwave Antenna Systems using Serpentine Mesh Layouts, *Adv. Funct. Mater.*, 2017, **27**(46), 1703059.

81 T. Jang, C. Zhang, H. Youn, J. Zhou and L. J. Guo, Semi-transparent and Flexible Mechanically Reconfigurable Electrically Small Antennas Based on Tortuous Metallic Micromesh, *IEEE Trans. Antennas Propag.*, 2017, **65**(1), 150–158.

82 F. Liu, Y. Chen, H. Song, F. Zhang, Z. Fan, Y. Liu, X. Feng, J. A. Rogers, Y. Huang and Y. Zhang, High Performance, Tunable Electrically Small Antennas through Mechanically Guided 3D Assembly, *Small*, 2019, **15**(1), 1804055.

83 B. Zhang, W. Li, Y. Yang, C. Chen, C.-F. Li and K. Suganuma, Fully Embedded CuNWs/PDMS Conductor with High Oxidation Resistance and High Conductivity for Stretchable Electronics, *J. Mater. Sci.*, 2019, **54**(8), 6381–6392.

84 J. H. Park, J. Seo, C. Kim, D. J. Joe, H. E. Lee, T. H. Im, J. Y. Seok, C. K. Jeong, B. S. Ma, H. K. Park, T.-S. Kim and K. J. Lee, Flash-Induced Stretchable Cu Conductor *via* Multiscale-Interfacial Couplings, *Adv. Sci.*, 2018, **5**(11), 1801146.

85 L. Sang, S. Li, B. Hu, K. Dai, M. Kraman, H. Yang and W. Huang, Reconfigurable Microstrip Patch Antennas on Flexible Substrates: A design method, *IEEE Antennas Propag. Mag.*, 2023, **65**(5), 35–45.

86 U. Boda, J. Strandberg, J. Eriksson, X. Liu, V. Beni and K. Tybrandt, Screen-Printed Corrosion-Resistant and Long-Term Stable Stretchable Electronics Based on AgAu Microflake Conductors, *ACS Appl. Mater. Interfaces*, 2023, **15**(9), 12372–12382.

87 H. Zhu, Y. Liu, Z. Chi, W. Zong, Z. Sun, X. Guo, T. Liu and B. Sun, A Stretchable Conductor Based on Spray-Coated Micro/Nano Scale Ag Flakes with Ultralow Resistance for Wearable Antennas, *Nano*, 2023, **18**(1), 2350001.

88 M. Sakovsky, J. Negele and J. Costantine, Electromagnetic Reconfiguration Using Stretchable Mechanical Metamaterials, *Adv. Sci.*, 2023, **10**(6), 2203376.

89 X. Li, J. Cai, X. Lu, Y. Shi, D. Gong, D. Su and D. Zhang, Stretchable Conductors Based on Three-Dimensional Microcoils for Tunable Radio-frequency Antennas, *J. Mater. Chem. C*, 2018, **6**(15), 4191–4200.

90 F. Nikbakhtnasrabadi, H. El Matbouly, M. Ntagios and R. Dahiya, Textile-Based Stretchable Microstrip Antenna with Intrinsic Strain Sensing, *ACS Appl. Electron. Mater.*, 2021, **3**(5), 2233–2246.

91 X. Chen, A. Liu, Z. Wei, L. Ukkonen and J. Virkki, Experimental Study on Strain Reliability of Embroidered Passive UHF RFID Textile Tag Antennas and Interconnections, *J. Eng.*, 2020, **2017**(1), 8493405.

92 C. Pan, Y. Ohm, J. Wang, M. J. Ford, K. Kumar, S. Kumar and C. Majidi, Silver-Coated Poly(dimethylsiloxane) Beads for Soft, Stretchable, and Thermally Stable Conductive Elastomer Composites, *ACS Appl. Mater. Interfaces*, 2019, **11**(45), 42561–42570.

93 Z. Chen, J. Xi, W. Huang and M. M. F. Yuen, Stretchable Conductive Elastomer for Wireless Wearable Communication Applications, *Sci. Rep.*, 2017, **7**, 10958.

94 P. Si, F. Jiang, Q. S. Cheng, G. Rivers, H. Xie, A. K. K. Kyaw and B. Zhao, Triple non-covalent dynamic interactions enabled a tough and rapid room temperature self-healing elastomer for next-generation soft antennas, *J. Mater. Chem. A*, 2020, **8**, 25073–25084.

95 M. S. de Medeiros, D. Goswami, D. Chanci, C. Moreno and R. V. Martinez, Washable, Breathable, and Stretchable E-textiles Wirelessly Powered by Omniphobic Silk-based Coils, *Nano Energy*, 2021, **87**, 106155.

96 X. Hu, L. Mou and Z. Liu, Stretchable Electromagnetic Interference Sielding and Atenna for Wireless Srain Sensing by Aisotropic Mcron-steel-wire Based Cnductive Eastomers, *Chin. Phys. B*, 2021, **30**(1), 018401.
97 M. Tang, P. Zheng, Y. Wu, P. Zhu, Y. Qin, Y. Jiang, R. Sun, C. P. Wong and Z. Li, Silver Dendrites Based Electrically Conductive Composites, Towards the Application of Stretchable Conductors, *Compos. Commun.*, 2020, **19**, 121–126.
98 Z. L. Fan Cai, J. C. Agar, C. P. Wong and J. Papapolymerou, presented in part at the 2012 IEEE/MTT-S International Microwave Symposium Digest, Montreal, QC, Canada, 17-22 June 2012.
99 Z. Li, L. Li, K.-S. Moon, F. Cai, J. Papapolymerous, C. P. Wong and Ieee, presented in part at the 2013 IEEE 63rd Electronic Components and Technology Conference, Las Vegas, NV, USA, 28-31 May 2013.
100 M. Tang, P. Zheng, K. Wang, Y. Qin, Y. Jiang, Y. Cheng, Z. Li and L. Wu, Autonomous Self-healing, Self-adhesive, Highly Conductive Composites Based on a Silver-filled Polyborosiloxane/Polydimethylsiloxane Double-network Elastomer, *J. Mater. Chem. A*, 2019, **7**(48), 27278–27288.
101 P. Zhou, L. Wang, G. Zhang, J. Jiang, H. Chen, Y. Zhou, D. Liang and L. Deng, A Stretchable Metamaterial Absorber With Deformation Compensation Design at Microwave Frequencies, *IEEE Trans. Antennas Propag.*, 2019, **67**(1), 291–297.
102 Costa Angeli, M. A. A. N., Fatemeh and Vena, Pasquale and Dahiya, Ravinder, presented in part at the 2019 IEEE International Conference on Flexible and Printable Sensors and Systems (FLEPS), Glasgow, UK, 08-10 July 2019.
103 H. Saghlatoon, M. M. Honari, R. Mirzavand, P. Mousavi, A. Kumar, T. G. La, H.-J. Chung and Ieee, presented in part at the 2017 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting, San Diego, CA, USA, 09-14 July 2017.
104 A. Kumar, H. Saghlatoon, T.-G. La, M. Mahdi Honari, H. Charaya, H. Abu Damis, R. Mirzavand, P. Mousavi and H.-J. Chung, A Highly Deformable Conducting Traces for Printed Antennas and Interconnects: Silver/Fluoropolymer Composite Amalgamated by Triethanolamine, *Flexible Printed Electron.*, 2017, **2**(4), 045001.
105 S. An, A. Meredov, A. Shamim and Ieee, presented in part at the 2018 48th European Microwave Conference (EuMC), Madrid, Spain, 23-27 September 2018.
106 A. W. Memon, B. Malengier, P. Van Torre and L. V. Langenhove, A Lattice-Hinge-Design-Based Stretchable Textile Microstrip Patch Antenna for Wireless Strain Sensing at 2.45 GHz, *Sensors*, 2023, **23**(21), 8946.
107 J. Zhu, Z. Hu, C. Song, N. Yi, Z. Yu, Z. Liu, S. Liu, M. Wang, M. G. Dexheimer, J. Yang and H. Cheng, Stretchable Wideband Dipole Antennas and Rectennas for RF Energy Harvesting, *Mater. Today Phys.*, 2021, **18**, 100377.
108 L. Ju, Z.-G. Liu, B.-Y. Yu, H. Chen, Z.-D. Xiao and W.-B. Lu, Stretchable and Dynamically Tunable Attenuator Based on Graphene, *IEEE Trans. Microwave Theory Tech.*, 2022, **70**(6), 2999–3008.
109 M. Rafiq, A. Imran, A. Rasheed and S. U. Zaman, A Review on the Manufacturing Techniques for Textile Based Antennas, *J. Eng. Fibers Fabr.*, 2024, **19**, 15589250241226585.
110 B. Mohamadzade, R. M. Hashmi, R. B. V. B. Simorangkir, R. Gharaei, S. U. Rehman and Q. H. Abbasi, Recent Advances in Fabrication Methods for Flexible Antennas in Wearable Devices: State of the Art, *Sensors*, 2019, **19**(10), 2312.
111 N. C. Raut and K. Al-Shamery, Inkjet Printing Metals on Flexible Materials for Plastic and Paper Electronics, *J. Mater. Chem. C*, 2018, **6**(7), 1618–1641.
112 L. Yang, A. Rida, R. Vyas and M. M. Tentzeris, RFID Tag and RF Structures on a Paper Substrate Using Inkjet-printing Technology, *IEEE Trans. Microwave Theory Tech.*, 2007, **55**(12), 2894–2901.
113 R. Salvado, C. Loss, R. Goncalves and P. Pinho, Textile Materials for the Design of Wearable Antennas: A Survey, *Sensors*, 2012, **12**(11), 15841–15857.
114 D. Qi, Z. Liu, W. R. Leow and X. Chen, Elastic Substrates for Stretchable Devices, *MRS Bull.*, 2017, **42**(2), 103–107.
115 D. Qi, Z. Liu, Y. Liu, Y. Jiang, W. R. Leow, M. Pal, S. Pan, H. Yang, Y. Wang, X. Zhang, J. Yu, B. Li, Z. Yu, W. Wang and X. Chen, Highly Stretchable, Compliant, Polymeric Microelectrode Arrays for In Vivo Electrophysiological Interfacing, *Adv. Mater.*, 2017, **29**(40), 1702800.
116 P. K. Sharma, N. Gupta and P. I. Dankov, Analysis of Dielectric Properties of Polvdimethylsiloxane (PDMS) as a Flexible Substrate for Sensors and Antenna Applications, *IEEE Sens. J.*, 2021, **21**(17), 19492–19504.
117 P. Fryn, S. Lalik, N. Gorska, A. Iwan and M. Marzec, Comparison of the Dielectric Properties of Ecoflex(R) with L,D-Poly(Lactic Acid) or Polycaprolactone in the Presence of SWCN or 5CB, *Materials*, 2021, **14**(7), 1719.
118 Y. Wang, C. Zhang, J. Lin, H. Sun, Y. Yang and W. Yang, A Strategy for Accurate Prediction of Dielectric Permittivity and Dielectric Strength in Polyimide, *High Voltage*, 2024, **9**(6), 1393–1401.
119 Y. Yoo, H. Jeong, D. Lim and S. Lim, Stretchable Screen-printed Metasurfaces for Wireless Strain Sensing Applications, *Extreme Mech. Lett.*, 2020, **41**, 100998.
120 J. A. Kartik Sondhi, S. Hwangbo, S. Guruva Reddy Avuthu, Y.-K. Yoon and Z. Hugh Fan, presented in part at the 2018 IEEE SENSORS, New Delhi, India, 28-31 October 2018.
121 G. Scetta, E. Euchler, J. Ju, N. Selles, P. Heuillet, M. Ciccotti and C. Creton, Self-Organization at the Crack Tip of Fatigue-Resistant Thermoplastic Polyurethane Elastomers, *Macromolecules*, 2021, **54**(18), 8726–8737.
122 H. Zhou, Design of a Biaxially Stretchable Microstrip Antenna Enabled by Buckled Au Thin Film on an Elastomeric Substrate, *J. Phys.: Conf. Ser.*, 2023, **2553**, 012064.
123 G. Xu, L. Yuan, X. Chen, W. Jia, M. Wang, L. Yang, J. Zhu and H. Cheng, Design of non-dimensional parameters in stretchable microstrip antennas with coupled mechanics-electromagnetics, *Mater. Des.*, 2021, **205**, 109721.
124 M. Maranha, A. F. Silva, P. A. Lopes, A. T. de Almeida and M. Tavakoli, Digitally Printed Liquid Metal Composite

Antenna for Energy Harvesting: Toward Energy-Autonomous Battery-Free Wearable Bioelectronics, *Adv. Sens. Res.*, 2023, **2**(2), 2200025.
125 X. Zhou, Y. He and J. Zeng, Liquid Metal Antenna-based Pressure Sensor, *Smart Mater. Struct.*, 2019, **28**(2), 025019.
126 L. Song, A. C. Myers, J. J. Adams and Y. Zhu, Stretchable and Reversibly Deformable Radio Frequency Antennas Based on Silver Nanowires, *ACS Appl. Mater. Interfaces*, 2014, **6**(6), 4248–4253.
127 L. Ju, B.-Y. Yu, M.-Y. Geng and W.-B. Lu, presented in part at the 2024 International Conference on Electrical, Computer and Energy Technologies (ICECET), 2024.
128 A. M. Hussain, F. A. Ghaffar, S. I. Park, J. A. Rogers, A. Shamim and M. M. Hussain, Metal/Polymer Based Stretchable Antenna for Constant Frequency Far-Field Communication in Wearable Electronics, *Adv. Funct. Mater.*, 2015, **25**(42), 6565–6575.
129 M. El Gharbi, J. Abounasr, R. Fernandez Garcia and I. Gil Gali, Textile Stretchable Antenna-Based Sensor for Breathing Monitoring, *IEEE Sens. J.*, 2024, **24**(24), 42018–42027.
130 S. H. Kim, A. Basir, R. Avila, J. Lim, S. W. Hong, G. Choe, J. H. Shin, J. H. Hwang, S. Y. Park, J. Joo, C. Lee, J. Choi, B. Lee, K.-S. Choi, S. Jung, T.-I. Kim, H. Yoo and Y. H. Jung, Strain-invariant Stretchable Radio-Frequency Electronics, *Nature*, 2024, **629**(8014), 1047–1054.
131 S. A. T. Soltani, S. Paul and J. C. Batchelor, presented in part at the 2020 14th European Conference on Antennas and Propagation (EuCAP), Copenhagen, Denmark, 15-20 March 2020.
132 Y.-S. Kim, A. Basir, R. Herbert, J. Kim, H. Yoo and W.-H. Yeo, Soft Materials, Stretchable Mechanics, and Optimized Designs for Body-Wearable Compliant Antennas, *ACS Appl. Mater. Interfaces*, 2020, **12**(2), 3059–3067.
133 S. D. Nivethika, B. S. Sreeja, E. Manikandan and S. Radha, A Stretchable Smart and Highly Efficient Radio Frequency Antenna on Low Cost Substrate, *Microwave Opt. Technol. Lett.*, 2018, **60**(7), 1798–1803.
134 M. Zandvakili, M. M. Honari, P. Mousavi and D. Sameoto, Gecko-Gaskets for Multilayer, Complex, and Stretchable Liquid Metal Microwave Circuits and Antennas, *Adv. Mater. Technol.*, 2017, **2**(11), 1700144.
135 Y. Su, X. Ping, K. J. Yu, J. W. Lee, J. A. Fan, B. Wang, M. Li, R. Li, D. V. Harburg, Y. Huang, C. Yu, S. Mao, J. Shim, Q. Yang, P.-Y. Lee, A. Armonas, K.-J. Choi, Y. Yang, U. Paik, T. Chang, T. J. Dawidczyk, Y. Huang, S. Wang and J. A. Rogers, In-Plane Deformation Mechanics for Highly Stretchable Electronics, *Adv. Mater.*, 2017, **29**(8), 1604989.
136 K. Hong, J. Cho and G. Shin, Stretchable, Multi-Layered Stack Antenna for Smart/Wearable Electronic Applications, *Materials*, 2022, **15**(9), 3275.
137 H. Yang, J. Li, X. Xiao, J. Wang, Y. Li, K. Li, Z. Li, H. Yang, Q. Wang, J. Yang, J. S. Ho, P.-L. Yeh, K. Mouthaan, X. Wang, S. Shah and P.-Y. Chen, Topographic Design in Wearable MXene Sensors with In-sensor Machine Learning for Full-body Avatar Reconstruction, *Nat. Commun.*, 2022, **13**(1), 5311.
138 K. Li, Z. Li, Z. Xiong, Y. Wang, H. Yang, W. Xu, L. Jing, M. Ding, J. Zhu, J. S. Ho and P.-Y. Chen, Thermal Camouflaging MXene Robotic Skin with Bio-Inspired Stimulus Sensation and Wireless Communication, *Adv. Funct. Mater.*, 2022, **32**(23), 2110534.
139 H. Yang, J. Li, K. Z. Lim, C. Pan, T. Tien Van, Q. Wang, K. Li, S. Li, X. Xiao, M. Ding, T. Chen, X. Liu, Q. Xie, P. Valdivia y Alvarado, X. Wang and P.-Y. Chen, Automatic Strain Sensor Design Via Active Learning and Data Augmentation for Soft Machines, *Nat. Mach. Intell.*, 2022, **4**(1), 84–94.
140 Z. Yan, T. Pan, G. Yao, F. Liao, Z. Huang, H. Zhang, M. Gao, Y. Zhang and Y. Lin, Highly Stretchable and Shape-controllable Three-dimensional Antenna Fabricated by "Cut-Transfer-Release" Method, *Sci. Rep.*, 2017, **7**, 42227.
141 F. Yang, Y. Tong, S. Zhang, J. Zheng, J. Zhu, H. Liu, Y. Hu, C. Zhang, Z. Chen, G. Chen and C. Song, Strain-Invariant Stretchable Antennas *via* Radical Surface Current Redistributions: Theory, Design and Experiments, *IEEE Trans. Antennas Propag.*, 2025, 1, DOI: **10.1109/tap.2025.3564785**.
142 T. Pan, C. Zhang, S. Zhang, D. Guo, M. Xie, M. Gao, Z. Huang, J. Zhu and Y. Lin, Skin-Attachable and Stretchable Patch Antenna with Fractal Design for Remote On-Body Motion Sensing, *ACS Appl. Mater. Interfaces*, 2023, **15**(23), 28240–28247.
143 P. Si, M. Liang, J. Zou, Y. Kuang, J. Zhang, Q. S. Cheng, Y. Kong, Y. Cai, G. Huang, Y. Wu, Z. Long, B. Zhao and D. Zhang, Battery-free antenna sticker for wireless sensing joint rotation, *Chem. Eng. J.*, 2025, **513**, 162691.
144 L. Xu, Z. Liu, X. Chen, R. Sun, Z. Hu, Z. Zheng, T. T. Ye and Y. Li, Deformation-Resilient Embroidered Near Field Communication Antenna and Energy Harvesters for Wearable Applications, *Adv. Intell. Syst.*, 2019, **1**(6), 1900056.
145 U. Ali, S. Ullah, J. Khan, M. Shafi, B. Kamal, A. Basir, J. A. Flint and R. D. Seager, Design and SAR Analysis of Wearable Antenna on Various Parts of Human Body, Using Conventional and Artificial Ground Planes, *J. Electr. Eng. Technol.*, 2017, **12**, 317–328.
146 A. Al-Sehemi, A. Al-Ghamdi, N. Dishovsky, N. Atanasov and G. Atanasova, On-body investigation of a compact planar antenna on multilayer polymer composite for body-centric wireless communications, *AEU-Int. J. Electron. Commun.*, 2017, **82**, 20–29.
147 P. J. Soh, G. A. E. Vandenbosch, M. Mercuri and D. M. M. P. Schreurs, Wearable Wireless Health Monitoring: Current Developments, Challenges, and Future Trends, *IEEE Microwave Mag.*, 2015, **16**, 55–70.
148 N. H. M. Rais, P. J. Soh, F. Malek, S. Ahmad, N. B. M. Hashim and P. S. Hall, presented in part at the 2009 Loughborough Antennas & Propagation Conference, 2009.