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A Review of Flexible Wearable RF Sensing Antennas

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Abstract: Flexible wearable RF sensing antennas have overcome traditional limitations through innovations in materials and structural design, emerging as a core technology in smart healthcare and the Internet of Things (IoT). Liquid metals and conductive fabrics provide high conductivity and biocompatibility, while serpentine and origami-inspired structures ensure mechanical durability. Advanced fabrication methods such as laser direct writing and inkjet printing enable high-precision manufacturing, and heterogeneous integration techniques expand functional applications. In the medical field, implantable neural modulation antennas have achieved up to 90% energy transmission efficiency. Military communication systems have demonstrated wideband gain characteristics. Future research will focus on biodegradable materials, miniaturized fabrication, and intelligent applications, driving the next revolution in human-machine interaction in the 5G and terahertz era.

Keywords: Flexible wearable antennas, textile antennas, multiband antennas

1. Introduction

1.1. Research background and significance

With the rapid development of the Internet of Things (IoT), smart healthcare, and wearable devices, flexible wearable RF sensors have become a critical technology for wireless communication and biomedical monitoring. These flexible RF sensors can seamlessly conform to the skin or be integrated into garments to enable real-time monitoring of physiological parameters such as heart rate and blood pressure. For instance, microstrip patch antennas based on textile substrates, using silver nanowire radiating elements, reduce system complexity and improve wearing comfort [1][2]. Furthermore, the widespread adoption of 5G and millimeter-wave technologies has greatly expanded the application potential of flexible sensors in smart cities and Industry 4.0 [3], including examples such as wearable sweat glucose sensors shown in Figure 1.

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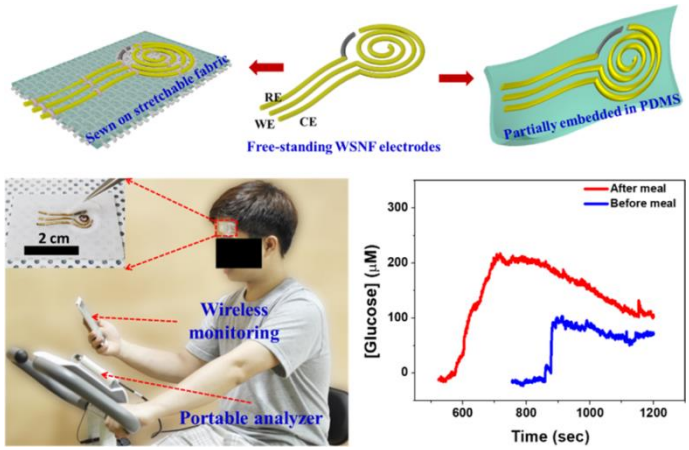


Figure 1: Wearable sweat glucose sensor [4]

1.2. Current research and development trends

1.2.1. Comparison of domestic and international research status

Table 1: Comparison of domestic and foreign research

Dimension	International Breakthroughs	Domestic Innovations
Material	Nano inkjet printing (precision up to 5 μm) [5]	Metal-organic framework electrodes [8]
Structure	Dual-band EBG antenna (efficiency up to 85%) [6]	MXene helical fibers (tensile strength 120 MPa) [9]
Application	Textile UWB antenna (operating range 2.85–9.81 GHz) [7]	Microfluidic sweat-powered energy (power 80.3 μW) [8]

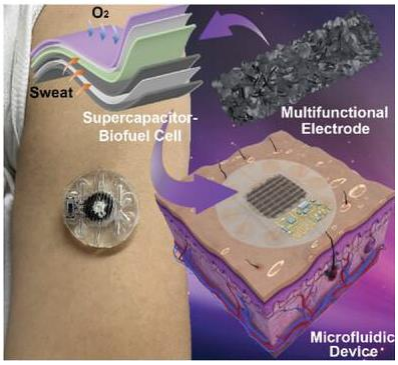


Figure 2: Flexible wearable RF antenna based on metal organic framework

1.2.2. Summary and outlook on research status

Currently, flexible RF sensors face challenges such as material stability and the lack of unified testing standards. As shown in Figure 2, flexible wearable RF antennas based on metal-organic frameworks (MOFs) are still under exploration. Future trends include multifunctional integration to enable synchronized analysis of physiological signals and environmental parameters, miniaturization and self-powering for reduced energy consumption, and expansion into emerging applications such as implantable medical devices and metaverse interaction interfaces. Key breakthroughs are anticipated in biodegradable materials and high-frequency antenna design.

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2. Material selection and substrate compatibility

2.1. Innovations and challenges in conductive materials

2.1.1. Liquid metals

Gallium-based liquid metals have emerged as ideal materials for flexible RF sensors due to their high electrical conductivity, stretchability, and self-healing properties [10]. Their typical application scenarios are illustrated in Figure 3.

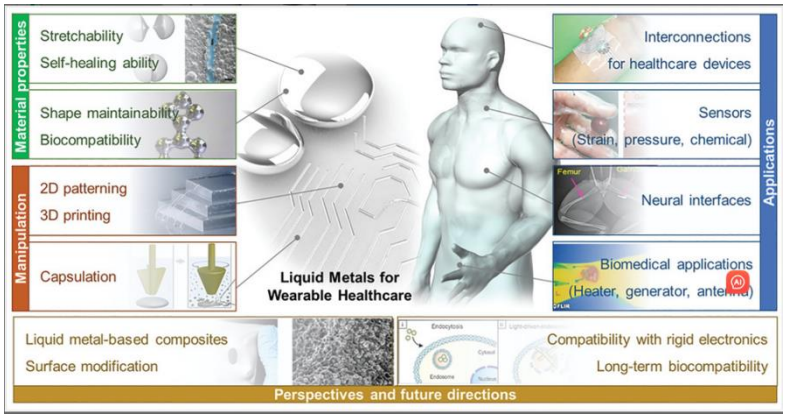


Figure 3: Application direction of liquid metal

Thanks to their biocompatibility, they are suitable for implantable medical devices. However, surface oxidation readily forms a gallium oxide layer, increasing contact resistance [11]. Encapsulation with PDMS can suppress oxidation, but overly thick encapsulation layers may cause RF signal attenuation. Huang's team combined Ti_3C_2 MXene with EGaIn to maintain bandwidth stability in the 1.7–4.0 GHz range under bending conditions [12].

2.1.2. Conductive fabrics

Silver fiber fabrics offer antibacterial properties but suffer from relatively high resistivity, which negatively affects antenna efficiency. Their wearable RF sensor application model is shown in Figure 4.

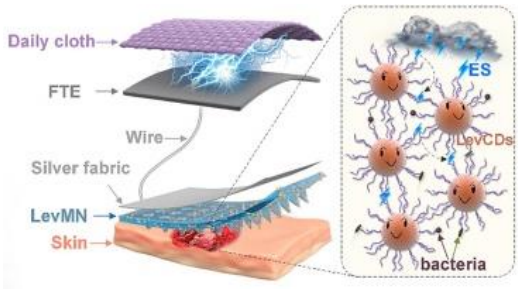


Figure 4: Silver fiber flexible wearable RF sensor [13]

Silver nanowires can enhance conductivity and reduce high-frequency signal loss [14]. Carbon nanotube (CNT) fabrics exhibit excellent breathability, but their electrical conductivity is insufficient and prone to degradation from friction or washing. Optimizing thermal welding techniques can improve the structural stability of CNT/PP-PE fabrics [15].

DOI: 10.54254/2755-2721/2025.24537

2.2. Optimization strategies for flexible substrates

2.2.1. Elastomer substrates

Polydimethylsiloxane (PDMS) is widely used in flexible electronics due to its low dielectric constant and good biocompatibility. However, its thermal expansion coefficient mismatches with that of metallic electrodes, causing thermal stress and microcracks [16]. Doping with $BaTiO_3$ nanoparticles can reduce dielectric loss and enhance the dielectric constant to 6.25, while mitigating thermal stress. A hybrid PDMS composite containing $BaTiO_3$ and CNTs achieved a dielectric constant of 120 at 100 Hz and significantly suppressed performance degradation caused by thermal stress [17].

2.2.2. Breathability and dielectric control in textile substrates

Textile substrates provide excellent breathability, but their porous structure leads to fluctuations in dielectric properties. Xu's team developed a polyester fiber with a gradient-doped CNT structure, achieving a dielectric constant fluctuation of less than 1.5% while maintaining breathability [18]. Huang et al. confirmed that this design effectively suppresses dielectric loss and reduces RF signal attenuation [19].

Liquid metals and conductive fabrics each offer distinct advantages, but challenges such as oxidation and high resistivity remain. Meanwhile, PDMS and textile substrates require further optimization in dielectric properties and mechanical stability to meet the performance demands of flexible RF sensors.

3. Antenna topology design and optimization

3.1. Design of conformal antenna topologies

Designing flexible and stretchable antennas requires maintaining stable electrical performance under mechanical deformation. The most common approaches involve serpentine and origami-inspired structures to optimize strain distribution.

3.1.1. Serpentine structures

3.1.1.1. Curvature radius optimization and strain dispersion mechanism

Serpentine antennas feature periodically meandering traces that effectively disperse mechanical strain and reduce stress concentration. Studies have shown that when the curvature radius is controlled between 50–100 μm, the resonant frequency shift under 30% strain remains below 2%, and the Specific Absorption Rate (SAR) is reduced by 40% (see Figure 5).

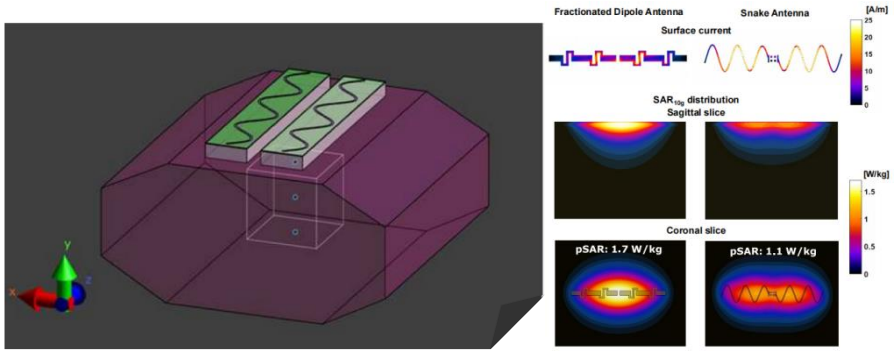


Figure 5: Design and SAR characterization of snake shaped flexible wearable RF antenna

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3.1.1.2. Substrate compatibility and fatigue life enhancement

Low-modulus elastomers reduce interfacial shear stress. When combined with plasma surface treatment, adhesion is enhanced, enabling the antenna to maintain gain fluctuations within 1 dB after 10,000 stretching cycles.

3.1.2. Origami structures

Reconfigurable antennas based on origami mechanics achieve strain absorption and electrical stability through geometric transformation. The key lies in optimizing folding patterns and co-designing materials and structures. A recently proposed egg-box origami phased array antenna addresses integration and stability limitations of traditional planar arrays and origami structures [20]. Its 2D mapping layout is illustrated in Figure 6.

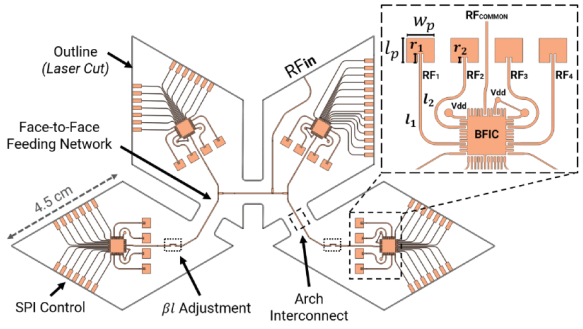


Figure 6: Two dimensional mapping layout of flexible origami antenna array

3.1.2.1. Fold-insensitive properties of origami structures

Origami antennas with multistable structures can withstand deformations from 0° to 180° without compromising electrical performance. Within the 24–32 GHz band, transmission loss fluctuates by less than ±0.005 dB/mm, and after 300 folding cycles, efficiency decreases by only 1.2%.

3.1.2.2. Multi-beam functionality and high integration design

A 4×4 origami phased array can achieve ±45° beam steering via mechanical folding, with sidelobe levels below –18 dB, supporting 5G MIMO applications. When modularly expanded to an 8×8 array, the system achieves a gain of up to 21 dBi.

3.2. Common sensing parameters of flexible wearable antennas

3.2.1. Impedance matching and power transmission efficiency

3.2.1.1. Impedance matching

Impedance matching ensures that the antenna input impedance is conjugately matched to the characteristic impedance of the transmission line, as defined by:

$$Z_{in} = Z_0^* \rightarrow R = 50\Omega, X = 0 \quad (1)$$

When the bending radius of a flexible antenna changes from its planar state, a reconfigurable matching network is needed to dynamically compensate for impedance variations.

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3.2.1.2. Return loss

Return loss quantifies the ratio of incident power to reflected power:

$$RL = -20\log_{10}|\Gamma| \quad [dB] \tag{2}$$

In practice, a vector network analyzer combined with a bending fixture should be used to simulate real-world wearable conditions and detect frequency shifts induced by deformation.

3.2.1.3. Voltage Standing Wave Ratio (VSWR)

VSWR measures the voltage peak ratio caused by impedance mismatch. To ensure stable VSWR during deformation, techniques such as optimizing ground plane shape to disperse current and using highly elastic conductive materials can be employed to minimize impedance variations under strain.

3.2.1.4. S-parameters

S-parameters describe the reflection and transmission characteristics of a multi-port network. For single-port antennas: S_{11} denotes the reflection coefficient at the input port. S_{21} denotes the transmission coefficient. For single-port antennas, S_{11} is directly related to impedance matching and is defined as:

$$S_{11} = 20\log_{10}|\Gamma| \quad [dB] \tag{3}$$

For flexible antennas, S_{11} should remain stable under mechanical deformation such as bending or stretching.

3.2.1.5. Bandwidth

Bandwidth refers to the frequency range over which antenna performance meets design requirements. The human body's high dielectric constant can significantly reduce antenna bandwidth.

3.2.2. Radiation characteristics and signal quality parameters

Table 2: Key performance indicators

Parameter	Definition	Wearable Application Requirement	Optimization Method
Gain	Directional radiation capability	2–5 dBi (at 2.4 GHz)	·EBG structures ·Metamaterial loading
Directivity	Energy concentration	Wide beam / Omnidirectional	Multi-arm helical design
Polarization	Trajectory of electric field vector	Circular polarization (axial ratio < 3 dB)	Crossed dipole structure

4. Fabrication processes and integration technologies

The fabrication processes and integration technologies of flexible RF sensors are critical to determining their RF performance, mechanical stability, and multi-physical field compatibility. In recent years, with the deep integration of micro-electro-mechanical systems (MEMS) and flexible electronics, high-precision patterning technologies have become increasingly refined.

4.1. Patterning technologies

The fabrication process of flexible RF sensors directly influences their overall performance. At present, the mainstream methods include laser direct writing, inkjet printing, and screen printing, each with distinct advantages.

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4.1.1. Laser direct writing

Laser direct writing (LDW) stands out for its ultra-fine processing capabilities. This technique employs femtosecond lasers to achieve a processing precision of ±10 μm, making it particularly suitable for handling thermally sensitive materials such as PDMS and polyimide (PI). In terms of flexibility and environmental adaptability, the LDW-fabricated structures can maintain stable operation even in underwater environments. Various application scenarios are illustrated in Figure 7.

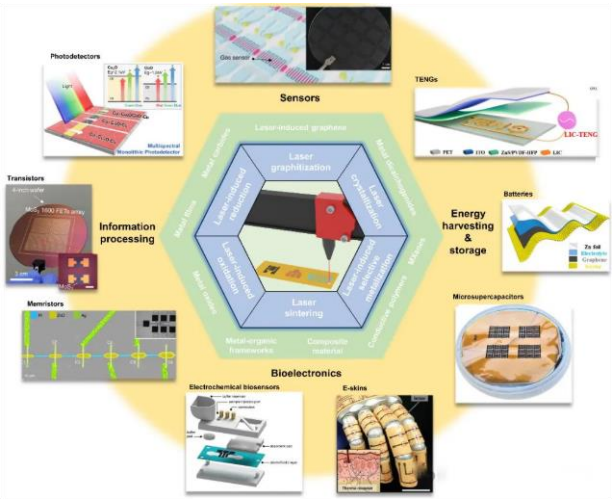


Figure 7: Different application scenarios of laser direct writing technology

4.1.2. Inkjet printing

Inkjet printing demonstrates excellent control at the micron scale. By optimizing the gradient sintering process of silver nanoparticle inks, conductivities as high as 3.2×10^7 S/m can be achieved. Recently developed graphene-based inks, enhanced via oxygen plasma surface pre-treatment, significantly improve substrate wettability, lowering sheet resistance to 18 Ω/sq. In ultra-wideband antenna fabrication, this technology has enabled edge roughness control within ±5 μm at the 5.5 GHz frequency band, supporting 2.9–12 GHz ultra-wideband performance [21].

4.1.3. Screen printing

Screen printing has made breakthroughs in balancing high resolution and high-frequency performance. By using MXene-based conductive inks, printed line widths as narrow as 50 μm can be achieved, with conductivity reaching 1.67×10^5 S/m, far exceeding that of traditional silver pastes [22]. Optimizing the surface morphology of substrates allows transmission loss at the 2.4 GHz band to approach that of bulk copper materials.

4.2. Heterogeneous integration

Heterogeneous integration enhances the performance and reliability of flexible RF systems through innovative material combinations and structural designs [23].

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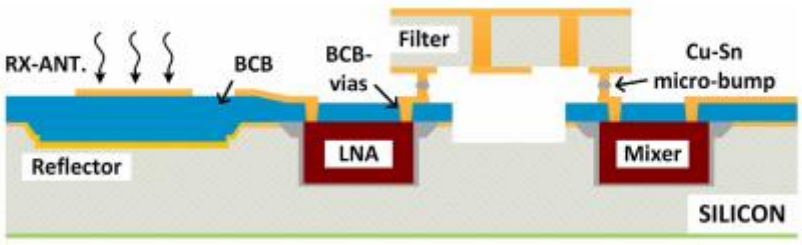


Figure 8: Sectional structure of W-band 3D heterogeneous flexible integrated receiver

A representative example is the development of a W-band receiver using a three-dimensional integration architecture, as shown in Figure 8. This design achieves an interconnection loss of just 0.21 dB at an operating frequency of 94 GHz. High-resistivity silicon effectively balances RF loss and thermal dissipation. Combined with a five-layer dielectric structure, the system effectively suppresses high-frequency crosstalk [24].

5. Performance optimization strategies for flexible wearable RF sensing antennas

5.1. Performance optimization of flexible substrates

5.1.1. Dielectric property regulation of substrates

The dielectric and mechanical properties of flexible substrates are critical for the stable operation of antennas. Studies show that polyimide substrates can achieve up to 93% radiation efficiency at 5.5 GHz, with resistance variation remaining below 5% after repeated bending cycles [25]. By adopting a defected ground structure (DGS), out-of-band suppression can be enhanced by 15 dB, and the dielectric resonator quality factor can be optimized to 26.16 [26]. Graphene-doped PDMS composites have been shown to improve antenna efficiency by 8% at 28 GHz, as detailed in Table 3.

Table 3: Performance comparison of different flexible substrate characteristics

Substrate material	ε_r	tanδ	Bindwidth	Peak Gain	Efficiency
Rogers 5880	2.2	0.0009	7.6	5.9	86.7
Denim	1.7	0.025	7.0	4.11	75.0
Rubber	3.0	0.015	5.05	3.98	89.9

5.1.2. Mechanical performance regulation of substrates

In terms of mechanical performance, the synergistic effect between PET substrates and metallic mesh conductive layers allows the resonant frequency deviation to remain within 0.1 GHz at a bending radius of 5 mm [27]. The geometry and characterization are illustrated in Figure 9.

DOI: 10.54254/2755-2721/2025.24537

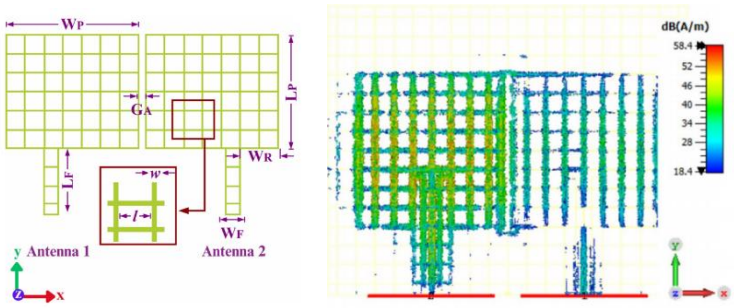


Figure 9: Geometric structure and characterization of flexible RF antenna with metal mesh conductive layer

5.2. Optimization of feeding and ground structures in flexible RF antennas

5.2.1. Hybrid feeding networks

Feeding structure design directly impacts both antenna performance and mechanical adaptability. A hybrid feeding network employing a four-layer PCB stacked architecture (see Figure 10) achieves a 13.3% impedance bandwidth in the 3.3–3.77 GHz range, with cross-polarization suppression reaching –25 dB [28]. Using a coplanar waveguide feed with gradient ground plane cuts, the axial ratio bandwidth was extended to 100%, while circular polarization gain fluctuations were kept under 0.3 dB.

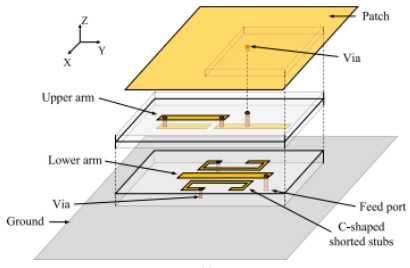


Figure 10: Flexible filtering antenna structure using hybrid feeding network

5.2.2. Defected Ground Structures (DGS)

DGS designs, incorporating rectangular defects and trapezoidal grooves, enable tri-band coverage across the 2.10–8.07 GHz range. In a four-element MIMO system, DGS integration increased isolation by 23 dB, while coupled current density was reduced from 12 A/m to below 2 A/m [29].

5.3. Optimization of radiation structures in flexible antennas

For multiband coordination, a wideband phase shifter design has been shown to support five-band coverage between 5.4–7.45 GHz, achieving 42% size reduction [30]. A combination of dielectric resonators and quasi-Yagi structures utilizing the TE_{181}/TE_{183} dual-mode characteristics enabled a working bandwidth of 8.7–11.1 GHz, improving gain by 2.8 dB [31].

Regarding coupling suppression, a Ta/Bi composite shielding material demonstrated a linear attenuation coefficient of 1.04228 cm^{-1}, 18.7% higher than conventional materials [32]. A DPCS structure based on characteristic mode analysis achieved 80 dB isolation, with an envelope correlation coefficient (ECC) reduced to 2×10^{-4} [33].

DOI: 10.54254/2755-2721/2025.24537

5.4. Common performance parameters of flexible wearable antennas

5.4.1. Mechanical characteristics

5.4.1.1. Strain range

The strain range reflects the antenna's capacity to undergo mechanical deformation. Liquid metal antennas can tolerate over 50% tensile strain.

5.4.1.2. Fatigue life

Fatigue life determines the long-term durability of antennas. Copper foil/PET antennas may experience up to 50% resistance increase after 10^4 bending cycles, while liquid metal and conductive textile antennas can endure over 10^6 cycles.

5.4.1.3. Elastic modulus

The elastic modulus is a key parameter representing the material's resistance to elastic deformation. It is defined as the ratio of stress (σ) to strain (ε), calculated as:

$$E = \frac{\varepsilon}{\sigma} \tag{5}$$

5.4.2. Electrical characteristics

The electrical performance parameters are summarized in Table 4.

Table 4: Performance indicator comparison

Parameter	Definition	Key Metric	Optimization Method	Typical Material Performance
Sensitivity	Deformation response capability	GF > 3	Microstructure design	CNT/PDMS (error < 5%)
Linearity	Input-output consistency	$R^2 > 0.98$	Pre-stretching treatment	Gradient-structured materials
Hysteresis	Deviation in cyclic response	< 5%	Elastomer composite	CNT/PDMS (20% lower deviation compared to metal foil)

5.4.3. Evaluation of wearability and comfort

The wearability and comfort evaluation of flexible antennas is presented in Table 5.

Table 5: Comfort evaluation metrics for flexible wearable antennas

Evaluation Dimension	Quantitative Indicator	Test Standard / Typical Value	Optimization Method
Breathability	Water vapor transmission rate	Textile substrate: >2000 g/m²/day Silicone encapsulation: <100 g/m²/day	·Porous structure design ·Selective encapsulation
Skin Irritation	Surface roughness Edge corner radius Cell viability	Ra < 1.6 μm Radius > 0.5 mm L929 cell viability > 80%	·Laser-polished edges · Biocompatible materials
Specific Absorption Rate (SAR)	Rate of electromagnetic energy absorption	Must comply with FCC/IEEE standards	·Optimize radiation direction ·EBG structure to reduce near-field coupling

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6. Application scenarios and representative cases

6.1. Applications of wearable flexible antennas in medical health monitoring

6.1.1. Wearable flexible antennas

Flexible antennas demonstrate tremendous potential in the healthcare sector. Operating in the 2.45 GHz ISM band, they can achieve a return loss of –23.34 dB and a radiation efficiency exceeding 30% [34]. A more advanced tri-band MIMO belt antenna features a goat-horn-shaped outer ring and an M-shaped inner ring structure, enabling multi-polarized radiation across the 2.37–6.03 GHz frequency range with radiation efficiency ranging from 46.1% to 80.1% [35]. When combined with millimeter-wave radar, these flexible antennas can perform fall detection with centimeter-level precision. A wearable flexible medical monitoring device using a goat-horn-shaped antenna is illustrated in Figure 13.

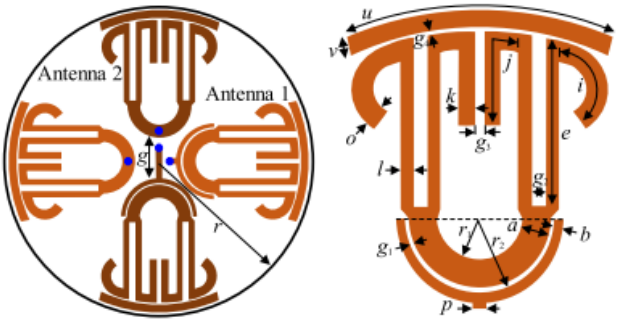


Figure 13: Goat horn wearable flexible medical detection device

6.1.2. Implantable flexible antennas

Significant breakthroughs have also been achieved in implantable applications. A recently developed spinal cord stimulation antenna system achieves 90% power transmission efficiency at the 2.4 GHz band. Its elastic modulus of 0.5–1.5 MPa closely matches that of spinal cord tissue, ensuring biomechanical compatibility [36]. A serpentine-structured implantable flexible antenna for medical monitoring is shown in Figure 14.

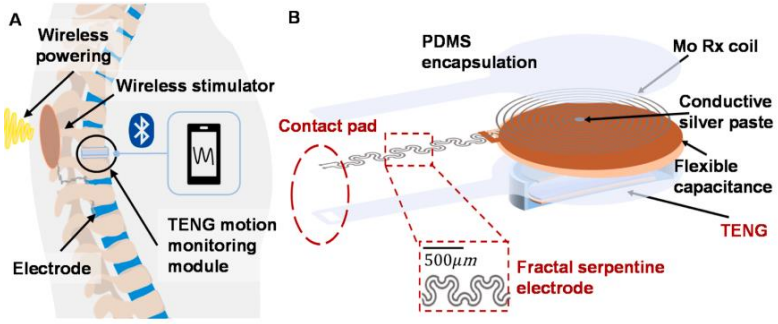


Figure 14: Serpentine implantable medical monitoring flexible antenna

6.2. Applications of wearable flexible antennas in civilian life

Flexible antennas are also gaining traction in consumer and civilian domains. A comparative overview of applications is provided in Table 6.

DOI: 10.54254/2755-2721/2025.24537

Table 6: Comparison of application cases of flexible antennas in civil field

Application Field	Technical Solution	Performance Indicators	Innovation Highlights
Consumer Electronics	Graphene NFC antenna	·Bending radius: 45 mm ·100,000 bending cycles ·Thickness: 55 μm	Ultra-thin flexible tag with anti-fatigue design
Agriculture / Food Logistics	Ethylene sensor + ML algorithm; Flexible tracking array	·Detection limit: 0.5 ppm ·Response time: 28 s / Accuracy: 97.5% · Positioning accuracy: < 3 cm	Stable low-temperature performance and rapid sensing
Industrial Inspection	256-element active array; 160 GHz flexible probe	·Mass: 0.1 g/cm² ·Crack detection: 0.2 mm ·Bending radius: 1.5 cm	Millimeter-wave penetration inspection with lightweight integration

7. Conclusion and outlook

Flexible wearable RF antennas have broken through traditional limitations by integrating innovations in materials and structural design, positioning themselves as a key enabling technology for smart healthcare and the Internet of Things (IoT). Liquid metals and conductive textiles offer high conductivity and biocompatibility, while serpentine and origami-inspired structures ensure mechanical durability. Advanced manufacturing processes such as laser direct writing and inkjet printing enable high-precision fabrication, while heterogeneous integration technologies expand the scope of functional applications. Looking forward, research will focus on: Biodegradable materials; Miniaturized manufacturing; Smart applications. These developments will drive breakthroughs in fields such as implantable medical devices and industrial monitoring, promoting a new era of human–machine interaction in the 5G and terahertz age.

References

[1] *Ali U, Ullah S, Kamal B, Matekovits L, Altaf A. Design, analysis and applications of wearable antennas: A review. IEEE Access. 2023;11:14458-86.*

[2] *Rais N, Soh PJ, Malek F, Ahmad S, Hashim N, Hall P, editors. A review of wearable antenna. 2009 Loughborough antennas & propagation conference; 2009: IEEE.*

[3] *Wagih M, Shi J. Wireless ice detection and monitoring using flexible UHF RFID tags. IEEE Sensors Journal. 2021;21(17):18715-24.*

[4] *Toi PT, Trung TQ, Dang TML, Bae CW, Lee N-E. Highly electrocatalytic, durable, and stretchable nanohybrid fiber for on-body sweat glucose detection. ACS applied materials & interfaces. 2019;11(11):10707-17.*

[5] *Paracha KN, Rahim SKA, Soh PJ, Khalily M. Wearable antennas: A review of materials, structures, and innovative features for autonomous communication and sensing. Ieee Access. 2019;7:56694-712.*

[6] *Zhu S, Langley R. Dual-band wearable textile antenna on an EBG substrate. IEEE transactions on Antennas and Propagation. 2009;57(4):926-35.*

[7] *Chen P, Wang D, Gan Z. Flexible and small textile antenna for UWB wireless body area network. Micromachines. 2023;14(4):718.*

[8] *Guan S, Li J, Wang Y, Yang Y, Zhu X, Ye D, et al. Multifunctional MOF‐Derived Au, Co‐Doped Porous Carbon Electrode for a Wearable Sweat Energy Harvesting–Storage Hybrid System. Advanced Materials. 2023;35(39):2304465.*

[9] *Zhou S, Zhang Y, Li X, Xu C, Halim J, Cao S, et al. A mechanically robust spiral fiber with ionic–electronic coupling for multimodal energy harvesting. Materials Horizons. 2024;11(15):3643-50.*

[10] *Zhao Z, Soni S, Lee T, Nijhuis CA, Xiang D. Smart eutectic gallium–indium: from properties to applications. Advanced Materials. 2023;35(1):2203391.*

[11] *Park YG, Lee GY, Jang J, Yun SM, Kim E, Park JU. Liquid metal‐based soft electronics for wearable healthcare. Advanced healthcare materials. 2021;10(17):2002280.*

DOI: 10.54254/2755-2721/2025.24537

[12] Huang CH, Yang X, Gong SQ, Zhang DX, Yan MD, Huo GZ, et al. Hierarchical‐Structured RGO@ EGaIn Composites as Advanced Self‐Healing Anode for Room‐Temperature Liquid Metal Battery. Advanced Materials. 2025;37(14):2419060.

[13] Zhang S, Jiang T, Han F, Cao L, Li M, Ge Z, et al. A wearable self-powered microneedle system based on conductive drugs for infected wound healing: A new electrical stimulation delivery strategy. Chemical Engineering Journal. 2024;480:148347.

[14] Cheng C-J, Balamurugan R, Liu B-T. Enhanced efficiencies of perovskite solar cells by incorporating silver nanowires into the hole transport layer. Micromachines. 2019;10(10):682.

[15] Tian G, Shi Y, Deng J, Yu W, Yang L, Lu Y, et al. Low-cost, scalable fabrication of all-fabric piezoresistive sensors via binder-free, in-situ welding of carbon nanotubes on bicomponent nonwovens. Advanced Fiber Materials. 2024;6(1):120-32.

[16] Li F, Wang L, Gao L, Zu D, Zhang D, Xu T, et al. Reducing Dielectric Loss of High‐Dielectric‐Constant Elastomer via Rigid Short‐Chain Crosslinking. Advanced Materials. 2024;36(47):2411082.

[17] Shi K, Zou H, Sun B, Jiang P, He J, Huang X. Dielectric modulated cellulose paper/PDMS‐based triboelectric nanogenerators for wireless transmission and electropolymerization applications. Advanced Functional Materials. 2020;30(4):1904536.

[18] Xu Y, Bai Z, Xu G. Constructing high-efficiency stretchable-breathable triboelectric fabric for biomechanical energy harvesting and intelligent sensing. Nano Energy. 2023;108:108224.

[19] Huang C, Huang S, Wang W, Huang X, Dianat A, Iqbal R, et al. Synthesizing Conductive Metal–Organic Framework Nanosheets for High-Performing Chemiresistive Sensors. ACS Applied Materials & Interfaces. 2025.

[20] Al Jamal H, Hu C, Kwao E, Zeng K, Tentzeris MM. Toward 5G/mm-Wave Shape-Changing Origami-Inspired Phased Arrays for Near-Limitless Arbitrarily Reconfigurable Radiation Patterns: Realization, Actuation, and Calibration. IEEE Transactions on Microwave Theory and Techniques. 2024.

[21] Labiano II, Alomainy A. Flexible inkjet-printed graphene antenna on Kapton. Flexible and Printed Electronics. 2021;6(2):025010.

[22] Chen S, Fu H, Si Y, Liu X, Wang Z, Duan Y, et al. Size effect enabling additive-free MXene ink with ultrahigh conductivity for screen printing of wireless electronics. Nano Research. 2023;16(8):11012-7.

[23] Yang X, Huang X-l, Zhou L, Zhang Z-q, Zhao J-z, Mao J-F. A 3-D heterogeneously integrated application of the RF-module with micro-bump filter and embedded AiP at W-band. IEEE Transactions on Components, Packaging and Manufacturing Technology. 2024.

[24] Zeng Q, Chen Z, He M, Wang S, Liu X, Xu H. Design of a Ka-band Heterogeneous integrated T/R module of phased array antenna. Electronics. 2024;13(1):204.

[25] Aliqab K, Armghan A, Alsharari M. A versatile semi-transparent quad-port multi and wide-band antenna for 4G/5G/WLAN/Wi-Fi 6E applications. Optical and Quantum Electronics. 2023;55(6):552.

[26] Xie Y, Chen F-C, Qian J-F. Design of integrated duplexing and multi-band filtering slot antennas. IEEE Access. 2020;8:126119-26.

[27] Abbasi MN, Aziz A, AlJaloud K, Chishti AR, Alqahtani AH, Abbasi D, et al. Design and optimization of a transparent and flexible MIMO antenna for compact IoT and 5G applications. scientific reports. 2023;13(1):20620.

[28] Du Z-T, Wang KX, Chen Z, Wong H. Design of a filtering antenna with hybrid feed structure for 5G communications. IEEE Transactions on Antennas and Propagation. 2023;71(12):9405-14.

[29] Wang S, Wu H, Duan Y. A Tri-Band Broadband Microstrip Antenna Based on DGS and Parasitic Elements. Iranian Journal of Science and Technology, Transactions of Electrical Engineering. 2022;46(3):883-92.

[30] Niksan O, Bemani M, SamadpourHendevari M. Miniaturized array antenna with reduced beam squinting. AEU-International Journal of Electronics and Communications. 2020;117:153110.

[31] Qian Z-Y, Yang L-L, Chen J-X. Design of dual-/wide-band quasi-Yagi antenna based on a dielectric resonator. IEEE Access. 2020;8:16934-40.

[32] Bondaruk A, Tishkevich D, Rotkovich A, German S, Zubar T, Vershinina T, et al. Flexible Ta/Bi structures for effective radiation shielding against ionizing radiation. Sensors and Actuators A: Physical. 2025;383:116229.

[33] Kang M-J, Park J, Heo H, Qu L, Jung K-Y. CMA-Based design of a Novel structure for isolation enhancement and Radiation Pattern correction in MIMO antennas. Scientific Reports. 2025;15(1):21.

[34] Dhanabalan SS, Sitharthan R, Madurakavi K, Thirumurugan A, Rajesh M, Avaninathan SR, et al. Flexible compact system for wearable health monitoring applications. Computers and Electrical Engineering. 2022;102:108130.

[35] Yang S, Zhang L, Wang W, Zheng Y. Flexible tri-band dual-polarized MIMO belt strap antenna toward wearable applications in intelligent internet of medical things. IEEE Transactions on Antennas and Propagation. 2021;70(1):197-208.

[36] Peng Z, Niu Z, Zeng C, Zhao W, Leng J, Liu Y. Design and functional verification of a flexible wireless spinal cord stimulator with spinal motion monitoring function. Nano Energy. 2025;139:110895.