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A Printed Monopole Antenna with Multiple Ground Plane Geometries for Multi-Protocol Wireless and Sweat Sensing Applications

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ABSTRACT A compact printed monopole antenna with multiple ground plane geometries is presented for multi-protocol wireless and sensing applications. The antenna, with physical dimensions of $25 \times 20 \times 0.8$ mm³ and three different ground plane shapes, operates across the C, X, and Ku bands, with the capability to reject interfering bands. It consists of a circular radiating patch, a coplanar waveguide transmission line, and arrow-shaped slots, designed on a Rogers RO4003C substrate. The antenna, with its original ground plane shape, covers three -10 dB operating bands, including 8.2–10.64 GHz, 12.1–24 GHz, 25.54–30 GHz. Although the simulation indicates rejection bands at 10.65–12.1 GHz and 24–25.54 GHz, the measured results show an improved impedance match. After modifying the ground plane, the second configuration operates exclusively within the X band. The third design is optimized for the C and Ku bands and rejects the X band frequencies. Additionally, this work introduces a miniaturized antenna sensor suitable for non-invasive hydration monitoring via sweat analysis. By integrating the sensor into athletes' shoes, it enables continuous, real-time monitoring during exercise, providing coaches with valuable insights to optimize hydration strategies and training intensity. The antenna sensor demonstrates a significant frequency shift in response to varying sweat concentrations, with a sensitivity of 20.57 MHz/1, allowing effective tracking of hydration levels throughout physical activity.

INDEX TERMS Biomedical applications, defected ground plane, microstrip antenna, multi-band antenna, monopole, X-band, sweat sensor.

I. INTRODUCTION

With the rapid growth of wireless communication systems and portable medical devices, miniaturized planar monopole antennas have become an effective feature for use in gathering places such as stadiums and arenas [1], [2], [3], [4]. These small-sized antennas can operate in multiple resonance modes and can be integrated with other devices to enhance overall functionality. Their key advantages include broad bandwidth, affordability, an omnidirectional radiation pattern, among others [5]. Consequently, the demand for compact multiband antennas has increased in recent years [6].

Achieving a compact, multiband antenna is challenging due to the trade-off between size and performance. To overcome this, researchers have widely utilized Defected Ground Structures (DGS) and specialized slot perturbations to alter surface current

paths, thereby modifying impedance bandwidth and radiation profiles without increasing physical boundaries. For example, recent wearable topologies have leveraged ground slots to enhance operational stability against frequency detuning [7], while alternative compact hexagonal patch structures have been evaluated for dual-band utility [8]. To safeguard performance under structural distortions, flexible planar antennas with low sensitivity to environment-induced shifts have also been realized [9]. Concurrently, advanced systems integrate compact patches with frequency-selective surfaces (FSS) to simultaneously boost peak gain and provide material sensing capabilities [10], while groove-slotted architectures implemented on textile layers offer promise for specialized healthcare configurations [11]. Additionally, manufacturing complexity and production costs can be

TABLE 1. Comparison of state-of-the-art studies with the current work.

Ref. Year	Excitation Type	Size (mm ³) Elect Size (λ ³)	Substra te	-10 dB Operating Bands (GHz)
[8] 2025	Microstrip Line	40 × 15 × 1/1.6 0.4 × 0.3 × 0.007	FR4 & Jeans	2.4/5 & 2.45/ 5.64
[9] 2025	Probe	36 × 36 × 2 0.3 × 0.3 × 0.008	Felt	2.45/10.5/12.5
[12] 2025	Microstrip Line	30 × 30 × 1.1 0.3 × 0.3 × 0.01	Glass	2.99–6.82/3.34– 3.44/4.07–4.56
[13] 2025	Microstrip Line	50 × 40 × 0.8 0.4 × 0.3 × 0.007	FR-4	2.45/3.43/7.69/8.25/ 9.79
[14] 2025	CPW	34 × 36 × 1 0.3 × 0.3 × 0.008	F4B	2.44–25
[16] 2025	Microstrip Line	240 × 200 × 1.6 0.3 × 0.2 × 0.002	FR-4	0.38–20
[17] 2025	Microstrip Line	160 × 260 × 1.52 0.2 × 0.3 × 0.002	TLY-5	0.42–35.96
[21] 2025	CPW	25.6 × 25.4 × 1.52 0.3 × 0.3 × 0.02	RO4003 C	3.1–10.6
[22] 2025	Microstrip Line	30 × 30 × 1.6 0.3 × 0.3 × 0.01	FR-4	3.32–11.96
[23] 2025	Microstrip Line	36.6 × 36.6 × 1.6 2 × 2 × 0.09	FR-4	16.92–18.74
[24] 2025	Microstrip Line	50 × 54 × 0.76 0.4 × 0.4 × 0.006	Taconic RF- 35(tm)	2.38–2.90/3.35– 3.85/5.06–5.80
[25] 2025	Microstrip Line	24 × 40 × 1.6 0.2 × 0.3 × 0.01	FR-4	2.5–4.2/7–9.8
[26] 2025	Microstrip Line	24 × 32 × 1.6 0.2 × 0.2 × 0.01	FR-4	2.6–5.8
[27] 2024	Microstrip Line	30 × 30 × 1.6 0.1 × 0.1 × 0.008	FR-4	1.51/4.30/7.57/11.3 6/14.04/15.00/15.95
[28] 2024	Microstrip Line	74 × 70 × 1.6 1 × 1 × 0.02	FR-4	4.01–4.82/7.6–7.94
[29] 2023	Microstrip Line	42 × 32 × 1.57 1.1 × 0.8 × 0.04	RT Duriot 5880	7.95–12.64
[30] 2023	CPW	35 × 34 × 0.13 0.2 × 0.2 × 0.01	polyimi de	2.26–3.16/4.93– 6.44/7.89–9.56
[31] 2023	Microstrip Line	40.5 × 30.5 × 1.6 0.3 × 0.2 × 0.01	FR-4	2.4–7.6
[32] 2023	CPW	36 × 30 × 0.9 0.3 × 0.2 × 0.007	Cotton	2.45
[33] 2023	CPW	25 × 35 × 0.787 0.3 × 0.3 × 0.008	RT Duriot 5880	3.2–20
[34] 2022	Microstrip Line	28 × 35 × 1.6 0.4 × 0.5 × 0.02	FR-4	4.57/5.86/6.25/8.89/ 10.78/12.49/14.2 8.2–10.64/12.1– 24/25.54–30
This work	CPW	25 × 20 × 0.8 0.3 × 0.2 × 0.01	RO4003 C	7.57–12.31 3.65–8.67/12.12– 14.5

reduced through strategies such as employing repetitive structures [12] and incorporating slots [13]. For example, [14] reported a coplanar waveguide (CPW)-fed monopole antenna with dimensions of $34 \times 36 \times 1$ mm³, suitable for superwideband applications. The designed antenna operates from 2.44 GHz up to over 25 GHz. Similarly, study [15] fabricated a d-shaped microstrip antenna with a size of $32 \times 31 \times 1.575$ mm³, targeting 5G applications and covering a broad frequency range. However, the antenna disadvantage is its large size that makes it unsuitable for integrating purposes. Additionally, as shown in [16] and [17], the antennas described are also relatively large but are capable of covering wideband frequencies. A comprehensive comparison of these state-of-the-art studies with the current work is detailed in Table 1.

Beyond conventional communication-only links, modern RF frameworks are expanding into multi-functional roles where a single radiator doubles as a passive sensor. Recent state-of-the-art designs include compact via-assisted circularly polarized antennas possessing dual-mode radiation characteristics optimized for real-time health monitoring systems [18]. Similarly, substrate integrated waveguide (SIW) platforms have enabled self-triplexing antenna-sensors capable of isolating multiple communication channels while maintaining dedicated sensing areas [19]. To achieve aggressive physical miniaturization profiles under these constraints, high-permittivity superstrate layers have been deployed to configure compact medical sensors [20]. Printed monopole antennas are among the most popular antenna sensors used in biomedical applications. They offer several advantages, including simple design, compactness, high directivity, and low cost. Due to their ability for real-time monitoring, these sensors are well-suited for applications such as sweat analysis [30], blood urea and glucose detection [35], and body temperature sensing [36]. They can be integrated into clothing and accessories, enabling continuous data collection from the human body. Given these capabilities, antenna sensors are poised to play a crucial role in the future of healthcare and biomedical monitoring.

In this work, a printed coplanar waveguide (CPW)-fed monopole antenna featuring a single-layer symmetric coplanar ground plane with modified slot geometries is proposed for C, X, and Ku band applications. While the baseline permittivity of the substrate ($\epsilon_r = 3.55$) contributes to standard size contraction, the extreme compactness of the design is primarily achieved via dedicated current-path elongation through the symmetric arrow-shaped slots. This structural layout provides true multi-protocol adaptability, distinguishing it from rigid conventional

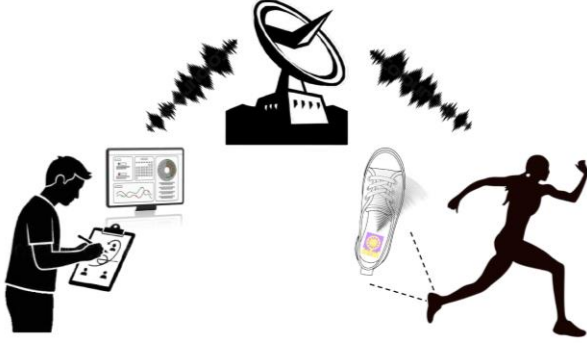


Fig. 1. Antenna sensor-based sweat monitoring for athletes

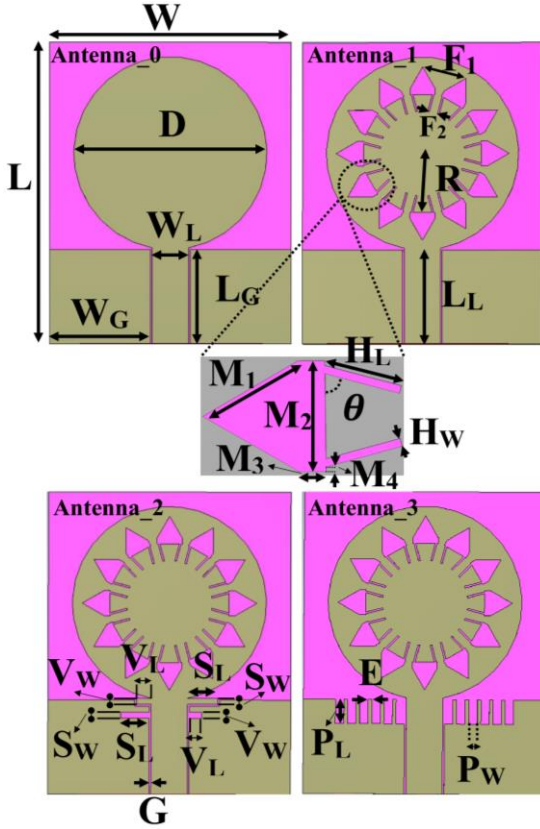
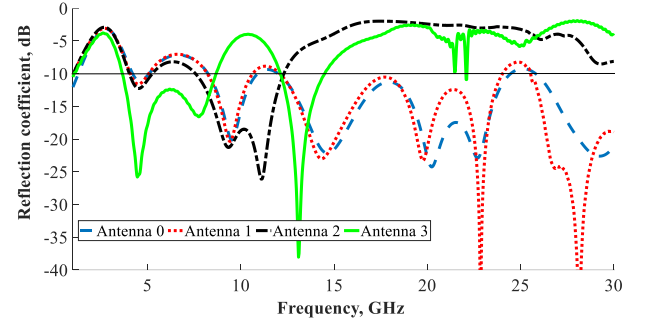
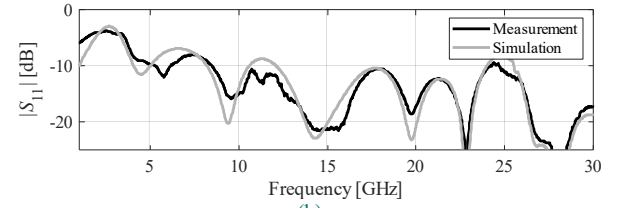


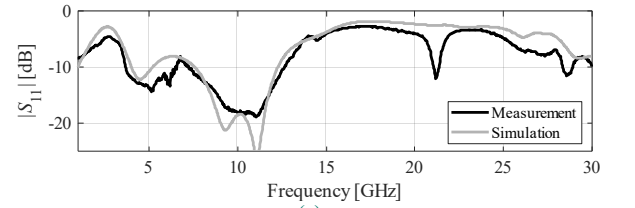
Fig. 2. Schematic geometries of Antennas 0, 1, 2, and 3 involved in the design process, where gray parts represent copper and purple parts represent the substrate ($\theta = 75^\circ$).



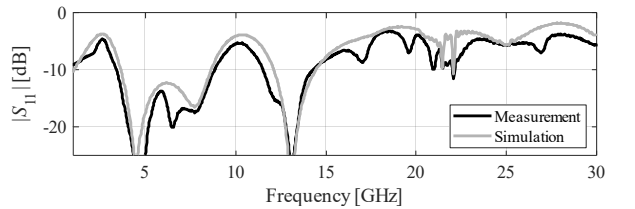
(a)



(b)



(c)



(d)

Fig. 3. Evaluation and experimental validation of the antenna development stages: (a) Overlaid simulated S_{11} responses for Antenna_0 through Antenna_3, and comparison of simulated and measured S_{11} characteristics for (b) Antenna_1, (c) Antenna_2, and (d) Antenna_3.

TABLE 2. Design Optimization Parameters for Antennas.

Parameter	Value (mm)	Parameter	Value (mm)	Parameter	Value (mm)
W	20	F ₁	3.73	G	0.2
L	25	F ₂	0.70	E	0.30
D	16	M ₁	2.80	V _L	1.20
L _L	7.94	M ₂	2.08	V _W	0.50
W _L	3	M ₃	0.50	S _L	2.50
L _G	7.80	M ₄	0.2	S _W	0.50
W _G	8.35	H _L	1.44	P _L	2
R	4.90	H _W	0.2	P _W	0.70

Fig. 1 illustrates the proposed sensing system for hydration monitoring. This antenna sensor can be

integrated into athletes' clothing to enable real-time monitoring of dehydration levels.

This article is organized into four main sections. Section II discusses the design principles of the proposed antenna and provides both simulated and measured results. Section III examines the antenna sensor performance and its applications. Finally, Section IV provides the conclusion and outlines future work.

II. ANTENNA DESIGN AND STRUCTURE

A. GEOMETRY

Fig. 2 illustrates the geometry of the monopole antenna featuring a single-layer coplanar ground structure, as listed in Table 2. The antenna is fabricated on an RO4003C substrate, which has a dielectric constant (ϵ_r) of 3.55, a loss tangent ($\tan\delta$) of 0.0027, and a height of 0.8 mm. As shown in Fig. 2, the circular radiating patch features 12 arrow-shaped slots. These slots are designed by combining a triangular element with sides M_1 and M_2 , a rectangular element with dimensions M_2 and M_3 , two legs, each with a length of H_L and a width of H_W , and a thin strip characterized by length and width denoted as W_L and L_L . The antenna is fed using a coplanar waveguide (CPW) technique. For Antenna_2, the ground plane is modified by loading an asymmetrical metallic strip onto the feed line and introducing an asymmetrical slot in the ground plane, with length parameters S_L and V_L , and width parameters S_W and V_W . In Antenna_3, the ground plane is modified by incorporating six symmetrical rectangular slots, each with length P_L and width P_W , with the spacing between the slots denoted as E . Additionally, the gap between the transmission line and other elements in all designs is $G = 0.2$ mm.

A common limitation found across wideband wearable antenna literature is the reliance on microstrip configurations with bottom-layer partial ground planes. While simple to implement, partial ground planes exhibit severe back-radiation properties that lead to massive impedance detuning, high tissue energy absorption (SAR), and diminished radiation efficiency when operated near the human body. To circumvent these operational disadvantages, the proposed architecture explicitly avoids multi-layer ground structures or conventional partial grounds, opting instead for a single-layer Coplanar Waveguide (CPW) feed topology. The CPW configuration forces the intense electromagnetic near-fields to concentrate horizontally across the top-surface gaps between the patch and the lateral grounds. This localized self-shielding boundary significantly suppresses back-radiation into lossy biological mediums. Simultaneously, it allows controlled surface fringing fields to interact directly with the external environment, a mechanism that is

fundamentally required to achieve high-sensitivity dielectric tracking for the device's secondary application as a non-invasive sweat sensor.

The antenna design process initiates with a fundamental circular monopole configuration, designated as Antenna_0, which serves as the reference geometry to establish initial resonance (See Fig. 3). To enhance impedance matching and optimize resonance characteristics, twelve arrow-shaped slots are symmetrically etched into the circular patch (Antenna_1); the resulting reflection coefficient (S_{11}) is illustrated in Fig. 3(b). As observed in the experimental validation of Antenna_1, the sharp simulated rejection bands appearing at 10.65–12.1 GHz and 24–25.54 GHz are noticeably smoothed out in practice, displaying a continuous, improved impedance match well below the -10 dB threshold. This discrepancy between the simulated characteristics and the measured response is primarily attributed to realistic non-idealities, including the dielectric losses of the Rogers RO4003C substrate, conductor losses driven by copper surface roughness, and parasitic effects from the manual SMA connector soldering. Further refinement of the ground plane leads to Antenna_2, which achieves high-efficiency performance across the 7.57–12.3 GHz frequency range [Fig. 3(c)]. Its compact footprint, lightweight profile, and fabrication simplicity make it an ideal candidate for X-band radar applications. Finally, as shown in Fig. 3(d), Antenna_3 demonstrates a robust ultrawideband (UWB) response, with a -10 dB operational bandwidth spanning 3.65–8.67 GHz and 12.1–14.5 GHz. This expansive bandwidth allows Antenna_3 to function as an effective sensor while maintaining spectral compatibility with existing communication standards, such as WiMax and WLAN.

While the evolutionary progression from Antenna_0 to Antenna_3 demonstrates a clear systematic optimization of the reflection coefficient curves shown in Fig. 3(a), the underlying physical mechanism of the slot configurations extends beyond simple current-path elongation. The baseline un-slotted radiator (Antenna_0) operates fundamentally on its primary physical patch dimensions. However, the introduction of the symmetric arrow-shaped slots behaves as an array of embedded, distributed reactive LC networks. The narrow-localized gaps within the slots behave as capacitive elements, while the adjacent narrow metallic paths act as series inductors. This localized reactive loading effectively alters the structural boundary conditions, shifting higher-order transverse magnetic modes (TM_{mn}) down into the target operational bands. This mechanism creates distinct ultra-resonance points without requiring an expansion of the physical footprint. Furthermore, the sharp inward notches of the arrow slots force a severe concentration of the reactive electric field (E-field) near

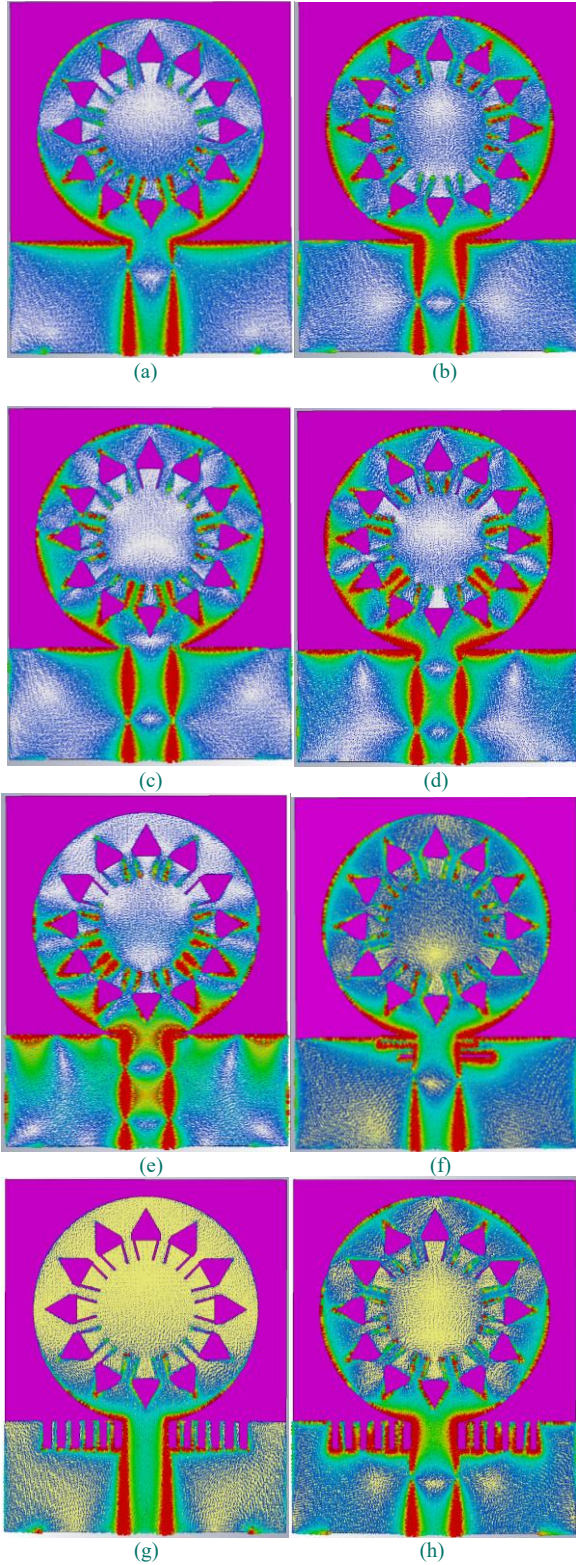


Fig. 4. Surface current distributions: (a)-(e) Antenna_1 at 9.42, 14.35, 19.76, 22.86 and 28.14 GHz, respectively, (f) Antenna_2 at 11.12 GHz, (g)-(h) Antenna_3 at 4.45 and 13.09 GHz, respectively. Scale: magnitude ranging from 0 to 20 A/m.

substrate material, optimizes impedance bandwidth matchings, and establishes an ultra-sensitive capacitive boundary layer that is essential for tracking sweat permittivity variations.

To validate the multi-protocol capability emphasized in this work, the discrete resonant frequencies of the proposed configurations are explicitly mapped to corresponding commercial wireless standards. The lowest operating spectrum supported by Antenna_3 (3.65–8.67 GHz) captures the rigid bandwidth allocations of standard WiMAX (3.5 GHz) and high-speed local networks under the WLAN IEEE 802.11a/n/ac/ax protocols (5 GHz), alongside sub-6 GHz 5G communication protocols. The intermediate operational spectrum established by Antenna_2 (7.57–12.31 GHz) and Antenna_1 (8.2–10.64 GHz) directly matches the standards set for X-band radar architectures and aerospace-satellite link protocols. The higher operational bands spanning 12.1–24 GHz and 25.54–30 GHz fulfill the strict technical specifications of Ku-band satellite television broadcasting (Direct-to-Home), maritime communication, and high-frequency millimeter-wave (mmWave) 5G network protocols. Concurrently, the independent low-frequency resonance allocated for sweat sensing operates within the C-band, mapping directly to low-power biomedical telemetry over standard body-centric networks. This extensive spectral coverage permits a miniaturized radiator asset to transition seamlessly across multi-protocol operational modes.

B. SURFACE CURRENT DISTRIBUTION

To further illustrate the antennas' operational behavior, surface current distributions were analyzed for Antenna_1 to 3 (Fig. 4). The color coding indicates current density levels, with red representing strong currents and blue indicating weaker currents. As shown in Fig. 4(a), the transmission line is well matched, resulting in minimal losses, and the current flows effectively toward the radiating element. As the frequency increases, the current density becomes more concentrated around the radiating patch, which is evident in the figure. Fig. 4(b) and 4(c) demonstrate that modifications to the ground plane in Antenna_2 and 3 cause the current to shift toward the edges of the structure, thereby enhancing the radiation performance, directivity, and efficiency. This shift underscores the effectiveness of the design adjustments in optimizing the antennas' functionality. Moreover, Fig. 4 highlights that alterations to the ground plane exert the most significant influence on the operational frequency of the antennas.

C. PARAMETRIC STUDY

To systematically evaluate the geometric choices and establish the physical mechanism behind the antenna's

multi-band operation, a rigorous parametric study was conducted on the primary tuning variables. The influence of the number of slots (B), and the critical ground plane slit lengths (S_L and V_L) on the input reflection coefficient (S_{11}) is systematically presented in Fig. 5. These parameters are vital because they directly perturb the surface current distribution, thereby governing the input impedance matching, return loss depth, and resonant frequency positioning. Fig. 5(a) illustrates the performance variance as the number of rectangular slots (B) is altered from 1 to 6. Parameter B serves as a primary mechanism for adjusting the reactive loading of the radiating structure. When B is varied, it alters the capacitive coupling across the patch boundaries. As observed in Fig. 5(a), changing B significantly impacts the impedance matching depth (S_{11} magnitude) across the band. While lower values of B lead to poor impedance matching or unwanted band segmentation, the optimized selection of $B = 6$ ensures an ideal compromise between stable multi-band resonance and excellent impedance matching, preventing destructive interference that could degrade the return loss bandwidth.

The effect of varying the slit length S_L from 0.5 mm to 3.0 mm on the antenna's response is depicted systematically in Fig. 5(b). Parameter S_L primarily controls the electrical path length of the fundamental surface currents flowing along the modified ground plane structure. As S_L scales upward, the physical path length for the currents increases, which translates to a clear downward displacement of the resonant frequency nodes. Concurrently, the plot reveals that adjusting S_L serves to fine-tune the input impedance matching within the target X-band. When S_L deviates from its optimized value of 2.5 mm, the impedance locus shifts, leading to mismatched transitions and narrowed operating bandwidths at the lower band edge. Additionally, Fig. 5(c) demonstrates the parametric behavior of the secondary slit length V_L as it is swept from 0.8 mm to 1.6 mm. While S_L establishes the primary current boundaries, V_L acts as a critical matching parameter for the upper-frequency bands (specifically tracking the X and Ku-band boundaries). The parameter sweeps show that variations in V_L introduce precise modifications to the slot-induced inductive and capacitive fields. By systematically tuning V_L to its optimized value of 1.2 mm, the impedance matching is optimized to achieve an uninterrupted, deep reflection coefficient profile well below -10 dB. If V_L is too small or too large, the impedance matching degrades rapidly at the band edges. Consequently, the definitive values chosen in Table I represent a mathematically optimized state where resonance frequency allocation and multi-band impedance matching bandwidth are simultaneously maximized.

355 D. RADIATION PATTERN

356 The far-field characteristics of the fabricated antennas
357 (Fig. 6(a)) were characterized within an anechoic
358 chamber, as shown in Fig. 6(b). Figures 6(c)–(e)
359 illustrate the simulated and measured realized gains as a
360 function of frequency; as observed, the experimental
361 results are in good agreement with the numerical data.
362 Furthermore, the simulated and measured far-field
363 radiation patterns were analyzed at the main resonant
364 frequencies. As shown in Fig. 7, the radiation patterns
365 for Antenna_1 (at 9.42, 14.35, 19.76, 22.86, and 28.14
366 GHz), Antenna_2 (at 11.12 GHz), and Antenna_3 (at
367 4.45 and 13.09 GHz) exhibit distinct gain and
368 beamwidth characteristics. At 9.42 GHz, Antenna_1
369 achieves a realized gain of 4 dBi with a broad
370 beamwidth. As the frequency increases to 14.35 GHz,
371 the gain reduces to approximately 0.66 dBi, while the
372 beamwidth and directivity remain relatively consistent.
373 Further frequency increments result in gains of 0.56 dBi
374 (19.76 GHz), -0.21 dBi (22.86 GHz), and 0.86 dBi
375 (28.14 GHz). Antenna_2 demonstrates a realized gain of
376 2.76 dBi at 11.12 GHz, characterized by a narrower
377 beamwidth and higher directivity. The numerical
378 analysis shows that the antenna achieves a high radiation
379 efficiency of -0.8726 dB (81.80%), while the total
380 efficiency reaches -0.8831 dB (81.60%). These values
381 confirm that the proposed structure maintains minimal
382 internal losses and exhibits highly efficient energy
383 radiation into the free-space environment, fully
384 supporting its capability for high-performance operation.
385 Meanwhile, Antenna_3 exhibits gains of 0.87 dBi and -
386 4.99 dBi at 4.45 GHz and 13.09 GHz, respectively. The
387 radiation patterns, evaluated at $\phi = 0^\circ$, highlight the
388 directional performance and effective energy
389 concentration of the proposed designs (Fig. 7).

390 As observed in the far-field performance plots, the
391 proposed antenna's realized gain drops significantly,
392 reaching negative values, at specific out-of-band
393 frequencies between the designated operational
394 resonances. This characteristic is primarily attributed to
395 the severe input impedance mismatch outside the
396 operating bands, where the reflection coefficient (S_{11})
397 approaches 0 dB, leading to dominant reflection losses
398 as governed by the realized gain relation $G_R = G_A (1 - |S_{11}|^2)$.
399 Under these non-resonant states, the surface
400 currents fail to distribute effectively across the radiating
401 aperture; instead, they become heavily localized and
402 confined within the reactive near-field regions of the
403 central arrow-shaped slot and ground plane slits,
404 suppressing far-field radiation. The direct consequence
405 of this behavior is highly advantageous, providing the
406 antenna with an inherent bandpass filtering profile. By
407 introducing high attenuation and poor radiation
408 capability at non-targeted frequencies, the structure
409 effectively mitigates out-of-band noise and suppresses

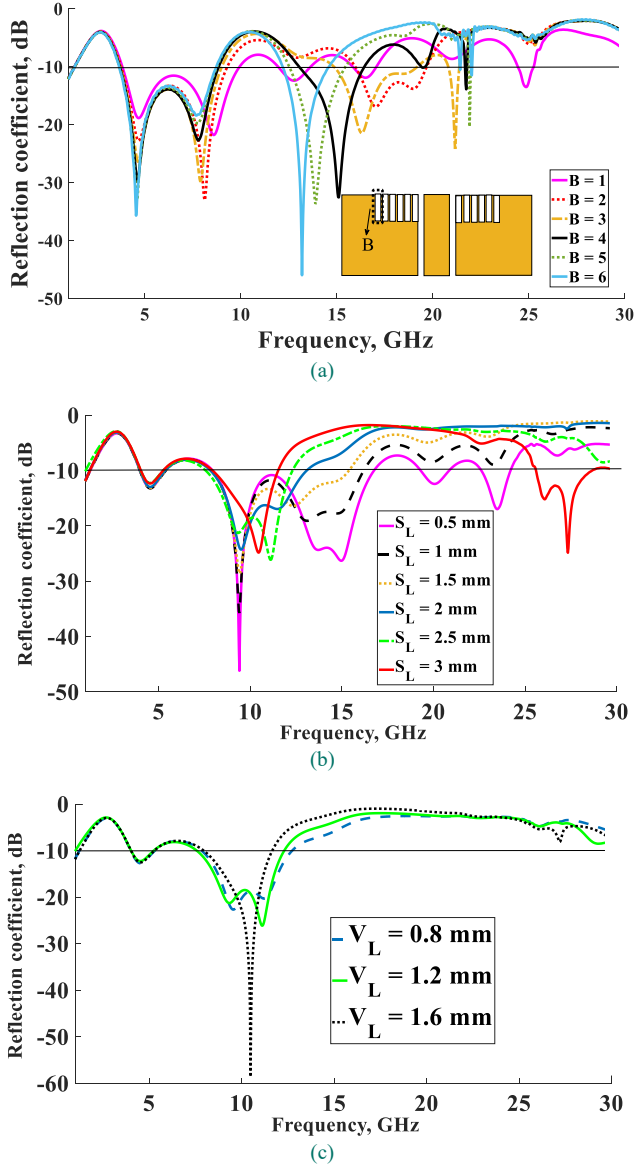


Fig. 5. Simulated antenna input reflection coefficients as functions of: (a) B, (b) S_L , and (c) V_L .

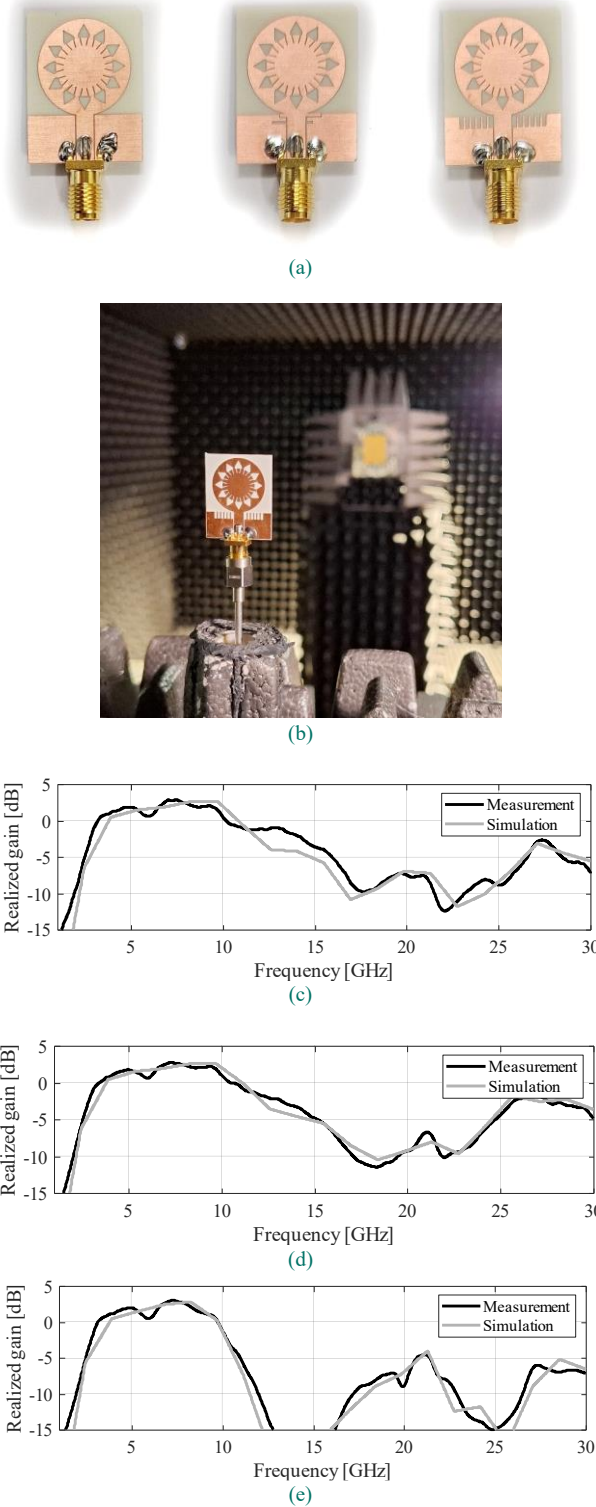


Fig. 6. (a) Antenna prototypes. (b) Measurement setup and partial far-field performance evaluation. Simulated and measured gain of (c) Antenna_1, (d) Antenna_2, and (e) Antenna_3.

adjacent-channel interference. This built-in frequency selectivity eliminates the necessity for external, bulky RF filtering networks, making it highly suitable for high-isolation multi-band communication systems.

III. ANTENNA SENSOR PERFORMANCE

Monitoring human sweat allows for the assessment of hydration levels in athletes, and these valuable data can also be leveraged for medical applications. The complex relative permittivity of sweat, denoted as $\epsilon_r(\omega, I)$, can be calculated by using the following equation:

$$\epsilon_r(\omega, I) = \epsilon_\infty(I) + \left(\frac{\epsilon_s(I) - \epsilon_\infty(I)}{1 - (j\omega\tau(I))^{1-\alpha}} \right) + \frac{\sigma_s}{j\omega\epsilon_0} \quad (1)$$

In this context, $\epsilon_\infty(I)$ represents the permittivity at infinitely high frequencies, while $\epsilon_s(I)$ corresponds to the static (low-frequency) relative permittivity. The

Radiation patterns (simulation – gray, measurement – black)

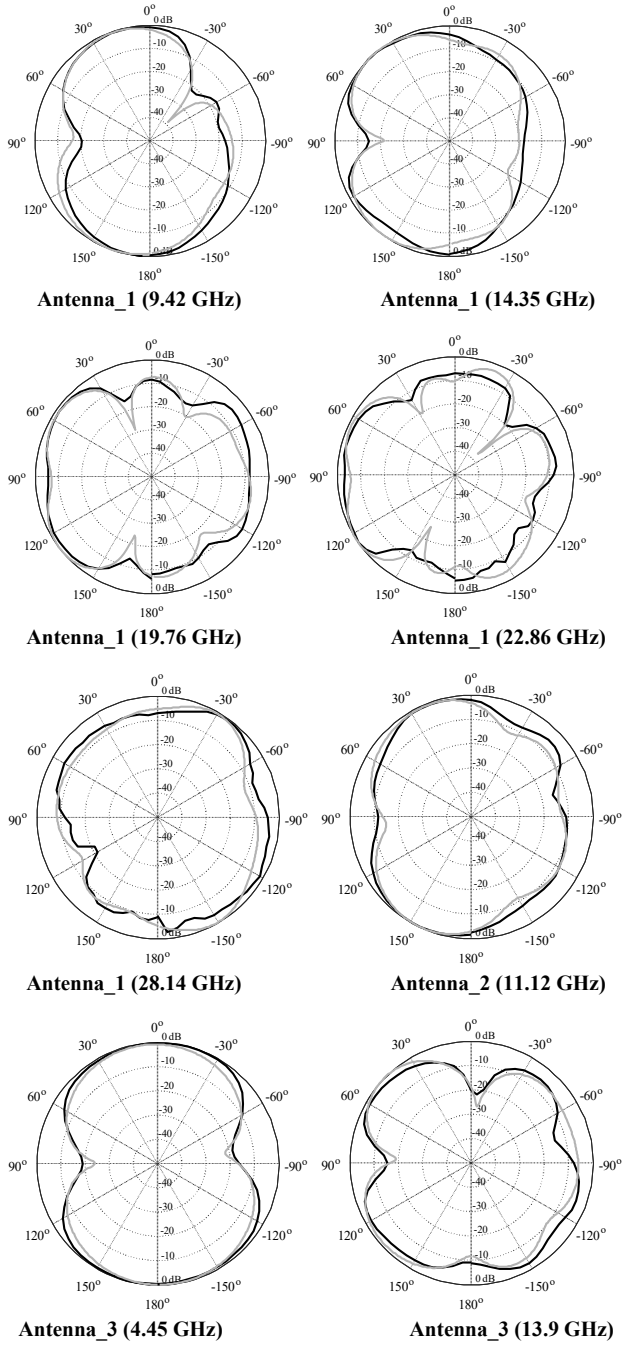


Fig. 7. Radiation Patterns of Antenna_1 at 9.42, 14.35, 19.76, 22.86, and 28.14 GHz; Antenna_2 at 11.12 GHz; and Antenna_3 at 4.45 and 13.09 GHz

permittivity of free space is represented by ϵ_0 . The parameter τ indicates the relaxation frequency, σ_s is the

static conductance, and α is the dispersion parameter. These variables collectively describe the frequency-dependent dielectric behavior of synthetic sweat, which varies depending on the concentration of dissolved substances (metabolites, minerals, and amino acids), I (mg/dL) [37].

It should be noted that the evaluation of the sweat-sensing mechanism in this work is conducted as a rigorous numerical feasibility study. While the primary multi-band communication capabilities of the antenna were validated via physical prototype measurements in an anechoic environment, executing highly controlled, repeatable concentration sweeps for fluidic tracking require specialized biomedical microfluidic infrastructure. Consequently, the sensing potential of Antenna_3 is evaluated using a high-fidelity electromagnetic solver by mapping the exact frequency-dependent complex permittivity (ϵ_r) of artificial sweat mixtures, derived from the established Cole-Cole dielectric model, directly onto the localized capacitive boundary of the antenna. This method provides a highly reliable, mathematically grounded prediction of the sensor's real-world behavior.

The arrow-shaped slots in the circular patch antenna significantly enhance its sensitivity to environmental changes caused by sweat, which is why Antenna_3 is selected for non-invasive, real-time sweat monitoring (see Fig. 1). To measure sweat concentration levels, a circular sponge with an approximate dielectric constant of $\epsilon_r = 1$ is placed in contact with the radiating patch, as also utilized in reference [30]. The sponge dimensions are 16 mm in diameter (b) and 2 mm in height (h), with an additional 0.1 mm gap to accommodate adhesive material (Fig. 8 (a)). These dimensions are chosen to optimize sweat absorption, enabling effective evaluation of sweat concentration levels. When perspiration occurs, the sweat penetrates into the sponge, interacting with the antenna's electromagnetic field and causing a shift in the resonant frequency. The simulated reflection coefficient (S_{11}) curves, with and without sweat loading, are shown in Fig. 8(b). It is observed that the resonant frequency shifts toward lower values upon sweat absorption. Additionally, a new resonance appears between the primary resonances, indicating a change in the antenna's response due to the surrounding dielectric medium. These frequency shifts demonstrate the antenna's potential as an effective sensor for sweat detection.

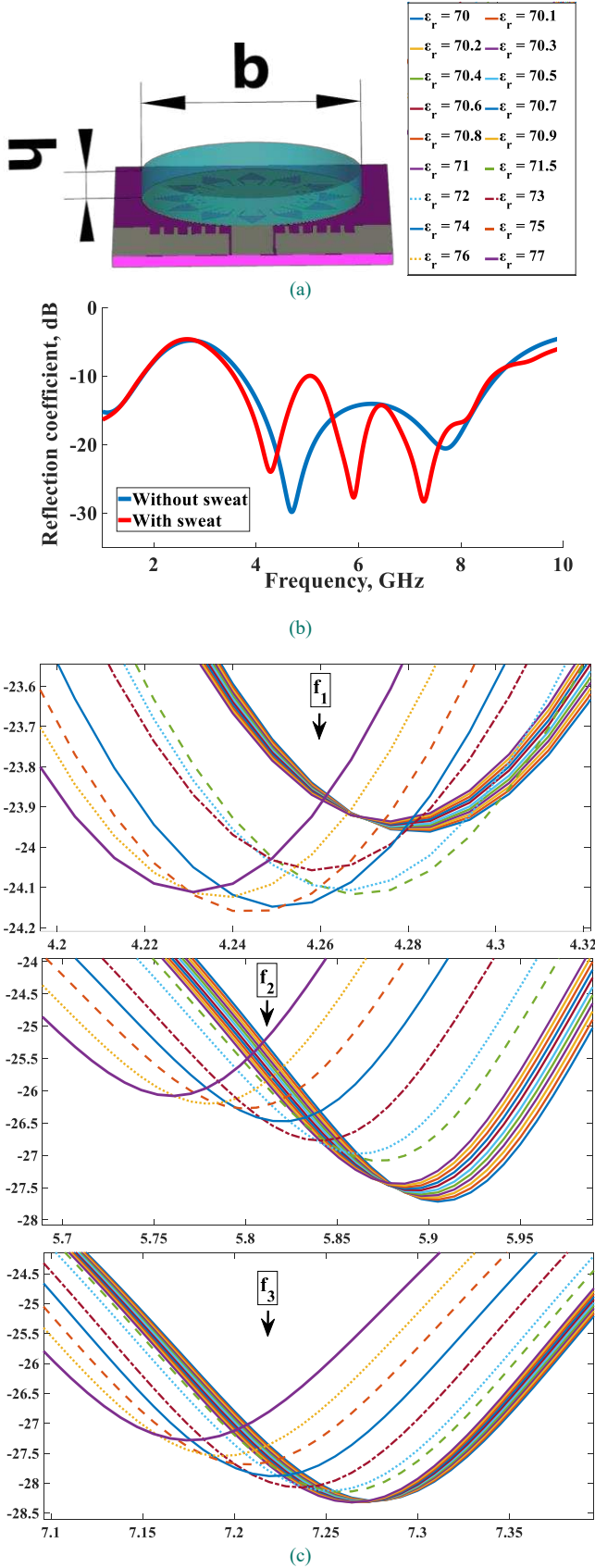


Fig. 8. (a) Dimensions of the proposed sponge integrated with the antenna sensor. (b) Simulated S_{11} of the antenna sensor with and without sweat. (c) Simulated S_{11} of the antenna sensor with different sweat concentrations.

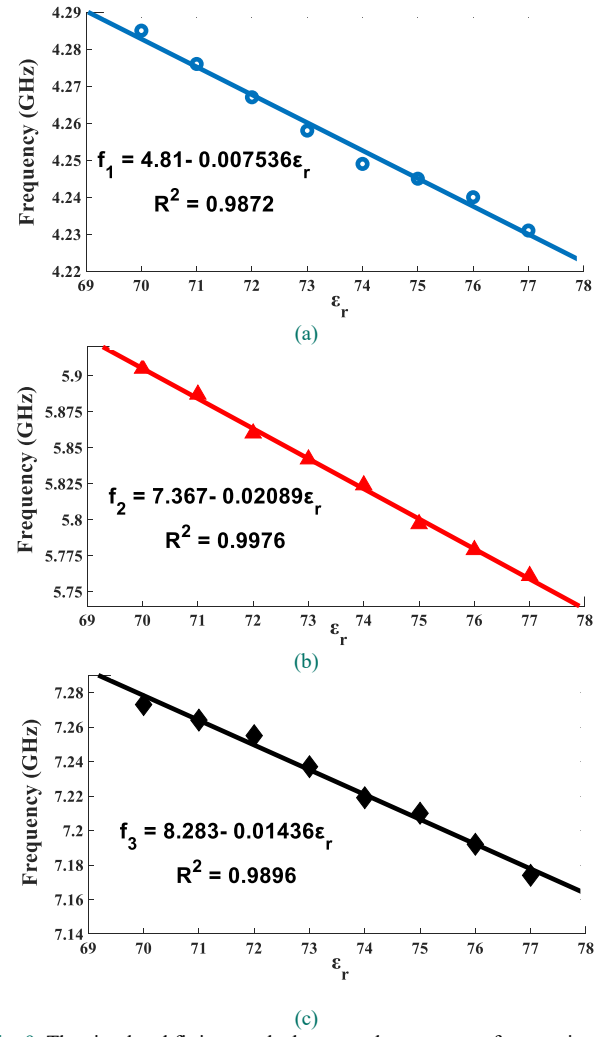


Fig. 9. The simulated fitting results between the resonance frequencies and sweat concentrations.

TABLE 3. Comparison Between Recently Reported Antenna Sensors.

Ref.	Size (mm ³)	Bandwidth (GHz)	Material	Sensitivity	Sweat Sensing
[38]	25×25×0.5	3.7–6.25	PDMS	-	No
[39]	28×28×0.5	0.61–1.75	PI film	5.58 MHz/ μ L	Yes
[40]	50×13.5×0.5	0.8–1	Various fabric substrates	-	Yes
[41]	25×40×1.5	2.2–2.8	RT5880	-	No
[42]	20×16×1.5	3.5, 4.9, 5.8	Treated jute fabric	-	Yes
[43]	50×60×0.18	2–4	Paper	6 MHz/ μ L	Yes
[44]	21×21×0.127	0.13	RT5880	-	Yes
[30]	35×34×0.13	2.26–3.16, 4.93–6.44, 7.89–9.56	Polyimide	4.57 MHz/1	Yes
This work	25×20×0.8	3.57–8.62	RO4003C	20.57 MHz/1	Yes

frequency (f_2) is highly sensitive to varying sweat concentrations. Specifically, f_2 decreases from 5.905 GHz to 5.761 GHz as the sweat concentration increases from $\epsilon_r = 70$ to $\epsilon_r = 77$. Similarly, the resonant frequencies f_1 and f_2 shift from 4.285 GHz to 4.231 GHz

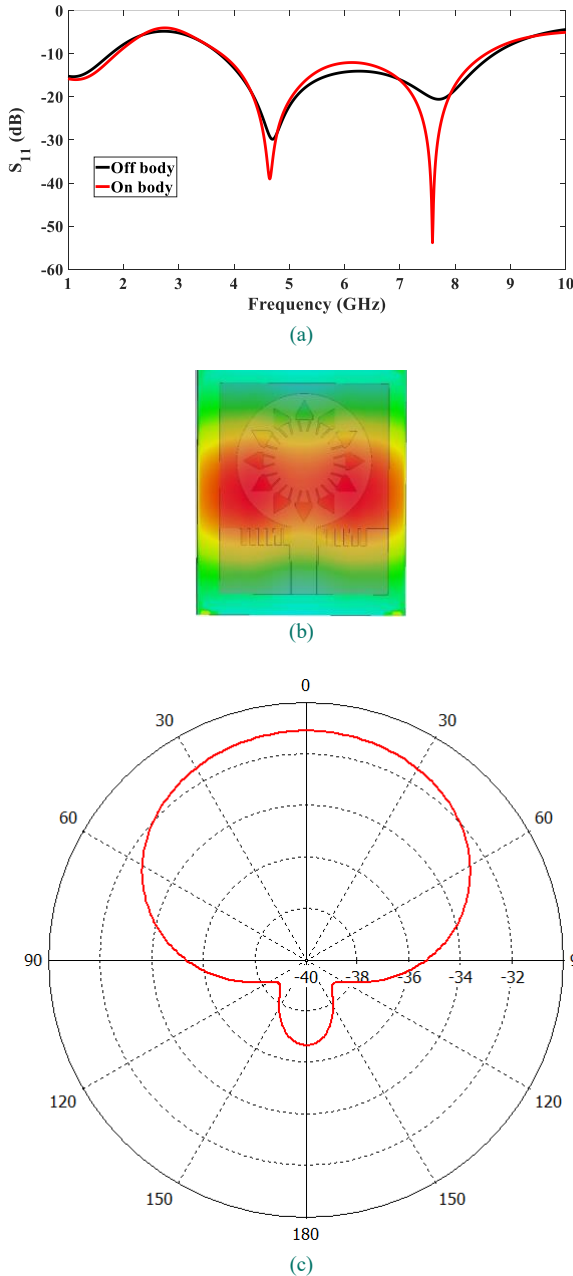


Fig. 10. Performance evaluation of the antenna sensor in proximity to the human body model: (a) Simulated reflection coefficient comparison under off-body (free space) and on-body scenarios, (b) 3D simulated Specific Absorption Rate (SAR) distribution on the multi-layered human tissue phantom at 4.45 GHz, and (c) 2D polar in-situ radiation pattern.

and from 7.273 GHz to 7.176 GHz, respectively. The simulated S_{11} magnitude for all three resonances (f_1 , f_2 , and f_3) remains below -24 dB, indicating strong reflection suppression and confirming the sensor's sensitivity to sweat levels. The relationship between the resonant frequencies and sweat concentration is depicted in Fig. 9 and can be expressed mathematically as:

$$f_1 = 4.81 - 0.02089\varepsilon_r \quad (2)$$

$$f_2 = 7.367 - 0.007536\varepsilon_r \quad (3)$$

$$f_3 = 8.283 - 0.01436\varepsilon_r \quad (4)$$

As illustrated in Fig. 9, the models exhibit excellent goodness-of-fit with Coefficient of Determination (R^2)

values of 0.991, 0.992, and 0.999 for the resonant frequencies f_1 , f_2 , and f_3 , respectively. This confirms a linear correlation between the relative permittivity of the sweat and the corresponding frequency shifts.

Furthermore, the sensitivity of the antenna sensor can be calculated using the following formula:

$$S = \frac{f_{max} - f_{min}}{\varepsilon_2 - \varepsilon_1} \quad (5)$$

Based on the analysis, the sensitivities for f_1 , f_2 , and f_3 are 7.71 MHz/1, 20.57 MHz/1, and 14.14 MHz/1, respectively. Notably, f_2 exhibits the highest sensitivity to variations in sweat concentration, making it the most responsive resonance. This characteristic enables the proposed antenna sensor to effectively monitor athletes' hydration levels. Its advantages include compactness, non-invasiveness, and real-time measurement capabilities.

Given the intended wearable application of the proposed antenna, it is imperative to investigate the electromagnetic interaction between the planar monopole structure and the human body. The human body inherently acts as a lossy dielectric reflector due to its high permittivity and conductivity, which can heavily influence impedance matching, induce frequency shifts, and raise safety concerns regarding backward electromagnetic absorption. To evaluate the detuning effects, the antenna was placed at a distance of 17 mm above a multi-layered tissue phantom, representing standard human skin, fat, and muscle equivalent properties. The comparative S_{11} results (Fig. 10(a)) illustrate that the close proximity to the body introduces a minor downward frequency shift across the operational bands. This is primarily attributed to the increased capacitive loading from the high-permittivity tissue. However, the fundamental multi-band characteristics are preserved, and the reflection coefficient remains safely below the -10 dB threshold for all target bands. Furthermore, the dielectric constants of the tissue layers (skin, fat, and muscle) are 36.2, 5.8, and 50.2, respectively. To ensure compliance with human safety regulations, the Specific Absorption Rate (SAR) was computationally evaluated to quantify the backward radiation absorbed by the tissue. The simulations were configured with a standard input power of 10 mW, and the spatial peak SAR was averaged over a 1 g volumetric mass. As depicted in the spatial SAR distributions in Fig. 10(b), the maximum SAR value recorded at 4.45 GHz is 0.218 W/kg. This value remains well below the strict regulatory limit of 1.6 W/kg, confirming that the proposed structure is exceptionally safe for continuous on-body operation. As depicted in Fig. 10(c), the 2D polar radiation pattern of the far-field realized gain ($\phi = 0^\circ$) exhibits a highly directive broadside beam pointing away from the body

tissue. Due to the high permittivity and conductivity of the underlying tissue layers, a significant portion of the backward radiation is absorbed or reflected away from the body. This results in an exceptional suppression of the back-lobe, with radiation levels dropping significantly to approximately -40 dB. This directive behavior ensures robust wireless link performance while simultaneously minimizing electromagnetic radiation absorption within the human body.

To ensure the reliability of the passive microwave sensor in practical scenarios, the cross-sensitivity effects of environmental factors, such as geometric deformation and fluctuating body-antenna proximity, must be isolated from the target sweat concentration metrics. This isolation is systematically achieved via structural design and field confinement. First, because the device is fabricated on a rigid Rogers RO4003C substrate rather than a flexible organic sheet, the antenna maintains total dimensional integrity, eliminating frequency detuning caused by structural bending or stretching. Second, for real-world deployment, the sensor is designed to be packaged inside a rigid, low-loss polymer housing that establishes a fixed physical inter-distance between the radiator and the human body, neutralizing proximity-induced loading variations. Finally, the Coplanar Waveguide (CPW) feeding network and symmetric arrow-shaped slots tightly focus the intense near-field electromagnetic energy directly at the surface interface. When sweat fills this localized sensing zone, its high relative permittivity dominates the localized capacitive and inductive boundary conditions, producing a distinct resonant frequency shift that safely decouples the sweat concentration analysis from ambient environmental interference.

Table 3 provides a comprehensive overview of various antenna sensors, emphasizing the use of frequency shift as a key sensing parameter.

IV. CONCLUSION

This paper presented a compact printed monopole antenna ($25 \times 20 \times 0.8 \text{ mm}^3$) featuring versatile ground plane geometries tailored for dual-functionality in wireless communication and sweat sensing. Fabricated on a RO4003C substrate, the design incorporates a circular patch, a coplanar waveguide (CPW) feedline, and arrow-shaped slots to achieve multi-band performance and high integration potential. Experimental results demonstrate that Antenna_1 achieves a wide -10 dB operational bandwidth across the 8.2–10.64 GHz, 12.1–24 GHz, and 25.54–30 GHz ranges. Antenna_2 and Antenna_3 were successfully optimized for X-band and L/Ku-band applications, respectively. A strong correlation was observed between simulated and measured results, validating the antennas'

reliability for high-speed wireless communication. Furthermore, the sensing capabilities of Antenna_3 were evaluated in a sweat-simulated environment. The antenna exhibited high sensitivity, with its resonant behavior shifting significantly in response to sweat concentration levels. These findings confirm the proposed sensor's efficacy for real-time hydration monitoring in athletes, offering a robust solution for health-tracking technology.

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