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Simulation and Performance Analysis of a Military Insignia Microstrip Patch Antenna at 2.45 GHz For Wireless Applications

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Abstract

This study proposes a design approach for developing a patch antenna whose radiating element replicates an exact image or logo of an entity; the proposed antenna was designed using the insignia of Nigeria army military rank (colonel) as a radiator. The antenna is engineered to operate at Industrial, Scientific, and Medical (ISM) and Wi-Fi spectrum for Wireless Body Area Network (WBAN) applications at 2.45 GHz intended for wireless military and defense communication applications. The proposed antenna structure was developed by strategically substituting the conventional rectangular shape with military insignia of colonel rank as a radiator. The antenna was designed on an FR-4 substrate with dielectric constant of 4.4 and thickness of 1.6 mm. Both free space and on-body simulation was carried out using Computer Simulation Technology (CST) Microwave software. Key antenna parameters were analysed. The results showed that the free space achieved a resonant frequency of 2.457GHz, S_{11} is -43.465dB, VSWR is 1.013, bandwidth of 101.4MHz, directivity is 5.342dBi, the gain is 2.551dBi, maximum surface current is 7305.42 A/m, and the radiation efficiency is 52.2%, while on-body shows that the resonant frequency is 2.473GHz, S11 is -20.81dB VSWR is 1.200, efficiency is 46.57% and most important SAR obtained is 1.64 W/Kg, the results obtained shows that the proposed antenna is suitable for military wireless communication systems, radar systems, surveillance equipment, tactical and defence wireless networks.

Keywords: *Microstrip patch antenna, military insignia antenna, CST Microwave Studio, ISM Band.*

1.0 Introduction

1.1 Background and Problem Statement

The rapid advancements in wireless communication technology are the driving force behind the research and development of a compact, lightweight, high-performance, and reliable antenna for modern communication system [1]. Specifically, in military and defence applications, antennas play a critical role in ensuring an uninterrupted secure communication, battlefield surveillance, radar operations, missile guidance, satellite communication, reconnaissance systems, high precision operation and tactical wireless networking. These applications require an antenna capable of operating efficiently at all times while maintaining its stable radiation characteristics, high gain, low power loss, and excellent impedance matching [2]. Also, the characteristics of the low profile and conformity to desire shape birth the desire to blend the antenna into its surroundings to avoid easy visible detection and identification. All these innovation often require novel antenna solutions [2].

Among the various antenna types available for wireless communication systems, the microstrip patch antenna (MPA) in particular have gained significant popularity due to its low profile, compact structure, low cost of production, low power consumption, light weight, ease of integration with microwave integrated circuits, and conformal nature [3]. These advantages make microstrip patch antennas highly suitable for portable military devices, airborne systems, unmanned aerial vehicles (UAVs), satellite systems, and modern defense communication equipment [4]. Furthermore, microstrip antennas can easily be manufacture using printed circuit board (PCB) technology, thereby simplifying manufacturing processes and reducing implementation cost [4].

Despite these advantages, conventional rectangular microstrip patch antennas suffer from several limitations, including narrow bandwidth, low gain, poor radiation efficiency, surface wave losses, and limited power handling capability [3]. These drawbacks reduce their effectiveness in high-performance military applications where reliable communication and stable signal transmission are critically essential [4]. Within the circle of microstrip antennas, there have been a significant number of design and development activities focused on application specifications. Therefore, the current published research works have introduced several antenna performance enhancement techniques such as slot loading [5], defected ground structures (DGS) [6], parasitic elements [7], stacked patches [8], metamaterials [9], electromagnetic band gap structures (EBG) [10], and much more patch geometry modification or special geometry shape [11] to overcome the stated drawbacks, also in designing the antenna for specific purpose and application.

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Among these enhancement methods, slot incorporation and geometry modification have proven to be one of the best effective techniques for improving the antenna characteristics [5, 12]. The insertion of slots into the radiating patch alters the surface current distribution and increases the effective electrical length of the antenna. This leads to improvements in bandwidth, gain, return loss, radiation efficiency, and impedance matching [12]. Additionally, modified geometrical structures can suppress unwanted surface waves and improve directional radiation characteristics required for tactical military communication systems [13].

Recently, the use of nonconventional shapes like logo-based or specific design structures has surfaced as a promising approach to enhance the performances of the antenna. But this structure is not only useful for performances improvement; it offers both electromagnetic performance benefits and aesthetic or identification-based functionalities, especially for labelling, customization of communication devices and personalized wearable communication gadgets [14].

While geometry of different irregular shapes and pattern representing an entity are the most works that have been widely reported in literature, an exclusive exact logo or exact specific shape design representing an entity is yet to mainstream in antenna research journals, most of the designed shape are fairly resemblance of the intended shape. Now, is it possible for designing exact logo or specific shape geometry patch antenna that is representing an entity in a very look alike?

The aim of this study is to design, simulate and analyze the performances of an exact military insignia microstrip patch antenna operating at 2.45 GHz for wireless applications, specifically designed for military wearable body armour communication equipment. The outcome of this study will contributes to the ongoing research and development of compact, high-performance, miniaturization and multiband operation wearable antennas for modern military advanced defense communication technologies. Also, it will provide an additional degree of freedom in antenna design especially for customization and identification of wireless communication equipment and military personnel personal communication gadget.

The proposed antenna employs an innovative radiating patch design, using military insignia of colonel rank as the design structure, and it was strategically positioned on the substrate to enhance current concentration and radiation performance. The antenna is designed on an FR-4 dielectric substrate due to its availability, low cost, and suitability for microwave applications. Signal was couple to the antenna through coaxial feeding techniques. Modeling, simulation and performance evaluation were carried out using CST Microwave Studio software. The antenna was modeled, simulated, and evaluated using CST Microwave Studio.

The designed antenna is well-suited for deployment in personalized military communication systems, which includes; tactical wireless networks, radar systems, surveillance devices, satellite communication, drone communication systems, defence monitoring systems, and if further developed into wearable antenna has a great potential in RFID and military personnel ranked personal communication gadget.

1.2 Literature Review

The latest state-of-the-art work on patch antenna performance improvement techniques by using modified unconventional shape for the patch and slotting are reviewed, the reviewed journals were selected mainly from the use of special shape and logo design as patch radiator, these are considered as pertinent to this work.

Many researchers have used uncommon special design structure to achieved their aim in antenna design, The authors in [15] proposed "A Novel Design of Dual-Band Circularly Polarized Microstrip Patch Antenna for Unmanned Aerial Vehicle Applications"**.** The antenna employs a uniquely etched circular radiating patch that resembles two short-handled spanners facing one another, complemented by multiple slots and stubs. In addition, the partial ground plane incorporates several horizontal, vertical, and square slots to optimize the resonant frequencies, impedance bandwidth, and axial ratio (AR). The optimized antenna occupies a compact size of $40 \times 40 \times 1.6$ mm^3 and achieves peak gains of 5.01 dBi and 5.27 dBi at 2.4 GHz and 5 GHz**,** respectively. It also provides −10 dB impedance bandwidths of 5.38% and 9.26%**,** together with 3 dB axial ratio bandwidths of 380 MHz and 80 MHz at the corresponding operating frequencies. The proposed radiator geometry demonstrates a high level of design creativity and effectively meets its intended electrical performance objectives. However, its geometric configuration is primarily intended for electromagnetic optimization and does not depict a recognizable symbol or entity. In contrast, the proposed antenna in this study is deliberately designed to replicate a meaningful military insignia while maintaining the required electromagnetic performance, thereby combining functional antenna characteristics with symbolic representation.

The authors in [16] presented a paper titled "Star Shaped Microstrip Patch Antenna Design with Slotted Ground Plane for Civil/Military Radio Location and Satellite Navigation Applications." The study focuses on the design and performance evaluation of a star-shaped microstrip patch antenna incorporating a slotted ground plane. The proposed antenna operates at a resonant frequency of 13.49 GHz and achieves an impedance bandwidth of 430 MHz with a return loss of −45.78 dB**,** indicating excellent impedance matching. Furthermore, the antenna exhibits a gain of 6.36 dB**,** a directivity of 6.16 dBi, and a fractional bandwidth of 3.18%**,** demonstrating its suitability for civil and military radio location as well as satellite navigation applications. Although the proposed

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star-shaped radiator presents a distinctive geometric configuration with excellent electromagnetic performance, its design is primarily intended to achieve the desired electrical characteristics rather than to represent a specific identifiable symbol. In contrast, the antenna proposed in this study is designed to replicate a recognizable military insignia while simultaneously satisfying the required electromagnetic performance for wearable military communication applications.

Authors in [17] present paper on "Mutual coupling reduction in UWB slotted antenna array using Uni-planar Compact Electromagnetic Band Gap (UCEBG) structures for wireless applications" the patch design has two array of eagle shape with slots, the design represents an Egyptian army emblem. The results show that a reduction in mutual coupling of 6 dB is achieved at first band (1.71 - 2.98) GHz, 10 dB at second band (4.26 – 5.62) GHz, and 6 dB at third band (6.57 – 9.16) GHz. With the results obtained, the antenna is suitable for use in military wireless applications. But the shape of the eagle designed is fairly resemblance to that of real eagle picture, because its parts were cut out from solid shape, this is reason this work is set to be a pathfinder for importing an exact shape or images instead of designing by cutting out the edges to form images when designing in antenna research circle.

In [18] the authors present work on "Development of Augmented Low-Cost, Compact, and Flexible Textile Antenna" the antenna was Inspired by the Algerian Special Forces logo, the antenna features a distinctive shape and demonstrates robust single-band performance suitable for wireless local area networks applications. The simulated results show a maximum gain of 4.3 dB at 5.5 GHz and a peak efficiency of 85% in free space, with a 10 dB impedance bandwidth of approximately 10%. It has potential applications in enhanced wireless communication, secure access control, and identification.

Also, the work was presented in [19] was on a wearable embroidered logo antenna at ISM band for military applications. The proposed designed antenna has the name of their institution "VTU" engraved on the patch used as slot and aesthetic design of the antenna, and it has size dimensions of 90 x 70 x1.57 mm^3 on the Jeans cloth used as substrate whose dielectric constant is 1.6. The proposed antenna was operating at the resonant frequency of 2.45GHz with a return loss of -20dB and a gain of 2dBi with VSWR of 1.4. The work shows good result with possibility of having a branded patch antenna designed with names or logo.

The authors in [20] presented the design of an all-textile antenna integrated into a military beret for GPS and RFID applications**.** The proposed antenna comprises a left-hand circularly polarized (LHCP) GPS patch antenna combined with a circular ring patch antenna fabricated using conductive threads to provide RFID functionality at 915 MHz. Performance evaluation showed that the antenna achieves a −10 dB return loss bandwidth that completely covers both the 915 MHz ISM band (902–928 MHz) and the GPS L1 band (1.563–1.587 GHz) when evaluated on a human body phantom. Owing to its flexibility and favorable electromagnetic characteristics, the antenna was identified as a suitable candidate for wireless body area network (WBAN) applications and can be directly integrated into military berets for wearable communication systems. Unlike the textile antenna integrated into a military beret, which emphasizes wearable integration and dual-band GPS/RFID operation, the proposed work focuses on the design of a military insignia-shaped microstrip patch antenna**,** where the radiating element itself represents a recognizable military emblem while achieving the desired electromagnetic performance for wearable military communication applications.

Likewise, for works on logo shape radiator, Authors of [21] proposed a Jia-shaped artistic microstrip patch antenna inspired by a Chinese character, achieving dual-band circularly polarized operation at 2.6 GHz and 3.4 GHz. The antenna demonstrated impedance bandwidths suitable for wireless applications and achieved a measured axial ratio below 3 dB over the operating bands, a unidirectional gain of 8.2 dBi within an operating bandwidth of 0.72 GHz were realized. This work confirms the feasibility of complex character-based geometries as an effective radiator in a patch antenna.

In a related work presented by Wang et.al [22], a culturally inspired Qing-shaped quad-band patch antenna based on calligraphic geometry was designed. The antenna operated at four resonant frequencies of approximately 1.7 GHz, 2.1 GHz, 2.6 GHz, and 3.0 GHz, covering multiple wireless communication bands. The reported results show that the return loss is less than −15dB at all resonances, demonstrating that symbolic shapes can be exploited for multiband behavior through controlled current path manipulation.

Authors in [23] proposed an UB Logo-Shaped microstrip antenna for Ultra-Wideband Frequency (UWB) applications; in which the logo of their university was used as the radiator geometry. The antenna was fabricated using FR-4 Epoxy material, from the simulations and measurements results, the antenna performances shows that VSWR is less than 2 at a dual resonance frequency of 2.2 GHz and 10.8 GHz; and it has a circular polarization at various frequencies in the range. But the designed logo in this work is not the perfect look alike of the original; that is why this present work is set to show the methodology.

All these review works provide the justification and basement for our military insignia radiator geometry design, which intended to represent the army insignia perfectly in their communication gadget, and pathway for advancement into wearable body armour.

2.0 Materials and Methods

The fundamental structure of a typical single rectangular MPA is illustrated in Figure 1, It consists of a conducting patch on top of the substrate and the ground plane below. The radiator is generally made of conducting material such as copper the most popular or any other conducting materials and it can take any possible shape. Dielectric constant of the substrate (ϵr) is typically in the range $2.2< \epsilon r <12$. For good antenna performance, a low dielectric constant with thick dielectric substrate is desirable, as it provides better radiation, better efficiency and larger bandwidth [3]. The dimensions and geometry of the radiating patch are among the primary factors influencing the operating frequency and overall performance of a microstrip patch antenna (MPA). In addition, the substrate properties, including its length, width, thickness, and dielectric constant, as well as the location of the feeding point, significantly affect the antenna's impedance matching, resonant characteristics, bandwidth, and radiation performance [24].

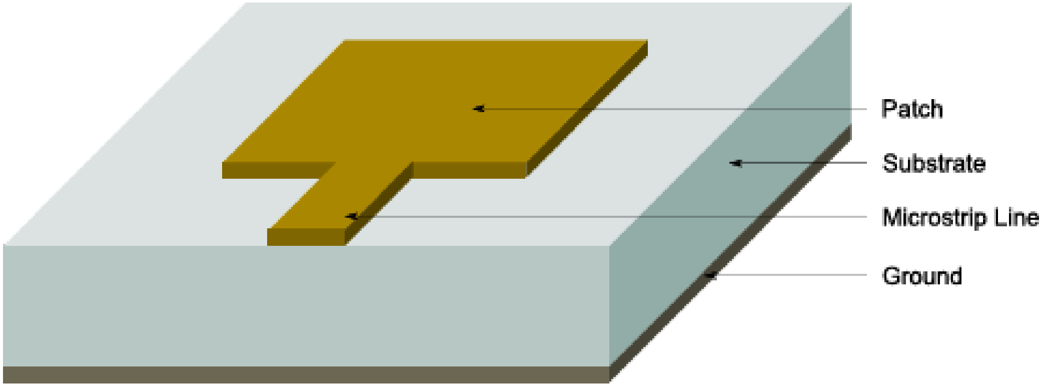


Figure 1: Constructional view of Microstrip Antenna and feed line [24]

This current proposed military insignia microstrip patch antenna was designed to operate in the ISM band 2.45GHz using a conventional single-layer microstrip antenna configuration. The antenna was theoretically designed using the popular standard transmission-line model equations as listed in [25] to determine the sizes of various aspect of the patch. Then, the simulation and optimization were carried out in full wave electromagnetic simulation CST, the design was modeled on FR4 epoxy substrate due to its low cost, wide availability, suitability for rapid prototyping and low-to-medium performance wireless applications. The FR4 substrate is characterized by a relative dielectric constant of $\varepsilon_r = 4.4$, a loss tangent of $\tan \delta = 0.02$, and a substrate thickness of $h = 1.6$ mm. The copper metallization thickness (t) is assumed to be 35 μm, consistent with standard printed circuit board (PCB) fabrication processes.

2.1 Proposed Antenna Design and Modeling

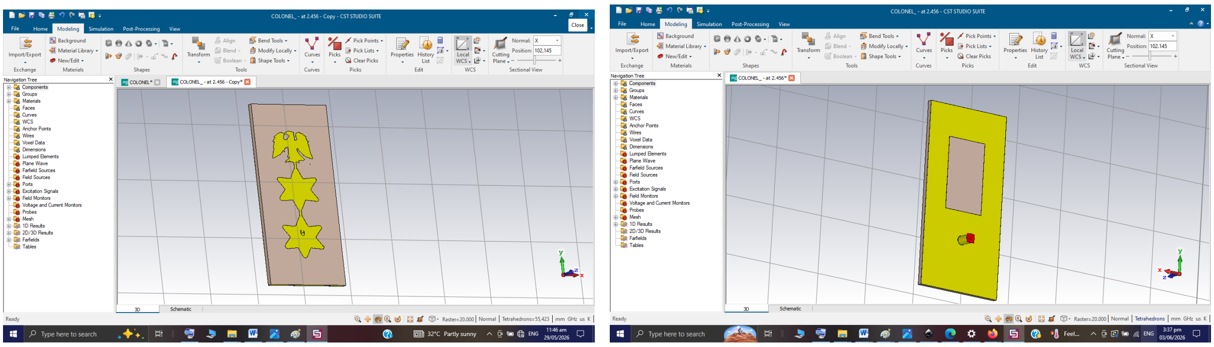
To provide a baseline guide for the initial dimensions of the proposed antenna since it is an unconventional irregular shape, a conventional rectangular microstrip patch antenna was first theoretically designed. The effective dielectric constant ε_{eff}, effective length L_{eff}, and patch width (W), ground length and width are estimated using the standard transmission-line model equations, the estimated values are shown in table 1. These dimensions served as a guild to determine the overall effective area of the proposed irregular shape very similar in proportion to the regular rectangular shape antenna, which is expected to effectively work at the desire frequency of operation.

Table 1: showing the estimated values of the dimensions

Description	**Symbol**	**Value (mm)**
Length of the ground	L_g	37.80
Width of the ground	W_g	47.21
Patch length	L_p	29.3
Patch width	W_p	37.61
Slot width	W_s	15.03
Slot length	L_s	24.80
Inner connector radius	R_{inn}	0.60
Coaxial insulator radius	R_{coax}	1.60
Outer connector radius	R_{out}	1.635
Feed hole Diameter	F_D	0.80

Having determined the estimated effective length and breadth theoretically, because CST is not graphic design software, the proposed image cannot be directly design in it. Therefore, the proposed military insignia (colonel rank) structure was designed by firstly copies the exact image directly into vector based image editor software, then edit the image and specified the dimensions (LxBxH) to the estimated values, and saved the image as a 3D vector file. Thereafter, the vector file was imported into CST and directly placed on top of the already model substrate with ground plane, other adjustments were carried out using modeling tools in CST environment. The image structure comprises of eagle and two stars aligned vertically, rather for each image to be an independent shape in the design structure, they were systemically connected in the middle by a thin stroke bar, the continuous electrical connection between the shapes is to ensure that the design function as a single radiating structure and to avoids unintended isolation or parasitic effects. To have a good impedance matching and other parameters improvement, a rectangular slot was created on the ground plane, which is common and easiest way of improving patch antenna performance.

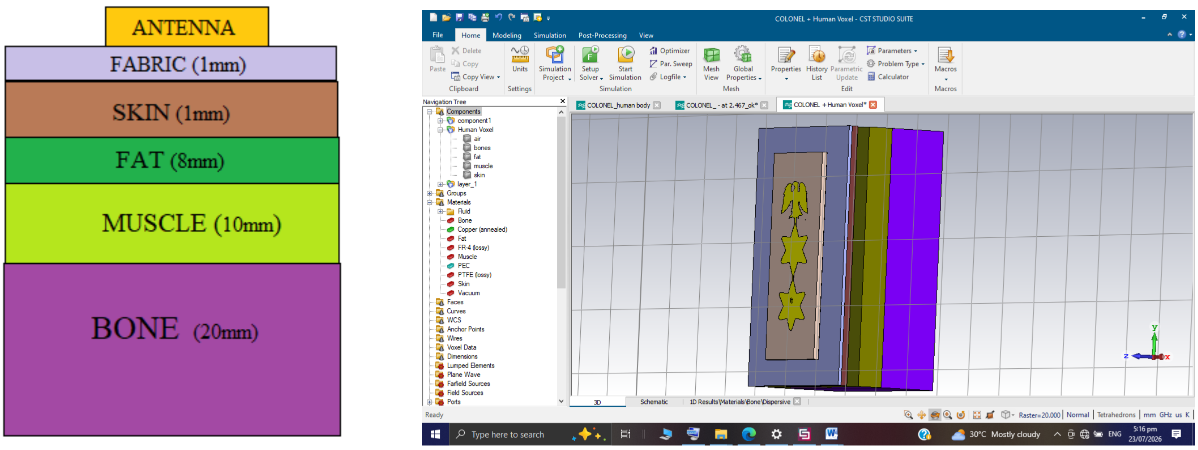
For a proper simulation, a coaxial probe feed is employed to excite the antenna due to its simplicity, ease of impedance matching, and appropriateness for single-layer microstrip patch configurations. Open (radiation) boundary conditions was applied, the frequency sweep range is selected to cover the ISM band, typically from (2.0 - 3.0) GHz, to ensure proper observation of the resonance behaviour and impedance bandwidth. A series of optimization were performed on the antenna before achieving a good result, the optimization procedures involve maximizing some parameters and minimizing others to achieve good resonance and other parameters at the target frequency, and a series of geometry adjustment were also carried out. The spacing between each structure, the structure connectivity, width and height of the each structure, feeding position, structure positioning and overall scaling factor are treated as key design parameters optimization that were carefully considered in this work. The modelling of the proposed military insignia (colonel rank) patch in CST environment was shown in Figure 2.



a b

Figure 2: Modeling of the proposed antenna in CST environment (a = front view, b = back view)

To further justify the credibility of the proposed antenna, since the ultimate use of the antenna will be in the wearable personal communication gadget; as the intended operating environment, the antenna was simulated in on-body scenario as shown in figure 3 to determine the changes in characteristics because the body significantly affects antenna performance.



(a) (b)

Figure 3: Modeling of the proposed antenna with human body phantom (a) 2D Body phantom model of five layers (b) 3D Body phantom model of five layers in CST environment

The proposed military insignia antenna is initially analyzed in a free-space environment to characterize its fundamental electromagnetic properties, after which wearable simulations are performed to evaluate its

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performance and applicability in practical on-body communication scenarios. The presence of the human body introduces dielectric loading and electromagnetic absorption, resulting in resonance frequency detuning, reduced gain and efficiency, and modification of the radiation pattern. Nevertheless, maintaining an acceptable impedance bandwidth, radiation efficiency, and directional radiation away from the body confirms the suitability of the proposed insignia antenna for wearable military communication applications.

3.0 Results and Discussion

The simulation performance of the proposed antenna was evaluated in free space, which means analyzing its electromagnetic performance without nearby objects, enclosures, or the impacts of the ground and the surroundings. This provides the antenna's intrinsic performance and is the standard first step before evaluating it in practical scenarios of on-body simulation. The performances were presented in terms of the following parameters: return loss, bandwidth, VSWR, antenna gain, directivity, efficiency, surface current distribution, directivity, radiation pattern, radiation efficiency, and importantly Specific Absorption Rate (SAR).

A. Reflection Coefficient (S_{11})

The S-parameters, particularly S_{11}, represents the reflected power from the antenna, which is also known as the reflection coefficient or return loss. Return loss in telecommunications is a signal reflection caused by irregularities or device insertion in a transmission channel, resulting in impedance mismatch, and is typically expressed in decibels (dB). For practical applications, the return loss for a specific frequency band must be less than or equal to -10 dB for the antenna to operate efficiently. The simulated reflection coefficient S_{11} of figure 4 shows that the antenna resonates at 2.457 GHz with a return loss of -43.465dB, this value indicates a very good impedance matching. This is attributed to the shape of the radiator that changes the current distribution on the patch, which directly affects the S_{11} result [12].

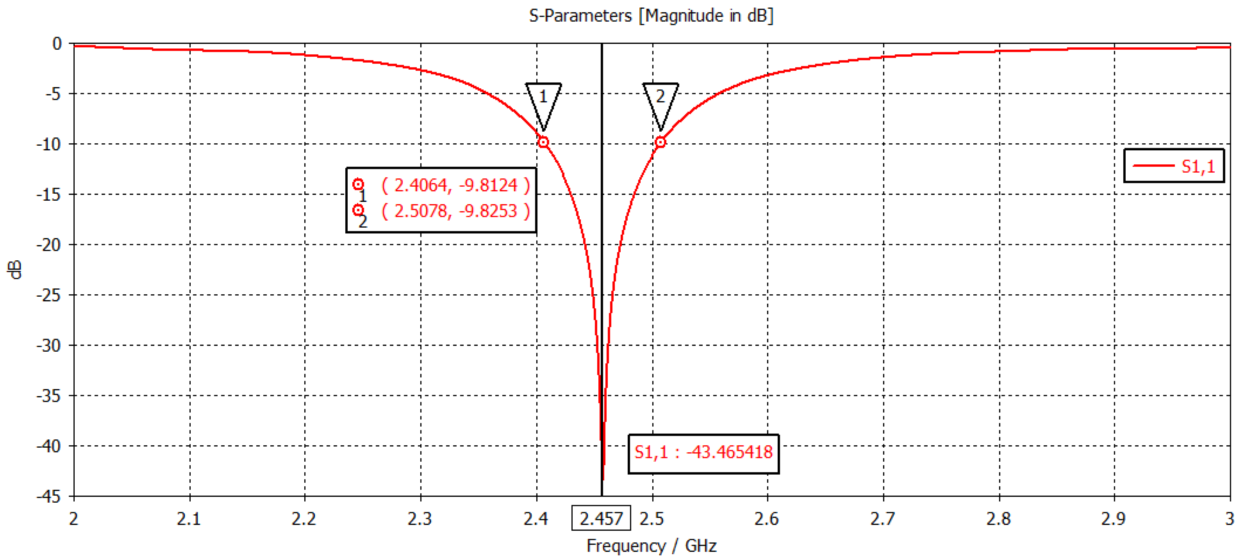

Figure 4: S_{11} plot of proposed antenna

B. Bandwidth

Bandwidth is calculated from the Figure 4 by taking the difference between the lower and higher resonant frequency across -10dB line. The simulated bandwidth of the proposed antenna extends from 2.4064GHz to 2.5078GHz in Figure 4, resulting in an absolute bandwidth of 101.4MHz and a fractional bandwidth of 4.13% centred around 2.45GHz. This bandwidth fully covers the entire ISM band, making the antenna suitable for wireless applications; such as Wi-Fi (IEEE 802.11b/g/n), Bluetooth, ZigBee, RFID, and other short-range wireless communication systems, the proposed antenna bandwidth can be attributed to the effective current distribution on the radiating patch.

C. Voltage Wave Standing Ratio (VSWR)

The voltage standing wave ratio (VSWR) is a key parameter used to evaluate the efficiency of power transfer between an antenna and its transmission line by indicating the level of impedance mismatch. A VSWR of 1 represents ideal impedance matching, where all the transmitted power is delivered to the antenna with no reflected power, although such a condition is rarely achieved in practice. For efficient antenna operation, a VSWR value between 1 and 2 is generally considered acceptable [25]. As shown in Figure 5, the proposed antenna exhibits a VSWR of 1.013, indicating excellent impedance matching with the transmission line. This low VSWR corresponds

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to minimal power reflection and efficient power transfer to the radiating element. The excellent matching performance is attributed to the optimized radiator geometry, which effectively adjusts the antenna input impedance to closely match the standard 50 Ω feed impedance.

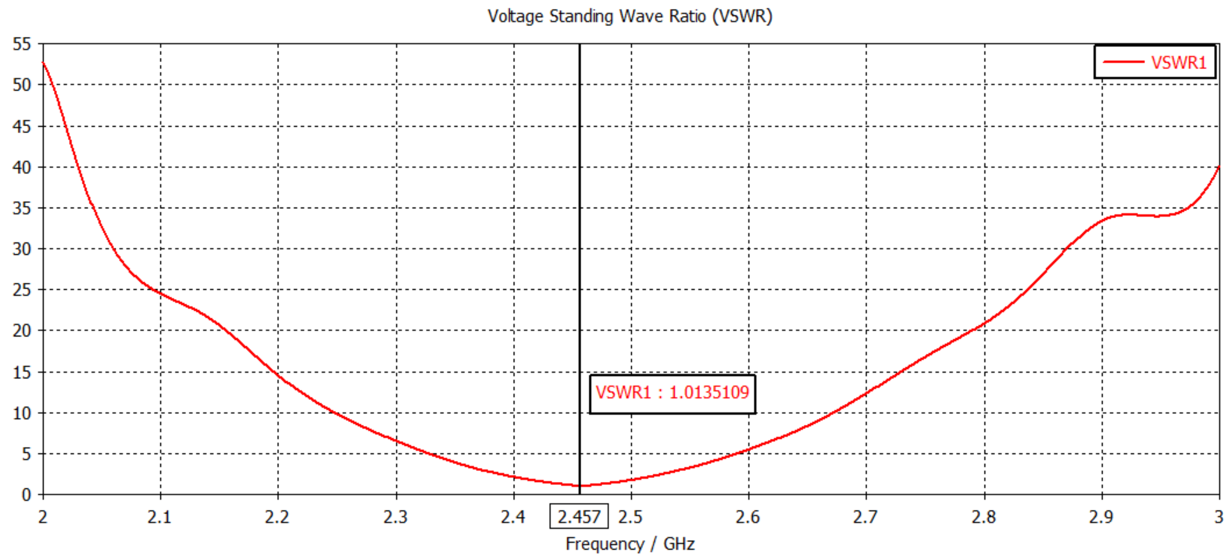

Figure 5: VSWR of proposed antenna

D. Impedance Matching

Impedance matching is achieved when the input impedance of an antenna closely corresponds to the characteristic impedance of its feeding transmission line. In most wireless communication systems, a feed-line impedance of 50 Ω is commonly adopted as the standard. Achieving an antenna input impedance near this value ensures efficient transfer of power from the source to the antenna while minimizing signal reflections at the feed point. Consequently, good impedance matching enhances radiation efficiency and improves the overall performance of the antenna.

The simulated input impedance value of the proposed antenna shown in Figure 6 is 49.905 Ω at the design operating frequency. This value closely approximates the standard 50 Ω characteristic impedance, demonstrating excellent impedance matching between the antenna and the feeding network. The small deviation of only 0.095 Ω indicates a negligible impedance mismatch, confirming that the antenna is well optimized for efficient operation within the intended frequency band. As a result, the antenna exhibits low return loss, a small reflection coefficient, and a voltage standing wave ratio (VSWR) close to unity, all of which are indicators of efficient power transfer. These characteristics contribute to improved radiation efficiency, enhanced gain, and reliable overall antenna performance. Therefore, the simulated impedance result validates the effectiveness of the proposed design methodology and demonstrates the antenna's suitability for practical wireless communication applications.

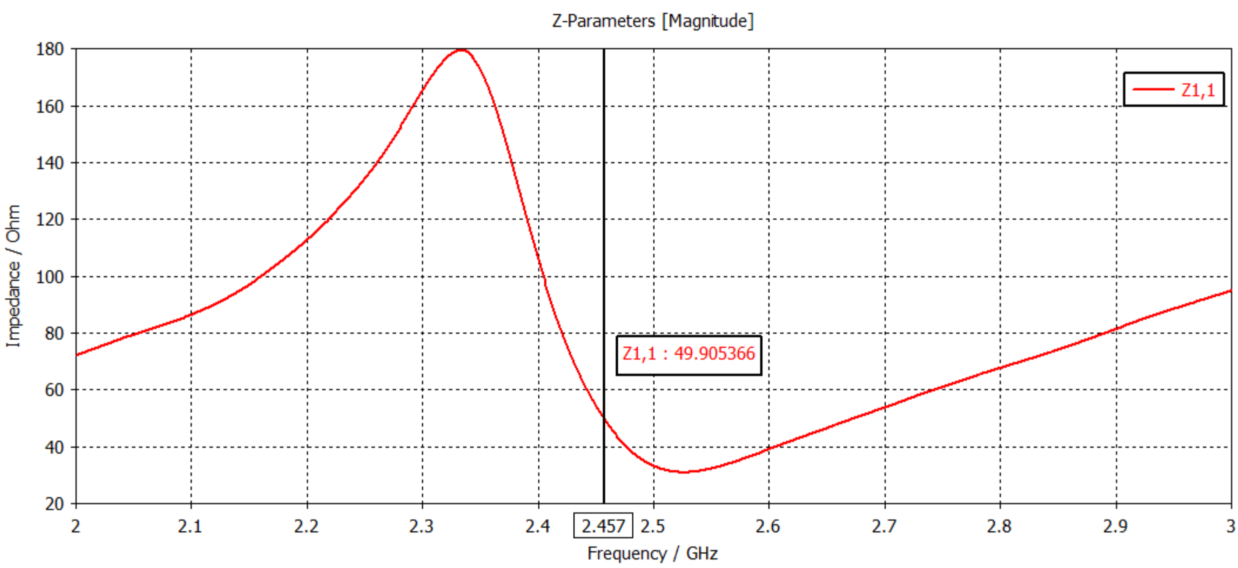

Figure 6: Impedance (Z) plot of proposed antenna

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E. Surface Current Distribution

Figure 7 shows the surface current distributions of the proposed antenna; surface current image reveals a strong current concentration around the edges of the irregular shapes of the radiator. The maximum surface current obtained is 7305.42A/m, This High surface current density confirms effective excitation of the resonant mode and demonstrates that the antenna geometry efficiently guides RF current toward the radiating edges, where electromagnetic radiation primarily occurs. For customized patch antennas of irregular shapes, localized current concentration around the edges is expected because the slots naturally created within the shape lengthen the current path and contribute to resonance tuning and impedance matching. The observed high current density therefore supports the excellent matching characteristics obtained from the S11 and VSWR results.

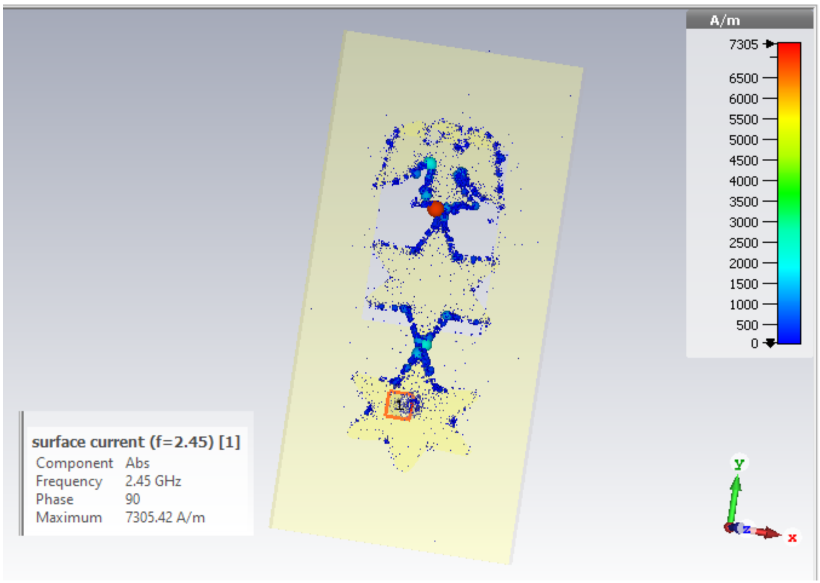


Figure 7: Surface current distributions of the propose antenna

F. Radiation Characteristics

A radiation pattern describes how the energy is radiated out into space by the antenna or how it is been received. It is represented by the far-field radiation properties of the antenna as a function of the spatial coordinates specified by the elevation angle Theta and the azimuth angle Phi. In figure 8, the 3D simulated radiation pattern of the proposed antenna is showed. The Figure shows the proposed antenna radiation pattern with phi = 90 direction, These patterns reveal that the proposed antenna exhibits a commendable azimuthal coverage, the main lobes of the radiation patterns are fixed in the end-fire direction (x-axis direction).

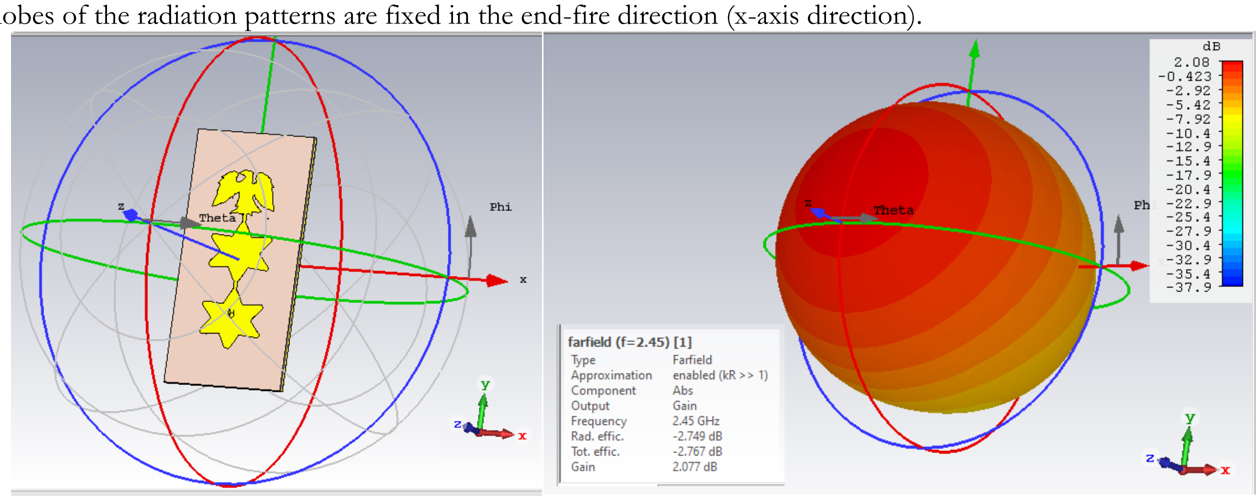
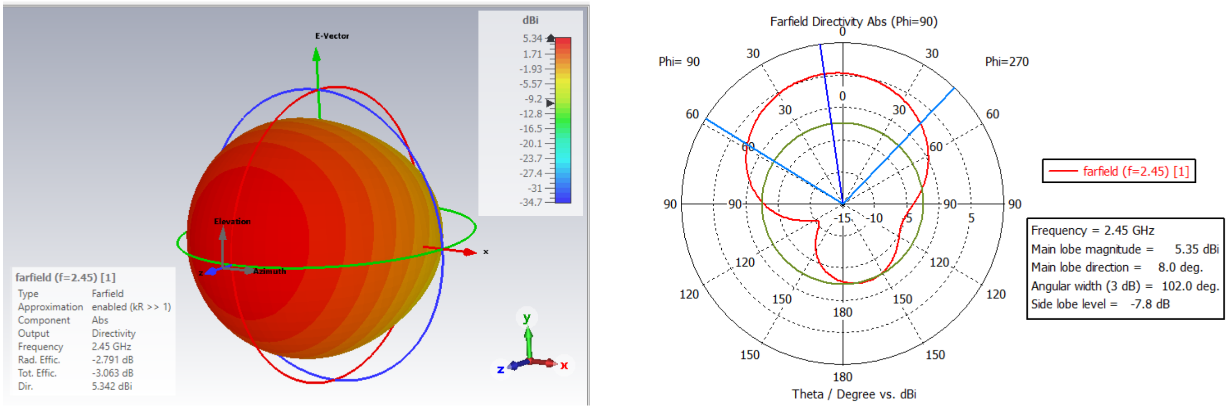


Figure 8: 3D Radiation characteristics of the propose antenna

G. Directivity, Gain and Radiation efficiency

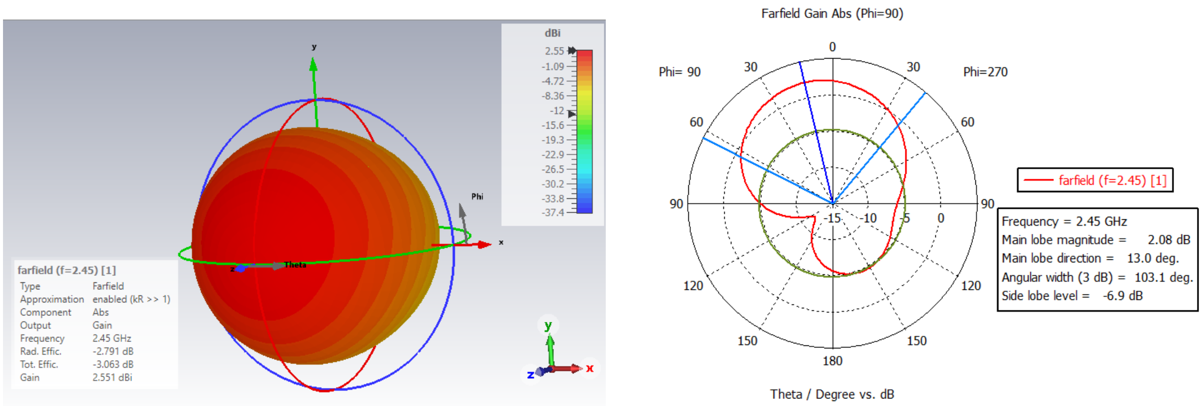
The term "directivity" refers to the ratio of the strength of an antenna's radiation in one particular direction to the average strength of its radiation across all directions [21]. Figure 9a show the 3D directivity of the propose antenna, it can be seen that it has a directivity of 5.342dBi at the targeted frequency. While Figure 9b shows the 2D directivity, the main lobe magnitude and direction are 5.35dBi and 8.0 deg respectively with an angular beamwidth of 102.0 deg. Stable radiation and directivity achieved ensures a higher range of the unscattered signal with low unwanted noise from the backward direction.



a b

Figure 9: Directivity pattern of the propose antenna (a = 3D, b = 2D)

Antenna gain is a measure of the ability of an antenna to concentrate radiated power in a particular direction relative to an isotropic radiator supplied with the same input power [21]. It therefore indicates how effectively the antenna directs electromagnetic energy toward its main radiation lobe. As shown in Figure 10(a), the proposed antenna achieves a peak gain of 2.551 dBi at 2.45 GHz. The corresponding far-field radiation pattern in Figure 10(b) exhibits a main-lobe magnitude of 2.8 dB with an angular beamwidth of 103.1°. The observed gain enhancement can be attributed to the improved directivity of the antenna, more uniform surface current distribution, and stronger fringing-field radiation resulting from the irregular patch geometry and the slot incorporated into the ground plane. These design features promote more efficient radiation, thereby improving the overall gain performance of the proposed antenna.



a b

Figure 10: Gain field configuration of the propose antenna (a = 3D, b = 2D)

H. Radiation Efficiency

Radiation efficiency (η_r) is an important performance parameter of a microstrip patch antenna, representing its ability to convert the accepted radio frequency (RF) power into useful radiated electromagnetic energy. It is defined as the ratio of the radiated power to the accepted input power, excluding losses due to impedance mismatch. Figure 11 presents the simulated radiation efficiency of the proposed antenna. As shown, the antenna achieves a radiation efficiency of 52.2%, indicating that slightly more than half of the accepted input power is effectively radiated, while the remaining power is dissipated through conductor, dielectric, and surface-wave losses. This result is consistent with the theoretical relationship between gain, directivity, and radiation efficiency, where radiation efficiency is expressed as the ratio of antenna gain to directivity. Since CST reports both gain and directivity in dBi, the radiation efficiency can be calculated using the following expression;

$$G_{dBi} = D_{dBi} + 10Dlog_{10}(\eta) \quad (1)$$

Where η is expressed as a decimal, which means the expected realized gain is approximately

$G_{\text{realized}} = 5.342 + 10log_{10}(0.522) = 2.518$ dBi.

The observed increase in radiation efficiency can be attributed primarily to the introduction of ground slots and structural modifications of the radiating patch. While the conventional regular microstrip patch antenna mostly supports relatively uniform surface current distribution with minimal disruption, the proposed design incorporates irregular edges that intentionally perturb the current paths to achieve the enhanced functionalities.

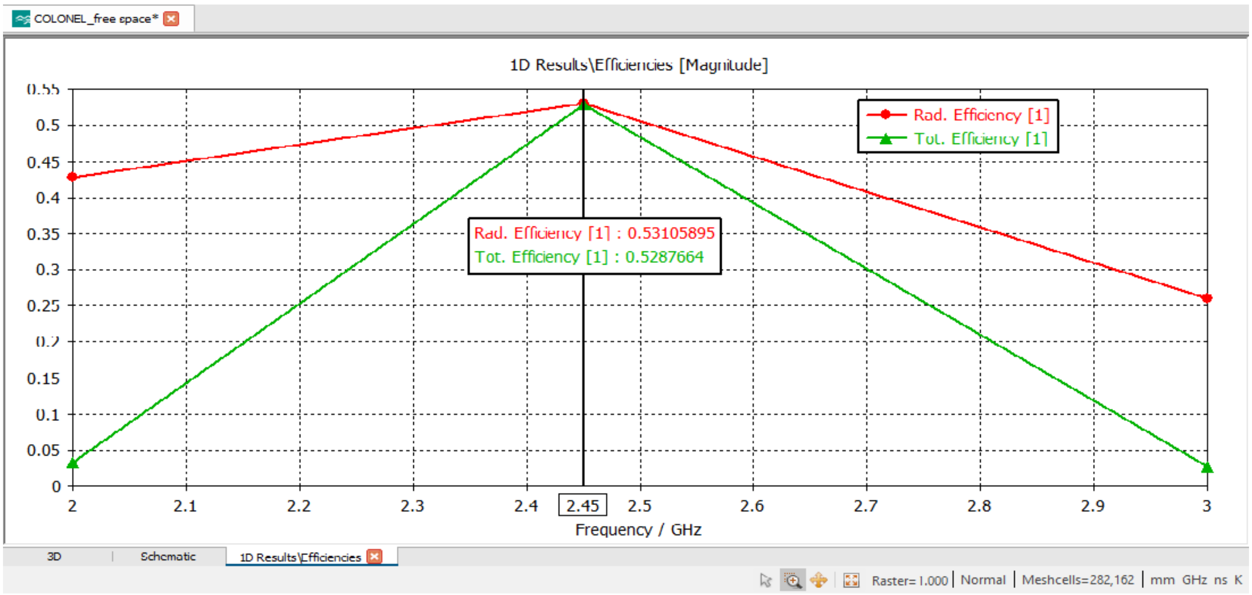
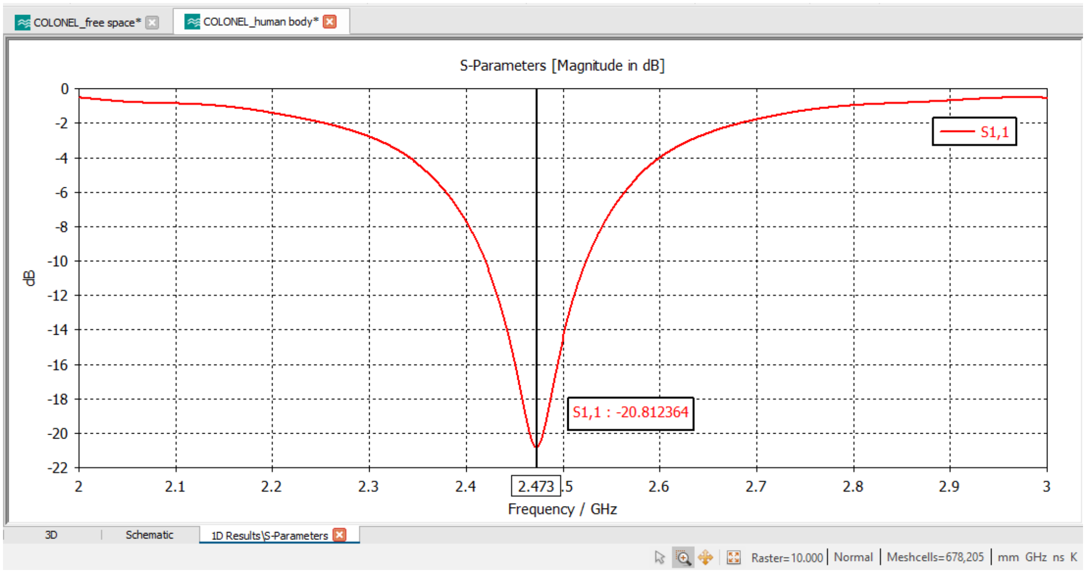


Figure 11: Radiation efficiency plot of the proposed antenna

All the radiation characteristics suggest that the proposed antenna is well suitable in all ramifications for applications in ISM band where reliable uninterrupted signal transfer is crucial especially in a military communication where precision is required. From the results it is seen that this special shape of the radiator does more than decorative cast but technically used for antenna parameter improvement and antenna branding.

I. On-body Performances

When simulating a patch antenna, results differ significantly between free space and on-body environments because the human body introduces absorption, scattering, and detuning effects. Since the antenna is intended to be worn as a military insignia on the chest or shoulder, the following results in Figure 12(a-d) were obtained in on-body simulation. The resonant frequency has shifted to 2.473GHz, while the return loss (S_{11}) is increase to -20.81dB, Voltage Standing Wave Ration (VSWR) obtained is 1.200, the efficiency has reduced to 46.57% which means that the gain and directivity have shifted, and most important specific absorption rate (SAR) obtained is 1.64 W/Kg which is within the acceptable safety range. As expected, the on-body scenarios affect the results, but the overall performance is within the acceptable range.



a

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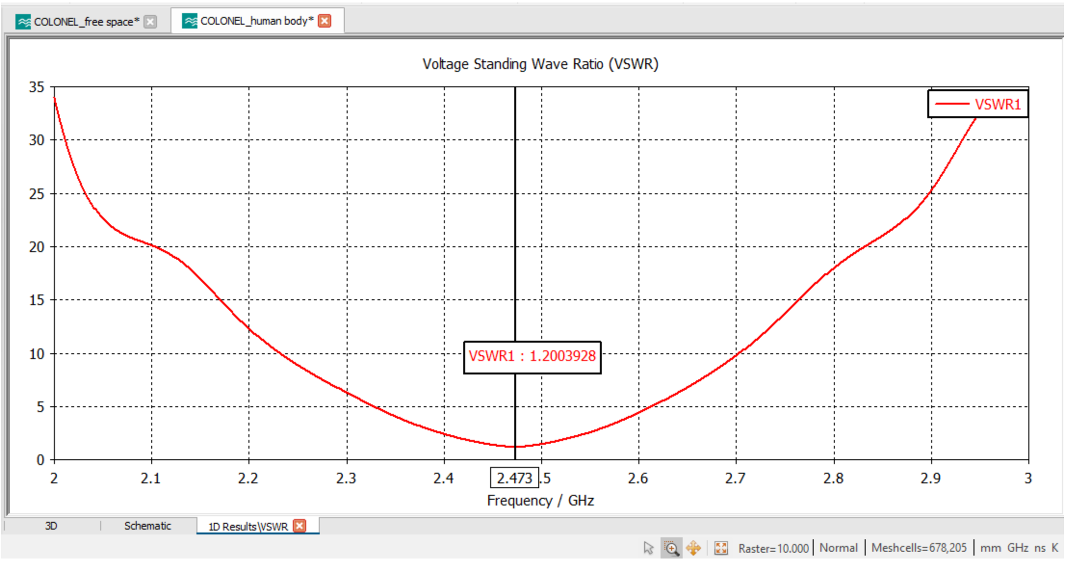
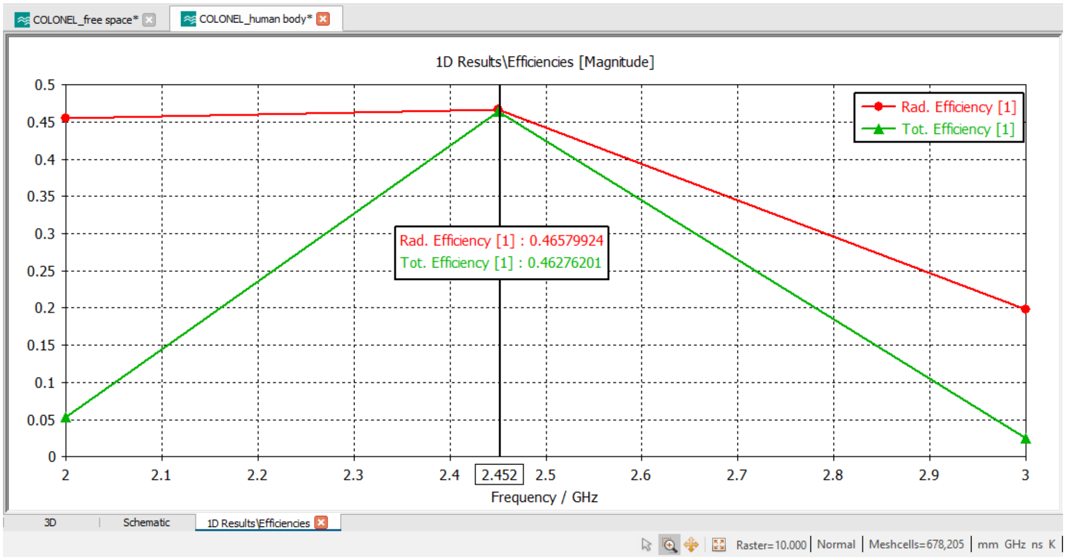
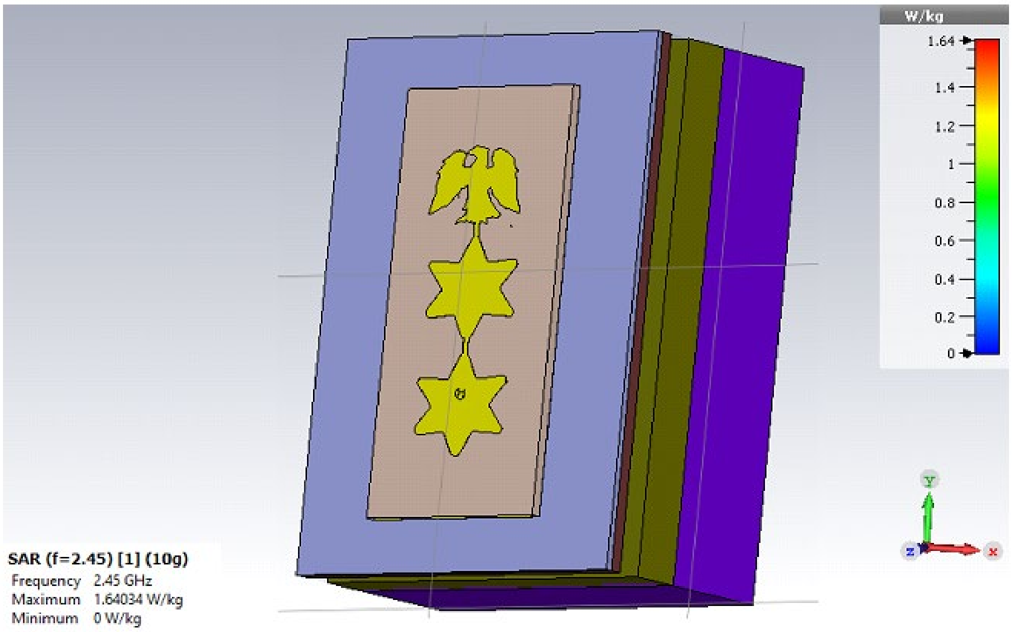


b



c



d

Figure12: On-body simulation results. (a = S11, b = VSWR, c = Efficiency, d = SAR)

J. Comparative Summary

Table 2: Comparative Summary of Free Space and On-Body

Parameter	Free Space	On Body
Resonant Frequency	Matches design	Shifts higher
Gain	High	Reduced
Efficiency	High	Lower due to absorption
Radiation Pattern	Symmetrical	Distorted
SAR	Not relevant	Critical safety factor

Overall, the comparison between free-space and on-body simulations in Table 2 demonstrates the robustness of the wearable antenna design. Although the proximity of the human body inevitably causes frequency detuning, reduced gain, lower radiation efficiency, and slight impedance mismatch, these effects are expected due to dielectric loading and tissue absorption. An antenna that continues to satisfy the design requirements under both conditions can therefore be regarded as well optimized for practical wearable wireless communication applications.

H. Previous Works Compared with Present Work Results

The performance of the proposed antenna was evaluated by comparing its simulated results with those of recently reported state-of-the-art antennas in the literature. The selected studies were limited to antennas featuring military insignia-inspired, logo-based, or other customized radiator geometries. The comparison, summarized in Table 3, considers key performance parameters including antenna dimensions, operating (center) frequency, reflection coefficient (S_{11}), voltage standing wave ratio (VSWR), gain, directivity, and efficiency. Although military insignia-shaped antennas are relatively uncommon in the literature, the proposed design demonstrates competitive performance when compared with existing customized antenna configurations operating in the ISM band. The obtained results confirm that the proposed antenna provides satisfactory electromagnetic characteristics, making it a suitable candidate for personal military communication devices and other wearable wireless communication applications.

Table 3: Comparison of present and past results

Research work	Year	Antenna dimension (mm)	Working frequency (GHz)	Return loss (dB)	VSWR	Gain (dB)	Directivity (dBi)	Efficiency (%)
[26]	2026	22.8x18.5	2.4	−21.56	<1.5	1.96	N/A	N/A
[1]	2025	40 × 24	2.45& 5.8	N/A	N/A	2.41&5.22	N/A	>90
[27]	2025	40 × 40	2.45	–20.08	N/A	5.1	N/A	0.03
[28]	2024	37.6x29.1	2.45	-27	1.1	2.28	5.99	N/A
[4]	2017	54 x 43	2.45	-20	1.4	2	N/A	94
[16]	2016	N/A	13.49	-45.78	1.009	6.36	6.16	N/A
This work		**44.7x16.4**	**2.45**	**–43.46**	**1.01**	**2.55**	**5.34**	**63.1**

4.0 Conclusion

A military insignia shape microstrip patch antenna operating at 2.45 GHz has been presented. The proposed antenna was designed by replacing the convectional rectangular with exact military insignia shape (colonel) on the radiating element, the design shape was employed as a functional active electromagnetic perturbation mechanism of the antenna, and a way of customizing the antenna solely for military use, with this design; an improved impedance matching, stable radiation characteristics were achieved without increasing antenna size or complexity. The proposed antenna was first simulated in free space demonstrating its intrinsic state and later simulated in human body phantom demonstrating antenna performance realistic on-body conditions. The numerical values obtained from free space simulation results show that the proposed antenna resonates precisely at 2.457GHz, with a return loss of -43.465dB, VSWR of 1.013, the maximum surface current is 7305.42A/m peak, gain of 2.551 dBi was realized, and a directivity of 5.342 dBi with the radiation efficiency of 52.2% were achieved. While results obtained from on-body simulation shows a slight differences, resonant frequency is 2.473GHz**,** S11 is -20.81dB VSWR is 1.200, efficiency is 46.57% and most important SAR obtained is 1.64 W/Kg, meaning the device remains safely below the European CE limit of 2.0 W/kg. These results confirm excellent impedance matching, appreciable bandwidth suitable for ISM band and wireless applications. Beyond electromagnetic performance, the proposed antenna provides practical advantages in terms of device identification, branding, and security marking, which are increasingly relevant in modern wireless systems such as IoT nodes, access points, wearable devices, and military

or branded institutional communication equipment. The innovation of this work is based on the systematically designing of the exact intended shape or logo against the convectional use of resemblance or representing the intended shapes as reported in the literature. Also this work served as a blue print for developing other military rank shape antenna, and developing any institutional logo shape antenna with ease.
Based on the results obtained in this study, future research should involve the fabrication and measurement of the proposed antenna to experimentally validate its simulated performance. This will provide a comprehensive assessment of its practical implementation and demonstrate its suitability for integration into advanced wearable personal military communication systems.

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