# Performance Evaluation of a Compact 2.5 GHz Microstrip Antenna on Rigid and Flexible Substrates for Wearable Applications

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***Abstract*—This work presents a substrate-level performance comparison of a compact microstrip antenna operating in the $2.5\,\mathrm{GHz}$ ISM band, designed and simulated using Ansys HFSS. The antenna structure is maintained unchanged $\mathbf{22}\,\mathrm{mm} \times \mathbf{15}\,\mathrm{mm} \times \mathbf{1}\,\mathrm{mm}$ overall size, microstrip-line excitation, partial ground plane, and performance tuning via stub loading and shorting pins) while the substrate is varied between FR4 and silicon rubber. The FR4-based antenna exhibits a pronounced return-loss minimum of $-31.34\,\mathrm{dB}$ at $2.52\,\mathrm{GHz}$, confirming excellent impedance matching. In contrast, the silicon-rubber configuration resonates at $2.53\,\mathrm{GHz}$ with a return loss of $-17.54\,\mathrm{dB}$. While FR4 delivers improved reflection characteristics, silicon rubber enables flexibility and conformal integration, which are important for wearable and medical Internet of Things (IoT) deployments. These observations underline the trade-off between electromagnetic matching performance and mechanical suitability for on-body biomedical systems.**

***Index Terms*—Microstrip antenna, ISM band, wearable antenna, flexible substrate, silicon rubber, FR4, medical IoT, HFSS simulation**

## I. Introduction

Healthcare IoT (Internet of Things) is growing rapidly and so is the use of small, wireless, battery-operated medical devices for continuous monitoring, remote diagnosis, and immediate transfer of physiological data. The antenna used in these systems is not just an accessory: it is the main radiating interface, which influences link reliability, power efficiency and quality of communication. Therefore, antennas designed to operate in a compact form need to be developed to ensure that future medical Internet of Things nodes can operate effectively. The 2.4–2.5 GHz ISM Band (Industrial, Scientific and Medical Band) is the most utilised electronic spectrum for wireless communication in medical and wearable Internet of Things in comparison with another available license-free spectrum. In addition to the global availability of this band, an antenna working in the 2.4–2.5GHz band will have compatibility with the short range of wireless standards, allowing low-powered communications between body mounted sensing devices and external devices such as gateways, smartphones, and monitoring devices. Moreover, antennas operating in the above-mentioned frequency should provide good matching and consistent radiation patterns at all times to ensure reliable transmission of data under real world environments where multipath propagation and near body loading will affect performance. Nevertheless, the antennas, both biomedical and wearable application-related, must meet performance requirements that are more demanding than that of conventional wireless and even some non-conventional antennas. To be functional, they must be compact in size and low-profile in shape with respect to their physical dimensions.

Additionally, to meet full functionality, they must also be able to minimize reflection loss and not have significant losses in operational efficiency while being resistant to frequency shifts due to the high-dielectric content and lossy nature of human tissue materials when they are in close proximity to the antennas. Making antennas smaller without compromising the performance of the match is challenging because when the physical size is made smaller, the bandwidth of the device expands and the amount of mismatch increases. To overcome any of the preceding limitations, many compact microstrip antennas are optimized through various techniques such as partial ground planes, stub loading techniques, and modifying the input impedance, which changes the current paths and increases the effective electrical length of the antenna without altering the physical size of the antenna.

Substrate selection, in addition to geometric optimization, has a huge impact on how well the antenna works and how well it performs in its medical IoT applications. Rigid substrates like FR4 are attractive materials because they are relatively inexpensive, easy to manufacture, and show similar electrical performance from production to production, generally providing superior impedance matching and a stable resonating frequency as long as the design is performed and tuned and fabricated in the planar configuration. On the other hand, flexible substrates like silicone rubber provide the conformality and body compatibility required for integration into the body or conforming to the body in other ways, such as by wrapping around the skin or connecting to a garment or wearable device, making them an advantage when using biomedical devices attached to the body. However, the flexibility of the substrate there is preferred creates the opposite problem when fabricating the device. This study presents a direct comparison of the RF characteristics of a 2.5 GHz microstrip antenna created from FR4 versus a soft silicone rubber substrate. Two different designs using the same geometry and the same feeding method were used to create a consistent sample set for each substrate material. The comparison of the two antenna types is based upon three main RF performance metrics: radiation patterns will be used to assess the directional characteristics, coverage consistency, and suitability for Medical Internet of Things (IoT) link applications; Voltage Standing Wave Ratio (VSWR) to assess the practical matching performance and reflected power across the operational frequency band of each design; and S11 or Reflection Coefficient to determine the impedance matching and resonant characteristics. The combined evaluation of Reflection Coefficient,Voltage Standing Wave Ratio and Patterns of Radiation demonstrate that there is an electrical-mechanical trade-off between a rigid substrate that has been designed to give an efficient match and a flexible one that has been designed for conformal application. Thus, this paper provides practical information pertaining to the selection of substrate materials used in ISM-band biomedical and on-body wearable devices.

## II. ANTENNA DESIGN PROCEDURE

### A. Design Specifications and Substrate Selection

The proposed compact microstrip antenna is designed to operate at 2.5 GHz for ISM-band medical IoT and wearable applications, with overall dimensions constrained to 22 × 15 × 1 mm³ to support integration into small wireless devices. To study the influence of substrate material on antenna performance and mechanical suitability, the same antenna geometry is implemented on two substrates:

- FR4 (Rigid substrate): relative permittivity $\varepsilon r$ = 4.4, loss tangent = 0.02
- Silicon rubber (Flexible substrate): relative permittivity $\varepsilon r$ = 3.3, loss tangent = 0.002

Both substrates [8] are modelled with a thickness of 1 mm to ensure a fair comparison. The antenna layout, feeding structure, and partial ground configuration are kept unchanged across both cases, so that variations in S11, VSWR, and radiation patterns can be attributed primarily to the dielectric and loss characteristics of the substrates, as well as the mechanical nature (rigid vs flexible) relevant to biomedical and on-body deployment.

### B. Basic Antenna Structure

A standard microstrip patch antenna configuration is employed for this antenna with a radiating patch layer printed on top of a substrate and a conductive ground plane on the bottom side of the substrate. The original patch shape was determined to resonate near 2.5 GHz and fit within the somewhat restricted footprint. However, due to the desire to further miniaturize the design[23], if the basic design is used alone, it will not provide the required performance for the best matching or most stable resonances. Therefore, modifications to the structure were made to enhance the performance.

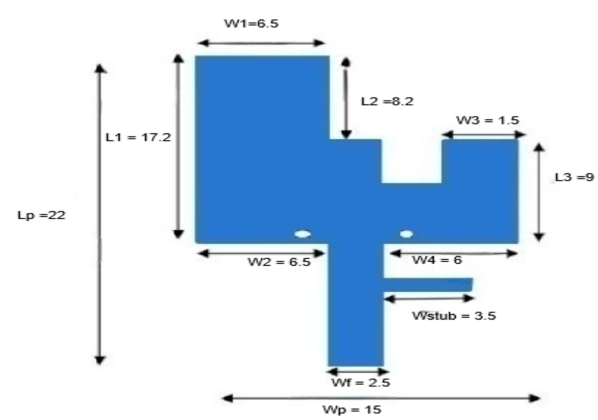


Fig. 1. Geometric view of the Designed Antenna.

### C. Stub Addition and Resonating Structure

Phase 1 of the design was to include a stub in the radiating structure to increase the effective electrical length without increasing the physical dimensions of the radiating structure.

TABLE I
ANTENNA DESIGN SPECIFICATIONS

| Antenna Parameters | Dimensions (mm) |
|---|---|
| $L_p$ | 22 |
| $W_p$ | 15 |
| $L_1$ | 17.2 |
| $L_2$ | 8.2 |
| $L_3$ | 9 |
| $W_1$ | 6.5 |
| $W_2$ | 6.5 |
| $W_3$ | 1.5 |
| $W_4$ | 6 |
| $W_{stub}$ | 3.5 |
| $W_f$ | 2.5 |

The stub would provide additional surface current path length which would result in the resonant frequency being shifted to move toward the target ISM band and would also create better coupling between the feed and the radiator. This modification very well concentrated the current at the important radiating edges of the patch and provides significant contribution to the overall gain of the return-loss characteristics achieved from both substrates used in the final design.

### D. Shorting Pin Integration

The second improvement made to the radiating structure was the introduction of shorting pins [1][2] between the patch and ground plane for further miniaturisation and improved impedance performance. The shorting pins also provide an alternate current path which causes the resonant frequency to drop and input impedance to stabilize. The number of shorting pins [5][6] and their spacing must be arranged in such a manner that the currents are controlled and therefore reduces the losses by reflection.

### E. Feeding Mechanism

To excite the antenna a microstrip feed line [7] was used due to its planar nature and ease of controlling impedance. In addition, the feed line was designed to exhibit a characteristic impedance of 50 ohms. In order to minimize losses associated with mismatched feeds, and to maximize the efficient transfer of power into the antenna, as well as ensure that the feed location is optimal, the location of the feed is designed based on the stub arrangement and the shorting pins.

### F. Ground Plane Configuration

To enhance the impedance match and improve the radiation characteristic of the antenna, a partial ground plane was constructed on the opposite side of the substrate from the antenna. A truncated ground plane changes the distribution of surface currents on the ground plane, and therefore interacts with the stub and shorting pins to provide an improvement in the return loss of the antenna and overall radiation characteristics of the antenna.

### G. Final Optimized Configuration for Substrate Comparison

The final optimized antenna has a compact volume of 22mm X 15mm X 1mm in dimensions and uses stub loading, shorting pins, a 50-ohm microstrip feed line, and a partial ground plane. The same optimized geometry was simulated on FR4 and silicon rubber [9],[10], providing a quantitative analysis of the substrate driven effects on S11, VSWR, and radiation patterns, and allowing for a direct comparison between a flexible, conformal, wearable oriented configuration and a stiff, rigid, high-matching configuration.

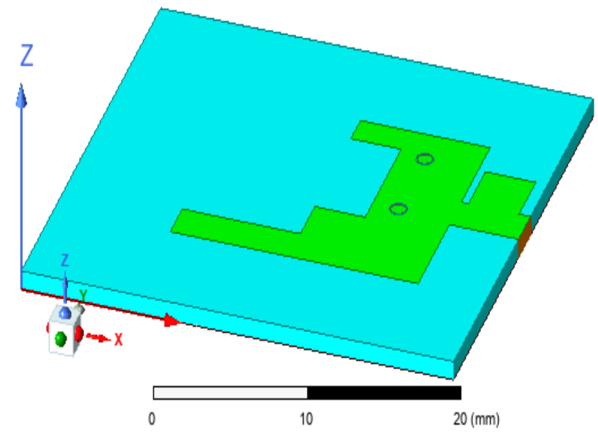


Fig. 2. Trimetric view of the designed antenna.

## III. Simulation Results

### A. Reflection Coefficient ($S_{11}$)

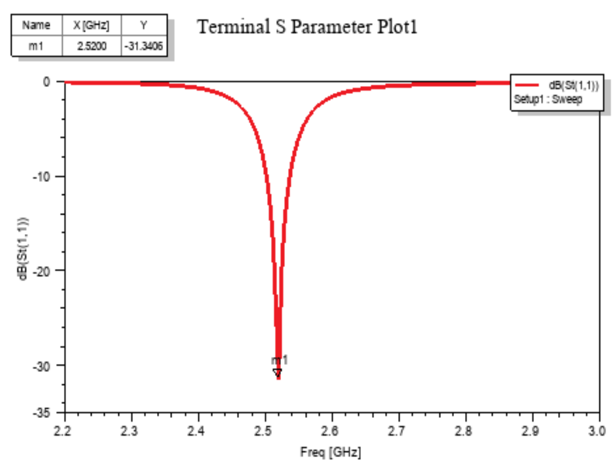


Fig. 3. Return loss of the proposed antenna using FR-4 as the substrate.

The simulation results of the return loss ($S_{11}$) of the microstrip antenna on an FR4 substrate in the 2.2–3 GHz frequency range are shown in Figure 3. As observed, the curve exhibits a clear resonance with a sharp and narrow dip located close to the desired 2.5 GHz ISM band, representing efficient impedance matching around 2.520 GHz with an $S_{11}$ value of $-31.34$ dB. This result implies that nearly 100% of the input power is radiated by the antenna, with only a negligible portion reflected back to the source. Such performance indicates strong coupling between the $50\,\Omega$ microstrip feed and the compact radiating structure formed by the partial ground plane, stub loading, and shorting pins. Therefore, the antenna design using the FR4 substrate enables effective tuning for ISM-band medical and Internet of Things (IoT) applications [**?**].

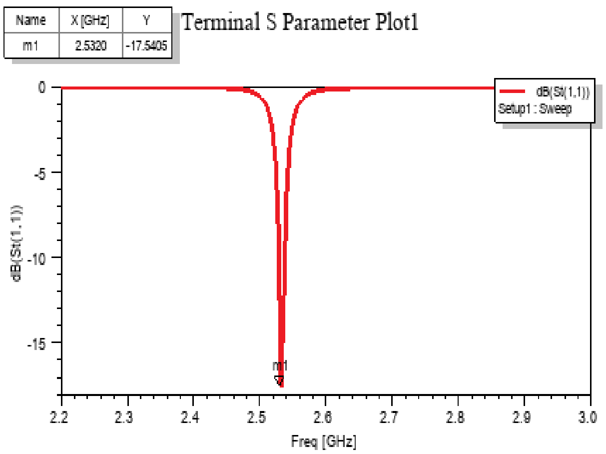


Fig. 4. Return loss of the proposed antenna using Silicon Rubber as the substrate.

In Fig. 4, the simulated reflection coefficient ($S_{11}$) of the antenna fabricated on a silicone rubber substrate ($\varepsilon_r = 3.3$, $\tan\delta = 0.002$) over the frequency range of 2.2–3.0 GHz is presented. As shown in the figure, a clear resonance appears within the ISM band of interest. The marker $m_1$ indicates a dip in $S_{11}$ at 2.532 GHz with a corresponding return loss of approximately $-17.54$ dB.

This return-loss value demonstrates that the antenna maintains good impedance matching on the flexible substrate, as it lies well below the commonly accepted $-10$ dB criterion. This indicates that most of the input power is efficiently transfe to the antenna radiator, with only a small portion reflected back to the source.

Furthermore, when compared with the FR4 substrate case, a slight upward shift in the resonant frequency and a comparatively shallower dip in the $S_{11}$ curve can be observed. This behavior occurs due to the change in the dielectric constant when transitioning to a lower-permittivity substrate [**?**]. In general, the plot confirms acceptable impedance matching around 2.5 GHz while allowing the antenna to maintain the flexibility required for conformal and wearable medical Internet of Things (IoT) applications.

The comparison of the reflection coefficient ($S_{11}$) for both substrates reveals that the antenna resonates close to 2.5 GHz, confirming proper operation within the ISM band. The FR4 substrate provides a significantly deeper return-loss dip ($-31.34$ dB at 2.520 GHz),demonstrating strong impedance matching and minimal reflection. In contrast, the silicone rubber substrate exhibits a slightly higher resonant frequency (2.532 GHz) with a shallower dip ($-17.54$ dB), suggesting that the impedance matching remains good but is comparatively weaker than that of the FR4 substrate [**?**]. Overall, FR4 offers superior reflection performance, while silicone rubber provides acceptable matching along with the added advantage of flexibility, adapting it for conformal and wearable antenna applications.

*B. Voltage Standing Wave Ratio (VSWR)*

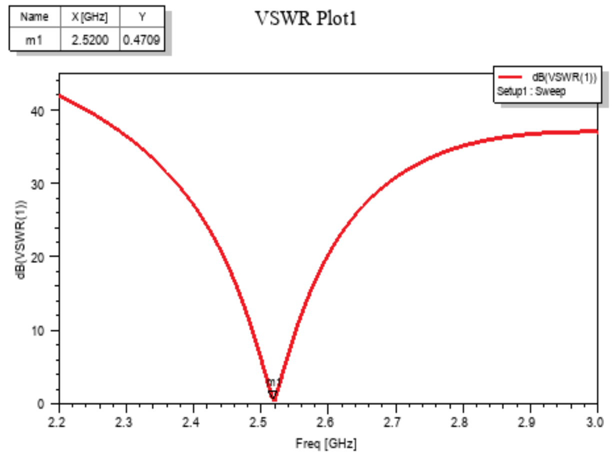


Fig. 5. VSWR of the proposed antenna using FR-4 as the substrate.

The simulated voltage standing wave ratio (VSWR) for the antenna built on FR4 (εr = 4.4, tanδ = 0.02) was demonstrated in figure 5. The antenna represents a distinct, sharp minimum at the ISM-band frequency (2.520GHz) revealing it is well matched to this frequency. The marker value of 0.4709 dB (VSWR) represents an actual VSWR of approximately 1.06, which is very close to the ideal value of 1. A low VSWR indicates that only a small quantity of input power is reflected back towards the source, while the majority of the input power is transferred to the antenna for radiation, confirming the excellent impedance matching of the antenna. The presence of a deep dip and stable curve about the resonant frequency also indicates effective coupling between the antenna's feed and radiator; thus, the FR4-based antenna is determined to be a good choice for reliable operation of wireless/IoT devices operating at 2.5 GHz.

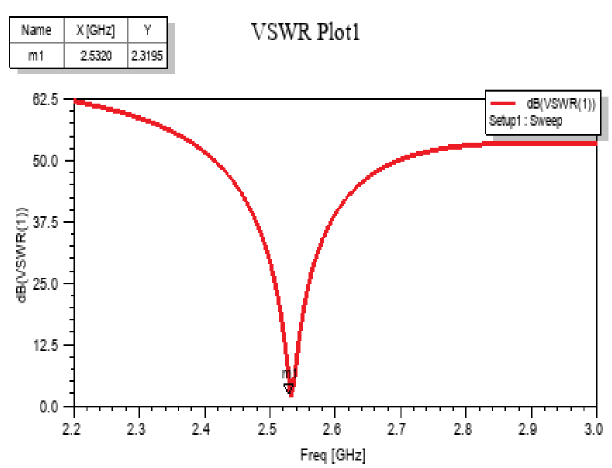


Fig. 6. VSWR of the proposed antenna using Silicon Rubber as the substrate.

The figure 6 presents the simulated VSWR response of the antenna when implemented on the silicone rubber substrate (εr = 3.3, tanδ = 0.002). A clear minimum occurs at 2.532 GHz, confirming that the antenna is tuned close to the 2.5 GHz ISM band on the flexible material. The marker is at 2.3195 dB(VSWR), which corresponds to an actual VSWR of approximately 1.30, implying good impedance matching (well within common acceptance limits such as VSWR ¡ 2). Compared with the FR4 case, the minimum is higher and the resonance is slightly shifted upward, reflecting the change in effective dielectric loading when moving to a lower-permittivity flexible substrate. Overall, the plot verifies that the antenna remains suitably matched on silicone rubber, though with a weaker match than FR4, while enabling the mechanical flexibility [22] required for wearable and on-body medical IoT applications. The FR4 substrate gives the strongest impedance match, seen as the deepest VSWR minimum around 2.52 GHz. With silicone rubber,[20],[21] the antenna still matches well near 2.53 GHz, but the VSWR minimum is higher, showing slightly increased mismatch compared to FR4.

### *C. 2D Radiation Pattern*

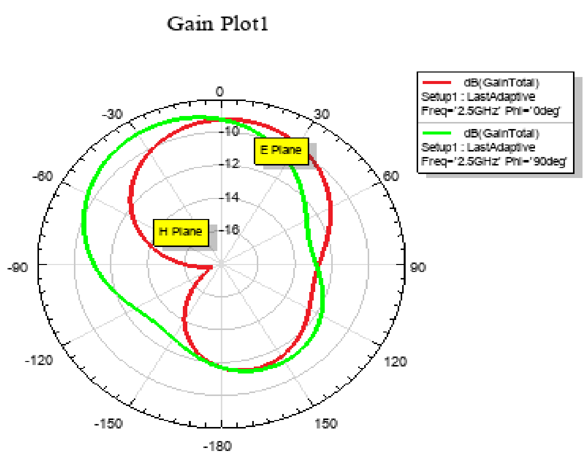


Fig. 7. 2D Radiation pattern of the proposed antenna using FR-4 as the substrate.

The far-field radiation pattern of the proposed antenna on an FR4 substrate at 2.5 GHz is depicted in Figure 7. The plot presents Gain Total (dB) in both main cuts, Φ = 0 and Φ = 90. There is a significant main lobe which indicates that the antenna radiates [14] much more clearly in the forward direction than it does in any other angle. The E-plane and H-plane pattern have a slight asymmetry and variation in their shapes, which are expected as a consequence of the compact structure, the partial ground plane that was used, and the stub loading and shorting pins that modified the current distribution [15] on the surface of the substrate. Overall, the radiation patterns confirm stable directionality at the target frequency of the ISM band for reliable wireless communication for compact medical/IoT devices.

The figure 8 exhibits the 2D polar far-field radiation pattern of the proposed antenna at 2.5 GHz when realised on a silicon

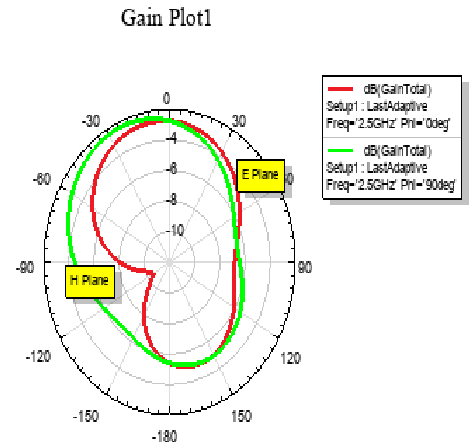


Fig. 8. 2D Radiation pattern of the proposed antenna using Silicon Rubber as the substrate.

rubber substrate with εr = 3.3 and tanδ = 0.002. The plot includes both principal plane cuts (Φ = 0° - E plane, Φ = 90° - H plane) measured using total realised gain (dB(GainTotal)). The directional radiation pattern indicates that the antenna radiates to a greater degree in the forward/broadside region (i.e., 0°) and is less susceptible to back-radiation (approximately ±180°)—confirming that the back-radiation is lower than that of other possible designs. A comparison of the two cuts reveals that the H-plane (Φ = 90°) has a much broader, smoother contour; while the E-plane (Φ = 0°) displays a somewhat-shaped/irregular contour; this variation can be attributed to the compact radiator design, partial ground plane, and loading elements that have created asymmetrical surface current distributions. The silicon-rubber implementation demonstrates a stable radiation pattern at 2.5 GHz, implying its potential application for conformal/wearable medical IoT devices where continuous coverage is required when the device is bent or placed against a patient. At 2.5 GHz, both FR4 and silicon rubber designs present a mainly directional radiation pattern with a forward main lobe and reduced back radiation. In both cases, the H-plane is smoother/broader than the E-plane due to the compact [16] structure with partial ground, stub, and shorting pins.

### *D. 3D Radiation Pattern*

Figure 9 (FR4) and Figure 10(silicon rubber) are the 3D far-field radiation characteristics of the same patch geometry realized on two different substrates. In both cases, the antenna exhibits a clear dominant main lobe radiating away from the patch (broadside/near-broadside behaviour) with comparatively weaker radiation in the opposite direction,suggesting that the structure maintains a generally directional pattern rather than a fully omnidirectional one.

When the substrate is changed from FR4 to silicon rubber, the overall shape of the pattern remains similar (same radiation mechanism and polarization), but the distribution of radiated energy typically becomes more "spread" with the flexible substrate—i.e., a slightly broader main lobe and reduced peak

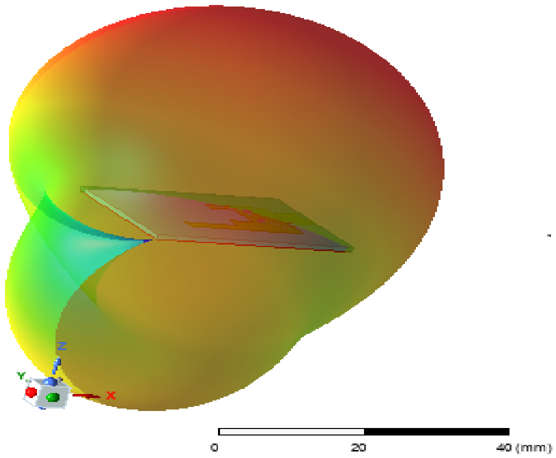



Fig. 9. 3D Radiation Pattern of the proposed antenna using FR-4 as the substrate.

TABLE II
COMPARISON MATRIX OF FR4 AND SILICON RUBBER SUBSTRATES

| Metric | FR4 substrate | Silicon rubber substrate |
|---|---|---|
| Substrate type | Rigid | Flexible / conformal |
| Relative permittivity ($\varepsilon_r$) | 4.4 | 3.3 |
| Loss tangent ($\tan\delta$) | 0.02 | 0.002 |
| Substrate thickness | 1 mm | 1 mm |
| Resonant frequency (approx.) | 2.520 GHz | 2.532 GHz |
| Minimum return loss ($S_{11}$) | $-31.34$ dB | $-17.54$ dB |
| VSWR at resonance (approx.) | $\approx 1.06$ | $\approx 1.30$ |
| Impedance matching strength | Excellent (very low reflection) | Good (acceptable, but weaker than FR4) |

intensity—because silicon rubber[17] commonly introduces different effective permittivity and higher dielectric loss compared with FR4, which can reduce radiation efficiency and slightly alter the current distribution on the patch. In contrast, the FR4 case tends to preserve a more concentrated main lobe (higher apparent directivity), while the silicon-rubber [18] case is expected to have mild pattern smoothing/beam spreading and potentially small changes in beam tilt due to the substrate's different electromagnetic loading. Overall, the figures indicate that substrate selection primarily affects radiation strength and lobe breadth (and hence gain/directivity), while the antenna's fundamental directional radiation behavior remains consistent across both implementations.

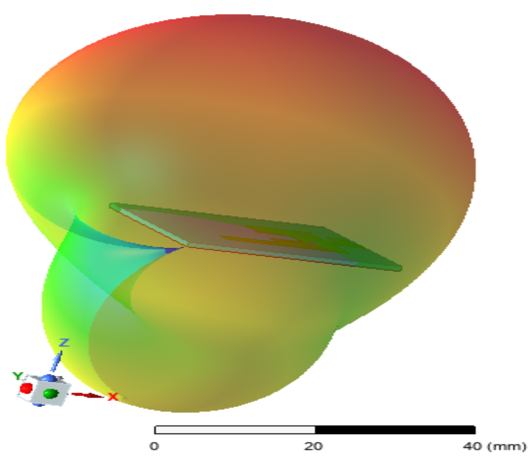



Fig. 10. 3D Radiation Pattern of the proposed antenna using silicon rubber as the substrate.

In summary, the FR4-based antenna achieves superior impedance matching, evidenced by a deeper S11 notch and a lower VSWR, and it tends to maintain a more focused directional radiation. The silicon-rubber design, while still operating effectively near the 2.5 GHz ISM band with a comparable directional pattern, displays comparatively reduced matching performance and a slight resonance shift. Overall, FR4 is preferable when peak RF performance is the priority, whereas silicon rubber is a practical choice when mechanical flexibility and conformal/wearable integration are more important.

## IV. CONCLUSION

Using HFSS, the authors of this paper conducted a comparison between two different substrate materials (FR4 and silicon rubber) for a compact 2.5 GHz ISM-band microstrip antenna, while keeping the geometry and feeding structure of the antenna constant. The results conclude that both substrates can be used to create resonance at or near the desired ISM frequency range, however, the two materials produced antennas with differing levels of impedance matching. The antenna manufactured on an FR4 substrate had a much better impedance match than the antenna manufactured on a silicon rubber substrate; the FR4 antenna had an S-parameter of -31.34 dB at 2.52 GHz and a VSWR of approximately 1.06 (representing very low power reflected back to the transmitter and highly efficient power transfer to the antenna). On the other hand, the antenna manufactured on silicon rubber had an S-parameter of -17.54 dB and a VSWR of approximately 1.30 at 2.53 GHz. Both the FR4 and silicon rubber antennas will work well in practical wireless applications, but the silicon rubber antenna will have a slightly larger mismatch compared to the FR4 antenna. Radiation-pattern analysis at 2.5 GHz showed that both implementations maintain a directional pattern [19] with a dominant forward main lobe and reduced back radiation, and the H-plane remains smoother/broader than the E-plane due to the compact structure with a partial ground plane, stub loading, and shorting pins. Overall, the study highlights a clear trade-off: FR4 is the better choice when maximum impedance matching and stable RF performance are the priority, making it suitable for rigid medical IoT nodes and compact wireless devices, whereas silicon rubber is preferred when conformal placement, flexibility, and wearable integration[22] are required, even though it results in slightly reduced matching performance. This comparison provides practical guidance for selecting substrate materials based on the intended application scenario in biomedical and wearable ISM-band systems.

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