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Research paper

S-Parameter Analysis of Three-Layered Aperture Coupled Antenna with a Flame Retardant-4 Composite Material as Substrate for Biomedical Applications

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ABSTRACT

In biomedical applications, particularly for tumor detection, the need for high-resolution imaging systems is critical. This paper presents the "S" parameter analysis of a three-layer stacked microstrip antenna with Defected Ground Structure (DGS) having a "+" shaped slot. The dimension of the antenna provides an enhanced performance ranging from 4.5-12 GHz. An aperture-coupled mechanism where a direct connection between feed and the FR-4 (Flame Retardant 4) substrate employing the need for three substrates having a dielectric constant (εr = 4.4) and having a thickness of 1.57mm each is utilized in this design. The composite material known as FR4 is structured with its fundamental layer consisting of fiberglass, woven into a thin, fabric-like sheet, providing essential structural support. This innermost layer of fiberglass imparts the necessary stability to FR4. It is then encased and secured by a flame-resistant epoxy resin. The antenna structure incorporates a parasitic patch as the topmost layer and an active patch that is placed below the substrate layer both of which incorporate slots for enhanced performance. The ground layer is sandwiched between the active layer and feedline which ensures separation between the two. Such a structure can help in optimizing both the radiating patch and the feedline independently. The performance of the designed antenna is studied for various slot configurations where the S-S-parameter analysis shows that the antenna provides wideband behavior which makes it suitable for biomedical applications like breast cancer detection. The S parameter analysis done in HFSS software shows a maximum return loss of -40dB which is performed for various slot configurations. The increasing demand for UWB communication systems underscores the critical importance of advanced antenna design to meet expanding data transmission requirements. The design of UWB antennas plays a crucial role in biomedical applications like breast cancer detection, where precise signal accuracy and penetration depth are essential for enhancing diagnostic efficacy and treatment monitoring.

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1. Introduction

With the rapid expansion of wireless applications spanning IoT, industrial automation, and healthcare, the demand for Ultra-wideband (UWB) communication systems has surged. UWB's unique ability to deliver high data rates, low power consumption, and resilience in complex environments makes it indispensable. Antenna design plays a pivotal role in optimizing the performance of UWB systems, ensuring seamless integration and reliable communication. As industries increasingly rely on UWB for connectivity, the pressure to innovate antenna designs intensifies, emphasizing the critical role they play in meeting the evolving demands of modern wireless communication.

This paper introduces a novel design of a three-layer stacked microstrip antenna with a Defected Ground Structure (DGS) incorporating a distinctive "+ shaped" slot. The selected dimensions (37x43x4.71 mm^3) are crucial for designing a compact and efficient antenna. These dimensions determine the antenna's physical size, which directly impacts its performance, especially in terms of bandwidth, resonance frequency, and radiation pattern. The selected dimensions (37x43x4.71 mm^3) are crucial for achieving compactness and efficiency in antenna design, ensuring optimal performance and integration in constrained electronic devices.

By carefully optimizing these dimensions, designers can achieve a balance between antenna size and performance, making it suitable for integration into compact devices while maintaining high efficiency and functionality.

The proposed antenna design employs an aperture-coupled mechanism, establishing a direct connection between the feed and the Flame Retardant 4 (FR-4) substrate [12]. This substrate, with a dielectric constant (ε_r) of 4.4 and a thickness of 1.57 mm for each of the three layers, forms a composite structure widely known as FR4. The FR4 material consists of a fiberglass layer providing structural stability and a flame-resistant epoxy resin for added protection.

Incorporating a parasitic patch as the topmost layer and an active patch positioned below the substrate layer, both equipped with strategically placed slots, the antenna design aims to enhance its overall performance. The ground layer, positioned between the active layer and the feedline, ensures proper separation, facilitating independent optimization of the radiating patch and feedline.

The dimensions chosen for the active patch define its resonance, impedance matching, and radiation pattern. Optimal sizing ensures efficient signal conversion and transmission. For the parasitic patch, dimensions control coupling with the active patch, affecting radiation properties and bandwidth. Careful selection achieves desired antenna effects without sacrificing impedance matching. Feedline dimensions determine impedance, power transfer efficiency, and signal propagation characteristics. Proper sizing minimizes losses and maximizes radiation efficiency. Each dimension contributes to the design rationale, aiming for resonance, efficient power transfer, and desired radiation characteristics tailored to the antenna's intended application.

This paper presents a comprehensive S-parameter analysis using High-Frequency Structure Simulator (HFSS) software, exploring various slot configurations [11]. The results demonstrate the antenna's wideband behavior, with a maximum return loss approaching -40 db. Such wideband characteristics make the antenna particularly suitable for biomedical applications, including breast cancer detection, where reliable communication and high-performance antennas are crucial. The main objective of the current work is to analyze the S-parameters of a three-layered aperture-coupled antenna using Flame Retardant-4 (FR-4) composite material as the substrate, with a focus on achieving wideband performance and low return loss for enhanced resolution and depth penetration in biomedical imaging applications, particularly for tumor detection.

2. Antenna Structure

The geometry of the three-layer stacked microstrip patch antenna is shown in Figure 1 below [1].

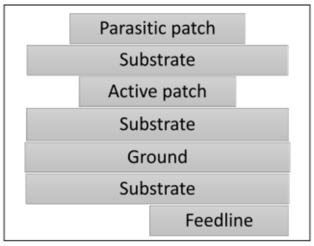

Fig.1. Geometry of three-layer stacked microstrip patch antenna

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In the innovative antenna design, the positioning of the parasitic and active patches, along with strategic layering, plays a crucial role in optimizing its performance. The parasitic patch is meticulously situated above the uppermost substrate, while the active patch resides just below it. To ensure effective isolation, an additional substrate layer separates the active patch from the ground plane. The feed line, responsible for signal transmission, is located beneath the bottommost substrate layer. All three substrate layers are crafted from FR4 material, exhibiting a consistent dielectric constant ($\varepsilon_r = 4.4$), and maintaining a thickness of approximately 1.57 mm.

The active and parasitic layers, vital for radiation characteristics, are constructed from copper with a thickness of 0.035 mm, expertly deposited atop the substrate layers. This careful arrangement and material selection contribute to the antenna's enhanced electromagnetic field control, promoting efficient signal transmission and reception. The use of FR4 substrate ensures uniformity in dielectric properties across the layers, facilitating stable and reliable performance within the desired ultra-wideband frequency range.

The selected parameters and design decisions significantly influence the antenna's wideband performance. Optimal active and parasitic patch dimensions, along with feedline geometry, are critical. Larger active patches expand bandwidth but may introduce higher-order resonances. Strategic parasitic patch configurations control radiation patterns for wider bandwidth, while improper placement limits performance. Feedline geometry affects impedance matching across frequencies, variations impact wideband efficiency. Pragmatically, balancing these parameters maximizes bandwidth while ensuring efficient signal transmission. A well-designed antenna accommodates diverse communication needs, enhances signal robustness, and adapts to varying environmental conditions, thus maximizing its utility across wide frequency spectra. The optimization of antenna design for wideband performance has practical implications for improving the accuracy and reliability of cancer detection systems, potentially leading to more precise imaging and earlier diagnosis.

3. Design Parameters

In the design of slotted structure patch antennas, critical parameters include resonant frequency (f_r), crucial for applications like wireless, radar, and satellites, targeted within the (4.5-12) GHz range. The dielectric constant (ε_r) of the chosen FR-4 substrate is set at 4.4 to optimize signal propagation. Additionally, a key consideration is the height of the substrate (h), set at 1.57 mm to ensure compact and lightweight antennas, *align* with the demands of modern communication applications. These parameters collectively contribute to the antenna's efficiency and suitability for diverse high-frequency communication scenarios.

4. Design Equations

Step 1: To calculate the width W of the patch.

$$W = \frac{v_o}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \quad (1)$$

where v_0: velocity of light in vacuum $=3*10^8$ m/s, ε_r: dielectric constant of the substrate chosen. f_r: resonant/operating frequency of the antenna

Step 2: To calculate the effective dielectric constant.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\left[1+12\frac{h}{W}\right]^{-1/2}, \frac{W}{h} > 1 \quad (2)$$

where ε_r is the relative dielectric constant of the material, h is the height of the substrate and W is the width of the patch calculated in Step 1.

Step 3: Calculate extension length ΔL.

$$\frac{\Delta L}{h} = 0.412\frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \quad (3)$$

Step 4: Calculate the effective length of the patch L

$$L = \frac{v_o}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \quad (4)$$

where v_0 is the velocity of light.

Step 5: Calculate the length of the patch

$$L = Leff - 2\Delta L \quad (5)$$

Step 6: Calculate the length (L_g) and width (W_g) of the ground plane

$$L_g = 6h + L \quad (6)$$

$$W_g = 6h + W \quad (7)$$

5. Antenna Structure and Design

The optimized parametric specifications used for designing the antenna are shown in Table 1[1].

Table 1. Antenna design parameters

Parameter	Dimension in mm
Length and width of substrate	37 X 43
Length and width of feedline	4.30 X 24.20
Length and width of ground	37 X 43
Length and width of parasitic patch	20.27 X 15.40
Length and width of active patch	27 X 21.50
"+" Slots on ground plane	16 X 16
Feedline with stub	24.20 X 4.30

The selected substrate is made of FR4 epoxy with a dielectric constant of 4.4 and dimensions measuring 37 x 43 mm. Figure 2 illustrates the arrangement of the substrate layers, highlighting the distinct structure that sets it apart from the other layers.

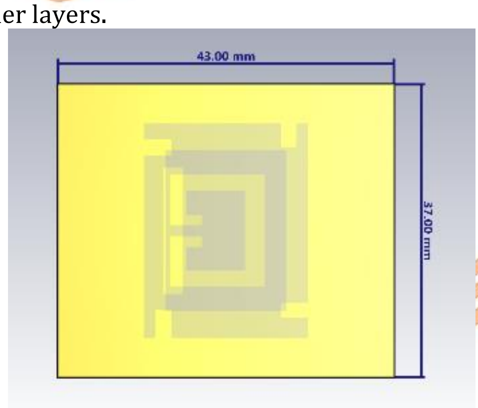


Fig. 2. Substrate dimension

The antenna design features a stratified configuration, with each layer having a height of 1.57 mm. The parasitic layer is positioned between the top and bottom substrates. Figure 3 depicts the stacked alignment of the chosen top and bottom substrate layers in the antenna structure [3].

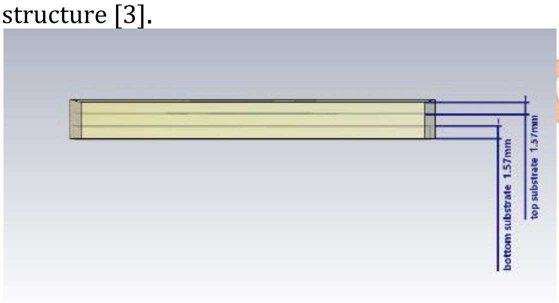


Fig.3. Assembled antenna layers

The primary radiating element in the stacked configuration structure is the lower active patch layer, with dimensions of 27 x 21.50 mm. Enhancing antenna performance, slots are integrated into the corners of the rectangular patch, measuring 3.50 mm horizontally and 2 mm vertically [6].

Figure 4 illustrates the active patch dimensions, incorporating a rectangular slot, 16 mm in the vertical direction, on the left end of the substrate [5].

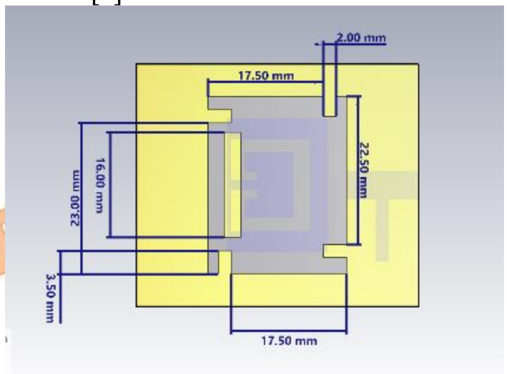


Fig.4. Dimensions of active patch

The uppermost layer serves as the parasitic substrate, functioning as a secondary radiating element with dimensions of 20.27 x 15.40 mm. A "U" shaped slot is integrated into the parasitic patch, with specific dimensions illustrated in Figure 5. This configuration contributes to achieving Ultra-Wideband (UWB) performance, facilitating enhanced impedance matching and expanding the antenna's impedance bandwidth.

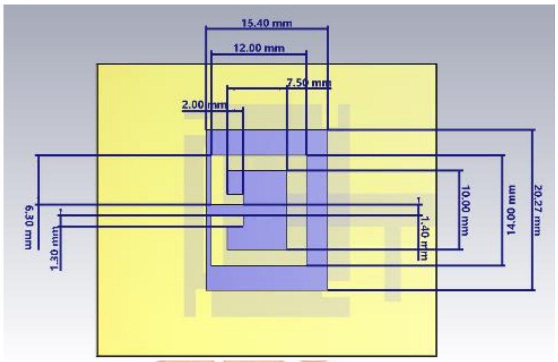


Fig. 5. Dimensions of parasitic patch

The ground plane features "plus" slots, measuring 16 x 16 mm, integrated into the central area. This defective ground structure has demonstrated its effectiveness in enhancing the excitation of resonant bands by both the parasitic and active patches [8]. The "plus" slot, formed by combining horizontal and vertical slots, is cut into the ground plane, contributing to an expanded bandwidth. The specific dimensions of this configuration are depicted in Figure 6.

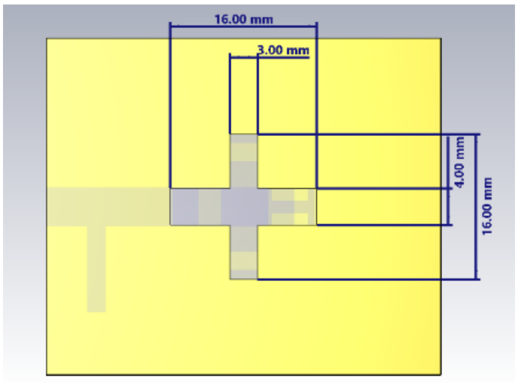


Fig. 6. Dimensions of the ground plane with "+" slot

The feed line, accompanied by a tuning stub, plays a role in enhancing impedance bandwidth. The width of the feedline facilitates improved coupling to the slot, and its optimization contributes to refining antenna characteristics. Figure 7 illustrates the dimensions of the rectangular-shaped tuning stub for the feedline.

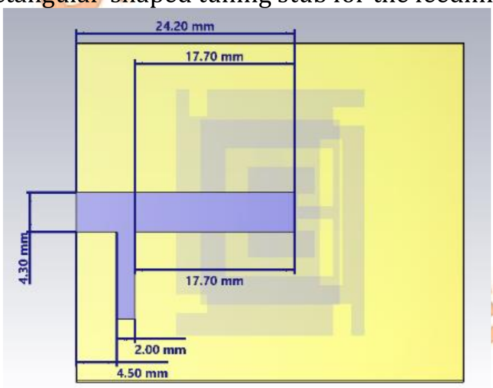


Fig 7. Dimensions of feedline with stub

The designed antenna was implemented in HFSS software to analyze its "S" parameters, incorporating the stacked layers, including the parasitic patch, active layer, defective ground structure with a central "plus" shaped slot, and the feedline with a rectangular tuning stub. Figure 8 illustrates the distinct layers of the designed antenna.

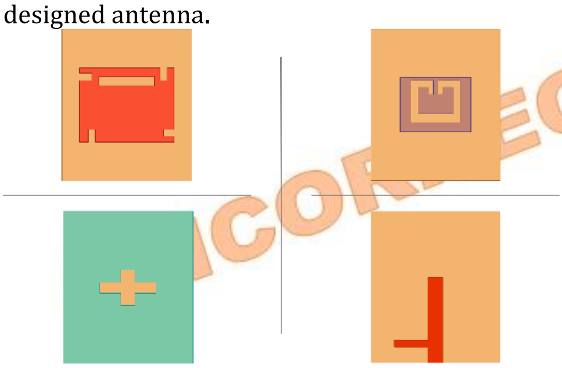


Fig. 8. Different layers of the designed antenna

The ultimate antenna configuration, comprising various layers, was simulated using the HFSS tool to comprehensively analyze its characteristics. Figure 9 depicts the final antenna structure, revealing the multi-layered stacked arrangement of its diverse components [10].

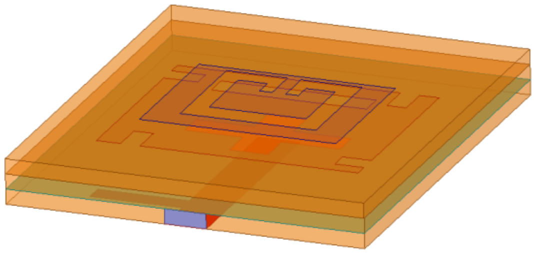


Fig. 9. Final antenna structure with the different stacked layers

Globally, researchers have identified these antenna structures as highly applicable for biomedical purposes, particularly in breast cancer detection and other diagnostic applications [9]. The configured antenna was positioned in parallel to a breast phantom model within HFSS. This model considers various layers of the human body, including the skin layer, fat layer, and a tumor placed inside the fat. The electrical properties of the layered breast phantom are detailed in Table 2 [1].

Table 2. Properties of the breast phantom

Layer	Dielectric constant	Electrical conductivity (S/m)	Thickness in diameter (mm)
Skin layer	36.587	2.3404	4
Fatty layer	4.8393	0.26229	32
Tumor	67	49	8

Figure 10 depicts the spherical breast phantom model positioned in proximity to the designed antenna model. The antenna is situated at a distance of 10mm from the breast phantom, and a thorough analysis of the S-parameters was conducted [1].

Fig. 10. Spherical breast phantom placed parallel to the designed antenna.

6. Results and Discussion

The antenna was initially fed using a horizontal planar feeding mechanism operating at a resonant frequency of 11.4 GHz, resulting in a return loss of -20 dB, as illustrated in Figure 11.

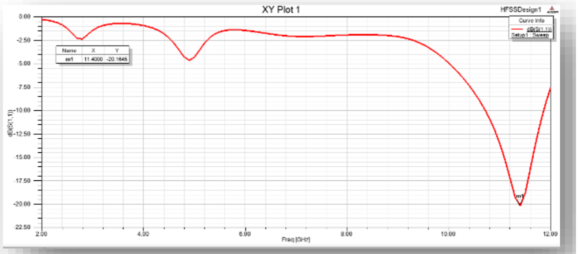


Fig. 11. Return loss for horizontal planar fed type

The ground plane was subsequently altered to feature a slotted configuration by introducing both horizontal and vertical slots, forming a defective ground structure. Figure 12 and Figure 13 illustrate the return loss obtained when incorporating horizontal and vertical slots, respectively.

Introducing the horizontal slot resulted in an S11 of -33.92 dB at a frequency of 10.5 GHz, -16 dB at 8.8 GHz, and -10.4 dB at 5.6 GHz.

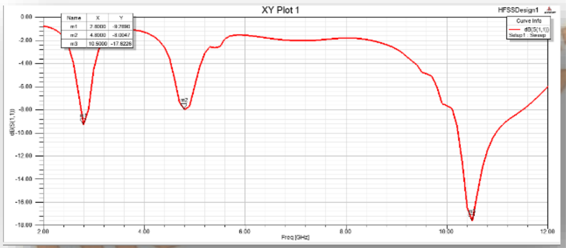


Fig. 12. Return loss for a horizontal slot in the ground plane

Incorporating the vertical slot yielded an S11 of -17.62 dB at a frequency of 10.5 GHz, -8 dB at 4.8 GHz, and -9.289 dB at 2.8 GHz.

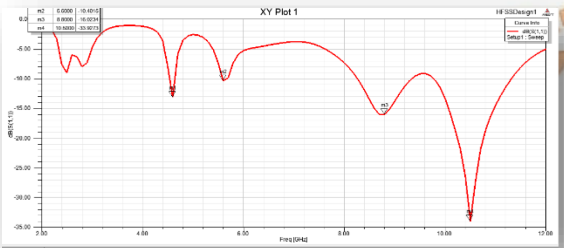


Fig. 13. Return loss for a vertical slot in the ground plane

A combination of horizontal and vertical slots, forming a "plus" symbol, was integrated into the central region of the ground structure to boost its performance and enhance return loss. The introduction of the "plus" slot resulted in a return loss of -22.79 dB at 10.4 GHz, -18.21 dB at 9.3 GHz, -17.84 dB at 5.7 GHz, and -16.06 dB at 4.7 GHz, as depicted in Figure 14.

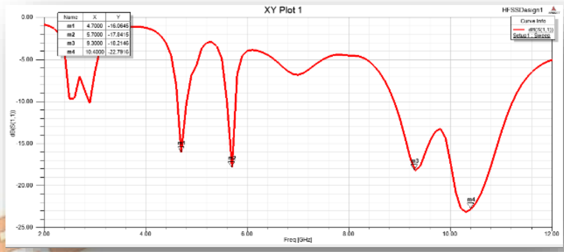
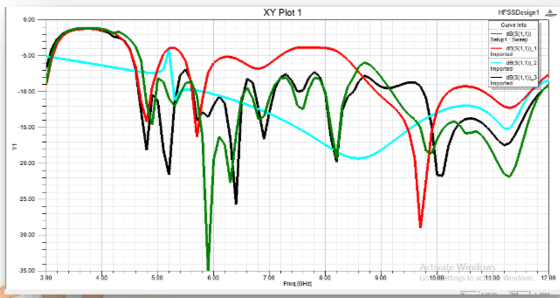


Fig. 14. Return loss for “+” slot in ground plane



Slots were incorporated into both the active and parasitic patches to enhance impedance matching and broaden the antenna's bandwidth. This configuration not only improves impedance bandwidth but also enhances the radiation characteristics of the antenna structures. Results depicting the return loss for the active patch and the parasitic patch with the insertion of slots are presented in Figure 15 and Figure 16, respectively.

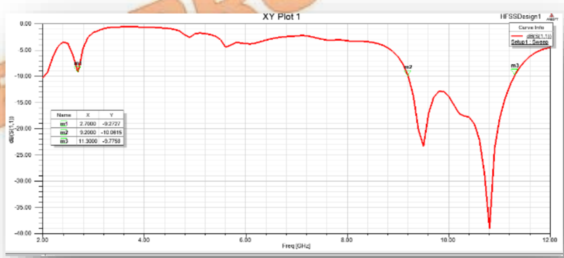


Fig. 15. Return loss for an active patch with slots

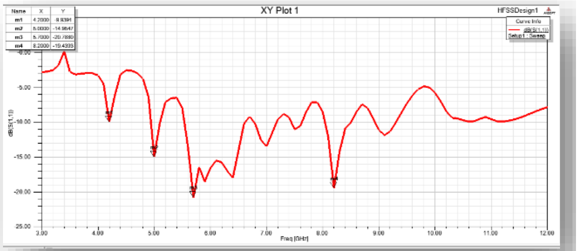


Fig. 16. Return loss for a parasitic patch with slots

Current research predominantly concentrates on altering the ground plane through the utilization of defective ground structures or partial ground structures. These modifications contribute to enhancing crucial antenna parameters such as bandwidth and gain. Figure 17 presents a comparative analysis of the designed antenna across various slot configurations, revealing an impressive return loss of nearly -39 dB at 10.8 GHz.

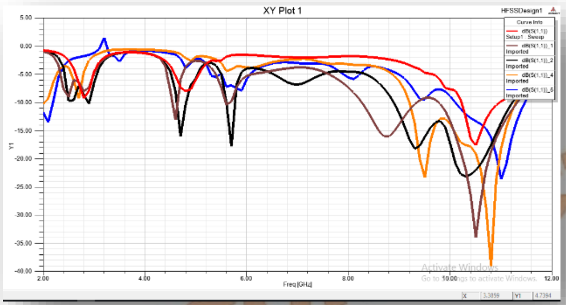


Fig. 17. Results comparisons of ground slots

The antenna's performance can also be enhanced by modifying the patch using different slot shapes. Figure 18 illustrates a comparison of return loss for various slots integrated into the patch layers, revealing an impressive return loss of nearly -35 dB at a frequency of 5.9 GHz.

Fig. 18. Results comparisons of patch slots

The aperture-coupled feeding technique has garnered attention by avoiding a direct connection between the feed and the radiating patch [10]. Modifications to the feed line, incorporating tuning stubs, contribute to enhancing the antenna's performance. Figure 19 illustrates the enhanced return loss of the feed stub, reaching almost -35 dB at 5.9 GHz.

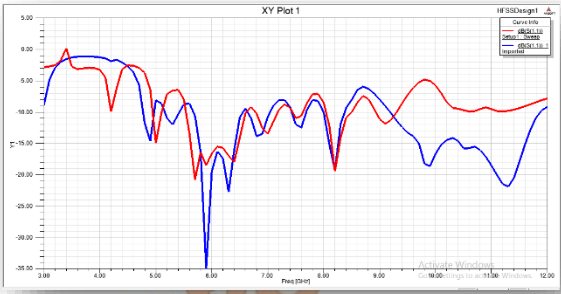


Fig. 19. Results comparisons of feed stub

A breast phantom was modeled in HFSS consisting of a skin layer of 4mm diameter, a fatty layer of 32mm diameter positioned inside the skin layer, and a spherical tumor of 8mm diameter positioned inside the fat layer. The entire arrangement was placed parallel to the radiating antenna structure and its return loss was observed.

A wideband characteristic was achieved, with the antenna resonating at multiple frequencies and exhibiting a return loss ranging from approximately -12.49 dB to -22.34 dB across frequencies spanning from 4.8 GHz to 11.3 GHz. Figure 20 visually illustrates the antenna's resonance at various frequencies, accompanied by the corresponding low return loss values.

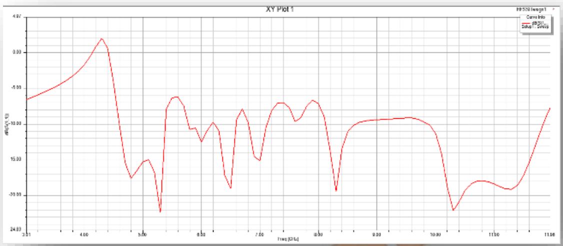


Fig. 20. Results with breast phantom placed parallel to the antenna structure

7. Conclusion and Future Expansion

The designed aperture-coupled antenna structure, featuring two stacked patch layers with rectangular slots, was analyzed for its "S" parameters and demonstrated a wideband return loss characteristic when placed parallel to a modeled breast phantom. The simulation in HFSS revealed a wideband resonance from 4.8 GHz to 11.3 GHz with multiple frequency resonances and low return loss values ranging from approximately -12.49 dB to -22.34 dB. Significant enhancements in antenna response were achieved through modifications to the patch layers, ground layer, and feedline with the tuning stub.

Major Findings

- Wideband Performance: The antenna achieved a broad frequency range from 4.8 GHz to 11.3 GHz.
- Low Return Loss: Maintained low return loss values, indicating efficient power transfer and minimal reflection.
- Multiple Resonances: Demonstrated multiple frequency resonances, enhancing detection capabilities.

Applications

- Medical Imaging: Adaptable for microwave imaging, improving the resolution and accuracy of breast cancer detection.
- Radar-based Tumor Detection: Potential use in radar-based systems for early and precise tumor identification.

Feasibility

The study confirms the feasibility of using optimized aperture-coupled antenna designs in medical applications, specifically for tumor detection. The wideband performance and low return loss values indicate that such antenna structures can significantly enhance the capabilities of current medical imaging technologies, offering better diagnostic tools for early cancer detection.

The three-layered aperture-coupled antenna, designed with FR-4 composite material, demonstrated a wideband resonance from 4.8 GHz to 11.3 GHz, crucial for medical imaging [13]gg. This broad bandwidth, achieved through stacked patch layers with rectangular slots, enhances resolution and depth penetration for tumor detection. The low return loss values (-12.49 dB to -22.34 dB) across this range indicate efficient radiation and minimal power reflection, essential for clear imaging. Modifications to the ground layer and feedline further optimized impedance matching, solidifying the antenna's suitability for advanced biomedical applications.

In conclusion, the study's findings have profound implications for tumor detection, revolutionizing medical imaging techniques and improving patient care. By leveraging antenna design principles, researchers can develop innovative solutions that enhance imaging resolution, penetration depth, and interference mitigation, paving the way for more effective tumor detection and personalized treatment approaches.

The potential application involves utilizing an array of such antenna elements around the human body, proving effective in tumor cell detection. In practical scenarios, the antenna may deviate from ideal conditions. Analyzing the difference in electrical properties between scenarios with and without tumors enables early-stage tumor detection, thereby reducing cancer-related mortality rates.

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

Appendixes

Appendixes appear after Conflicts of Interest.

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