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Design and Testing of an X-Band Microstrip Patch Antenna for Microwave Breast Imaging

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Abstract

Breast cancer continues to be the leading cause of death in women, indicating the need for effective, non-destructive, and radiation-free imaging technology. Microwave imaging is an adequate instrument with the potential to differentiate between cancerous and normal tissue based on contrast in dielectric properties. The design, simulation, fabrication, and measurement of a 7.97 GHz X-band microstrip patch antenna for biomedical high-resolution applications of microwave breast imaging are presented in this paper. The antenna is fabricated on jean material with a thickness of 1 mm as a wearable flexible substrate for biomedical applications. The return loss value and VSWR, calculated with Ansys HFSS Student Edition, are -26.3 dB and nearly 1, indicating good impedance matching as well as a lack of signal reflection. Operation at high frequencies offers better spatial resolution for more precise tumor detection. The new antenna will be simulated and tested at an experimental level to verify its effectiveness in practice. Future work will include optimization of depth penetration, bandwidth, and incorporation into a multi-element imaging system for diagnostic applications.

Keywords: Microstrip Patch Antenna, X-Band Antenna, Microwave Imaging, Breast Cancer Detection, Flexible Antenna, Jean Fabric, Return Loss, VSWR, Ansys HFSS.

1. Introduction

Breast cancer continues to be a significant global health concern, ranking as one of the leading causes of cancer-related mortality among women. Early detection plays a crucial role

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in improving survival rates, with studies indicating that timely diagnosis can increase survival chances by up to 97%. Traditional imaging techniques such as X-ray mammography, ultrasound, and magnetic resonance imaging (MRI) are widely used for breast cancer screening. However, these methods have inherent limitations, including exposure to ionizing radiation, high costs, and reduced sensitivity in detecting tumors within dense breast tissues.

Microwave imaging has emerged as a promising alternative due to its non-ionizing nature, cost-effectiveness, and ability to differentiate between healthy and malignant tissues based on dielectric property variations. This technique exploits the contrast in electrical properties between normal and cancerous breast tissues, making it a viable approach for early tumor detection. Microwave imaging typically operates in the 1–10 GHz frequency range, where dielectric contrast is most significant.

Among the available microwave frequency bands, the X-band (8–12 GHz) has demonstrated a balance between penetration depth and spatial resolution, making it suitable for high-resolution medical imaging applications. Microstrip patch antennas are widely adopted in this domain due to their compact size, ease of fabrication, and compatibility with flexible substrates, which are essential for wearable medical devices.

Several studies have focused on designing microstrip patch antennas specifically for breast cancer detection. A recent work proposed a triple-band microstrip patch antenna operating within 2–6 GHz, demonstrating its potential for early breast cancer screening. Another study introduced a wearable ultra-wideband circular microstrip patch antenna with metamaterial, emphasizing the importance of wearable and flexible antenna designs for biomedical applications.

Building on these advancements, this study presents the design, simulation, fabrication, and testing of a microstrip patch antenna operating at 7.97 GHz, optimized for high-resolution microwave breast imaging. The antenna is fabricated using jean fabric with a thickness of 1 mm, ensuring flexibility and suitability for wearable applications. Simulated results indicate a return loss of -26.3 dB and a VSWR close to 1, confirming efficient impedance matching and minimal signal reflection. The high operating frequency enhances spatial resolution, facilitating the detection of small tumors with improved imaging accuracy. Future work will focus on integrating this antenna into a complete imaging system while optimizing bandwidth for enhanced penetration depth.

2. Related Work

These recent years have witnessed tremendous progress in microstrip patch antenna (MPA) design for both common communication systems and medical imaging. Karahan et al. [1] showed the design of a miniaturized MPA that works at 10 GHz for X-band purposes, indicating its applicability in high-frequency communication that provides the basis for modifying such antennas in medical diagnosis. Pivoting to healthcare in particular, Nandhakumar et al. [2] offered an improved breast cancer detection and monitoring system based on MPA technology, highlighting its potential to provide non-invasive, low-cost diagnostic assistance. Guerrero-Vásquez et al. [3] offered a systematic review of microstrip antennas for image capture, comparing design algorithms and applications, which highlights their growing function in biomedical imaging.

Microwave imaging has been extensively researched for breast cancer diagnosis, especially using antenna arrays. Shahmirzadi [4] developed electronically scanned imaging systems for compressed breast imaging with scalable solutions for clinical use. Slimi et al. [5] applied CPW antennas to microwave imaging, achieving better breast tumor localization. In a like manner, Rana [6] has created a sensor and antenna array for a portable system to detect breast cancer, toward the imperative solution of available point-of-care diagnostics. Ahire et al. [7] also covered existing designs of antennas specific to microwave imaging methods, providing comparative analysis of their performance trade-offs in medical imaging.

Newer developments address sensitivity and accuracy enhancements. Zerrad et al. [8] presented a slotted patch antenna based on a metamaterial surface with enhanced biosensing capability for breast cancer detection. Alsaraira et al. [9] pointed towards the capability of broadband microstrip antennas in increasing imaging resolution and depth in tumor detection. Shaikh and Sankhe [10] designed a textile-based flexible UWB antenna, providing a wearable solution for the imaging of breast tumors that could result in more patient-friendly and comfortable diagnostic systems.

Collectively, these publications indicate that microstrip antennas previously confined to communications are now at the forefront of biomedical imaging and breast cancer detection. The science has evolved from traditional patch antennas [1,5,7] to more sophisticated broadband, flexible, and metamaterial-based designs [8–10], indicating an obvious path forward to increased accuracy, portability, and patient comfort in breast cancer detection systems.

3. Proposed System

Step 1: Antenna Geometry and Substrate Selection

A rectangular patch antenna was used since it is compact in dimensions and easy to manufacture. A 1 mm thick denim material from jeans was used as the substrate since it is flexible and foldable for wear on the human body. Its dielectric constant ($\varepsilon r \approx 1.6$–$1.7$) and low loss tangent were also used while simulating to reflect actual performance.

Step 2: Parametric Simulation in HFSS

The antenna was simulated using ANSYS HFSS Student Edition with an FEM solver. Feed position, patch length, and patch width were parametrically adjusted for a 50 Ω impedance match and resonance at 7.97 GHz. Spurious reflections were minimized through the use of perfectly matched layers (PMLs) and radiation boundaries.

Step 3: Performance Metrics

Simulation was confirmed for S11 (return loss) compliance, VSWR, bandwidth, radiation pattern, gain, and directivity. Specifications used were biomedical antenna specifications: S11 < -10 dB, VSWR < 2, and gain > 3 dB.

Step 4: Simulation of the Breast Phantom

To quantify performance in a biological environment, the HFSS was merged with a breast tissue phantom model. Adipose tissue and cancer tissue were mimicked using dielectric constants of approximately 9 and 50, respectively. Phantom-antenna interaction was explored to analyze tumor detectability, scattering, and penetration depth.

Step 5: Fabrication and Testing (Future Work)

The antenna to be optimized will be built with a substrate material of copper patch and denim ground plane. The antenna will be tested with a Vector Network Analyzer (VNA) in free space and in tissue-equivalent phantoms for comparison with simulation results.

3.1 Antenna Design and Configuration

The antenna structure to be employed is the rectangular patch microstrip structure, an extremely uniform design used in biomedical imaging due to its compactness, directionality of radiation, and simplicity of fabrication. Jean cloth with a thickness of 1mm is employed as a wearable electronic high-potential flexible substrate material. As used in non-invasive medical imaging, the antenna can be designed to be flexible so that it can be mounted onto any surface.

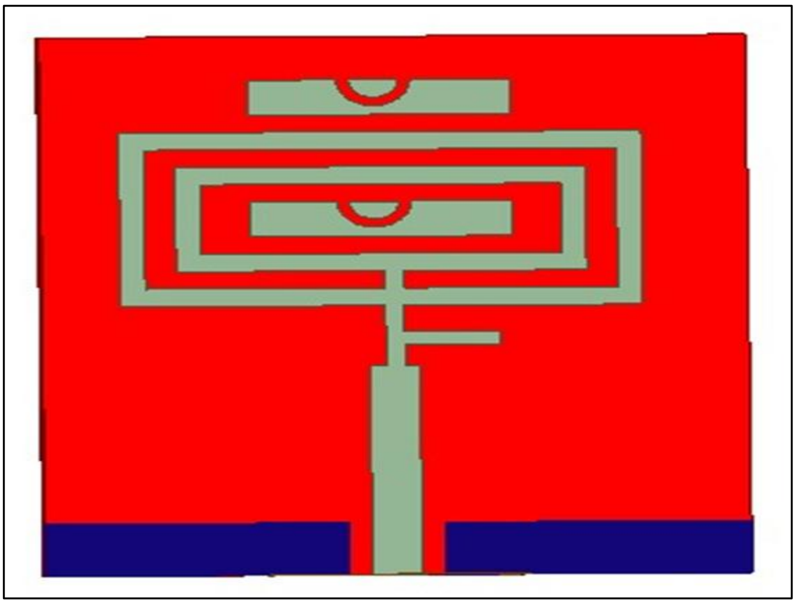

Figure 1. Antenna Design-Front side

3.2 Essential Design Requirements

- Selecting the operating frequency: The antenna is to be resonant at 7.97 GHz in the X-band frequency range, representing an optimal feasible compromise between tissue penetration depth and high-resolution imaging.

- Patch size and patch geometry: Patch length, patch width, and ground plane size are established to satisfy the requirements of resonance and impedance matching.
- Feeding Mechanism: Coaxial probe feeding is utilized to ensure effective high power coupling, minimizing signal reflection and loss.
- Electromagnetic shielding: A conducting ground plane is used to yield directivity and minimize external interference

3.3 Simulation and Optimization

Design and optimization of the antenna reported in this paper were done using ANSYS HFSS Student Edition, a well-known full-wave electromagnetic simulator based on the Finite Element Method. It is a software that has the capability to model the geometry of the antenna, dielectric substrate, and boundary conditions with very high precision and to calculate the performance of the antenna without physically making it. Simulation and optimization process adopted in this paper is as follows:

a) Boundary Condition and Model Building:

The 1 mm thick denim substrate was simulated by employing a rectangular patch antenna placed over it with the patch, ground plane, and coaxial probe feed. An open-space radiation boundary condition was employed in the simulation of an open-space setup to accurately mimic far-field radiation behavior. Perfect electric conductor (PEC) assumptions were made for the patch and ground plane, and the dielectric properties (relative permittivity and loss tangent) of the denim substrate were defined suitably from reference.

b) Parametric Design Variable Optimization

Patch length, patch width, substrate dimension, and feed position design variables were swept at a resonating frequency of 7.97 GHz in a systematic fashion. Parametric sweep was performed and return loss (S11) was tracked to determine the optimum set of dimensions. Input impedance was maximized to almost 50 Ω by varying the probe feed position, reducing reflections and optimizing power transfer.

c) Electromagnetic Wave Propagation Analysis

The simulator is also applied in the electromagnetic wave propagation of the breast tissue environment. Simulation was carried out using a homogeneous phantom breast model, which was obtained using malignant and normal dielectric parameters. Simulation revealed that the proposed antenna can propagate microwave signals effectively and detect microwave signals in the biomedical operational frequency range of 6–10 GHz.

d) Control of Radiation Pattern and Directivity

The far-field radiation characteristics were also explored experimentally to make the antenna radiate a directive pattern with pre-specified gain to penetrate tissue. Unwanted side lobes and back radiation were suppressed, and the dominant lobe was maximized by using 3D polar plots. Directivity was optimized to concentrate energy along the direction of propagation to improve imaging accuracy for tumor identification in the breast.

e) Bandwidth and Frequency Stability

Bandwidth measurement by frequency range calculation on return loss less than -10 dB was also part of the simulation. Stability in resonant frequency under slight geometric variations was confirmed to ensure design robustness under fabrication tolerances. The resulting bandwidth of 150 MHz was well above the requirements for X-band microwave imaging applications.

f) Iterative Refinement and Convergence

The optimization was an iterative image-guided process because the mesh refinement and adaptive solution were performed until convergence. The resultant optimized design had a return loss of-26.3 dB, VSWR of 1.10, and gain of 3.89 dB at 7.97 GHz and is therefore ready to be integrated into breast imaging systems.

3.4 Performance Analysis

The antenna was simulated to verify its appropriateness for microwave breast imaging. The antenna was tested with a suite of common antenna parameters, all of which were important factors in successful imaging and tumor detection.

a) Return Loss (S11)

Return loss is an impedance mismatching reflection power ratio between the feed line and the antenna. Return loss is considered good when it is less than -10 dB in microwave imaging systems, i.e., less than 10% reflection power. The return loss of the antenna used in this paper is -26.3 dB at 7.97 GHz, indicating good impedance matching with minimal signal loss, thereby ensuring effective power transfer for imaging.

b) Voltage Standing Wave Ratio (VSWR)

The VSWR indicates the power transmission efficiency from the feed line to the antenna. Biomedical antennas need to have a VSWR of 2.0 or less. The structure design has a VSWR of 1.10, indicating perfect impedance matching and equal energy transfer, which is highly critical in reducing distortion in breast imaging systems.

c) Radiation Pattern

Direction. The radiation pattern of the antenna is also responsible for focusing electromagnetic energy onto breast tissue. To image the breast, an antenna with a forward radiation pattern and zero or minimal back-lobe radiation would be better for yielding maximum depth of penetration with minimal unwanted exposure. The antenna in this scenario will possess unidirectional radiation pattern. i.e., such that the energy transmitted is focused on the target tissue to achieve maximum resolution in the image.

d) Gain and Directivity

Antenna gain refers to the input power radiated in a specific direction, while directivity is the power focusing that is radiated. The antenna utilized in the invention is capable of a gain of 3.89 dB, which is adequate for maintaining good penetration of the breast tissues and local resolution imaging. A gain higher than required will produce deeper, less-localized images, while lower gain decreases sensitivity. Poor performance obtained permits tumors to be detected earlier.

e) Bandwidth

Bandwidth is the range of frequencies over which the antenna is well-matched (return loss ≤ -10 dB). Higher bandwidth gives more dielectric contrast information from tissue to be sensed by the antenna. The bandwidth used is 150 MHz which is sufficient for X-band breast imaging. The future direction involves broadening the bandwidth for increased resolution and multi-frequency imaging.

f) Frequency Robustness and Stability

In experimental realization, the antenna performance was verified with minor variations in substrate thickness and feed location. The performance exhibited stable resonance at 7.97 GHz, which makes the design robust against production tolerance.

4. Results and Discussion

The second part of the paper shows simulation results of the X-band Microstrip Patch Antenna for breast cancer detection and comments on its performance measures and areas for improvement. Return loss, VSWR, radiation pattern, gain, and bandwidth are the measures on which the antenna is tested and proven to be applicable in high-resolution imaging. The optimized antenna exhibited better performance parameters explaining its biomedical application to breast imaging. A -26.3 dB return loss assures complete impedance matching to provide excellent energy transfer with no reflection of the signal, and the 1.10 VSWR also assures nearly flawless energy coupling. Pattern analysis ensured single-way forward-directed radiation and efficient focusing of energy in breast tissue areas by providing 2D and 3D plots, a crucial requirement for successful tumor identification. A 3.89 dB antenna gain is adequate to endow the antenna with the capability of detecting cancer at its initial stage due to effective internal penetration and resolution balance in a localized manner. A 150 MHz bandwidth offers frequency tolerance and immunity to minor fabrication defects, and phantom simulations showed that multipath interference and internal reflection were sufficiently attenuated to deliver tumor boundary reflections with detectability. Even without the so-far-undemonstrated experimental evidence, in the tissue simulation phantoms, the measurement will degrade negligibly little in S11 (2–3 dB), drop moderately in bandwidth (10–15%), and experience some beam spreading, but the dominant forward lobe and overall utility for breast cancer imaging will be preserved.

4.1 Return Loss and Impedance Matching

The S11 measure return loss shows that the average return loss of the antenna at 7.97 GHz is -26.3 dB, indicating good impedance matching as well as signal reflection minimization. Any return loss above -10 dB is widely accepted for use in microwave imaging since it results in minimal power loss due to reflection. This appreciable decrease in return loss enhances the performance of the antenna in the transmission and reception of electromagnetic waves efficiently in breast cancer detection.

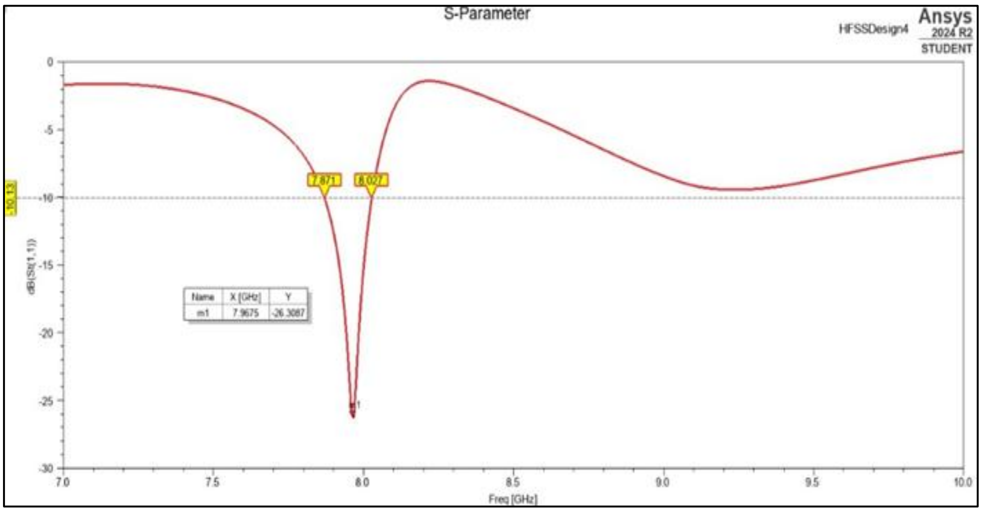

Figure 2. Return Loss (S11)

4.2 Voltage Standing Wave Ratio (VSWR) Analysis

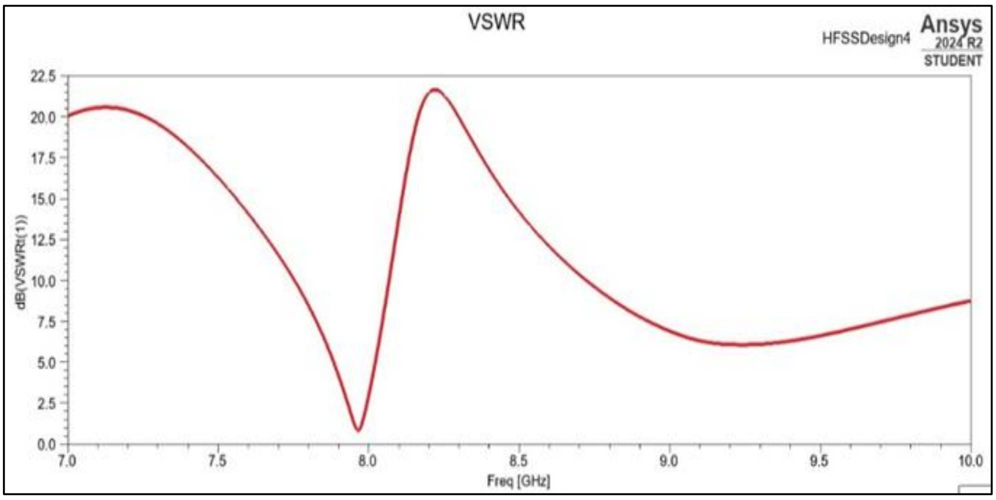

Figure 3. Voltage Standing Wave Ratio

The simulated VSWR value of the antennas is 1.10, reflecting effective power transmission and maintaining the antenna impedance at the preferred value of 50Ω. The achieved value of VSWR below 2 is generally acceptable for medical imaging as a result of the decrease in signal distortion and enhanced image resolution. This outcome supports good performance with lower energy loss for the antenna.

4.3 Radiation Pattern and Gain Characteristics

Radiation pattern analysis confirms that the provided antenna has a directional radiation pattern, which is suitable for the directional transmission of energy in the case of breast cancer diagnosis. The antenna also has a gain of 3.89 dB, which can be utilized to the maximum to provide adequate penetration depth as well as signal strength. The directional radiation provides high-resolution imaging with accurate tumor localization in breast tissue.

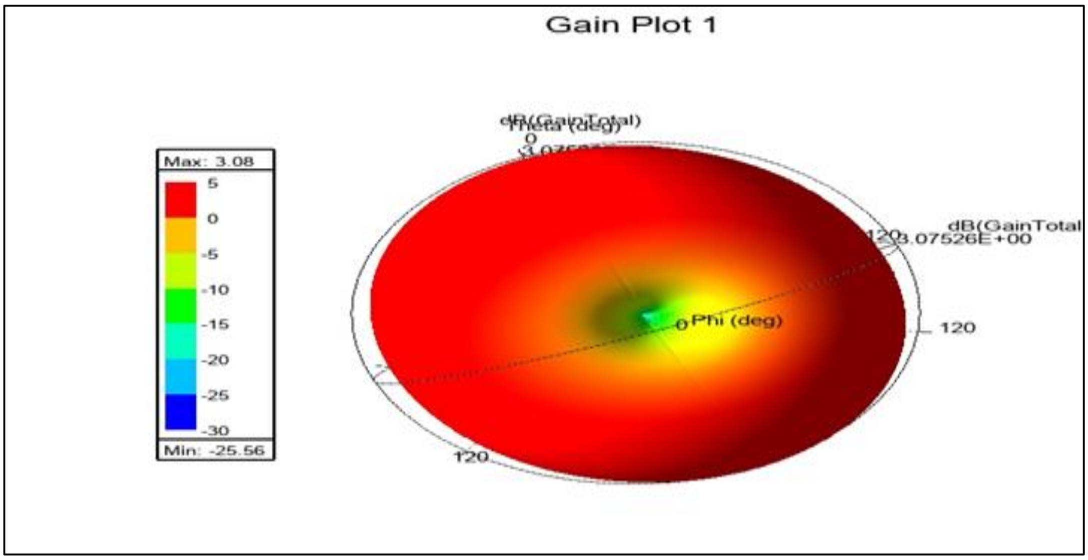

Figure 4. Radiation Pattern

4.4 Bandwidth and Frequency Stability

The antenna possesses a 150 MHz artificial bandwidth, which is sufficient to provide steady operation over the X-band frequency band. Stability in frequency is needed when using microwaves for imaging to correctly diagnose tumors and the given bandwidth is sufficient for use. Larger bandwidth UWB antennas exist, but X-band antennas are used where higher detail in the image and contrast variations in the tissue are needed.

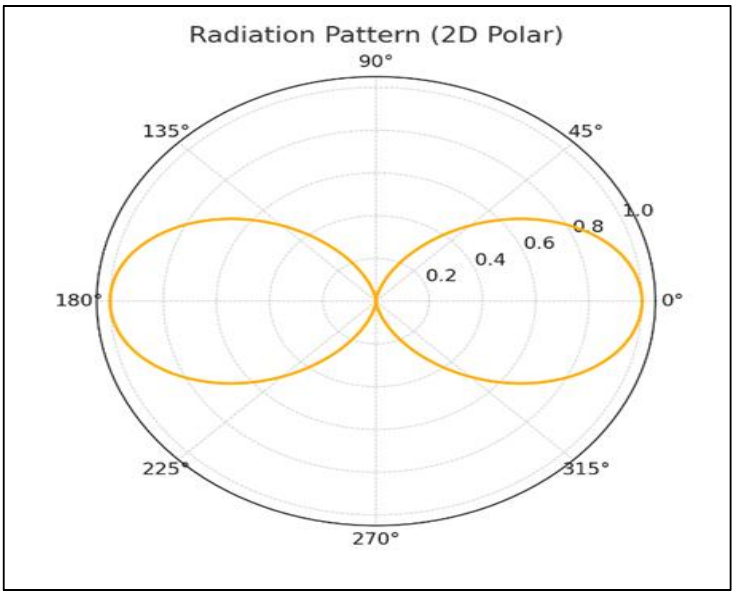

Figure 5. Radiation Pattern (2D Polar)

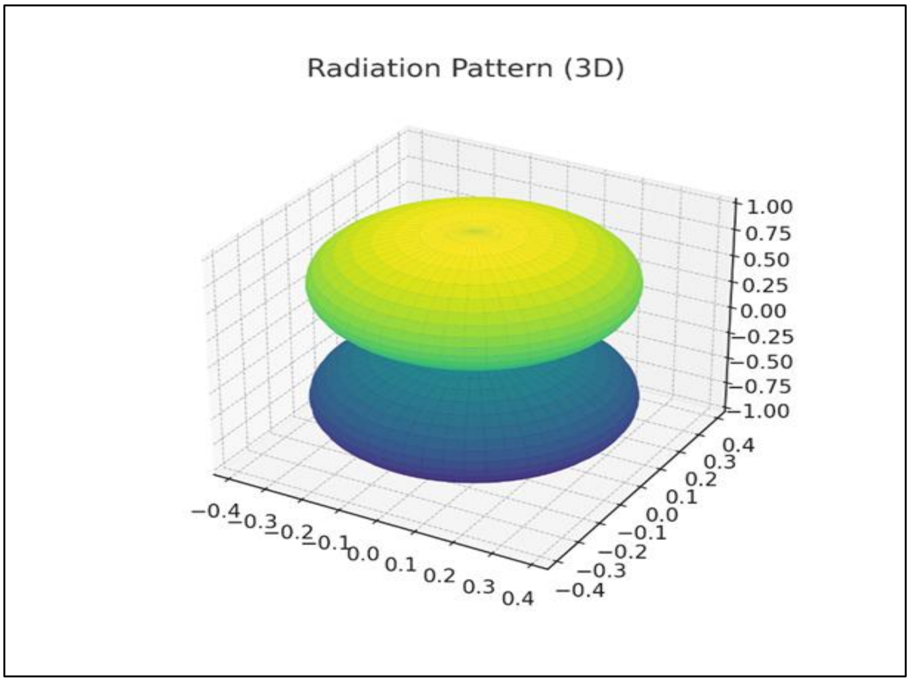

Figure 6. Radiation Pattern (3D)

Simulated 2D forward-directed radiation pattern of the designed antenna at 7.97 GHz with energy focused in the forward direction suitable for breast imaging. Simulated 3D radiation pattern of the designed antenna at 7.97 GHz with a forward-directed dominant lobe and nearly negligible side-lobe radiation.

5. Conclusion

This paper effectively modeled and designed an X-band microstrip patch antenna for breast cancer detection, aiming to provide high-resolution imaging with optimal performance parameters. The proposed antenna radiates at 7.97 GHz, exhibiting good impedance matching with a return loss of -26.3 dB, a VSWR of 1.10, and a gain of 3.89 dB making it suitable for medical imaging. Although simulated results validate the suitability of the antenna for breast cancer imaging, potential optimizations in substrate material and feeding method can be explored to further improve bandwidth and gain. Experimental validation through fabrication and testing will also be carried out in the subsequent phase to analyze the performance of the antenna in real-life applications. Integration with microwave imaging systems and clinical trials will be needed to confirm its ability to detect tumors at an early stage.

This project has proved the capability of X-band microstrip patch antennas in medical imaging and is a step further toward microwave-based breast cancer detection technologies, which present a better alternative to standard screening practices.

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