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Design and Performance Analysis of a Tissue-Load Stable H-Slotted Patch Antenna for 2.45 GHz Breast Phantom Sensing Applications

Salaudeen K. Olawale, Sani Saminu, Yahya A. Suleima, Muniru O. Idris & Adisa Y. Adebayo
Biomedical Engineering Department, University of Ilorin,
P.M.B 1515, Ilorin 240003, Nigeria

Adamu H. Jabire
Department of Electrical and Electronics Engineering,
Taraba State University, Jalingo 660242, Nigeria

***Corresponding Author Email Address:** salaudeen.ko@unilorin.edu.ng

Abstract

The detection of solid tumors, especially in the breast, is crucial to improving patient outcomes and minimizing the side effects of cancer treatment. This study presents a highly miniaturized rectangular H-slotted PIFA operating in the 2.45 GHz ISM band; the design incorporates an H-shaped slot on top of the radiating patch to reduce the antenna size and improve current-path meandering. Simulation results from CST Studio Suite indicate that the proposed design resonates at 2.45 GHz with a -10 dB impedance bandwidth of approximately 277 MHz (2.33 – 2.61 GHz), a record Return Loss (S11) of -51.65 dB, and a VSWR of 1.005 in free-space conditions, demonstrating a near-perfect impedance match. The antenna exhibits a realized gain of 3.5 dBi at 70% efficiency. and a directional radiation pattern with a directivity of 4.16 dBi, enabling effective electromagnetic energy penetration into breast tissues. The antenna was also shown to be stable in its resonant frequency while modeled within a three-layered breast phantom model (skin-fat-gland). The presence of a 5 mm malignant tumor produces a noticeable shift in the reflection coefficient from -51.65 dB to -39.20 dB, demonstrating the antenna's sensitivity to dielectric-property variations between healthy and cancerous tissues. Finally, a maximum 1-g averaged specific absorption rate (SAR) of 0.103 W/kg at 10 mW input was achieved, which is substantially below the FCC safety limit of 1.6 W/kg. The results demonstrate that the proposed H-slotted antenna is a compact and stable sensor with the capability to detect early-stage breast tumors effectively

Keywords: Breast Cancer detection, Microwave imaging, SAR, Patch Antenna, ISM Band.

Introduction

Breast cancer is still one of the leading causes of death from cancer in women across the world. The earlier it is diagnosed and treated, the better the treatment outcome and survival rate will be. While mammography, ultrasound, CT scans, MRI scans, and other forms of imaging are all commonly used to screen for breast cancer, they also have many shortcomings. These include using ionizing radiation on patients; being uncomfortable for patients; being expensive; and being less sensitive when examining extremely dense breasts (El Misilmani, Naous, Al Khatib, & Kabalan, 2020; Kaur & Goyal, 2020). One potential new technology for breast cancer screening uses microwaves instead of X-rays or ultrasound. Microwaves use non-ionizing electromagnetic waves to create images of the inside of the body by identifying differences in how various types of tissue reflect and scatter the microwaves. Tumors appear larger in terms of permittivity and conductivity than do healthy tissues. Therefore, there are measurable differences in how microwave energy is reflected through the body to allow for the detection of tumors (El Misilmani et al., 2020; Elsherif & Makkey, 2021).

In comparison to the other technologies that are currently available, microwave imaging systems offer many advantages. They are relatively inexpensive, small enough to be taken with the patient, and can be used repeatedly (Ahmed, Ibrahim, Islam, Sumon, & Islam, 2023). The ISM band is an ideal compromise of imaging resolution and penetration in terms of frequencies among all of the existing options, with its frequency at 2.45 GHz (El Misilmani et al., 2020; Zurnaci, 2023). In addition to this, as reviewed recently by El Misilmani et al. (2020) and Hasan Mahfuz, Mahfouz, Baladi, and Kishk (2024); the performance of antennas is very important when considering the detection of tumors; therefore, they can be broken down into several aspects such as gain, impedance matching, bandwidth, radiation properties, SAR, etc. The results showed that, as expected, slot-loaded antennas provide improvements to the antenna's performance at a reasonable size penalty. Several researchers noted, however, that despite these advancements, there are still antennas being produced that have larger physical sizes than needed, contain complex geometries, lack sufficient impedance matching, or will lose stability when used on the body (i.e., loaded into a breast tissue). Due to this, developing small antennas that can consistently produce low return-loss values and operate stably while physically being loaded within breast tissue continues to be an area of research. A rectangular microstrip patch antenna was proposed by Kumar and Nagaveni (2020). It had an approximate size of 40 x 35 mm², and it operated at 2.45 GHz. In this case, the return loss was around −28.7 dB, and its gain is 3.2 dBi. Good radiation performances were observed, although good but moderate gain and poor sensitivity to tumor location were shown Kumar and Nagaveni (2020). A modified rectangular patch antenna for detecting early breast cancer based on 2.45 GHz was proposed in Elsherif and Makkey (2021). This antenna has provided very good impedance match as evidenced by its S11 value (−42 dB) and VSWR (1.015). They have demonstrated significant changes in the current density and power dissipation distribution when cancerous tissue is present. As a result, while the overall design of the antennas is satisfactory in terms of size, the

dimensioning of the antennas is clearly suboptimal for compact devices, and no data on the radiation parameters (gain and directivity) are available. Ajnadkar et al. (2021) developed an ISM band rectangular microstrip antenna using a defected ground plane that can be used to improve impedance match. The antenna has an approximate area of 1600 square millimeters (mm), produces a reflection coefficient (S11) of −31.4 decibels (dB), and has a gain of 3.8 dBi. Although the defect in the ground improves impedance match, due to the physical size being too large, it is less suitable for use in small biomedical devices. Kırkgöz and Kurt (2022) proposed a modification to a rectangular patch antenna, which measures 1400 square millimeters (mm^2) and operates at 2.45 GHz. The antenna exhibits a gain of 4.1 dBi and a directivity of 5.2 dBi with an S11 value of −35.5 dB. Due to varying conditions of the biological tissues in contact with the antenna, there was significant variation in frequency stability. Elsaadi et al. (2023) studied a microstrip antenna structure fabricated onto a fairly large substrate that was about 100 x 100 mm. The antenna worked at 2.45 GHz and had a return loss of less than -30 dB, as well as a gain greater than 7 dBi. However, the structure has a rather high SAR value of nearly 20.8 W/kg, which is higher than what is allowed by the IEEE standards and therefore can be considered unsuitable to be used in real-world medical applications. Zurnaci (2023) proposed a multi-slotted rectangular microstrip patch antenna working at 2.46 GHz and made from an FR-4 substrate. The size of the patches is 29.14 x 37.58 mm^2, S11 = -25.45 dB, and VSWR = 1.113. The reported SAR value of 0.052 W/kg satisfies the required IEEE safety requirements. However, the additional slots make this antenna more complex to fabricate and could increase the difficulty in finding the optimal design. Samad and Rahman (2021) developed a wearable circular patch antenna working at 2.43 GHz. The antenna had a return loss of –26.63 decibels (dB), a directivity of 8.86 dBi, and an SAR (Specific Absorption Rate) of 0.355 Watts/kilogram. High directivity was achieved by this design; however, the antenna's gain characteristics were not reported in detail.

A standard rectangular microstrip patch antenna was first created in this study, utilizing traditional transmission line equations for operation at the ISM frequency of 2.45 GHz. An H-slot was then cut into the radiating portion of the patch to both reduce the size of the antenna and improve its performance. By providing an additional effective surface current path, the H-slot allows for improved impedance matching and resonance stability while maintaining the same physical size as the original antenna. Using CST Studio Suite, the optimal configuration of the H-slots was determined. Finally, the new antenna design was tested in free-space conditions and inside a multilayered breast phantom to assess the potential use of the new antenna for early detection of breast tumors.

Design Methodology

The proposed antenna is an example of a rectangular microstrip patch that is printed on a dielectric substrate. Three major stages of the method are as follows: Mathematical Modeling, Free Space Measurement (Characterization); Performance

Evaluation in a Modeled Biological Environment. The size of the antenna was selected from a set of standard equations to design a conventional microstrip antenna at resonance.

Design Flow Chart

The flowchart diagram illustrates the iterative optimization process used to reach the final results, as shown in Figure 1.

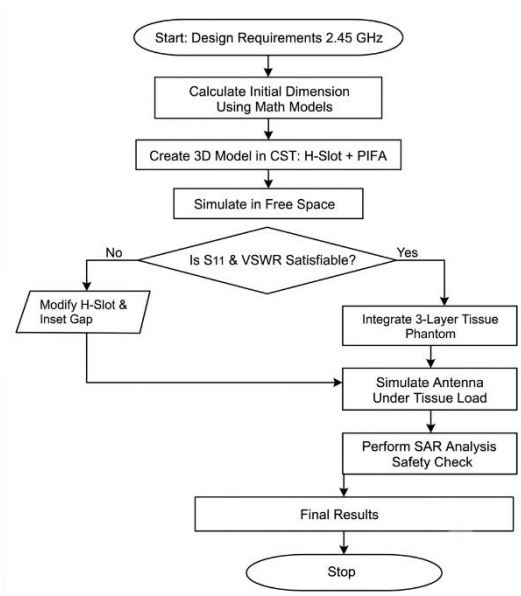


Figure 1: Antenna design and evaluation flowchart

Geometrical Modeling and Mathematical Approach

The first step in designing the antenna using Standard Formulas. It began by selecting the physical parameters of the rectangular microstrip patch for the 2.45 GHz ISM Band. Those values were then input into standard microstrip antenna design formulas to determine the resonant operating frequency of the patch based on both its width (Wp) and its length (Lp). Both the width and length of the microstrip patch are dependent upon the dielectric constant (εr) of the substrate and the height (h) of the FR-4 substrate. The fundamental resonant frequency of a rectangular microstrip antenna is determined from

$$f_r = \frac{c}{2L\sqrt{\varepsilon_{eff}}} \qquad 1$$

Equation (1) defines patch width, with the primary effect on radiative quality and bandwidth. The wider the patch width, the better the radiation quality and the broader the band.Where$f_r$is the resonant frequency, c is the speed of light, p is the patch length, and ε_{eff} is the effective dielectric constant.

The effective dielectric constant is given by,

$$\varepsilon_{eff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}(1+12\frac{h}{W_p})^{-\frac{1}{2}} \qquad 2$$

Equation (2) represents the fringe field, as it relates to the space in the air that fringe fields extend from the patch and relates to a real permittivity value that an electromagnetic wave sees when propagating through the patch.Where ε_r is the dielectric constant of the substrate and h is the substrate thickness.Patch width (W_p) and patch length (L_p) are determined using the following equations

$$W_p = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad 3$$

Equation (3) gives the resonant length of a patch with consideration of an effective dielectric value.

$$L_p = \frac{c}{2L\sqrt{\varepsilon_{eff}}} \qquad 4$$

Equation (4) gives an estimate of how much extra electrically long is needed to go in order to be able to resonate at 2.45 GHz. The width of the ground plane (W_g) and the length of the ground plane (L_g) were found using the following formulas

$$W_g = 6h + W_p \qquad 5$$

$$L_g = 6h + L_p \qquad 6$$

The equations (5) and (6) will provide the best dimensions for the ground plane, so we have minimum diffraction from the edge of the ground plane and are assured of good radiative performance.

Antenna Design Evolution and Parametric Analysis

The geometric progression of the antenna design is realized across three distinct phases as depicted in Figure2. ANT 1: base case (solid patch): A conventional microstrip patch antenna with a rectangular radiating element 35 mm x 26.50 mm on a 40mm x 40 mm substrate, utilizing a conventional full ground plane.ANT 2: step 1 (partial ground): The ground plane is reduced to a height of 9mm, creating a partial ground plane structure. This modification alters the capacitive coupling between the patch and the ground, significantly affecting impedance matching and bandwidth.ANT 3: final case (H-Slot):An H-shaped slot (with 3 mm central gap width) is etched directly into the center of the radiating patch while maintaining the partial ground plane.

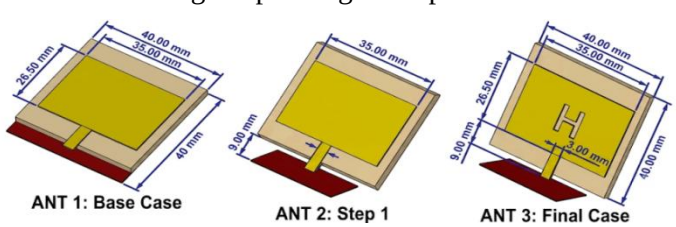


Figure 2: geometry of the proposed antenna design evolution

Parametric optimization was carried out in CST Studio Suite by varying slot dimensions, feed location, and ground plane length as shown in Table 1. The optimum values were selected based on maximum impedance matching and resonance at 2.45 GHz.The design evolution and the geometry of the antenna are shown in Figures 2 and 3.

Table 1: Antenna design optimized parameters

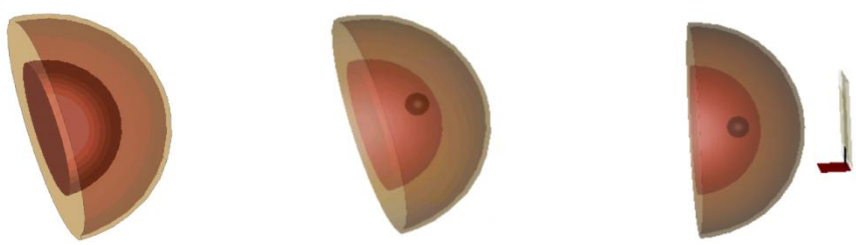
Parameter	Value (mm)	Parameter	Value (mm)
Copper thickness	0.035 mm	Feed width	3
Patch length	26.5	Vertical slot height	4
Patch width	35	Horizontal slot length	10
Substrate thickness	1.6	Sloth width	1.5
Substrate size	40x40	Feed length	6

Biological Environment and Breast Modeling

To assess whether the antenna is appropriate for use in medical applications, an electromagnetic multi-layered breast phantom was developed using CST. There are 4 layers to the breast phantom, which are representative of: skin, fat, glandular tissue, and tumour tissue, as shown in Figure3. As well as the number of layers, the dielectric constants used in the phantom were based on reported experimental results of dielectric constants of biological tissues at microwave frequency(Getachew, Tesfaye, et al., 2024). The position of the antenna relative to the breast phantom was kept fixed, as can be seen in Figure 4. A sphere tumour of radius 5mm was placed in the breast phantom.

Table 2: Electrical properties of a woman's breast.

Tissue	Relative Permittivity	Conductivity (S/m)	Density (kg/m^3)
Skin	38	1.46	1100
Fat	5.28	0.10	910
Glandular	48.2	1.71	1040
Tumor	55	2.3	1050



a b c

Figure 3: (a) 3D breast phantom without tumor, (b) with tumor and (c) antenna position in the breastphantom

Performance Requirements for Microwave Breast Cancer Detection

According to IEEE C95.1, the average Specific Absorption Rate (SAR) in one gram of tissue should be no greater than 1.6 Watts per kilogram. Also, a return loss of less than −10 dB and a Voltage Standing Wave Ratio (VSWR) of less than 2 demonstrates a good impedance match. A gain of 2 through 6 dBi provides enough depth of penetration into the body as well as spatial resolution to detect tumors in the breast. This antenna will satisfy both of these conditions.

Table 2: Standard performance requirements for breast cancer

Parameter	Recommended value	IEEE/FCC Requirement
Return value	< or = 10	Standard antenna requirement
Gain	2-6 dBi	Sufficient penetration
Directivity	3-6 dBi	Stable radiation
SAR (1-g)	1.6 W/kg	IEEE C95.1

Results and Discussions

Design Stage Performance in Free Space

The performance impact of each design stage can be analyzed from the Return Loss (S11) plot shown inFigure 4. The introduction of the H-slot optimizes the impedance matching perfectly, yielding a deep, sharp resonance peak precisely at 2.45 GHz

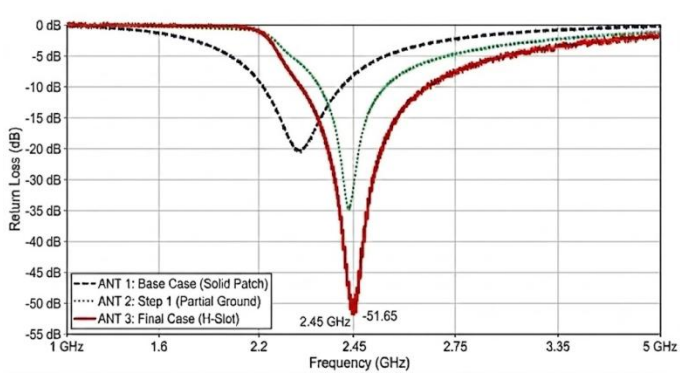
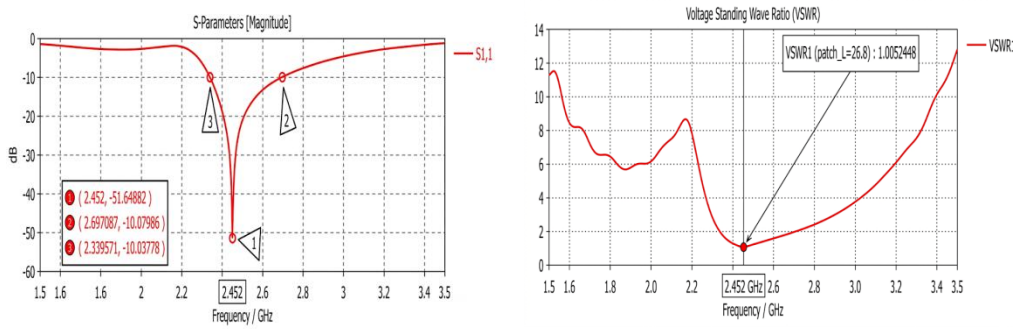


Figure 4: Comparisonof return loss of the design stages

Free Space Performance and Efficiency

A new H-slot rectangular antenna prototype, measuring 27 × 35 mm, was evaluated through simulations in free space. Its base performance characteristics were evaluated under these conditions. The results from simulation studies showed that the antenna's Return Loss (S11), as shown in Figure 5(a), is −51.65 dB, a significant improvement over the previous result. Additionally, as shown in Figure 5 (b), the Voltage

Standing Wave Ratio (VSWR) of the antenna is 1.005; therefore, the input impedance of the radiating element closely matches that of the transmission line.



a b

Figure 5: a: Return loss on free air and b: VSWR in free space on free air

The Fairfield directivity is determined to be 4.16 dB with a main lobe at 15.0° as depicted in Figure6. Therefore, the antenna delivers focused energy toward the diagnostic target.

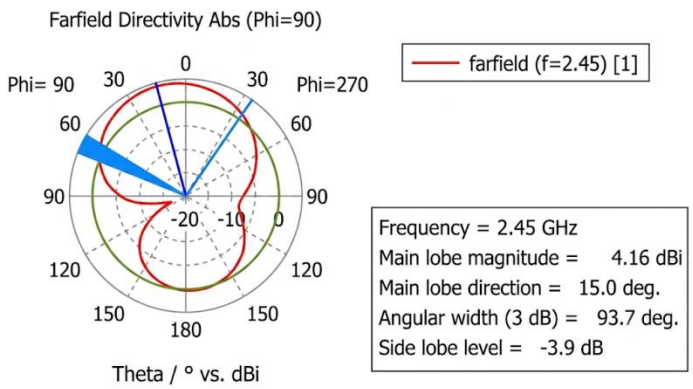
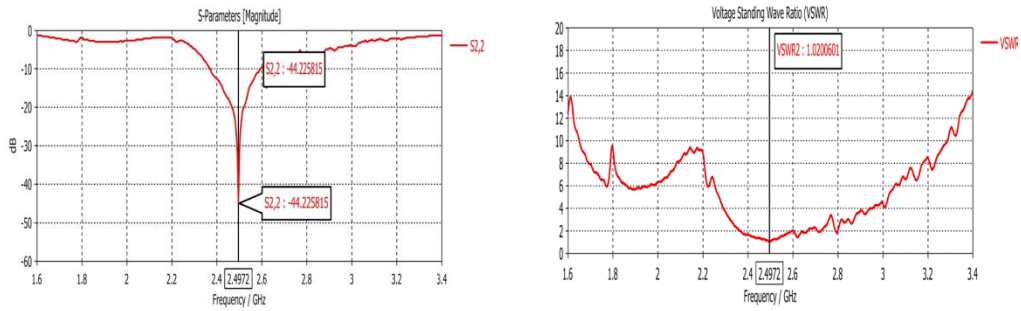


Figure 6: Fairfield directivity output.

Performance Under Healthy Breast

To determine whether this antenna would perform effectively in clinical applications, it was attached to a 3-layered breast phantom. It was observed that once the antenna was loaded with the breast phantom tissues, it maintained a stable output; additionally, the antenna showed a low Voltage Standing Wave Ratio (VSWR) of 1.020 at 2.497 GHz, as seen in Figure 7. The extremely minor changes in the VSWR (1.005 to 1.020) indicate that the design parameters for the H-slot size of (10mm x 4mm) are far

less affected by the high permittivity of human tissue than typical rectangular meander designs or circular patches.

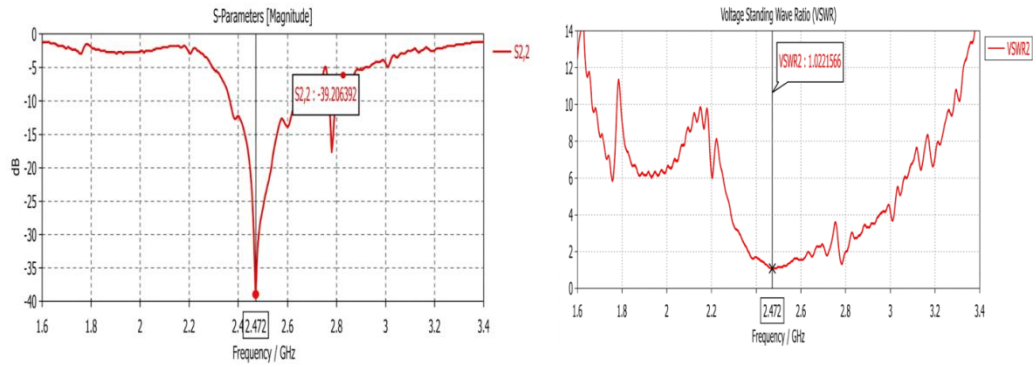


a b

Figure7: a: Return loss in a healthy breast andb: VSWR in a healthy breast

Detection of Infected Breast

The diagnostic performance of the antenna was tested by utilizing this phantom to evaluate the presence or absence of malignant tissue that would result in changes in S11 (reflection coefficient) to -39.2 dB at 2.472 GHz. A significant element in detecting tumors based on dielectric differences in normal vs. abnormal cells is the magnitudes and frequencies associated with variations in S11. Sensitivity is therefore crucial when attempting to detect small anomalies at an early stage with respect to the proposed system.



a b

Figure 8: a, Return loss with a tumor,and b, VSWR in a breast with a tumor

Radiation Safety and SAR Analysis

The safety performance of the proposed antenna system has been shown in two ways: Peak Power Loss Density and SAR. The peak power loss density for the proposed

antenna is 26,304 W/m^3. Figure 9 shows how much less heat will be transferred into adjacent tissues as compared to other systems, due to the ability of the proposed diagnostic system to transmit diagnostic signals. When the proposed diagnostic system is operated at a standard low-power excitation level of 10 mW, which is typical of many medical devices, it would have a SAR value that is well below the maximum allowed by the FCC. Because of the high efficiency of the proposed diagnostic system, along with the low absorption of energy from the system, it can meet all biocompatibility requirements and safety regulations for extended periods in a clinical environment.

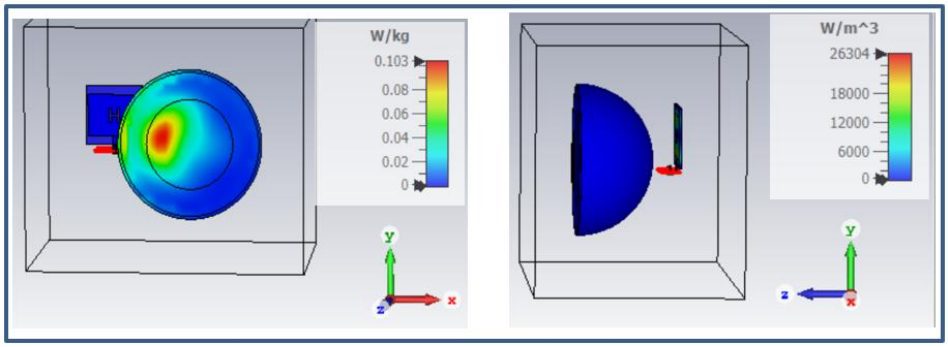


Figure 9: 3D distribution model: (a) 1g averaged SAR (max = 0.103 W/kg), (b) power loss density for 10 mW acceptable power

Comparative Performance Analysis

The proposed antenna has a good trade-off between being small, having good impedance matching, and ensuring safety at the frequency used for 2.45 GHz ISM band breast cancer detection, as illustrated in Table 3. The proposed antenna demonstrates the best impedance match with the smallest VSWR value of 1.005 and the largest return loss of −51.65 dB when compared to other designs, thus demonstrating efficient power transmission. The proposed antenna is also very compact, with dimensions of 27×35mm, which are less than those of many previously reported antennas, but has a very low Specific Absorption Rate (SAR) of 0.103 W/kg, therefore meeting all international safety standards. Although the antenna's gain (3.5dBi) is lower than that reported in several research articles, it is still sufficient for near-field biomedical sensing applications. In conclusion, the proposed antenna presents an attractive compromise in terms of miniaturization, low SAR, and a high level of impedance matching, and can be considered a suitable candidate for application in breast cancer detection.

Table 3: Comparison of Antenna Design and Performance Metrics

Author	Antenna size (mm)	Resonant freq (GHz)	Return loss (dB)	VSWR	SAR 1g (W/kg)	Gain/ (dBi)
Kumar & Nagaveni (2020)	40 × 35	2.45	−28.70	NR	NR	3.20
Elsherif & Makkey (2021)	NR	2.45	−42.00	1.015	NR	NR
Ajnadkar et al. (2021)	40 × 40	2.45	−31.40	NR	NR	3.80
Kırkgöz & Kurt (2022)	35 × 40	2.45	−35.50	NR	NR	4.10
Elsaadi et al. (2023)	100 × 100	2.45	< −30.00	NR	20.80	> 7.00
Zurnaci (2023)	29.14 × 37.58	2.46	−25.45	1.113	0.052	NR
Samad & Rahman (2021)	Circular Patch	2.43	−26.63	NR	0.355	NR
Proposed antenna	**27 × 35**	**2.45**	**51.65**	1.005	0.103	3.50

Conclusion

In this work, we have demonstrated the design and modelling of a rectangular H-slotted microstrip patch antenna suitable for detecting the first signs of early-stage breast cancer. It was found that when placed in free air space, it exhibited nearly ideal impedance matching conditions. This is illustrated by an almost perfect Return Loss (S11), as well as a near-perfect Voltage Standing Wave Ratio (VSWR).The functionality of the breast cancer detector design was tested using a three-layered breast phantom. In a biological setting, the antenna also showed stability at resonance. The presence of a malignant tumor clearly caused a significant shift in the antenna's reflection coefficient. The antenna will allow for a safe patient environment because the SAR (Specific Absorption Rate) is significantly below the maximum SAR of 1.6 W/kg that is permitted under[19]. Due to its small size, high efficiency, biocompatibility, and many possibilities

for utilization in monostatic and/or multistatic microwave imaging systems, it is an inexpensive means of performing early clinical diagnostic testing.

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