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A Low-Cost Microstrip Patch Antenna Based Metamaterials for Non-Invasive Breast Tumor Detection

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Abstract: Microstrip antennas have been widely used for various broadband purposes. Despite their many promises, their use in medical applications has been limited by their narrow bandwidth and loss in high-frequency bands. This work aims to design a patch sensor, a low-cost microstrip sensor suitable for biomedical applications, specifically for the detection of breast cancer tumours. The proposed antenna sensor consists of three layers: ground, substrate, and microstrip sensor, which can be easily fabricated using standard printed circuit board methods. A comparative study was carried out between two resonance frequencies at 1.8 GHz and 2.9 GHz, which frequencies were investigated with remarkable precision, simulating the presence and absence of a tumour cell. Using CST Studio Suite 3D computer simulation technology software for electromagnetic field simulation and analysis, the results show that the model can detect tumour phase changes and return loss depth. The results show that the return loss of the antenna decreases to -39 dB at 1.8 GHz and -12 dB at 2.9 GHz, and a phase shift is observed in the presence of tumour cells. The differential absorption rate (0.746 and 0.934 W/kg) was also calculated and found to be within the acceptable range and not exceeding the standard value. Two parameters are considered in this study, namely frequency phase shift and depth reflection return loss. Taken together, this study concludes that a lower frequency band increases penetration depth but decreases resolution. At the same time, the higher frequency band provides better clarity, but reduces the ability to penetrate deeply, as observed in the frequency range between 1.8 GHz and 2.9 GHz. The proposed work could provide a method for designing electromagnetic sensors for biomedical applications.

Keywords: ***Antenna; Specific Absorption Rate; Breast Tumour; Phase Shift; Return Loss.***

I. INTRODUCTION

Cancer has been the most prominent health concern over the past 50 years and has the potential to impact various healthy organs in the body. Nevertheless, breast cancer remains the most predominant form of cancer among women internationally [1, 2].

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Breast cancer has caused the deaths of around 8.2 million individuals [3]. Regrettably, over 1.8 million cases of breast cancer are reported globally each year, and it is projected that the number of people affected by breast cancer will increase from 14 million to 22 million over the next twenty years, with the possibility of further escalation [4, 5]. Because breast cancer has a high rate of occurrence, it is regarded as one of the most perilous forms of cancer, notably for women. As a result, women require regular screening and examinations.

One of the most common techniques to diagnose breast cancer is Mammography via X-ray [6], which is seen as the only way for women who do not show early symptoms. Nevertheless, this approach may lead to a worsening of the quality of life for patients because of incorrect diagnoses and inaccurate initial test results [7]. Another method to diagnose breast malignant tumours is ultrasound imaging, which occasionally suffers from recognizing the differences between diseased and healthy cells, especially in the initial phase [8]. Another advanced technique is the MRI, magnetic resonance imaging, which is used for women with dense breast tissue. Although MRI is highly sensitive, it is also costly and complex. Furthermore, the tumour cannot be precisely located using this technique, potentially resulting in incorrect extraction or another difficulty [10].

There are limitations to former techniques, including errors, positioning issues, the need for large equipment, complexity, and high costs. A new technique has been used as a promising technique with low price, reduced complexity, high information rate precision, non-ionising, and low power intensity, namely microwaves [6, 8, 9, 11]. Microwave imaging (MWI) systems are currently gaining considerable interest as a different method for detecting breast cancer [12] and consider to be early diagnosis technique for breast cancer. When breast cancer is identified early, survival rates can be as high as 97%. The MWI is a modern, dependable, and very effective method for identifying breast cancer early on [10, 13]. MWI is dependent on Metamaterial (MTM), an electromagnetic substance that possesses distinctive properties rarely seen in the natural world [13]. The Metamaterials are synthetic objects that reveal extraordinary characteristics such as negative permeability ($\mu < 0$), negative permittivity ($\varepsilon < 0$) and negative refractive index [14] in the desired frequency range [15, 16]. The MTMs are used in a diversity of practical applications, including microwave and terahertz applications [16, 17, 18], antennas [19], sensors [14-16], sensitive detectors [17], polarization transducers [20, 21], radar [20], absorbers [22] and cloaking [23].

The most valuable way to treat breast cancer is through early detection, as survival ratios can increase when the cancer is caught early [7]. This paper presents the numerical design of a novel patch antenna for breast cancer detection using microwaves. This method and layout offer a dependable and highly effective means of identifying breast cancer in its initial stages. This study is believed to be valuable for biomedical purposes, including the detection of cancerous tumour cells. The Studio Suite CST analysis and simulation software was utilized to model and simulate numerical outcomes.

II. METHOD

The primary objective of this project is to design and construct a microstrip patch antenna for detecting and differentiating alterations in backscattered signals resulting from changes in the electrical characteristics of cells and tissues. The backscattered signal can be used to distinguish between normal and cancerous cells based on alterations in the electrical properties of tissues. The patch antenna is crucial and must be carefully evaluated in the scheme.

The underlying concept of this technique is to produce a microwave electromagnetic signal, which is then transmitted to a human cell. Some of the signal reflects towards the antenna based on the cell's dielectric properties. Research [5, 24] has shown that the dielectric properties of a cancer cell are higher than those of a normal cell. Therefore, a clear indication of a cancerous cell is demonstrated by a notable backscattered microwave signal. Moreover, significant evidence, such as the phase shift and return loss, can be gathered from the scattered back signal, representing the presence of a tumour cell. Additional considerations are taken into account in the antenna design, such as directivity of radiation, gain, mismatching, and SAR absorption rate.

A. Patch Section Formula

Due to its thin profile and ease of configuration and manufacturing, the microstrip patch antenna was selected for its suitability in compact design. The design utilises a substrate made of fire-resistant epoxy resin and fibreglass composite (FR4). With a dielectric constant of ε_r=4.3, a thickness of h=1.6mm, and a loss tangent of 0.025. Furthermore, a copper ground layer with a thickness of 0.035 mm is utilised, and a microstrip line feed is employed as the primary feeding method to ensure a 50 Ω impedance match. The formula provided is for the dimensions of the patch [25],

Length of patch:

$$L = \frac{1}{2f_r\sqrt{\varepsilon_{reff}}\sqrt{\mu_0\varepsilon_0}} = -2\Delta L \qquad (1)$$

Where h is substrate thickness:

$$\varepsilon_{reff} = \frac{\varepsilon_{r+1}}{2} + \frac{\varepsilon_{r-1}}{2}\left[1 + 12\frac{h}{w}\right]^{-1/2} \qquad (2)$$

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

Wide of patch (Wp):

$$w = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \qquad (4)$$

where ε_r = dielectric constant of substrate
ε_{reff} = Effective dielectric constant
W_p = Width of the patch

B. Substrate and Ground Planes

Length of substrate plane (Ls):

$$L_s = 6h + L \qquad (5)$$

Wide of substrate plane (Ws):

$$W_s = 6h + W \qquad (6)$$

The size of the ground is similar to the width of the substrate, but the length has been shortened to enhance performance and adjust the resonance frequency to the desired range.

C. Antenna Sensor Design

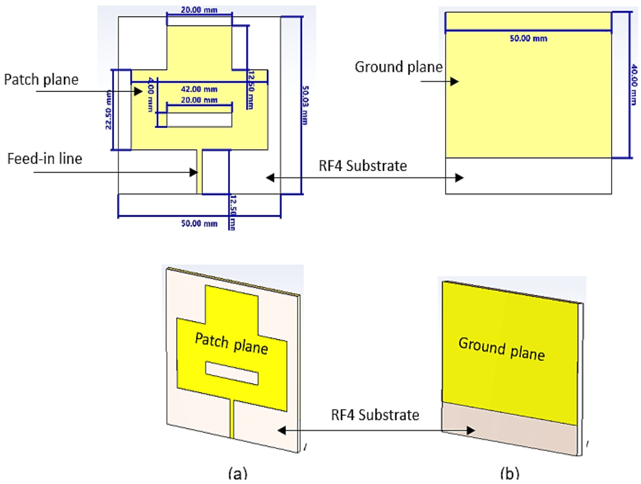

Figure 1. Microstrip Antenna Structure, (a) Frontage and (b) Backside

Figure 1 illustrates the design layers, which comprise three deposits: ground, substrate, and patch layers. The dimensions of the substrate are 50 mm × 50 mm, while the patch sensor is 42 mm × 45 mm. Figure 1 illustrates that the ground surface is modified by cutting off a small part from the underside and adding a rectangular opening slot to the patch surface. Based on its design, the proposed design was created with various resonant frequencies, specifically at 1.8 GHz and 2.9 GHz. All modifications to the structure design, such as slots and cutoffs, will improve and enhance the antenna's efficiency in terms of gain, radiation, and return loss.

III. RESULTS

In this section, a comparison study of simulated results for the antenna sensor is discussed, examining both resonance frequencies at 1.8 and 2.9 GHz, with and without the presence of tumour cells, as shown in Figure 2.

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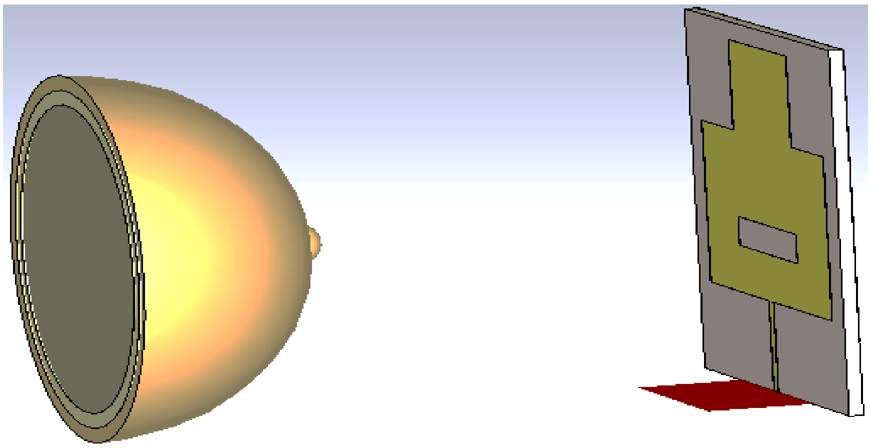


Figure 2. Antenna Sensor with Breast Model

Figure 2 illustrates that the phantom breast consists of three layers: the outer skin (breast skin), the fibroglandular layer of the breast, and the inner layer, which is composed of breast fat. Figure 3 illustrates the breast layers.

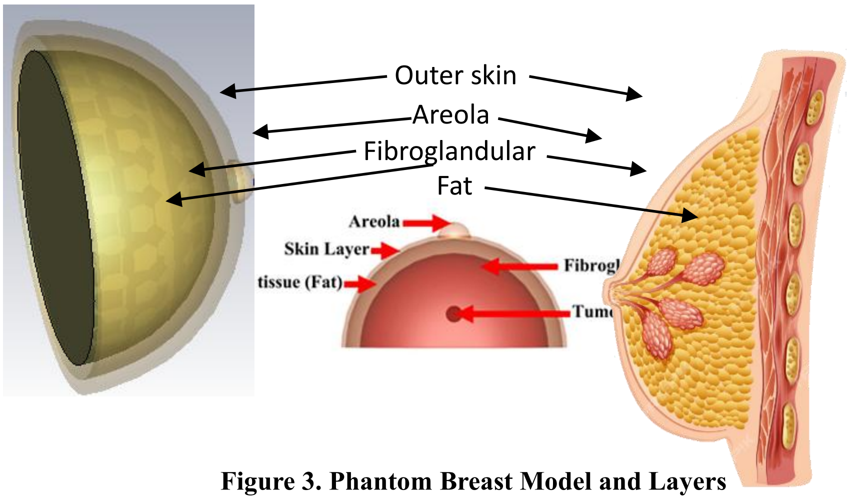
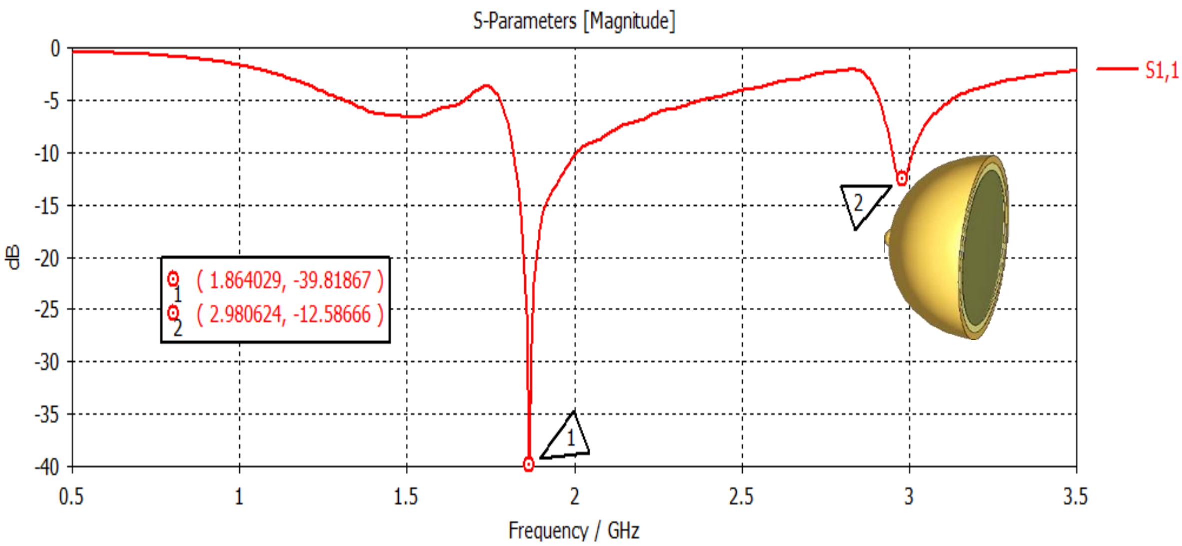


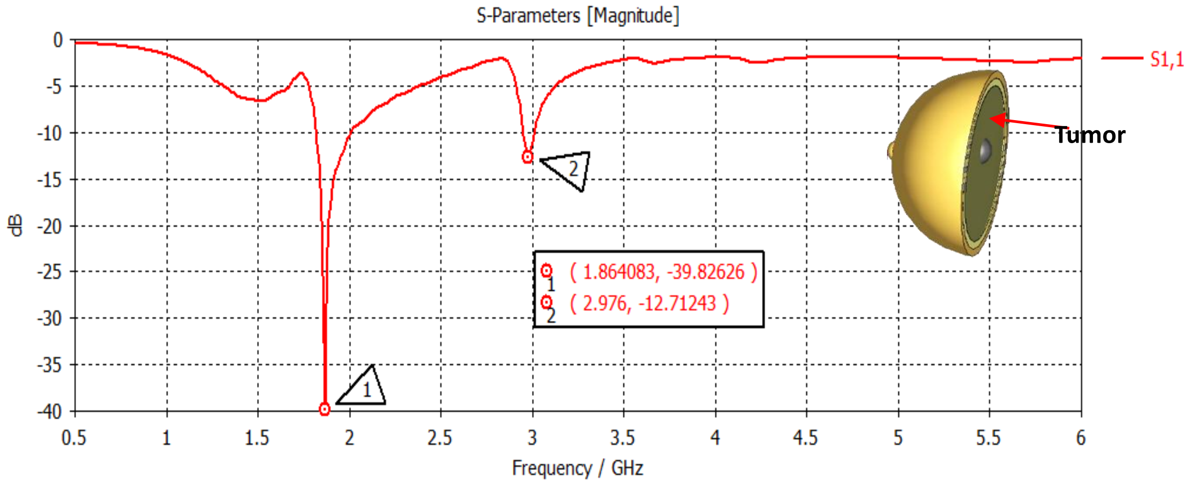
Figure 3. Phantom Breast Model and Layers

A. Return Loss:

One of the most critical parameters is the return loss (S11), which exhibits significant variation at the resonant frequencies of 1.8 GHz and 2.9 GHz. All reflection factors are less than -10dB, which meets the criteria. Figure 4 shows the S11 profile curves in both the ordinary breast in Figure 4 (a) and the cancerous breast in Figure 4 (b).



(a)



(b)

Figure 4. Parameter of (S11), (a) Not Including a Tumor Cell and (b) with Tumor Cell

Figure 4 shows the phase shift at 1.8 GHz between a standard cell and an affected cell, which is very small, approximately 54 Hz. In contrast, at 2.9 GHz, the phase difference is approximately 125 MHz. Although the return loss at 1.8 GHz is -39 dB, which is significantly better than the S11 (-12 dB) at 2.9 GHz by around 27 dB, the resolution of the higher band frequency is notably improved. Furthermore, the depth value of S11 is an additional consideration used as an indicator of tumour cells. At a frequency of 1.8 GHz, the depth difference is 0.0076 dB (with and without tumour cells), whereas at the resonance frequency of 2.9 GHz, it is 0.13 dB.

B. The Voltage Standing Wave Ratio (VSWR)

The VSWR indicates how well an antenna and its connecting feed line match and should ideally be kept within an acceptable range, typically less than 2, for the desired resonant frequency. Therefore, the results of the simulated antenna sensor are depicted in Figure 5 below.

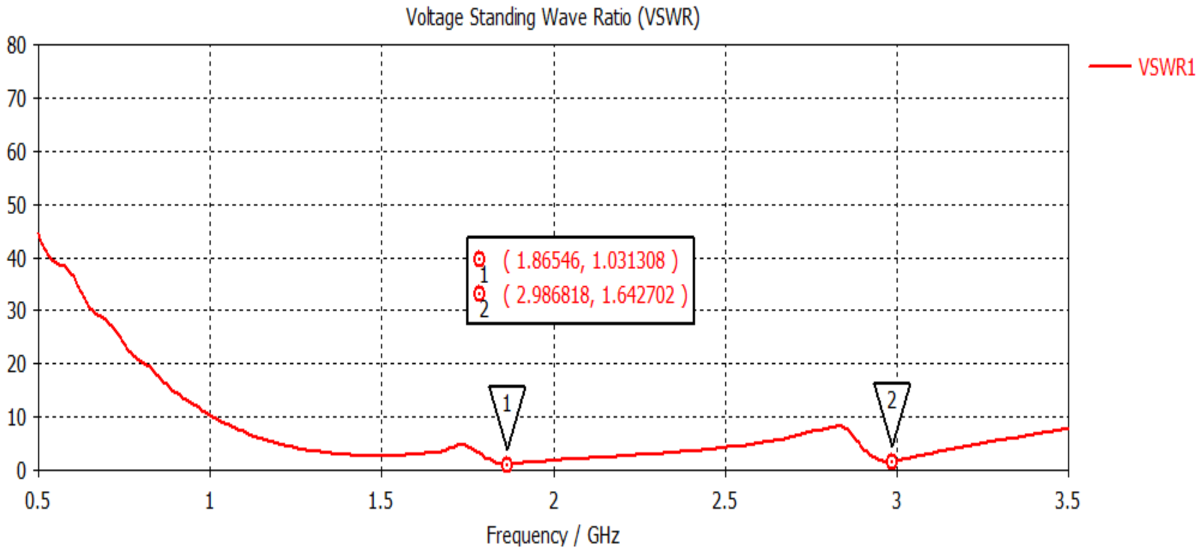


Figure 5. The Voltage Standing Wave Ratio (VSWR)

At both frequencies of 1.8 and 2.9 GHz, the VSWR values are 1.03 and 1.64, respectively. A VSWR value of less than 2 is considered appropriate for the majority of antenna applications. The antenna can be considered to have a "good quality match and balance"; however, when the VSWR value goes beyond 2, it implies that the antenna is not tuned correctly. The values of VSWR are less than 2 at both resonance frequencies, indicating that the design structure is in good match and within an acceptable range.

C. Radiation Pattern

Measurements are recorded in tables for spherical coordinates theta and phi. This is how spherical coordinates correspond to Cartesian axes: If Theta is 0, it represents a complete circle (360 degrees), and if Phi is 0, it means the x-z plane. Fi at 90 corresponds to the y-z plane, while Theta at 90 represents the x-y plane. The x-z plane (ϕ = 0) is known as the E-plane, and the y-z plane (ϕ = 90) is known as the H-plane. Figure 6 shows the radiation pattern of the proposed antenna in the x-z plane (E plane) and y-z plane (H plane). Additionally, Figure 6 displays the 3-dimensional radiation pattern. E and H-level beams are preferred because the main spokes remain stable when the beams are wide-sided.

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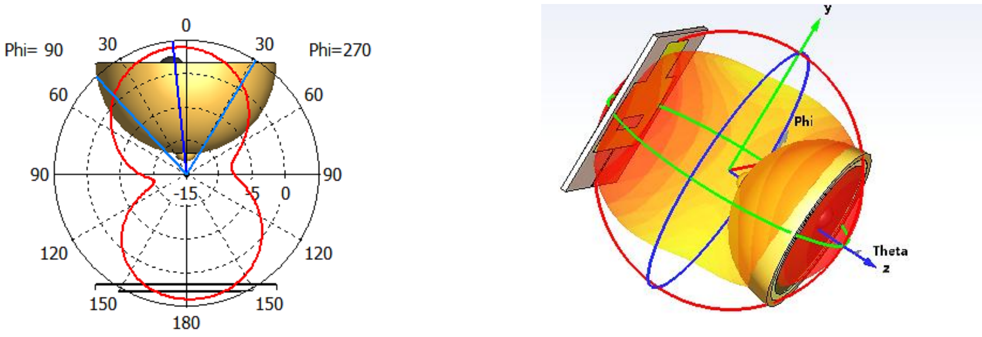

(a) (b)

Figure 6. Radiation Shape at 1.8 GHz in H-Plane (y-z Plane) and E-Plane (x-z Plane)

The main portion magnitude is 3.94 dBi, as seen in Figure 6(a), and the main lobe direction is 6 degrees. And the angular width (3dB) = 74.4 degrees. The gain and directivity patterns are simulated and plotted for all resonance frequencies. The observed values show that the directivities at 1.8 GHz and 2.9 GHz are 3.773 dBi and 3.264 dBi, respectively. Whereas the gain at 1.8 GHz is 0.995 dBi and at 2.9 GHz is 1.804 dBi. All calculations above were performed in the presence of tumour cells.

D. Specific Absorption Rate (SAR)

The absorption rate of radiation, especially SAR, is one of the most critical parameters to consider. To avoid adverse health effects, the absorption of the antenna must not exceed 2 W/K. The IC on Non-Ionising Radiation Protection (ICNIRP) has advised this value as a limit in 1998. The absorption index is assessed by dividing the total power absorbed by the human body by the person's weight. To calculate SAR, you need to input the electric field (measured in V/m), material conductivity (measured in S/m), and mass density (measured in kg/m³) into CST simulations.The local specific absorption rate (SAR) is determined as a numeric value for each volume element and transforms into a function that represents the spatial distribution of energy. Local SAR refers to the mass average value within a specific tissue volume for this function. The average local SAR values are calculated in tissue masses of approximately 10g as outlined in the TTCA No. In 1989 and 1995, these values were established by European standards organisations (CENELEC), while the value of 1g was set by the United States' ANSI/IEEE C95.1-1992. A cuboid with an average volume is being utilized. Therefore, this study has determined and provided the maximum specific absorption rate (SAR) values for 10g and 1g masses as 0.746 W/kg and 0.934 W/kg, respectively. In simpler words, SAR measures how quickly the body absorbs RF energy. In countries where the limit is based on an average of 1 gram of tissue, the SAR limit is 1.6 watts per kilogram, while in countries where the limit is based on an average of 10 grams of tissue, the SAR limit is 2.0 watts per kilogram. Therefore, the antenna design presented in this study is appropriate for use in the field of biomedicine, as both SAR values at 10g and 1g do not surpass 1.6 W/kg.

IV. DISCUSSION

The proposed design was modelled using CST Studio. Initially, the patch antenna sensor was simulated with a full ground plane and without a slot on the patch antenna. By using the full ground plane, the S11 was remarkable, with a value of more than -30 30dB. However, on the other hand, the SAR radiation exceeded the standard value of 1.6 W/kg. However, after removing 10 mm from one side of the ground plane, the SAR radiation fell within a suitable range, which is less than 1.6 W/kg.

Moreover, the frequency was approximately 6 GHz, which is distant from the lower band frequency, making it beneficial for biomedical purposes. Then, a rectangular slot with a width of 20 mm and a length of 4 mm was introduced on the patch antenna to enhance its performance. The frequency is shifted to a lower band, ~3 GHz. Two resonance frequencies, 1.8 GHz and 2.9 GHz, were introduced. Lowering the frequency increases the penetration depth but decreases the resolution. A comparative study between 1.8 GHz and 2.9 GHz showed that the higher frequency gives better resolution but less penetration depth. Using lower frequencies allows for deeper penetration with less loss, while higher frequencies provide better resolution but with limited phase shift and depth value. Therefore, the frequencies of 1.8 and 2.9 GHz have been chosen as the optimal options for imaging normal and tumour breast cells at a depth of 3-5 cm.

Therefore, the penetration of high-band frequency will be less, and this could be resolved by mounting different patch sensors around the breast. However, if the tumour is located at a depth, then the lower band frequency could be used for greater deep penetration.

The difference between S11 and its depth value, as well as the phase shift in the frequency, is observed due to the presence and absence of tumour cells. These results are acceptable and warrant further investigation into their practical application.

V. CONCLUSION

In summary, a novel design and inexpensive antenna sensor were created and tested for detecting microwave breast cancer at frequencies of 1.8 and 2.9 GHz. CST software was employed for the creation and simulation of the structure. The antenna patch achieved a healthy return loss (S11) of -39 dB at the lowest frequency, while at higher frequencies, the return loss is around -12 dB.

The return loss depth in the higher band is less than that in the lower band. In contrast, the higher band frequency affords more identifiable detection and higher resolution than the lower band frequency. A comparison study of two resonance frequencies was conducted. A phantom breast with lumps and without tumours was assessed to confirm the validity of the method. The parameters, such as directivity, SAR, and VSWR, were taken into consideration in this design. The proposed design is a suitable alternative for use in biosensor applications and microwave detection of breast cancer.

DECLARATION STATEMENT

Funding	No, I did not receive.
Conflicts of Interest	No conflicts of interest to the best of our knowledge.
Ethical Approval and Consent to Participate	No, the article does not require ethical approval or consent to participate, as it presents evidence.
Availability of Data and Materials	Not relevant.
Authors Contributions	I am the sole author of the article.

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Haydn Green Institute for Innovation and Entrepreneurship, the University of Nottingham, UK. Intellectual property (IP) related to magneto-resistive technology has been filed with Cambridge Enterprise, the University of Cambridge, UK.