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Design and Miniaturization of a Capacitive Coupled Patch Antenna for Biomedical Applications

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ABSTRACT : *Breast cancer affects many women and can be fatal if not treated properly. The most important factor in detecting and interfering with cancer tissue is early detection. Breast cancer detection methods include X-ray mammography, magnetic resonance imaging (MRI), and ultrasound. However, These detection methods have certain limitations. Poor contrast for malignant/benign cancer tissue, for example, accounts for between 4 and 34% of all breast cancers missed. Microwave detection for breast cancer is a promising technology, and several studies are being conducted in this field. The permittivity and conductivity of all materials vary, which causes errors in dielectric parameters. Therefore, an approach with increased sensitivity is necessary in order to determine the correct values of the dielectric parameters of biological samples. In the present work, the design of a planar patch-type antenna with capacitive coupling is introduced by partitioning the patch through a gap in this study. The suggested design enhances the antenna's sensitivity to material dielectric properties.*

In this paper, a compact-size microstrip antenna for microwave imaging to diagnose breast cancer was developed in computer simulation technique (CST) Studio Suite Software utilizing the FR-4 (Lossy) substrate material ranging from 6.1 GHz to 6.6 GHz and resonating at 6.38 GHz. In the CST MWs, a breast model with tumors was formed using skin, fat, glandular, and cancer-affected tissues. In free space and after applying the antenna to the cancer-affected breast phantom, the Return Loss (S_{11}) value was found to be between -25.68 dB and -24.13 dB, respectively. Increasing the capacitive coupling within the patch design improves the antenna performance and indicates that an antenna model is a good option for breast cancer diagnostics. The proposed model showed a considerable shift in return loss of approximately 1.55 dB between the presence and absence of the tumor, with a resonance shift of around 20 MHz.

KEYWORDS *Microwave, Patch antenna, Capacitive coupling, Return loss,Breast cancer*

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I. INTRODUCTION

Breast cancer is the second-leading cause of cancer-related death worldwide and the most common non-skin cancer in women. Each year, this cancer claims the lives of thousands of women [1]. According to the World Health Organization (WHO), more than 2.3 million new cases are recorded in 2020. Early detection, though, reduces death and helps to increase survival rates [2].

Implantable medical devices (IMD) are increasingly becoming employed for physiological monitoring as well as the administration of both pharmaceutical and electrical therapy. Since the first completely implantable cardiac pacemaker was established more than 50 years ago the IMD industry has grown rapidly and diversified [3]. As a consequence, there are now a wide variety of medical devices available for conditions ranging from cardiac diseases, such as the implantable cardioverter-defibrillator and the loop recorder, to non-cardiac ones, such as deep brain stimulators, bladder stimulators, and diaphragmatic pacemakers [4]. Most current IMDs have a telemetry system that allows the implant and external devices to communicate with each other. This communication link may be used to configure the IMD's operational configurations temporarily or permanently, obtain real-time and stored physiological data, and inquire about the IMD system status and therapy history [4]. Since the implanted sensors should communicate with external devices, integrated compact antennas are required. Developing antennas that can operate in tissue is a challenging task. Tissue conductivity, impedance matching, antenna size, low power requirements, and biocompatibility are all important design parameters that should be taken into consideration [5].

Microwaves are used in many fields of medicine, such as hyperemia, non-contact diagnosis, disease therapy, and so on due to their features, such as high frequencies and short wavelengths [6, 7]. When microwaves travel through a living organism, it results in degrees of attenuation, phase shift, polarization, dispersion, and other effects. One of the major challenges of microwave telemetry systems is to develop antennas with a small size, which helps to miniaturize the implant, and a high radiation efficiency, which helps to prolong the life of the IMD. When compared to traditional microwave antennas, the microstrip antenna is smaller, lighter, very flat, compact, mechanically convenient, and has a wider range of electrical performance, ease of fabrication, and conformity.

The microstrip antenna usually consists of a dielectric substrate that is placed between a radiating patch on top and a ground plane on the other side of a microstrip patch antenna. The patch is constructed of a conductive material such as copper or gold and it can be shaped in any way [8]. Therefore, the microstrip antenna was used in a wide range of applications not only in wireless communications but also in medical applications, such as in tissue detections [9-13]. Patch antennas often employ a multiple-array technique to improve their gain[14].It can be utilized as a dielectric-based biosensor that resonates based on the dielectric and other physical characteristics of biological tissues[15, 16]. However, employing numerous patches in a multiple array system typically increases antenna size, making this technology incompatible where size is a constraint.

The reflected information from biological phantoms can be recorded and evaluated using an appropriate signal processing approach for getting 3D images of the subject under test [3]. Microstrip Patch Antennas may be designed using a wide range of frequency bands. Some output parameters of microstrip patch antennas, such as Return Loss (S11), Radiation Pattern, Directivity, and Polarization, should be properly evaluated for better diagnosis.

In this study, a modified microstrip antenna to detect breast cancer tumors is developed in a computer simulation technique microwave studio (CST MWs) and operates at a frequency range of (6.1-6.6 GHz). The suggested antenna includes a multilayer configuration and contains an independent line that feeds the radiating elements via electromagnetic coupling, allowing for greater miniaturization and a smaller microstrip antenna size. Images based on simulation results are used to evaluate the variations in electromagnetic field values as the antenna device is positioned beneath the breast skin. In our simulation studies, we found that adding more capacitance to a patch antenna can improve its gain and sensitivity.

II. SIMULATION METHODOLOGY

A series LCR circuit is essentially a bandpass filter that passes a certain range of frequencies while attenuating all others. As demonstrated in [17], the equivalent circuit of the radiating patch based on the expansion cavity model [18] is a parallel combination of resistance (RP), inductance (LP), and capacitance (CP) as shown in Figure 1. The S11 response of the microstrip patch antenna is approximated by connecting series LCR circuits in parallel. This modeling approach is one of the simplest ways to describe the S11 response of a microstrip patch antenna [19].

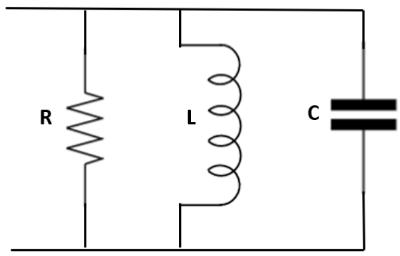

Figure 1. Equivalent circuit of the rectangular patch antenna.

As illustrated in Figure 2, our proposed antenna under investigation is a group of compact capacitive coupled symmetric patches. The suggested design has an overall size of w = 28.66 mm and l = 29.89 mm. The substrate for PCB is FR-4 with a relative dielectric constant of 4.3 and a loss tangent of 0.02 in the frequency range 6.1-6.6 GHz. The copper layer is 0.365 mm thick, and the total thickness of the antenna is 1.8 mm. The patches are placed on the substrate's top layer and the ground plane makes up the substrate's bottom layer. The coaxial probe of the inner conductor feed extends from the ground plane through the PCB substrate to the top layer feed, which capacitively couples the patches.

The resonant frequency of the antenna is controlled not only by its width and length but also by the combination of inductance and capacitance incorporated in the patch [14]. In our study, It is shown how adding capacitance increases antenna gain, radiation field, and sensitivity. The antenna element covers a frequency band of 6.1-6.6 GHz, which is a promising frequency region for the dielectric characterization of biological samples [3]. Capacitive feeding is essential for an effective patch size reduction. As shown in Figure 2, the design of a suggested micro-strip patch antenna for a rectangular microstrip patch antenna; the length [l] and width (w) are calculated as follows [20]:

$$W = \frac{c}{2f_r\sqrt{(\epsilon_r + 1)/2}} \quad (1)$$

where c denotes the speed of light, fr is the frequency of the antenna, and εr the permittivity.

The proposed microstrip antenna design is modeled employing electromagnetic 3-D finite integration method (3-D FIT) software using computer simulation technology (CST MWS) [21, 22]. Figure 2 depicts the structure of the proposed microstrip design's simulated unit cell. To provide extra distances for far-field computations, the unit cell is surrounded by air as an open area boundary condition (BC), along with the x, y, and z directions. In this study, the feed element, which comprises a waveguide port coupled to the driven element, excites the microstrip design. The s-parameter and patch antenna directivity are used as figures of merit to evaluate the performance of the proposed design. The directivity of the traveling wave can be defined as [23, 24]:

$$D(\theta,\phi) = 4\pi\frac{P(\theta,\phi)}{\int P(\theta,\phi)d\Omega} \quad (2)$$

P(θ,ϕ) is the transmitted power per unit solid angle in the specified direction divided by the total power radiated per solid angle.

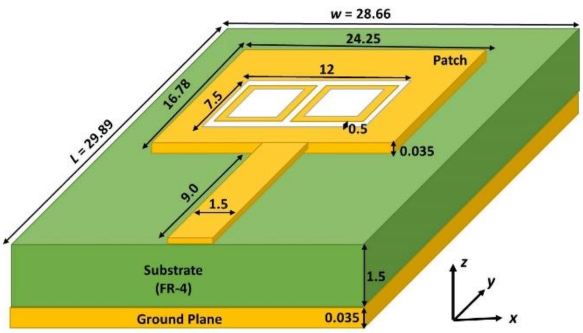

Figure 2. Illustration of patch antenna dimensions.

III. BASIC BREAST DESIGN

Several breast phantom models have been used by researchers [1, 2, 8]. Both phantoms differ in their relative permittivity (ε) and conductivity (σ). The female breast structure in this study is modeled as the basic breast structure shown in Figure 3. The designed breast model consists of three different parts: skin, fat, and tumor. The first two parts (skin and fat) are called normal tissue, and the tumor part is called malignant tissue. Permittivity, electrical conductivity, and density are the dielectric parameters used to create normal and malignant tissues. The skin of the breast model has a radius of 30 mm and a thickness of 4 mm [13]. Furthermore, the fat has a radius of 26 mm and a thickness of 5 mm, also the tumor is 5 mm in size. The Breast Model is depicted in Figure 3, and the dielectric parameter values utilized to create the human breast model are taken from [8].

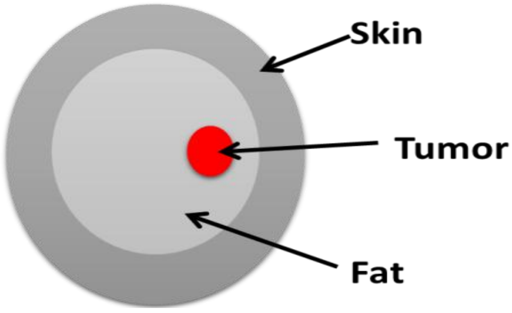

Figure 3. Basic breast phantom design.

Different dielectric properties (Electrical conductivity, relative permittivity, etc.) were employed to investigate the influence of radio-frequency interaction on Phantom proximity. The dielectric parameters of breast tissues (both malignant and normal) can be significantly changed by frequency spectrum changes [25]. These parameters of various types of breast tissues can also be changed depending on their structures and contents, these changes are then applied to calculate the electric and magnetic fields in the various structures [2]. Different permittivity and conductivity values in structures cause different electromagnetic field values. This parameter is critical for detecting cancerous tissue. The proposed free space antenna was applied to the phantom at an operating frequency of around 6.4 GHz after the cancer-affected breast model was created by the finite integration method (FIT) via CST MWs.

IV. RESULTS AND DISCUSSIONS

IV.I. RETURN LOSS (S_{11}) AND VSWR

The simulations were performed by the FIT method via the CST MWs. Evaluations are provided in this study by analyzing electromagnetic field values over breast tissue with and without a tumor. Three antenna structures have been constructed, constructed by adjusting the capacitive coupling on a microstrip patch by splitting the patch through a gap. Breast tissue with and without tumor is simulated for the optimum antenna design. Here we report that the antenna gain, radiation field, and sensitivity are enhanced by introducing additional capacitance. A small area around the rectangle was cut out to introduce additional capacitance (Figure 4). The antenna structures were numerically modeled and analyzed. The optimized performance parameters, such as return loss and voltage standing wave ratio (VSWR) were simulated in the absence of the breast model.

Figure 5 depicts the simulation results of the initial and the improved design. The resonant frequency of the initial design (Figure 4(a), P1) was found to be 6.37 GHz using CST MWs. Figure 4(a) was modified (Figure 4(b), P2), and the obtained results of the resonant frequency, S11, and electric field were 6.372 GHz, -15.565 dB, and 18.71 dB V/m, respectively.

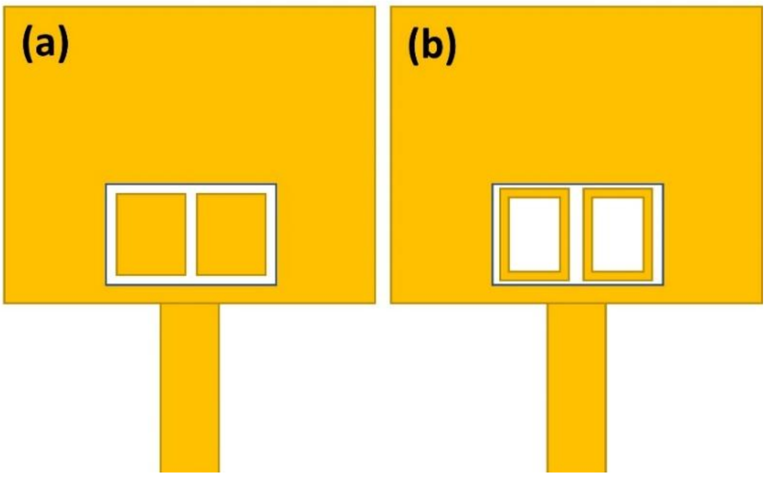

Figure 4. (a) Initial model of the patch antenna (P1), and (b) modified model (P2).

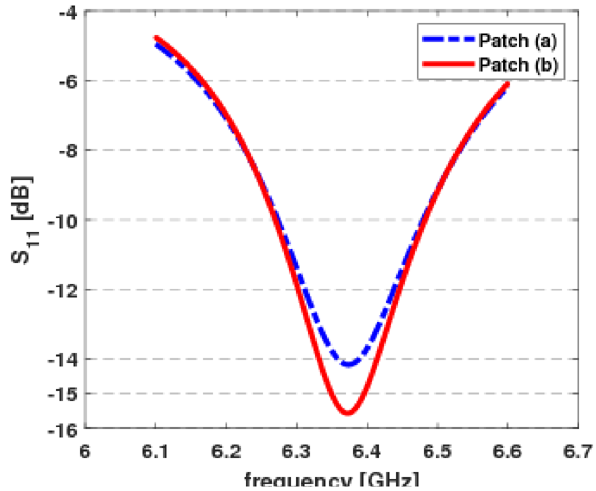

Figure 5. The frequency dependence of the S_{11}.

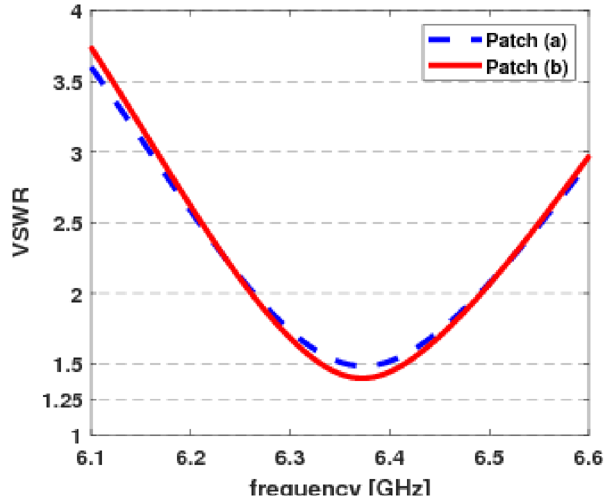

Figure 6. VSWR as a function of the frequency

The comparison of the VSWR data for the patch design (P1) and the improved design (P2) is shown in Figure 6. This figure illustrates that the design of (P2) has good matching when compared to the patch design (P1). At 6.37 GHz, the optimal design (P2) has a VSWR of 1.39, whereas the patch design (P1) has a VSWR of 1.48.

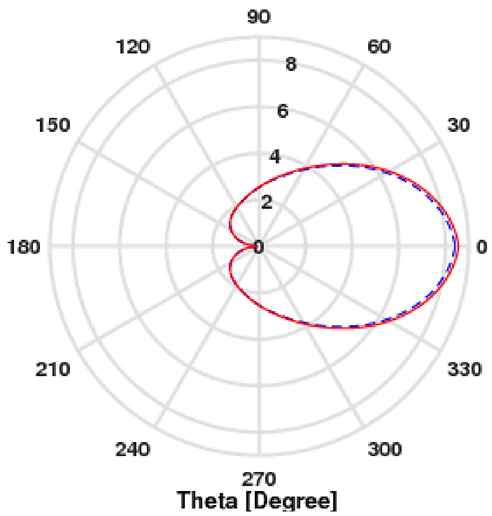

Figure 7. Comparison between the field radiation pattern of P1 (blue dotted line) and radiation pattern of P2 (red solid line) at the resonance frequency.

Figure 7 depicts the field radiation pattern of tilted patch antennas at the resonance frequency of 6.37 GHz. This figure shows that the field in the forward direction is enhanced. It is worth noting that the electric field and also directivity are enhanced as a result of the effective coupling between array patches, as well as the lower side and back-lobe levels.

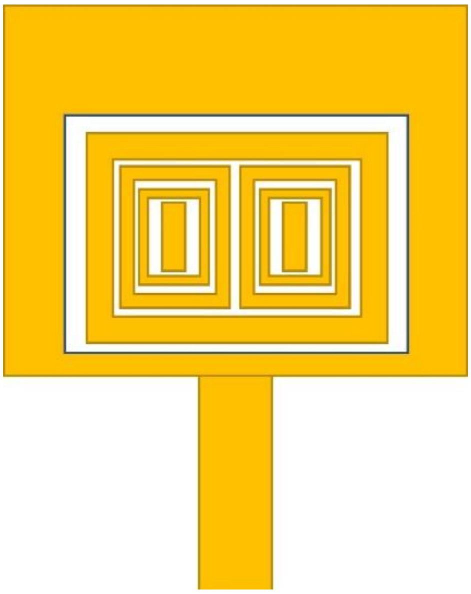

Figure 8. Optimized patch design (P3).

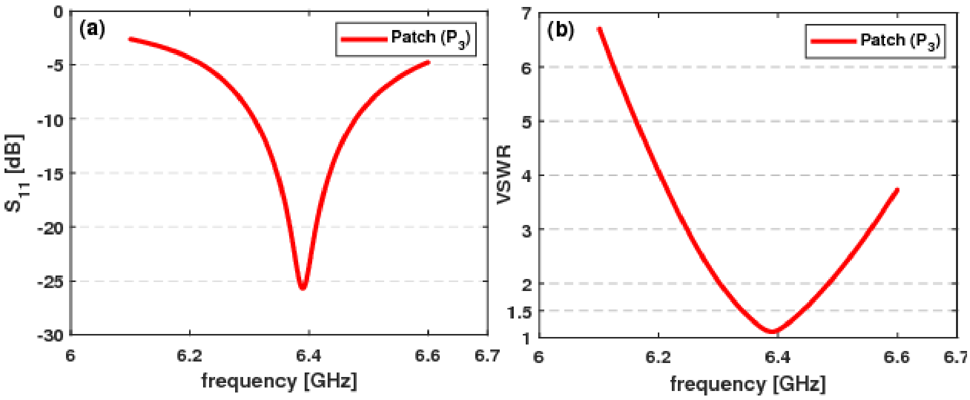

Figure 9. (a) S_{11} parameter as a function of the frequency and (b) variation of the VSWR with frequency.

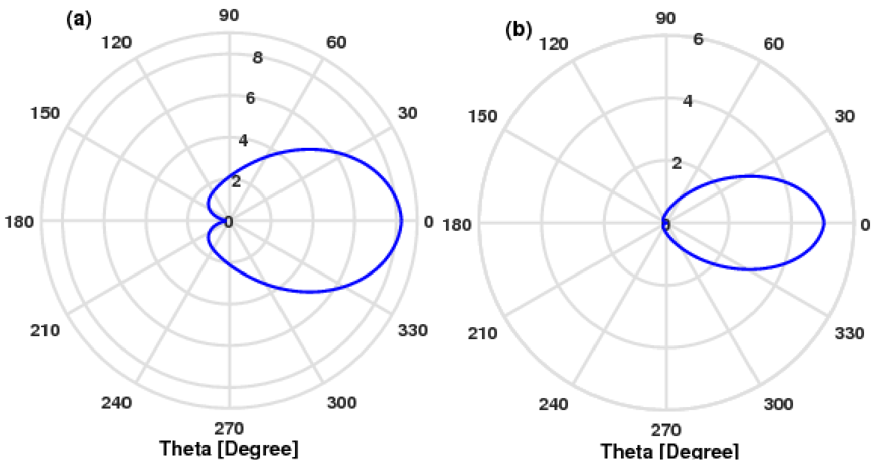

Figure 10. (a) Field radiation pattern and (b) directivity radiation pattern

An additional capacitance is used to enhance the antenna performance as shown in Figure 8. The S11 and the VSWR are used to describe the performance of the patch antenna. The scattering parameter is employed as a figure of merit, which is defined as the ratio of the peak signal in one direction to the reflected signal in the opposite due to a transmission line mismatch. Figure 9(a) shows the (S11) as a function of frequency for the optimized patch antenna (P3). This figure shows that the S11 for the improved design is very low with good impedance matching. In comparison to previous designs, the S11 achieved -26 dB at f = 6.38 GHz. Therefore, increasing the capacitive coupling enhances the S11 while reducing the power level of the reflected wave. Furthermore, the VSWR of the optimized antenna design shows an improvement as compared with the previous designs. The VSWR of the patch design is enhanced to 1.1 at f = 6.38 GHz due to the low loss level as shown in Figure 9 (b).

Figure 10 shows the field and directivity polar plots of the improved antenna (P3) at the resonance frequency. It is revealed from this figure that the field in the forward directions is enhanced as can be seen in Figure 10(a). It would also be seen from this figure that the electric field and the directivity are enhanced by increasing the capacitive coupling of the patch design.

IV.II. CANCER DETECTION

In this work, the evaluations are presented by studying the return loss, VSWR, and electromagnetic field levels over breast tissue with and without tumor. The previously proposed three antenna structures were studied through adjusting the capacitive coupling on the microstrip patch. Breast tissue with and without tumor is simulated for each antenna structure.

Figure 11 is a graph that depicts the differences in return loss and VSWR values for the first antenna design (P1) with and without a tumor. The red line on the graph indicates return loss or VSWR values in the absence of a tumor. On the graph, the blue line depicts return loss or VSWR values with the tumor. The difference in return loss levels between breast tissue with and without tumor is significant for diagnosing. The circles on the graph represent distinct differences between simulation results with and without tumor. The return loss and the VSWR in the absence of the tumor are -14.17 dB and 1.487 at 6.37 GHz, respectively. After embedding the tumor the VSWR value becomes 1.5 with a 0.87 % increase while the return loss is -13.89 dB with a 1.97 % of increase at 6.35 GHz and a shift of around 0.19 dB compared to the case without the tumor.

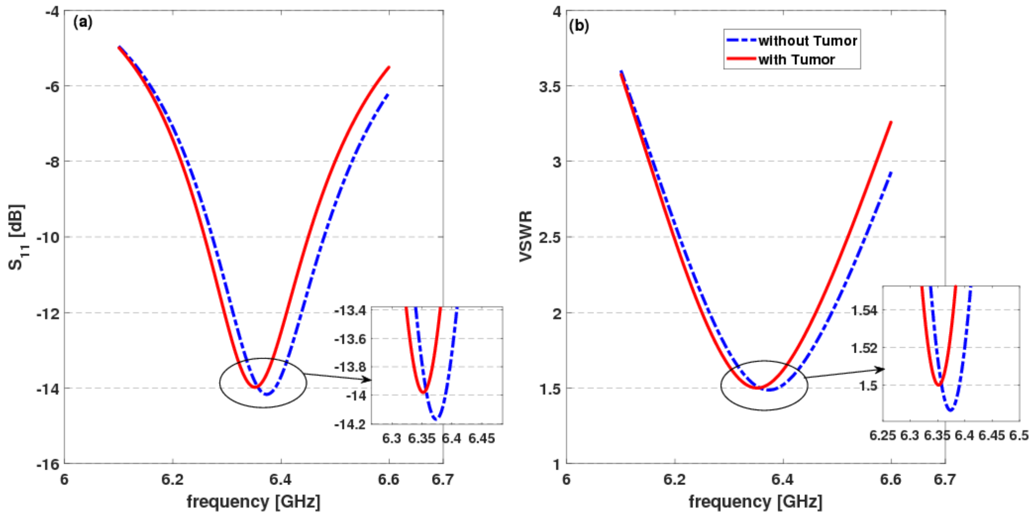

Figure 11. (a) The return loss and (b) the VSWR for the design P1 with and without tumor.

Figure 12 demonstrates the return loss and the VSWR for the antenna design (P2) in the presence of the breast model, without and with a 5 mm-radius tumor, respectively. Without a tumor, the S11 and VSWR are -15.57 dB and 1.4 at 6.37 GHz, respectively. The VSWR value is 1.466 with an increase of 4.56 % and the return loss after inserting the tumor is -14.47 dB with an increase of 7 % at 6.35 GHz and a difference of 1.1 dB.

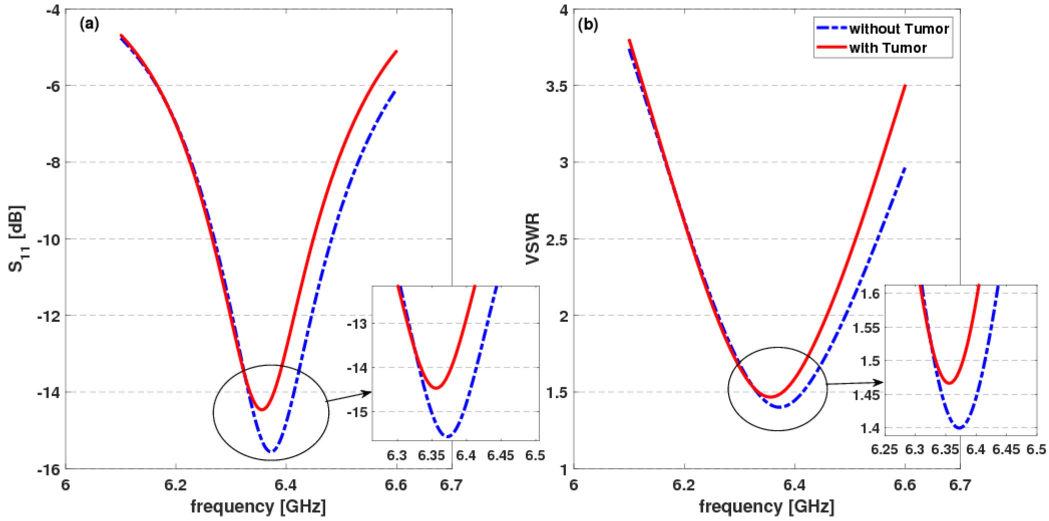

Figure 12. (a) The return loss and (b) the VSWR for the design P2 with and without tumor.

Figure 13 is a graph that depicts the differences in return loss and VSWR values with and without tumor for the optimized design (P3). As illustrated in the graph, variations in return loss and the VSWR levels denoted by circles play a vital influence in defining tumor occurrence. In free space, the designed model had a return loss and VSWR of -25.68 dB and 1.11 at 6.38 GHz, respectively. A VSWR of 1.133 and a return loss of -24.13 dB were recorded in the phantom model with a tumor with a significant shift in the return loss of around 1.55 dB with a resonance frequency shift between the presence and the absence of the tumor of around 20 MHz.

Table **1** shows the results of the antenna performance parameters in free space and the presence of the tumor.

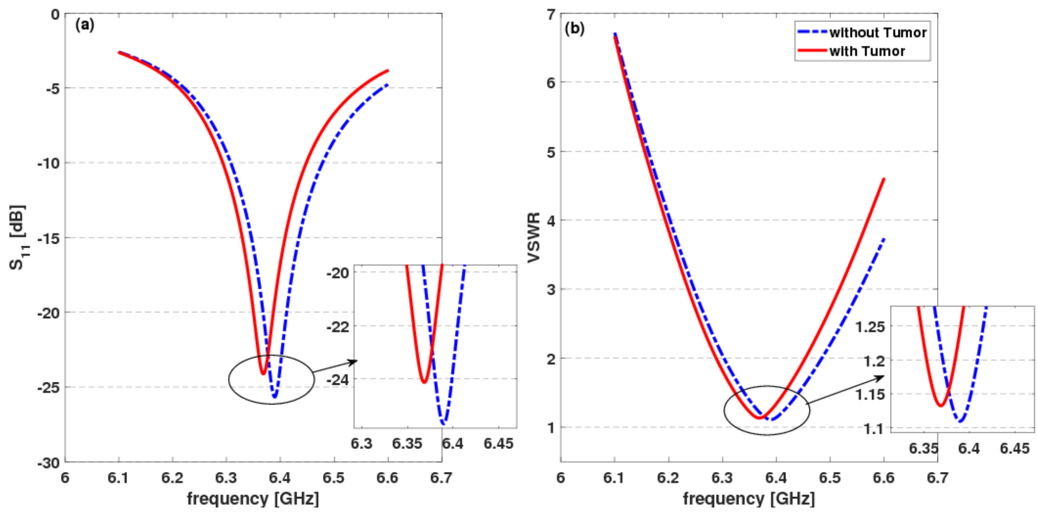

Figure 13. (a) The return loss and (b) the VSWR for the design P3 with and without tumor.

Table 1. Comparative study of the antenna parameters.

Design	S_{11}			VSWR			Frequency		
	Without tumor [dB]	With tumor [dB]	% change	Without tumor	With tumor	% change	Without tumor[GHz]	With tumor[GHz]	Frequency shift [MHz]
P_1	-14.17	-13.98	1.97	1.487	1.5	0.87	6.373	6.352	21
P_2	-15.57	-14.47	7	1.4	1.466	4.56	6.372	6.356	16
P_3	-25.68	-24.13	6.03	1.11	1.133	2.03	6.389	6.369	20

V. CONCLUSION

In this research, inset-fed rectangular microstrip antenna structures are studied in order to detect early breast cancer. The antenna design at 6.38 GHz is modeled with a basic 3D breast shape. several antenna designs are investigated by modifying the capacitive coupling on the microstrip patch. Based on the dielectric properties of a real human breast, a breast model was proposed to calculate the antenna's return loss of -25.68 dB in free space and -24.13 dB with the tumor-affected breast model.

According to our results, increasing the capacitive coupling improves the return loss and, as a result, the sensitivity of the antenna structure to detect breast cancer. Finally, from the data obtained, it is concluded that the antenna was capable of identifying breast cancer from the cancer-affected breast via microwave detection technique. However, in consideration of future demand, these parameters can be enhanced to satisfy the requirements of overcoming the challenges associated with the Breast Cancer detection process. The third antenna configuration, based on simulation results and graphical observation, provides the best detection for breast cancer.

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