Ultra-Wide-Band Microstrip Patch Antenna Design for Breast Cancer Detection

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ABSTRACT

In this paper, a novel design for an ultra-wide-band (UWB) microstrip antenna with enhanced bandwidth for early detection of breast cancer has been proposed. It has been designed using CST software, which is a 3D analysis software package for electromagnetic components and systems design, analysis, and optimization. FR-4 has been used as a substrate, with dimensions of 60 × 70 mm, having a circular patch with a defected ground structure to reach the desired outcomes. The antenna has a peak gain of 4.431 dBi and works between 1.6 GHz and 10 GHz, which gives a bandwidth of 8.4 GHz with an average of –15 dB. The result of the simulation is presented in terms of radiation pattern, bandwidth, and return loss, and the validation of the proposed work is presented by the gain and the efficiency. A breast phantom model has been designed containing a tumor placed in a specific location, This, when combined with the kinetics of contrast medium propagation in various tissues, may effectively simulate normal breast tissue. The cancerous tumor is detected using specific absorption rate (SAR) analysis. The SAR is the rate of energy absorption in a tissue and is measured in W/kg. The SAR results are a maximum at the coordinates (1.085, 9.47273, 32.25), close to the actual location of the tumor at (0, 10, 40) The results display the ability to detect the tumor inside the breast and to reveal its location with high accuracy, and the antenna radiation meet the SAR standards.

I. INTRODUCTION

Cancer is one of the deadliest diseases, especially when it becomes malignant and invades the body, spreading to the other organs. It results from the abnormal growth process of cells and is hard to detect even with modern technology. One of the most common types of cancer worldwide is breast cancer, which claims the lives of many women. Therefore, while it is imperative to address this situation and to find a solution by developing a cure, it is even more important to develop methods to detect its presence in the body. Years of research have proved that the most important element in curing cancer is detection in the early stages, before it becomes uncontrollable and spreads to more organs. Many techniques have been proposed, like mammography [1], MRI [2], and ultrasound detection [3]. These technologies are of limited value in detecting cancer on an early stage, mostly due to poor contrast. Therefore, by the time a cancer is detected, the probability of cure is reduced.

The antenna is a device that transmits and receives signals in the form of electromagnetic waves [4]. It has been implemented in the medical field in general applications and more specifically, in cancer. It has been used for diagnosis and treatment, while sometimes only to transmit information. Radio frequency identification (RFID) is used in monitoring systems and medical implants, and in microwave imaging. Thus, antennas can be used for communication and/or as a treatment device.

Several techniques have been used to detect cancer, such as microwave imaging [5] and radar-based microwave tomography [4-7].

Malignant breast tumors are detected using ultra-wide-band microwave [8]. The UWB can be achieved by several antennas such as a microstrip in [9] with a bandwidth ranging from
8.1 to 12.8 GHz, having a defected ground structure. A simple composition can be made to produce an antenna array having a bandwidth ranging from 300 MHz to 4.15 GHz [10]. The metamaterial (MTM) technique is proposed in [11] in order to achieve better performance in terms of efficiency and gain, in a UWB planner antenna for systems of wireless communication.

In [a], a detailed assessment of the idea, theory, and applications of compound right/left-handed transmission lines (CRLH-TLs) in antenna system designs has been presented. For all instances based on CRLH MTM-TLs, assessments are conducted based on physical dimensions, frequency bandwidth, materials, gain, radiation efficiency, and radiation characteristics. Because of the usage of MTM, structural complexity is reduced. The MTM antennas outperform conventional antennas thanks to a more cost-effective production process. Mohammad Alibakhshikenari and colleagues used the CST Microwave Studio to conduct a feasibility analysis on a novel design for a super-wide impedance planar antenna based on a 2 × 2 microstrip patch antenna (MPA) [b]. The suggested antenna construction overcomes the limited bandwidth of the current microstrip patch designs. The antenna is suitable for microwave and millimeter-wave systems such as UWB, RFID, massive MIMO for 5G, and radar systems. In [c], Mohammad Alibakhshikenari offers a thorough systematic and theoretical investigation of different mutual-coupling suppression (decoupling) strategies, with a particular emphasis on metamaterial and metasurface (MTS) methodologies. It is demonstrated that mutual-coupling reduction solutions prompted by MTM and MTS theories can provide an increased level of isolation between neighboring radiating elements using easily realistic and cost-effective decoupling structures, with negligible impact on the array’s properties such as bandwidth, gain, radiation efficiency, and physical footprint using SAR for microwave imaging [12-14].

It is known that the frequency of the microwave band increases in the human body. Therefore, to ensure the safety of the human body and to determine whether it is affected by the radio waves, SAR is usually used in wireless devices. The SAR can be used for isolation improvement as a technique of coupling in a microstrip array antenna [15]. We need flexible antennas with a compact size, a low impact on the human body, and a small SAR; for example, for communication outside the body, patch antenna is used due to its relatively small size, simple design, and high gain [5-7], [15-24] characteristics.

For medical applications, specifically in imaging, diagnosis, and treatment, microstrip antennas are widely used [25]. Moreover, a microstrip is easy to install in the human body due to its flexibility, and the concept of wearability is used in this domain, to ensure flexibility [26].

A wearable microstrip patch antenna is designed, which is known for its small size, low cost of fabrication, and low energy consumption. The mathematical approach, a basic circular antenna design, and the proposed antenna will be discussed in Section II of this paper. The results of the simulations can be seen in Section III. In Section IV, the breast phantom model is shown additionally, and the proposed method of detection can be seen in Section V. Finally, Section VI presents the discussion and conclusion.

II. METHODOLOGY

A. Mathematical Approach

This section deals with the design formulas for the basic microstrip patch antenna [27]. These formulas have been used to construct a mathematical model, which forms the fundamental design. This is the initial step in achieving the final design and then adjusting it to meet the required results.

1) Antenna Design Procedure

For finding the width [25]:

\[
W = \frac{C}{2f_0 \sqrt{\varepsilon_{\text{eff}}}}
\]

Based on the height, width, and dielectric constant of the substrate, the effective dielectric constant can be found [28]:

\[
\varepsilon_{\text{eff}} = \frac{(\varepsilon_r + 1)}{2} + \frac{(\varepsilon_r - 1)}{2} \left[1 + \frac{12h}{W}\right]^{\frac{1}{2}}.
\]

For finding the effective length [25]:

\[
L_{\text{eff}} = \frac{C}{2f_0 \sqrt{\varepsilon_{\text{eff}}}}.
\]

For finding the length extension [28]:

\[
\Delta L = 0.412h\left(\frac{W}{h} + 0.258\frac{W}{h} + 0.264\right).
\]

Then, finally finding the actual length of the patch [28]:

\[
L = L_{\text{eff}} - 2\Delta L.
\]

having the following parameters:

- \(c\) is the speed of light, \(3 \times 10^8\) (m/s)
- \(f_0\) is the resonance frequency (Hz)
- \(\varepsilon_r\) is the relative permittivity of the dielectric substrate (F/m)
- \(W\) is the width of the patch (mm)
- \(h\) is the thickness (mm)
- \(L\) is the length of the patch (mm).
Based on the formulas of rectangular microstrip antenna, the circular antenna can be obtained. The radius is given by [4]:

\[ \text{radius} = \frac{\sqrt{(W+h) \times (L+h)}}{2} \]  \hspace{1cm} (6)

where \( W \) is the width, \( L \) is the length, and \( h \) is the thickness. It has been found that multiplying the thickness of the patch by 1.5 gives more accuracy. Thus, the formula will be [4]:

\[ \text{radius} = \frac{\sqrt{(W+h \times 1.5) \times (L+h \times 1.5)}}{2} \]  \hspace{1cm} (7)

The radius can also be found by using the resonant frequency \( (f_r) \) using [4]:

\[ r = \frac{k_{mn} \times c}{2\pi f_r \sqrt{\varepsilon_r}} \]  \hspace{1cm} (8)

Having \( \varepsilon_r \) as relative permittivity, \( k_{mn} \) is \( m \)th zero of the derivatives of the Bessel function of order \( n \), and \( c \) is the velocity of light in free space.

B. Designing the Basic Antenna

To begin the detection process, we started with a basic design of a microstrip circular patch antenna with a specific dimension to be placed over the breast. The advantages of using a circular patch over the normal rectangular patch are a better bandwidth [29] and the ability to use the design formula to retrace the frequency at which those dimensions of the antenna will operate.

A 60 × 70 mm circular microstrip patch antenna is designed with the FR-4 substrate with a dielectric property of \( \varepsilon_r = 4.3 \). The design can be seen in Fig. 1, and the measurements are shown in Table I.

C. Designing the Antenna

A partial ground technique is used to increase the capacitance between the radiating surface and ground to reduce the radiation of the back lobe [30]. The ground plane width is 58.5 mm. With two side slots of 2.25 mm, and with a rectangular slot of 1 mm length and 10 mm width, the defected ground ensures wide bandwidth and better gain [31]. Additionally, the feedline has been adjusted to 3.1 to ensure impedance matching with 50 ohms. The substrate dimensions of the proposed design are 63 × 72 mm, keeping the FR-4 as the substrate with thickness of 1.6 mm and copper as the radiating surface with thickness of 0.1 mm. The circular patch has the same radius of 18 mm. However, patch antennas have their own limitations, such as small bandwidth and poor gain. In order to achieve better results, we used different slotting techniques, a slot of 14 mm width and 0.5 mm length has been made in the center of the patch, which yields better performance and better gain and bandwidth for this design. The design can be seen in Fig. 2. The dimensions are shown in Table II.

III. THE RESULTS OF THE SIMULATION

A. Return Loss and Voltage Standing Wave Ratio

The basic design shows a good return loss, as seen in Fig. 3. However the voltage standing wave ratio (VSWR) is above 2 as shown in Fig. 4, which indicates a mismatch that will cause a high reflection of the power. This problem must be solved to obtain better bandwidth. Thus, we should have an original approach to achieve better VSWR performance. The proposed technique is discussed in the next sections.

The return loss S11 can be seen in Fig. 5, which shows an ultra-wide-band that ranges from 1.6 GHz to 10 GHz under−10 dB. The VSWR is less than 2 for the whole range of the band, as shown in Fig. 6.
B. Radiation Pattern, Gain, and Directivity

The proposed antenna experiences a gain and directivity of 4.431 dBi and 5.197 dBi, respectively, as shown in Fig. 7 and 8, respectively. Fig. 9 shows the radiation gain and efficiency curves. The radiation pattern at 3.664 GHz is shown in Fig. 10.

IV. BREAST PHANTOM MODEL

In this section, a breast phantom model having 4 mm thickness, seen in Fig. 11, is designed using CST, to simulate the antenna, and the results are observed. In the modeling of the model, proper material has to be chosen, since CST software does not contain those materials in its libraries by default. Therefore, a material definition is provided having the parameters of permittivity, electrical conductance, density, heat capacity, and thermal conductance, listed in Table III, for each layer [32,33]. A tumor is placed at a location having the coordinates of (0, 10, 40) to test our antenna. The tumor has the parameters listed in Table III. Fig. 12 and 13 show the breast phantom along with the tumor.

V. CANCER DETECTION USING SAR

The SAR is a measurement of the absorption of the electromagnetic energy by human tissues when exposed. It is defined as the power absorbed by tissues per mass, its unit of measure is Watts per kilogram. The SAR value can be used for 10 g mass of tissue, the values will be calculated in W/kg at each point in the tissue [33]:

$$\text{SAR}_{\text{local}}(r,\omega) = \frac{\sigma(\omega)|E(r,\omega)|^2}{2\rho(r)}$$ (9)
Calculation of the local SAR value can be made using (10). First, a cube having specific mass is found for each point. The power loss density is then integrated over the cube, and the value in total is divided over the mass of the cube. Calculation of the average SAR value can be made using (10):

\[
\text{SAR}_{\text{average}}(r, \omega) = \frac{1}{V} \int \frac{\sigma(r, \omega) |E(r, \omega)|^2}{2 \rho(r)} \, dr
\]  

(10)

Having the \(\sigma(r, \omega)\) material conductivity [S/m], dielectric material density at \(r\) in [kg/m\(^3\)] as \(\rho(r)\) – mass, \(E(r, \omega)\) the electric field within the tissue [V/m], and the volume is \(V\) [m\(^3\)]

The breast phantom model is placed (20 mm) away from the antenna, which will radiate toward the phantom, and the response is reflected back to the antenna so that the antenna can receive it, as seen in Fig. 14.

The simulation is made for 10 g of mass tissue at 3.664 GHz having the tumor located at the coordinates (0, 10, 40).

The results of the simulation show a maximum SAR value of 0.69, which satisfies the SAR limitation of 1.6 W/kg, which is considered as hazardous for the human body. Thus, the antenna can be used for biomedical applications because the maximum SAR value is less than 1.6 W/kg. The coordinates
Fig. 5. Return loss of the proposed antenna.

Fig. 6. VSWR of the proposed antenna.

Fig. 7. Fairfield directivity output.

Fig. 8. Fairfield gain output.
where the maximum SAR value occurs are (1.085, 9.47273, 32.25) [mm] where \( x = 1.085, y = 9.47273, \) and \( z = 32.25 \) as shown in Table IV.

The tumor was located manually at (0, 10, 40) [mm], where \( x = 0, y = 10, \) and \( z = 40 \) when designing the breast phantom model, which is considered the real tumor location. After the SAR analysis, the location of the tumor is predicted at (1.085, 9.47273, 32.25) [mm], where \( x = 1.085, y = 9.47273, \) and \( z = 32.25 \). This gives a rough idea of the location of the tumor compared with the actual location of the tumor; therefore we can say that it can easily identify the tumor location. The real tumor location and the predicted tumor location can be seen in Fig. 14.

A comparison of several studies has been made in terms of antenna type, bandwidth, gain, and whether the study
addresses cancer detection as intended. As seen in Table V [35-38], in terms of bandwidth, study [34] shows a better bandwidth, while better gain is presented by study [22]. While [35] and [36] have very efficient imaging, their design is more complicated, which increases the (ROS) rate which is the risk of
failure. Our study shows a better detection of cancer using the SAR analysis, with acceptable bandwidth and gain.

VI. CONCLUSION

A 60 × 70 mm microstrip circular patch antenna is designed for the detection of cancer at the early stages, with low cost and high efficiency. In the proposed design, copper is the conductive element used for the radiating surface, and for the defected ground with a circular microstrip patch, an FR-4 substrate has been used with $\varepsilon_r = 4.3$. Return loss analysis shows a bandwidth ranging from 1.6 GHz to 10 GHz under $-10 \text{ dB}$, and VSWR is below two for the entire band, which ensures good

### TABLE IV. SAR RESULTS

| Calculation Results | Power loss density monitor used | Power loss density monitor used | Power loss density monitor used |
|---------------------|---------------------------------|---------------------------------|---------------------------------|
| Power loss density monitor used | Power loss density monitor used | Power loss density monitor used | Power loss density monitor used |
| Power scaling [W]    | None                            | None                            | None                            |
| Stimulated Power [W] | 0.5                             | 0.5                             | 0.5                             |
| Accepted Power [W]   | 0.499823                        | 0.499823                        | 0.499823                        |
| Average cell mass [g]| 2.53793e−05                     | 2.53793e−05                     | 2.53793e−05                     |
| Averaging method     | IEEE/IEC 62704-1                | IEEE/IEC 62704-1                | IEEE/IEC 62704-1                |
| Averaging mass [g]   | 10                              | 10                              | 10                              |
| Entire Volume        | Min ($x, y, z$) [mm]             | Min ($x, y, z$) [mm]             | Min ($x, y, z$) [mm]             |
|                      | −45.1269, −49.6269, −13.7269     | −45.1269, 49.6269, 63.6269       | −45.1269, 49.6269, 63.6269       |
|                      | Max ($x, y, z$) [mm]             | Max ($x, y, z$) [mm]             | Max ($x, y, z$) [mm]             |
|                      | 45.1269, 49.6269, 63.6269        | 45.1269, 49.6269, 63.6269        | 45.1269, 49.6269, 63.6269        |
|                      | Volume [mm³]                     | Volume [mm³]                     | Volume [mm³]                     |
|                      | 692 939                         | 692 939                         | 692 939                         |
|                      | Absorbed power [W]              | Absorbed power [W]              | Absorbed power [W]              |
|                      | 0.07612                         | 0.07612                         | 0.07612                         |
|                      | Tissue volume [mm³]             | Tissue volume [mm³]             | Tissue volume [mm³]             |
|                      | 56 547.9                        | 56 547.9                        | 56 547.9                        |
|                      | Tissue mass [kg]                | Tissue mass [kg]                | Tissue mass [kg]                |
|                      | 0.0555005                       | 0.0555005                       | 0.0555005                       |
|                      | Tissue power [W]                | Tissue power [W]                | Tissue power [W]                |
|                      | 0.0187236                       | 0.0187236                       | 0.0187236                       |
|                      | Average power [W/mm³]           | Average power [W/mm³]           | Average power [W/mm³]           |
|                      | 3.3111e−07                      | 3.3111e−07                      | 3.3111e−07                      |
|                      | Total SAR [W/kg]                | Total SAR [W/kg]                | Total SAR [W/kg]                |
|                      | 0.337359                        | 0.337359                        | 0.337359                        |
|                      | Max. point SAR [W/kg]           | Max. point SAR [W/kg]           | Max. point SAR [W/kg]           |
|                      | 9.67361                         | 9.67361                         | 9.67361                         |
|                      | Maximum SAR (10 g) [W/kg]       | Maximum SAR (10 g) [W/kg]       | Maximum SAR (10 g) [W/kg]       |
|                      | 0.694738                        | 0.694738                        | 0.694738                        |
|                      | Maximum at ($x, y, z$) [mm]     | Maximum at ($x, y, z$) [mm]     | Maximum at ($x, y, z$) [mm]     |
|                      | 1.085, 9.47273, 32.25            | 1.085, 9.47273, 32.25            | 1.085, 9.47273, 32.25            |
|                      | Avg. vol. min ($x, y, z$) [mm]   | Avg. vol. min ($x, y, z$) [mm]   | Avg. vol. min ($x, y, z$) [mm]   |
|                      | −10.2492, −1.86151, 20.9158     | −10.2492, −1.86151, 20.9158     | −10.2492, −1.86151, 20.9158     |
|                      | Avg. vol. max ($x, y, z$) [mm]   | Avg. vol. max ($x, y, z$) [mm]   | Avg. vol. max ($x, y, z$) [mm]   |
|                      | 12.4192, 20.807, 43.5842        | 12.4192, 20.807, 43.5842        | 12.4192, 20.807, 43.5842        |
|                      | Largest valid cube [mm]         | Largest valid cube [mm]         | Largest valid cube [mm]         |
|                      | 22.7176                         | 22.7176                         | 22.7176                         |
|                      | Smallest valid cube [mm]        | Smallest valid cube [mm]        | Smallest valid cube [mm]        |
|                      | 21.9791                         | 21.9791                         | 21.9791                         |
|                      | Avg. vol. accuracy [%]          | Avg. vol. accuracy [%]          | Avg. vol. accuracy [%]          |
|                      | 0.0001                          | 0.0001                          | 0.0001                          |
|                      | Calculation time [s]            | Calculation time [s]            | Calculation time [s]            |
|                      | 38 457                          | 38 457                          | 38 457                          |
reflection efficiency. The breast phantom was created with a tumor located manually at (0, 10, 40) for the SAR analysis. The maximum SAR value is suitable for use in biomedical applications. The SAR maximum is at (1.085, 9.47273, 32.25), which indicates that the SAR value is higher at the location of the tumor cells, which enables the easy detection of cancer cells.

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