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Research Article

# Comparison of Performances of Two Different Antipodal Vivaldi Antennas in Microwave Breast Cancer Detection Systems

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ABSTRACT

In this study, two different antipodal Vivaldi antennas were designed using CST MWS simulation program. The proposed antipodal Vivaldi antennas were designed using 1.6 mm thick FR4 material. The dielectric constant of this material is 4.4 and the loss tangent value is 0.002. The impedance of the feed port is 50 Ω and the copper thickness is 0.035 µm. The compact size of the first antenna is 30 mm x 36 mm, its gain is 5.04 dB and its directivity is 6.48 dB. The size of the second antenna is 38 mm x 33.5 mm, its gain is 7.68 dB and its directivity is 8.77 dB. In the simulation environment, two phantoms were created by placing spherical tumors with two different diameters, each inside a separate heterogeneous breast phantom. Then, the designed antennas in the simulation environment were tested for tumor detection performance on the phantom using the radar-based microwave breast cancer imaging technique (RMWI). After the signal processing stages, tumor images were obtained. In microwave imaging methods, the performance of two different antennas on tumor detection was observed in terms of gain and directivity. In the breast cancer detection study using RMWI technique, the importance of antenna properties such as gain and directivity was emphasized.

## Introduction

Breast cancer is a type of cancer that occurs in 32% of women [1]. It is also the most common cancer in women in approximately 157 countries. The World Health Organization's goal is to reduce global breast cancer deaths by 2.5% per year between 2020 and 2040. This is expected to prevent 2.5 million deaths [2].

Positron emission tomography (PET), ultrasound, mammography and magnetic resonance imaging (MRI) detection are important imaging tools for breast cancer detection [3]. However, imaging techniques have several disadvantages. The MRI imaging technique is not suitable for those with claustrophobia and sensitivity to the contrast materials used, and is a time-consuming, expensive imaging method. The experience of doctors is very important in ultrasound imaging, and the resolution is not good in detecting small masses. Tomography requires experienced physician due to radiation damage and poor resolution. Positron emission tomography imaging has a carcinogenic effect and this method is not suitable for patients with metabolic abnormalities [4].

Normal and malignant tissues in the breast have different electrical properties. Microwave imaging detects tumors by detecting these differences. Microwave imaging is an important alternative to other imaging methods. This system uses electromagnetic waves and the system has no ionizing effect. It uses non-ionizing electromagnetic waves to examine an unknown tumor target based on scattering. Therefore, it has enabled the development of this imaging technique [5].

In microwave imaging, the antenna sends low-power radio-frequency (RF) signals toward the breast and collects the reflected signals. It analyzes the collected signals to reconstruct the image. The antenna used here acts as both a transmitter and a receiver.

RMWI reveals the electrical properties of tissues by solving the inverse scattering problem [6]. The aim of RMWI is to detect objects (tumors) and determine their location. The antenna used as a sensor sends a Gaussian pulse signal to the target (chest). The sum of the reflected signals is the sum of the signals reflected from the tissues in the chest and environmental noise. Using filtering techniques, unwanted parts of the reflected signals are eliminated and the tumor response is obtained [7].

There are many important factors in the RMWI technique. The antenna used in this technique must have features such as bandwidth, directionality (radiance) and gain suitable for microwave imaging. In addition, factors such as the density of the breast tissue used as a phantom in this system, the size of the tumor and signal processing techniques are important. In these systems, antenna types such as resonant, patch, bowtie, monopole, dipole and antipodal Vivaldi are used [8, 9, 10, 11, 12]. Using antipodal Vivaldi antennas in these systems provides various advantages to other antennas [13]. Antipodal Vivaldi antennas used in these systems are good candidates for these systems due to their high performance (gain, directivity, bandwidth, impedance matching etc.) [14, 15, 16, 17, 18]. There are many antipodal Vivaldi antennas designed with different techniques using microwave imaging system for breast cancer detection in the literature [13, 19, 20, 21, 22, 23, 24, 25, 26, 27].

Rubber, polyimide, silicone, polycarbonate and FR4 are used as substrates in antenna designs. FR4 substrate is ideal for the design of antipodal Vivaldi antennas due to the desired bandwidth, impedance matching, stable radiation values, high gain, good directivity, compact size, low cost and easy availability [28, 29, 30].

The directional performance of antipodal Vivaldi antennas can be improved by changing some of their geometrical properties. The antenna geometry was optimized using particle swarm optimization and the gain and directivity of the Vivaldi antenna were increased [22, 31].

With RMWI system, the signals reflected from the target (breast phantom) are the sum of environmental noises and signals reflected from all breast tissues. To obtain the tumor response, other reflected signals need to be filtered [57, 58, 59]. For this purpose, adaptive Wiener filter is an effective filtering algorithm and has been used in studies in the literature [27, 32, 33, 34, 35]. After the filtering algorithm stage, DAS and DMAS are used as reference image generation algorithms for imaging the tumor response [36, 37]. The DMAS imaging algorithm is an extended version of DAS with higher contrast resolution [38, 39]. Due to this advantage, the DMAS algorithm has been used as an ideal algorithm for tumor detection [27, 37].

In the RMWI system, breast phantom tissues, which are target objects, should be designed in accordance with the electrical properties of the real breast. The design of artificial breast phantom tissues according to appropriate electrical properties in simulation and experimental environments has been presented in scientific studies [40, 41]. In order to model these tissues in the CST MWS environment, a design suitable for the electrical properties of real breast tissues was made [42].

**Materials and Methods**

The proposed antipodal Vivaldi antennas are designed using FR4 material with a thickness of 1.6 mm. The dielectric constant of this material is 4.4 and the loss tangent value is 0.002. The feed port has an impedance of 50 Ω and the copper thickness is 0.035 µm. All designs and simulations were made using the CST MWS simulation program.

The exponential form (inner and outer edge taper) equations used in the designs of the antipodal Vivaldi antenna:

$$y = C_1 e^{Rx} + C_2 \quad (1)$$

Here $R$ is the angle ratio, $y$ is the curve and $C_1$ and $C_2$ geometric parameters are calculated in the following equations.

$$C_1 = \frac{y_2 - y_1}{e^{Rx_2} - e^{Rx_1}} \quad (2)$$

$$C_2 = \frac{y_1 e^{Rx_2} - y_2 e^{Rx_1}}{e^{Rx_2} - e^{Rx_1}} \quad (3)$$

The starting points of the curves in the antennas are $y_1$ and $x_1$; the ending points are $y_2$ and $x_2$.

The purpose of particle swarm optimization used in antenna design is to determine the direction of particle movement in the solution space. This optimization technique assumes that the particles should move towards the best positions from the calculated positions. To update the particle positions at each step, they can be stored in an M x N matrix, where M is the number of particles in the simulation and N is the number of dimensions of the problem [43, 44]. In this way, the best particle position can be obtained by performing iteration operations. The best positions are represented by the M x N matrices P = ($P_{ij}$) and G = ($g_{ij}$), respectively.

The position and velocity of the particles are updated at discrete intervals.

$$Vuptaded = Vprevious + C_1 n_1 (P-X) + C_2 n_2 (G-X) \quad (4)$$

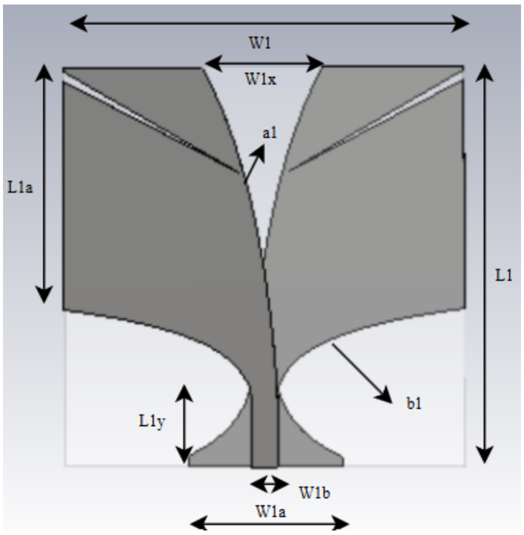
The positions and velocities of the particles are updated at discrete intervals in the range $0 \leq n_{1,2} \leq 1$, $C_1$ and $C_2$ determine the influences on the trajectories of the particle [45]. Finally, the particles move according to the desired best position.

$$Vuptaded = Vprevious + V.\Delta t \quad (5)$$

Where At is either a unit time step.

In 2002, the Federal Communications Commission allowed unlicensed use of the 3.1-10.6 GHz frequency band, thus increasing interest in studies in this area. Using the above equations, antennas were optimized and designed to cover the allowed frequency operating range.

In this study, two different antipodal Vivaldi antennas were designed. The antenna dimensions are 30 mm x 36 mm and 38 mm x 33.5 mm. The antenna designs were carried out using the CST MWS simulation program.

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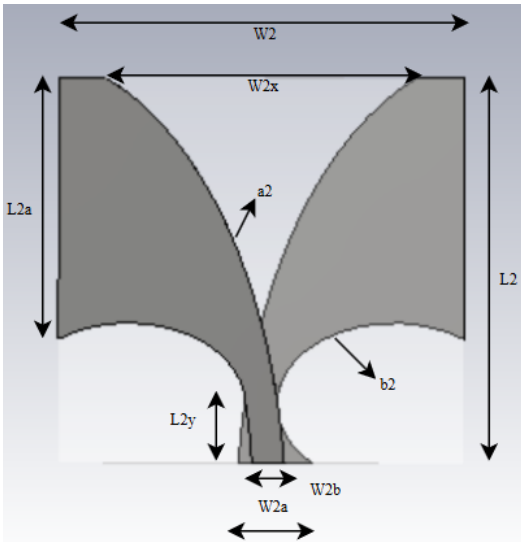



b.

Figure 1. Antipodal Vivaldi antennas configuration: (a) antipodal Vivaldi -1; (b) antipodal Vivaldi-2.

Table 1. Geometric Configurations of Opposite Polarity Antipodal Vivaldi Antennas

| Parameter-1 | Antipodal Vivaldi antenna value (mm)-1 | Parameter-2 | Antipodal Vivaldi antenna value (mm)-2 |
|---|---|---|---|
| W1 (Antenna width) | 30 | W2 (Antenna width) | 38 |
| L1 (Antenna length) | 36 | L2 (Antenna length) | 33.5 |
| W1x (Spacing width) | 10.5 | W2x (Spacing width) | 26 |
| L1y (Flap length) | 22 | L2y (Flap length) | 23 |
| L1a (Port length) | 7 | L2a (Port length) | 6 |
| W1a (Port width) | 14 | W2a (Port width) | 7 |
| W1b (Port width) | 2.4 | W2b (Port width) | 2.6 |
| a1 (Elliptical edge) | 0.3 | a2 (Elliptical edge) | 0.08 |
| b1 (Elliptical edge) | 0.095 | b2 (Circular diameter) | 11.5 |

Two different antipodal Vivaldi antennas were designed as seen in Figure 1. The measurement results of the antennas for the S11 over-frequency are as shown in Figure 2.

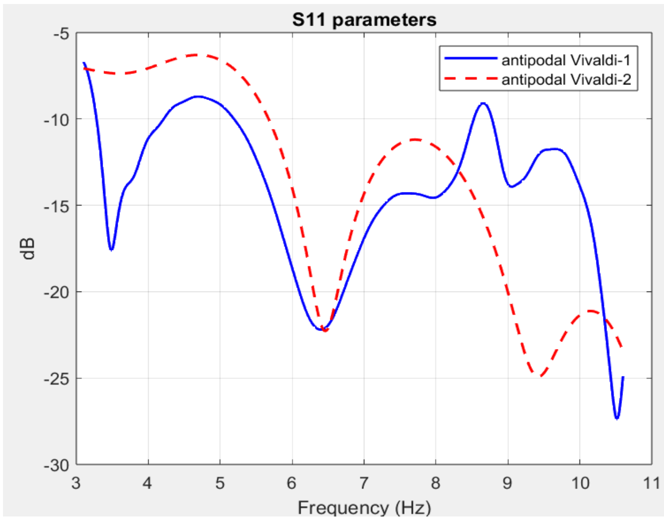
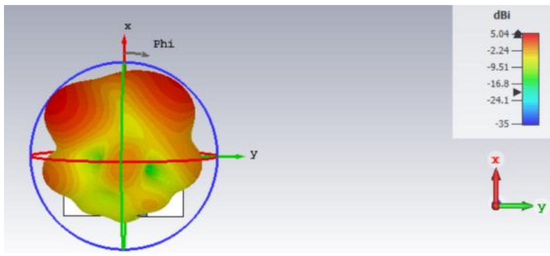



Figure 2. S11 over-frequency parameters: (a) antipodal Vivaldi -1; (b) antipodal Vivaldi -2.

The gain and directivity results of the designed antipodal Vivaldi antennas are shown in Figure 3.

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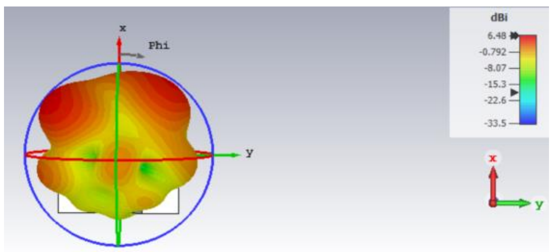


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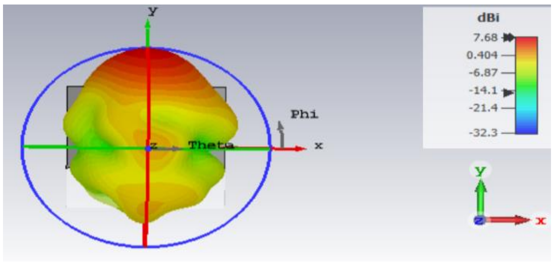


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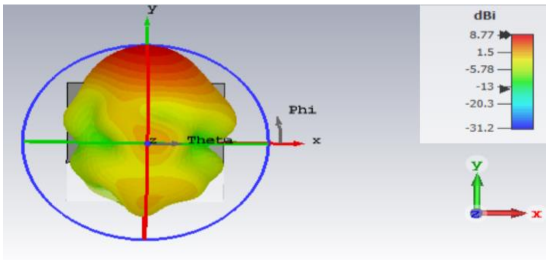



d.

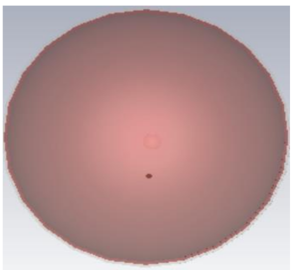
Figure 3. Antenna parameters: (a) gain, antipodal Vivaldi-1; (b) directivity, antipodal Vivaldi-1; (c) gain, antipodal Vivaldi-2; (d) directivity, antipodal Vivaldi-2.

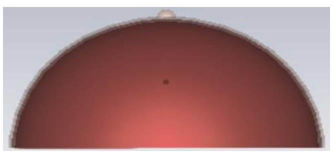
As a result of the operations performed, the first antenna gave the best result at the frequency of 10.3 GHz with a gain of 5.04 dB and a directivity of 6.48 dB; The second antenna gave the best result at the frequency of 10.5 GHz with a gain of 7.68 dB and a directivity of 8.77 dB.

**RMWI System and Imaging in Simulation Environment**

Female breasts have different tissues (fat, glandular, lymph, muscle and nipple etc.). The electrical properties of the tissues are different at microwave frequencies. Tumor detection with RMWI is based on the high contrast between the relative permittivity and conductivity of healthy tissue and cancerous tissue [46].

In the simulation program, two heterogeneous breast phantoms with electrical properties suitable for breast tissues were created. The first phantom was 100 mm in diameter and its interior was covered with fat (36%), glandular tissue (60%) and a 1 mm diameter tumor; its exterior was covered with 2 mm skin tissue and the nipple was added. The other phantom contained a 10 mm diameter tumor and was designed with fat (36%), glandular tissue (42%), 2 mm skin and the nipple. The phantoms created in Figure 4 are shown in the XY and YZ planes and 12 different measurement positions of the antennas around the phantom are shown in Figure 5.





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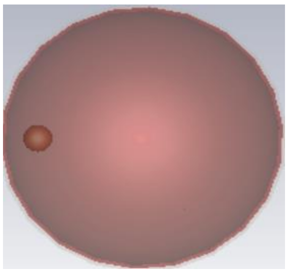
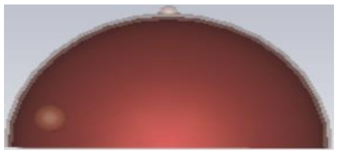




c. d.

Figure 4. CST Heterogeneous breast phantom simulation: (a) XY (1 mm diameter tumor); (b) XZ (1 mm diameter tumor); (c) XY (10 mm diameter tumor); (d) XZ (10 mm diameter tumor).

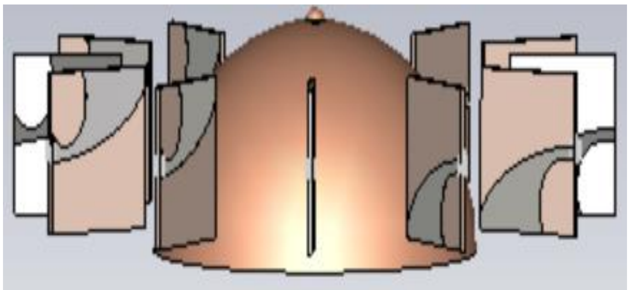


Figure 5. Positioning of antipodal Vivaldi antennas at 12 different points around the phantom.

To detect the tumor in the phantom, a Gaussian signal is sent to the target and the reflected signals are collected. The collected signals are preprocessed to remove artifacts [47]. Then, to find the tumor response, other signals are suppressed and filtered to obtain a low amplitude tumor response.

A RMWI system was developed on CST MWS with antipodal Vivaldi antennas used as a transmitter sending Gaussian pulse signal and a receiver collecting the reflected signals. In this system, antipodal Vivaldi antennas were rotated in twelve different positions around the tumor heterogeneous breast phantom and measurements were made. Calibration process was performed using a tumor-free heterogeneous phantom. The tumor response was found by subtracting the signals reflected from healthy breast tissues from the total signal reflected from the tumorous breast. is the subtraction method stage. The subtraction method is expressed in equation 6:

$$S^{TY} = S^{T} - S^{H} \quad (6)$$

In equation (6); $S^T$ represents the signal in each channel, $S^H$ represents the signal scattered from the tumor-free breast, and $S^{TY}$ represents the tumor response signal obtained as a result of filtering. The image was enhanced using gauss band-pass filtering to eliminate artifact effects [48]. Hilbert transform was used for integration of the incident wave. Thus, the tumor image was obtained.

The envelope of the signal for the tumor response is obtained by the Hilbert transform. This transformation is expressed in Equation 7.

$$H[s(t)] = \frac{1}{\Pi}\int_{-\infty}^{+\infty} \frac{s(r)}{s(t-r)}\, dr \quad (7)$$

$$S_A(t) = s(t) + jh[s(t)] \quad (8)$$

$$S_A(t) = A(t)e^{j\omega(t)} \quad (9)$$

Here $S_A(t)$ is the analytical signal, $s(t)$ is the filtered real signal, $H[s(t)]$ is the complex composition, and Equation 9 shows the time envelope.

Delay-multiply-sum (DMAS) focusing method was used for tumor detection using ultra-wideband confocal technique. In this method, signals reflected back from the simulated target using finite difference time domain method are shifted in time domain, multiplied double and summed to form a focal point. Difference multiplication operation was performed according to DAS. This method is shown in Equation 10.

$$I(r_0)= \int_0^T [\sum_{m=1}^{M-1} \sum_{j=(m+1)}^{M} x_m(r_m(r_0))x_j(r_j(r_0))]^2 dt \quad (10)$$

Here, for each pixel, $\tau_m$ represents the delay time, $x_m$ represents the tumor response, and the energy of the pixel energy at distance r is expressed as $I(r_0)$.

$I(r)$ is the energy of pixels at location $r(x, y, z)$. Here, $v$ is the wave velocity, $\Delta t$ is the time steps, and $d_i$ is the distance between the pixel and the antenna. Time delay (Equation 9), distance (Equation 12), speed of the wave (Equation 11) are shown below respectively.

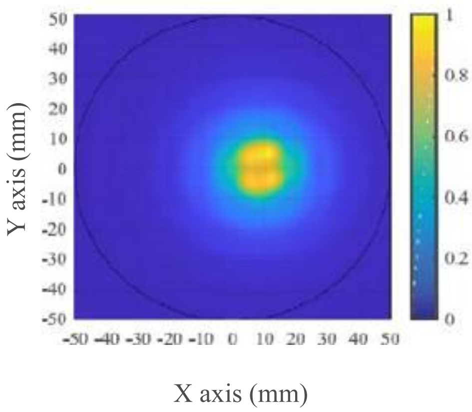
$$r_n(r) = \frac{2}{v\Delta t} d_i \quad (11)$$

$$d_i = \frac{\sqrt{(x-xi)2+(y-yi)2+(z-zi)2}}{v} \quad (12)$$

$$v = \frac{c}{\sqrt{\varepsilon r}} \quad (13)$$

Here, $\varepsilon_r$ represents the relative permittivity of the medium and $c$ represents the speed of light.

In the simulation environment, small spherical tumors with diameters of 1 mm and 10 mm were placed in the heterogeneous breast phantom, as seen in Figure 4. After applying signal processing steps to the heterogeneous and dense breast phantom, images obtained from two different antennas were generated, as seen in Figures 6 and 7.

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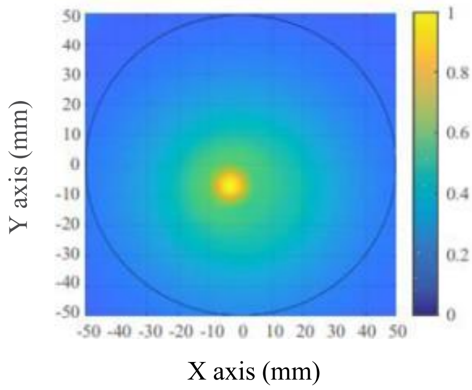


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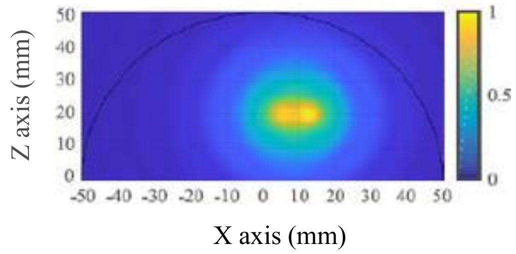


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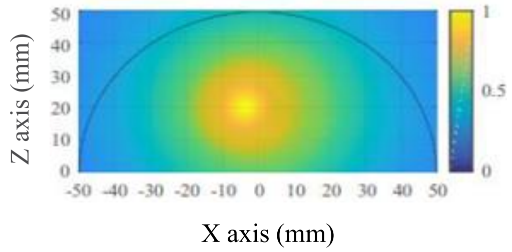
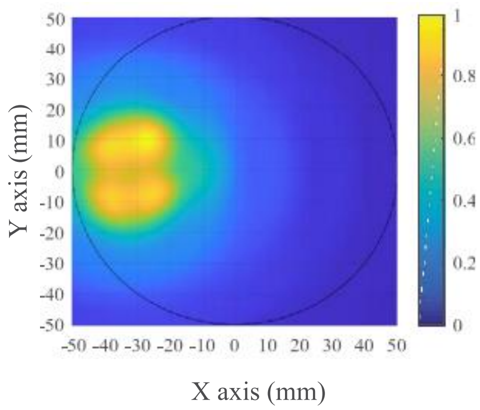



d.

Figure 6. Images of the tumor in the heterogeneous breast model with a diameter of 1 mm in the X-Y and X-Z planes: (a) X-Y, antipodal Vivaldi-1; (b) X-Y, antipodal Vivaldi-2; (c) X-Z, antipodal Vivaldi-1; (d) X-Z, antipodal Vivaldi-2.

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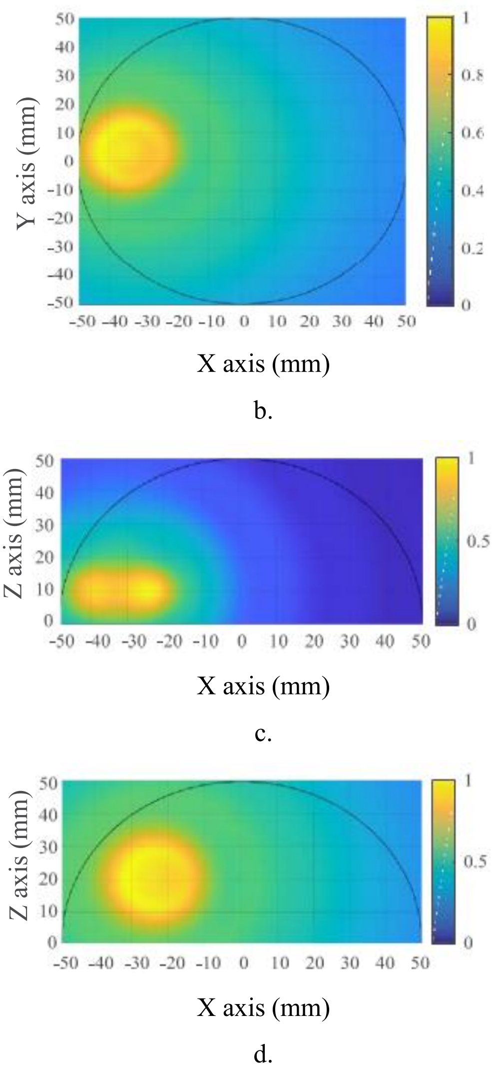


Figure 7. Images of the tumor in the heterogeneous breast model with a diameter of 10 mm in the X-Y and X-Z planes: (a) X-Y, antipodal Vivaldi-1; (b) X-Y, antipodal Vivaldi-2; (c) X-Z, antipodal Vivaldi-1; (d) X-Z, antipodal Vivaldi-2.

The tumor detection performance of two different antipodal vivaldi antennas was compared. In the measurement made with the number one antenna, the tumor image was scattered due to the low focus of the antenna directivity in the tumor image and a double image was obtained. The image of the tumor placed on the created heterogeneous breast model was obtained with a more uniform single-focus image compared to the first antenna due to the high gain and directivity properties of the second antenna. In addition, images close to the tumor location were obtained in the measurements made using two different antennas. However, in the measurements made with the antenna with high gain and directionality, the tumor response was displayed more smoothly and without a scattered focus. This showed us the importance of gain and directionality.

## Conclusions

In this study, two different antipodal vivaldi antennas and heterogeneous breast phantoms containing tumors of different sizes were designed using the CST MWS simulation program. A radar-based system was established for breast cancer detection in the simulation environment. Measurements were made by placing spherical tumors of different diameters into the heterogeneous phantom. The tumor detection performances of the designed antennas were tested on phantoms using the RMWI technique. After the signal processing stages, tumor images were obtained. The effects of the gain and directionality of the antennas on tumor detection in microwave imaging methods were investigated. The importance of antenna performances in this imaging technique was determined. As a result, it was emphasized that the gain and directionality of the antennas are very important in breast cancer detection studies using RMWI technique.

## Ethics committee approval and conflict of interest statement

"There is no need to obtain permission from the ethics committee for the article prepared"

"There is no conflict of interest with any person / institution in the article prepared"

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