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DESIGN AND OPTIMIZATION OF A VIVALDI ANTENNA FOR EARLY CANCER DETECTION: SAR AND CURRENT DENSITY ANALYSIS

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Abstract- Worldwide, breast cancer is a leading cause of death for women and is one of the most prevalent cancers. Early detection is essential to improving survival rates and reducing associated mortality. This paper presents the design and optimization of a Vivaldi antenna, specifically tailored for breast cancer detection. The antenna operates in the FCC-recommended band (3.1 GHz - 10.6 GHz), the antenna was simulated using CSTMWS. The optimized design achieved a resonance frequency of 4.173 GHz, a reflection coefficient (S11) of -68.37 dB, and a VSWR of 1.0007. The SAR analysis revealed a maximum value of 1.385 W/kg for small tumor sizes, adhering to safety standards set by the FCC and the European Union. Additionally, the current density distribution was evaluated, with the highest recorded value reaching 330 A/m². These results confirm that the optimized Vivaldi antenna offers excellent performance, including wide bandwidth, high gain, and effective tumor detection, positioning it as a promising candidate for biomedical applications, particularly for the early detection of breast cancer.

Keywords: Breast Cancer, Early Detection, Microwave Imaging, Vivaldi Antenna, SAR, Current Density, Biomedical Applications.

1. INTRODUCTION

The majority of deaths among women worldwide is caused by breast cancer, which is one of the most common cancers. Detecting breast cancer at an early stage is crucial to improve survival chances and reduce associated mortality [1-3]. Current screening methods, such as mammography and MRI, have certain limitations. Although mammography is effective, it suffers from high rates of false positives and false negatives, particularly in women with dense breast tissue. Additionally, it can cause discomfort due to the compression of breast tissue and exposes patients to radiation. MRI, on the other hand, is expensive, less accessible, and often requires the injection of contrast agents.

Microwave-based technologies offer a promising, non-invasive alternative for the early detection of breast tumors. They rely on the differences in dielectric properties between healthy and cancerous tissues, allowing for the early localization of anomalies [4, 5]. Among the various antenna configurations used in these systems, the Vivaldi antenna stands out for its advantages. It offers a wide bandwidth, low reflection, good directivity, and efficient impedance matching, making it ideal for breast cancer detection [6, 7]. Compared to other techniques, such as patch antennas [4, 5] or dipole antennas [8], the Vivaldi antenna demonstrates superior performance in terms of accuracy and tissue penetration, while maintaining optimal electromagnetic safety.

The proposed design in this study aims to optimize a Vivaldi antenna for the early detection of breast tumors [6, 9], ensuring compliance with safety standards related to electromagnetic field exposure. The SAR is a key parameter in evaluating the safety of medical devices that use electromagnetic fields. It measures the amount of radiofrequency energy absorbed by biological tissues, expressed in [W/kg]. Monitoring SAR is essential to ensure user safety and to prevent undesirable biological effects [10, 11]. The FCC imposes strict SAR limits to guarantee public safety [1], [12-14].

In addition to SAR, current density is another crucial factor in evaluating electromagnetic safety and performance [18]. It represents the amount of electric current flowing through a unit area of tissue cross-section. Accurate monitoring of current density ensures that electromagnetic fields do not cause harmful effects on biological tissues [15]. This study presents the design and optimization of a Vivaldi antenna for early breast cancer detection. It analyzes the distribution of SAR, current density, and the dielectric properties of various biological layers of the breast. The results show that the proposed antenna offers excellent performance in terms of low reflection, wide bandwidth, and effective tumor detection, while complying with safety standards.

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2. ELECTROMAGNETIC INTERACTION WITH BIOLOGICAL TISSUES: SAR, CURRENT DENSITY, AND VIVALDI ANTENNA THEORY

2.1. SAR

The SAR measures the amount of radiofrequency energy absorbed by body tissues when exposed to electromagnetic fields. The rate of energy absorption per unit mass of tissue over time is quantified. SAR is calculated using Equation (1) [16]:

$$SAR = \frac{dW}{dt \times dm} = \frac{\sigma E^2}{\rho} \tag{1}$$

The SAR is a crucial indicator for assessing human tissue exposure to magnetic fields, particularly in the context of medical devices and Wireless communication equipment. Proper monitoring of SAR is essential to ensure user safety and to avoid undesirable biological effects such as tissue heating [11, 12].

The FCC enforces strict SAR limits to ensure public safety, capping it at 1.6 W/kg for 1 gram of tissue. In contrast The EU establishes a restriction of 2 W/kg that is averaged over 10 grams of tissue. For whole-body exposure, the allowable SAR is limited to 0.08 W/kg. These regulations are designed to minimize thermal risks and other potential biological effects associated with prolonged exposure to magnetic fields [13].

2.2. Current Density in Biological Tissues

The current density of a material is defined as the electric current flowing per unit area of cross-section. It is expressed in [A/m²]. Current density is a fundamental concept in electromagnetism and electrical engineering [17], particularly in analyzing the electrical properties of materials, including biological tissues [14], [18]. Current density is calculated using Equation (2):

$$J = \sigma E \tag{2}$$

2.3. Theory Of Vivaldi Antennas

Vivaldi antennas are designed based on electromagnetic principles, allowing them to operate efficiently across a wide frequency range. The shape of the exponentially tapered slot is described by Equation (3) [9], [19]:

$$Y(x) = \pm y_0 e^{\alpha x} \tag{3}$$

where, $Y(x)$ is the slot width at position x along the slot, y_0 is the initial slot width, and α is the exponential taper constant, determined based on the desired bandwidth and antenna characteristics

3. CONFIGURATION ANTENNA

3.1. Antenna Structure Description

The geometric configuration of the PVA used for breast cancer detection is illustrated in Figure 1. The geometric configuration of the PVA for breast cancer detection is shown in Figure 1. Fabricated on an FR4 substrate a permittivity of 4.3, the antenna has dimensions of 96.5×51.5 mm². The final dimensions, optimized using CSTMWS, are detailed in Table 1.

The Vivaldi antenna consists of a microstrip feed line and an exponentially tapered radiating structure. On one side of the antenna substrate, the slot has an exponentially tapered shape, with one end forming a circular cavity and the other left open.

The cavity functions as an open circuit, effectively minimizing reflections during the transition from the microstrip line to the slot line. The shape of the taper and the cavity determines the main characteristics of the antenna. To feed the Vivaldi antenna, a transition from the microstrip line to the slot line is designed, ensuring impedance matching over a wide frequency range, as illustrated in Figure 1. In our application, the exponentially tapered slot of the PVA can be defined by Equation (4). We use $y_0 = \frac{w_s}{2}$ and $\alpha = \frac{ft}{10^3}$. Therefore, the exponential curve equation becomes:

$$Y(x) = \pm \frac{w_s}{2} e^{\frac{ft*x}{1000}} \tag{4}$$

for $0 \le x \le L_2$.

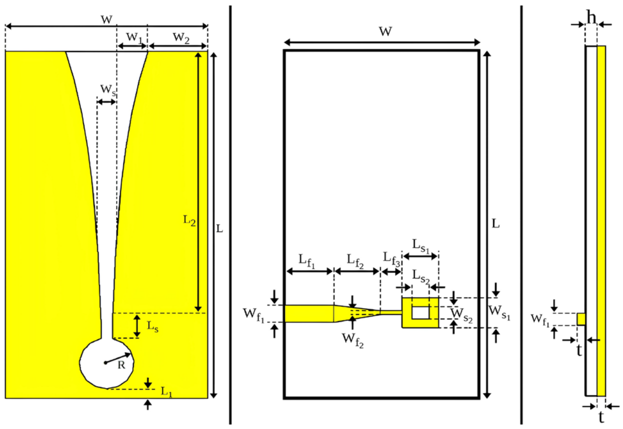


Figure 1. Geometry of the PVA: Top, bottom and side views

Table 1. Dimension of the PVA

Parameter	Dimension (mm)	Parameter	Dimension (mm)
L	96.5	L_g	18.71
W	51.5	L_{f1}	11.01
f_t	31	L_{f2}	10.32
W_1	9.54	L_{f3}	4.91
W_2	15.71	W_{f1}	3.04
W_s	0.99	W_{f2}	0.76
L_1	2.5	L_{s1}	3
L_s	0.76	W_{s1}	3.84
L_2	76	L_{s2}	0.9
R	8	W_{s2}	1.6
tangent	0.0035	h	1.57

3.2. Performance of the Antenna

3.2.1. Reflection Coefficient Analysis of the PVA

Figure 2 shows the reflection coefficient of the PVA, which shows a measured bandwidth at -10 dB ranging from 3.87 GHz to 4.49 GHz with a bandwidth of 0.617 GHz. The resonance frequency is located at 4.173 GHz with a reflection coefficient of -68.37 dB. These results indicate that the antenna offers excellent performance in terms of low reflection and wide bandwidth, making it ideal for breast cancer detection applications.

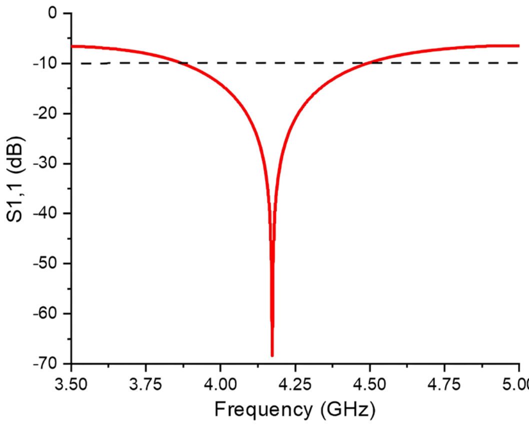


Figure 2. Reflection coefficient (S_{11}) of the proposed antenna

3.2.2. Visor Analysis of the PVA

The Figure 3 illustrates the VSWR characteristic of the PVA. This characteristic shows that the operating band has a minimum VSWR of about 1.0007, very close to the ideal value of 1, and remains below 2. Additionally, the antenna has been qualified with a VSWR below 2 over the operational frequency range of 3.85 GHz to 4.51 GHz.

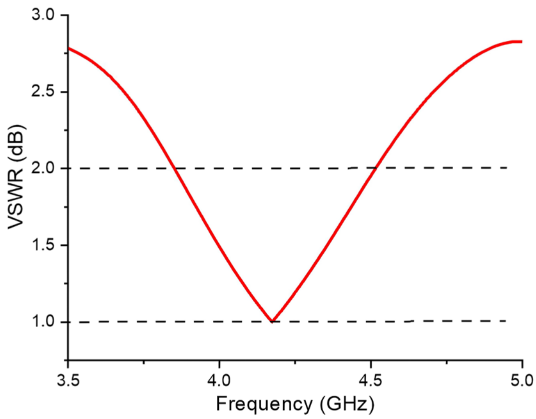


Figure 3. VSWR characteristic of the PVA

3.2.3. Maximum Gain Analysis of the PVA

The Figure 4 illustrates the variation of the maximum gain of the antenna as a function of frequency. It is observed that the antenna gain starts slightly above 5.07 dB at a frequency of 3.87 GHz, representing the minimum gain point. As the frequency increases, the antenna gain gradually increases and reaches a maximum of about 6.06 dB at 4.48 GHz. This trend indicates that the antenna's performance improves with increasing frequency in the range of 3.87 GHz to 4.49 GHz.

3.2.4. Radiation Pattern Analysis of the PVA

The Figure 5 presents the radiation pattern of the PVA in the H-plane and the E-plane have φ =90° and 0°, respectively. The radiation pattern in polarization shows that the antenna has a marked directivity in the H-plane with a maximum gain of about 10 dB. The main and side lobes indicate varied directional performance, essential for understanding the antenna's behavior in different applications. Knowledge of the lobes and nulls is crucial for optimal positioning and orientation of the antenna in practical systems.

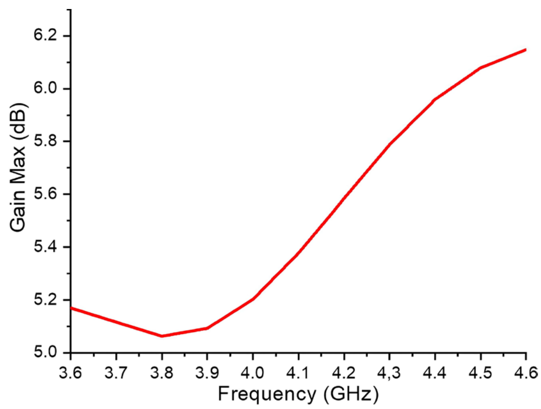


Figure 4. Maximum gain of the PVA

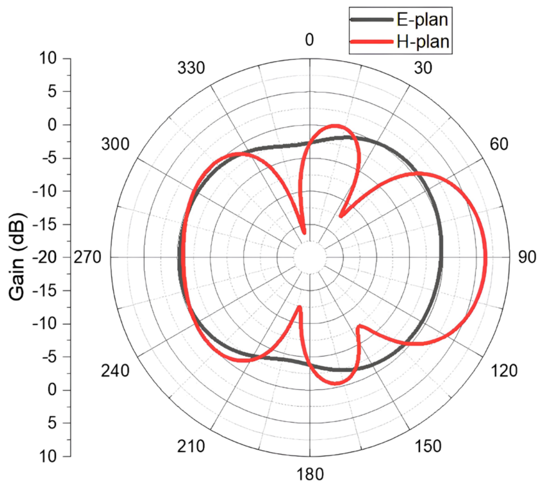


Figure 5. The PVA's radiation pattern in the H-Plane and E-Plane

The 3D radiation pattern reveals that the antenna has significant directivity with a maximum gain of 6.44 dBi. The color variations show how the gain changes in different directions, with a strong concentration around the Y-axis. This information is crucial for understanding how to orient the antenna for optimal performance in practical applications, maximizing gain in desired directions.

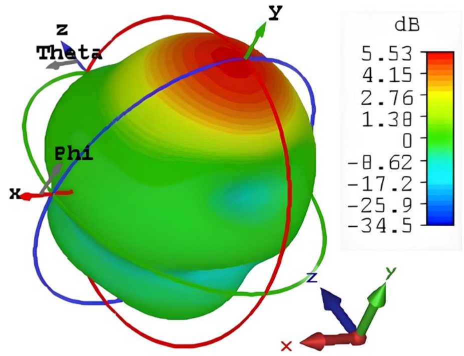


Figure 6. 3D radiation pattern of PVA

Table 2. Dimension of proposed patch antenna

Ref.	BW [GHz]	RF [GHz]	Return Loss [dB]	Gain [dB]	Dimensions [mm^3]
[7]	2.5-8.5	-	-	8.5	63×51×1
[20]	0.5-4.5	1.4, 2.5, 3.7	-	7	75× 5×1
[21]	2.5-11	-	-	7.2	40×40×1.6
[22]	5 -12	-	-	12.27	157.4×104.9×0.787
PVA	3.87-4.49	4.173	-68.37	6.44	96.5×51.5×1.57

4. MODELING BREAST LAYERS AND TUMOR IMPACT ON SAR DISTRIBUTION AND CURRENT DENSITY

4.1. Modeling and Dielectric Properties of Breast Biological Layers

To analyze the impact of the Vivaldi antenna on breast tissues, an elliptical breast model was used. The model is characterized by its height of 50 mm, a main axis of 100 mm, and a minor axis of 60 mm (representing a semi-spherical breast). It includes several layers representing the skin, fat, mammary gland, and tumors. The model is designed to accurately replicate the anatomical structure of the breast, allowing for precise simulations of electromagnetic interactions.

4.1.1. Dielectric Properties of Different Biological Layers

The dielectric properties of various biological layers used in simulations are crucial for modeling the propagation of electromagnetic waves. The following values have been adopted for each layer:
- Skin: Dielectric permittivity of 39, conductivity of 1.1 [S/m]. The average density of the skin is about 1100 [kg/m³] [17].
- Adipose Tissue (Fat): Dielectric permittivity of 5.3, conductivity of 0.1 [S/m]. Density about 920 [kg/m³] [23].
- Mammary Gland: Dielectric permittivity of 9, conductivity of 0.4 [S/m]. Density about 1040 [kg/m³] [24].
- Tumor: Dielectric permittivity of 50, conductivity de 4 [S/m], Density between 1000 [kg/m³] to 1200 [kg/m³] [17], [23].

These properties enable accurate simulation of how electromagnetic waves interact with the various tissue layers of the breast.

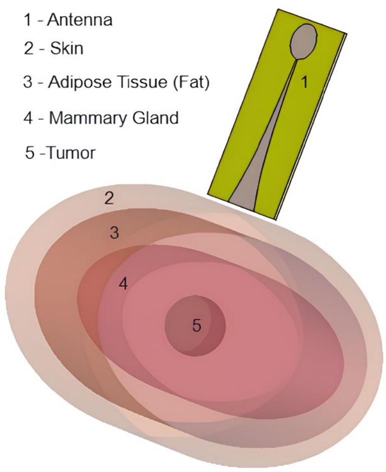


Figure 7. The breast model with tumors

The breast model used includes a tumor modeled as spheres with a radius of 5 mm, placed at a well-defined distance from the Vivaldi antenna. The tumor is integrated into the model to evaluate the effect of its size and position on the distribution of the SAR and current density.

4.2. Impact of Tumor Size and Position on SAR Distribution

In the context of early breast cancer detection using radar systems, it is crucial to understand how antenna characteristics and biological tissue properties influence the absorption of electromagnetic waves. A key metric in this analysis is the SAR, which measures the electromagnetic energy absorbed per unit mass of body tissue. This section examines several aspects of SAR variation, including tumor radius, distance between the antenna and the tumor, and the relationship between antenna-breast distance and maximum SAR. Simulation results at a frequency of 4.173 GHz are presented to illustrate how these variables influence SAR and, consequently, the effectiveness and safety of the detection system.

4.2.1. SAR Analysis as a Function of Tumor Radius Variation

The Figure 8 shows the variation of maximum SAR (W/kg) as a function of tumor radius *R* (mm). The curve indicates an overall decrease in maximum SAR as the tumor radius increases, with small tumors (radius close to 0 mm) having a high SAR around 1.385 W/kg. As the tumor radius increases to about 6 mm, the SAR decreases rapidly, then this decrease becomes slower beyond 6 mm, reaching about 1.33 W/kg at 20 mm. The larger the tumor radius, the lower the measured maximum SAR, likely because the electromagnetic waves spread over a larger surface of the tumor, thus reducing the intensity absorbed per unit mass.

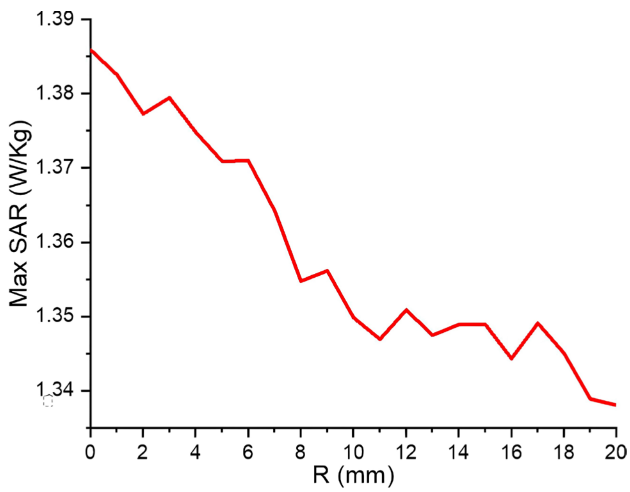


Figure 8. Variation of maximum SAR as a function of tumor radius

4.2.2. SAR Analysis as a Function of Antenna-Tumor Distance Variation

Figure 9 illustrates the variation of maximum SAR depending on the distance between the antenna and the tumor. The curve indicates an overall decrease in maximum SAR as the distance increases, with short distances (close to 20 mm) having a high SAR around 1.37 W/kg. As the distance increases, the SAR shows fluctuations but decreases overall, reaching about 1.345 W/kg at 30 mm.

These fluctuations may be due to variations in the electromagnetic energy absorption by tissues at different distances and resonance effects. Despite this, the general trend is a decrease in SAR with increasing distance, indicating that the intensity of electromagnetic waves absorbed per unit mass of tissues decreases as the distance increases.

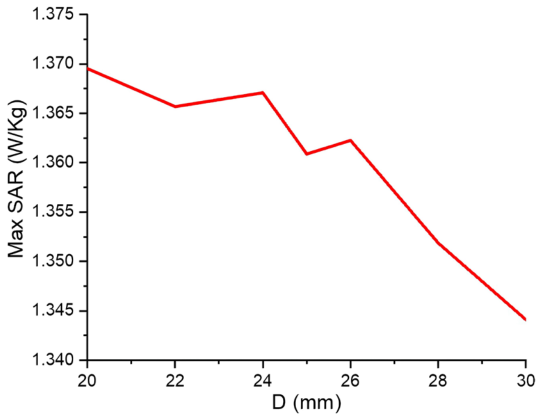
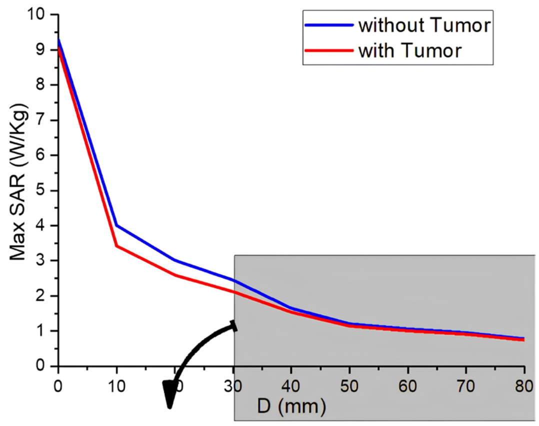


Figure 9. Variation of maximum SAR as a function of antenna-tumor distance

4.2.3. SAR Analysis as a Function of Antenna-Breast Distance with and without Tumor

The Figure 10 shows the variation of maximum SAR (W/kg) as a function of the distance *D*, comparing the results with and without a tumor. The curves indicate an overall decrease in maximum SAR as the distance increases, with high values close to 9 W/kg at short distances (0 mm). As the distance increases, the SAR decreases rapidly, then more slowly beyond 20 mm. The presence of the tumor seems to slightly reduce the maximum SAR at short and medium distances, probably due to the absorption and scattering of electromagnetic waves by the tumor. This difference becomes less significant at larger distances, with both curves converging to similar values: 0.77 W/kg in the absence of a tumor and 0.7 W/kg in the presence of a tumor. These observations show that the measurement point and the antenna's distance strongly influence SAR, and the presence of the tumor modifies the SAR distribution, especially at short distances.



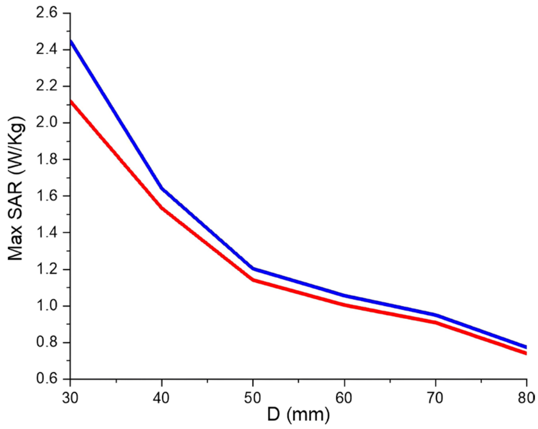


Figure 10. Variation of maximum SAR as a function of distance with and without tumor

4.3. Analysis of Current Density Distribution in Vivaldi Antenna for Breast Cancer Detection

4.3.1. Current Density Distribution as a Function of Tumor Radius for Vivaldi Antenna Applications

The Figure 11 shows a graph of current density (A/m²) as a function of Tumor radius, indicating a significant decrease in current density from approximately 330 A/m² at the center (*R* = 1 mm) to about 203 A/m² at 10 mm, after which it stabilizes with slight fluctuations up to 11 mm. This rapid initial decrease indicates a high concentration of current at the center, dispersing quickly outward. The stabilization around 203 A/m² between 10 mm and 11 mm suggests a uniform distribution of current in this region, which is crucial for minimizing hotspots and ensuring safety in medical applications such as the Vivaldi antenna for breast cancer detection. The slight increase beyond 11 mm may be due to edge effects or variations in material properties, highlighting the importance of monitoring current density to comply with safety standards and optimize device performance.

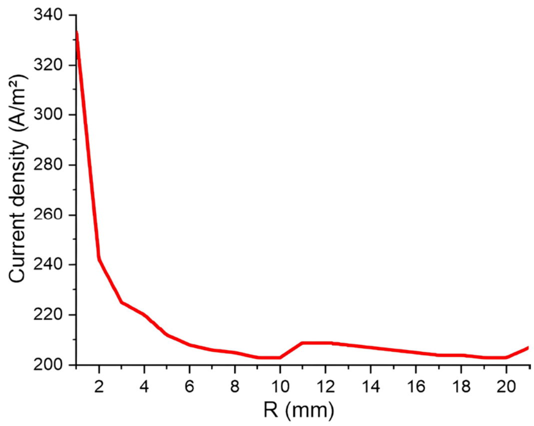


Figure 11. Current density distribution as a function of tumor radius indication

4.3.2. Impact of Distance Between Tumor and Antenna on Current Density

The provided Figure 12 shows a graph of current density as a function of the distance between the tumor and the fixed position of the antenna, indicating stability at around 212 A/m² over the entire range from 20 mm to 90 mm. This consistency suggests that changing the distance does not significantly affect the current density, ensuring a stable distribution despite minor adjustments. This is crucial for medical applications, such as the Vivaldi antenna for breast cancer detection, guaranteeing reliable performance and compliance with safety standards while allowing for effective tumor detection.

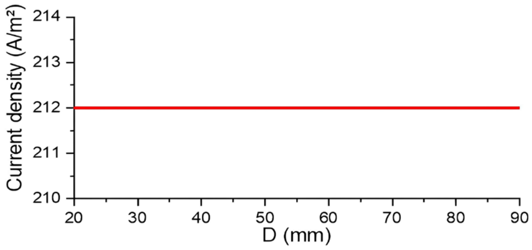


Figure 12. Impact of distance between tumor and antenna on current density distribution

4.3.3. Analysis of Current Density Distribution as a Function of Distance Between Breast and Antenna for Various Tumor

The Figure 13 shows a graph of current density (A/m²) as a function of the distance between the breast and the antenna position for different tumor radius. For $R = 1$ mm, the current density starts around 340 A/m² and fluctuates significantly between 300 A/m² and 370 A/m², indicating high variability. For $R = 3$ mm, the current density is more stable, varying between 200 A/m² and 270 A/m² with less pronounced fluctuations. The curve for $R = 5$ mm shows smoother variations between 200 A/m² and 250 A/m². The most stable and lowest current densities are observed for $R = 10$ mm, fluctuating slightly between 180 A/m² and 230 A/m². It is observed that the current density reaches a maximum value at $D = 35$ mm and a minimum value at $D = 15$ mm for all tumor Radius. This trend suggests that there are specific positions of the antenna relative to the tumor that maximize or minimize the current density. These variations could be due to constructive or destructive interferences of the electromagnetic waves at these particular distances.

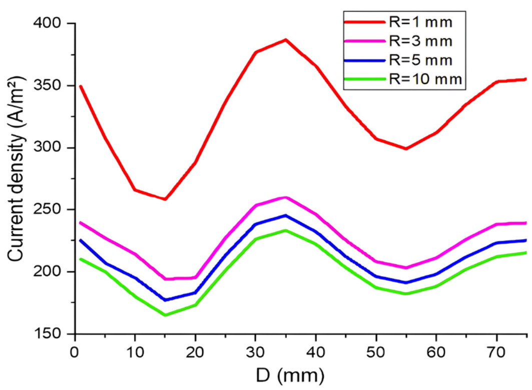


Figure 13. Current density distribution as a function of distance for various tumor sizes (R)

5. CONCLUSIONS

In conclusion, the PVA presented in this study, with its low reflection losses, excellent VSWR, high gain, and optimized radiation pattern, proves to be an ideal solution for early breast cancer detection. It ensures reliable and efficient performance, minimizing risks while maximizing detection quality. The analyses of SAR and current density distribution as functions of tumor radius, antenna-tumor distance, and antenna-breast distance at a fixed simulation frequency of 4.173 GHz provide valuable insights for optimizing the antenna in medical applications. The SAR analysis shows that the antenna's radiation exposure remains within acceptable limits, decreasing as the tumor size increases and as the distance between the antenna and the tumor grows, ensuring compliance with FCC safety standards. The current density distribution reveals consistent performance across various tumor sizes and distances, confirming the antenna's reliability for practical medical applications.

The PVA offers significant advantages for biomedical applications by providing an excellent balance between performance and safety. This design enables effective tumor detection while reducing risks to human tissues. Future work should focus on experimental validation, antenna fabrication, and testing with tissue-mimicking phantoms to ensure consistency with simulations. Exploring Vivaldi antenna arrays and integrating them with advanced imaging systems could further enhance detection capabilities and resolution, contributing to the advancement of medical diagnostic technologies.

Perspectives for future work: In order to overcome these limitations, experimental tests must be carried out to validate the results obtained in simulation, using tissue phantoms simulating the properties of human tissues. Additionally, the integration of Vivaldi antenna arrays could improve resolution and detection capabilities. Finally, the association of this antenna with advanced imaging systems, such as microwave tomography, could offer even more efficient solutions for the early diagnosis of breast cancer.

NOMENCLATURES

1. Acronyms

PVA: Proposed Vivaldi Antenna
SAR: Specific Absorption Rate
FCC: The Federal Communications Commission
MRI: Magnetic Resonance Imaging
RF: Radiofrequency
CSTMWS: Computer, Simulation, Technology' Microwave, Studio
VSWR: Voltage Standing Wave Ratio
BW: Bandwidth
RF: Resonance frequency
D: Distance

2. Symbols / Parameters

Kg: Kilogram
A: Amperes
m: Meter

W: Watts
J: Current density
σ: Electrical-conductivity
ρ: the-tissue-mass-density
E: Electric-field

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