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Early Detection of Breast Tumour Using Quasi-Static Microwave Imaging with Two Elements Tapered Slot Vivaldi MIMO Antenna

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***Abstract:** A quad-static microwave imaging system designed for medical use, with an emphasis on early-stage breast tumour detection, is presented in this paper. A compact two-element MIMO Vivaldi antenna, designed for practical microwave imaging, is used in the proposed system. The antenna is appropriate for radar-based diagnostic systems due to its end-fire radiation characteristic. With a maximum gain of 16.98 dBi at 2.75 GHz, it operates across a broad frequency range from 2 GHz to 14.8 GHz. Additionally, it satisfies the FCC (USA) limit for localized SAR, which is 1.6 W/kg averaged over 1 gram of tissue. With overall dimensions of 49 × 85 × 0.8 mm³, the antenna is designed and simulated on an affordable FR4 substrate that offers both structural compactness and a wide bandwidth. For validation, HFSS was used to create and simulate a breast phantom model that replicated the dielectric characteristics of human tissue. When the transmission coefficient (S21 and S41 parameters) is used to analyse the system, it is shown that tumours as small as 4 mm in diameter can be detected. The findings support the suggested antenna and imaging system's ability to accurately detect small breast tumours, potentially leading to earlier diagnosis and better treatment outcomes.*

***Keywords:** Microwave Imaging, Vivaldi Antenna, Breast Tumour Detection, SAR Analysis, Ultrawideband (UWB).*

Nomenclature:
UWB: Ultra-Wideband
SAR: Specific Absorption Rate
TSVA: Tapered Slot Vivaldi Antenna

I. INTRODUCTION

Breast cancer remains one of the leading causes of cancer-related mortality among women worldwide. It is currently estimated that there were more than 2.3 million cases of breast cancer diagnosed in 2022 [1] that continues to grow each year, attesting to the continuing global problem, as well as the ongoing need for better development in early detection methods. The most significant prognostic indicator for patient outcomes and survival rates is the detection of cancer at the earliest disease stage, and therefore, it is important to use advanced acceptable imaging methods.

Traditional diagnostic methods, such as mammograms, MRI, and PET scans, have been the primary diagnostic methods associated with breast cancer. "Despite the effectiveness of these imaging techniques, they pose numerous problems: mammograms utilise ionising radiation, while MRIs are advised against for high-risk populations, such as pregnant women. The disadvantage of both the mammogram and MRI is that they may cause discomfort, incur high costs, and sometimes result in a false-positive or false-negative diagnosis, which causes anxiety or inappropriate treatment.

Microwave imaging represents an emerging modality for breast cancer detection due to the favourable safety profile associated with an absence of ionizing radiation [2], [3]. The exposure levels associated with the type of microwave imaging used in this study are similar to everyday RF exposure from cellular telephones and Wi-Fi devices, making it a safe option for patients. In addition to safety, it is an economical, non-invasive, and comfortable alternative to other modalities, addressing many of the limitations of traditional imaging. It has been reported that ultra-wideband (UWB) frequencies represent an appropriate balance of needed tissue penetration depth and image quality to detect evidence of breast tumours [4]. Microwave imaging systems in the literature are typically categorized as active, passive, or hybrid methods [5]. This study employs active, radar-based microwave imaging, in which a transmitting antenna transmits focused pulses of microwave energy into the breast tissue, and a receiving antenna detects the energy that returns after interacting with the tissue. Computational algorithms are applied to the returned energy signals to reconstruct internal structures and detect anomalies.

The difference in dielectric properties between malignant and healthy tissues, resulting from their varying water content, enables tumour detection. Tumour cells typically retain higher water levels, resulting in elevated dielectric values compared to normal tissue [6].

The antenna is essential for efficient radar-based microwave imaging. For precise tumour detection, the antenna needs to be small, wide-band, high-gain, and directional. These features have been documented for several UWB antenna designs, such as tapered slot, horn, stacked patch, dielectric resonator, antipodal, and

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printed monopole designs [7], [8], [9], [10].

Different antenna configurations can be implemented in microwave imaging systems, namely monostatic, bistatic, and multistatic. In a monostatic configuration, a single antenna is used for both transmission and reception. A bistatic configuration employs separate transmit and receive antennas, thereby simplifying system design and reducing mutual coupling. In a quasi-static configuration, the number of transmitting and receiving antennas is equal, but each antenna switches roles over time. Multistatic configurations consist of a single transmitting antenna and multiple receiving antennas, enabling more complex imaging but at the cost of greater system complexity. In this work, a quasi-static configuration is adopted to balance system simplicity and imaging reliability. [11], [12], [13].

II. ANTENNA DESIGN

The proposed antenna's structure is illustrated in Fig. 1. It is constructed on an FR4 substrate with a thickness of 0.8 mm, a dielectric constant of 4.4, and a loss tangent of 0.02. The radiating element features an exponentially tapered slot, which facilitates end-fire radiation. While the width of the flare's opening controls the lower frequency limit, the minimum gap width in the taper largely determines the antenna's upper operating frequency. Furthermore, the dimensions and form of the slot are crucial in determining the radiation properties and general pattern of the antenna [15], [16].

The flare profile of the tapered slot can be expressed mathematically as follows:

$$y = a_1 e^{Rz} + a_2$$

were

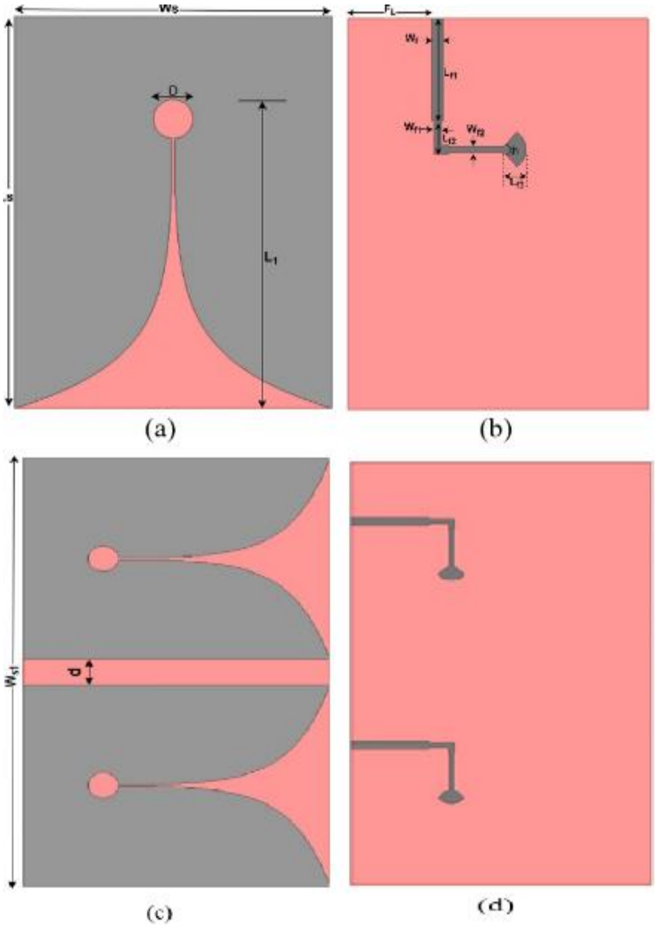
- The transverse dimension of the flare at longitudinal position z is denoted by y.
- R stands for the exponential opening rate, which regulates the slot's expansion rate.
- Boundary conditions at the beginning and ending points of the taper determine the constants a_1 and a_2, which are computed as follows:

$$a_1 = \frac{y_2 - y_1}{e^{Rz_2} - e^{Rz_1}}, a_2 = y_1 - c_1 e^{Rz_1}$$

The optimized geometric parameters of the antenna are summarized in Table I.

Table I: Parameters of the Antenna

Parameter	Dimension(mm)	Parameter	Dimension(mm)
Ws	40	Lf1	13
Ls	48	Lf2	4.2
L1	39	Lf3	7.3
Ws1	85	Wf	1.75
D	5	Wf1	1.02
FL	11.35	Wf2	0.73
θ(angle)	30°		



[Fig.1: Simulated Antenna Designing (a) Single Element Front View (b) Single Element Back View (c) Two Element MIMO Front View (d) Back View]

III. BREAST PHANTOM MODEL DESIGNING

To precisely depict the anatomical structure of the human breast, a breast phantom model was created. The three main tissue layers that make up the breast are fibrous, fatty, and skin tissue. Individual differences in the proportions of these layers were mirrored in the phantom design by allocating dielectric characteristics to each tissue type [14].

The skin and fat layers are meticulously modelled to have thicknesses of 4 mm and 5 mm, respectively, and the phantom has a radius of 30 mm. Table II displays the phantom model's characteristics. The phantom has been built and simulated to investigate microwave interactions in HFSS. The accompanying figure shows comparative simulation results for scenarios with and without a tumour inclusion.

Table II: Properties of Breast Phantom Model

Layer	Radius (mm)	Dielectric Constant
Skin	30	2.6
Fat	26	2.37
Fibro	21	23
Tumour	5	62

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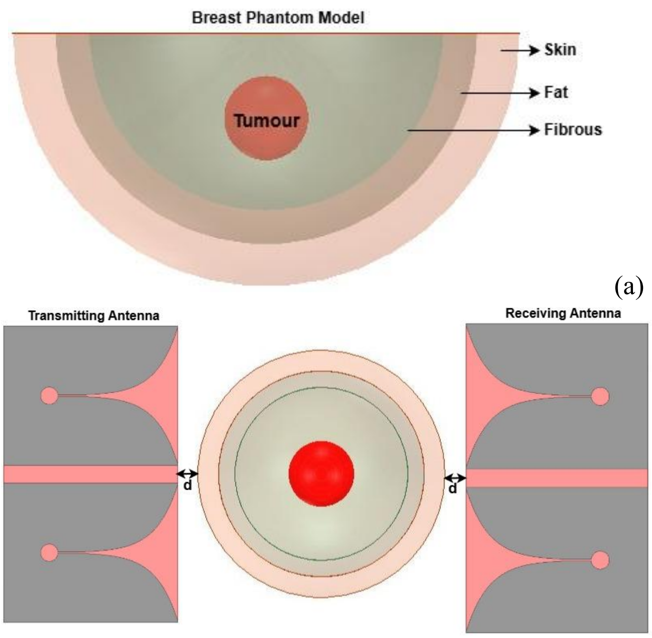


(b)

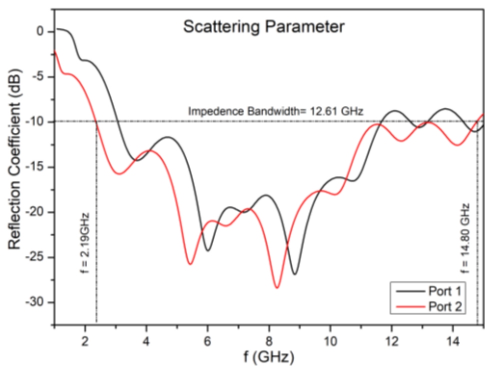
[Fig.2: (a) Breast Phantom model (b) Model with Transmitting and Receiving Antenna]

IV. SIMULATED RESULTS AND DISCUSSION

In this section, the simulated performance characteristics of the designed antenna system are presented. To determine whether an antenna is suitable for imaging applications, essential parameters, including the transmission coefficient, antenna gain, reflection coefficient, and specific absorption rate (SAR), have been assessed. While the results of the gain and transmission coefficients show radiation efficiency and signal propagation, the reflection coefficient results confirm impedance matching. Furthermore, SAR analysis ensures that the antenna meets safety standards for human exposure. All of the results support the practical viability and design efficacy of the antenna.

A. Reflection Coefficient

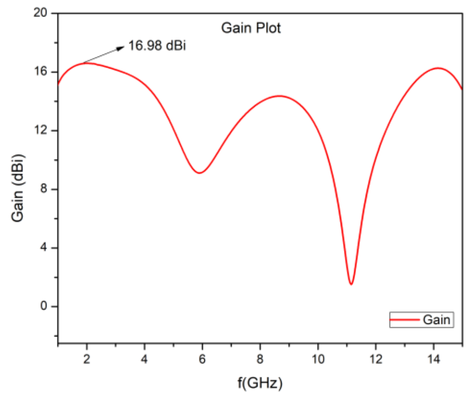
The reflection coefficient provides insight into impedance matching at the antenna ports. Simulated results for S_{11} and S_{22} are depicted in Figure 3. Both coefficients remain below -10dB across the operating range, confirming excellent matching characteristics at both ports. The achieved impedance bandwidth of 12.61GHz demonstrates an ultrawideband response, which is highly advantageous for microwave imaging applications.



[Fig.3: Reflection Coefficient at Port 1 and Port 2]

B. Gain

Figure 4 shows the remarkably high maximum gain of 16.98 dBi for the tapered slot Vivaldi antenna (TSVA). Because of its higher gain, the antenna is especially well-suited for microwave imaging applications, increasing its efficiency and boosting penetration and imaging resolution.

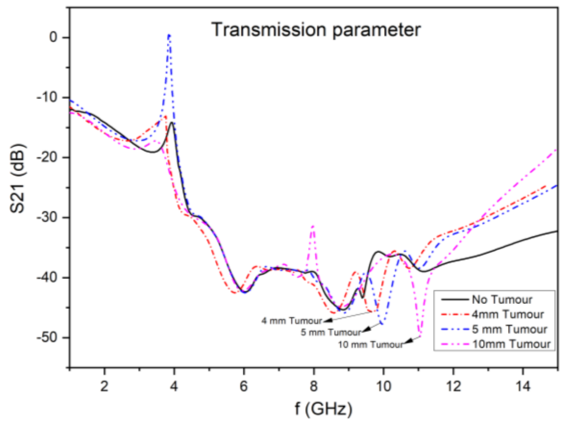


[Fig.4: Gain of Proposed Two-Element MIMO Antenna]

C. Microwave Imaging and Transmission Coefficient

Transmission coefficients (S_{31}, S_{41}, S_{32}, and S_{42}) were measured during simulation for both tumour-free and tumour-sized scenarios. These coefficients describe the power transfer between the transmitting and receiving antenna ports. Because the phantom model is placed between these antennas, the presence of a tumour alters the transmission parameters by influencing the propagation of microwave pulses.

Figure 6 compares transmission coefficients for cases without a tumour and with tumours of different sizes. In tumour-free conditions, the transmission coefficient is lower; however, when a tumour is present, it introduces an obstruction, altering the power flow through the breast tissue. For analysis, the S_{21} and S_{41} plots without a tumour were used as a baseline, and the corresponding plots for tumour cases were compared with them. A distinct separation between the traces is observed within the 4GHz to 8GHz frequency range, allowing for precise identification of tumour presence as small as 4mm. These findings confirm that the developed model can reliably detect the tumours within the phantom.



(a)

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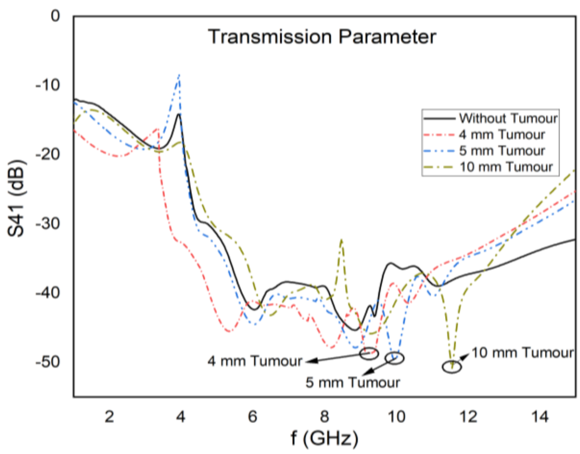


(b)

[Fig.5: Transmission Coefficient of Proposed Antenna (a) S21 (b) S41]

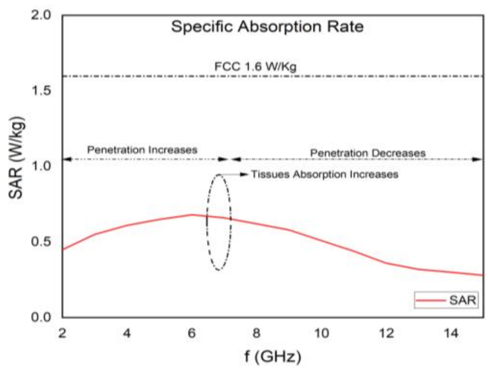
D. SAR Analysis at Breast Phantom

The power absorbed per unit mass of biological tissue exposed to an electromagnetic field is measured bioelectromagnetically by the Positioning Specific Absorption Rate (SAR). It is essential to ensure that the radiation from the imaging antenna remains within safe limits for human exposure. Since the RF field interacts closely with human tissue in applications such as breast tumour detection, evaluating SAR is critical.

The mathematical definition of SAR is:

$$SAR = \frac{\sigma |E|^2}{\rho}$$

where ρ is the mass density of the tissue (kg/m³), |E| is the electric field magnitude (V/m), and σ is the tissue conductivity (S/m). In accordance with regulatory standards such as IEEE C95.1 and ICNIRP guidelines [17], [18], this expression is widely used. The FCC (USA) sets a maximum localised SAR of 1.6 W/kg, averaged over 1 gram of tissue [19], in accordance with international regulatory bodies. For the general public, the ICNIRP (Europe) and IEEE C95.1-2019 recommend 2.0 W/kg averaged over 10 grams of tissue. These limitations apply up to 10 GHz and have been expanded to 15 GHz for use in medical imaging research. While adhering to regulations, SAR is extracted within the frequency range of 2–15 GHz. According to IEC/IEEE 62704-4, post-processing is done using HFSS's integrated SAR averaging function over 1g and 10g masses [20], [21], [22], [23].



[Fig.6: Specific Absorption Rate]

V. COMPARISON ANALYSIS

We compared the proposed antenna system with state-of-the-art solutions to gain a clear understanding of developments in breast tumour detection technologies. Essential factors such as the minimum detectable tumour size, compliance with safety regulations, material costs, and technical methodology are considered in this comparison. By examining these characteristics, the unique benefits and novel aspects of this work are evidently displayed alongside well-established findings in the literature.

Table III: Comparison Analysis

Reference	Tumour Size Detected	SAR Value	Cost / Material	Technical Approach/Notes
[24]	5 mm	27.2–48.6 (high)	Moderate; PCB	SAR-based, high max SAR, phantom tested
[25]	5 mm	Not stated	Low; FR4	Portable UWB tapered slot, high gain, low cost
[26]	Not stated	0.152–0.774 (very low)	Moderate; flexible	Triangular slotted UWB, wideband, wearable
[27]	2–5 mm	0.99–2.46	Moderate; standard	SAR distribution, multi-age analysis
[28]	~6 mm	Not stated	Moderate; meta-Vivaldi	Metamaterial UWB array, compact
[29]	~5 mm	Within safe limits	Low	Several UWB antennas are affordable and have high accuracy
[30]	~5 mm	Not stated	Low; portable	IR-UWB, embedded antenna, early diagnosis
Proposed	**4 mm**	**≤1.6 (FCC safe)**	**Low; FR4**	**Quasi-Static, UWB, Low SAR**

VI. CONCLUSION

Ultra-wideband antennas with wide impedance bandwidth are crucial for early tumour detection, offering deep tissue penetration and high-resolution imaging to resolve healthy and malignant tissues. The presented antenna allows detection of tumours as small as 4 mm and meets all safety requirements, as demonstrated by SAR analysis, which shows exposure within the FCC limit. This makes the system both effective for early diagnosis and safe for patient utilisation.

DECLARATION STATEMENT

The authors confirm that all individuals listed as authors contributed substantially to the conception, design, execution, or interpretation of the reported work. Each author's specific contributions have been clearly identified.

After aggregating input from all authors, I must verify the accuracy of the following information as the article's author.

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- **Author's Contributions:** The authorship of this article is contributed equally to all participating individuals.

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