Design and Validation of a Microwave Breast Imaging Prototype

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ABSTRACT

Breast cancer detection remains a global health priority, as early and accurate identification can significantly improve clinical outcomes by reducing diagnosis time and enabling timely intervention. Yet many diagnostic methods remain costly, complex, or harmful. In this work, we present an improved microwave imaging system for early breast cancer detection, as it is a non-ionizing method, safe for repeated use, and cost-effective. Our system employs two independent Hyperfrequency (HF) sources configured as transmit and receive units, interconnected through an Arduino-controlled Radio Frequency (RF) switching network built around HMC321ALP4E microwave switches, with Vivaldi antennas arranged in a custom 3D-printed support for flexible positioning. The proposed architecture enhances signal routing, reduces complexity, and supports multi-antenna configurations without manual intervention. The resulting microwave images of the breast phantoms reveal clear phase contrasts, enabling precise tumor localization, with a simple, fast, non-invasive, and non-ionizing system suitable for cost-effective breast cancer screening.

Keywords-Arduino-controlled RF system; breast cancer detection; microwave imaging; Vivaldi antenna

I. INTRODUCTION

Breast cancer remains the most frequently diagnosed cancer and a leading cause of cancer-related mortality among women worldwide. Early detection is essential, as it significantly improves survival rates and enables less invasive treatment options. Conventional screening modalities such as X-ray mammography, ultrasound, and Magnetic Resonance Imaging (MRI) have played fundamental roles in breast cancer management, but each presents notable limitations [1]. Mammography, though widely used, exposes patients to ionizing radiation, can be uncomfortable due to breast compression, and often has reduced sensitivity in younger women and those with dense breast tissue. Ultrasound and MRI, though non-ionizing, are either operator-dependent or costly, and MRI may require contrast agents that are not suitable for all patients [2].

In response to these challenges, microwave imaging has emerged as a promising alternative and complementary technique for early breast cancer detection. Microwave imaging leverages the significant contrast in dielectric properties between healthy and malignant breast tissues, enabling the identification of tumors without the use of ionizing radiation or painful compression [3]. This approach is inherently non-invasive, safe for repeated use, and cost-effective, making it particularly important for frequent screening and for use in resource-limited settings [4]. Recent advances in microwave imaging technology have demonstrated its ability to detect small tumors, including those in dense breast tissue, with high sensitivity and specificity. Clinical prototypes and pilot studies have shown that microwave imaging systems can achieve detection rates comparable to, or in some cases exceeding, those of traditional imaging modalities, especially in challenging patient populations [5].

Despite these technological advances, the practical implementation of microwave imaging systems in real-world clinical environments remains constrained by challenges of scalability, portability, and cost [6]. In this study, we present a compact, cost-effective, and fully modular microwave imaging system specifically designed for early breast cancer detection. The proposed system utilizes a pair of Hyperfrequency (HF) sources operating independently as transmitter and receiver units, combined with HMC321ALP4E microwave switches to perform dynamic routing across a 24-element Ultra-Wideband (UWB) Vivaldi antenna array [7]. Antenna selection and timing control are fully automated through an Arduino Uno microcontroller, optimizing the scanning process and reducing human intervention. A custom-designed 3D-printed support ensures precise and repeatable antenna alignment around a realistic multilayer breast phantom, thereby enhancing measurement consistency and imaging accuracy. The overall architecture is adapted to deliver high-resolution imaging while maintaining low power consumption, minimal complexity, and strong cost-effectiveness.

II. OVERALL ARCHITECTURE

The proposed microwave imaging system implements a component-based design structured around three main functional units: the Radio Frequency (RF) unit, the control and processing unit, and the communication unit. This separation allows for scalable development, ease of integration, and targeted optimization of each subsystem. The RF unit is responsible for signal transmission and reception through dedicated HF sources, and an antenna array arranged around the imaging region. The control and processing unit manages the sequencing of signal routing and system timing, whereas the communication unit facilitates data transfer for real-time visualization and analysis.

Figure 1 provides an overview of the system architecture, highlighting the interaction and data flow between the three primary functional units. The RF section handles signal generation and switching across multiple antennas. The control unit coordinates the activation sequence, ensuring precise signal acquisition, whereas the communication interface transfers the collected data to an external platform for processing. This architecture supports synchronized operation and is designed to be adaptable for future upgrades, including advanced imaging techniques and enhanced control protocols. The modular approach also improves maintainability and system reliability, making the platform well-suited for experimental validation and potential clinical deployment.

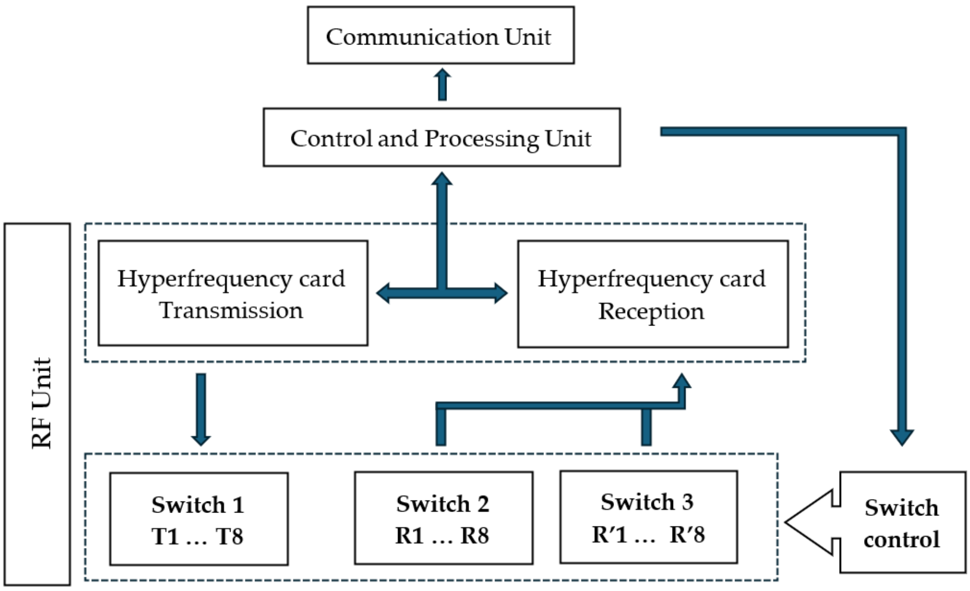


Fig. 1. Functional diagram of the proposed system.

III. SYSTEM COMPONENTS

A. Radio Frequency Unit Design

The RF unit is a critical part of the microwave imaging system, comprising two key components: the microwave switches and the HF source. For signal routing, the system integrates two nonreflective Gallium Arsenide (GaAs) Single Pole Eight-Throw (SP8T) switches, model HMC321ALP4E from Analog Devices [8]. These switches support frequencies up to 8 GHz and offer low insertion loss and high isolation, making them well-suited for microwave imaging applications [9]. Each switch features an integrated binary decoder, reducing control line requirements to just three logic signals. They operate with a control voltage of 0/+5 V and require a fixed +5 V bias.

The switching sequence is managed by an Arduino Uno board, which simplifies digital control through its General-Purpose Input/Output (GPIO) interface [10]. This approach has been successfully implemented in similar microwave imaging systems [11]. The HF sources ensure high-frequency signal generation and reception with the necessary bandwidth and stability required for accurate microwave imaging [12].

B. Control Unit

The control unit uses an Arduino Uno microcontroller to manage the HMC321ALP4E microwave switches [13]. It generates digital control signals that manage the switching logic [14]. This facilitates the dynamic selection of Vivaldi antennas for both transmission and reception [15]. The switch incorporates an integrated binary decoder. The system uses UWB antennas that provide wide bandwidth and high resolution for breast imaging [15]. The Arduino coordinates switching operations with the HF sources to ensure precise and repeatable control of the RF signal paths [16]. This configuration provides a cost-effective and scalable approach to antenna selection management within the imaging system [17].

C. Antenna Configuration and 3D-Printed Support

The system uses antipodal Vivaldi antennas for both transmission and reception. This emerging technology is selected for its UWB characteristics, high gain, and directive radiation pattern, essential features for achieving high-resolution and accurate microwave imaging [18]. Their broad operational bandwidth enables the detection of subtle dielectric variations in breast tissue, which is critical for distinguishing between healthy and malignant regions [19].

Figure 2 shows a top-view image of the fabricated microstrip antipodal Vivaldi antenna. The tapered slot structure and smooth flare transitions are clearly visible, confirming the design's suitability for broadband operation. A SubMiniature version A (SMA) connector is mounted near the feed line termination, ensuring stable and low-loss RF transmission during experimental measurements. This connector placement preserves impedance matching and minimizes reflections, maintaining optimal radiation characteristics during imaging trials. The antipodal Vivaldi antenna was fabricated on an FR4 substrate with a relative permittivity of $\varepsilon_r = 4.4$ and a thickness of 1.6 mm and fed by a 50 Ω microstrip line. The antenna was designed to operate over a wide frequency range covering the 2–4 GHz band used in this work. Measured results confirm good impedance matching with $|S_{11}|$ below −10 dB over the operating band. The complete antenna design and validation are reported in our previous work [20].

To ensure accurate and repeatable antenna positioning during imaging procedures, a custom 3D-printed support structure was developed. This circular frame includes 24 evenly spaced positions arranged angularly around the imaging area, enabling the antennas to be systematically rotated and repositioned for full spatial coverage. The structure is divided into three vertical levels, each supporting a ring of antenna positions at different heights. This multi-level configuration enhances volumetric imaging by capturing electromagnetic responses from multiple tissue depths within the breast phantom. Each position is equipped with alignment guides to maintain consistent antenna orientation and spacing relative to the imaging target [21].

Fig. 2. Top-view of the fabricated microstrip Vivaldi antenna, showing the tapered slot and SMA connector.

Figures 3 and 4 illustrate the 3D model of the support and its fabricated counterpart, respectively. The printed structure provides both mechanical stability and flexibility in measurement configuration, which helps maintain directional signal integrity and minimizes variability across acquisition points [22].

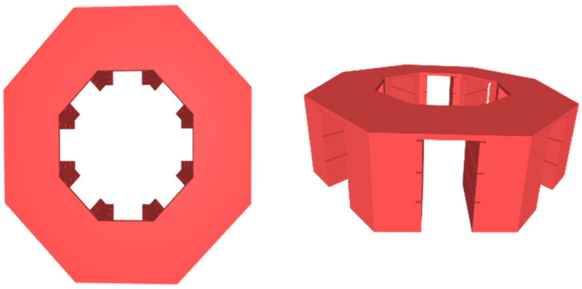


Fig. 3. 3D model of the antenna support structure with 24 antenna positions across three levels.

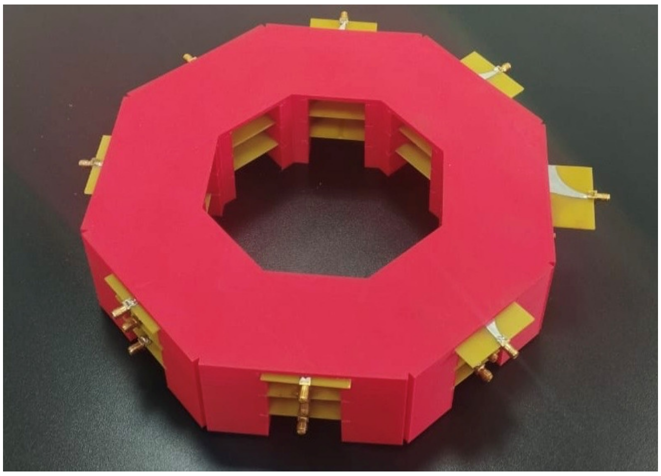


Fig. 4. Fabricated 3D-printed antenna support structure with a three-level design.

D. Breast Phantom Design

To validate the performance of the microwave imaging system, we developed multilayer breast phantoms that accurately mimic the dielectric and anatomical properties of human breast tissue. These phantoms are composed of layered structures representing skin, fat, glandular tissue, and tumor inclusions, enabling realistic simulations of microwave signal propagation and scattering. The inclusion of heterogeneous dielectric profiles ensures the emulation of clinically relevant tissue contrasts, essential for evaluating imaging sensitivity and spatial resolution [23].

Figure 5 illustrates different configurations of the breast phantom used during experimentation: a tumor-free model, a model with a tumor inclusion, and a cross-sectional view showing the internal tissue layers. These models allow the analysis of tumor detectability under controlled conditions, facilitating repeatable and comparative measurements [24]. Figure 6 presents realistic breast models fabricated in our laboratory and used in this experiment. These two multilayer phantoms and realistic models served as essential tools for verifying the microwave system's tumor localization performance in both idealized and complex scenarios.

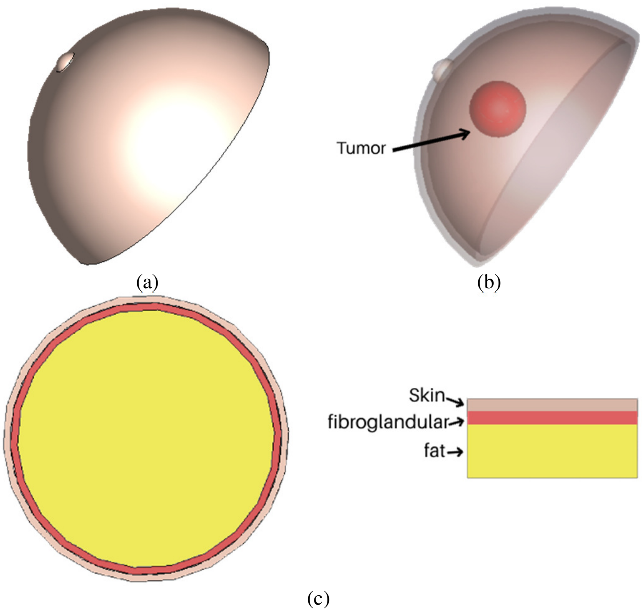
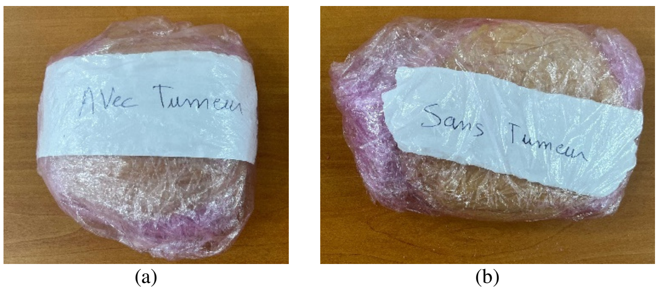


Fig. 5. Multi-layer breast phantom models: (a) without tumor, (b) with tumor, (c) detailed layers of the breast.



(a) (b)

Fig. 6. Realistic breast models for microwave imaging (developed in our laboratory): (a) breast with tumor, (b) healthy breast.

E. Communication and Processing Units

To ensure seamless data management, the communication unit facilitates the transfer of raw data from the HF receiver cards to an external computer through the Universal Serial Bus (USB) 3.0, guaranteeing efficient and reliable data transmission [25]. The processing unit handles the organization and preparatory processing of the collected signals, including filtering, calibration, and digitization, preparing the data for subsequent advanced analysis [26]. This modular design enhances system flexibility and scalability, enabling easy upgrades and integration with various signal processing algorithms and visualization tools [27].

IV. EXPERIMENTAL SETUP

Experimental validation of the proposed microwave imaging system was conducted using a modular setup comprising HF cards, HMC321ALP4E microwave switches, an Arduino Uno microcontroller, and antipodal Vivaldi antennas mounted on a custom 3D-printed support [28], operating over the 2–4 GHz frequency range. A sine wave signal was sequentially transmitted from the antennas arranged circularly around the breast phantom and the reflected signals were received by the antenna array and routed through the switches to the receiving HF cards. The Arduino microcontroller controlled the switching sequence to ensure precise synchronization between transmission and reception cycles, enabling data acquisition at multiple angular positions [29, 30].

Figure 7 illustrates the fundamental architecture of the proposed system. The process starts with a transmitted signal S_e, which propagates through the environment and interacts with the target object. Two receiving antennas, separated spatially by approximately $\lambda/4$ (one-quarter wavelength), capture the scattered signals, producing two distinct received signals: S_{r1} and S_{r2}. After reception, the signal from the second antenna, S_{r2}, undergoes complex conjugation, producing S_{r2}^*. The two signals, S_{r1} and S_{r2}^*, are then multiplied together:

$$S_{r1} \cdot S_{r2}^* = v_{r1}\, v_{r2}\, e^{j(\theta_{r1}-\theta_{r2})} \quad (1)$$

This operation isolates the relative phase difference $(\theta_{r1} - \theta_{r2})$ between the two received signals. By multiplying one received signal by the complex conjugate of the other, the absolute phase components associated with the propagation path and hardware offsets are canceled, whereas the relative phase information is preserved. This relative phase difference is highly sensitive to local dielectric property variations inside the breast phantom caused by the presence of a tumor. As a result, spatial phase perturbations can be exploited for accurate tumor localization using a single mathematical relation, without relying on amplitude-based measurements.

Figure 8 presents a top view of the experimental configuration used to evaluate the performance of the proposed microwave imaging system. The setup consists of antipodal Vivaldi antennas arranged circularly around the breast phantom, with precise angular spacing maintained by a custom 3D-printed holder. The measurement platform also integrates the switching network, HF sources, and control electronics, all positioned to minimize external interference and cable losses [31, 32].

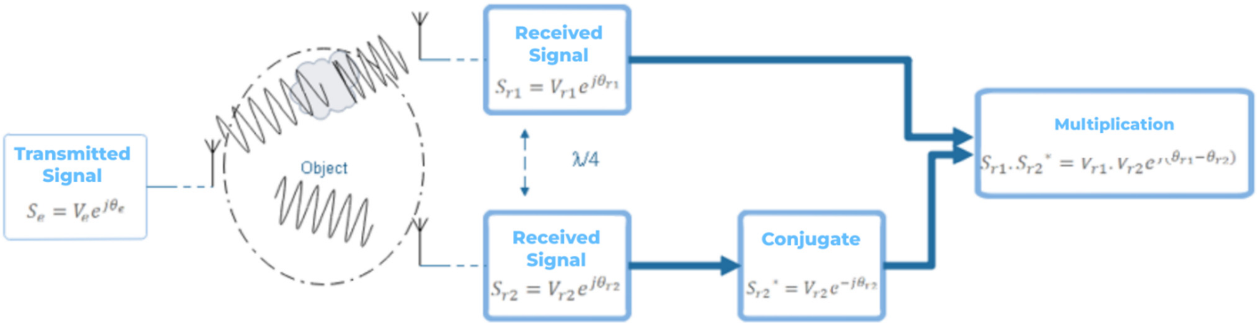


Fig. 7. Illustration of the phase difference method applied for a single target position within the system.

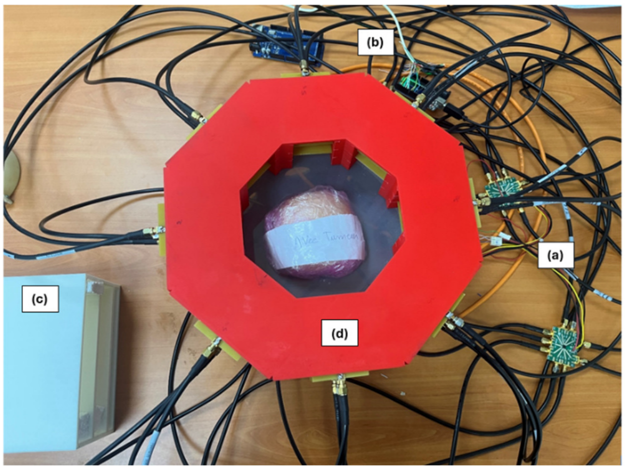


Fig. 8. Overall system architecture showing interconnection of all subsystems in the experimental setup: (a) switches, (b) Arduino card, (c) HF sources, (d) antenna array system containing 24 antennas arranged on three levels and the breast phantom.

Figure 9 illustrates the spectrum of the transmitted signal, a Continuous-Wave (CW) sinusoidal signal centered at 3.5 GHz. This signal is generated by an HF source and fed to the active transmitting Vivaldi antenna via the SP8T microwave switch. The clean spectral profile confirms the signal's frequency stability and purity, which are essential for consistent wave propagation and reliable signal reflection analysis during tumor detection experiments [33].

CW excitation has been shown to provide improved Signal-to-Noise Ratio (SNR) and localization performance in microwave imaging systems [34]. Accurate signal generation and controlled antenna transmission are therefore critical to ensuring repeatable, high-resolution imaging results.

A. *Calibration, Measurement Uncertainty, and Repeatability*

Before performing imaging measurements, a reference acquisition was performed using the tumor-free phantom to establish a stable baseline phase profile. Measurement uncertainty is mainly attributed to cable and connector repeatability, variations in switch insertion phase, and minor deviations in antenna positioning. The scan was repeated under identical conditions to verify the stability of the system's phase, confirming repeatable phase trends suitable for reliable tumor localization.

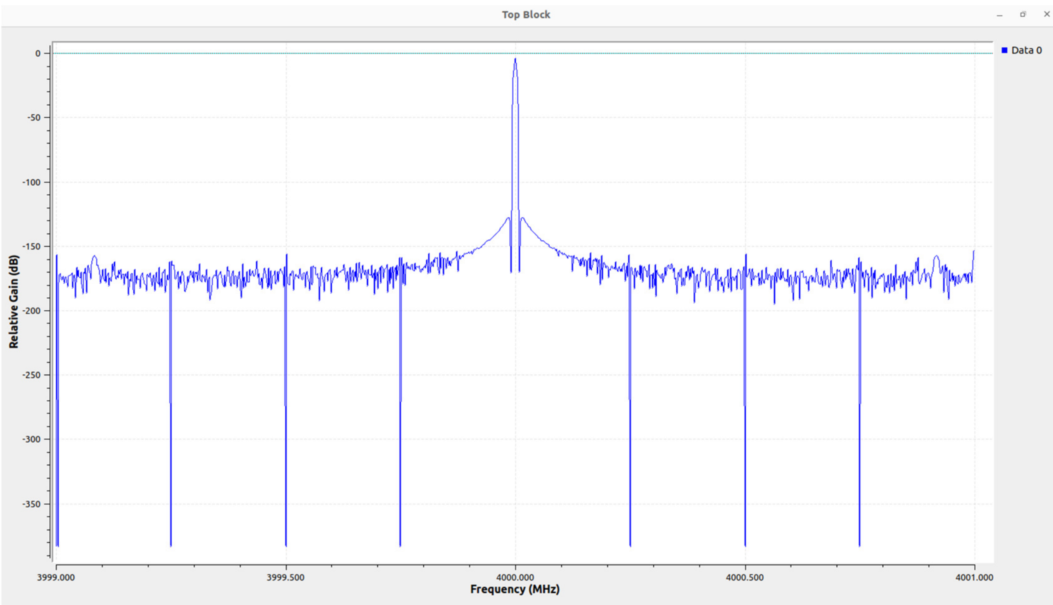


Fig. 9. Spectrum of the 3.5 GHz CW sinusoidal signal generated by the HF source for transmission via Vivaldi antennas.

V. RESULTS AND DISCUSSION

The microwave imaging system that used antipodal Vivaldi antennas arranged in a three-tier configuration comprising eight receivers on the first level, eight transmitters on the second level, and eight receivers on the third level demonstrated strong capability in detecting the presence of breast tumors. The system operates over the 2–4 GHz frequency range using HF cards, which provide stable and precise signal acquisition suitable for biomedical microwave imaging [35].

The performance of the proposed system is evaluated using phase-based metrics, including maximum phase difference, spatial consistency across antenna positions, and effective vertical localization capability. Phase analysis revealed clear differences between healthy and tumor-affected breast tissues. In the first-level measurements, a pronounced negative phase shift was observed at antenna position 4. Specifically, the tumor-affected tissue exhibited a shift of approximately −3.3 rad compared to the healthy tissue baseline, with the maximum phase difference reaching nearly −4 rad at this position (Figure 10) [36]. This lower array measurement reflects the electromagnetic response closest to the breast phantom base. The localized negative shift at position 4 indicates a strong perturbation of the electromagnetic field, suggesting tumor proximity in that region [37].

In contrast, the third-level measurements captured the field response from above, showing complementary phase shifts at antenna positions 2 and 5. Position 2 registered a positive phase deviation of approximately +2.2 rad, whereas position 5 showed a negative shift of about −2.3 rad (Figure 11) [38]. These vertical array measurements offer additional spatial insight into the tumor's extent. The distinct phase signatures observed at multiple angles are consistent with the presence of a single dominant tumor, rather than multiple anomalies [39].

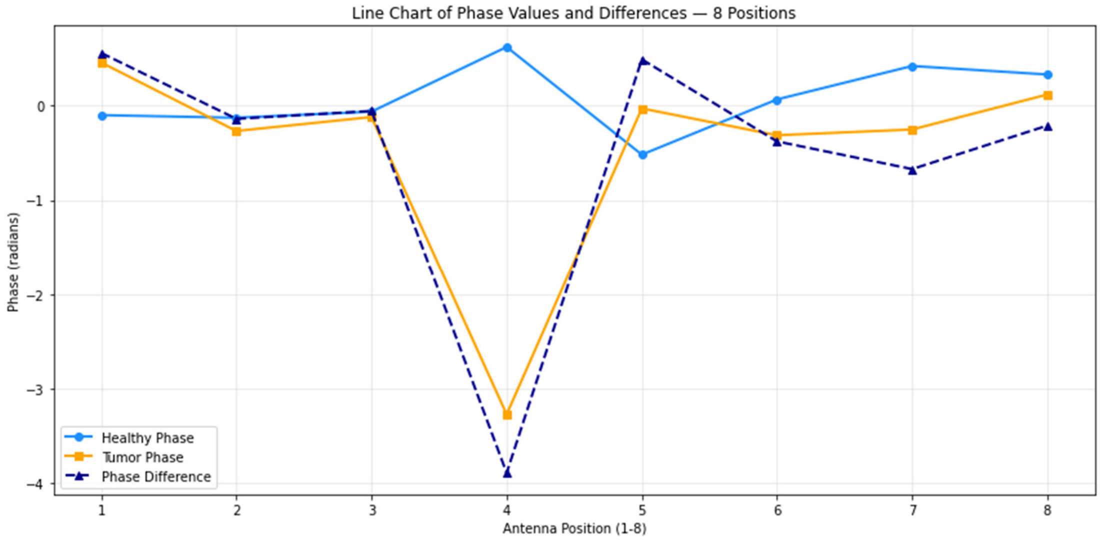


Fig. 10. Phase measurements for the 8 positions of the first level of the healthy breast, tumor-present breast, and phase difference.

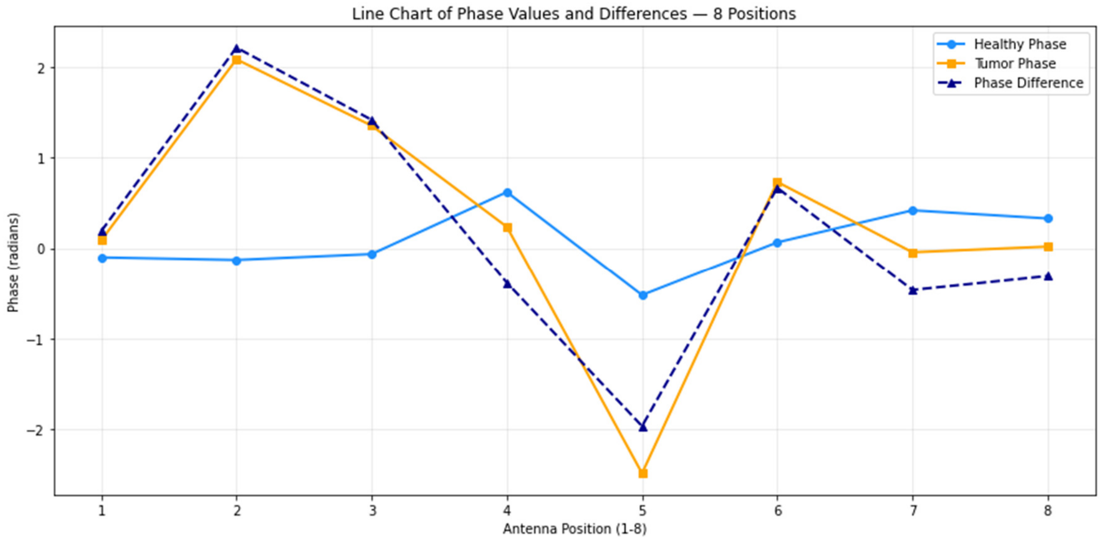


Fig. 11. Phase measurements for the 8 positions of the third level of the healthy breast, tumor-present breast, and phase difference.

The symmetry and localization of the phase perturbations across tiers validate the system's high sensitivity to dielectric property variations between healthy and tumorous tissues. Such findings align with recent theoretical and experimental studies that employed phase analysis for detecting internal dielectric anomalies [40]. Furthermore, Table I compares the proposed microwave imaging prototype with representative experimental systems reported in the literature, focusing on system-level characteristics that are consistently reported across studies.

TABLE I. COMPARATIVE PERFORMANCE OF THE PROPOSED MICROWAVE IMAGING SYSTEM AND RECENT LITERATURE

Study	Configuration	Frequency band (GHz)	No. of antennas	Validation type
[41]	Portable UWB system	3.1–10.6	8–16 (array)	Phantom
[42]	Single-plane UWB array	3.1–11	12	Multilayer phantom
This work	3-tier, circular system	2–4	24	Multilayer phantom

Figure 12 presents a two-dimensional tumor localization map obtained at 4 GHz using the proposed microwave imaging system. The X and Y axes represent spatial coordinates across the imaging plane in centimeters, ranging approximately from −10 cm to +10 cm, with the map center (0,0) corresponding to the breast phantom's center within the imaging setup. The color scale illustrates the scattering intensity at each location, where the bright central region (yellow/white) indicates a high scattering response, signifying the tumor's precise location. Surrounding darker areas (ranging from red to black) correspond to lower scattering intensities, representing healthy tissue or regions with minimal dielectric contrast.

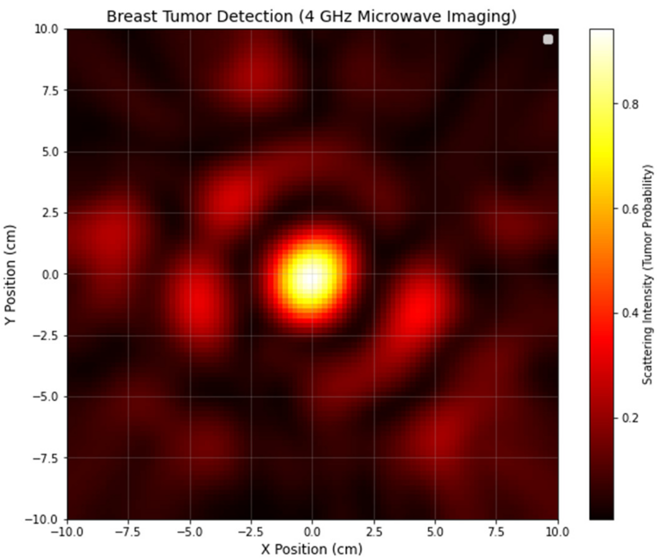


Fig. 12. 2D microwave imaging reconstruction map at 4 GHz, where the bright region indicates the tumor location due to high scattering intensity.

The adjacent color bar quantitatively maps these scattering intensities, with values near 1 highlighting the tumor's position. This visualization demonstrates the system's high spatial resolution and sensitivity in accurately localizing dielectric anomalies, underscoring its potential for effective, non-invasive breast cancer detection.

VI. CONCLUSION

This study demonstrates the effectiveness of the proposed microwave imaging system in detecting and localizing breast tumors through precise phase analysis. The bipolar phase shifts, negative at tumor boundaries and positive within the tumor core, provide a reliable signature to distinguish malignant from healthy tissue. The strong spatial correlation between phase anomalies and reconstructed images confirms the system's accuracy in estimating tumor size, location, and internal structure. Experimental results demonstrate a maximum phase difference of approximately 4 rad in tumor-affected regions and an effective vertical localization capability of about 8 mm enabled by the three-tier antenna configuration. These results highlight the potential of microwave imaging as a non-invasive, cost-effective tool for early breast cancer detection.

This work presents an experimentally validated breast imaging prototype that exploits phase-domain information and a three-level antenna array to enhance tumor localization. The results demonstrate the practical feasibility of using bipolar phase behavior as a robust indicator for tumor detection, extending beyond simulation-based studies and basic performance evaluations, and contributing to the advancement of practical microwave imaging systems for breast tumor detection.

Future work will focus on improving image reconstruction algorithms and testing diverse anatomical models to enhance clinical applicability and robustness.

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