

Received 25 October 2024, accepted 7 November 2024, date of publication 11 November 2024,
date of current version 26 November 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3496117

TOPICAL REVIEW

Microstrip Patch Antennas for Breast Tumor/Cancer Cell Detection—Challenges, Designs, and Future Opportunities: A Review

M. M. HASAN MAHFUZ¹, (Member, IEEE), A. M. MAHFOUZ¹, (Member, IEEE),
ELHAM BALADI², (Member, IEEE), AND AHMED A. KISHK¹, (Life Fellow, IEEE)

¹Department of Electrical and Computer Engineering, Concordia University, Montreal, QC H3G 1M8, Canada

²Department of Electrical Engineering, Polytechnique Montréal, Montreal, QC H3T 1J4, Canada

Corresponding author: M. M. Hasan Mahfuz (md.mahfuz@mail.concordia.ca)

This work involved human subjects or animals in its research. The authors confirm that all human/animal subject research procedures and protocols are exempt from review board approval.

ABSTRACT Breast cancer is a major killer of women worldwide and one of the leading causes of death overall. It involves the progressive abnormal growth of breast tissue which, if detected at an early stage, can be diagnosed as a tumor. Traditional breast cancer screening methods, such as X-ray mammography, magnetic resonance imaging, and ultrasound scanning, present several drawbacks, making them less than ideal. These drawbacks include high costs, exposure to potentially hazardous radiation, and patient inconvenience. Due to these challenges, researchers have been motivated to seek alternative methods, one of which involves the application of microwave technology. In recent years, wearable and flexible patch antennas have gained popularity due to their appealing characteristics and the potential to develop lightweight, compact, low-cost, and adaptable solutions for biomedical applications. This article provides an overview of microwave approaches for breast tumor detection using microstrip patch antennas. In particular, recent advancements in active microwave imaging and microwave-based methods are reviewed. The primary goal of this work is to offer researchers and medical professionals an understanding of the underlying principles, techniques, and challenges associated with microwave imaging for breast tumor/cancer detection. Additionally, this study aims to highlight the fact that, as of now, commercially available, cost-effective microwave-based technologies for imaging or detecting breast tumors/cancer are relatively scarce. This observation is not meant to imply that microwave technology is ineffective for breast tumor/cancer diagnosis; rather, it seeks to spark a constructive discussion about why, despite years of dedicated research, a widely accessible commercial technology has yet to be made available.

INDEX TERMS Flexible antennas, ISM band, UWB, breast tumor/cancer, SAR, wearable antenna, breast tissue, biomedical application, IoT.

I. INTRODUCTION

In 2020, there were 2.3 million new cases of female breast cancer, making it the most frequent cancer in women worldwide [1]. Cancer was ranked as the world's second-largest cause of death in a recent announcement made by the World Health Organization (WHO) [2], [3]. Early detection and

The associate editor coordinating the review of this manuscript and approving it for publication was Ravi Kumar Gangwar¹.

intervention are most effective in reducing mortality rates, as individuals diagnosed with early-stage cancer have the greatest opportunity for curative therapy and long-term survival [4]. There is a higher incidence of breast cancer in low and middle-income nations where there is less access to healthcare, and many women are diagnosed with advanced or metastatic illness [5], [6]. As a result, the survival rates of women with breast cancer differ greatly depending on the income level, with the highest rates of survival being found in

high-income countries. It is therefore impossible to place an adequate amount of emphasis on the significance of breast cancer screenings performed at an earlier stage in regions with limited resources [7].

Wearable radio frequency circuits, a relatively new development in modern technology, are accelerating the development of new diagnostic concepts and methods. These wearable circuit modules are proposed to be inserted within several types of flexible antennas that can be worn. Medical diagnosis, navigation, tracking, ultrawide-band (UWB) radar technology [8], [9], [10] mobile computing, and public safety protection are all made possible through the usage of flexible microstrip patch antennas (MPAs) [11], [12]. In licensed or unlicensed frequency spectrum, these modules can operate in the Industry Scientific and Medical (ISM) band. Breast cancer clinical diagnosis applications currently available do not include wearable elements. Wearable modules are passive components used in microwave imaging (MI) systems, and they have been employed in clinical studies to introduce wearable features. This feature recognizes the diagnostic module's advantages, including: (i) design simplicity, (ii) cost-effectiveness, (iii) their potential to be used in multiple tests in the event of errors in clinical trials, and (iv) in the case that guilt feelings are not addressed in clinical trials modules that are convenient for patient health care systems. Breast cancer is caused by abnormal cells that multiply and spread to other body parts [2]. Analysis of breast cancer in 187 countries throughout the world found that the incidence of breast cancer grew from 641,000 cases per year in 1980 to 1,643,000 cases per year in 2010 [3]. A silent disease such as cancer does not present itself with symptoms until it has progressed to an advanced stage. In most cases, breast cancer is identified at a later stage and with a greater risk of recurrence for young women [13]. Successful medical therapy and cure can be achieved if the disease is discovered early. It is possible to use low-cost breast cancer imaging devices based on microwave technology because of the great contrast between healthy tissues and tumors. As a result, it can meet high-resolution and deep-penetration scanning criteria while allowing for rapid tumor detection [14]. Its non-ionizing nature will lessen safety hazards and let women, especially young ones, undergo safe and regular breast screening.

The scanned image in microwave imaging is reconstructed by utilizing the wave reflected from the breast [15], [16]. Anatomical reflection or transmission can be examined by comparing the electrical characteristics of normal and diseased tissues [17]. Early detection of breast tumors/cancer can be improved by employing microwave imaging instead of mammography, according to several scientific studies (Fig. 1) [18], [19], [20]. The antennas in these systems are either single elements or arrays that are placed close to or in touch with the breast [19], [20], [21]. As a result, the creation and optimization of antennas is critical to the overall performance of the detection system. Recently, flexible and textile antennas and other antenna types have been used in the imaging systems indicated above [7], [22]. The development

of wearable microwave imaging systems or textile sensors for imaging has only attracted a small number of research groups. The wearable system developed by the University of Montreal uses a flexible printed circuit board (PCB) substrate to route all signals, assemble the system, and calibrate the device [15], [18]. Wearable, flexible antennas are now the most popular choice for wearable systems because of their low cost, comfort, flexibility, and safe specific absorption rate (SAR) values [23], [24], [25]. The present comprehensive article offers the most recent studies of flexible microstrip patch antennas in breast tumors/cancer detection.

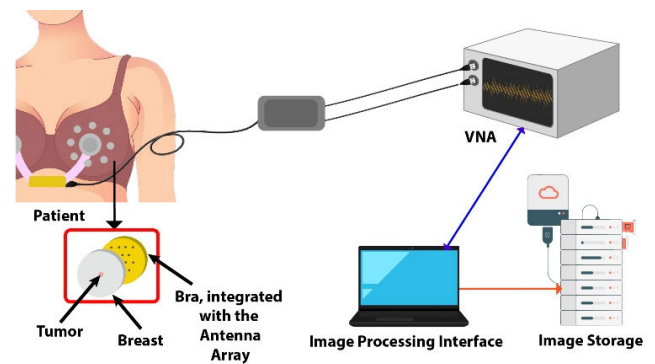


FIGURE 1. Schematic of the data collection apparatus.

II. ANTENNA STRUCTURE DETAILS AND SUBSTRATE

A compact multi-input multi-output (MIMO) antenna capable of working for Wireless Body Area Networks (WBAN) and breast cancer imaging is given in [26]. A vertically polarized leaf and a horizontally polarized tree antenna are developed, as shown in Fig. 2. Shorting pins, stubs, and parasitic spiral are added to the MIMO antenna to reduce the coupling effects and eliminate undesired resonances. The two-port MIMO cells are separated by 2 mm and rotated by 90° to produce three more cells. The ShieldIt™ conductive textile uses two layers of denim and felt substrates with dielectric constants of 1.2 and 1.8 and thicknesses of 0.5 mm and 0.9 mm, respectively. The antenna has a large bandwidth that ranges from 4.8–30 GHz. Near-field microwave imaging was used to test the antenna's performance in both on-body (breast) and free-space situations, as illustrated in Fig. 3. Another study suggests using an EF-shaped microstrip patch antenna constructed from reinforced epoxy materials and printed on woven cloth, as illustrated in Fig. 4 [11]. The proposed wearable antenna in his work was tested with composite materials for cancer coverage in malignant organs, and the results were applied in the Microwave Imaging System (MIS). Another antenna module made of cotton was developed in the 3.32 GHz band (Fig. 5). The 3.33 GHz band was made available using a polyester woven antenna module [11]. Another research study created a full-ground UWB antenna fed via a SIW transition and a GCPW on a denim textile substrate to provide a wide bandwidth while keeping SAR

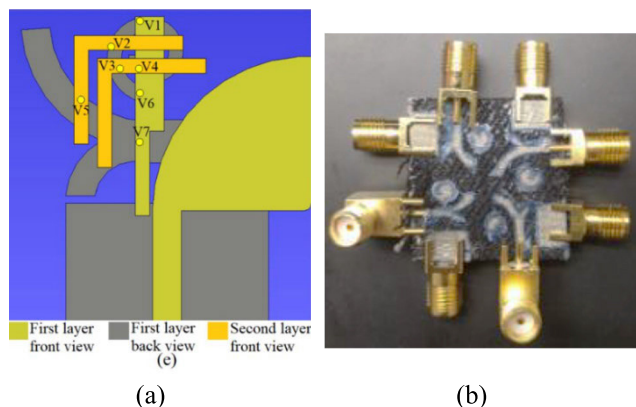


FIGURE 2. Dual-polarized MIMO antenna (a) Overlay view with all layers (shorting pins V1 to V7 and (b) photo of the fabricated antenna [26].

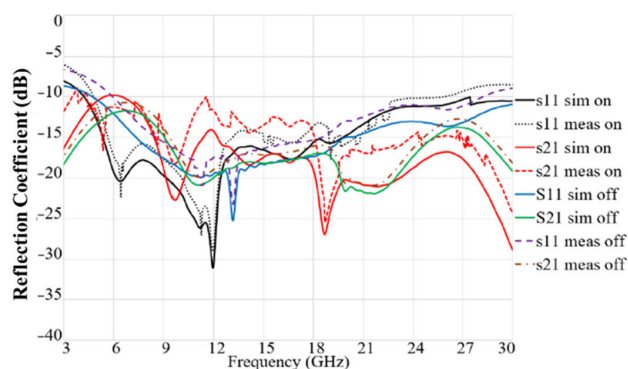


FIGURE 3. Simulated and measured S-parameters of the single MIMO antenna on the breast phantom (on-body) and free space (off-body) configurations [26].

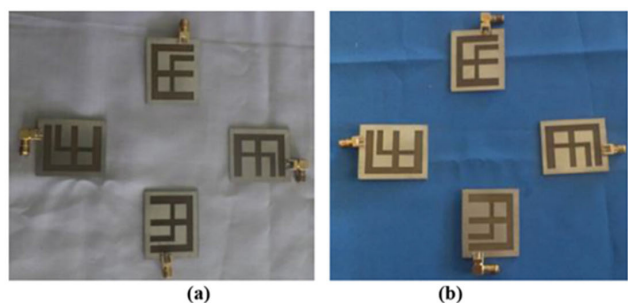


FIGURE 4. E_f -shape antenna (a) cotton and (b) polyester wearable substrate [11].

below acceptable levels for the one-gram (1.6 W/Kg) and the ten-gram (2 W/Kg) tissue standard [24]. Fig. 6(a) illustrates the photo of the fabricated antenna, and Fig. 6(b) shows its reflection coefficient. A large bandwidth of 7–28 GHz, with a maximum gain of 10.5 dBi in one direction, has been obtained. Using the antenna's performance in free space as a starting point, the radiation properties of the breast tumor are examined to identify various scenarios, including central tumors with and without skin, as well as multiple tumors (two and three) within the breast. The reconstructed images

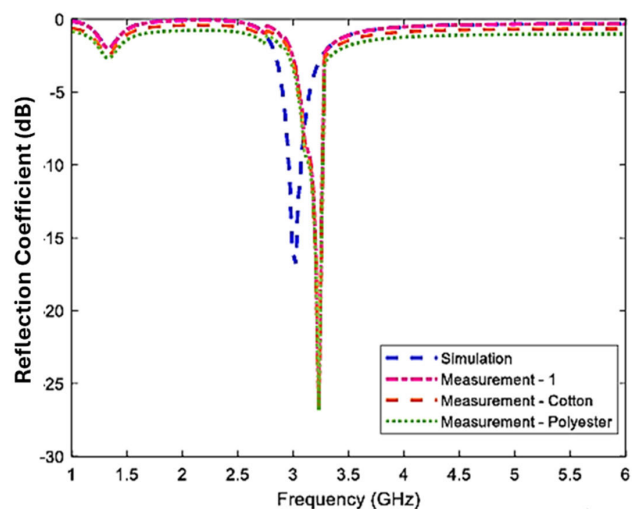


FIGURE 5. Simulated and measured reflection coefficients. The measurements are for 3 cases [11].

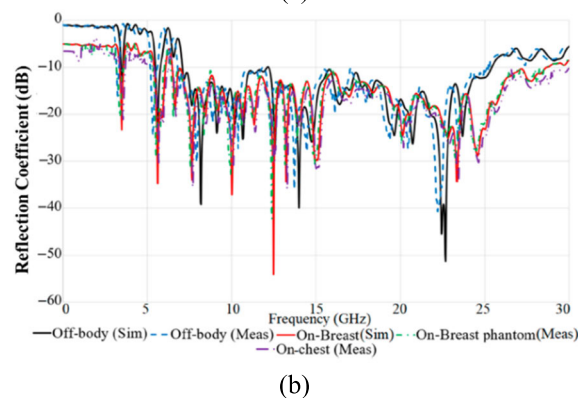
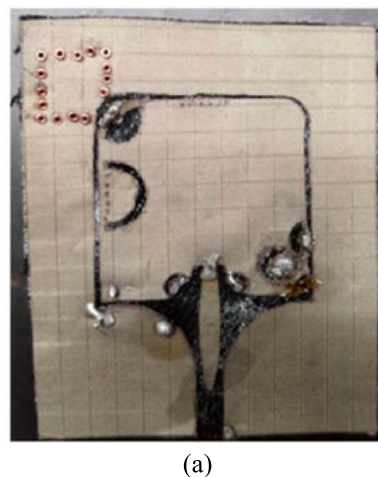


FIGURE 6. Antenna on denim textile substrate (a) photo of the fabricated antenna and (b) simulated and measured reflection coefficients off-body and on-breast [24].

demonstrated that the antenna could be an acceptable option or a wearable WBAN system for breast cancer surveillance and imaging due to its strong performance on a soft medium such as a breast.

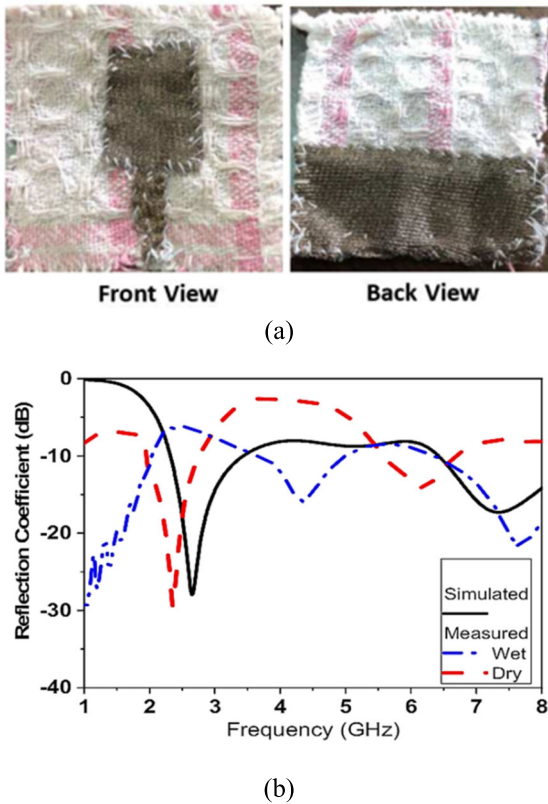


FIGURE 7. Monopole textile antenna (a) photo of the front and back and (b) Simulated and measured (wet, dry condition) reflection coefficients [27].

Another research [27] introduced a low-cost, completely textile antenna-based sensor operated between 2–6 GHz. Cotton substrate and textile conductor were used to create the $50 \times 50 \text{ mm}^2$ monopole antenna prototype, as shown in Fig. 7(a). After being washed and dried, the suggested textile sensor still functions as intended, according to the S_{11} in Fig. 7(b). The findings obtained by placing one and two sensors in contact with a breast model demonstrated the ability of the sensor to identify aberrant tissues. SAR was also measured and found to be lower than the minimum acceptable value. The textile sensor was a step towards establishing a wearable microwave breast imaging device to help women receive safe and frequent breast screenings. Detection of skin cancer with xeroderma pigmentosum (XP) illness was one potential use of medical imaging. A small monopole antenna with an AMC structure to reduce the SAR level was recently proposed for this application [28]. The antenna provided a suitable response to the specified conditions and displayed UWB characteristics. The AMC structure's physical dimensions are shown in Fig. 8(a). Fig. 8(b) shows good agreement between measured and simulated reflection coefficients below -10 dB within the 8–12 GHz range.

Another recent study introduces a small UWB slotted patch antenna for microwave breast imaging systems, which can detect tumors in their earliest stages [29]. The antenna was developed and optimized within a coupling medium with

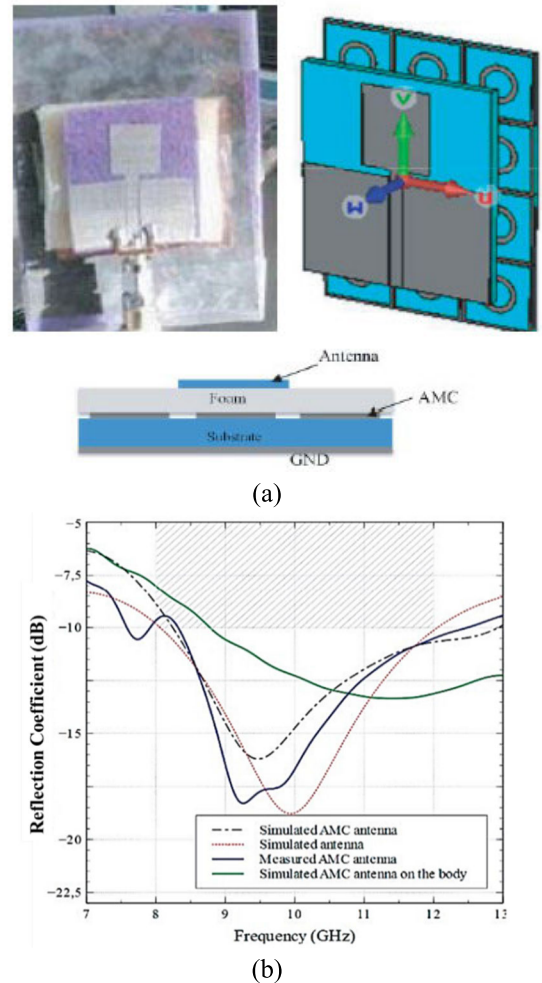


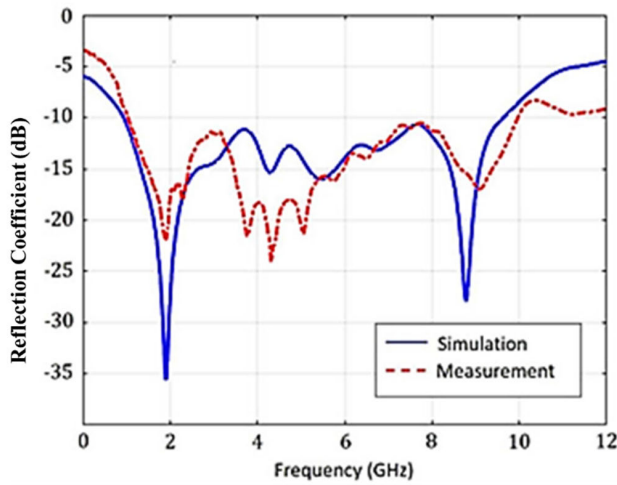
FIGURE 8. Monopole antenna backed by AMC surface (a) photo and sketch of the antenna and cross-section view and (b) Reflection coefficients, simulated in three scenarios and measured with the AMC [28].

electrical properties comparable to natural breast tissue to decrease reflections between the antenna and the breast. The antenna's wideband performance is achieved by fabricating the ground plane with a rectangular slit and L-shaped sleeves, as illustrated in Fig. 9(a). The additional rectangular slit helps primarily with matching, while the L-shaped sleeves help with both matching and bandwidth. The antenna has a fractional bandwidth of 165% and operates between 0.9 and 9.6 GHz (Fig. 9b), allowing for excellent penetration and resolution. In addition to this, the suggested antenna is quite small, measuring only $16 \times 16 \text{ mm}^2$. In the simulation scenario, 31 antennas are constructed into an array around a realistic breast phantom to demonstrate imaging of a spherical tumor measuring 5 mm in diameter inside the breast.

For early-stage detection, a tiny-shaped meandering line microstrip patch antenna operating at a low-frequency range was presented in Fig. 10(a) [30]. The antenna was placed over a healthy breast and a breast with cancer, both of

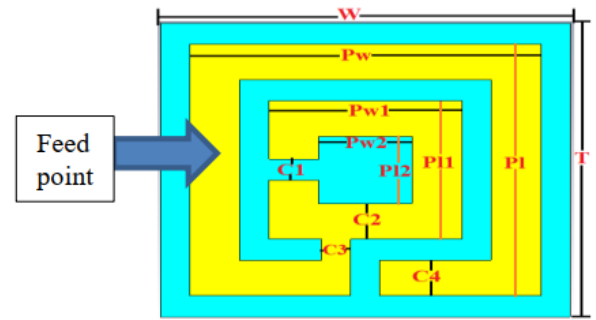


(a)

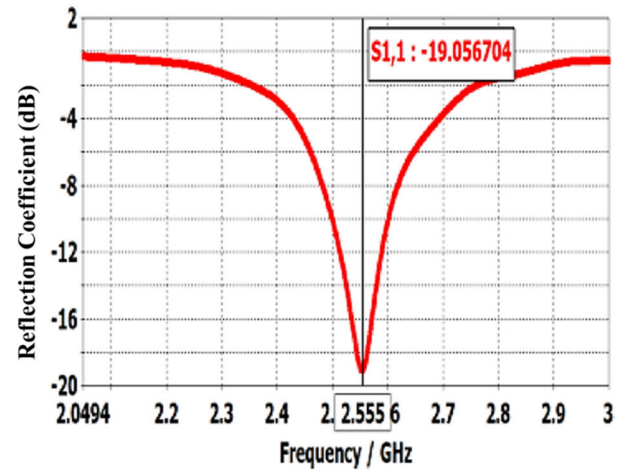


(b)

FIGURE 9. Slot patch antenna (a) photo of the fabricated antenna and (b) measured and simulated reflection coefficients [29].



(a)



(b)

FIGURE 10. Meandering line microstrip antenna (a) geometry parameters and (b) simulated reflection coefficient [30].

which retained the essential characteristics for analysis of the antenna's performance and parameters. The reflection coefficient shown in Fig. 10(b) have aided in cancer detection primarily as an indicator due to their significant reduction in the presence of a tumor, which was a malignant tumor with a 4.50 dielectric conductivity/relative permittivity grown inside the breast to a diameter of 5 mm. In [31], a flexible ultra-wideband 4×1 MIMO antenna was introduced for breast cancer detection applications. The antenna had a ground plane with slots and oval radiating patches, as shown in Fig. 11(a). Improving antenna performance and scattering signals was the primary goal of utilizing the 4×1 MIMO antenna configuration. Each element was constructed on $16 \times 16 \times 0.254$ mm³ malleable Rogers RT/duroid 5880 (tm) CPW-fed. Thus, the 4×1 MIMO antenna had dimensions of $16 \times 71.5 \times 0.254$ mm³. The frequency range of operation for the 4×1 MIMO antenna was 3.2–14 GHz (Fig. 11b), and its radiation pattern is directional. S_{11} , gain, isolation, envelope correlation coefficient, diversity gains, and SAR were used to measure the antenna's performance. Breast phantoms measured the S-parameters of both the transmitting and receiving antennas. All of the parameters were located within an acceptable range. The H-shape UWB dielectric resonator (DR) sensor [32] was designed for breast tumors

detection and can be directly attached to the skin without a matching medium. It has provided wide beam width, reducing path loss, and maintains high efficiency with low distortion. The compact size allowed multiple sensors to be placed closely on the breast. The sensor's performance is validated through frequency and time domain analyses, demonstrating accurate tumor detection. It features a modified design for better impedance matching and reduced footprint. The DR sensor showed high efficiency, low distortion, and effective localization of tumors using time-windowing techniques. The work in [33] presented a microwave breast imaging model that used a multilayer phantom to detect malignant tumors using an 8-elements array of compact, flexible Vivaldi antennas. The photo of the Vivaldi element is shown in Fig. 13(a). Fig. 13(b). shows the reflection coefficients of the element. An 8-element array of this element was designed so that each element transmits in sequence at a time the 8-elements receive, and the eight elements receive. Thus, the backscattering from the breast phantom is received at the end due to eight different transmitters, and the same 8-elements receive the reflected signal due to each transmitter.

For a combined microwave imaging and hyperthermia system, a tapered slot antenna (TSA) with a compact meander line resonator that can switch between operations in

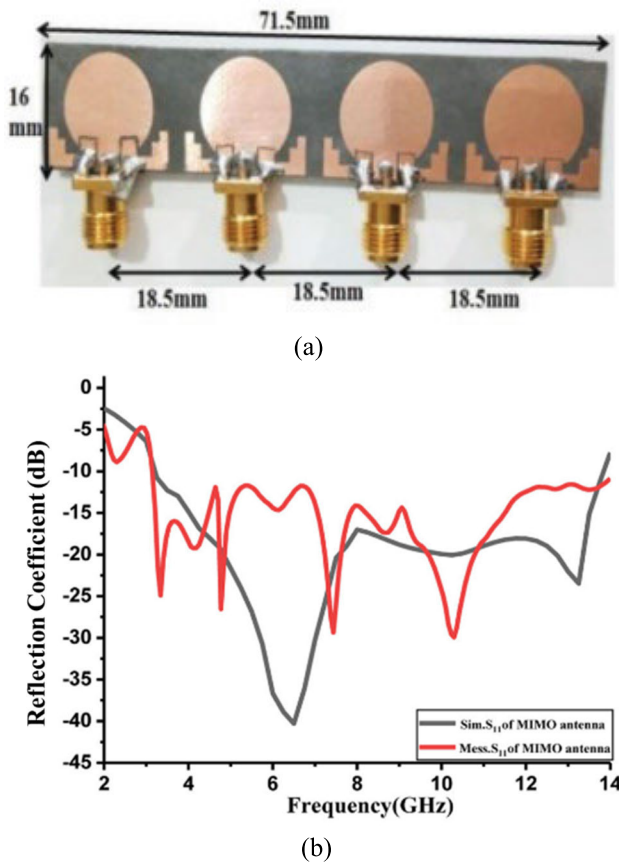


FIGURE 11. 4 × 1 MIMO antenna (a) fabricated antenna and (b) measured and simulated S_{11} [31].

wideband and narrowband configurations was proposed [34]. A compact meander line resonator was built below the tapered slot to keep the wideband TSA's characteristics to a minimum. The resonator displayed narrow band-pass characteristics via a single PIN diode. The fabricated antenna is shown in Fig. 14(a). A coupling effect transfers the electromagnetic energy to the meander line resonator, allowing efficient frequency switching. The frequency switching was implemented by mounting a PIN diode on the meander line resonator. Thus, the suggested antenna operated in a real-time frequency switching mode between 3.1–10 GHz, used for microwave imaging. The UWB reflection coefficient is shown in Fig. 14 (b). The 2.45 GHz ISM band shown in Fig. 14(c) was utilized for microwave hyperthermia. The study in [35] aimed to create a circular, UWB MIMO antenna array (Fig. 15a,b) with four individual components that may be worn by a patient and used to detect and localize tumor cells in a heterogeneous breast phantom. While using FR4 as the substrate, the antenna element operated at 2.40–10.6 GHz, as illustrated in Fig. 15(c), while employing Dacron fabric, the frequency range is 2.57–12.6 GHz. The proposed detecting system has a single transmitting antenna and several receiving antennas. When a Dacron fabric is used as the substrate for the antenna, gains of 5.49 dBi, 9.87 dBi,

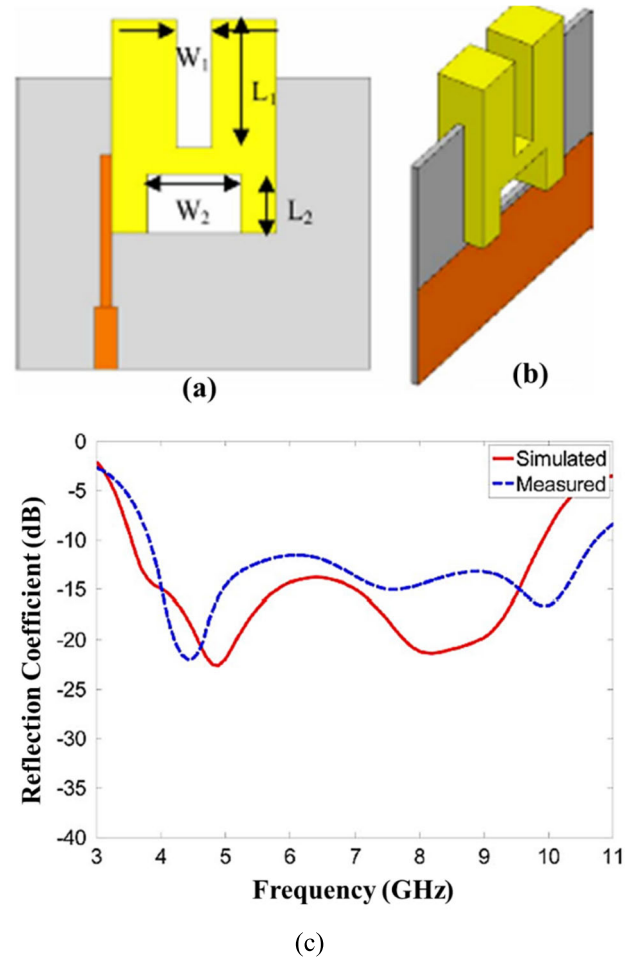


FIGURE 12. UWB DRA sensor (a) front view, (b) isometric view and (c) simulated and measured reflection coefficient [32].

11.9 dBi, and 14.7 dBi are obtained at the resonance frequencies of 2.84 GHz, 3.87 GHz, 5.83 GHz, and 8.24 GHz, respectively. In addition, the suggested antenna has a flexible design that exhibits low bending effects in both the vertical and horizontal planes across its full frequency spectrum of operation.

The S-parameters of the proposed approach can successfully identify and precisely localize even very tiny tumors. Additionally, the SAR findings suggest that the amount of power absorbed by the breast phantom tissues complies with the IEEE guidelines. Thus, it confirms that the recommended antenna is suitable for the early identification and localization of breast cancer. A microstrip patch antenna (Fig. 16a,b) is optimized for wideband microwave imaging (MWI) in another work and is proposed as a cost-effective solution [36]. The proposed structure is loaded with an AMC to boost the antenna's efficiency, and the simulated & measured return loss is illustrated in Fig. 16(c). These data show that adding the AMC improves the antenna's frequency selectivity at 8.6 GHz, with a peak realized gain of 9.9 dBi in the simulations and 10.61 dBi in the measurements. Cancer

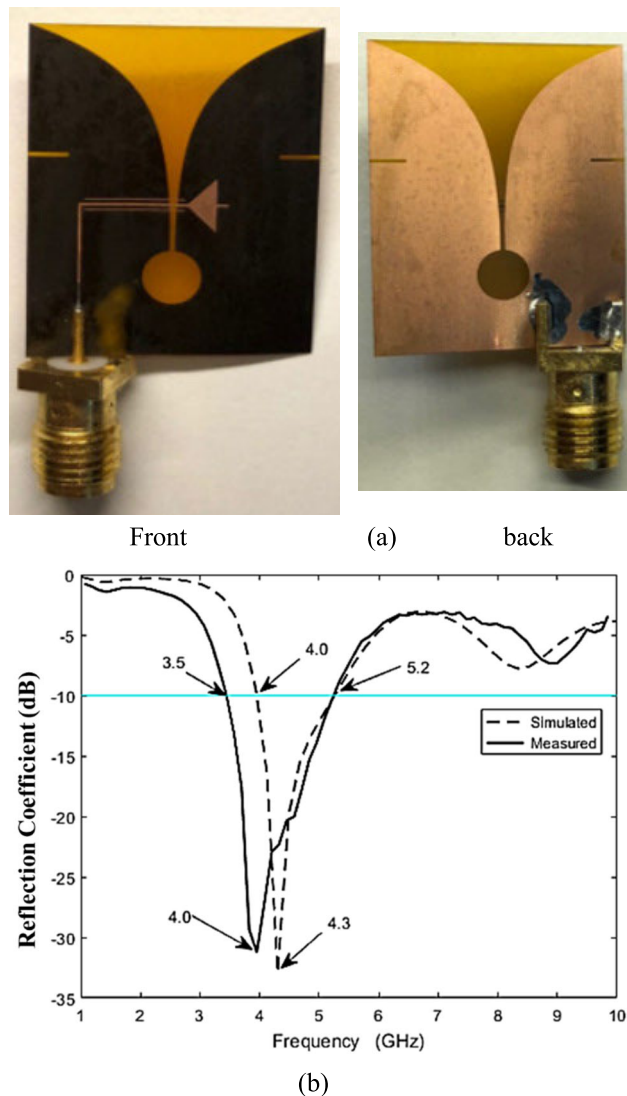


FIGURE 13. Flexible Vivaldi antenna, (a) photo of a single element back and front and (b) simulated and measured reflection coefficient [33].

tumor cell identification has been computationally simulated using tumor-bearing breast phantom models and an antenna functioning as a transceiver. The research has profound implications for the development of electromagnetic biosensors. An easy-to-understand model for the 2.45 GHz hyperthermia treatment of breast cancer was proposed in [37]. The suggested model comprises nine antennas and a breast cancer tumor cluster represented by a numerical breast. To begin the inquiry, a single-slot antenna was designed (Fig. 17a), and its performance at the desired frequency of 2.45 GHz was evaluated (Fig. 17b); the antenna's return loss was decreased by -47 dB, and its bandwidth was increased to 78 MHz compare to design-1. The SAR it took to get a decent result was lower than the required IEEE threshold of 1.6 W/kg for an input power of 1.5 W. A novel, inexpensive, flexible antenna for a non-invasive, highly sensitive method of early malignant tumor detection may help lower the number of fatalities

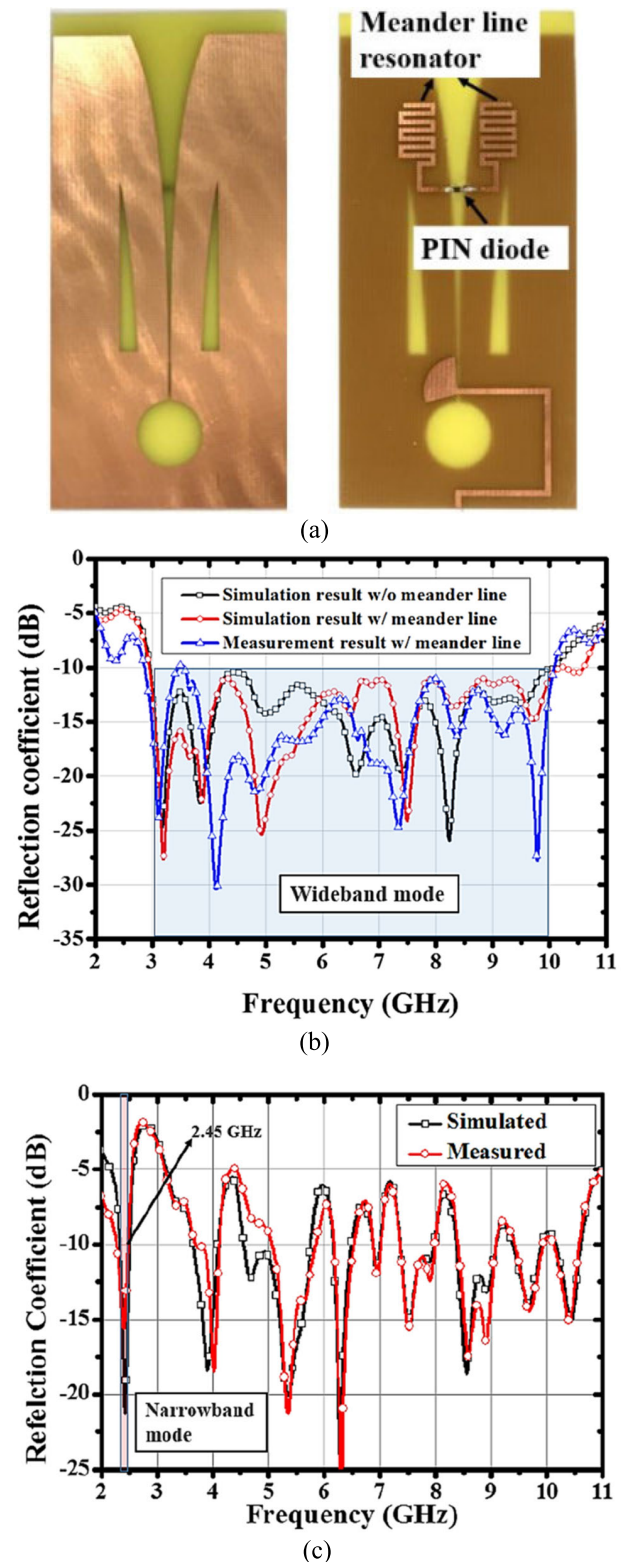


FIGURE 14. TSA with meander line and the PIN diode (a) TSA photo of the front and back, (b) measured and simulated reflection coefficients of UWB mode for microwave imaging, and (c) simulated and measured narrow-band mode for microwave hyperthermia [34].

from delayed breast cancer diagnosis. The thin film Kapton substrate and CST MWS software were used to construct

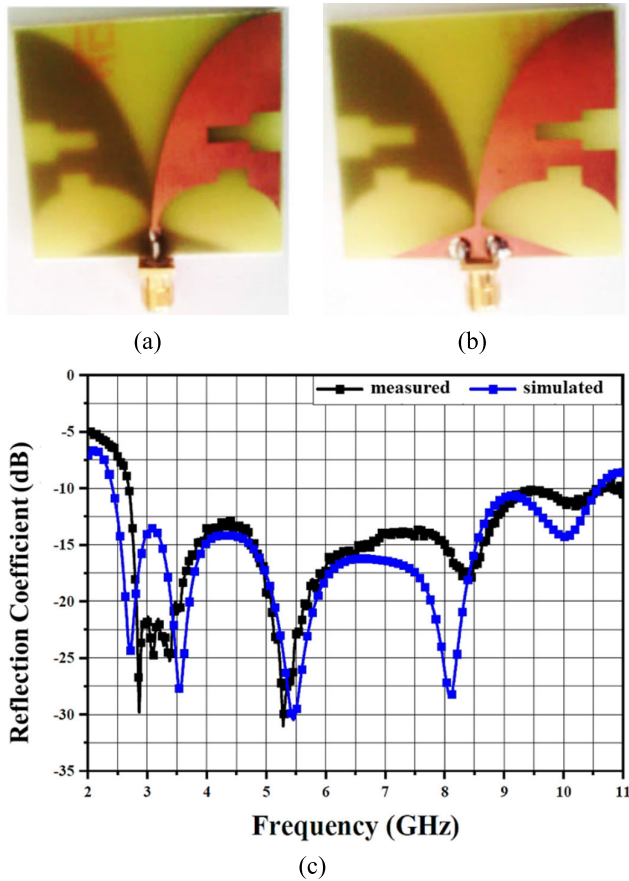


FIGURE 15. Antipodal Vivaldi Antenna (a) Top view, (b) rear view and (c) measured and simulated reflection coefficient [35].

the flexible antenna (Fig. 18a). The suggested antenna operated in the S-band (with a reflection coefficient (S_{11}) below -10 dB and exhibits UWB characteristics (Fig. 18b), hence delivering a significant bandwidth of around 2.4 GHz at a center frequency of approximately 3 GHz. The S-parameter of the newly designed antenna was modeled using an inhomogeneous multi-layer model of a woman's breast to forecast how the human body may affect the antenna's performance. A compact stair-shaped dielectric resonator antenna (DRA) designed for microwave breast cancer detection features a quarter-wavelength choke to minimize ground plane size (Fig. 19a,b) [38]. Achieving over 40% reflection coefficient (Fig. 19c) of -10 dB centered at 6.5 GHz with a 50Ω coaxial port validated the design numerically and experimentally. The sensor maintains good matching without additional matching media when in contact with tissue. A two-element sensor array and comparisons with dipole antennas highlight the DRA's potential for frequency-domain detection. The DRA was fabricated using Rogers material (duroid 6010) and optimized with WIPL-D software. The choked ground plane is created using Rogers RO4003C and soldering material for easy fabrication.

The human breast was the focus of the transparent flexible UWB antenna design [40] A miniaturized flexible transparent

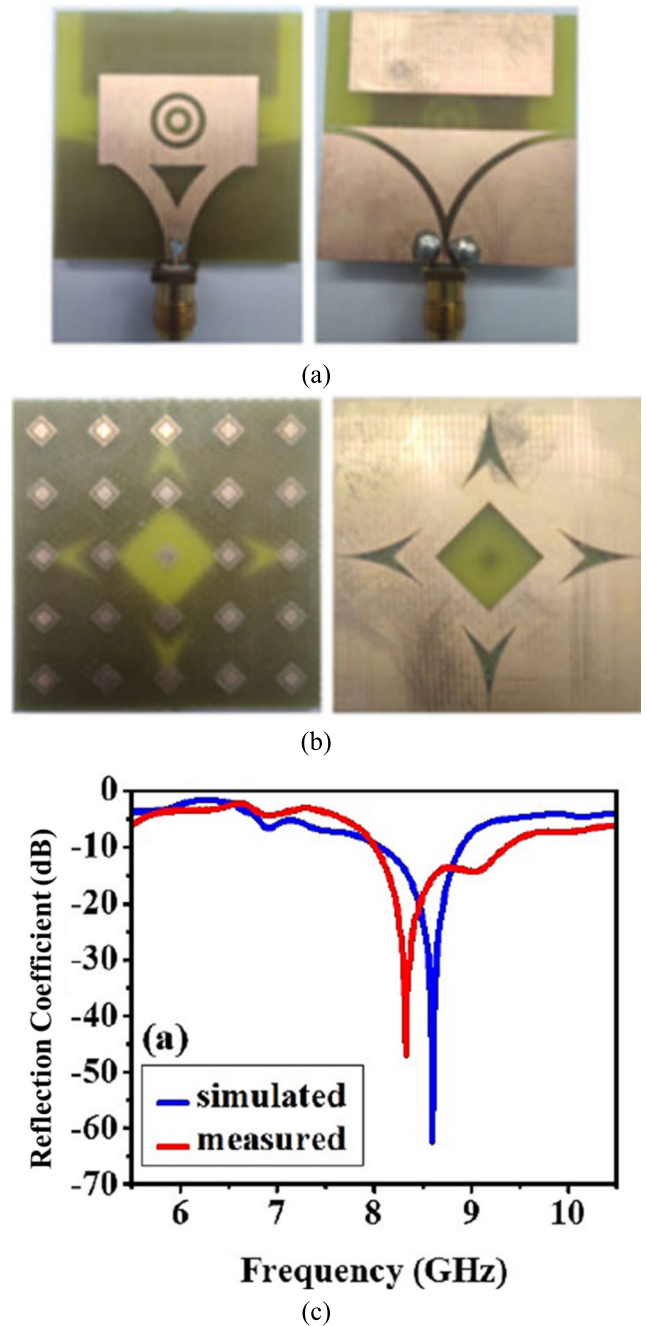


FIGURE 16. AMC structure based antenna's (a) MPA front and back views, (b) view of the AMC from both directions prototype after fabrication, and (c) measured & simulated S_{11} are used with AMC [36].

UWB antenna was designed using Kapton polyimide, which has a dielectric constant of 3.5, as a substrate and indium tin oxide (ITO) as a conductor. The fabricated antenna is shown in Fig. 20(a). The antenna's frequency and time domain performances are studied and analyzed using an ITO transparent conductor. The suggested antenna can reach a BW of 3.26–23.37 GHz. The reflection coefficients are illustrated in Fig. 20(b). Since the reconstructed tumor image agrees well with the simulation, measurement findings, and time-domain

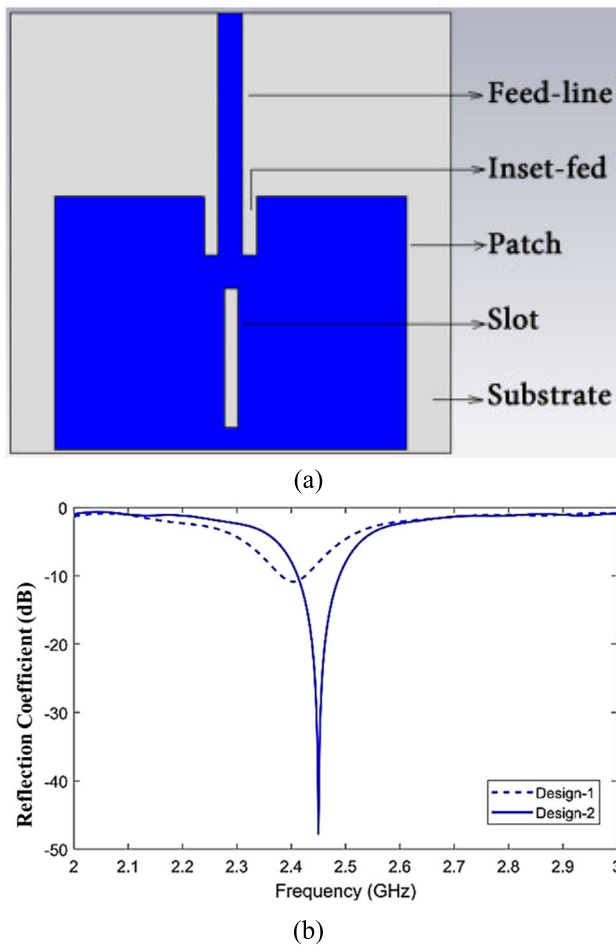


FIGURE 17. (a) RPA antenna's front view and (b) simulated S_{11} [37].

considerations, the antenna can be used for purposes including breast and skin cancers. The patch antenna in [41] was woven into a textile shaped like a Jerusalem cross. Existing test beds are utilized to deploy the breast tumor detection application. Cotton and polyester weave fabrics were used in the patch strips' printed designs (Fig. 21a,b), with a resonant of 5.8 GHz (Fig. 21c). These weaved modules did not cause any radiation to be reflected onto the human body. Fabric modules attached to a breast phantom model were used to research the extent to which cancer had spread throughout the organ. Therefore, the woven fabric was excellently suitable for breast cancer detection application in the microwave imaging system under the various kinds of resolution stages correspondingly. The authors in [42] aimed to design and validate a directional Vivaldi antenna. Compared to a conventional Vivaldi antenna to detect electromagnetic waves at roughly 5 GHz emitted by the tumor cells. Compared to a conventional Vivaldi antenna, the suggested antenna was 33% more compact because of using metamaterials in its design, as illustrated in Fig. 22(a). It had respectable radiation properties, with a gain of 6.2 dB at 5 GHz and a reflection coefficient of -25 dB, as shown in Fig. 22(b). At an operating frequency of 5 GHz, the suggested metamaterial has

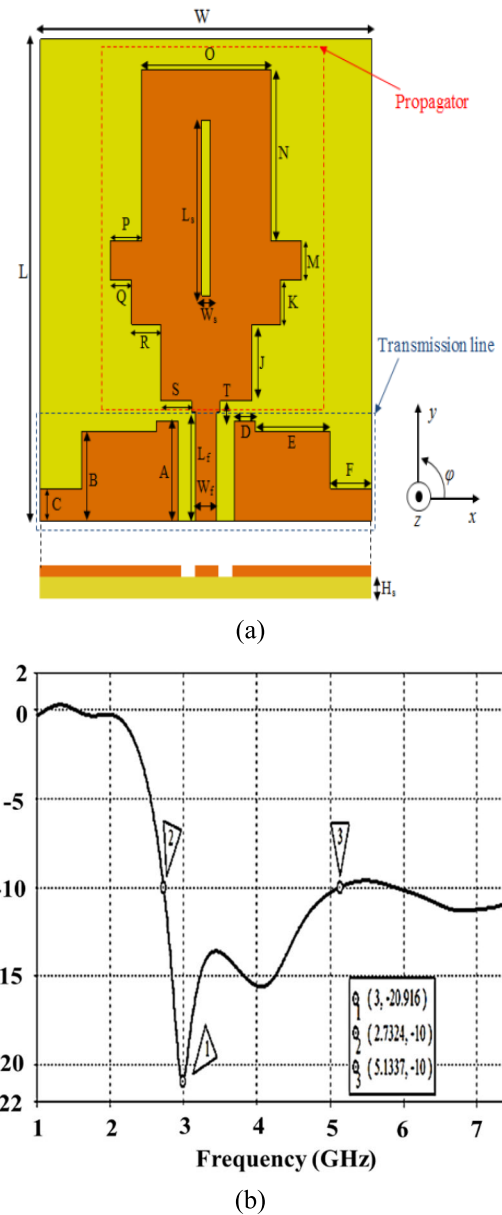


FIGURE 18. Developed antenna's (a) geometrical shape and (b) simulated S_{11} [39].

a unit cell size of $0.058\lambda \times 0.054\lambda$. An array constructed from the described antennas has been shown in experimental research to detect tumors in a liquid breast phantom with pinpoint accuracy by analyzing the amplitude of S_{11} at its minimum. To facilitate breast imaging and wireless body area network (WBAN) applications, the research in [43] introduced a metamaterial-based flexible wearable UWB antenna. The structure of the wearable antenna needed to be low profile while also being made of flexible materials. Six metamaterial unit cells with a modified grain rice shape were inserted into the antenna's split ring resonator to improve the antenna's bandwidth, gain, and directivity while keeping the SAR below 2 W/kg (Fig. 23a). The suggested antenna can function across a wide frequency range of 6.5–35 GHz (Fig. 23b) with

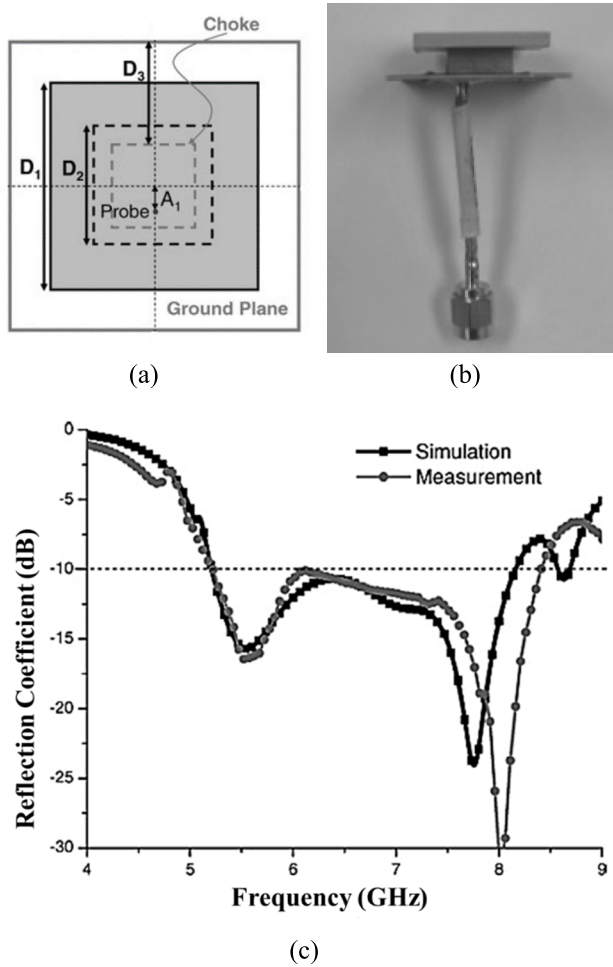


FIGURE 19. Stair-shaped DRA sensor, (a) geometry, (b) photo, and (c) simulated and measured reflection coefficient [38].

a maximum gain and directivity of 8.85 dBi and 10 dBi, respectively, and more than 70% radiation efficiency across its working frequency band. The results showed that the simulation and measurement of the suggested technique for detecting an existing tumor with a diameter of 4 mm from any place inside the breast were in good agreement. Using a microstrip patch antenna, a new measurement scheme for the breast phantom was provided, which was efficient, thorough, and compact [44]. Slots were carved into the patch and ground plane to increase the antenna's (Fig. 24a) electrical length and provide a high-gain, omnidirectional radiation pattern. This technique expanded the antenna's usable frequency range while maintaining or improving its gain and efficiency. The antenna had overall dimensions of 23 mm $\times$ 21 mm. The antenna has a fractional bandwidth of roughly 117%, 3.1–12 GHz (Fig. 24b), and an omnidirectional radiation pattern with a reflection coefficient of -10 dB. The antenna's performance on breast phantom measurements is validated by analyzing its response with a tumor sample using a variety of antenna parameters. To detect unwanted tumor cells deep within the breast, a simulation model was suggested where

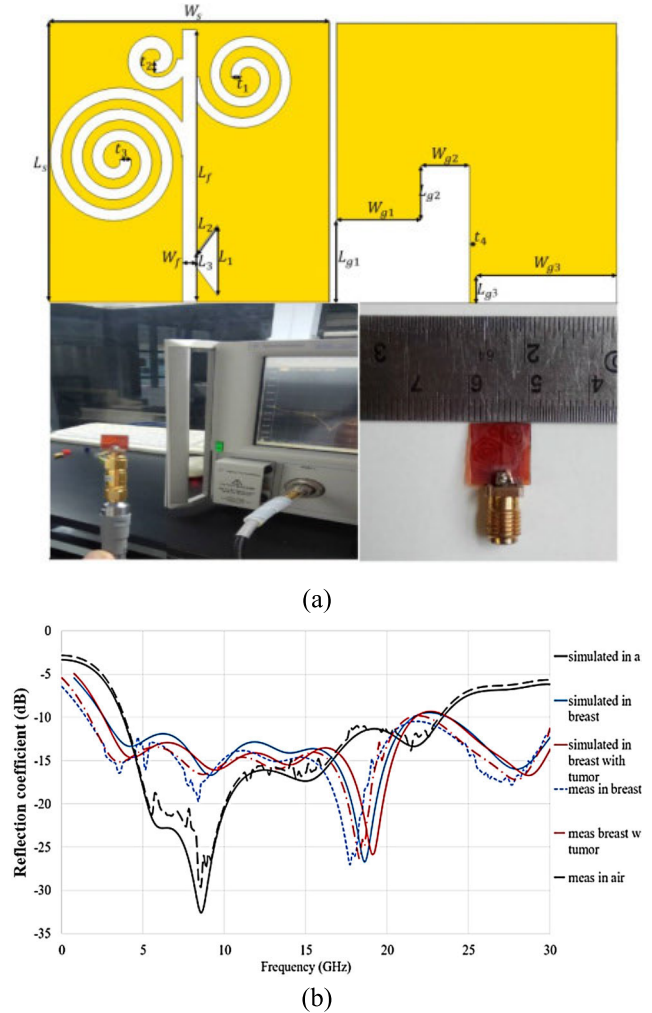


FIGURE 20. Flexible UWB antenna (a) photo of the prototype test equipment and (b) measured and simulated reflection coefficient in air, breast and breast with tumor [40].

the antennas function as a transmitter in a breast phantom measurement system.

A flexible UWB antenna was developed to detect breast cancer [45]. Monopole dual-polarized antenna printed on flexible PDMS dielectric with a 32 mm $\times$ 32 mm dimension. To increase the isolation between the antennas, a neutralization line that connects the monopole's ground planes and two stubs loaded at the monopole was added (Fig. 25a,b). When applied to the breast tissue, it covered a wide band ranging from 2.7–14 GHz (Fig. 25c). Because of the antennas' use of polarization diversity, a smaller array footprint was sufficient for wearable breast imaging applications without sacrificing the high accuracy of tumor identification. The study aimed to describe the design and construction of a reconfigurable textile antenna for microwave breast imaging that was based on a metamaterial (MTM) and supplied by a directional CPW employing RF varactor diodes and Fig. 26 (a,b,c) illustrated the fabricated antenna [46]. The results of the simulation and measurement of the MTM-based CPW-fed reconfigurable textile antenna indicated a

TABLE 1. Provides a synopsis of different substrates and designs employed in detecting breast tumor/cancer cells.

Citation	Size (mm ²)	Substrate	Antenna type or shape	ϵ_r	h (mm)	Operating band (GHz)	SAR (W/Kg)	
							1 gm	10 gm
[11]	28.9×37.25	Textile woven	E _F shape	3.8	1	3.32/3.33	---	---
[24]	60×50	Denim	Ground coplanar waveguide	1.4	0.7	7–28	0.7	0.171
[26]	24×24	Felt & denim	Vertically and horizontally polarized leaf and tree shape	1.2, 1.8	0.5, 0.9	4.8–30	0.115	0.671
[27]	50×50	Cotton	Monopole	1.9	2	2–6	1.16	---
[28]	36×48	Felt	AMC structure CPW coplanar	1.22	6.12	8–12	0.0996, 0.0704, 0.104	---
[29]	16×16	FR-4	Slotted patch	4.3	1.6	0.9–9.6	---	---
[30]	14×14	Rogger RO30100	Meandered line patch	10.2	0.5	2.56	---	1.24
[31]	16×71.5	Roggers RT/duroid5880(tm)	Elliptical shape MIMO	2.4	0.254	3.2–14	1	---
[33]	25×20	Flexible polyimide	Vivaldi	3.5	0.1	4–9.4	---	---
[34]	80×40	FR-4	Meander line	4.3	0.8	2.45	---	---
[35]	42.85×42.85	FR-4	Vivaldi	4.65	1.6	2.57–12.6	0.804	1.75
[36]	35.6×35.6	FR-4	5×5 array	4.4	1.6	2–14	---	---
[37]	50×50	FR-4	RPA	4.3	1.6	2.45	1.04	---
[39]	22×20	Kapton polyimide	Rectangular slot	3.5	0.05	2.73–5.13	---	---
[40]	10×10	Kapton polyimide	Spiral patch	3.5	0.125	3.26–23.37	---	---
[41]	---	Fabric woven	Jerusalem crossed patch	4.83,3.8	---	5.2	---	---
[42]	67×46	Roger	Metamaterial Vivaldi	10.2	0.64	5	---	0.0062
[43]	10×15	Denim fabric	Elliptical UWB	1.2	0.7	6.5–35	0.355	0.164
[44]	23×21	FR-4	Tapered slot	---	1.6	3.1–12	---	---
[45]	32×32	Flexible PDMS	Circular octagonal ring	2.7	0.75	2.7–14	---	---
[46]	80×61	Shield Super TM	Metamaterial	0.17	1.44	4–15	---	0.121
[47]	20×14	5-(4-(perfluorohexyl)phenyl)thiophene-2-carbaldehyde	RPA	---	1.6	4–6	---	---
[48]	20×19	FR-4	AMC structure	4.3	1.6	4.1–9.7	---	---
[49]	70×50	Jeans	Tuning fork shape	1.7	1	5.79	1.37	0.837
[51]	40×9	FR-4	Sierpinski fractals	4.4	1.6	2.79–12	---	---
[52]	70×60	Cotton	RPA with defected ground structure	1.6	1.6	1.6–11.2	---	---
[53]	0.30 λ ×0.31 λ	Rogers RT5880	Semi circle-shaped planar	2.2	1.575	2.3–11	---	---
[54]	36×36	FR-4	Antipodal Vivaldi	4.4	1.6	3.05–12.2	---	---
[55]	53×50	Kapton polyimide	Two elements array with T-junction	3.4	0.125	2–4	---	---

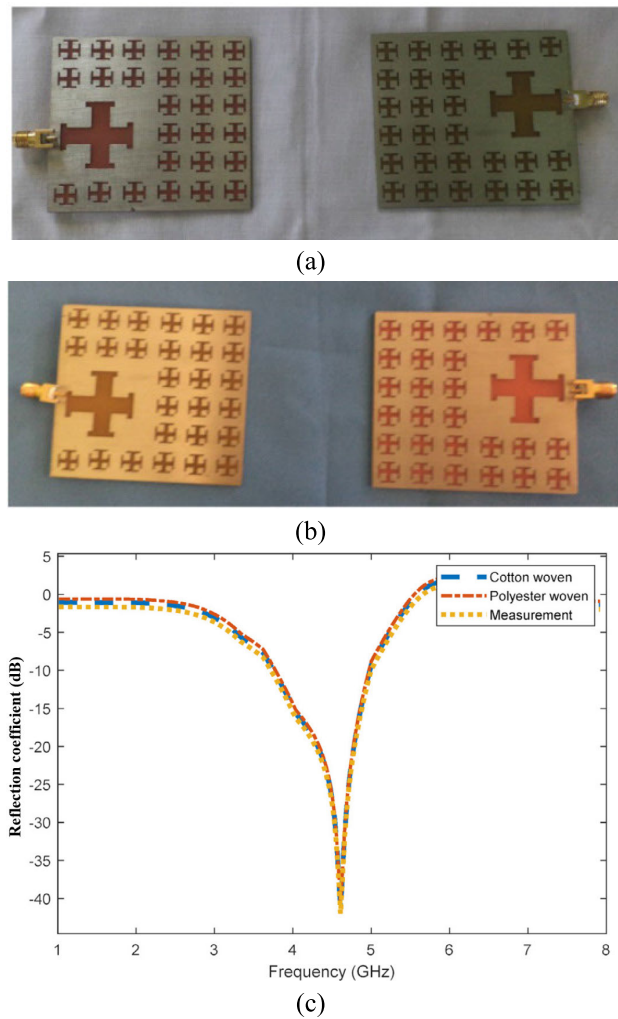


FIGURE 21. Woven fabric from (a) cotton, (b) polyester, and (c) their simulated and measured reflection coefficients [41].

continuous frequency reconfiguration to a discrete frequency band between 2.42 GHz and 3.2 GHz with a frequency ratio of 2.33:1, with a static bandwidth of 4–15 GHz (Fig. 26d). This frequency band was found to have a frequency ratio of 2.33:1. The deformed condition and analysis of the MTM-based reconfigurable antenna near the breast phantom were also performed. Image reconstruction employing delay-and-sum (DAS) and delay multiply-and-sum (DMAS) algorithms tested on a custom-made realistic breast phantom with heterogeneous tissue composition using this microwave imaging setup for simulation and measurement tests. It has been suggested clinical application of this approach for breast cancer diagnosis because the MWI system was able to detect a malignancy as tiny as 10 mm in the breast phantom.

Herein, a small UWB antenna was present on a flexible substrate that can be used for microwave imaging [47]. Presenting a bi-static radar-based imaging system with two omnidirectional antennas was simpler and more compact than previous microwave-based imaging systems, such as an array

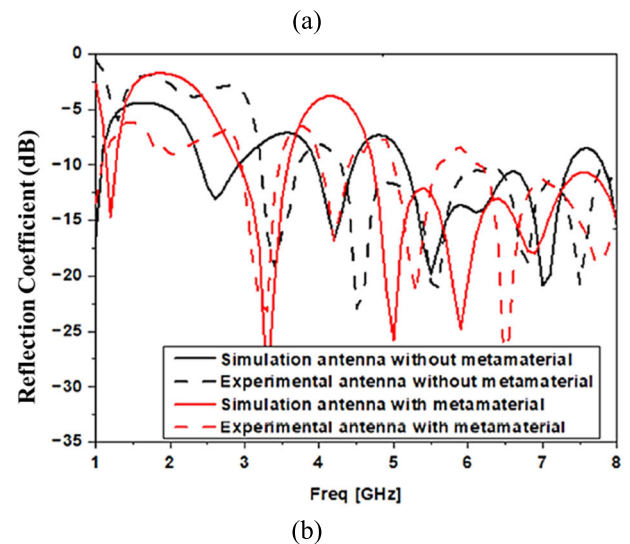
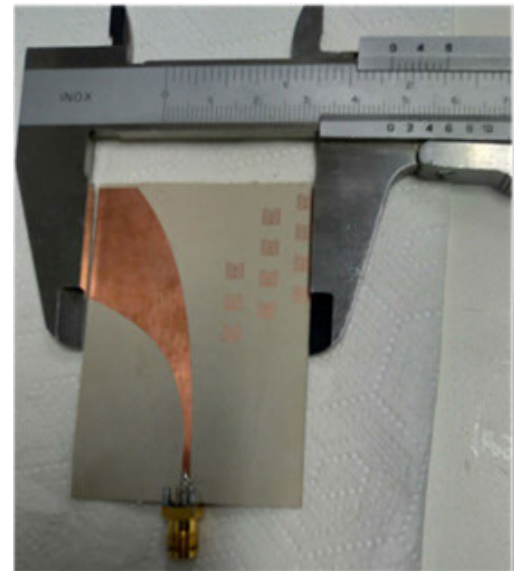


FIGURE 22. Vivaldi antenna (a) fabricated photo and (b) compared simulated and measured S_{11} with and without metamaterial [42].

of sixteen antennas. The antenna was $20 \times 14 \text{ mm}^2$ (Fig. 27a) and operated between 4–6 GHz (Fig. 27b). It was necessary to take into account the electromagnetic performances of the antennas. At the same time, the bent was easily implanted into a bra. In contrast to the recently reported flexible antennas, electromagnetic performance and imaging reconstruction were demonstrated for bending situations. The concept has been validated by testing the electromagnetic performances of a homogenous multilayer model of female breast phantom in both flat and bending situations. It was shown that the antenna has a good omnidirectional radiation pattern, with an average efficiency of over 70% and a gain of over 1 dBi, even when bent. The ultimate goal of the realized antenna was to inspire the development of a biodegradable, antenna-based bra for use in the early detection of breast cancer. Both theoretical and experimental work was done on developing a small multilayer UWB patch antenna for microwave breast

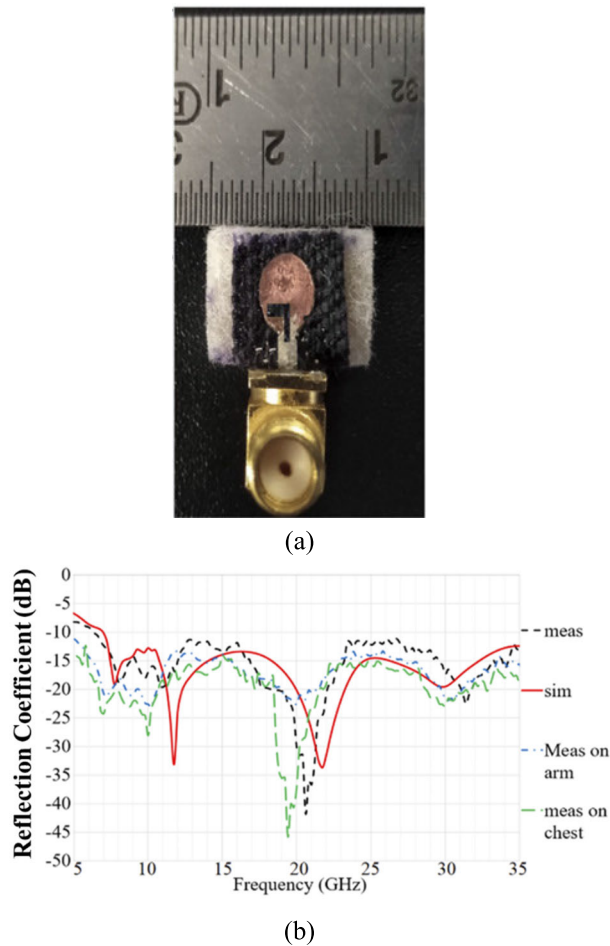


FIGURE 23. Antenna build with MTM (a) photo and (b) compared simulated and measured S_{11} and measurements of the antenna on the arm & chest [43].

imaging (MWI) applications [48]. However, to increase the antenna's bandwidth, the radiating element of the suggested original antenna was modified by the addition of a modified split ring resonator (SRR) and slits in the patch in addition to the ground plane (Fig. 28a,b,c,d,e), which improved the antenna's ability to transmit and receive electromagnetic waves. The antenna was then outfitted with a uniplanar AMC structure comprising a 3×3 array of square-modified SRR unit cells to obtain the necessary antenna parameters for MWI applications, such as the gain and directivity. The compact final prototype was $20 \times 19 \times 1.6 \text{ mm}^3$, but it achieved a reflection coefficient of less than -10 dB over a bandwidth of 7 GHz, 4.1–9.7 GHz (Fig. 28f) with a gain of more than 5 dBi. Finally, a breast phantom model with a tumor sample and a simulation model of the antennas that function as a transceiver was presented for the detection of cancerous tumor cells within the breast. Using a textile (jeans-based) flexible antenna, breast tumor detection was demonstrated in this work [49]. Jeans were used as a model for the proposed textile antenna, and copper was used as a patch (in the shape of a tuning fork) and ground plane (Fig. 29a)

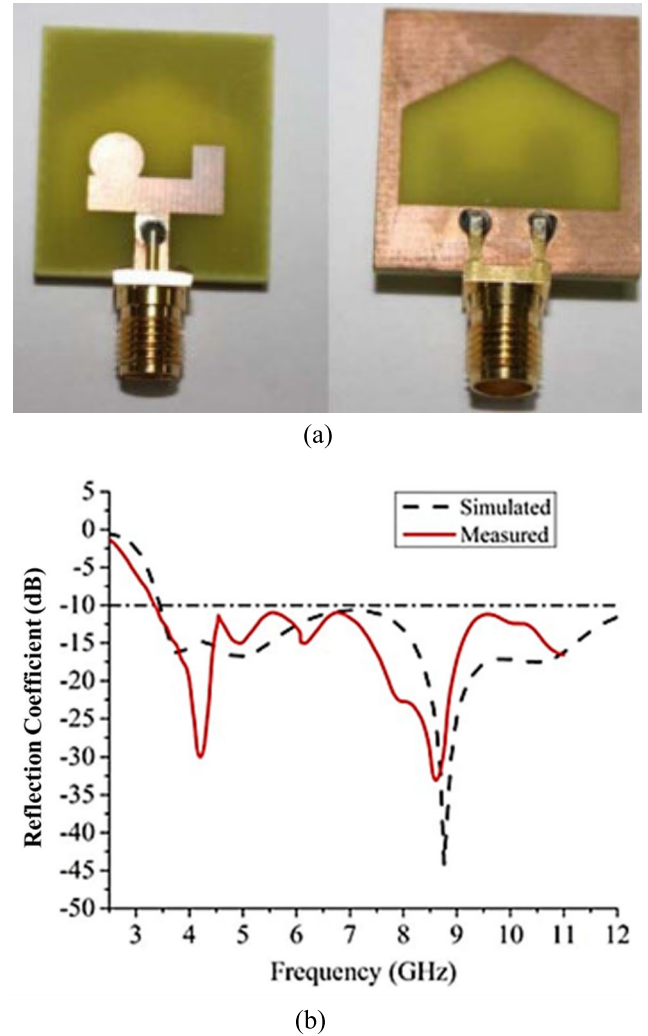
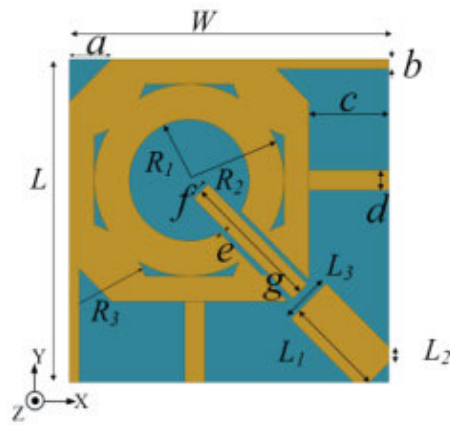


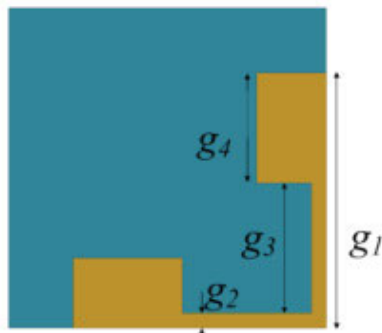
FIGURE 24. Taperd slot antenna (a) photo of the top side (left) and bottom (right) & (b) simulated and measured S_{11} [44].

in an antenna simulation. Jeans serve as a model for the antenna's substrate. To optimize antenna performance and guarantee human safety in the presence of electromagnetic waves, multiple simulations were carried out by CST MWS-2021 to determine the reflection coefficient, VSWR, 3-D & 2-D radiation pattern, surface current, radiation efficiency (%), and SAR. Such a textile antenna, designed as a tuning fork, resonated at 5.7911 GHz (Fig. 29b) of the ISM band. For 1 gm & 10 gm of tissue, respectively, the SAR value was calculated to be 1.37 W/Kg and 0.837 W/Kg through modeling. Perhaps most importantly, the proposed antenna can be utilized in tandem with microwave scattering technology to aid in the identification and detection of breast tumors with only a little difference between healthy and unhealthy breast tissue.

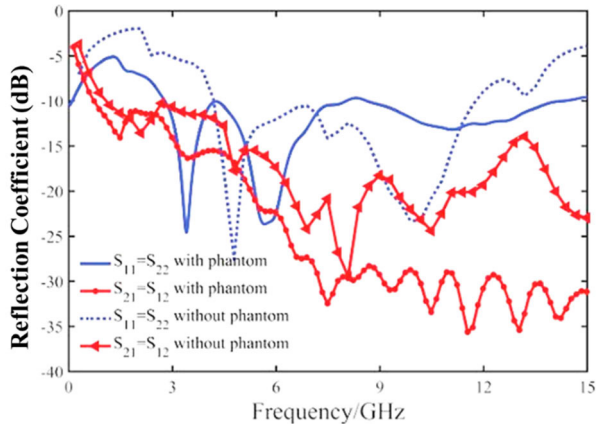
A UWB Sierpinski fractal micro-strip patch antenna (MSA) with decreased ground was developed and used for cancer detection by transmitting microwave signals into a homogenous breast model [51]. The proposed method was



(a)



(b)



(c)

FIGURE 25. Proposed UWB antenna's, (a) top, (b) rear view, and (c) simulated S_{11} [45].

considered a potential substitute for the current methods because of its low cost, lack of involvement in dangerous ionizing radiations, increased radiation efficiency, and compact antenna size (Fig. 30a). Such an antenna with a reduced ground allowed it to reach UWB and increase bandwidth. Regarding bandwidth, the ideal antenna achieved 9.71 GHz, (2.79–12 GHz) (Fig. 30b). A unique design (Fig. 31a) provided for an enhanced bandwidth wearable microstrip patch UWB antenna for use in breast cancer detection [52]. The antenna operated between 1.6–11.2 GHz (Fig. 31b).

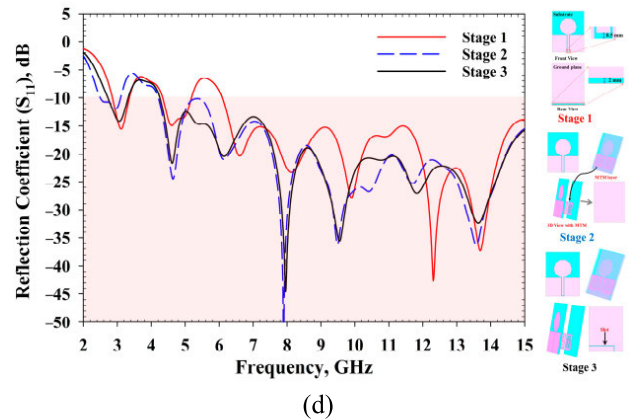
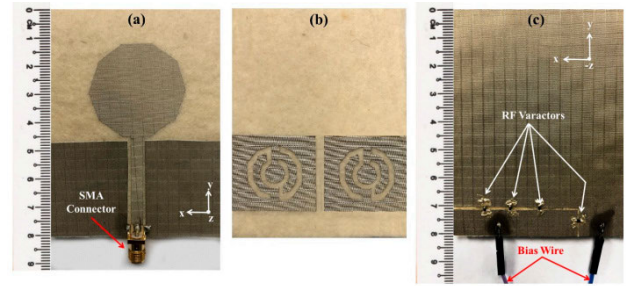
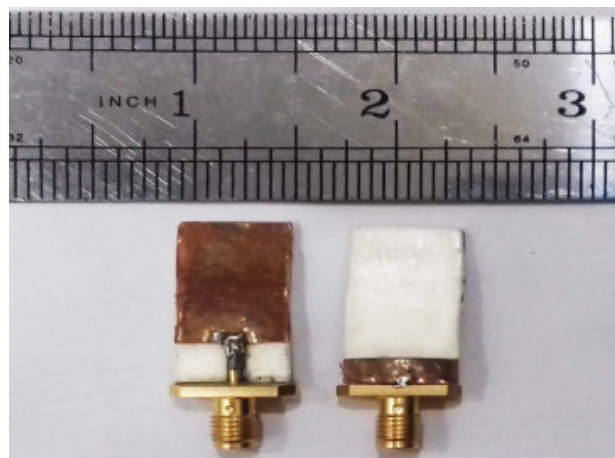
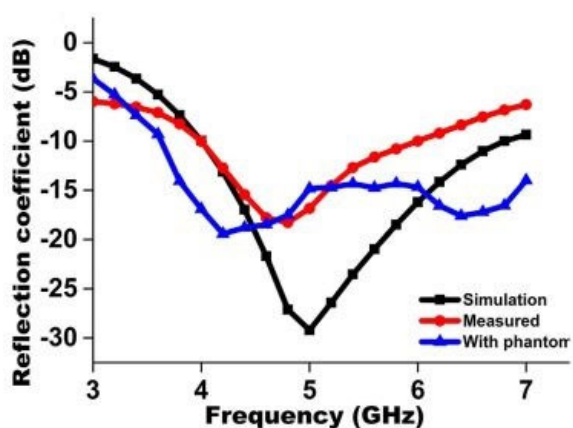


FIGURE 26. MTM-driven reconfigurable antenna prototype shows the three layers of fabrication: (a) the top, (b) the MTM & (c) the bottom layer, and (d) reflection coefficient [46].

The antenna had a rectangular feed line connected to a rectangular radiating patch, which is an antenna concept implemented in a breast cancer screening device that women can wear. A small planar UWB antenna was introduced (Fig. 32a), and an antenna array configuration was used for microwave breast imaging [53]. A semicircular patch with slots and a partly trapezoidal ground were used to create the proposed antenna. Several parameters were optimized for great performance. The antenna accomplished an operational bandwidth of 8.70 GHz, 2.3–11 GHz (Fig. 32b) with an acceptable impedance matching, 5.80 dBi of maximum gain, and a consistent radiation pattern. Many measurements were performed to determine its performance. A 16-antenna array-based setup was proposed to measure the breast phantom's backscattering signal. Within this arrangement, one antenna acts as the transmitter, and the remaining 15 antennas receive the scattered signals. The data were collected using the phantoms “with tumor” and “without tumor” configurations. In a later step, the Iteratively Corrected Delay and Sum (IC-DAS) image reconstruction algorithm was applied to locate the tumor in the breast phantom. After the algorithm analyzes and processes the backscattering signal, the reconstructed images are shown to prove the algorithm's imaging prowess. A unique UWB antipodal Vivaldi antenna was developed (Fig. 33a,b) with three sets of slots to diagnose breast cancer as a sensor in microwave imaging systems [54]. The suggested antenna operated at 3.05–12.2 GHz (Fig. 33c). The antenna's were investigated, and the results showed that they satisfied the requirements for UWB radar applications with



(a)

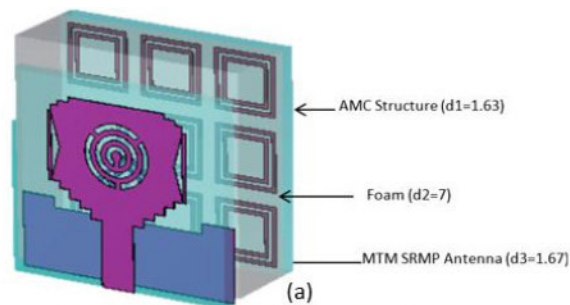


(b)

FIGURE 27. UWB flexible antenna (a) fabricated prototype and (b) measured and simulated reflection coefficients with and without phantom loads [47].

linear phase response, nearly constant group delay, UWB, and directional properties at most of the operating frequency. Cylindrically arranged breast-mounted antennas were used to transmit a Gaussian pulse and receive the reflected signal. Following the signal processing, the tumors were screened at the correct places using a high resolution. Finally, a fully automated method for scanning the prone breast phantom with monostatic radar was created. To carry out experimental measures, a realistic electrically and anatomically realistic homogenous breast phantom that featured a tumor on the interior was constructed. When applied to a breast tumor, the suggested antenna and the microwave imaging system built with this antenna are well-suited for early detection of this disease.

Table 1 summarizes the information on 29 different antennas on substrates. By reducing the surface wave losses caused by the substrate, antenna impedance bandwidth was enhanced. Substrates were required to have low dielectric constants. A planar antenna's bandwidth can be improved by increasing its dielectric thickness; however, this



(a)



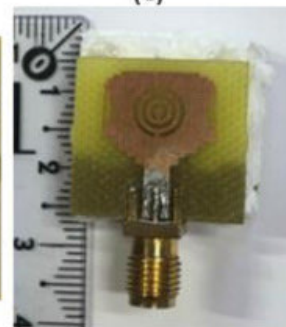
(b)



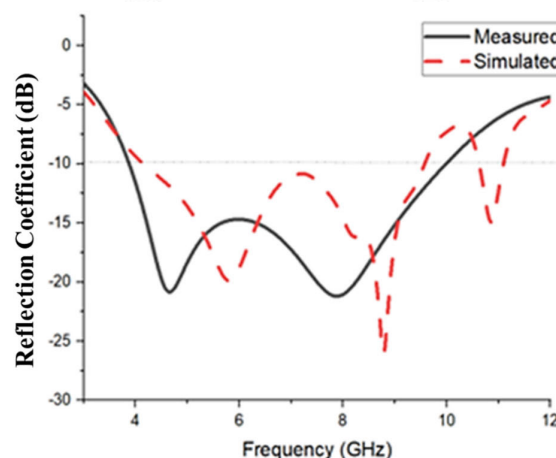
(c)



(d)



(e)



(f)

FIGURE 28. (a) 3-D structure, (b-e) fabricated proposed antenna, and (f) combination of simulated & measure S_{11} [48], [50].

method did not generally optimize its performance. Gain and bandwidth were two aspects that were compromised

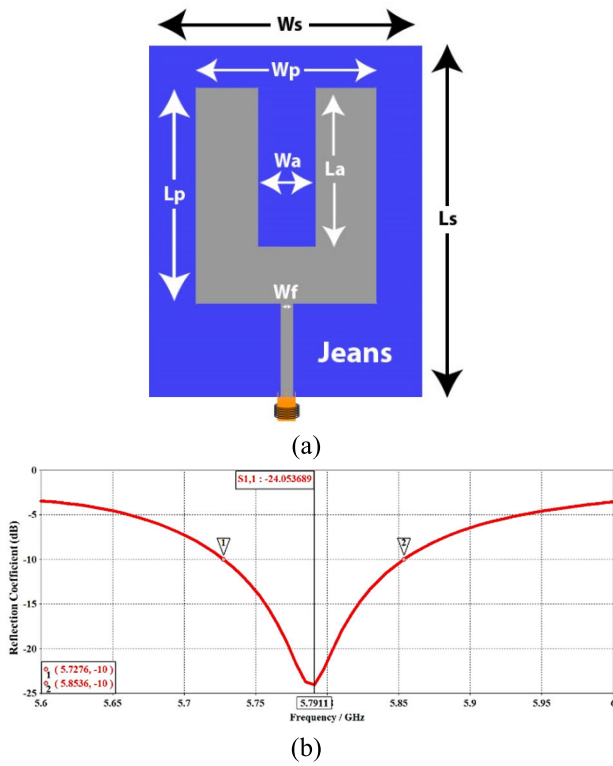


FIGURE 29. (a) Tuning fork shape wearable antenna's layout and (b) simulated S_{11} [49].

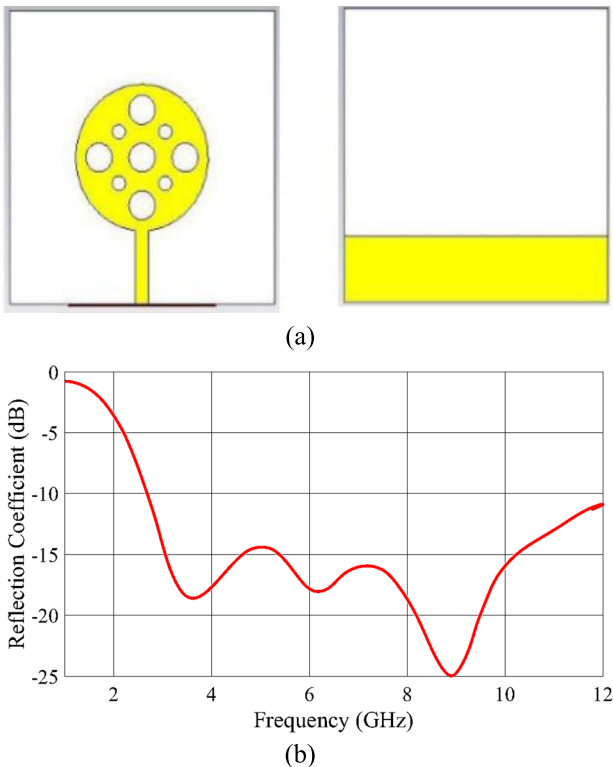


FIGURE 30. Proposed UBW antenna's (a) front & rear view and (b) S_{11} [51].

by its dielectric thickness. The substrate thickness was a common factor that impacted the structural dimensions

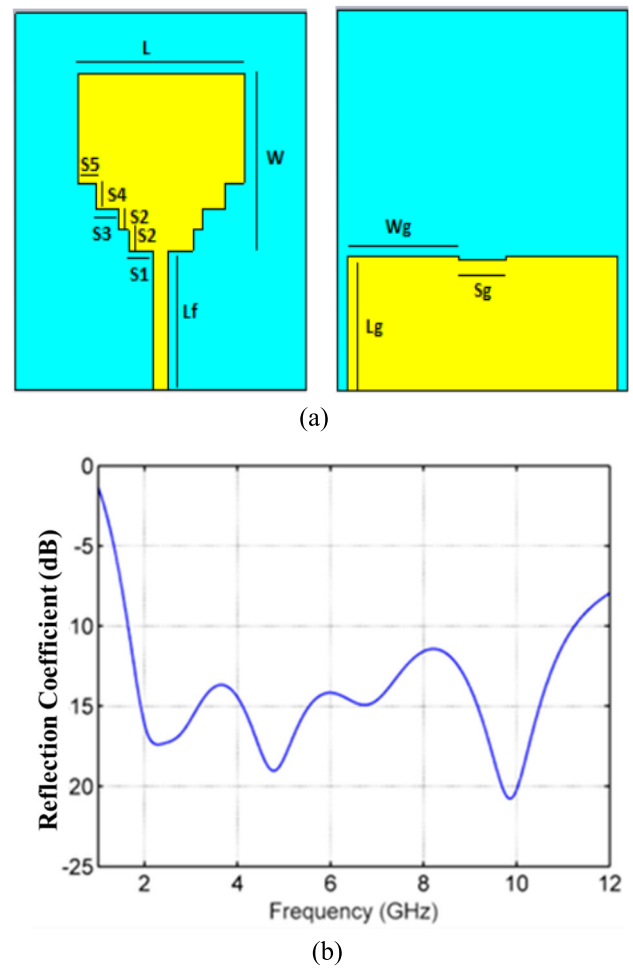
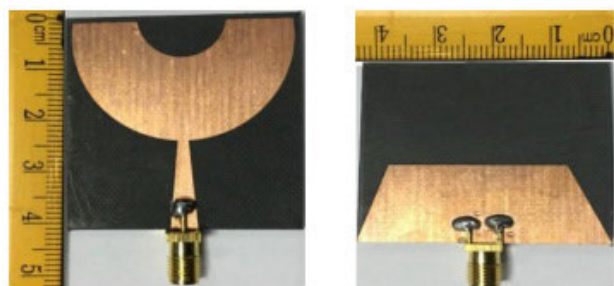


FIGURE 31. UWB antenna (a) front and back of the antenna substrate and (b) simulated reflection coefficients [52].

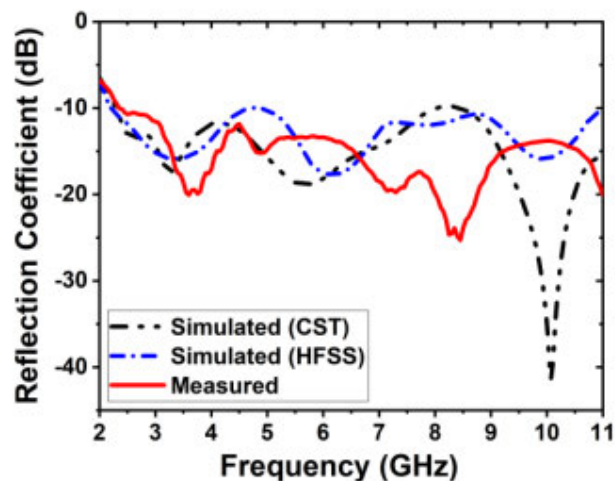
of the antenna. Consideration of the size, efficiency, and difficulty of establishing various applications (such as ISM band, Wi-MAX, UWB, WLAN, Bluetooth, etc.) was crucial when designing integrated wearable antennas. This section highlights the significant influence of denim fabric, Rogers RT 5880, and Kapton polyimide on antenna design. In addition to being cost-effective, such substrates are readily available on the market. According to the findings of this research, the substrates made of Kapton polyimide, denim, and Rogers RT 5880 exhibit remarkable performance in terms of bandwidth and gain, while also being compact.

III. METHOD OF BREAST TUMORS/CANCER DETECTION

Computed tomography (CT), positron emission tomography (PET), magnetic resonance imaging (MRI), ultrasound, and X-ray imaging are widely used medical diagnostic techniques for detecting cancer, stroke, tumors, and other malignant conditions in the human body [56], [57]. Each of these imaging modalities has its unique advantages and limitations. **Negative Aspects of CT and X-ray Imaging, Exposure to**



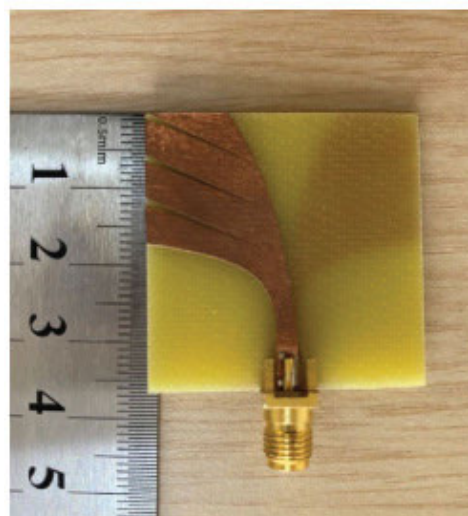
(a)



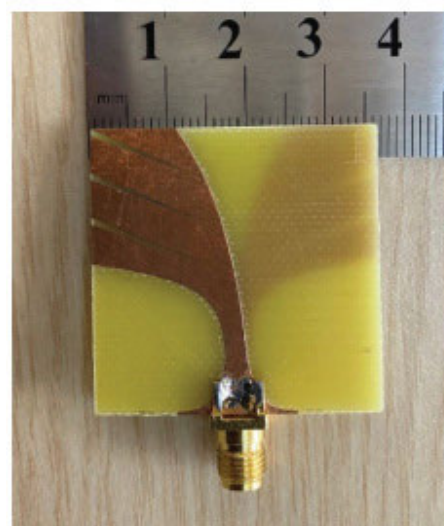
(b)

FIGURE 32. SPA antenna (a) photo and (b) measured and simulated reflection coefficients [53].

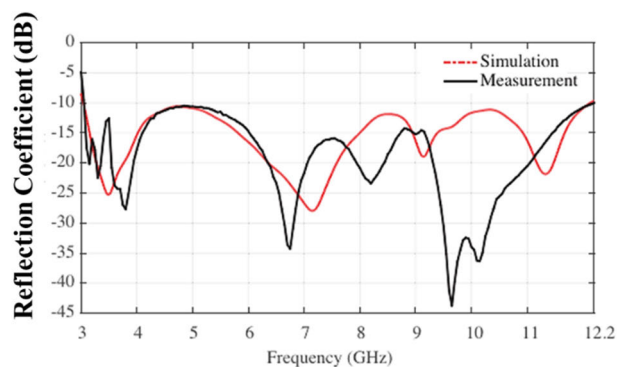
Harmful Radiation: Both CT and X-ray imaging involve ionizing radiation, which can damage living tissues and increase the risk of cancer. CT scans generally expose patients to higher doses of radiation than standard X-rays due to the detailed cross-sectional images they provide. **High Rate of False Negatives:** These techniques can sometimes fail to detect abnormalities, especially in the early stages of disease. This high rate of false negatives can delay diagnosis and treatment, potentially worsening patient outcomes. **Decreased Sensitivity:** CT and X-ray imaging may have lower sensitivity in detecting certain types of tumors or subtle pathological changes compared to other imaging methods such as MRI or PET. **Increased Cancer Risk:** Prolonged or repeated exposure to ionizing radiation from CT and X-ray imaging increases the risk of developing cancer. The risk is proportional to the dose and frequency of exposure, making it a significant concern, especially for patients requiring multiple scans over time. **MRI Imaging, Advantages:** MRI is highly effective in visualizing soft tissues, making it particularly useful for detecting disorders such as breast/brain tumors, spinal cord injuries, and joint abnormalities. It does not involve ionizing radiation, making it safer for repeated use. **Disadvantages:** MRI is more costly than other imaging techniques and may be less effective in certain



(a)



(b)



(c)

FIGURE 33. Configuration that has been fabricated of the intended Vivaldi antenna: (a, b) front, rear view and (c) simulated & measured reflection coefficient [54].

situations, such as imaging bone structures. Additionally, it can be less accessible due to the higher costs and longer

scan times. **Ultrasound Imaging, Advantages:** Ultrasound is a non-invasive and cost-effective imaging technique that does not involve ionizing radiation. It is particularly useful for monitoring fetal development, evaluating abdominal organs, and guiding needle biopsies. **Disadvantages:** Ultrasound cannot provide as detailed images as other modalities like MRI or CT, making it less effective for diagnosing certain conditions. **PET Imaging, Advantages:** PET scans are highly effective in differentiating between malignant and non-cancerous cells, which is crucial for accurately diagnosing and staging cancers. **Disadvantages:** PET scans involve the use of radioactive tracers, which can pose risks, particularly for pregnant women. The radiation exposure, although typically low, still requires careful consideration. **Advances in Microwave Imaging:** In recent years, numerous studies have focused on developing imaging systems using microwave technology for the early detection and diagnosis of various disorders, including cancer, tumors, strokes, and internal brain bleeding. Microwave imaging offers several potential benefits: **Non-Ionizing Radiation:** Unlike CT and X-ray imaging, microwave imaging does not use ionizing radiation, reducing the risk of radiation-induced cancer. **Early Detection:** Microwave imaging has the potential for early detection of various conditions due to its sensitivity to changes in tissue properties. **Safety and Accessibility:** This technique is expected to be safer and more accessible, providing a cost-effective alternative to existing imaging modalities.

Overall, while each imaging technique has its strengths and weaknesses, ongoing research and technological advancements continue to improve diagnostic capabilities, aiming for safer, more accurate, and cost-effective methods for detecting and diagnosing medical conditions [57], [58], [59], [60]. Two methods exist in microwave imaging (MWI): radar and tomography-based imaging. Microwave tomography-based imaging (MWTI) is a technique that involves the transmission of a narrowband microwave signal into the breast to determine the breast's dielectric characteristics. It uses a network of receiving antennas to gather the backscattered signals. Nevertheless, this technology necessitates the utilization of many transmitting and receiving antennas. The reconstruction algorithm is computationally demanding, and tackling the non-linear inverse scattering problem is another need. Antennas, either the transmitting antenna alone (monostatic), a network of antennas (multistatic), or are employed to Tx and Rx backscattered signals in radar-based imaging. The monostatic configuration can be utilized from various angles to generate adequate image channels. The alternative approach, a multistatic antenna array, gathers backscattered signals through several stationary antennas in one spot. This technique sidesteps the mechanical problems with monostatic imaging systems. In recent years, imaging technologies have developed successfully to operate on this principle [7], [59], [61]. Antennas are really important for obtaining high-quality images in MWI. A transmitting antenna transforms into a receiving antenna (sensor) during the subsequent iteration,

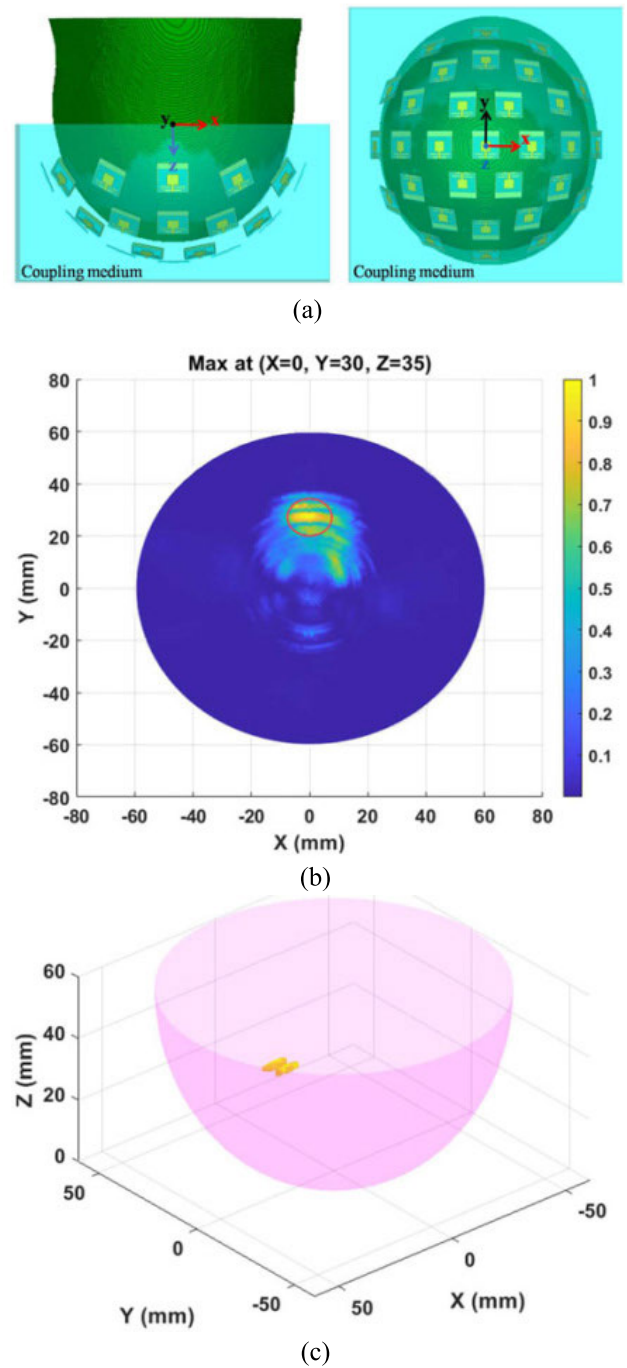


FIGURE 34. Antenna array systems for tumor detection (a) Arrangement of the antenna array surrounding the breast model, (b) 2D image shows a tumor located at coordinates ($X = 0$ mm, $Y = 30$ mm, $Z = 35$ mm) within the breast model and (c) image generated by 3D reconstruction of the identified tumor [29].

functioning as transceivers (Tx/Rx). Therefore, meticulous antenna design is necessary to fulfill the system's needs. According to recent research, antennas for MWI should be compact, have high gain, radiate directed power, and have a wide bandwidth [61]. Another crucial factor is the operational frequency band; lower bands allow for deeper

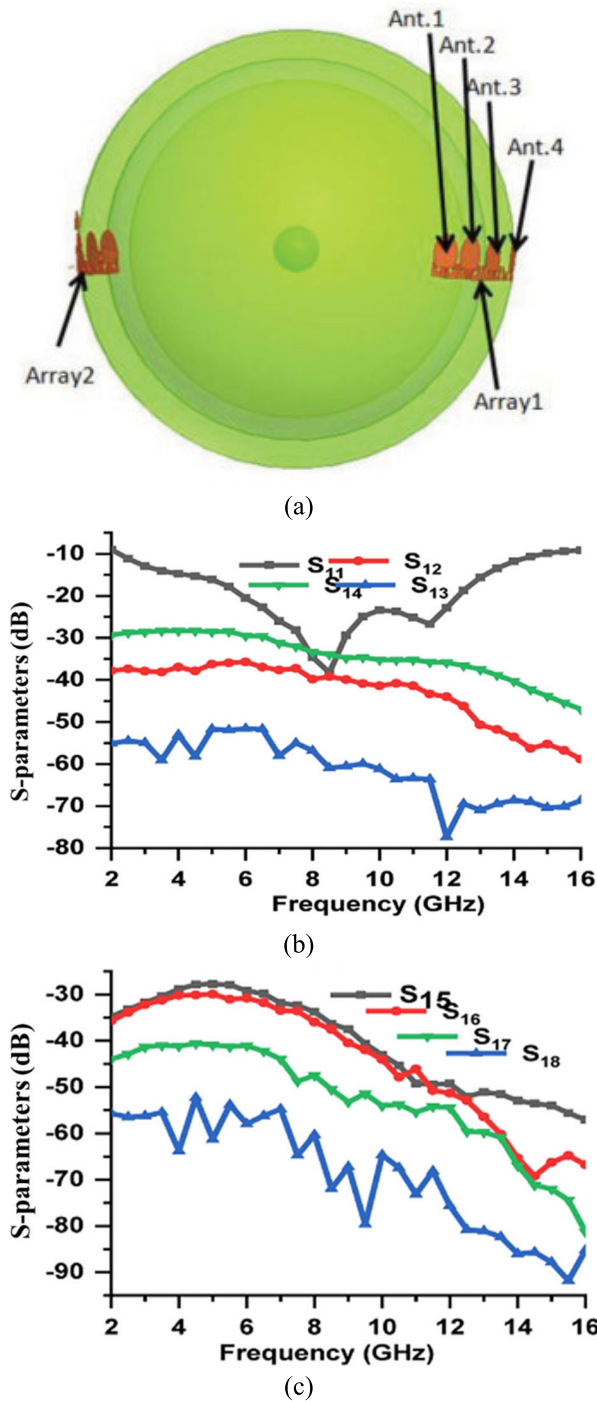


FIGURE 35. MIMO breast system and S-parameters when port 1 is active (a) MIMO model with heterogeneously, (b) S_{1i} ($i = 1,2,3,4$) of Tx antenna, and (c) S_{1i} ($i = 5,6,7,8$) of the Rx antenna [31].

penetration, while higher bands provide superior range resolution. On the other hand, a bigger antenna footprint is needed for lower frequencies, while power losses are higher at higher frequencies. A woman's breasts are a complicated and uneven mosaic of skin, adipose tissue, glands, and muscle. Several uniform layers, each representing the characteristics of skin, fat, glands, and muscle, can be stacked

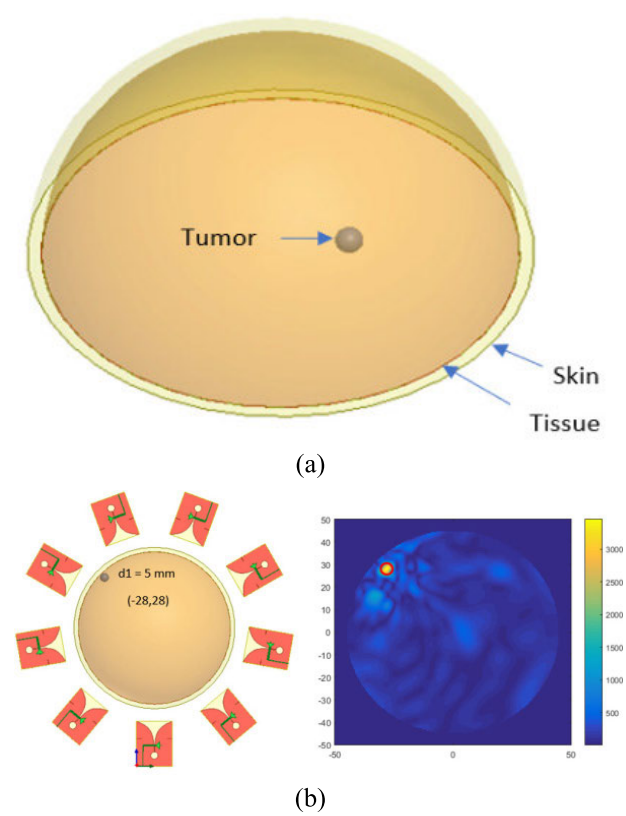


FIGURE 36. (a) Suggested a breast phantom model and (b) configuration of the image & detection of tumor [33].

to simulate this heterogeneous environment. Preprocessing backscattered signals to eliminate reflections and artifacts is essential for effective imaging systems. The literature reports some artifact removal algorithms. Fig. 34(a) shows that the antenna array is developed in the simulation environment to demonstrate that the suggested antenna can detect breast tumors based on its performance [29]. Reconstructing the high-fidelity tumor images relies on the received signal being strong enough. At the chosen frequencies, the simulation results provide a strong signal, proving that the suggested antenna has an excellent near-field radiation characteristic around the breast model. In addition, the breast phantom contains a tumor that is 5 mm in diameter. According to the simulation setup in Fig. 34(a), the tumor is positioned inside the glandular tissue with the exact coordinates of ($x = 0$ mm, $y = 30$ mm, $z = 35$ mm) for this specific study. Next, the tumor's precise position is determined using a multistatic radar-based imaging technique. Given that an array with N elements will have N monostatic time-domain signals and $N(N-1)/2$ bistatic time-domain signals. As a result, the simulation environment collects $N(1+(N-1))/2$ time-domain signals equivalent to 496 signals from the 31 elements. A calibration process is applied once the recorded signals have been obtained to remove the effects of the coupling medium and the skin. After calibration, two- and three-dimensional picture reconstructions are carried out using an enhanced

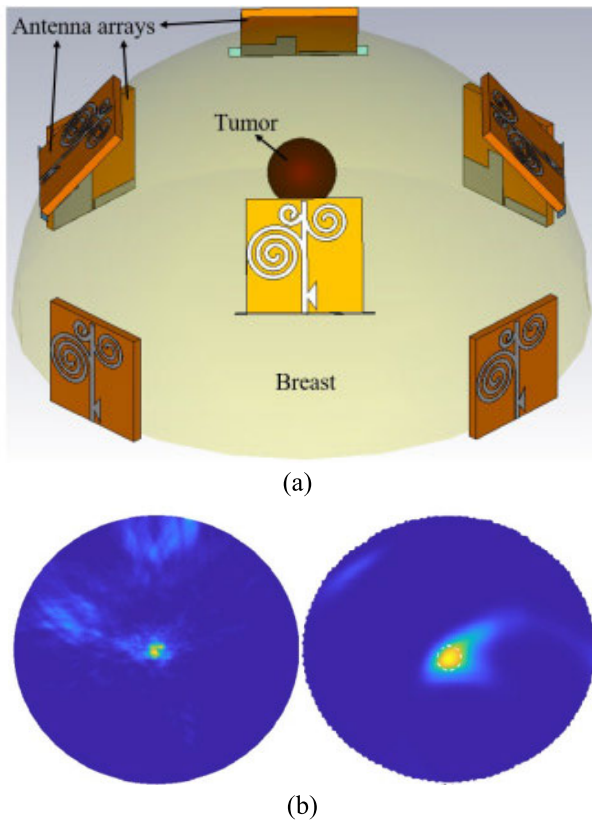


FIGURE 37. 8-element array surrounding a breast (a) sketch of the simulated environment and (b) measured (left) and simulated (right)-image from the time-reversal algorithm's reconstruction of the picture [40].

DAS algorithm. The 2D and 3D tumor reconstructions are shown in Fig. 34(b,c). A red circle in Fig. 33(b) illustrates the tumor location and the intensity of the reconstructed image, which is quite accurate. Fig. 34(c) shows the creation and viewing of 3D pictures for accurate tumor detection.

Multiple antenna pairs were used to calculate the amplitude S_{21} (transfer) for the Tx and Rx MIMO antennas with phantom depicted in Fig. 35(a) [31]. The breast phantom, Tx, and Rx antennas were all located close to one another in the suggested breast cancer detection system, which allowed for complicated propagation and antenna response, as the electrical characteristics of biological tissues determined such performance. Simulations were used to study various antenna pair's power efficiency and group delay. The power Tx and Rx while using the UWB pulsing antenna is shown in Fig. 35(b) and (c). Breast cancer detection can benefit from this approach because of its high fidelity, greater than 0.87. The MATLAB software was used to acquire the different parameters, including group delay, power efficiency, fidelity, and figure of merit. A recent study created a half-sphere breast phantom miming the human breasts electrical characteristics [33]. In addition to having three layers, the phantom had a radius of 45 mm. A dielectric constant of 36 and a conductivity of 4 S/m characterize the skin layer with a width

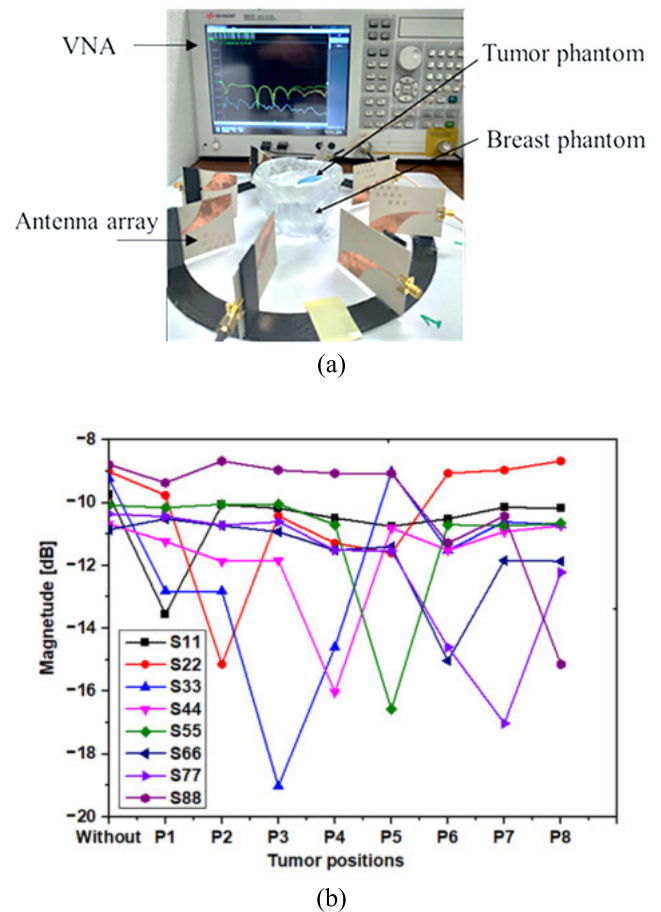


FIGURE 38. 8-element array surrounding a breast phantom (a) photo of the experimental setup and (b) S_{1i} ($i = 1, 2, \dots, 8$) at 5.34 GHz [42].

of 2.5 mm. There was a conductivity of 0.4 S/m and a dielectric constant of 9, indicating that the fat layer (was 42.5 mm wide). A 2.5 mm diameter and 5 mm radius spherical tumor were implanted in various locations within the phantom. For the tumor, a relatively high dielectric constant of 55 and a conductivity of 4 S/m were considered. The imaging setup included a transmitting and receiving antenna element ringed by the suggested breast phantom. The Vivaldi antenna served as both a transmitter and receiver. The nine antenna elements served as both transmitters and receivers. Fig. 36(b) illustrates that the nine antennas are arranged in a grid pattern, each 10 mm apart from the phantom. The antennas' radiating sides were facing the phantom. All antennas received a signal from Antenna1, as Tx at 4.3 GHz. The 3.65–5.2 GHz range was used to collect backscattered signals. Because tumors include high-dielectric material, the results demonstrate that their presence enhanced the reflected signal magnitude. In addition, the signal strength was reduced in the absence of the tumor in the breast phantom. Various tumors were detected inside the suggested half-spherical breast model using the imaging setup depicted in Fig. 36(b). The suggested technique might detect even 2.5, 5, and 10 mm radii tumors with different positions in the breast. The dark blue item

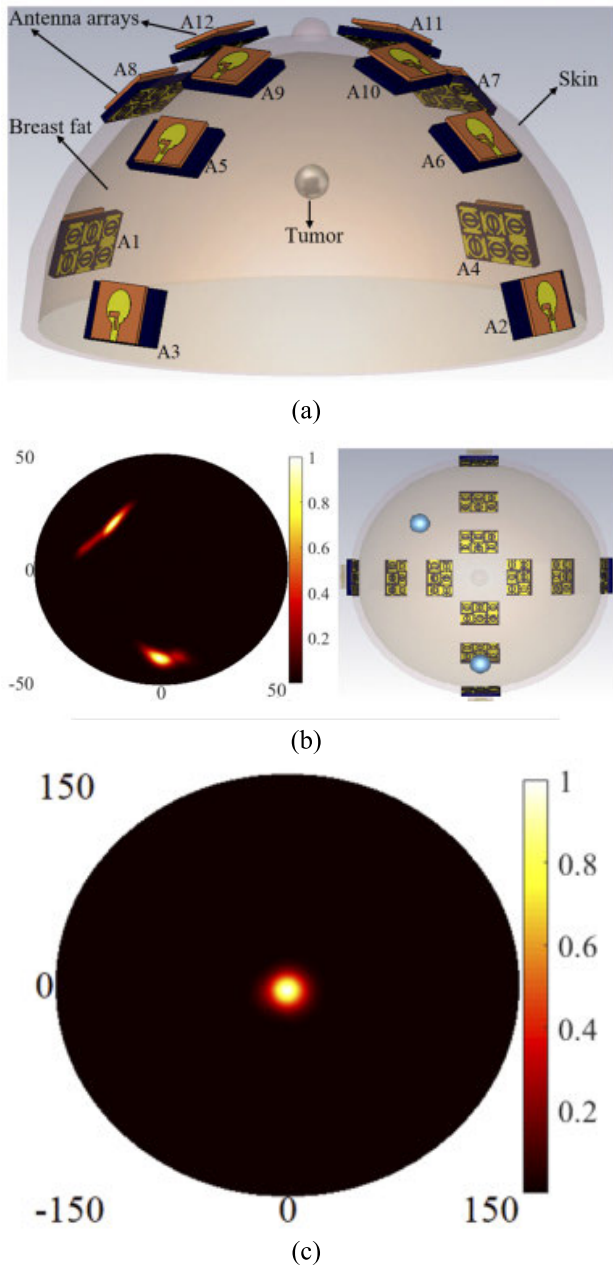


FIGURE 39. Antenna elements arranged in two plane cuts around the breast (a) a 3D sketch of the model, (b) an image of two breast tumors reconstructed (left), and a top view (right) of the array, and (c) an image of breast phantom with a 150 mm radius [43].

represents typical healthy tissues (Fig. 36b). The reconstruction image revealed the tumor's size and position as a red circle.

To allocate a 5 mm tumor in the middle of a 75 mm breast phantom, an 8-element array was positioned around the breast antenna (Fig. 37a) [40]. The time-domain features were studied and assessed using the breast phantom to test the suggested antenna's performance in a realistic setting similar to the breast. The direction vector's actual component was when the signal from one antenna reaches the other seven antennas (Antenna1 is operational). Since the

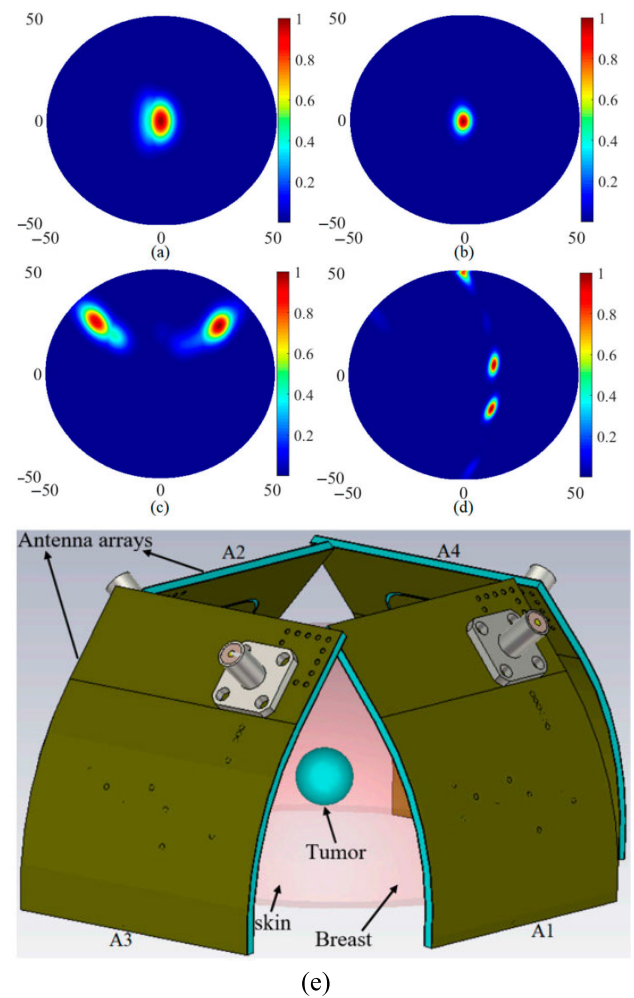


FIGURE 40. Reconstructed images from the four array signals and time reversal algorithm: choose from the central tumor with (a) skin, (b) without skin, (c) two tumors, (d) three tumors and (e) simulated breast phantom's antenna array setup [24].

electromagnetic waves can pass through the breast sample relatively easily, this enhances the system's power efficiency and the antenna's capacity to detect breast tumors. Fig. 37(b) shows the finalized image of the tumor in the breast's center, which was created by applying a conventional time-reversal algorithm to the received pulses from all the arrays extracted from CST after the time domain investigations and examinations of the antenna were completed. The suggested structure for the antenna array used in tumor detection is illustrated in Fig. 38(a) [42]. With its eight pieces arranged in a circular and symmetrical pattern, the antenna array features antennas in a 45° apart. An antenna array system presents several challenges, the most significant of which is determining the maximum distance when the antenna reader can identify the tumor. To detect tumor cells, the eight antennas were positioned 25 mm distant from the surface of the breast phantom. The scenario that has been provided for the diagnosis of breast cancer relates to the use of the first antenna as a transmitter. In contrast the remaining seven

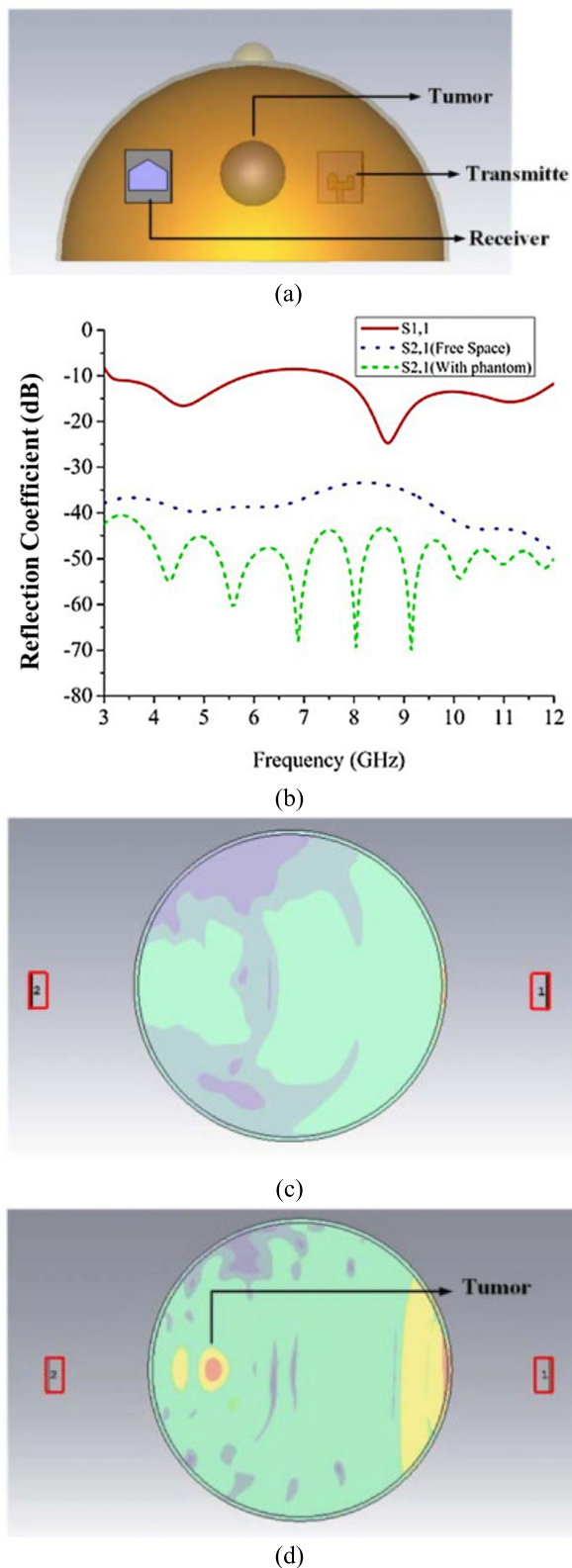


FIGURE 41. Tx and Rx arrangements (a) sketch of the arrangements with breast phantom, (b) S-parameters, (c) image of a healthy breast, and (d) image of a breast has a tumor [44].

antennas were utilized as receivers. If S_{11} is the lowest, then, just like with the other antennas, it has been inferred

that position 1 has a tumor (Fig. 38b). Also, a tumor and, by extension, an infected breast, cannot be present when the S_{11} readings of the eight antennas do not show a peak. Some significant parameters that can potentially influence the imaging processes were explored and evaluated before constructing an image of a tumor in the breast utilizing the simulation data [43]. Following the simulation configuration depicted in Fig. 39(a), twelve antenna arrays were situated near the breast to study the consequences of those arrays on one another. One of the most important aspects that must be considered is the presence of the receiving signals from various arrays. One array, A1, serves as the transmitter in these studies, while the others serve as receivers. The findings showed that the UWB antenna setup could detect a tumor with a diameter of 4 mm. A tumor with a diameter of 4 mm was selected for this experiment to determine whether the antenna arrays could detect a target smaller than the size. However, 12 antenna arrays eliminated all artifacts and clutter from the skin layers and the other arrays, resulting in the cleanest reconstructed image. To assess the capabilities of the UWB antenna system for image reconstruction, two tumors—one in the middle and one off center—are placed inside the breast. A robust time-reversal algorithm was utilized to reconstruct the image. Fig. 39(b) illustrates that both tumors were identified appropriately. Despite this, there were a few insignificant pieces of clutter. Another important consideration was checking if the antenna system could detect the same 4 mm diameter tumor in a larger breast sample. Due to this, the imaging environment in the simulation was designed to accommodate a breast size with a diameter of 150 mm. Fig. 39(c) demonstrates that the antenna system can detect and localize the tumor within a bigger breast sample.

Within the breast phantom with a 100 mm diameter, the simulation setup of the proposed wearable antenna is depicted in Fig. 40(e). The array of elements consisted of four individuals [24]. The tumor image was reconstructed through signal analysis using the received signals and with the temporal delay. The on-body and off-body received signals from the various array elements (A2-A4). The other arrays received the signals from Array1 (A1). Although the signal's amplitudes varied and altered, their shapes remained unchanged when shown to the breast model. Investigating and evaluating the proposed antenna's characteristics in on-and off-body conditions (with and without tumors) led to an evaluation of the antenna's capability in image reconstruction of breast tumors under different conditions, including those with and without skin, two and three tumors, and a central tumor and Fig. 40(a)–(d) show that the reconstructed image was created using the robust time reversal algorithm described in [62]. The round tumors were identified with pinpoint accuracy in the four scenarios. The photos only showed tiny, unnoticeable clutter. To comprehend the functionality of the suggested microwave imaging system [44], it was modeled in CST using a breast phantom. Two antennas were designed to face the breast phantom. While one was performing the role of a Tx,

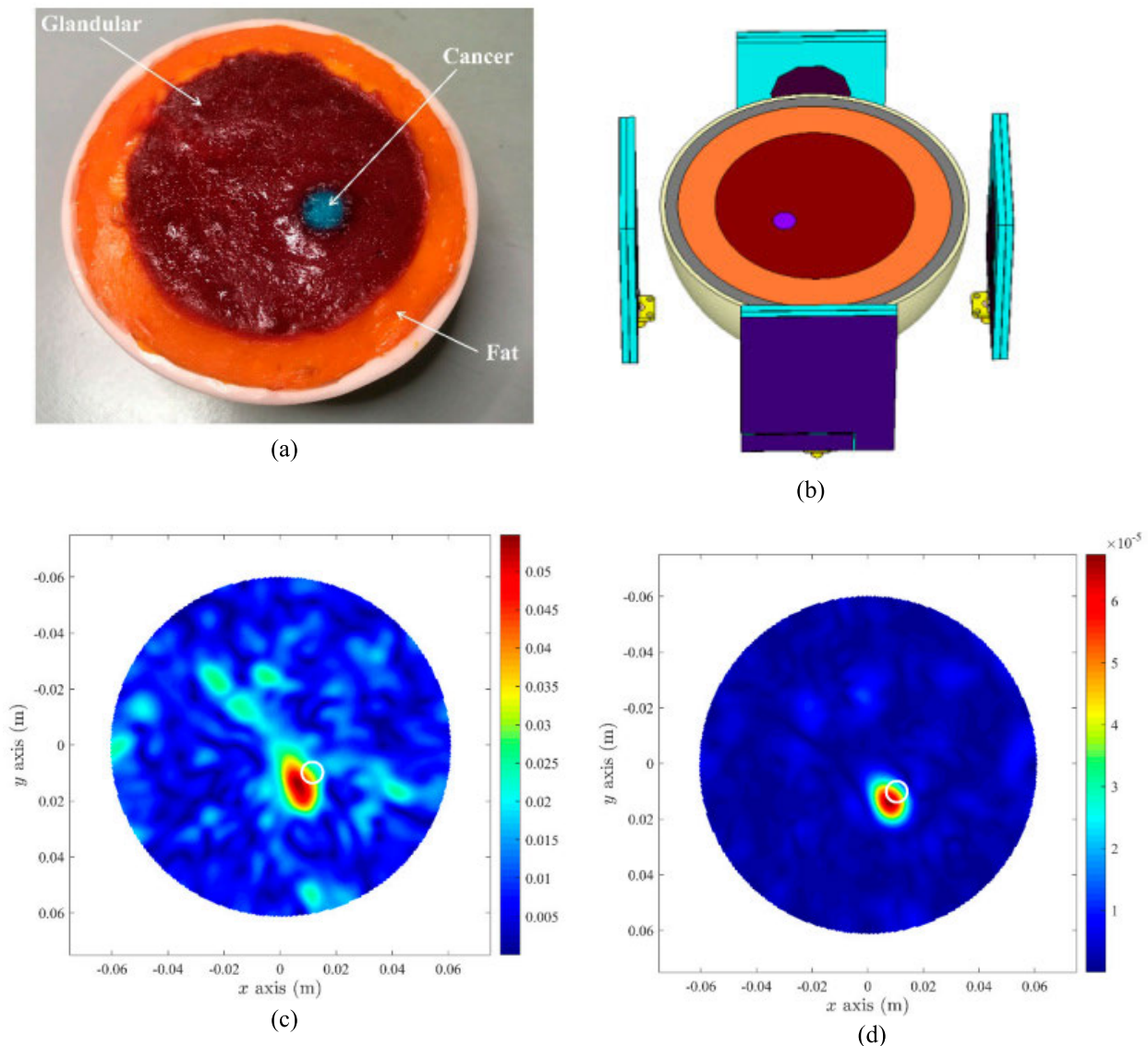


FIGURE 42. (a) Phantom heterogeneous breast, (b) simulation setup, (c, d) microwave imaging findings from experimental setup using DAS and DMAS algorithms respectively [46].

the other acted as Rx. Fig. 41(a) shows the antenna's simulated arrangement around the breast phantom. At 300 mm from the sender, the receiving antenna is computed, and the narrow pulse is transmitted by broadcasting Antenna 1. In two cases, one with and one without a breast phantom, the correlation between S_{11} and S_{21} was analyzed to determine the antennas' performance. Antenna placement on the breast phantom's periphery yields the reflection coefficient. These antennas were effective from 3.1–12 GHz. Fig. 41(b) displays the S_{11} of the array system. The S_{21} results of breast phantom and free space significantly differ between Antenna 1 and 2, indicating a considerable variation. The results of E-field imaging at 4.6 GHz are displayed in Fig. 41 (c,d). According to the concentration of the red color, the absolute location of the tumor can be determined. The red color's concentration determines the tumor's location. The photos demonstrate that

the tumor's position and presence can be discerned using high-resolution imaging. The tumor's sensitivity is highlighted in red, while the normal breast tissue is colored blue. In general, microwave breast phantom imaging outcomes validate the antenna's suitability for microwave imaging. The various components that make up the breast phantom [46]. Food colorings were used to graphically depict the various tissue layers of breast phantoms and cancer. The fat layer was represented by egg yellow, the glandular and skin layers by carmoisine, and the cancer layer by genuine blue. Following this, the 3D-printed breast phantom was molded to perfection. Fig. 42(a) depicts the study's heterogeneous breast hemispherical phantom of radius 60 mm. In addition, 3 mm thick silicone breast pads that are commercially available were used as a protective covering to keep the shape during the rest of the analysis. Four antennas are depicted in Fig. 42(b)

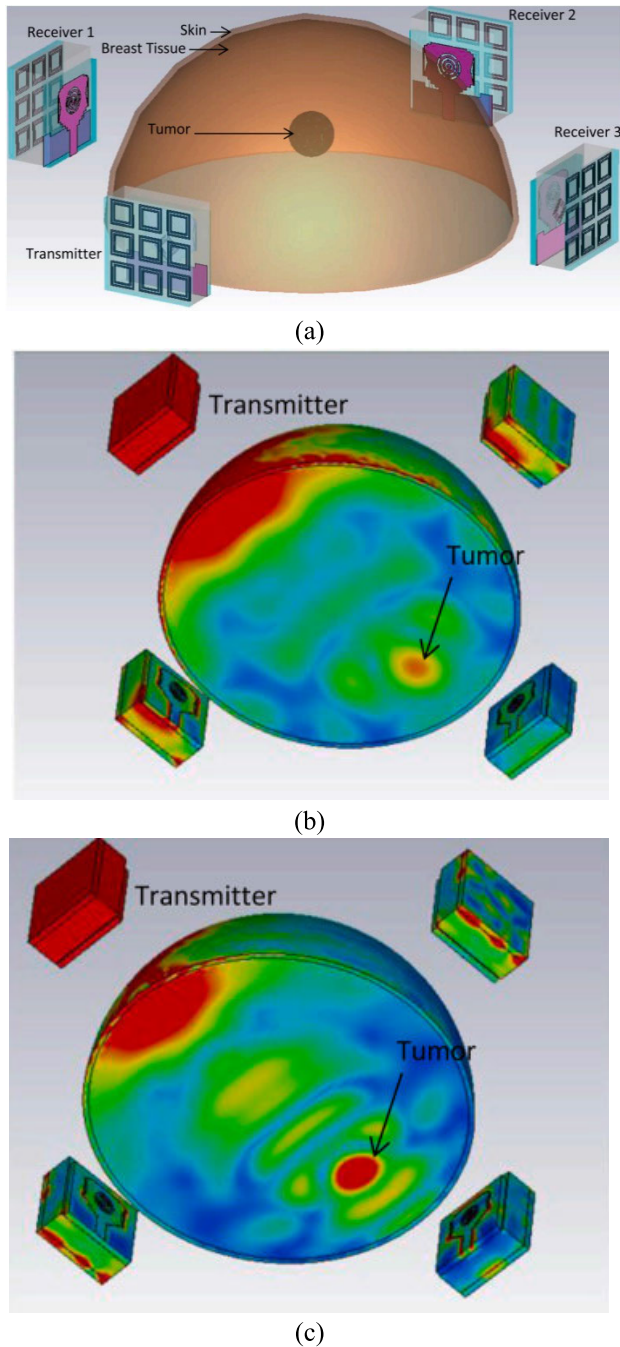


FIGURE 43. (a) Configuration of the simulation setup, (b) 5.8 GHz and (c) 8.7 GHz MWI findings the array of the antenna [48].

for simulation. For every given measurement, a multistatic setup used one antenna to broadcast and multiple antennas to receive, allowing for the reception of all transmitted and backscattered signals. Fig. 42(c,d) show the experimental setup-based reconstruction of the image, with the high-contrast region standing in for the cancer's actual location. Compared to the image generated by the DAS algorithm, the one derived from the DMAS method was more accurate in pinpointing the precise location of the malignancy. Since the picture quality depends on both the quality of the signal

generated by the antennas and the maximum number of data samples, increasing the sampling of backscattered data can resolve the issue of imprecise cancer localization on the image.

Fig. 43(a) displays the antennas and the proposed breast phantom [48]. By examining a correlation between S_{11} , S_{21} , S_{31} , and S_{41} for both the reference settings and the configuration of the complete model, it is possible to witness the system's performance. Fig. 43(b) and (c) show the results of simulating the electric field of the array prototype at two important frequencies to better understand the variation in signal scattering. Only Antenna 1 is producing energy in this scenario. Contrary to popular belief, microwaves exhibit distinct behavior when they come into contact with different types of tissues, both in density and dielectric properties. Because tumor cells emit a signal than normal breast tissue, the percentage of signal scattering inside normal tissue is larger than that of tumor cells. In tumor cells, the density of received signals is high. In addition, the imaging results show a notable contrast between benign and cancerous breast tissue scatter signals. A high-resolution image in a concentrated red color further emphasizes the tumor cell's location. Fig. 44(a) and (b) show the illustrated configuration for the imaging [53]. A breast phantom was utilized to detect breast tumors and examine the performance of the 16-antenna array. The breast phantom is surrounded by a horizontal and vertical arrangement of sixteen antennas, constituting a sixteen-antenna array. An eight-antenna array is placed horizontally, and another eight-antenna array is placed vertically in the sixteen-antenna array imaging scenario; both arrays were placed at the same distance from the breast phantom. The other fifteen antennas receive the backscattered signal. One sends out microwave pulses as the transmitter in this scanning process. The imaging equipment collects the backscattered signal data, which are then processed using the IC-DAS image reconstruction algorithm in MATLAB. Fig. 44(c,d) show the result of the target imaging after the algorithm processes the data. Both the breast phantom without and with the tumor are shown in Fig. 44(c) and 44(d), respectively, as reconstructed pictures. It is observed that the red-colored target tumor has been detected. Nevertheless, the suggested approach shows promise as a microwave breast imaging tool for tumor detection by effective analysis of backscattering signals.

IV. FUTURE OUTLOOK

Since breast microwave sensing uses non-ionizing radiation and the substantial discrepancy in the dielectric characteristics of healthy and cancerous tissues, it may be an effective method to detect breast cancer [63]. Researchers have mostly concentrated on the modality's ability to identify tumors rather than its diagnostic value, despite promising estimates of its sensitivity from both phantom and patient studies. The current range of 20–65% for the specificity of the modality does not show any substantial clinical utility [64]. Because of the well-documented detrimental effects of false

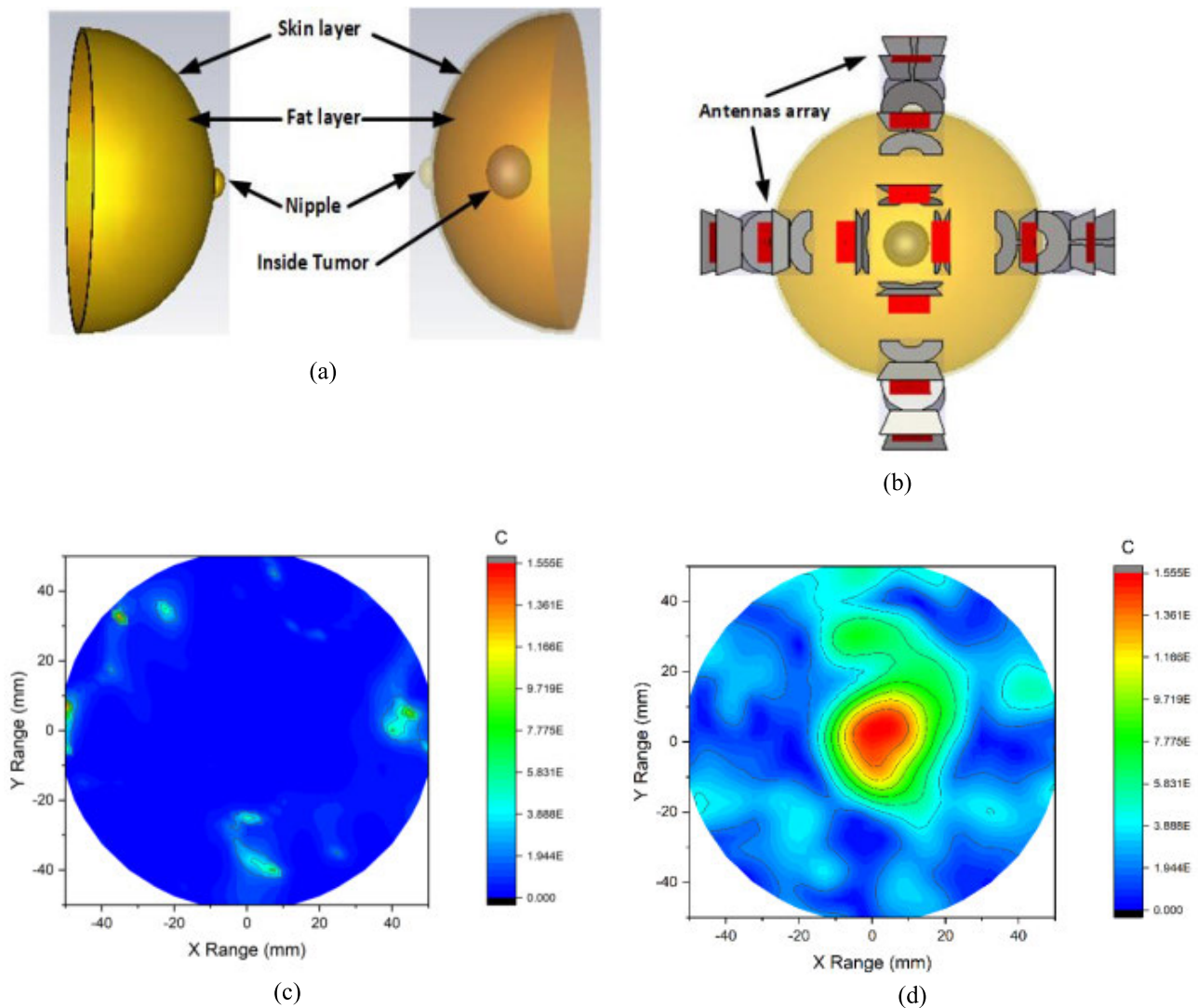


FIGURE 44. (a) Tissue layers in the breast, with and without tumor, (b) the 16-antenna array is seen in its top view during the configuration, and (c,d) phantom free of tumor & bearing tumor [53].

positives in mammography, specificity is an important metric to examine when assessing the effectiveness of a diagnostic tool; this is especially true in breast cancer screening. It would be helpful for future research to compare breast reconstructions of women with and without tumors quantitatively. So yet, measures for evaluating image quality have only been based on data collected from individual pixels or on an exhaustive understanding of the actual tissue characteristics and geometries. These methods lack robustness and are unfit for evaluating the modality's efficacy in blind or double-blind studies. Many current measures evaluation the picture quality, focusing on either the accuracy (such as localization error) or the contrast (like signal-to-clutter ratio). Traditional picture quality metrics like noise, artifacts, and resolution have been disregarded. An important and growing research area attracting international academics and research group cooperation is the clinical uses of

microwave sensing for breast tumors/ cancer diagnosis. Its diagnostic sensitivity and specificity must be assessed to determine whether a microwave-based method is clinically viable. Method for evaluating picture quality must do more than characterize contrast; they must also examine picture artifacts.

Like any radio-electronic system, microwave imaging systems rely on transducers as medium couplers; the antenna's efficiency determines how well the system can reconstruct images. The optimization of this antenna type allows for the construction of portable systems, which in turn makes the equipment easier to operate and means less time and money spent on testing. Furthermore, the data utilized for the picture reconstruction provide more precise early-stage cancer tissue diagnosis. Many antennas have been described in this manuscript to improve the accuracy of cancer tissue detection systems.

REFERENCES

- [1] H. Sung, J. Ferlay, R. L. Siegel, M. Laversanne, I. Soerjomataram, A. Jemal, and F. Bray, "Global cancer statistics 2020: GLOBOCAN estimates of incidence and mortality worldwide for 36 cancers in 185 countries," *CA, Cancer J. Clinicians*, vol. 71, no. 3, pp. 209–249, May 2021, doi: [10.3322/caac.21660](https://doi.org/10.3322/caac.21660).
- [2] L. Wang, "Microwave sensors for breast cancer detection," *Sensors*, vol. 18, no. 2, p. 655, Feb. 2018, doi: [10.3390/s18020655](https://doi.org/10.3390/s18020655).
- [3] S. O. Azubuike, C. Muirhead, L. Hayes, and R. McNally, "Rising global burden of breast cancer: The case of sub-saharan Africa (with emphasis on Nigeria) and implications for regional development: A review," *World J. Surgical Oncol.*, vol. 16, no. 1, p. 63, Mar. 2018, doi: [10.1186/s12957-018-1345-2](https://doi.org/10.1186/s12957-018-1345-2).
- [4] D. Crosby, N. Lyons, E. Greenwood, S. Harrison, S. Hiom, J. Moffat, T. Quallo, E. Samuel, and I. Walker, "A roadmap for the early detection and diagnosis of cancer," *Lancet Oncol.*, vol. 21, no. 11, pp. 1397–1399, Nov. 2020, doi: [10.1016/s1470-2045\(20\)30593-3](https://doi.org/10.1016/s1470-2045(20)30593-3).
- [5] O. Ginsburg et al., "Breast cancer early detection: A phased approach to implementation," *Cancer*, vol. 126, no. S10, pp. 2379–2393, May 2020, doi: [10.1002/cncr.32887](https://doi.org/10.1002/cncr.32887).
- [6] S. N. Mahmood, A. J. Ishak, T. Saeidi, H. Alsariera, S. Alani, A. Ismail, and A. C. Soh, "Recent advances in wearable antenna technologies: A review," *Prog. Electromagn. Res. B*, vol. 89, pp. 1–27, 2020, doi: [10.2528/pierb20071803](https://doi.org/10.2528/pierb20071803).
- [7] P. P. Ray, D. Dash, and D. De, "A systematic review of wearable systems for cancer detection: Current state and challenges," *J. Med. Syst.*, vol. 41, no. 11, p. 180, Nov. 2017, doi: [10.1007/s10916-017-0828-y](https://doi.org/10.1007/s10916-017-0828-y).
- [8] W. Huang and A. A. Kishk, "Design of dielectric resonator sensor with minimized ground plane size for microwave breast cancer detection," in *Proc. IEEE Antennas Propag. Soc. Int. Symp.*, Jun. 2006, pp. 1115–1118. <https://ieeexplore.ieee.org/abstract/document/1710731/>
- [9] H. M. E. Misilmani, T. Naous, S. K. A. Khatib, and K. Y. Kabalan, "A survey on antenna designs for breast cancer detection using microwave imaging," *IEEE Access*, vol. 8, pp. 102570–102594, 2020, doi: [10.1109/ACCESS.2020.2999053](https://doi.org/10.1109/ACCESS.2020.2999053).
- [10] M. Z. Mahmud, M. T. Islam, N. Misran, A. F. Almutairi, and M. Cho, "Ultra-wideband (UWB) antenna sensor based microwave breast imaging: A review," *Sensors*, vol. 18, no. 9, p. 2951, Sep. 2018, doi: [10.3390/s18092951](https://doi.org/10.3390/s18092951).
- [11] K. Sakthisudhan, B. Murugesan, V. Saravanan, and P. N. S. Sailaja, "Textile EF shaped antenna based on reinforced epoxy for breast cancer detection by composite materials," *Mater. Today, Proc.*, vol. 45, pp. 6142–6148, 2021, doi: [10.1016/j.matpr.2020.10.465](https://doi.org/10.1016/j.matpr.2020.10.465).
- [12] M. M. H. Mahfuz, M. R. Islam, C.-W. Park, E. A. A. Elsheikh, F. M. Suliman, M. H. Habaebi, N. A. Malek, and N. Sakib, "Wearable textile patch antenna: Challenges and future directions," *IEEE Access*, vol. 10, pp. 38406–38427, 2022, doi: [10.1109/ACCESS.2022.3161564](https://doi.org/10.1109/ACCESS.2022.3161564).
- [13] P. Vijayakumari, R. Guttula, V. N. Sireesha, J. S. Balamourougane, A. Engidayehu, and Sakthisudhan, "Wearable transceiver with composite test-beds for breast cancer diagnosis," *Mater. Today, Proc.*, vol. 45, pp. 3120–3123, Jan. 2021, doi: [10.1016/j.matpr.2020.12.206](https://doi.org/10.1016/j.matpr.2020.12.206).
- [14] R. J. Davies, "Electrical bioimpedance analysis as a biomarker of breast density and/or breast cancer risk," Patent U.S. 8 738 124 B2, May 27, 2014. [Online]. Available: <https://patents.google.com/patent/US8738124B2/en>
- [15] D. O'Loughlin, M. O'Halloran, B. M. Moloney, M. Glavin, E. Jones, and M. A. Elahi, "Microwave breast imaging: Clinical advances and remaining challenges," *IEEE Trans. Biomed. Eng.*, vol. 65, no. 11, pp. 2580–2590, Nov. 2018, doi: [10.1109/TBME.2018.2809541](https://doi.org/10.1109/TBME.2018.2809541).
- [16] M. A. Aldhaeebi, K. Alzoubi, T. S. Almonneef, S. M. Bamatraf, H. Attia, and O. M. Ramahi, "Review of microwaves techniques for breast cancer detection," *Sensors*, vol. 20, no. 8, p. 2390, Apr. 2020, doi: [10.3390/s20082390](https://doi.org/10.3390/s20082390).
- [17] S. Kwon and S. Lee, "Recent advances in microwave imaging for breast cancer detection," *Int. J. Biomed. Imag.*, vol. 2016, pp. 1–26, Jan. 2016, doi: [10.1155/2016/5054912](https://doi.org/10.1155/2016/5054912).
- [18] E. Porter, H. Bahrami, A. Santorelli, B. Gosselin, L. A. Rusch, and M. Popovic, "A wearable microwave antenna array for time-domain breast tumor screening," *IEEE Trans. Med. Imag.*, vol. 35, no. 6, pp. 1501–1509, Jun. 2016, doi: [10.1109/TMI.2016.2518489](https://doi.org/10.1109/TMI.2016.2518489).
- [19] B. M. Moloney, D. O'Loughlin, S. Abd Elwahab, and M. J. Kerin, "Breast cancer detection—A synopsis of conventional modalities and the potential role of microwave imaging," *Diagnostics*, vol. 10, no. 2, p. 103, Feb. 2020, doi: [10.3390/diagnostics10020103](https://doi.org/10.3390/diagnostics10020103).
- [20] B. Borja, J. A. Tirado-Mendez, and H. Jardon-Aguilar, "An overview of UWB antennas for microwave imaging systems for cancer detection purposes," *Prog. Electromagn. Res. B*, vol. 80, pp. 173–198, 2018, doi: [10.2528/pierb18030302](https://doi.org/10.2528/pierb18030302).
- [21] D. Srinivasan and M. Gopalakrishnan, "Breast cancer detection using adaptable textile antenna design," *J. Med. Syst.*, vol. 43, no. 6, p. 177, Jun. 2019, doi: [10.1007/s10916-019-1314-5](https://doi.org/10.1007/s10916-019-1314-5).
- [22] X. Lin, Y. Chen, Z. Gong, B.-C. Seet, L. Huang, and Y. Lu, "Ultrawideband textile antenna for wearable microwave medical imaging applications," *IEEE Trans. Antennas Propag.*, vol. 68, no. 6, pp. 4238–4249, Jun. 2020, doi: [10.1109/TAP.2020.2970072](https://doi.org/10.1109/TAP.2020.2970072).
- [23] W. El May, I. Sfar, J. M. Ribero, and L. Osman, "Design of low-profile and safe low sar tri-band textile ebg-based antenna for IoT applications," *Prog. Electromagn. Res. Lett.*, vol. 98, pp. 85–94, 2021, doi: [10.2528/pierl21051107](https://doi.org/10.2528/pierl21051107).
- [24] S. N. Mahmood, A. J. Ishak, T. Saeidi, A. C. Soh, A. Jalal, M. A. Imran, and Q. H. Abbasi, "Full ground ultra-wideband wearable textile antenna for breast cancer and wireless body area network applications," *Micromachines*, vol. 12, no. 3, p. 322, Mar. 2021, doi: [10.3390/mi12030322](https://doi.org/10.3390/mi12030322).
- [25] M. M. Hasan Mahfuz, M. Rafiqul Islam, M. Hadi Habaebi, and J. Chebil, "Design of wearable textile patch antenna using C-shape etching slot," *Int. J. Interact. Mobile Technol.*, vol. 16, no. 11, pp. 107–120, Jun. 2022, doi: [10.3991/ijim.v16i11.30101](https://doi.org/10.3991/ijim.v16i11.30101).
- [26] S. N. Mahmood, A. J. Ishak, A. Jalal, T. Saeidi, S. Shafie, A. C. Soh, M. A. Imran, and Q. H. Abbasi, "A bra monitoring system using a miniaturized wearable ultra-wideband MIMO antenna for breast cancer imaging," *Electronics*, vol. 10, no. 21, p. 2563, Oct. 2021, doi: [10.3390/electronics10212563](https://doi.org/10.3390/electronics10212563).
- [27] D. Elsheikh and A. R. Eldamak, "Microwave textile sensors for breast cancer detection," in *Proc. 38th Nat. Radio Sci. Conf. (NRSC)*, vol. 1, Jul. 2021, pp. 288–294.
- [28] A. Mersani, L. Osman, and J.-M. Ribero, "Flexible uwb amc antenna for early stage skin cancer identification," *Prog. Electromagn. Res. M*, vol. 80, pp. 71–81, 2019, doi: [10.2528/pierm18121404](https://doi.org/10.2528/pierm18121404).
- [29] M. Salimitorkamani, M. Mehranpour, and H. Odabasi, "A compact ultrawideband slotted patch antenna for early stage breast tumor detection applications," *Int. J. Microw. Wireless Technol.*, vol. 15, no. 4, pp. 572–580, Aug. 2022, doi: [10.1017/s1759078722000861](https://doi.org/10.1017/s1759078722000861).
- [30] M. A. A. Rakib, S. Ahmad, M. H. K. Khan, M. Haque, T. M. Faruqi, M. S. Jahan, and J. K. Mim, "A meandered line patch antenna at low frequency range for early stage breast cancer detection," *Indonesian J. Electr. Eng. Informat.*, vol. 9, no. 3, Sep. 2021, Art. no. 3, doi: [10.52549/v9i3.2824](https://doi.org/10.52549/v9i3.2824).
- [31] P. K. Rao and R. Mishra, "Elliptical shape flexible MIMO antenna with high isolation for breast cancer detection application," *IETE J. Res.*, vol. 69, no. 1, pp. 325–333, Jan. 2023, doi: [10.1080/03772063.2020.1819887](https://doi.org/10.1080/03772063.2020.1819887).
- [32] K. S. Ryu and A. A. Kishk, "Evaluation of dielectric resonator sensor for near-field breast tumor detection," *IEEE Trans. Antennas Propag.*, vol. 59, no. 10, pp. 3738–3745, Oct. 2011, doi: [10.1109/TAP.2011.2163790](https://doi.org/10.1109/TAP.2011.2163790).
- [33] A. M. Qashlan, R. W. Aldhaeheri, and K. H. Alharbi, "A modified compact flexible vivaldi antenna array design for microwave breast cancer detection," *Appl. Sci.*, vol. 12, no. 10, p. 4908, May 2022, doi: [10.3390/app12104908](https://doi.org/10.3390/app12104908).
- [34] S. Lim and Y. J. Yoon, "Wideband-narrowband switchable tapered slot antenna for breast cancer diagnosis and treatment," *Appl. Sci.*, vol. 11, no. 8, p. 3606, Apr. 2021, doi: [10.3390/app11083606](https://doi.org/10.3390/app11083606).
- [35] T. G. Abouelnaga, E. K. I. Hamad, S. A. Khaleel, and B. Beiranvand, "Defining breast tumor location using a four-element wearable circular UWB MIMO antenna array," *Appl. Sci.*, vol. 13, no. 14, p. 8067, Jul. 2023.
- [36] M. N. Hamza, Y. I. Abdulkarim, S. R. Saeed, O. Altıntaş, R. H. Mahmud, B. Appasani, and C. Ravariu, "Low-cost antenna-array-based metamaterials for non-invasive early-stage breast tumor detection in the human body," *Biosensors*, vol. 12, no. 10, p. 828, Oct. 2022.
- [37] M. Elsaadi and R. Hamad, "Breast cancer hyperthermia treatment based on slotted patch antenna at 2.45 GHz," *Circuits Syst.*, vol. 14, no. 5, pp. 10–18, May 2023, doi: [10.4236/cs.2023.145002](https://doi.org/10.4236/cs.2023.145002).
- [38] W. Huang and A. A. Kishk, "Compact dielectric resonator antenna for microwave breast cancer detection," *IET Microw., Antennas Propag.*, vol. 3, no. 4, p. 638, 2009, doi: [10.1049/iet-map.2008.0170](https://doi.org/10.1049/iet-map.2008.0170).

- [39] A. Afyf, L. Bellarbi, A. Achour, N. Yaakoubi, A. Errachid, and M. A. Sennouni, "UWB thin film flexible antenna for microwave thermography for breast cancer detection," in *Proc. Int. Conf. Electr. Inf. Technol. (ICEIT)*, May 2016, pp. 425–429, doi: [10.1109/EITech.2016.7519635](https://doi.org/10.1109/EITech.2016.7519635).
- [40] T. Saeidi, S. N. Mahmood, A. Juraiza Ishak, S. Alani, S. M. Ali, I. Ismail, and A. R. H. Alhawari, "Miniaturized spiral UWB transparent wearable flexible antenna for breast cancer detection," in *Proc. Int. Symp. Netw., Comput. Commun. (ISNCC)*, Oct. 2020, pp. 1–6, doi: [10.1109/ISNCC49221.2020.9297255](https://doi.org/10.1109/ISNCC49221.2020.9297255).
- [41] M. Venkatesan, A. Karthikayen, N. S. Kumar, and K. Sakthisudhan, "A 6×6 array of Jerusalem crossed patch printed on textile woven & cancer diagnostic by composites," *Mater. Today: Proc.*, vol. 45, pp. 6433–6437, Jan. 2021, doi: [10.1016/j.matpr.2020.11.277](https://doi.org/10.1016/j.matpr.2020.11.277).
- [42] M. Slimi, B. Jmai, H. Dinis, A. Gharsallah, and P. M. Mendes, "Metamaterial vivaldi antenna array for breast cancer detection," *Sensors*, vol. 22, no. 10, p. 3945, May 2022.
- [43] A. R. H. Alhawari, A. H. M. Almwagani, A. T. Hindi, H. Alghamdi, and T. Saeidi, "Metamaterial-based wearable flexible elliptical UWB antenna for WBAN and breast imaging applications," *AIP Adv.*, vol. 11, no. 1, Jan. 2021, Art. no. 015128.
- [44] M. T. Islam, M. Samsuzzaman, M. N. Rahman, and M. T. Islam, "A compact slotted patch antenna for breast tumor detection," *Microw. Opt. Technol. Lett.*, vol. 60, no. 7, pp. 1600–1608, Jul. 2018, doi: [10.1002/mop.31215](https://doi.org/10.1002/mop.31215).
- [45] H. Zhang and H. Li, "Flexible dual-polarized UWB antennas for breast tumor imaging," in *IEEE MTT-S Int. Microw. Symp. Dig.*, Dec. 2020, pp. 1–2, doi: [10.1109/NEMO49486.2020.9343495](https://doi.org/10.1109/NEMO49486.2020.9343495).
- [46] K. Hossain, T. Sabapathy, M. Jusoh, S.-H. Lee, K. S. A. Rahman, and M. R. Kamarudin, "Negative index metamaterial-based frequency-reconfigurable textile CPW antenna for microwave imaging of breast cancer," *Sensors*, vol. 22, no. 4, Jan. 2022, Art. no. 4, doi: [10.3390/s22041626](https://doi.org/10.3390/s22041626).
- [47] A. Rahman, M. T. Islam, M. J. Singh, S. Kibria, and M. Akhtaruzzaman, "Electromagnetic performances analysis of an ultra-wideband and flexible material antenna in microwave breast imaging: To implement a wearable medical bra," *Sci. Rep.*, vol. 6, no. 1, Dec. 2016, Art. no. 1, doi: [10.1038/srep38906](https://doi.org/10.1038/srep38906).
- [48] F.-E. Zerrad, M. Taouzari, E. M. Makroum, J. E. Aoufi, M. T. Islam, V. Özkaner, Y. I. Abdulkarim, and M. Karaaslan, "Multilayered metamaterials array antenna based on artificial magnetic conductor's structure for the application diagnostic breast cancer detection with microwave imaging," *Med. Eng. Phys.*, vol. 99, Jan. 2022, Art. no. 103737, doi: [10.1016/j.medengphy.2021.103737](https://doi.org/10.1016/j.medengphy.2021.103737).
- [49] M. M. H. Mahfuz, M. R. Islam, M. H. Habaebi, N. A. Malek, and M. W. Sami, "Design of a flexible textile antenna for early breast tumor detections," in *Proc. 9th Int. Conf. Comput. Commun. Eng. (ICCCE)*, Aug. 2023, pp. 394–399, doi: [10.1109/iccce58854.2023.10246060](https://doi.org/10.1109/iccce58854.2023.10246060).
- [50] F.-E. Zerrad, M. Taouzari, E. M. Makroum, S. Ahmad, F. Ö. Alkurt, M. Karaaslan, M. T. Islam, and M. I. Hussein, "Symmetrical and asymmetrical breast phantoms with 3D-printed anatomical structure for microwave imaging of breast cancer," *IEEE Access*, vol. 10, pp. 96896–96908, 2022, doi: [10.1109/ACCESS.2022.3205004](https://doi.org/10.1109/ACCESS.2022.3205004).
- [51] J. J. J. Sheela, S. Rosaline, S. T. Mugila, S. S. Sri, and V. P. Kumar, "UWB Sierpinski fractal antenna for breast tumour detection using SAR," *IOP Conf. Ser., Mater. Sci. Eng.*, vol. 1055, no. 1, Feb. 2021, Art. no. 012063, doi: [10.1088/1757-899x/1055/1/012063](https://doi.org/10.1088/1757-899x/1055/1/012063).
- [52] F. Alsharif and Ç. Kurnaz, "Wearable microstrip ultra-wideband antenna used for early breast cancer detection," *Skin*, vol. 46, p. 1, Apr. 2018.
- [53] A. Hossain, M. T. Islam, M. T. Islam, M. E. H. Chowdhury, H. Rmili, and M. Samsuzzaman, "A planar ultrawideband patch antenna array for microwave breast tumor detection," *Materials*, vol. 13, no. 21, p. 4918, Nov. 2020.
- [54] H. Özmen and M. B. Kurt, "Radar-based microwave breast cancer detection system with a high-performance ultrawide band antipodal vivaldi antenna," *TURKISH J. Electr. Eng. Comput. Sci.*, vol. 29, no. 5, pp. 2326–2345, Sep. 2021, doi: [10.3906/elk-2010-49](https://doi.org/10.3906/elk-2010-49).
- [55] A. Afyf, L. Bellarbi, F. Riouch, A. Errachid, and M. A. Sennouni, "Flexible antenna array for early breast cancer detection using radiometric technique," *Int. J. Biol. Biomed. Eng.*, vol. 10, pp. 10–17, Jan. 2016.
- [56] H. Been Lim, N. Thi Tuyet Nhung, E.-P. Li, and N. Duc Thang, "Confocal microwave imaging for breast cancer detection: Delay-Multiply-and-Sum image reconstruction algorithm," *IEEE Trans. Biomed. Eng.*, vol. 55, no. 6, pp. 1697–1704, Jun. 2008, doi: [10.1109/TBME.2008.919716](https://doi.org/10.1109/TBME.2008.919716).
- [57] A. Alikhassi, X. Li, F. Au, S. Kulkarni, S. Ghai, G. Allison, and V. Freitas, "False-positive incidental lesions detected on contrast-enhanced breast MRI: Clinical and imaging features," *Breast Cancer Res. Treatment*, vol. 198, no. 2, pp. 321–334, Feb. 2023, doi: [10.1007/s10549-023-06861-y](https://doi.org/10.1007/s10549-023-06861-y).
- [58] M. Faisal, A. Gafur, S. Z. Rashid, M. O. Shawon, K. I. Hasan, and M. B. Billah, "Return loss and gain improvement for 5G wireless communication based on single band microstrip square patch antenna," in *Proc. 1st Int. Conf. Adv. Sci., Eng. Robot. Technol. (ICASERT)*, Dhaka, Bangladesh, May 2019, pp. 1–5, doi: [10.1109/ICASERT.2019.8934474](https://doi.org/10.1109/ICASERT.2019.8934474).
- [59] V. Karthik and T. Rama Rao, "Investigations on SAR and thermal effects of a body wearable microstrip antenna," *Wireless Pers. Commun.*, vol. 96, no. 3, pp. 3385–3401, Oct. 2017, doi: [10.1007/s11277-017-4059-9](https://doi.org/10.1007/s11277-017-4059-9).
- [60] M. Alibakhshikenari, B. S. Virdee, P. Shukla, N. O. Parchin, L. Azpilicueta, C. H. See, R. A. Abd-Alhameed, F. Falcone, I. Huynen, T. A. Denidni, and E. Limiti, "Metamaterial-inspired antenna array for application in microwave breast imaging systems for tumor detection," *IEEE Access*, vol. 8, pp. 174667–174678, 2020, doi: [10.1109/ACCESS.2020.3025672](https://doi.org/10.1109/ACCESS.2020.3025672).
- [61] J. V. Vaghiasya, C. C. Mayorga-Martinez, and M. Pumera, "Wearable sensors for telehealth based on emerging materials and nanoarchitectonics," *NPJ Flexible Electron.*, vol. 7, no. 1, Jun. 2023, Art. no. 1, doi: [10.1038/s41528-023-00261-4](https://doi.org/10.1038/s41528-023-00261-4).
- [62] T. Saeidi, I. Ismail, S. N. Mahmood, S. Alani, and A. R. H. Alhawari, "Microwave imaging of voids in oil palm trunk applying UWB antenna and robust time-reversal algorithm," *J. Sensors*, vol. 2020, pp. 1–21, Oct. 2020, doi: [10.1155/2020/8895737](https://doi.org/10.1155/2020/8895737).
- [63] K. Aliqab, I. Nadeem, and S. R. Khan, "A comprehensive review of in-body biomedical antennas: Design, challenges and applications," *Micro-machines*, vol. 14, no. 7, p. 1472, Jul. 2023, doi: [10.3390/mi14071472](https://doi.org/10.3390/mi14071472).
- [64] D. O'Loughlin, B. L. Oliveira, A. Santorelli, E. Porter, M. Glavin, E. Jones, M. Popovic, and M. O'Halloran, "Sensitivity and specificity estimation using patient-specific microwave imaging in diverse experimental breast phantoms," *IEEE Trans. Med. Imag.*, vol. 38, no. 1, pp. 303–311, Jan. 2019, doi: [10.1109/TMI.2018.2864150](https://doi.org/10.1109/TMI.2018.2864150).



M. M. HASAN MAHFUZ (Member, IEEE) was born in Gazipur, Bangladesh. He received the B.Sc. and M.Sc. degrees in electrical and computer engineering. He is currently pursuing the Ph.D. degree with Concordia University, Montreal, Canada, under the supervision of Prof. Ahmed A. Kishk's. His current research interests include microstrip patch antennas, mmWave antennas, wearable textile antennas for biomedical applications, array antennas, automotive radar systems, head imagine systems, and the applications of the phased array antennas. In acknowledgment of his exceptional academic accomplishments, he has been bestowed the Concordia University International Tuition Award of Excellence.



A. M. MAHFOUZ (Member, IEEE) received the B.E. degree in electrical engineering from Assiut University, Assiut, Egypt, in 2014, the M.Sc. degree in 2020, with a focus on the design of implanted antennas for biomedical applications, and the Ph.D. degree from Concordia University, in 2023, under the esteemed supervision of Prof. Ahmed A. Kishk. He then joined the Department of Electrical Engineering, Assiut University, as a Teaching Assistant, in 2016. His current research interests include machine-learning-based antenna design, electromagnetic brake systems modeling, radiation pattern analysis and synthesis, computational electromagnetics, antenna design for bio-implants, and satellite feeders. He has been awarded the Concordia University International Tuition Award of Excellence in recognition of his outstanding academic achievements.



ELHAM BALADI (Member, IEEE) received the B.Sc. degree in electrical engineering–telecommunications from Iran University of Science and Technology, Tehran, Iran, in 2013, and the Ph.D. degree in electromagnetics and microwaves from the University of Alberta, Edmonton, AB, Canada, in January 2019. She was a Postdoctoral Fellow with the University of Toronto, Toronto, ON, Canada, from February 2019 to February 2021, where she conducted

research on the modeling and development of reconfigurable antenna arrays for space applications. She was an Antenna and RF Filter Design Engineer with Syntronic Research and Development Canada, Ottawa, ON, Canada, from February 2021 to August 2022, where she worked on the development of RF cavity filters, duplexers, and multiband antennas for 5G, the IoT, and wireless communication systems. She joined the Electrical Engineering Department, Polytechnique Montréal, Montreal, QC, Canada, as an Assistant Professor, in September 2022. She has been a Lecturer with York University, since Winter 2020, and the University of Alberta, since Winter 2017. She developed a novel class of resonant metasurfaces during her Ph.D. degree and investigated their applications for shielding, imaging, and selective transmission. Her research interests include the development of novel multi-band multi-beam antenna arrays, metasurfaces, reconfigurable intelligent surfaces, microwave sensors, and radar imaging technologies. She was a recipient of the University of Alberta Doctoral Recruitment Scholarship, Alberta Innovates Technology Futures Scholarship, the IEEE AP-S Doctoral Research Award, and two honorable mention awards in the student-paper competitions of the 2016 and 2017 IEEE AP-S Symposia. She serves as a reviewer for multiple IEEE and OSA journals. She serves as the Chair for the IEEE Antenna and Propagation Section and the Vice-Chair for the IEEE Women in Engineering in Montreal.



AHMED A. KISHK (Life Fellow, IEEE) received the M.Eng. and Ph.D. degrees from the Department of Electrical Engineering, University of Manitoba, Winnipeg, MB, Canada, in 1983 and 1986, respectively. In 1986, he joined the Department of Electrical Engineering, University of Mississippi, Oxford, MS, USA, where he was a Professor, from 1995 to 2011. Since 2011, he has been a Tier 1 Canada Research Chair in advanced antenna systems and a Professor with Concordia

University, Montreal, QC, Canada. He has published over 550 refereed journal articles and 750 conference papers. He has co-authored four books and 13 chapters and was the editor of eight books. According to Google Scholar, his work was cited over 35,238 with an H-index of 80 in the 9th edition of Research.com ranking of the best scientists in Electronics and Electrical Engineering; it is based on data consolidated from various sources, including OpenAlex and CrossRef. The bibliometric data for estimating the citation-based metrics were gathered, in December 2022. He was ranked first at Concordia University, 23rd in Canada, and 401 worldwide. He was the 2017 AP-S President. He and his students was a recipient of many awards. He received the Microwave Theory and Techniques Society Microwave Prize, in 2004.

• • •