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A Circular Shape Arc Slot Ultra-Wideband Antenna for Biomedical Applications

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Abstract

In modern communication systems, ultra-wideband (UWB) technology has garnered substantial attention due to its superior attributes compared to traditional narrowband communication systems. Over the past decade, UWB technology has also found applications in microwave-based imaging systems. This study introduces a simple planar coplanar waveguide-fed circular shape arc slot antenna designed specifically for biomedicine and microwave medical imaging applications. The proposed design is implemented on a 1.6-mm-thick FR4 substrate with a relative permittivity of 4.4 and a loss tangent of 0.0009. The antenna has physical dimensions of 26 mm × 29 mm and achieves an impressive bandwidth of 16.6 GHz, spanning 2.4 to 19 GHz. It exhibits a peak gain of 2.5 dBi and consistent omnidirectional radiation characteristics. Thorough temporal analysis validates the antenna's performance within acceptable limits, which is further affirmed through practical fabrication and testing, demonstrating strong agreement with simulation results.

Key Words: Circular Shape Arc Slot, Coplanar Waveguide, Gain, Omni-directional, Ultra-Wideband.

I. Introduction

Wireless communication has revolutionized global information sharing, providing enhanced mobility through data transmission without physical connections [1, 2]. At the core of this technology is the ultra-wideband (UWB) antenna, which covers a broad frequency spectrum, boosting spectrum efficiency, data rates, and coexistence with other systems. UWB's capability in indoor positioning, obstacle penetration, and impulse radar applications makes it valuable in indoor tracking, sensor networks, and imaging [3, 4]. UWB antennas play a crucial role in diverse fields, from wireless USB and radar systems to medical imaging and non-destructive testing, driving advancements in wireless technology and beyond. Their potential in high-resolution microwave imaging is especially promising for medical diagnosis and industrial inspection, solidifying their role in critical applications [5].

Several UWB antenna systems have been proposed for bio-

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medical applications [6–13]. In [6], an efficient UWB antenna for biomedical applications features a coplanar waveguide (CPW)-fed printed circular ring fractal, enabling low-power short-range wireless communication, which is highly beneficial for microwave and millimeter-wave medical imaging. The antenna's UWB performance is achieved by incorporating wedged slots in the radiating patch on a low-loss substrate and optimizing the antenna impedance by truncating a CPW partial ground plane from the edges. In [7], a UWB monopole antenna was designed for body-centric imaging applications. The antenna was modeled and designed using CST Microwave Studio. A parallel surrogate model-assisted hybrid differential evolution for antenna optimization was employed to expedite the design process while ensuring it met specifications. A UWB antenna with full ground was proposed in [8]. The antenna used several slots, pins, and electromagnetic band gap structures to attain wideband performance. A UWB antenna for biomedical imaging applications with dimensions of 40 mm × 45 mm and a maximum gain of 2.9 dBi is reported in [9]. In [10], a unique UWB-resistive dipole antenna is introduced for microwave imaging. The antenna minimizes internal reflections and enhances suitability for imaging with chip resistors strategically placed on its arms, resulting in a UWB response from 1 GHz to 10 GHz, albeit with larger size and complexity. In [11], a multi-resonance UWB antenna for microwave imaging is developed using an E-shaped slot and parasitic structure. This feature extends the frequency range to 15 GHz but poses challenges in maintaining radiation characteristics. In [12], a UWB system with wideband resonance from 2.84 to 11 GHz is presented. In [13], a UWB system with a bandwidth ranging from 3.89 to 17.09 GHz and a peak gain of 5.87 dBi is reported. The total dimension of the reported structure is 26 mm × 31 mm.

The current study introduces a new CPW-fed circular arc slot antenna designed for near-field microwave imaging in biomedical applications, particularly breast cancer detection. The antenna is engineered to ensure wideband coverage and excellent time-domain characteristics, which are crucial for accurate imaging. Experimental results demonstrate its effectiveness over a broad frequency range (2.4–16.6 GHz), with a peak gain of 3.6 dBi at 8.5 GHz, enabling signal transmission across this spectrum. Time domain analysis reveals group delays of less than 1.5 ns for both face-to-face (F2F) and side-by-side (SbS) configurations, minimizing pulse distortion, which is essential for accurate microwave imaging. The antenna compares favorably to other UWB antennas used for imaging, confirming its potential for practical microwave imaging applications, such as breast cancer detection.

II. ANTENNA DESIGN

Fig. 1 shows the proposed UWB antenna. This proposed

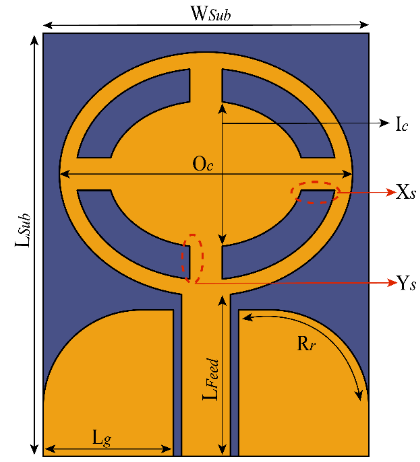


Fig. 1. Proposed circular shape arc slot antenna.

CPW antenna is developed using FR4 material, which has a relative permittivity of 4.4 and a thickness of 1.6 mm. The CPW feed technique is employed due to its various advantages, such as low losses, coplanar nature, and ease of fabrication. The dimensions of the proposed antenna are listed in Table 1. The evolutionary progression of the antenna design is depicted in Fig. 2. The developmental trajectory is structured into three distinct phases: Design A, Design B, and the final proposed Design C. In the initial stage, Design A consisted solely of a circular ring accompanied by a rectangular ground plane. The resulting resonance exhibited a tri-band pattern, as illustrated by the black line in Fig. 2(d). Subsequently, enhancements were made in Design B by introducing an inner circular patch and semicircular slots positioned at the four cardinal ends.

This modification led to the emergence of two prominent wideband resonance bands. In the final design, Design C, the rectangular ground plane was ingeniously transformed into a shark fin configuration. This innovation yielded an extensive bandwidth response spanning from 2.4 to 19 GHz, satisfying the voltage standing wave ratio 2:1 criterion.

Fig. 3 illustrates the surface current distribution at resonance frequencies of 4, 8, 12, and 14 GHz. Specifically, Fig. 3(a) pro-

Table 1. Proposed antenna dimensions

Parameter	Value (mm)
W_{sub}	26
L_{sub}	29
I_c	9
Y_s	2
R_r	6
L_g	9
O_c	18
X_s	2

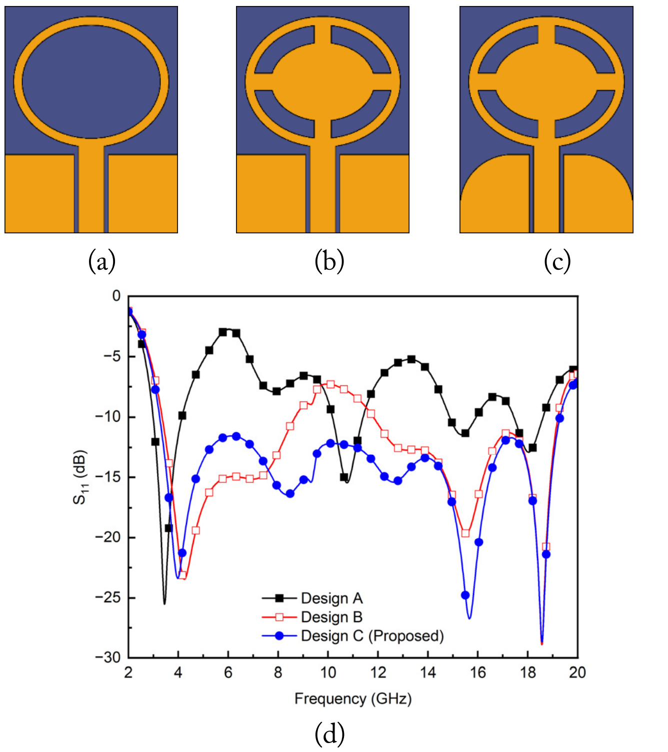


Fig. 2. Design evolution: (a) Design A, (b) Design B, (c) Design C, and (d) S_{11} of design evolution.

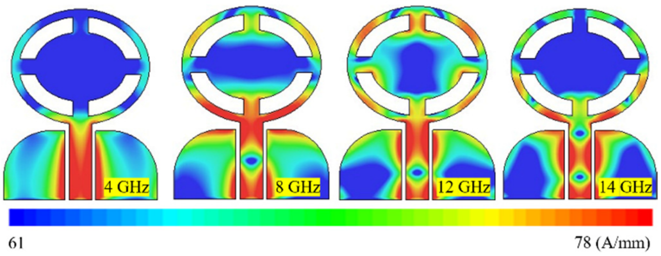


Fig. 3. Surface current patterns.

vides insight into the current patterns at 4 GHz. Evidently, the lower edges of the circular rings and the side of the ground plane adjacent to the feed line exhibit a heightened concentration of current, particularly at lower frequencies. Shifting to 8 GHz (Fig. 3(b)), current induction becomes pronounced along the upper edges of the shark fin-shaped ground plane, highlighting its role in generating mid-band resonances. As the frequency moves to higher levels, the current distribution shifts toward a constructive inclination at the circular patch and outer ring, as evidenced in Fig. 3(c) and 3(d).

The antenna's capacity for achieving a parametrically controlled UWB response is precisely examined by manipulating its key parameters, as depicted in Fig. 4. Notably, Fig. 4(a) shows the impact of varying Lg values, revealing a substantial influence of the Lg strip on the antenna's resonance behavior. This strip's evaluation across three intervals, each differing by 0.5 mm, underscores its significance. Augmenting the ground plane length induces a decline in primary resonance levels, with the most favorable outcome occurring at 9.0 mm. Similarly, Fig. 4(b) explores the antenna's resonance response concerning the radius of the shark fin-shaped ground. This geometric attribute significantly shapes the frequency spectrum, particularly from 4.5 to 7.5 GHz, with secondary effects extending to nearly 12 GHz. Specifically, lower values like 4.5 mm enhance the primary resonance while compromising the secondary, whereas gradual increments improve the secondary resonance while moderately affecting the primary. Ultimately, an optimal equilibrium is realized at 6 mm.

III. Results and Discussions

Following fabrication, the proposed antenna underwent rigorous testing. The outcomes are presented in Fig. 5, illustrating a comparative analysis of simulated and measured *S*-parameter responses. Impressively, the measured *S*-parameters align with the simulated data, attesting to the model's accuracy. The antenna's efficacy is vividly portrayed in Fig. 6, depicting a radia-

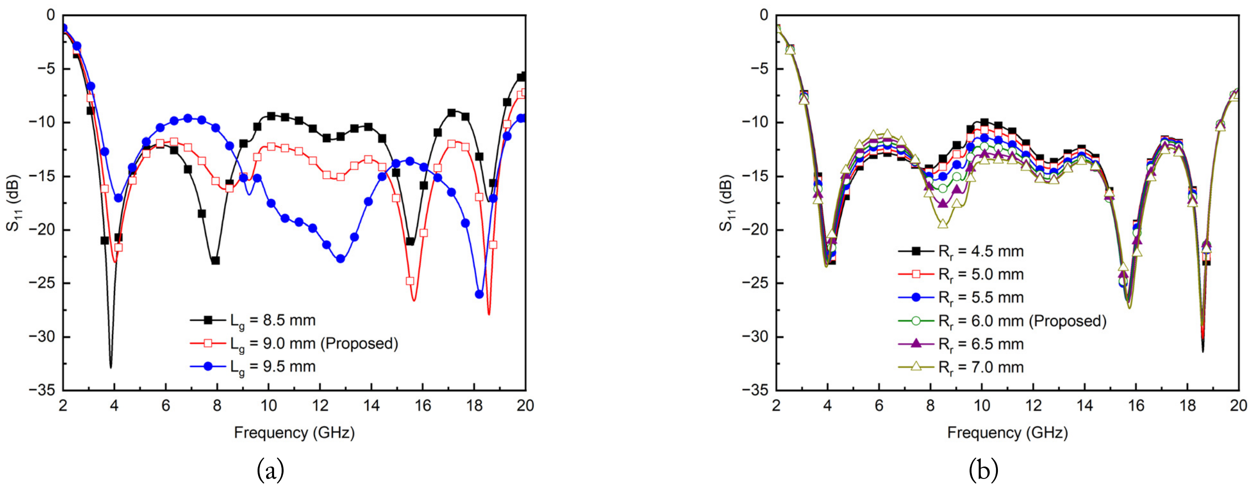


Fig. 4. Parametric analysis of the proposed antenna w.r.t. (a) L_g and (b) R_r.

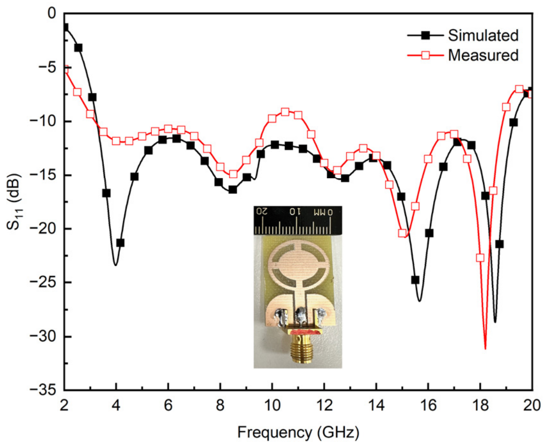


Fig. 5. S_{11} of the proposed antenna.

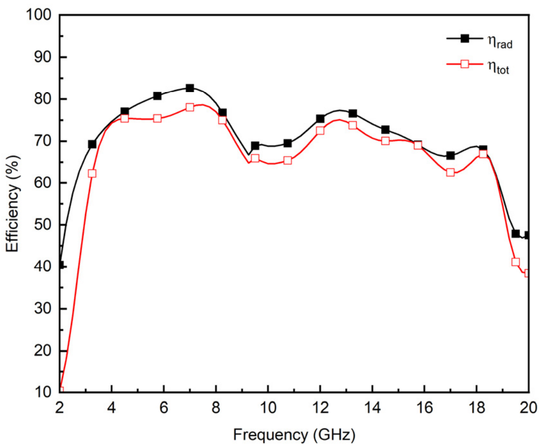


Fig. 6. Radiation and total efficiency.

tion efficiency range of 70%–82% and a total efficiency of 62%–72%. Furthermore, Fig. 7 provides insights into the simulated and measured gain, showcasing a remarkable peak gain of 5.2 dBi. Notably, this peak gain aligns exceptionally well with the simulated prediction, further validating the antenna's performance and the robustness of the proposed model.

Fig. 8 shows the radiation pattern of the propped UWB system. The figure illustrates the comparative radiation attributes

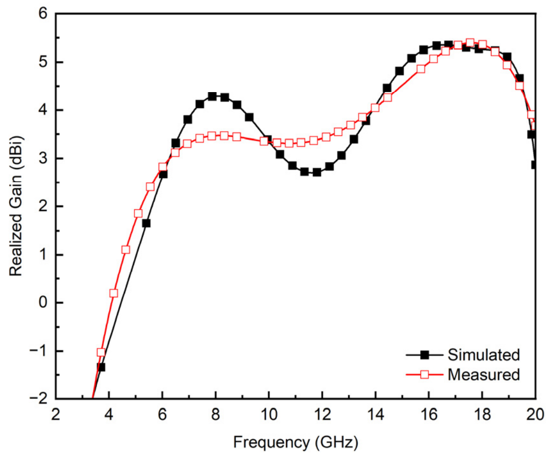
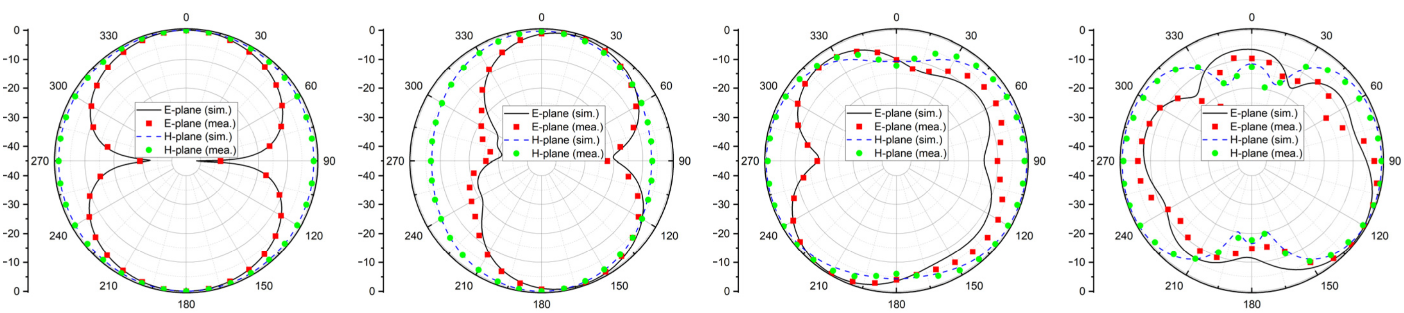


Fig. 7. Simulated and measured gain.

of the proposed fractal antenna, as both simulated and measured. The investigation encompasses the E- and H-planes across distinct frequencies of 4, 8, 12, and 16 GHz. The antenna exhibits notable bi-directional radiation traits within the E-plane while manifesting omnidirectional characteristics within the H-plane. Remarkably, the radiation patterns remain consistently stable across the entire operational bandwidth, which is a significant feature for biomedical applications.

Time domain analysis is crucial for engineers to understand how antennas emit signals over time, aiding in optimizing performance, adapting radiation patterns, and addressing interference. This analysis also evaluates impedance, reflections, and environmental effects, ensuring antennas work well in changing conditions. In wireless communication, where fading and multipath are key concerns, time domain analysis improves reliability. Fig. 9 shows the time domain analysis of the proposed UWB antenna. The antennas are placed SbS and F2F, as illustrated in Fig. 9(a) and 9(b). The distance among the radiating elements is set at 30 cm in both configurations. The isolation among the radiating elements is noted to be less than 32 dB in both cases. A Gaussian pulse, centered at 8 GHz with a frequency band of 1–15 GHz, is utilized to excite the antennas. Fig. 9(d) and 9(e)



(a) (b) (c) (b)

Fig. 8. Radiation patterns at (a) 4 GHz, (b) 8 GHz, (c) 12 GHz, and (d) 16 GHz.

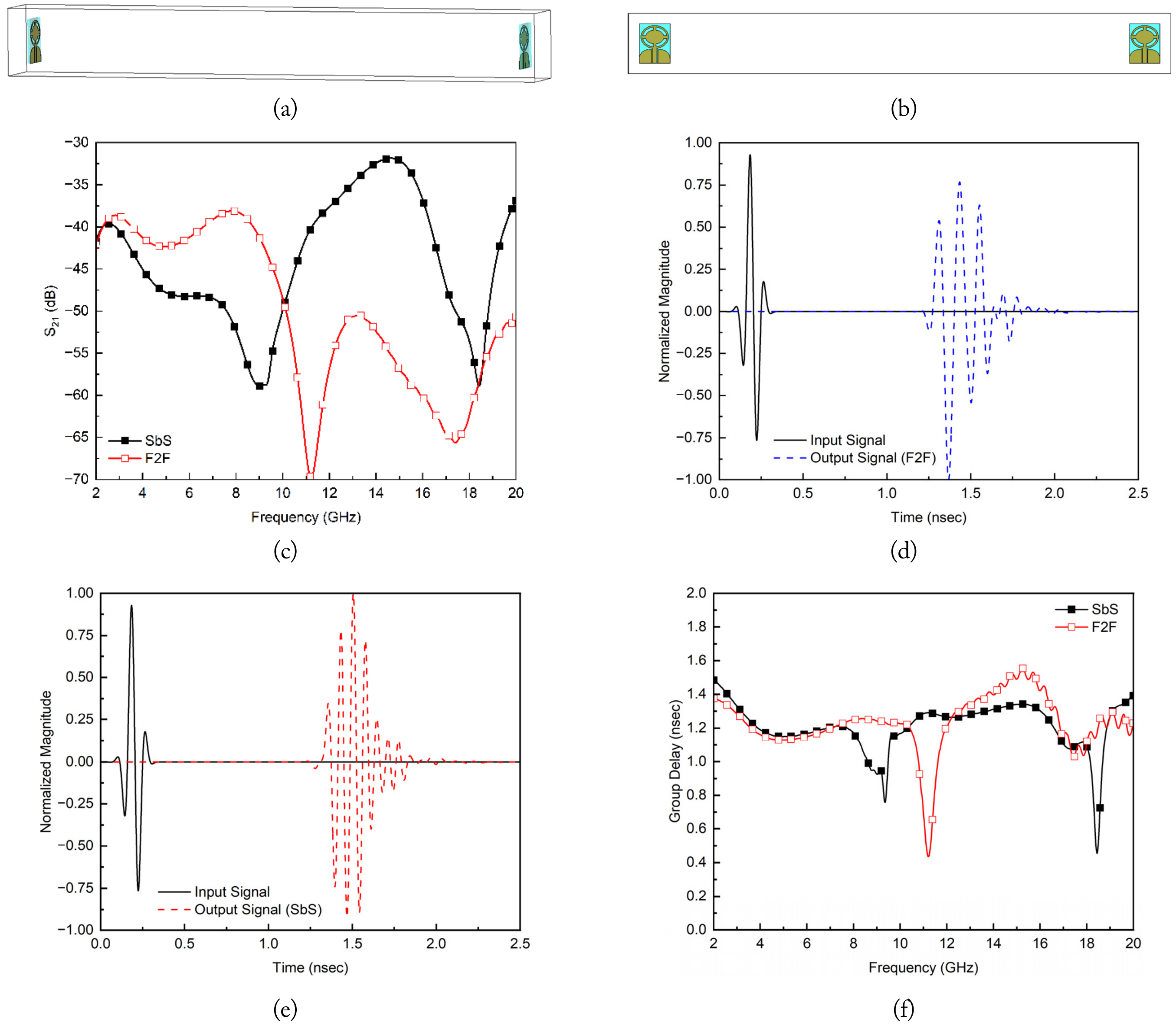


Fig. 9. (a) F2F configuration of the antennas, (b) SbS configuration of the antennas, (c) transmission coefficient for the F2F and SbS configurations, (d) normalized input and output pulses for F2F arrangement, (e) normalized input and output pulses for SbS arrangement, and (f) group delay.

show the normalized amplitudes of both input and output signals for both configurations. The group delay is shown in Fig. 9(e), which is noted to be <1.4 ns for the entire bandwidth. The results in Fig. 9(d) and 9(e) demonstrate that the antenna is capable of preserving the pulse shape, offering a high degree of fidelity, thereby making it a suitable candidate for use in microwave medical imaging (MMI) systems. Further analysis of Fig. 9(f) reveals that in the F2F configuration, the antenna offers an almost constant group delay in the range of 3–10 GHz. Considering that in microwave-based medical imaging applications, the band of 3–8 GHz offers a fair compromise between signal penetration capability and the resolution of the reconstructed image, the proposed antenna appears to be an excellent choice for use in MMI applications in its F2F configuration.

A general setup of the multiple-input multiple-output system at the breast phantom model is depicted in Fig. 10. The antenna elements are placed next to each other at 45° angles, covering the entire phantom undergoing testing. A detailed comparison with state-of-the-art antennas is presented in Table 2. The proposed antenna system performs well in terms of bandwidth characteristics, stable directional radiation patterns, and compact size.

IV. CONCLUSION

A novel planar UWB antenna has been introduced for applications in near-field microwave imaging. This antenna features a distinctive radiator configuration, utilizing a modified circular-shaped arc slot structure fed through a CPW. To enhance im-

Table 2. Proposed antenna comparison with published literature

Study	Bandwidth (GHz)	Size L × W (mm)	Gain (dBi)	Efficiency (%)
Saleem et al. [6]	3–20	25 × 35	5.36	N/A
Mahmood et al. [8]	1.2–5	40 × 45	2.9	N/A
Lin et al. [9]	7–28	50 × 60	10	88
Lee et al. [10]	3.4–12.5	16 × 21	5	85
Addepalli et al. [12]	2.84–11	18 × 26	7	75
Desai et al. [13]	3.89–17.09	26 × 31	5.87	N/A
Proposed	2.4–19	26 × 29	2.9	90

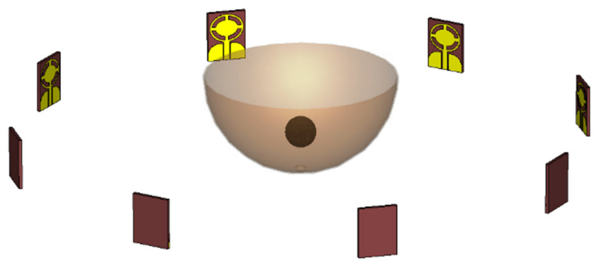


Fig. 10. Near-field microwave imaging setup with a tumor inside a breast phantom.

pedance matching, a trapezoidal-shaped ground plane has been ingeniously incorporated into the design. The resulting antenna design boasts an impressive impedance bandwidth spanning a remarkable 16.6 GHz, encompassing frequencies from 2.4 to 19 GHz. This antenna stands out for its consistent radiation characteristics throughout the entire operational bandwidth and excellent time domain properties, making it exceptionally well-suited for near-field MMI applications.

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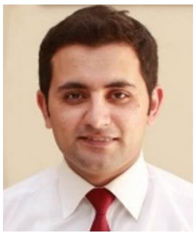

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