https://doi.org/10.3311/PPee.37073



**Periodica Polytechnica Electrical Engineering and Computer Science**, 69(2), pp. 207–214, 2025

# An Improved Design of UWB Slotted Antipodal Vivaldi Antenna for Through-wall Imaging (TWI) Systems

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Received: 07 April 2024, Accepted: 28 April 2025, Published online: 19 May 2025

**Abstract**

This paper presents an improved design of an Ultra-wideband (UWB) Slotted Antipodal Vivaldi Antenna (SAVA) for through-wall imaging (TWI) systems. The antenna, featuring slots on both flares, is designed on a 1.58 mm thick Rogers 5880 material substrate and operates within the 3 GHz to 10 GHz range. The slots, both rectangular and circular, contribute to the improved performance of the antenna. Experimental testing of the fabricated antenna reveals a measured $|S_{11}|$ of less than or equal to −10 dB and a Voltage Standing Wave Ratio (VSWR) below 2. The antenna exhibits an improved radiation pattern and achieves a maximum simulated gain of 11.7 dB within the operating range. The measured results align well with the simulated ones, thereby validating the design method. The proposed design, characterized by a compact aperture width, offers high gain, ultra-wide bandwidth, and directional radiation characteristics. These features make it suitable for TWI systems. This work contributes to the ongoing advancements in antenna design for imaging systems.

**Keywords**

Slotted Antipodal Vivaldi Antenna (SAVA), compact aperture width, TWI, UWB

## 1 Introduction

TWI technology holds immense significance due to its versatile applications and transformative impact across various domains. Its primary role lies in enhancing safety and security, allowing first responders to assess emergencies in real time and detect concealed threats during security operations [1–3]. Additionally, TWI plays a critical role in search and rescue missions, aiding in the timely location and retrieval of individuals trapped in hazardous environments [4]. Furthermore, TWI contributes to non-invasive medical diagnostics, enabling early detection of diseases and abnormalities by visualizing internal structures [5, 6]. In the realm of construction and infrastructure maintenance, it assists in evaluating structural integrity and planning renovations, ensuring the safety and durability of buildings [7, 8].

In the field of TWI, the antenna plays a central role, serving as a critical link for transmitting and receiving electromagnetic signals [9]. Its indispensability lies in collecting vital data from obscured environments. By emitting electromagnetic waves and capturing their reflections, antennas facilitate the penetration of barriers, including walls, revealing concealed spaces. The antenna's quality and effectiveness significantly impact on the resulting image resolution, clarity, and depth, making it a pivotal component for achieving precise and detailed through-wall imaging. Among the antenna types suitable for TWI, the antipodal Vivaldi antenna (AVA) stands out as an excellent option [10]. Known for its exceptional features, this innovative antenna design is well-suited for tasks that require high-resolution imaging and sensitive detection even when obstructive barriers are present.

The AVA antenna, a specialized type of antenna, is renowned for its wide bandwidth and focused radiation

**Cite this article as:** Ahmed, S., Joret, A., Katiran, N., Abbasi, M. I., Khan, F. S. "An Improved Design of UWB Slotted Antipodal Vivaldi Antenna for Through-wall Imaging (TWI) Systems", Periodica Polytechnica Electrical Engineering and Computer Science, 69(2), pp. 207–214, 2025. https://doi.org/10.3311/PPee.37073

pattern [11]. It excels in applications demanding high-frequency operation, such as TWI. This antenna features a tapered slot structure, resembling a flared horn shape, which enables efficient generation and transmission of electromagnetic waves across a broad frequency spectrum. Its carefully optimized geometry ensures high gain and low sidelobe levels. Notably, the AVA antenna's wide bandwidth allows it to operate effectively across various frequencies, [12, 13] making it suitable for applications.

Requiring flexibility in frequency selection or operation over multiple frequency bands. Several key challenges and requirements must be addressed to develop an optimal antenna for TWI applications. One of the primary requirements is wideband operation, as UWB enables high-resolution imaging, enhances signal penetration, and improves the detection of concealed objects. Additionally, high gain and directionality are crucial, as a high-gain antenna with a directional radiation pattern ensures focused electromagnetic energy transmission toward the target, reducing interference and enhancing imaging clarity. Another significant challenge is efficient signal penetration, where the antenna must minimize signal attenuation and dispersion while propagating through materials such as concrete, wood, and metal reinforcements. For field applications, the antenna should also have a compact size and lightweight structure, ensuring portability without compromising performance. Furthermore, low sidelobes and interference suppression are essential to minimize unwanted reflections, improving the signal-to-noise ratio and enhancing target detection accuracy. To achieve stable and efficient operation, impedance matching and low VSWR must be maintained, ensuring proper power transfer and reducing signal loss, typically with a Voltage Standing Wave Ratio (VSWR) below 2. Additionally, robustness and environmental resilience are vital, as TWI antennas need to withstand harsh environmental conditions, including extreme temperatures, humidity, and physical obstructions. The ability to operate over multiple frequency bands further enhances the antenna's adaptability, allowing flexibility in different imaging scenarios. Finally, cost-effectiveness and fabrication feasibility play a crucial role in ensuring that the antenna design remains practical for real-world deployment in various applications, including security surveillance, search and rescue operations, and structural integrity assessments. Developing an antenna that meets these requirements is critical for advancing TWI technology, improving its effectiveness, and expanding its applicability across diverse domains.

This research paper introduces a UWB antenna design of SAVA for TWI applications. The antenna incorporates both rectangular and circular slots on its flares, effectively extending its electrical length while minimizing surface waves. Constructed on a Rogers 5880 substrate with a thickness of 1.58 mm, the antenna exhibits a consistent radiation pattern, achieves a maximum gain of 11.7 dB, and demonstrates low return loss and VSWR.

## 2 Slotted Antipodal Vivaldi Antenna (SAVA) design

SAVA antenna is fabricated using Rogers 5880 material, which features a slotted pattern. The radiating element has a thickness of 1.58 mm. For excitation, the antenna employs a 50 Ω microstrip line with a width (*Wc*) of 4.60 mm. Rogers 5880 material is specifically chosen for its favorable tangential loss properties, contributing to high gain [14]. The SAVA design incorporates two elliptic curves of identical size, as demonstrated in [15, 16].

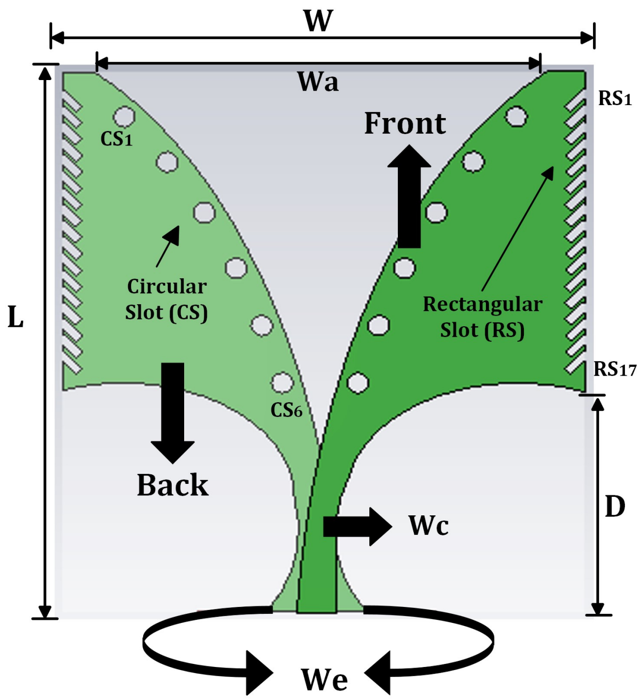
The antenna consists of two essential components: the feed line and the radiating flared wings. To enhance performance, the SAVA utilizes a slot structure [17]. The flared wings of the SAVA include six circular slots (CS) of identical size. Additionally, there are seventeen rectangular slots (RS) positioned at 45 degrees along the edges of the antenna, spaced 0.80 mm apart from each other. These rectangular slots have a length of 2.80 mm and a width of 1 mm. The antenna design process was carried out using CST Microwave Studio® [18], a powerful electromagnetic analysis software. This software allows us to design, analyze, and optimize various electromagnetic systems. For our specific antenna, we optimized its dimensions in millimeters, as detailed in Table 1. Additionally, the different layouts of the antenna are visually depicted in Fig. 1 (a) illustrates the geometrical arrangement, while Fig. 1 (b) showcases the CST layout.

## 3 Simulation results

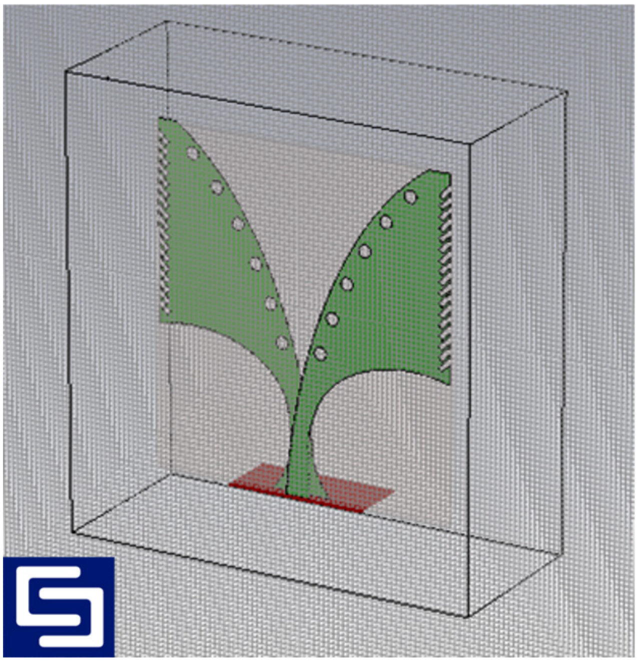
Fig. 2 presents the simulated far-field directivity plots for SAVA at frequencies ranging from 3 GHz to 10 GHz. These plots were generated using CST Microwave

**Table 1** Dimensions of SAVA

| Parameters | Value (mm) | Parameters | Value (mm) |
|---|---|---|---|
| *W* | 60.70 | *We* | 11.80 |
| *L* | 66.20 | CS (1-6) (*L* & *W*) | 2.50 |
| *D* | 27 | RS (1-17) (*W*) | 1 |
| *Wa* | 53 | RS (1-17) (*L*) | 2.80 |
| *Wc* | 4.60 | RS (angle) | 45° |

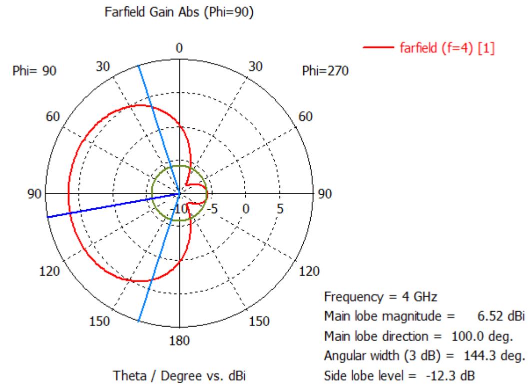



(a)

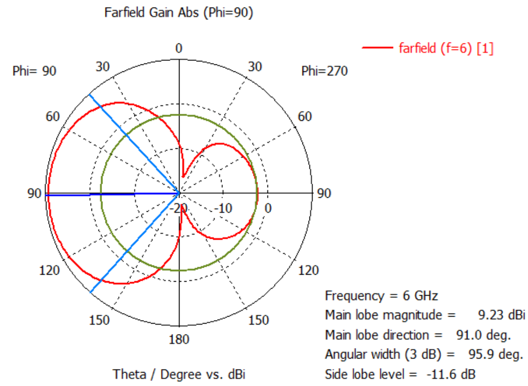


(b)

**Fig. 1** SAVA antenna layout, (a) Geometric layout, (b) CST layout




(a)

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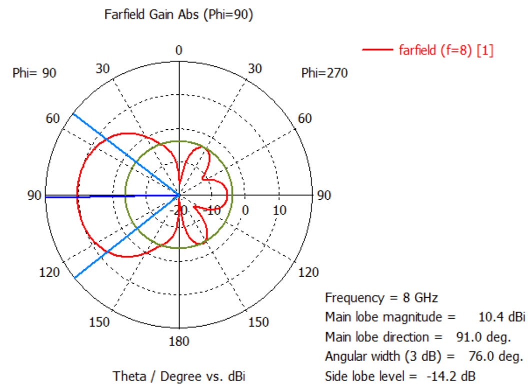
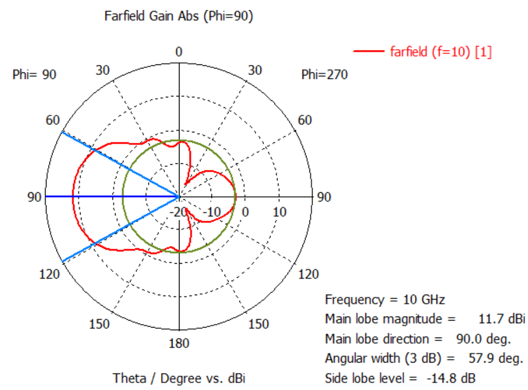



(c)




(d)

**Fig. 2** Far-field directivity plots of SAVA, (a) 4 GHz, (b) 6 GHz, (c) 8 GHz, (d) 10 GHz

Studio® [18], which provides insights into how the antenna's energy is distributed into space. Parameters such as main lobe magnitude, main lobe direction, side lobe level (SLL), and angular width are depicted in these plots at specific frequencies. The main lobe refers to the primary direction of radiation, while the side lobes are secondary, less intense lobes. By examining these plots at different frequencies, it can understand how the antenna behaves across the frequency spectrum, including changes in main lobe direction, magnitude, and the presence of side lobes.

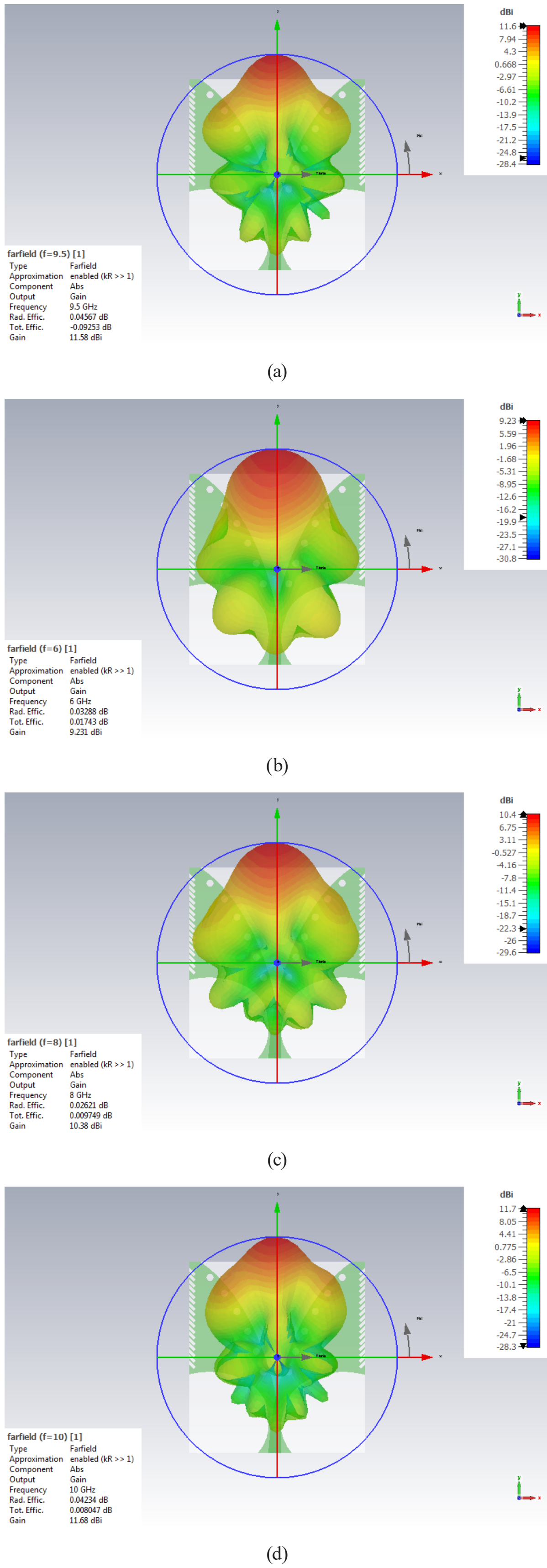
Fig. 3 illustrates the three-dimensional far-field radiation pattern of SAVA across the same frequency range (3 GHz to 10 GHz). Unlike the two-dimensional directivity plots, these 3D visualizations provide a more comprehensive view of the antenna's radiation characteristics. They show both the intensity and direction of the electromagnetic waves emitted by the antenna. The visualization of gain at specified frequencies is particularly highlighted. The gain represents the antenna's ability to focus energy in a particular direction compared to an isotropic radiator (an idealized point source radiating uniformly in all directions). Overall, these simulations and visualizations aid in understanding the performance and behavior of the SAVA antenna across different frequencies. These simulation results optimize the design for specific applications by analyzing factors such as radiation pattern, directivity, and gain.

Antenna gain is a crucial parameter that characterizes the directional performance of an antenna. Table 2 lists the gain of an antenna at different frequencies ranging from 3 GHz to 10 GHz. Generally, as the frequency increases from 3 GHz to 10 GHz, the gain of the antenna also tends to increase. This trend is common in many types of antennas, especially directional ones. The gain values listed in Table 2 range from 2.8 dB to 11.7 dB, indicating that the antenna is capable of providing significant directionality and concentration of radiation. Higher gain values signify more focused radiation in a particular direction.

Fig. 4 illustrates the simulated gain of the SAVA antenna across the UWB frequency range, spanning from 3 GHz to 10 GHz. Notably, the antenna's gain experiences an increment between 6 GHz and 10 GHz frequencies. Moreover, the simulated peak gain occurs at 10 GHz, reaching approximately 11.7 dB. At the same time, Fig. 5 presents the simulated gain of SAVA in the H-plane at 10 GHz, registering approximately 11.7 dB. Hence, the proposed antenna demonstrates advantageous radiation properties.

## 4 Antenna fabrication and experimentation

Fig. 6 depicts the prototype of the fabricated SAVA antenna, showcasing both its front and back views. The measurements were conducted using a vector network analyzer, specifically the Rohde & Schwarz model ZNB20. During the fabrication process, Rogers RT/Duroid 5880 dielectric substrates were employed, characterized by a dielectric constant ($\varepsilon r$) of 2.2 and a thickness of 1.58 mm. These details contribute significantly to our comprehensive




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

**Fig. 3** Three-dimensional far-field radiation pattern of SAVA, (a) 4 GHz, (b) 6 GHz, (c) 8 GHz, (d) 10 GHz

**Table 2** Gain of SAVA

| Frequency (GHz) | Gain (dB) |
|---|---|
| 3 | 2.8 |
| 4 | 6.5 |
| 5 | 7.7 |
| 6 | 9.2 |
| 7 | 10.7 |
| 8 | 10.4 |
| 9 | 10.7 |
| 10 | 11.7 |

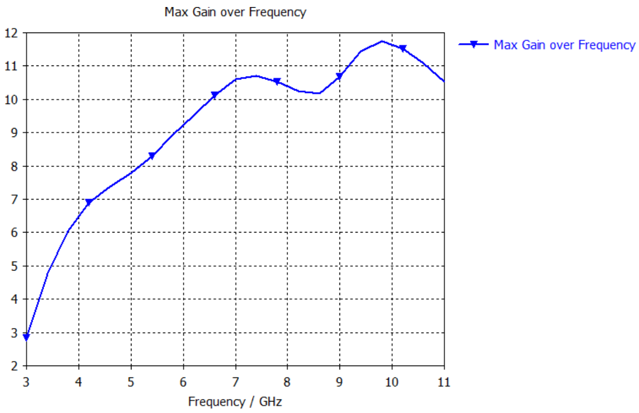



**Fig. 4** Simulated gain of SAVA over UWB band

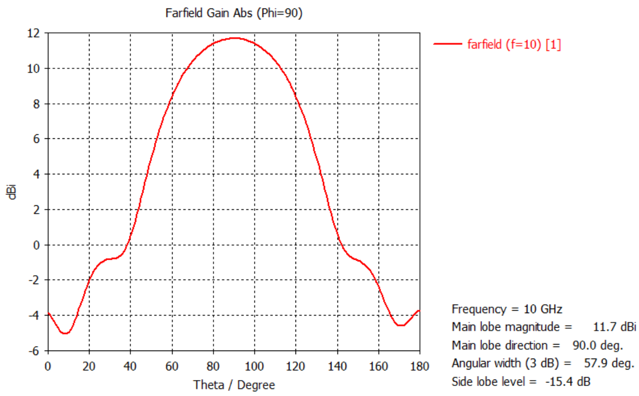
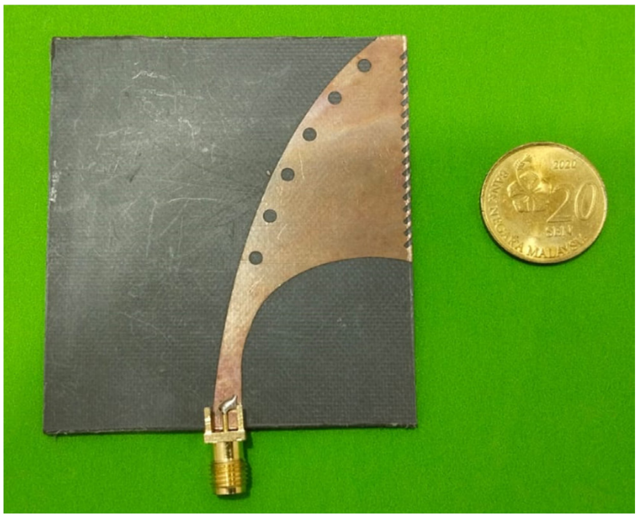



**Fig. 5** Simulated gain of SAVA in H-plane at 10 GHz

understanding of the physical structure and characteristics of the SAVA antenna being examined.

The graph in Fig. 7 illustrates the comparison between the measured and simulated reflection coefficient ($S_{11}$) for a specifically designed antenna operating in the UWB frequency spectrum. $S_{11}$ represents how much electromagnetic energy is reflected from the antenna due to impedance mismatches or other factors. The acceptable range for the reflection coefficient is specified to be below −10 dB. In other words, the goal is to minimize the reflected energy, ensuring efficient power transfer and reduced



(a)

(b)

**Fig. 6** Fabricated SAVA prototype, (a) Front, (b) Back

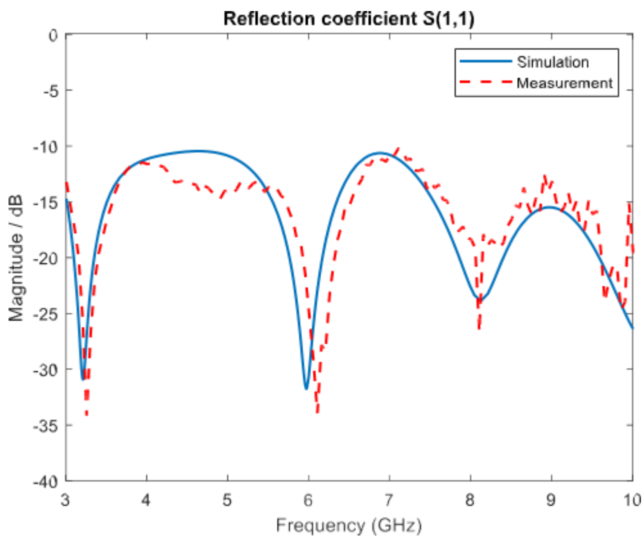



**Fig. 7** Measured and simulated ($S_{11}$)

signal loss. Both the simulated and measured reflection coefficients consistently fall below the specified threshold of −10 dB. This alignment indicates that the designed antenna performs well in terms of impedance matching. The graph suggests that the impedance-matching performance remains effective across the entire UWB band. This is a positive outcome, as maintaining impedance matching over a wide frequency range ensures reliable communication and optimal antenna performance.

VSWR is a measure of how well an antenna matches its transmission line or system. It quantifies the efficiency of power transfer and the extent of reflections due to impedance mismatches. The Fig. 8 illustrates the comparison between the measured and simulated VSWR. Lower VSWR values indicate better impedance matching. The acceptable range for VSWR is specified to be below 2. Staying within this range ensures minimal signal loss and efficient energy transfer. Both the simulated and measured VSWR consistently remain below the threshold of 2. This alignment indicates that the designed antenna successfully achieves impedance matching throughout the UWB spectrum.

### 4.1 Comparison of antenna performance

The proposed UWB SAVA is highly suited for TWI applications due to its key design advantages that enhance imaging performance. The antenna's unique design contributes to improved impedance matching and minimized surface wave effects, resulting in superior signal penetration through obstacles. Its ultrawide bandwidth ensures operation over a broad frequency range, facilitating high-resolution imaging and enhanced target detection even in cluttered environments. Additionally, the high gain

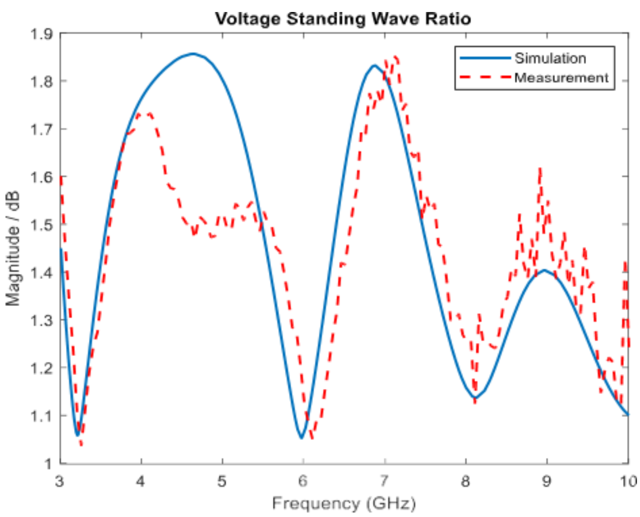



**Fig. 8** Measured and simulated VSWR

and directional radiation characteristics optimize energy focusing on the region of interest, reducing interference and enhancing image clarity. These advantages make the proposed SAVA an excellent choice for TWI applications.

Table 3 provides a comparative assessment of the proposed antenna design in contrast to previously studied antennas. The analysis focuses on critical aspects, including operating frequency range, substrate, physical dimensions, gain, and potential applications. The proposed design stands out due to several remarkable features:

- Compact form factor: It boasts a small and efficient design. Wide frequency range: It operates across the UWB spectrum.
- High gain: The antenna achieves significant signal amplification.
- Impedance bandwidth: The measured impedance bandwidth is characterized by $|S_{11}| \leq -10$ dB.
- Compact aperture size: At just 53 mm, it is notably smaller than the referenced antennas [9, 19–22].

### 4.2 Novelty of work

This research presents a novel UWB antipodal Vivaldi antenna (AVA) with a unique slotted structure and a compact 53 mm aperture, achieving high gain, ultrawide bandwidth, and directional radiation, representing a significant advancement in UWB antenna technology.

## 5 Conclusion and future work

In this research, an improved UWB slotted antipodal Vivaldi antenna (SAVA) was designed and analyzed, incorporating rectangular and circular slots to enhance performance. The proposed antenna demonstrated key advantages, including an extended effective electrical length, reduced surface waves, and improved radiation

**Table 3** The proposed antenna's performance comparison to previously reported antennas in the literature

| Ref. | Substrate | Peak gain (dB) | Freq. (GHz) | Sizes (mm) | Application |
|---|---|---|---|---|---|
| [9] | FR4 | 9.2 | 1.85–9.2 | 119 × 70 | TWI |
| [19] | Rogers RO3003 | 8.5 | 3.99–12.28 | 136 × 66 | RADAR |
| [20] | FR4 | 8.2 | 1.9–12 | 128 × 70 | TWR |
| [21] | Taconic RF-60 | 11 | 7–11 | 52 × 88 | Detection |
| [22] | FR4 | 7.66 | 1–4 | 91 × 108 | See through the wall |
| This work | Rogers 5880 | 11.7 | 3–10 | 66.20 × 60.70 | TWI |

characteristics. With a compact aperture width of 53 mm, the fabricated prototype exhibited ultrawide bandwidth, high gain, and directional radiation, making it a promising candidate for Through-Wall Imaging (TWI) applications. The measured $S_{11}$ below −10 dB and VSWR below 2 validated its impedance matching, confirming efficient signal transmission. The simulation results further verified the expected radiation characteristics, positioning the SAVA as a significant advancement in UWB antenna technology.

While the current study successfully validates the antenna's impedance characteristics and overall design effectiveness, The measurements of radiation pattern and gain could not be conducted due to facility constraints. Future work will focus on experimental validation of these parameters to further substantiate the simulated results. Additionally, optimizing the antenna's design for improved sidelobe reduction and penetration efficiency will be explored, enhancing its applicability in advanced detection and sensing systems.

**Acknowledgment**

This research was supported by the Ministry of Higher Education (MOHE) through the FRGS (FRGS/1/2021/ICT09/UTHM/02/1) and Universiti Tun Hussein Onn Malaysia (UTHM) through the Postgraduate Research Assistant Grant (GPPS) (vot H567). The author sincerely expresses gratitude to the Microelectronic Fabrication LAB at Universiti Tun Hussein Onn Malaysia for providing the necessary fabrication facilities. Special thanks are also extended to the Advanced Telecommunication Research Center (ATRC), Universiti Tun Hussein Onn Malaysia, for offering the experimental measurement facilities.

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