

A 2-18 GHz Antipodal Vivaldi Antenna for Signal Direction Finding Applications

Antena Vivaldi Antipodal 2-18 GHz untuk Aplikasi *Direction Finding* Sinyal

Deri Latika Herda¹, Joko Suryana², Frenzi Agres Yudithia³, Popy Maria⁴, Najla Raiqah Luthfiah⁵

^{1,4,5} Politeknik Negeri Padang; email: deri@pnp.ac.id, popymaria@pnp.ac.id

² Institut Teknologi Bandung; email: joko.suryana@stei.itb.ac.id

³ Politeknik Kesehatan Siteba; email: frenziagresyudithia@gmail.com

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Corresponding Author: Deri Latika Herda

ABSTRACT — The demand for advanced direction-finding systems operating in the 2-18 GHz frequency range has surged due to their role in cellular, satellite, and military applications. This increased demand has also led to a rise in illegal transmissions within this spectrum, highlighting the need for accurate signal detection and localization. This paper discusses the design and analysis of a compact antipodal Vivaldi antenna (AVA) aimed at detecting illegal transmitters within the 2-18 GHz band. Direction-finding systems require antennas with wide bandwidth, high gain, and directional radiation patterns to meet performance criteria. The Vivaldi antenna, with its tapered slot design, offers these features, making it ideal for precise signal detection. Designed on an FR-4 substrate with a relative permittivity of 4.6, the antenna's performance was optimized using CST Microwave Studio software. The antenna was fabricated using wet etching on a copper conductor. Measurement results show that the antenna exhibits a directional radiation pattern, with a maximum gain of 10.527 dBi at 8 GHz, surpassing the simulated gain of 8.12 dBi, and an average measured gain of 5.975 dBi, exceeding the design requirement of 4 dBi. Operating effectively across a 2.7-18 GHz range, the antenna achieves a bandwidth of 15.3 GHz, fulfilling 95.625% of the specified range. Despite minor shifts in the reflection coefficient due to dielectric permittivity variations in the FR-4 substrate, the antenna demonstrates strong performance for direction-finding applications. This study highlights the AVA's potential for high-performance detection of illegal transmitters and discusses design challenges and opportunities for optimization.

KEYWORDS — 2-18 GHz, Antipodal Vivaldi Antenna, Direction Finding, FR-4

ABSTRAK — Permintaan untuk sistem pencarian arah canggih yang beroperasi di rentang frekuensi 2-18 GHz telah meningkat karena perannya yang penting dalam aplikasi seluler, satelit, dan militer. Peningkatan permintaan ini juga menyebabkan meningkatnya transmisi ilegal dalam spektrum ini, yang menyoroti kebutuhan akan deteksi dan lokalisasi sinyal yang akurat. Makalah ini mendiskusikan desain dan analisis antena Vivaldi antipodal (AVA) kompak yang ditujukan untuk mendeteksi pemancar ilegal dalam pita frekuensi 2-18 GHz. Sistem pencarian arah memerlukan antena dengan bandwidth lebar, gain tinggi, dan pola radiasi arah untuk memenuhi kriteria kinerja. Antena Vivaldi, dengan desain slot yang meruncing, menawarkan fitur-fitur ini, menjadikannya ideal untuk deteksi sinyal yang tepat. Antena ini dirancang pada substrat FR-4 dengan permitivitas relatif 4,6, dan kinerjanya dioptimalkan menggunakan perangkat lunak CST Microwave Studio. Proses fabrikasi dilakukan dengan teknik etsa basah pada konduktor tembaga. Hasil pengukuran menunjukkan bahwa antena ini memiliki pola radiasi satu arah, dengan gain maksimum 10,527 dBi pada 8 GHz, melebihi gain simulasi sebesar 8,12 dBi, dan rata-rata gain terukur 5,975 dBi, melampaui persyaratan desain 4 dBi. Antena beroperasi efektif pada rentang 2,7-18 GHz dengan bandwidth 15,3 GHz, memenuhi 95,625% dari rentang yang ditentukan. Meskipun terdapat pergeseran minor pada koefisien refleksi akibat variasi permitivitas substrat FR-4, antena ini menunjukkan kinerja yang kuat untuk aplikasi *direction finding*. Studi ini menyoroti potensi AVA untuk deteksi pemancar ilegal berkinerja tinggi dan membahas tantangan desain serta peluang untuk optimasi lebih lanjut.

KATA KUNCI — 2-18 GHz, Antena Vivaldi Antipodal, Direction Finding, FR-4

I. INTRODUCTION

In recent years, the demand for advanced direction-finding systems operating within the 2-18 GHz frequency range has significantly increased. These systems play a critical role in radar, navigation, and communication, with particular emphasis on detecting and localizing signals across a wide range of frequencies, including those used in cellular, satellite, and military applications [1]. The 2-18 GHz spectrum is increasingly crowded, and the need to pinpoint illegal transmissions or interference within this range has become paramount. In Indonesia, the Ministry of Communication and Informatics monitors the use of the radio frequency spectrum by detecting the positions of illegal transmitters through a direction finding (DF) system, aiming to minimize illegal frequency usage within specific frequency bands [2]. The direction-finding antennas used for these purposes must

meet stringent performance specifications to ensure accurate detection and localization of signals in this complex environment. Frequency range is a primary specification for direction-finding antennas, particularly within the 2-18 GHz range. This broad frequency span allows antennas to operate effectively across critical communication bands, ensuring versatility in detecting signals from various sources and technologies. Direction finding antennas must also be designed to exhibit wide to capture a broader spectrum of signals, which enhances their ability to distinguish between different sources and avoid performance degradation in dynamic environments [3]. Increasing the bandwidth further improves the accuracy of direction finding by offering a wider spectral view of incoming signals, which is essential for precise detection and localization [4]. Gain, another critical specification, indicates the antenna's capacity to concentrate energy in a particular direction. For direction-finding, high gain is essential to enhance signal resolution and to accurately identify the location of signal sources. The 2-18 GHz frequency range encompasses various types of signals that often operate close to one another in frequency. High gain helps reduce interference and allows the antenna to differentiate between closely spaced signals. Recent innovations in antenna design have focused on increasing gain while maintaining compact form factors, making them suitable for portable or space-constrained direction-finding systems [5]-[6]. In addition to gain, antenna's radiation pattern, including beamwidth and sidelobe levels, is critical for precise direction-finding. Antennas with well-defined and narrow directional radiation patterns are preferred for their ability to pinpoint signal sources with high precision [7]. Recent research emphasizes the importance of minimizing sidelobes to reduce false detections and improve the reliability of direction-finding systems [8]. Size and weight are also significant considerations, particularly for portable or space-constrained applications. Recent developments have focused on creating lightweight and compact antennas without compromising performance [9].

Recent advancements in direction-finding (DF) antennas have highlighted the increasing demand for systems that can operate effectively across wide frequency ranges, particularly from 2 to 18 GHz. Among various antenna designs, the antipodal Vivaldi antenna, with its tapered slot design, has gained attention due to its broad impedance bandwidth, directional radiation pattern, and high gain, making it a perfect fit for modern DF applications [10]-[12]. In comparison to traditional dipole or loop antennas, which offer simpler designs and are widely used in DF systems, the antipodal Vivaldi antenna offers exceptional efficiency in terms of signal resolution and angular accuracy due to its ability to handle wideband signals and focus energy on specific directions [13]-[14]. Furthermore, recent studies have shown that while phased array antennas can offer high accuracy, they tend to be more complex and expensive, especially for systems requiring coverage across a broad spectrum like 2-18 GHz [15]. In contrast, the antipodal Vivaldi antenna combines compact size with high performance, making it a versatile option for both portable and fixed DF systems. Moreover, the cross-polarization rejection and low sidelobe levels of Vivaldi antennas have been found to be highly beneficial for reducing interference and improving signal localization in dynamic environments [16]-[17]. These characteristics make them highly competitive in applications such as satellite communications, military surveillance, and spectrum monitoring. Advances in material science and microfabrication techniques have led to improvements in antenna efficiency and reduced fabrication costs [18]-[19]. For instance, the use of advanced dielectric substrates and precision manufacturing methods has resulted in antennas with improved impedance matching and reduced radiation pattern distortions [20]-[21]. Despite their advantages, challenges remain in optimizing the antipodal Vivaldi antenna for direction-finding applications. Issues such as achieving optimal impedance matching across the Ultra-Wideband (UWB) spectrum and minimizing interference from surrounding signals require ongoing research and development. Addressing these challenges through innovative design and material enhancements is crucial for advancing the capabilities of direction-finding systems.

This research focuses on designing a compact antipodal Vivaldi antenna using an FR-4 substrate for direction-finding applications in the 2-18 GHz frequency range, specifically for detecting illegal transmitters. FR-4 is used as a substrate material for antenna design due to its cost-effectiveness, availability, and good mechanical properties. As an inexpensive and easily accessible material, FR-4 is an ideal choice for rapid prototyping and low-cost antenna fabrication. Additionally, FR-4 has decent electrical insulating properties, ensuring reliable performance in most antenna designs. The material also provides good mechanical strength, which ensures durability, and its compatibility with standard PCB manufacturing techniques such as etching and milling allows for easy and cost-effective mass production. Although other materials such as PTFE may offer lower dielectric losses at higher frequencies, FR-4 remains a preferred option due to its well-balanced performance and affordability in a wide range of antenna applications [22]-[24]. This paper provides a comprehensive analysis of the antipodal Vivaldi antenna, detailing its design considerations, simulation results, and experimental validation.

II. PROPOSED ANTENNA DESIGN

Figure 1 depicts the stages of antenna development. The initial stage involves determining the specifications for the direction-finding antenna, as outlined in Table I. The antenna is designed to function across 2-18 GHz frequency range, providing an average gain of 4 dBi. It is made of copper, with a thickness of 0.035 mm, and mounted on an FR-4 substrate that is 1.6 mm thick, having a relative permittivity of 4.6.

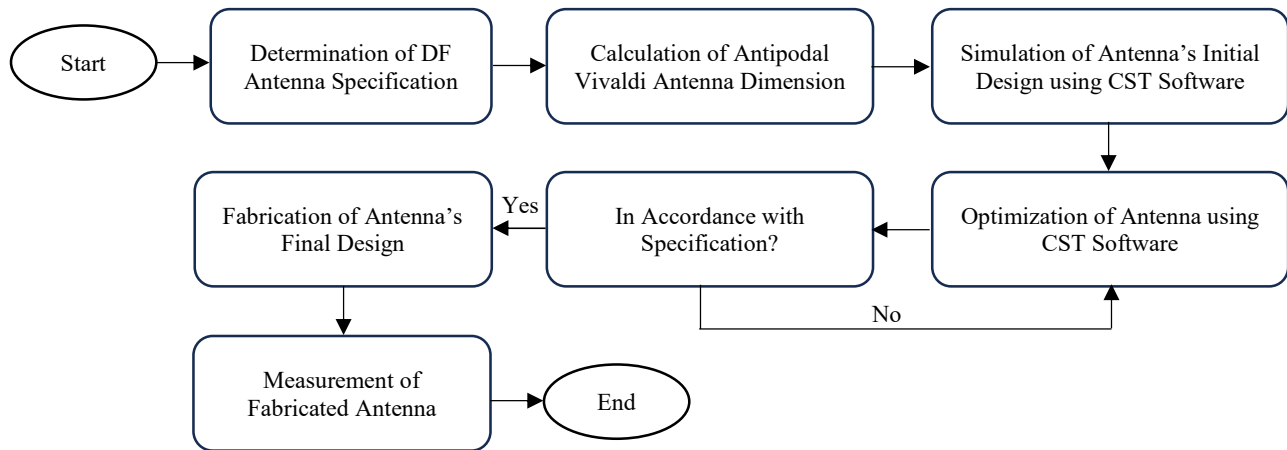


Figure 1. Flow chart of proposed antenna design

TABLE I
ANTENNA SIZE DETAILS

Parameters	Values
S_{11}	≤ -10 dB
VSWR	≤ 2
Bandwidth	16 GHz
Operating Frequency	2 – 18 GHz
Average Gain	4 dBi
Radiation Pattern	Directional

Once the specifications were defined, the Antipodal Vivaldi Antenna (AVA), known for its wide impedance bandwidth, directional radiation pattern, and high gain was selected for development in the direction-finding system. The AVA was designed by determining the key parameters that shape the antenna using the following formulas:

$$W = L = \frac{c}{2fl} \sqrt{\frac{2}{\epsilon_r + 1}} \quad (1)$$

$$R_1 = \frac{W}{2} + \frac{w_f}{2} \quad (2)$$

$$R_2 = \frac{W}{2} - \frac{w_f}{2} \quad (3)$$

$$R_{S2} = \frac{R_2}{2} \quad (4)$$

The width of the microstrip line is determined using the following equation:

$$\epsilon_{r_{eff}} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \frac{1}{\sqrt{1 + 12 \frac{h}{W}}} \quad (5)$$

$$Z_c = \begin{cases} \frac{60}{\sqrt{\epsilon_{r_{eff}}}} \ln \left[\frac{8h}{W_0} + \frac{W_0}{4h} \right] & , \frac{W_0}{h} \leq 1 \\ \frac{120\pi}{\sqrt{\epsilon_{r_{eff}} \left[\frac{W_0}{h} + 1.393 + 0.667 \ln \left(\frac{W_0}{h} + 1.444 \right) \right]}} & , \frac{W_0}{h} > 1 \end{cases} \quad (6)$$

The length of the microstrip line can be calculated using (7) and (8).

$$\lambda_g = \frac{c}{f \sqrt{\epsilon_r}} \quad (7)$$

$$L_f = \frac{\lambda_g}{4} \quad (8)$$

The AVA, designed based on the calculation, is illustrated in Figure 2, with the dimension details provided in Table II.

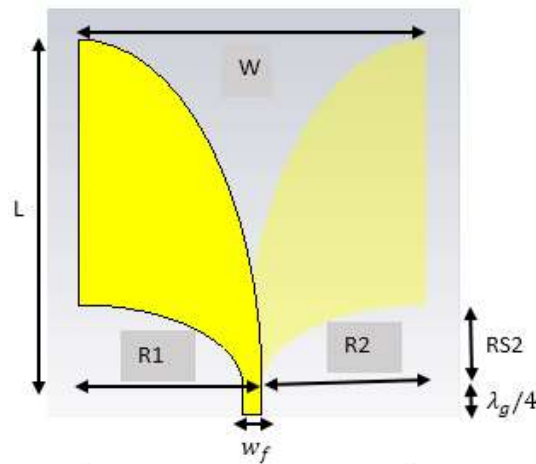


Figure 2. Initial design of the antipodal Vivaldi antenna

TABLE II
 INITIAL ANTENNA SIZE DETAILS

Parameters	Values (in mm)
W	85.821
L	44.821
w_f	2.43
L_f	3.62
R_1	23.6255
R_2	21.1955
R_{S2}	10.59775

The initial antenna design was simulated using CST software. The simulation results, as shown in Figure 3, indicated that the best S_{11} value was -50.004125 dB at 2.304 GHz, while the worst S_{11} value was -2.4391982 dB at 3.125 GHz. Overall, the simulation results did not meet the required specifications. Most of the S_{11} values within the 2–18 GHz frequency range were above -10 dB, which is the required threshold. Therefore, the antenna was optimized to meet the specifications. The optimization was carried out using a trial-and-error method in CST software, which involved modifications to the ground plane, increase of the arm width, and extension of the transmission line.

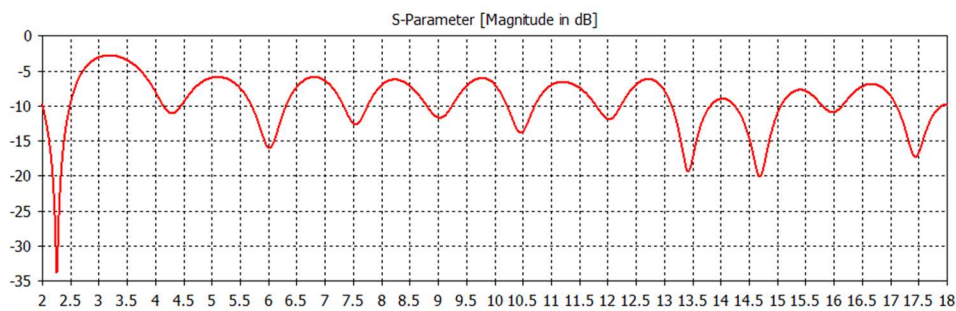
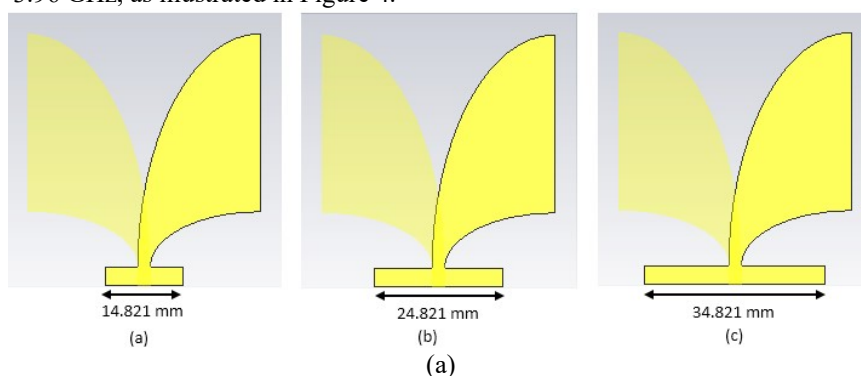


Figure 3. S_{11} graph of initial design

The modification of the ground plane showed that increasing its width reduced S_{11} , thereby enhancing the antenna's bandwidth. Ground plane *c*, with a width of 34.821 mm, produced the optimal S_{11} response, where the specification was not met only in the frequency range of 2.32–3.96 GHz, as illustrated in Figure 4.



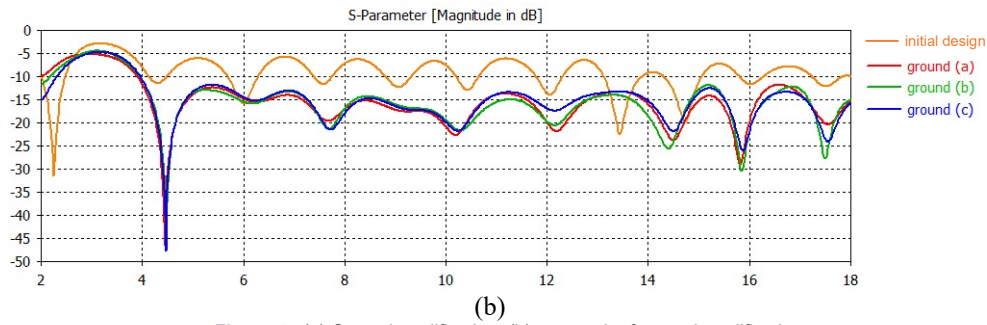


Figure 4. (a) Ground modification, (b) S_{11} graph of ground modification

The method of increasing the arm width was chosen because the S_{11} values from the ground modification did not meet the requirements at lower frequencies. This is consistent with the theoretical principle that as the operating frequency decreases, the antenna dimensions must increase. An arm width of 85.821 mm resulted in the best S_{11} graph, as shown in Figure 5, where only the frequency range of 2.43–3.33 GHz (approximately 0.9 GHz) failed to meet the S_{11} specification of ≤ -10 dB.

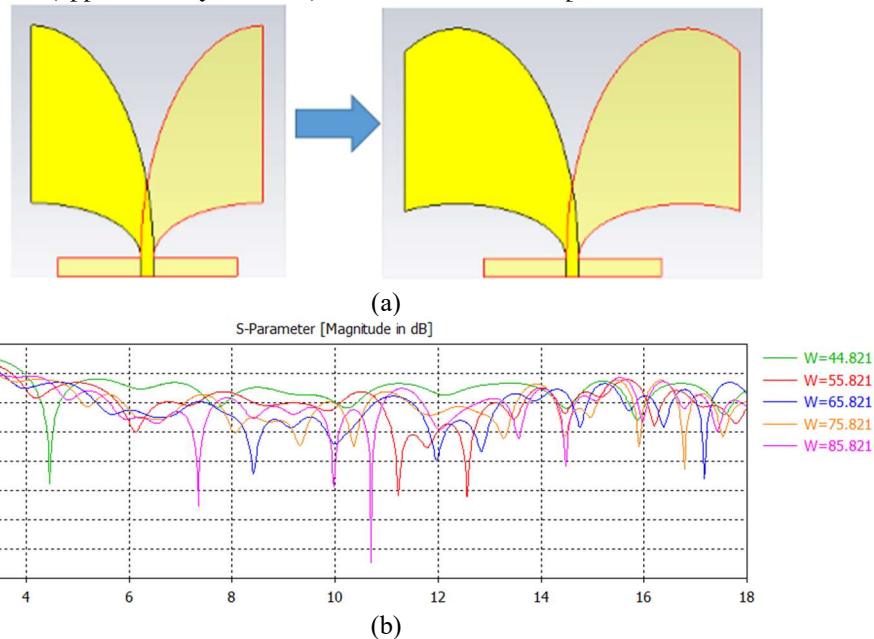


Figure 5. (a) Arm width optimization, (b) S_{11} graph of arm width optimization

Since these methods still did not meet the S_{11} requirements at lower frequencies, further optimization was done by increasing the transmission line length. The transmission line length of 24.379 mm shifted the S_{11} graph to lower frequencies—essentially shifting the graph to the left—ensuring that the S_{11} requirement was met across the 2 to 18 GHz range, as displayed in Figure 6.

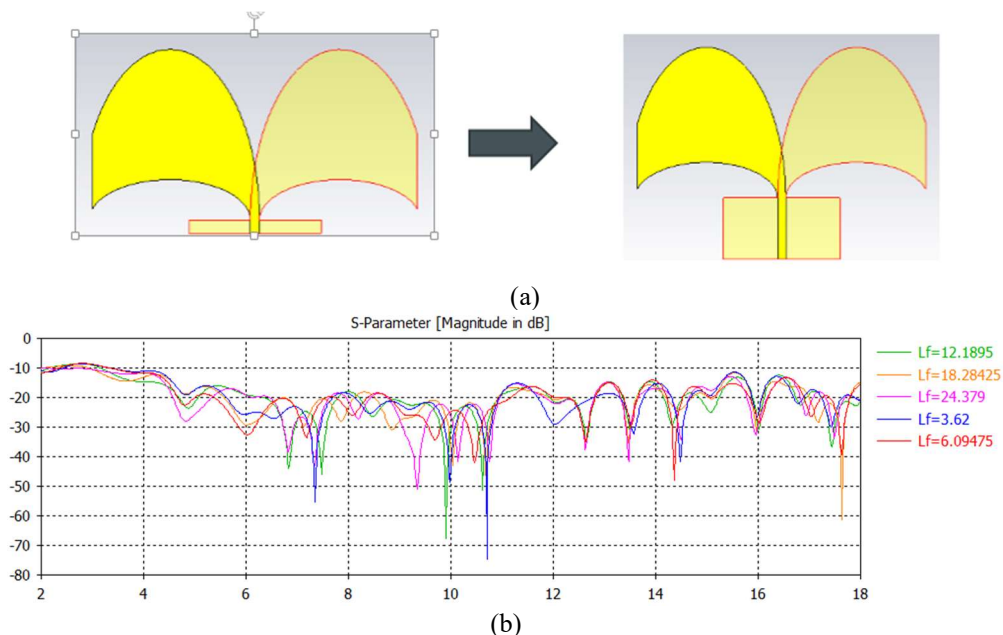


Figure 6. (a) Transmission line optimization, (b) S_{11} graph of transmission line optimization

Once the design was finalized as shown in Figure 7, with the details provided in Table III, the fabrication of the antenna's final design takes place. The fabricated antenna was then tested through measurement to evaluate its real-world performance.

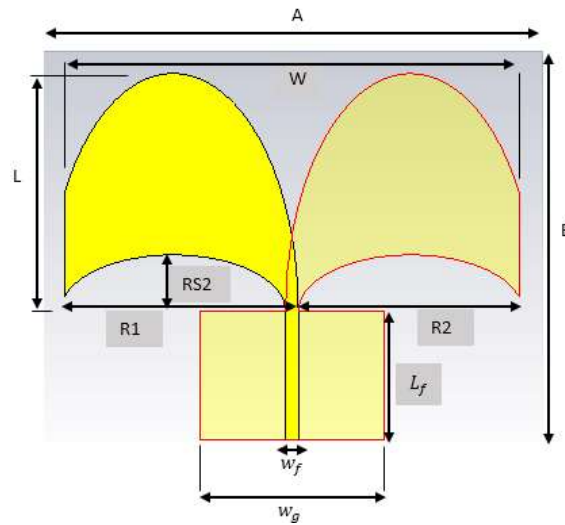


Figure 7. The final design of antipodal Vivaldi antenna

TABLE III
FINAL ANTENNA SIZE DETAILS

Parameters	Values (in mm)
W	85.821
L	44.821
w_f	2.43
L_f	24.379
R_1	23.6255
R_2	21.1955
R_{S2}	10.59775
w_g	34.821
A	94.14
B	73.2

III. RESULTS AND DISCUSSION

The fabricated antenna, as shown in Figure 8, was obtained using the wet etching technique, where the conductor is patterned onto a substrate made from an electrical material. The substrate is FR-4 Epoxy with a relative permittivity of 4.6 and a thickness of 1.6 mm. The printed antipodal Vivaldi antenna measures 94.14 x 73.2 mm, and the conductor used for the patch is copper with a thickness of 0.035 mm.

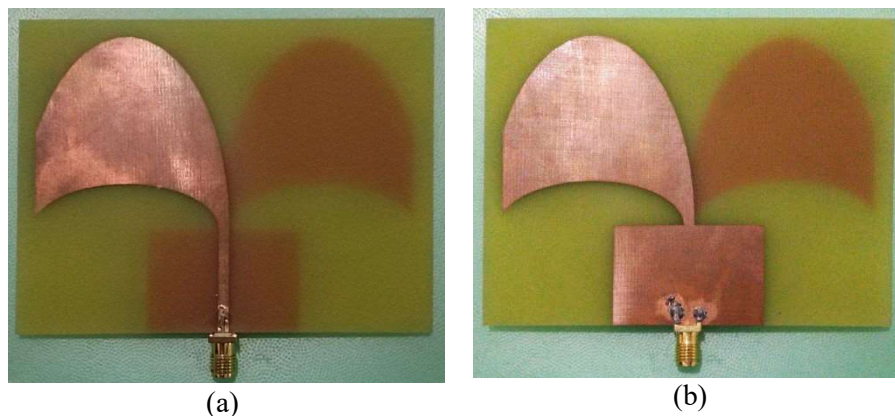


Figure 8. Fabricated antipodal Vivaldi antenna (a) front-side; (b) back side

The measurement results, as displayed in Figures 9 and 10, show a shift towards higher frequencies for both the reflection coefficient and VSWR. From the reflection coefficient measurements, it can be concluded that the antenna operates within the 2.7-18 GHz range (bandwidth of 15.3 GHz) with a minimum value of -29.602 dB at 16.25 GHz. The VSWR < 2 condition is met within

the frequency range of 2.7-18 GHz, with a minimum value of 1.0685 at 16.25 GHz. Within 2-2.7 GHz band, the reflection coefficient is still considered good, with a maximum value of -9.371 dB at 2.15 GHz. Despite similar patterns, there are still differences between the measured and simulated results for the reflection coefficient and VSWR. These differences are due to the dielectric permittivity variation, with the permittivity of FR-4 typically ranging from 4.4 to 4.8 [24]. The dielectric permittivity value of the FR-4 epoxy substrate used in fabrication is uncertain and differs from the value assumed in the simulation. Measurements indicate a shift towards higher frequencies, suggesting that the dielectric permittivity of the fabricated substrate is less than the 4.6 value used in the simulation.

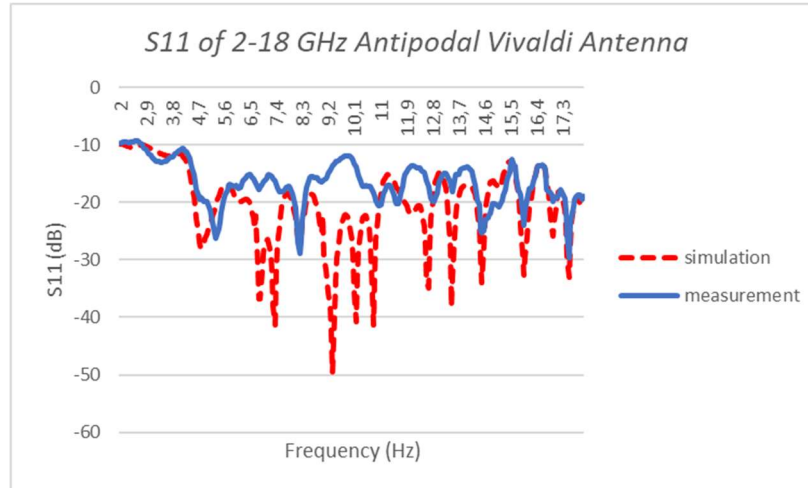


Figure 9. S_{11} of the antipodal Vivaldi antenna

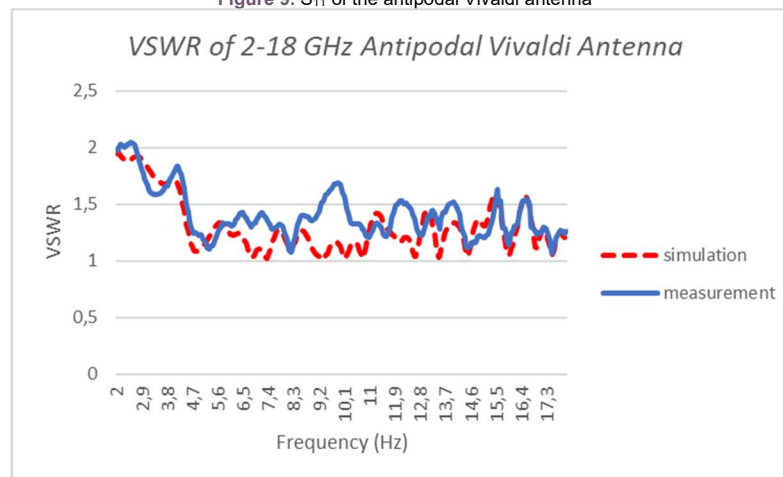


Figure 10. VSWR of the antipodal Vivaldi antenna

Measured radiation patterns, shown in Figures 11 and 12, closely resemble the simulated patterns, with the main lobe in the elevation plane remaining around 90° , consistent with the simulation results. However, at 8 GHz, the direction of the main lobe in the azimuth plane deviates significantly from the simulated direction (90°). These differences are attributed to the data being collected by rotating the angle in 10° increments, which may lead to less precise measurements.

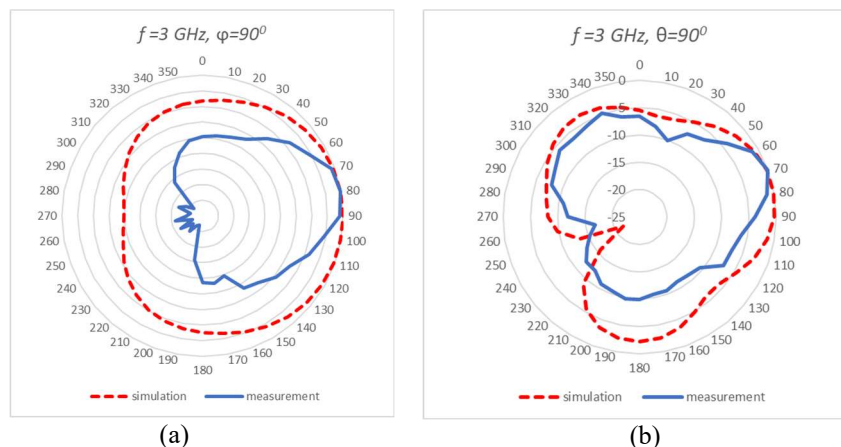


Figure 11. Radiation pattern on 3 GHz (a) azimuth at $\varphi=90^\circ$; (b) elevation at $\theta=90^\circ$

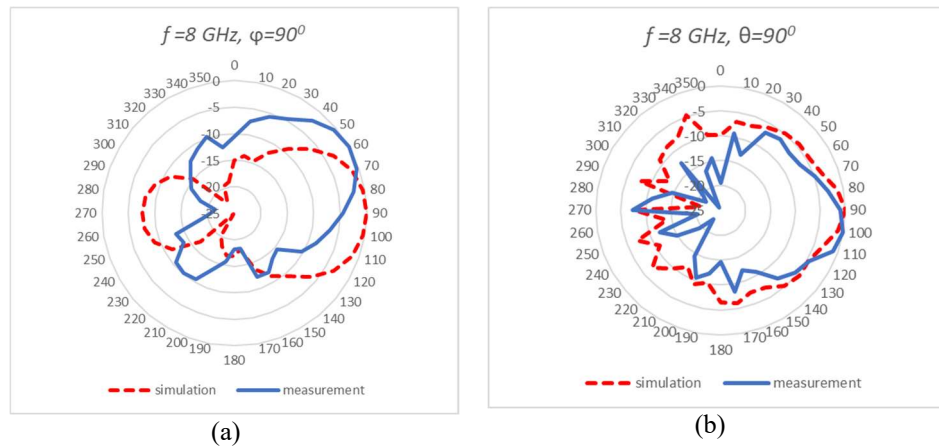


Figure 12. Radiation pattern on 8 GHz (a) azimuth at $\varphi=90^\circ$; (b) elevation at $\theta=90^\circ$

Figure 13 demonstrates that the measured gain values surpass the simulated gain values. The measurement shows a maximum gain of 10.527 dBi at 8 GHz, compared to a maximum of 8.12 dBi from the simulation at the same frequency. The average measured gain is 5.97558 dBi, which exceeds the average simulated gain of 5.1558 dBi. This average gain meets the specified requirements (4 dBi).

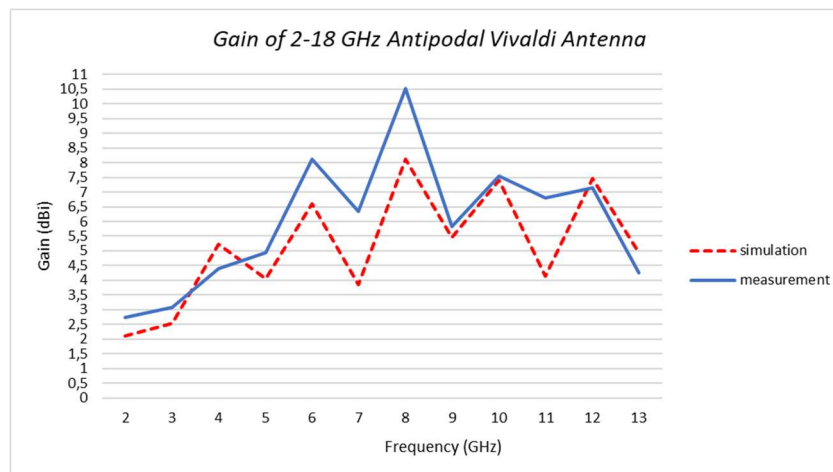


Figure 13. Gain of the antipodal Vivaldi Antenna

The proposed antenna design generally meets the direction-finding antenna specifications, though there are a few areas that could be further optimized. The average gain of the fabricated antenna surpasses the required specifications, indicating it is suitable for the intended application. However, while the bandwidth is close to the target, achieving 95.625% of the specified range, it still falls slightly short and could benefit from further refinement. Additionally, the S_{11} performance, particularly in the lower frequency range of 2–2.7 GHz, could be improved. Enhancing the return loss in this range would broaden the bandwidth of the antenna. The radiation pattern is directional and meets the specification, but there is potential for narrowing the beamwidth to enhance the performance of direction-finding systems. A more-focused radiation pattern would improve angular resolution and help the antenna perform better in accurately locating signal sources. In conclusion, while the antenna design meets most of the required specifications, improvements in bandwidth, S_{11} performance at lower frequencies, and radiation pattern narrowness would further optimize its performance for direction-finding applications.

IV. CONCLUSION

The evaluation of the fabricated antipodal Vivaldi antenna (AVA) confirms its suitability for direction-finding applications within the 2-18 GHz range. Manufactured using a wet etching technique on an FR-4 Epoxy substrate, the antenna demonstrates a 2.7-18 GHz operational range with a bandwidth of 15.3 GHz, fulfilling 95.625% of the specified bandwidth. Although the reflection coefficient and VSWR indicate good performance across the frequency range, slight shifts toward higher frequencies were observed, likely due to variations in the substrate's dielectric permittivity. The directional radiation patterns at 3 GHz and 8 GHz closely match the simulations, with minor discrepancies attributed to measurement inaccuracies. Notably, the measured gain surpasses simulations, reaching 10.527 dBi at 8 GHz compared to 8.12 dBi in the simulation, and an average gain of 5.98 dBi, exceeding the required 4 dBi. These results underscore the antenna's strong performance for high-precision direction-finding, positioning it as an effective tool for detecting unauthorized transmitters. Further refinements in the 2–2.7 GHz range and beamwidth narrowing could further optimize its performance for specialized applications.

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