

Article

Design of Antipodal Vivaldi Antenna with Circular Load for Bandwidth Enhancement in Radar Applications

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Abstract: Radio Detection and Ranging (RADAR) attracts a lot of attention because it has an important role in life through its various applications such as in security, navigation, transportation, telecommunications and medical applications. Ultra-wideband radar applications require accurate, high-resolution detection and good penetration capabilities. To fulfil this, the bandwidth required must be greater, resulting in a narrower pulse width. In this case, an antenna using ultra-wideband technology is needed to accommodate this. This research discusses the design of an ultra-wideband antipodal vivaldi antenna with the addition of circular loads designed to increase bandwidth in radar applications. The design and simulation in this study used CST Studio Suite 2019 software and then measured with a Vector Network Analyzer (VNA) to determine antenna performance. The results of this study show that the antenna can work at a frequency of 898.85 MHz to more than 3.2 GHz with a unidirectional radiation pattern. In addition, the gain generated in this study is 6.6 dBi, S1.1 -17.01 dB, and a bandwidth of more than 2301.15 MHz.

Keyword: Bandwidth, Microstrip Antenna, UWB, UWB Radar, Vivaldi Antenna

1. Introduction

Radar has become a very important technology in various applications such as security, navigation, transportation, telecommunications, and the medical field [1], [2]. In use, radar obtains information about objects around us by using electromagnetic waves [3]. One of the main challenges in the development of radar systems is achieving high resolution, good accuracy, and optimal penetration capability. To achieve this, ultra-wideband radar technology using a large bandwidth is needed.

Ultra-Wideband is a short-range communication system that requires large bandwidth, and according to Federal Communication Commission (FCC) regulations, an antenna is said to be UWB when the bandwidth width is greater than 20% of its centre frequency [4], [5]. With a wide bandwidth, the ultra-wideband radar pulse can provide higher time resolution, allowing the radar system to detect objects or targets with higher precision in the time domain [6], [7]. Here, antennas have an important role in transmitting and receiving radar signals, so to achieve optimal performance the type of antenna that has a conically widened patch slot. The large bandwidth and consistent directivity of this vivaldi antenna caused the antenna to be widely developed. Therefore, wideband or ultra-wideband applications are suitable for this antenna [8].

The authors propose to design and realise a microstrip antenna using antipodal vivaldi patches and adding circular weights to each antenna arm to analyse the effect of adding circular weights on

its bandwidth. The antenna's substrate material used is FR-4 Epoxy (lossy), and the designed antenna operates in the frequency range of 1.25 GHz – 2.75 GHz, following the UWB antenna specifications for UWB radar applications, which require a bandwidth of $\geq 20\%$, a gain above 3 dBi, and S1.1 value of ≤ -10 dB, and a unidirectional radiation pattern.

2. Literature Review

2.1. Vivaldi Antenna

The vivaldi antenna consists of thin conductor sheets placed on top of another thin conductor sheet, with a substrate layer in between [9]. The vivaldi antenna is characterised by a tapered slot patch width, a wide bandwidth, and consistent directivity [10]. Therefore, it is suitable for wideband or ultra-wideband applications [11].

2.1.1. Conventional Antipodal Vivaldi Antenna

The antipodal vivaldi antenna is a type of antenna designed to support a wide frequency range, particularly in radar and wireless communication applications. This antenna is known for its wide radiation pattern and responsiveness to high frequencies. Its design features antipodal elements shaped like open hands, with ends that diverge, forming a "V" shape as shown in Figure 1, which is a characteristic feature. This structure allows the antipodal vivaldi antenna to produce an excellent radiation pattern for capturing and transmitting signals across various frequencies [4]. W_{sub} is the width of the substrate, and l_{sub} is the length of the substrate. In the design of this conventional antipodal vivaldi antenna, the substrate width value is adjusted to match the width of the antenna patch ($w = W_{sub}$). To calculate the patch width, the following Equation 1 can be used [8]:

$$w = \frac{c}{2f_0 \sqrt{\frac{\epsilon_r + 1}{2}}} \quad (1)$$

Where c is the speed of light (3.10^8 m/s), f_0 is the frequency used, and ϵ_r is the dielectric constant used [13]. The patch length can be determined after calculating the fringing field effect for the radiating element (ΔL), as shown in Equation 2 [14]. For the effective radiating element length (L_{eff}), Equation 3 is used [8]:

$$\Delta L = 0.412h \frac{(\epsilon_r + 0.3) \left(\frac{W}{h} + 0.264\right)}{(\epsilon_r - 0.258) \left(\frac{W}{h} + 0.8\right)} \quad (2)$$

$$L_{eff} = l_p + 2\Delta L \quad (3)$$

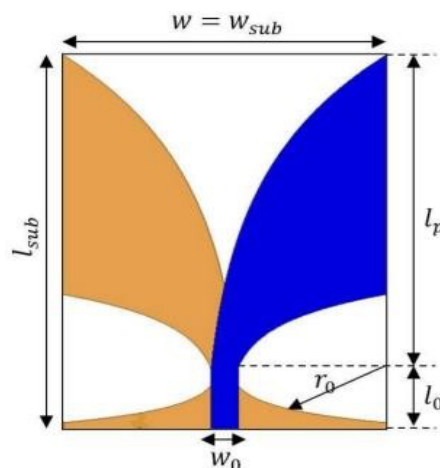


Figure 1. Conventional Antipodal Vivaldi Antenna [12]

The length of the substrate in the design of this antipodal vivaldi antenna can be determined by adding the effective radiating length of the antenna with the length of the microstrip line.

r_0 is the circular radius used by the microstrip to achieve the transition from the microstrip to the parallel strip line [1], [15]. The equation for the circular radius is [16], [17]:

$$r_0 = \frac{F}{\sqrt{1 + \frac{2h}{\pi\epsilon_r F} \left[\ln \left(\frac{\pi F}{2h} \right) \right] + 1.7726}} \quad (4)$$

The value of r_0 is obtained using the following equation [16], [17]:

$$F = \frac{8.791 \times 10^9}{f_0 \sqrt{\epsilon_r}} \quad (5)$$

2.2. Antipodal Vivaldi Antenna with Circular Loads

The shape of the circular antipodal vivaldi antenna is illustrated in Figure 2, where the yellow patch represents the top side patch, while the red patch represents the bottom side patch [15].

Circular loads are applied to each arm with a diameter d that is twice the radius of the load (r_0), and the value of r_0 can be determined using Equation 4. The centre point (x_0, y_0) and the radius of the circular load are r . The equation is formulated as follows [15]:

$$(x_0, y_0) = \begin{cases} x_0 = r_0 + d - r \\ y_0 = r_0 + \frac{(l - r_0)}{2} \end{cases} \quad (6)$$

$$r = \left[\frac{\frac{(l - r_0)^2}{4} + d^2}{2d} \right] \quad (7)$$

$$d = 2r_0 \quad (8)$$

The added circular load can improve the lower boundary radiation capability of a conventional vivaldi antenna and also cause the propagation current to travel further along the curve of the circular load, resulting in a wider bandwidth [15], [18].

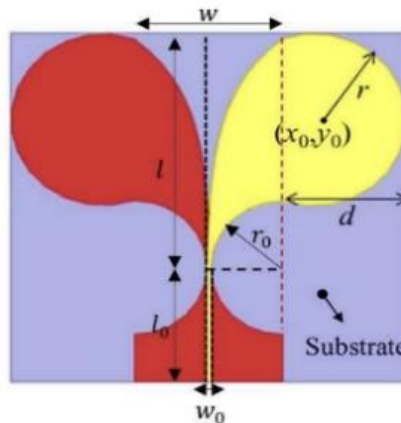


Figure 2. Antipodal Vivaldi Antenna with Circular Loads [15]

3. Antenna Design and Realisation

The specifications and design illustrations of the antenna to be developed, as well as the expected performance, can be seen in Table 1, Figure 3 and Figure 6.

3.1. Design of Conventional Antipodal Vivaldi Antenna

Based on the calculations using Equations 1, 2, 4, 6, 7, and 8, the dimensions for the antipodal vivaldi antenna are obtained, as shown in Table 2, and the design illustration of the conventional antipodal vivaldi antenna is depicted in Figure 3.

Table 1. Antenna Specifications

Specification	Value
Frequency	1.25 GHz – 2.75 GHz
$S_{1,1}$	≤ -10 dB
Bandwidth	≥ 1500 MHz ($\geq 75\%$)
Gain	≥ 3 dBi
Radiation Pattern	Unidirectional
Substrate	FR-4 Epoxy ($\epsilon_r = 4.3$; $h = 1.6$)
Patch	Copper Annealed ($h = 0.035$)

Table 2. Design Dimensions of The Antipodal Vivaldi Antenna

Dimension	Conventional	Circular Load	Descriptions
$w_{sub} = w$	45.50 mm	288 mm	Substrate width
l_{sub}	90.00 mm	205.00 mm	Substrate length
w_p	45.50 mm	120.00 mm	Patch width
l_p	66.00 mm	189.00 mm	Patch length
l_0	24.00 mm	16.00 mm	Feeding length
w_0	13.50 mm	4.98 mm	Feeding width
r_0	21.00 mm	10.00 mm	Circular radius length
(x_0, y_0)	-	(22,24)	Centre point of circular load
d	-	184 mm	Diameter of circular load
r	-	92 mm	Radius of circular load

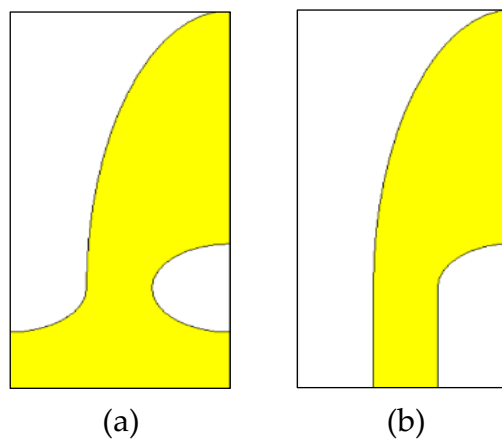


Figure 3. Design of Conventional Antipodal Vivaldi Antenna: (a) Front Side; (b) Back Side

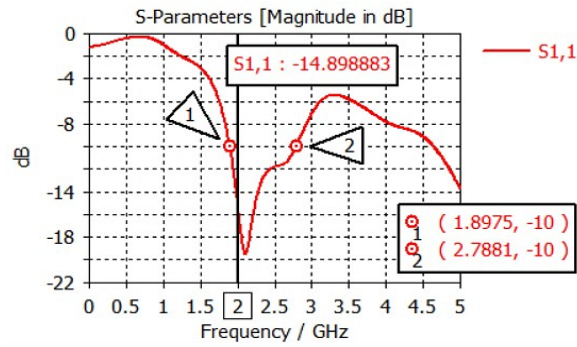


Figure 4. S_{1,1} and Bandwidth of the Conventional Vivaldi Antenna

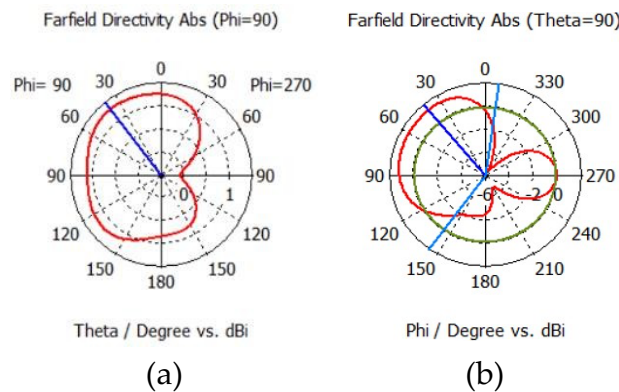


Figure 5. Radiation Pattern of the Conventional Vivaldi Antenna (f = 2 GHz): (a) E-Plane; (b) H-Plane

Based on the simulation result, the S-Parameter value within the designed frequency range meets the antenna specification standard at -14.898883 dB, as shown in Figure 4. Meanwhile, the bandwidth value complies with the FCC standard for radar and other ultra-wideband applications, achieving 890.6 MHz (38.01%). However, this bandwidth doesn't yet meet the desired antenna specification target of over 1500 MHz or more than 75%. Additionally, the antenna gain falls below the desired specification target with a value of 1.133 dBi, as seen in Figure 5. Therefore, circular loads need to be added to each arm of the antenna to increase both the bandwidth and gain to meet the desired specifications.

3.2. Design of Antipodal Vivaldi Antenna with Circular Loads

From the conventional antipodal vivaldi antenna design, the obtained bandwidth and gain values still don't meet the target specifications. Therefore, circular loads are added to each arm of the antenna with dimensions, as shown in Table 2, and the antenna design is illustrated in Figure 6.

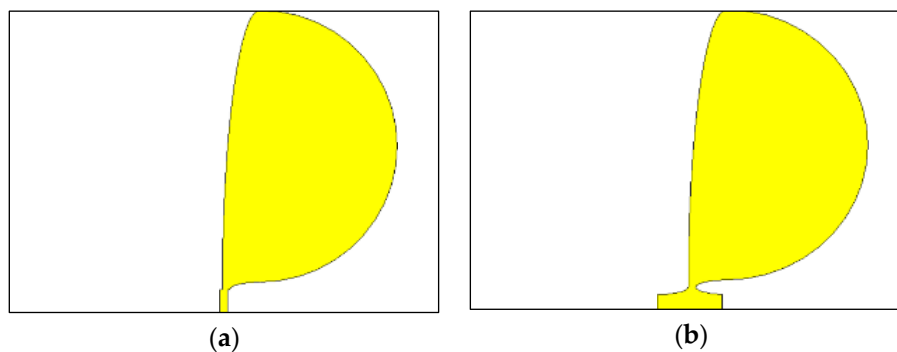


Figure 6. Design of the Antipodal Vivaldi Antenna with Circular Load: (a) Front Side; (b) Back Side

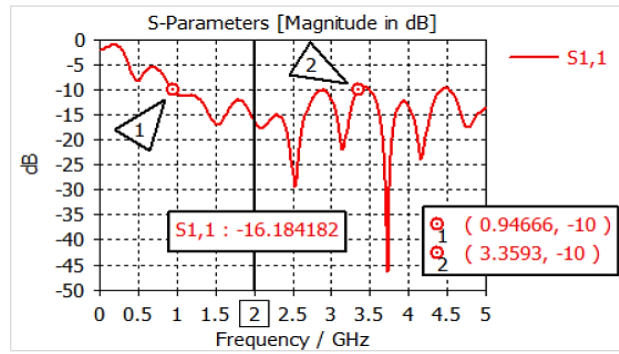


Figure 7. S_{1,1} and Bandwidth of the Antipodal Vivaldi Antenna

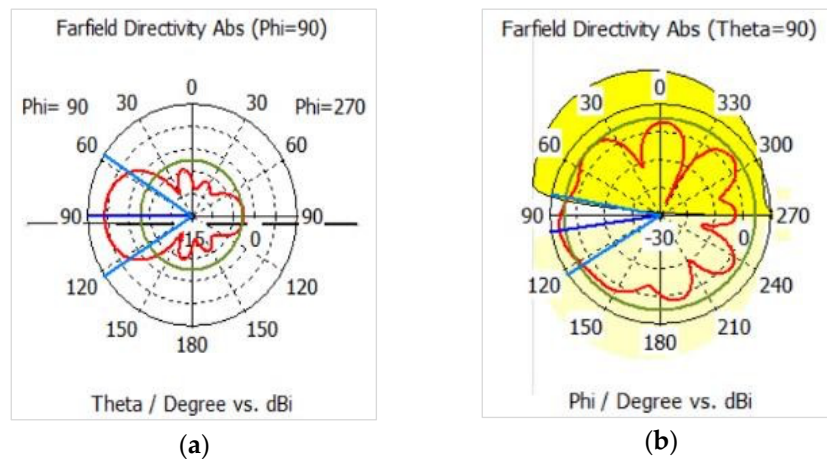


Figure 8. Radiation Pattern of the Antipodal Vivaldi Antenna with Circular Loads ($f = 2$ GHz): (a) E-Plane; (b) H-Plane

After simulation, the S_{1,1} value and bandwidth within the designed frequency range meet the target at -16.184182 dB, with the bandwidth expanding from 890.6 MHz (before adding the circular loads) to 2412.55 MHz, equivalent to 112%, as shown in Figure 7. The radiation pattern of the antipodal vivaldi antenna with circular loads produces a unidirectional pattern with a gain of 5.535 dBi, as shown in Figure 8. This meets the desired antenna specification target, allowing the process to proceed to the next stage, which is antenna fabrication and performance measurement to determine the actual performance of the antenna.

3.3. Realisation of Antipodal Vivaldi Antenna with Circular Loads

The antenna that has been designed and simulated to achieve the desired reference frequency is then fabricated, as shown in Figure 9 below.

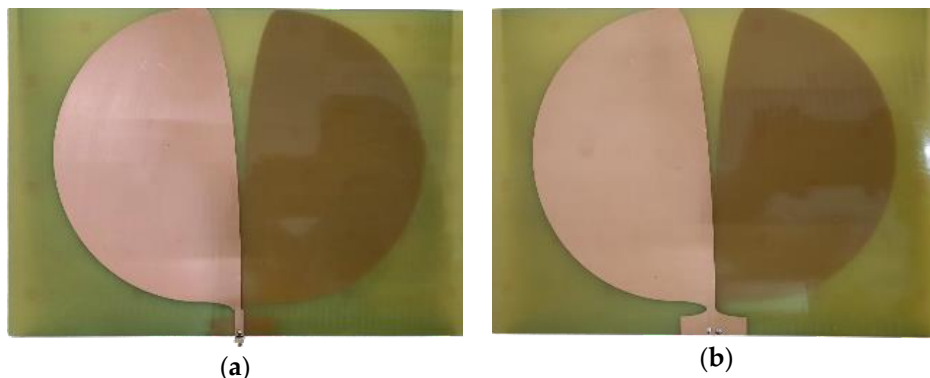


Figure 9. Fabricated Antenna: (a) Front Side; (b) Back Side

4. Result and Discussion

4.1. Measurement Result of the Antipodal Vivaldi Antenna with Circular Loads

The fabricated antenna was measured for its parameters to determine the actual performance of the fabricated antenna.

The measurement results of the S-Parameter can be seen in Figure 10, where the S_{1,1} value is -17.01 dB, which is not significantly different from the simulated S_{1,1} value of -16.184182 dB. The obtained result is below -10 dB, indicating that the antenna's reflection power is comparable to the received power by the antenna [19].

In general, the higher the S_{1,1} value, the better the antenna is at matching its impedance, resulting in less signal power being reflected back to the source. A high S_{1,1} value indicates good antenna efficiency and optimal transmission performance [20]. From the measurement results, the graph shows many ripples, which can be attributed to several factors, such as the presence of other elements or structures near the antenna, non-uniformity in the antenna construction materials, especially in the PCB or antenna substrate, which can cause variations in power reflection characteristics. Additionally, changes in temperature, humidity, or other environmental factors can affect the material characteristics of the antenna, leading to variations in power reflection. Calibration factors of the VNA may also influence the measurement results.

The measurement results also showed a bandwidth of over 2301.15 MHz, equivalent to 112.28%. This exceeds the target antenna specification of at least 1500 MHz or a minimum of 75%. The achieved bandwidth represents a significant improvement compared to the conventional antenna design without circular loads.

4.2. Comparison of Bandwidth Parameters between Simulation and Measurement Result

From the simulation process of the S-Parameter for the conventional antipodal Vivaldi antenna design and the circular load design, the comparison of S-Parameter values can be seen in Figure 11. Meanwhile, the comparison of S-Parameter values between the simulation results of the Vivaldi antenna using circular loads and the measurement results of the fabricated design can be viewed in Figure 12.

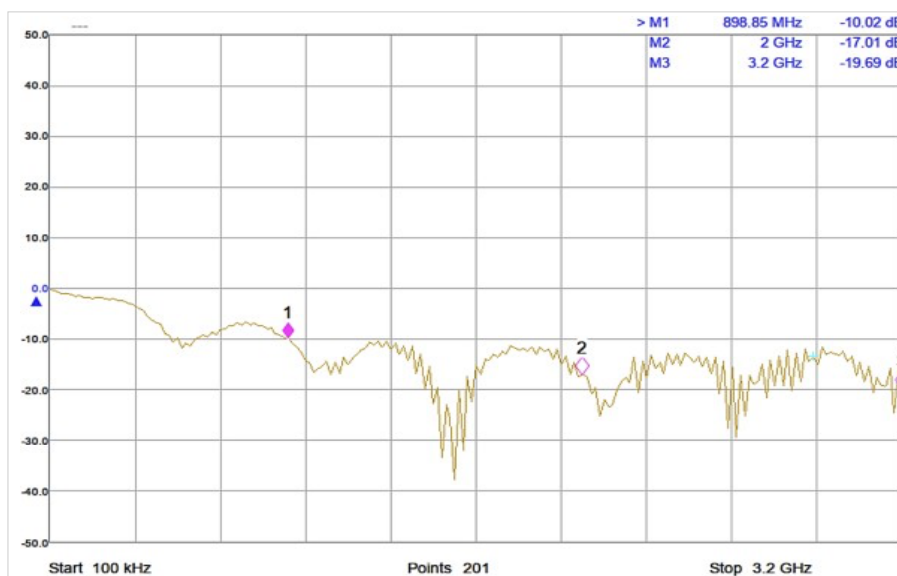


Figure 10. Measurement Result of S_{1,1} and Bandwidth of the Antipodal Vivaldi Antenna with Circular Loads

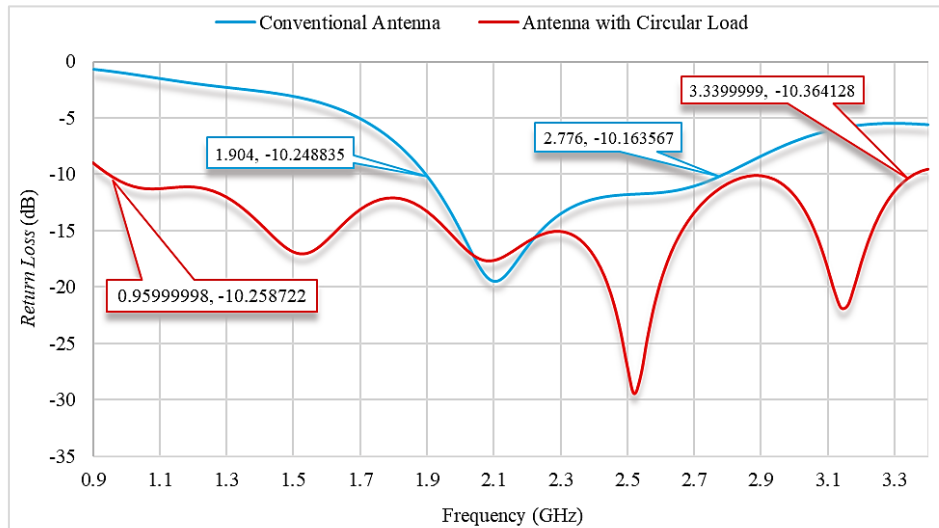


Figure 11. Comparison of Bandwidth between the Simulation Results of Conventional Vivaldi Antenna Design and The Simulation Results of Antipodal Vivaldi Antenna Design with Circular Loads

The simulation results indicate that the addition of circular loads significantly affects the bandwidth expansion. As the diameter of the circular load increases, the frequency range that constitutes the bandwidth also broadens. This frequency range expansion is illustrated in Figure 11. For the conventional antipodal Vivaldi antenna simulation, the frequency range for the bandwidth is from 1.8975 GHz to 2.7881 GHz, resulting in a bandwidth of 890.6 MHz or approximately 38.01%. Meanwhile, the simulation with circular loads shows the frequency range for the bandwidth extending from 0.94665 GHz to 3.3592 GHz, resulting in a bandwidth of 2412.55 MHz or around 112%. The bandwidth increased by 73.99% or approximately 1521.95 MHz after adding the circular load. Figure 11 also shows that the $S_{1,1}$ values for both the conventional antenna design and the design with circular loads meet the $S_{1,1}$ standardisation for antennas, being less than -10 dB, indicating that the antenna's reflected power is comparable to its received power.

Furthermore, from the measurement and simulation process of the S-Parameter for the circular antipodal Vivaldi antenna design, the comparison of bandwidth values is presented in Figure 12. It can be observed that the bandwidth value is 2412.55 MHz, while the measurement of the fabricated antenna yielded a bandwidth of over 2301.5 MHz, as the VNA's maximum frequency can only reach up to 3.2 GHz, equivalent to 112.28%. When comparing the simulated design with the fabricated design, the bandwidth expansion increased by over 28%.

The substantial bandwidth offers advantages for ultra-wideband radar applications, where a larger bandwidth allows ultra-wideband radar pulses to provide higher time resolution. This enables the radar system to detect objects or targets with greater precision in the time domain.

The comparison results in Figure 12 indicate that the measurement results display a ripple in the graph. This phenomenon can be attributed to several factors, such as the presence of other elements or structures close to the antenna and lack of material uniformity in the antenna construction, particularly in the PCB or antenna substrate, which may cause variations in reflection characteristics. Additionally, changes in temperature, humidity, or other environmental factors can affect the material characteristics of the antenna, leading to fluctuations in power reflection. Calibration issues with the Vector Network Analyzer (VNA) can also influence measurement results. If the equipment is not properly calibrated, discrepancies between various components, including transmitters, signal-directing elements, and receivers, will result, causing measurement results to deviate from the actual characteristics of the measured device.

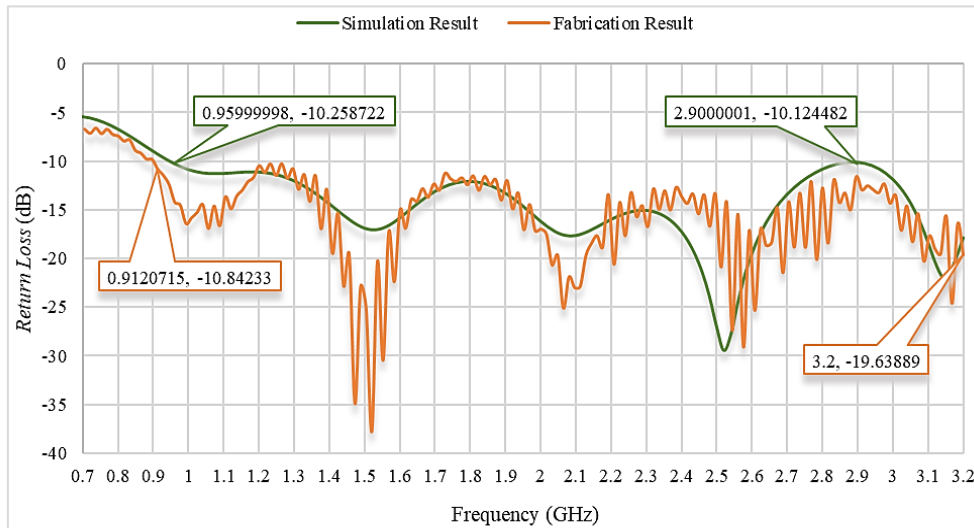


Figure 12. Comparison of Bandwidth between Simulation and Fabrication Results of Circular Antenna Vivaldi Antipodal

Such conditions are common, and in this case, optimisation to enhance antenna performance is not necessary as long as the $S_{1,1}$ measurement remains within the standard performance parameter for antennas, which is less than -10 dB. However, if the $S_{1,1}$ value during the measurement process exceeds -10 dB, optimisation of the antenna design and remanufacturing are required. Generally, a smaller $S_{1,1}$ value (less than -10 dB) indicates better antenna performance in impedance matching and reduced signal power reflection to the source. A low $S_{1,1}$ value also reflects good antenna efficiency and optimal transmission performance.

The comparison between the radiation patterns and gain of the circular antipodal Vivaldi antenna for simulation and fabrication is presented in Figure 13-(a) for the E-Plane and Figure 13-(b) for the H-Plane.

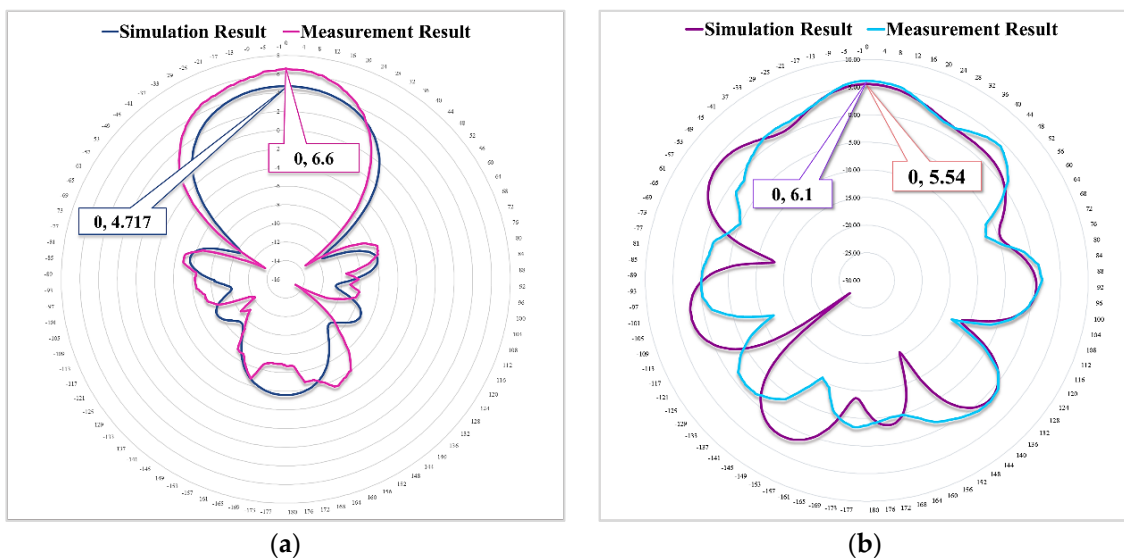


Figure 13. Comparison of Radiation Pattern between Simulation and Fabrication of Antenna Vivaldi Antipodal: (a) E- Plane; (b) H-Plane

Table 3. Comparison of Antenna Parameters for the Antenna Vivaldi Antipodal Design

Antenna Parameters	Results of Antenna Vivaldi Antipodal Simulation		Results of Antenna Vivaldi Antipodal Fabrication
	Conventional	With Circular Load	With Circular
S _{1,1}	-14.898883 dB	-16.184182 dB	-17.01 dB
Bandwidth	890.6 MHz	2412.55 MHz	≥ 2301.15 MHz
Gain	1.133 dBi	5.535 dBi	6.6 dBi
Radiation Pattern	Omnidirectional	Unidirectional	Unidirectional

The simulation results using CST Studio Suite 2019 for the radiation pattern and gain in the E-Plane show a linear directional radiation pattern with a peak gain of 4.717 dBi. During the antenna measurement, when the reference horn faced horizontally, and the test antenna faced vertically, the test antenna yielded a vertical linear directional radiation pattern with a peak gain of 6.6 dBi at 0° phi, as shown in Figure 13-(a).

The simulation results using CST Studio Suite 2019 for the H-Plane show a peak gain of 5.535 dBi. During measurement, when the reference horn antenna faced vertically, and the test antenna faced horizontally, the test antenna exhibited a horizontal linear directional radiation pattern with a peak gain of 6.1 dBi at 0° theta. The measurements in both the E-Plane and H-Plane yielded a linear polarisation with a directional radiation pattern and optimal gain of 6.6 dBi, which meets the specifications of the designed antenna.

The differences between the simulation and measurement results are due to various factors, including the fact that the antenna measurements were not conducted in a specialised or anechoic chamber, thus being affected by unwanted wave reflections from surrounding objects.

To simplify, a comparison of antenna parameters between simulation and fabrication results can be seen in Table 3 below.

5. Conclusions

The antenna can operate at frequencies from 898.85 MHz to over 3.2 GHz and achieves a measured S_{1,1} value of -17.01 dB with a gain of 6.6 dBi. The increase in bandwidth from the simulation results between the conventional antenna design and the design with the added circular load is 74.27%, from 890.6 MHz (equivalent to 38.01%) to 2412.55 MHz (equivalent to 112%). Meanwhile, the increase in bandwidth between the fabricated antenna design and the simulation design with the added circular load exceeds 28%, reaching more than 2301.15 MHz (equivalent to over 112.28%). This bandwidth increase is influenced by the diameter of the circular load. The larger the diameter of the circular load, the greater the bandwidth value. The resulting radiation pattern is unidirectional, which in radar applications can help direct electromagnetic wave energy in a specific direction, as well as enhance angular resolution and the ability to detect and distinguish targets with high precision.

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