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International Journal of Electrical and Electronics Research (IJEER)
Research Article | Volume 14, Issue 1 | Pages 18-26 | e-ISSN: 2347-470X

Design and Analysis of Vivaldi Antenna for UWB Applications

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ABSTRACT- This paper is about the design and analysis of an ultra-wideband Vivaldi antenna. The antenna is fabricated on FR4 of size 90x53 mm² and thickness of 1.4 mm. The slot profile of the antenna is exponentially tapered and is designed to support ultra-wideband (UWB) communication. Two identical slots were made on the radiator of the antennas to enhance the efficiency of radiation and reduce surface current. Measurement results show that it has a wide operating frequency of 3 GHz to 12 GHz with good impedance of (S_{11} < -10 dB) across all the band. The gain of the antenna is measured to be 8.37 dBi which is classified as high gain antenna and may be utilized in high frequency and other high gain applications. This design enables end-fire radiation, meaning the directional radiation characteristic of Vivaldi antennas in the axis of the antenna aperture, and steady directional operation, suitable to advance communication systems, such as 5G, radar, ground-based radar (GPR), microwave imaging, and ultra-wideband sensing as well as the FR4 material is a low cost and viable substrate to be used in various applications. The suggested antenna was developed and simulated through Computer Simulation Technology (CST) software, and it showed fair correspondence between theoretical and experimental findings, which showed correctness in the design. In general, the proposed antenna presents an attractive prospect for next-generation broadband wireless applications that require compact, wideband, and high-performance radiating elements.

Keywords: Ultra-wideband, FR4, ground-penetrating radar, Gain, CST.

ARTICLE INFORMATION

Author(s): Mustafa Ghanim, Mohaimen Q. Algburi, and Ayman N. Muhi;

Received: 06/06/25; **Accepted**: 19/01/26; **Published**: 10/03/26;
E- ISSN: 2347-470X;
Paper Id: IJEER250151;
Citation: 10.37391/ijeer.140103
Webpage-link:
https://ijeer.forexjournal.co.in/archive/volume-14/ijeer-140103.html

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1. INTRODUCTION

A tapered slot antenna (TSA) or Vivaldi antenna is an ultra-wideband (UWB) antenna that has been of great interest in recent wireless communication systems because of its wide bandwidth, high gain, and end-fire radiation pattern [1]. The Vivaldi antenna is a major contribution to antenna theory, both in theory and practice. It was invented in the 1970s and is still quite new in comparison to more traditional antennas such as dipoles, loops, and patches [2]. A Vivaldi antenna is a planar, two-port, end-fire, exponentially tapered antenna, usually made on a microstrip or printed circuit board. The popularity of wireless communication has led to the research of antennas, which has increased the need for simple, cheap, and efficient antennas [3]. However, the growing variety of applications poses technical issues that lead to creative antenna ideas used in many applications such as RFID and IoT devices [4]. The Vivaldi antennas possess good characteristics: they are small, light, low profile, rugged and not sensitive to fabrication errors. The combination of these properties with the high frequency range, high radiation efficiency, and low distortion make the Vivaldi antennas an optimal solution to most of the applications [2].

The latest developments in the radar sector have become relevant due to their extensive application in aircraft system, civil structures and medical devices [5]. This is evidenced by the technological applications that identify random elements or quantify the distance between objects in medical institutions through cancer cell detection systems [6] and civil buildings through ground penetrating radar (GPR). The most important element of radar design is the development of antennas. The significant influence of radar performance is based on gain and bandwidth, which requires controlled standards of implementation. UWB antennas offer solutions to meet these needs. The Linear TSA is a specific form of the Vivaldi antenna that has size benefits as well as multi-frequency potential. The gain improvement of TSA antennas is up to 5 dB to 6 dB [7], depending on the design. Conversely, this performance limit is caused by the main design factors and operational frequencies. In other studies, the authors tried to increase the gain parameter such as in the research [8], whereas in the study presented in [9], the Design and Analysis of Antipodal Vivaldi Antennas for Breast Cancer Detection was the focus. The Vivaldi antenna operates in the end-fire traveling wave antenna family presented in [10] and has theoretically infinite bandwidth, allowing multiple antenna systems to be used. The Vivaldi antenna requires a large antenna size to achieve excellent performance in its low operating band; this was discussed in research [11]. The work [12] highlights an ultra-wide-band design for long-range electromagnetic detection, which is appropriate for remote sensing and surveillance applications. In contrast, in the research [13] next-generation wireless systems (5G/6G) are targeted by realizing a wide-bandwidth Vivaldi antenna in a CMOS 0.18 um process, which provides compact, high-performance integration. The research in [14] confirms that the minimum antenna width must extend to half the wavelength in order to achieve effective radiation.

Recent publications also emphasize different approaches to optimizing the antenna performance in different frequency bands. A detailed analysis of 5G antenna issues highlighted the significance of improving the parameters through efficient techniques to ensure rapid network requirements [15]. Researchers have worked on interference reduction in the UWB domain via dual-notch properties of cognitive radio [16] and realization of high gain in satellite communications with multilayer structures [17]. Moreover, miniaturization and radiation efficiency have been greatly improved with the creation of compact S-shaped structures [18] and slotted monopole structures [19] that have made efficient operation at ISM and GSM frequencies possible.

The design and optimization of Vivaldi antennas to be used in radar applications have been the subject of several studies, each with its own contribution to the field and approach. The authors in [20] introduced an extensive overview of Vivaldi antenna designs, and their flexibility for UWB applications. They stated that the tapering profile and feed mechanism must be optimized to obtain the desired bandwidth and gain characteristics. In a different work [21] that was aimed at designing a Vivaldi antenna with a modified feeding structure that improved impedance matching and minimized back radiation, thus leading to an overall better performance in radar systems. In [22], a metamaterial layer was used with a Vivaldi antenna to come up with a new concept, which substantially increased bandwidth and gain. This new design demonstrated that one could utilize advanced material, and traditional antenna designs to meet the high requirements of current radar designs. One of the studies discussed in [23] determined the effect of various substrate materials and thickness on the Vivaldi antenna design and the study established that, these parameters influence performance parameters of the antenna like the return loss and the radiation efficiency.

Finally, this research explains how an UWB Vivaldi antenna was designed and analyzed to be effective in communication systems. The antenna can cover a broad frequency range of 3 GHz to 12 GHz that can be used in numerous wireless communication applications, including radar, satellite, and other UWB applciations. The proposed antenna features a wide impedance bandwidth and directional radiation properties, which are realized here by proper design and simulation. FR4 material was used as a readily available and inexpensive substrate with dimensions of 90 x 53 mm^2, and the antenna was fed with 50 ohms. The major performance parameters of the proposed antenna are the high gain of about 8.37 dBi over the operating frequency range, which offers strong signal strength and enhanced reliability of the communication link. The design is done by optimizing the flare structure of the antenna and slot line to obtain the required broadband properties with a compact size and high radiation efficiency. The simulation outcomes indicate that the antenna has stable radiation patterns and low side lobe levels, which proves that the antenna can be used in various communication systems.

2. VIVALDI ANTENNA DESIGN

The Vivaldi antenna is widely used today. This is because its shape, size, and weight are perfectly suited to the requirements of modern communications technology, which prioritizes these factors, making the antenna easy to use [1]. The simplest form of Vivaldi antenna design is the traditional form of two parallel conductive layers, separated by an insulating layer. The upper conductor is a thin piece of copper representing the radiator. The lower conductor is a theoretically infinite ground field. They are separated by a non-magnetic insulating layer.

Initially, Vivaldi antenna design is characterized by defining the exponentially tapered aperture, feed structure, and substrate properties to attain the required bandwidths. The key design equations and steps are as follows [24].

To Calculate Effective Dielectric Constant (ε_{eff}):

$$\mathcal{E}_{eff} = \frac{\mathcal{E}_r+1}{2} + \frac{\mathcal{E}_r-1}{2}\left(1 + 12\frac{h}{Wf}\right)^{-0.5} \tag{1}$$

Where;
h = substrate height (1.4 mm), Wf= microstrip feedline width, (Wf≈2.8 mm, ε_r = 4.4 for FR4 at 50 Ω and 1.4 mm thickness).

The lowest usable frequency is roughly determined by the aperture width (≈ λ/2) along the exponential taper. Using the 53 mm width:

$$f_{min} = \frac{c}{2W\sqrt{\mathcal{E}_{eff}}} \tag{2}$$

$$f_{max} = \frac{c}{2h\sqrt{\mathcal{E}_{eff}}} \tag{3}$$

For practical UWB operation, designers usually achieve f_{max} ≈ (10-15) GHz on FR4 due to losses and flare limitations.

$$Z_0 = \frac{60}{\sqrt{\mathcal{E}_{eff}}}\ln\left(\frac{8h}{W_f} + \frac{W_f}{4h}\right) \tag{4}$$

The Guided Wavelength (λ_g):

$$\lambda g = \frac{c}{f\sqrt{\mathcal{E}_{eff}}} \tag{5}$$

Where;
C: speed of light, f: resonance frequency

The Antenna Length (L):

$$L \approx \lambda g \text{ to } 2\lambda \tag{6}$$

The Exponential Taper equation:

$$y(x) = \pm c.e^{ax} \tag{7}$$

Where;

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x: is the distance along the antenna length, *y(x)*: is the half-width of the slot at position *x*, *a*: is the flare constant and *c*: is the initial half-gap at *x*=0

Flare Constant *(a)*:

$$a = \frac{1}{L}\ln\left(\frac{y_{max}}{c}\right) \quad (8)$$

Where;

y_{max}: half the substrate width

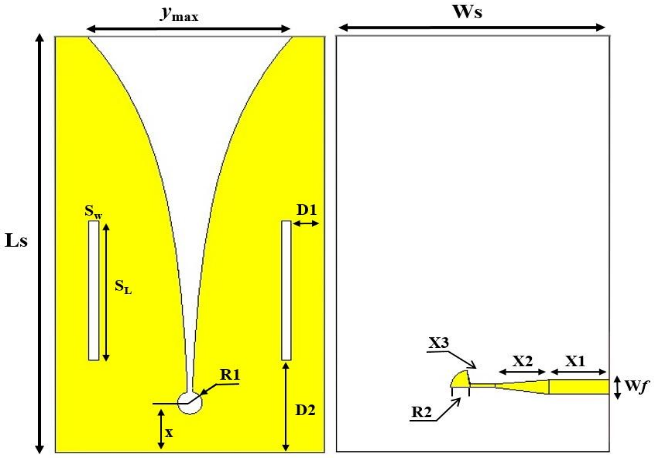

Figure 1. Vivaldi antenna design, (a): front view, (b): back view

Table 1. Dimensions of the Vivaldi antenna

Parameters	Value (mm)	Parameters	Value (mm)
Ls	90	S_W	2
Ws	53	S_L	30
Wf	2.8	R1	2.4
D_1	6.5	D_2	20
y_{max}	40	X	8
X1	11.7	X2	10.35
X3	4.92	R2	3.8
Ls	90	S_W	2

Figure 1 presents a Vivaldi antenna printed on an FR4 substrate of 90 mm × 53 mm × 1.4 mm, relative permittivity εr = 4.4, and loss tangent tanδ ≈ 0.02. The antenna was simulated using CST Studio Suite version 2021. The proposed antenna features a typical exponentially tapered slot in the middle that allows UWB performance and end-fire radiation. A circular cut at the bottom of the taper is connected to a 50-ohm microstrip feed line where energy transfer is efficient. The taper enables a gradual transition of impedance, which enables traveling-wave propagation over a broad frequency range [25]. The radiator has two narrow rectangular slots etched symmetrically to suppress unwanted surface currents, which contribute to radiation efficiency and minimize back-lobe radiation. The antenna structure was developed with standard Vivaldi design equations and refined by tuning the important parameters of flare rate, taper length, and slot location to obtain the best impedance match and desired radiation patterns. FR4 offers a low-cost and readily manufacturable solution and allows operation at the target multi-band frequencies. *Table 1* shows the dimensions of the Vivaldi antenna.

3. RESULT AND DISCUSSION

In this section, the reflection coefficient of the proposed antenna is studied. *Figure 2* shows the simulation of the S_{11} curve of the proposed antenna in the frequency range (1-15 GHz). The S_{11} factor is the ratio of reflected energy to the input power, usually measured in dB. The S_{11} value of less than -10 dB means that the antenna is compatible and radiates the majority of the received power instead of reflecting it. The antenna operates in dual operating bands at 1.77-1.93 GHz and 3-14.5 GHz, achieving good impedance matching of less than 10 dB throughout the operating band. The analysis shows that the proposed antenna covers a wide frequency spectrum, enabling it to operate in a variety of applications, indicating that the antenna is designed to operate in multiple and wide bands. This wide application range makes the antenna appropriate to recent wireless communications applications that need representation of various frequency bands, including radar, Wi-Fi, WiMAX and fifth generation 5G technologies. The figure indicates that the performance is less than -10 dB over much of the range, indicating good radiation efficiency and a wide band response, making it suitable for multi-beam and broadband applications.

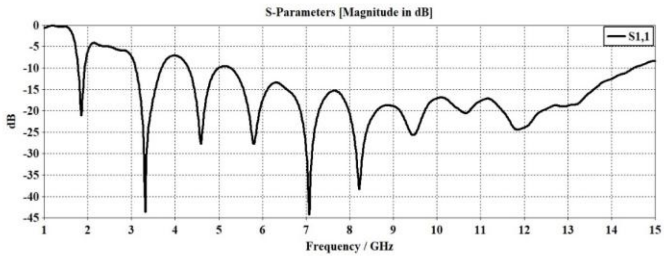

Figure 2. Return loss of Vivaldi antenna

The voltage standing wave ratio (VSWR) measurement stands for the mismatch ratio that exists between the antenna and its connected feed line. The evaluation method operates as an efficiency measure for all radio frequency transmission devices including transmission lines. A VSWR measurement in the region between 1 to 2 provides proper matching conditions for antenna applications. The simulation results displaying VSWR appear in *figure 3*.

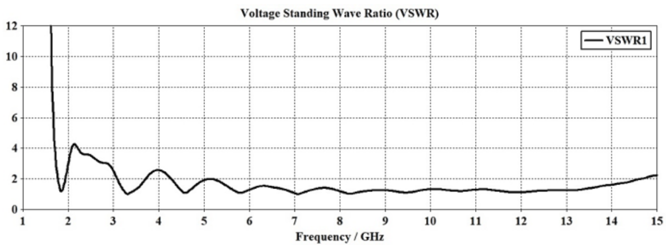

Figure 3. simulation results displaying VSWR

Figure 4(a) shows the 3D radiation patterns of the Vivaldi antenna at four frequencies: 3.3 GHz, 4.58 GHz, 5.8 GHz, and 7 GHz, while *figure 4(b)* shows the gain along the operating range. The 3D radiation pattern is rather wide at 3.3 GHz, with

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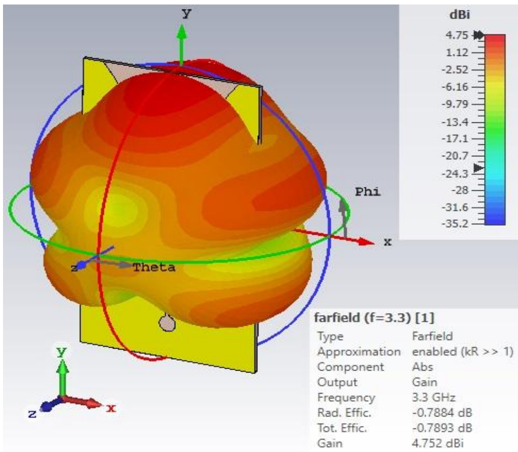
a gain of 4.75 dBi and considerable directionality. The higher the frequency, the greater the directivity of the antenna. The radiation at 4.58 GHz is more concentrated along the end-fire direction (positive Y-axis) with a better gain of 6.82 dBi. At 5.8 GHz, the beam is narrower, and the gain is 7.99 dBi, which means better radiation performance. Finally, at 7 GHz, the pattern is more directional, and the maximum gain is 8.37 dBi. It is noted that the antenna gains rise, and the radiation pattern becomes more directional with increase in frequency. This is characteristic of Vivaldi antennas, which have frequency-selective directional radiation and thus can be applied to wideband and high-gain applications. In other terms, the Vivaldi antenna has frequency-dependent directivity, which means that the beam is wider and has moderate gain at lower frequencies (around 3–5 GHz) and smaller and higher gain at higher frequencies (>7 GHz). This quality makes it good for applications that need a lot of bandwidth and high gain. The current distribution is optimized to enhance the antenna performance because the etched slots give better impedance matching leading to better radiation results. Due to design changes, the performance of the Vivaldi antenna can be maintained without loss of gain. Consequently, the antenna can be used in different applications such as 5G networks, radar, satellite communications, and wireless communication networks.



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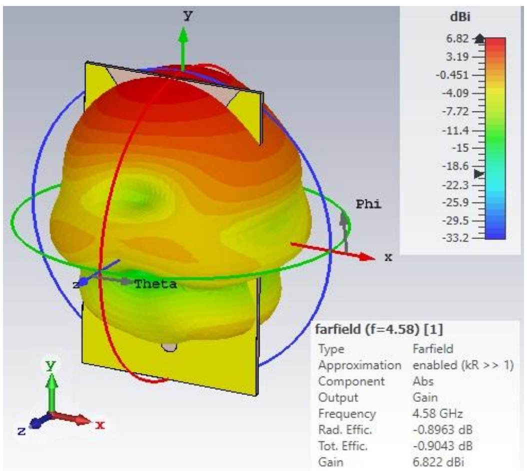

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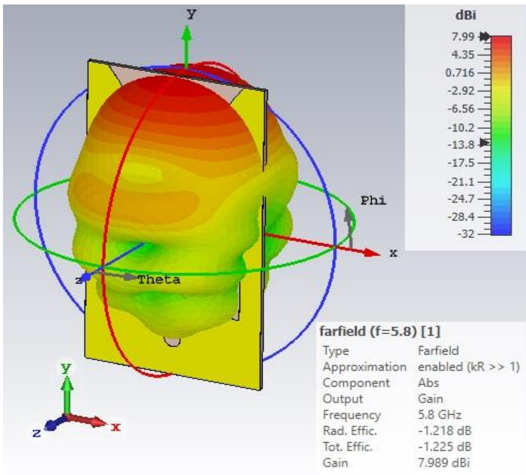
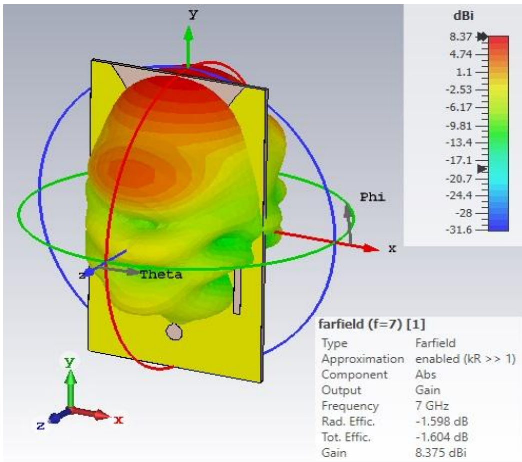
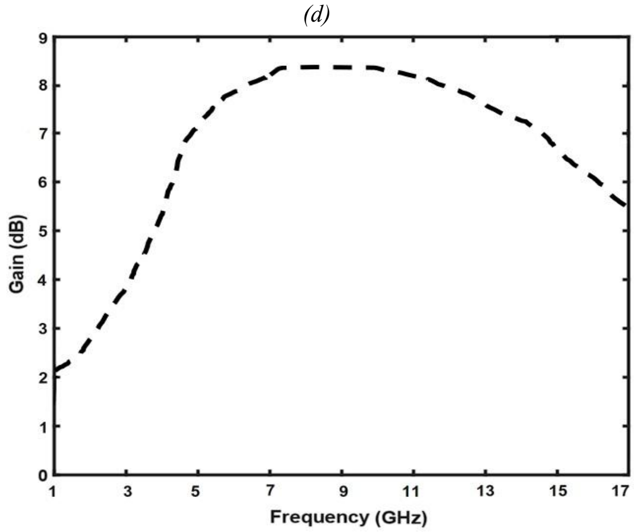


(c)



(d)



(e)

Figure 4. 3D radiation patterns of the Vivaldi antenna: (a) at 3.25 GHz, (b) at 4.5 GHz, (c) at 5.8 GHz, (d) at 7 GHz, and (e) gain along the operating range

Figure 5 shows the 2D radiation patterns of the Vivaldi antenna at four frequencies: 3.25 GHz, 4.5 GHz, 5.8 GHz, and 7 GHz in two main planes, E-plane (Phi = 0°, red curves) and H-plane (Phi = 90°, black curves). The 3.25 GHz pattern is fairly wide in both planes and is slightly asymmetric in the H-plane. At higher frequencies (4.5 GHz) the E-plane is more directional, and the H-plane has multiple lobes, which implies more complicated field interactions. The E-plane narrows further and has higher directivity at 5.8 GHz, whereas the H-plane has more side lobes. Lastly, the antenna radiates more directionally in the E-plane with several peaks in the H-plane at 7 GHz, indicating strong end-fire behavior. This is thanks to good impedance matching. In general, the trends verify that the Vivaldi antenna is more directional as frequency increases, with good end-fire radiation properties, which are suitable for wideband and high-gain communication systems.

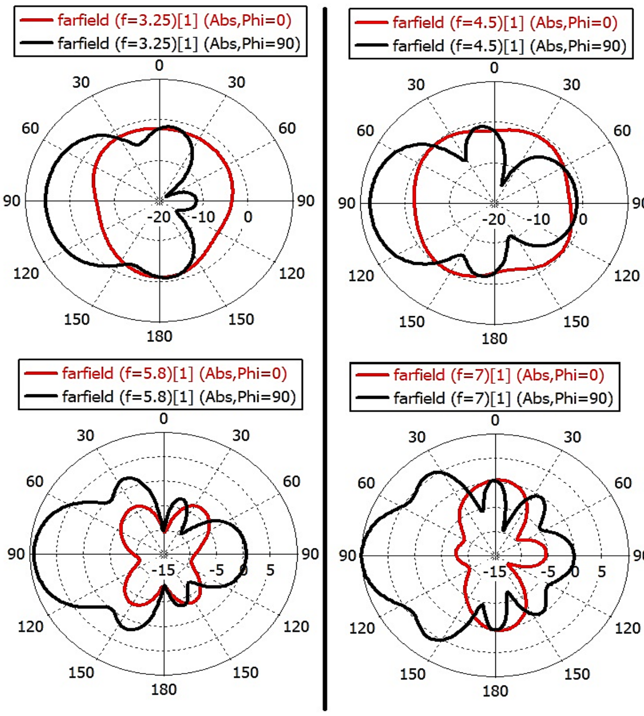


Figure 5. 2D radiation patterns of the Vivaldi antenna at 3.25 GHz, 4.5 GHz, 5.8 GHz, and 7 GHz

Figure 6 shows the current surface distribution on the Vivaldi antenna at two frequencies (a) 3.25 GHz and (b) 5.8 GHz. The current at both frequencies is mostly localized along the tapered slot edges and the feed region, which means that the radiating structure is efficiently excited. The 3.25 GHz surface current is fairly evenly distributed along the taper and expands outward, with the traveling-wave properties necessary to end-fire radiation. The two vertical slots cut on both sides of the taper are effective in disrupting and suppressing undesired surface currents on the ground plane, which minimizes back-lobe radiation and increases forward directivity.

The surface current at 5.8 GHz is more focused and intense around the feed and taper edges, and of greater magnitude (up to 85.12 A/m), indicating stronger field interaction and radiation efficiency at higher frequencies. The slots still reduce the propagation of surface waves, which avoids the loss of energy and leads to cleaner radiation.

The slots are important in current shaping as they disrupt surface waves and redirect the energy into the principal radiation direction. This leads to better impedance matching, increased bandwidth and gain. In general, the surface current distribution is well-controlled, and the parasitic currents are suppressed by slots, which allows the antenna to be broadband and directional, typical of high-efficiency Vivaldi designs.

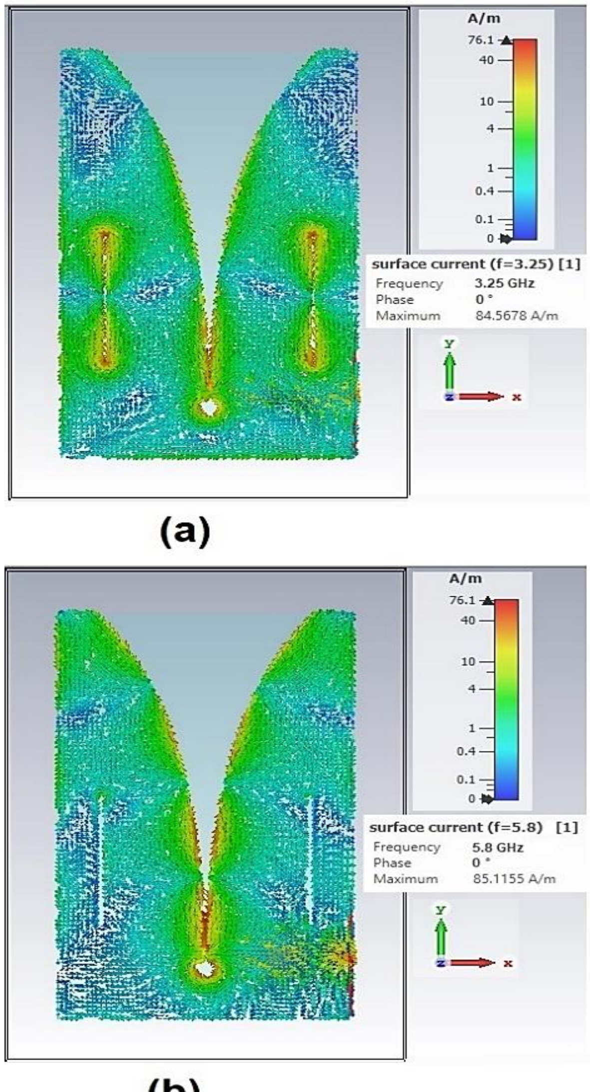


Figure 6. surface current concentration: (a) at 3.25 GHz, (b) at 5.8 GHz

A parametric study was conducted to verify the effect of the Flare constant on the performance of the proposed antenna. Three cases were studied at values of 71 mm, 76 mm, and 81 mm to evaluate the antenna response within UWB and impedance matching.

Figure 7 illustrates that all three examples attained UWB performance regarding reflection coefficients ($S_{11} < -10$ dB) over the majority of the examined frequencies; however, the degree of impedance matching differed among the cases. The value of Flare constant of 76 mm proved to have better overall performance compared to the other two cases and showed significantly lower value of return loss at most of the frequencies, and higher value of gain and efficiency within the range of operation.

The use of the values of 71 mm or 81mm resulted in the decrease of the impedance matching at specific frequencies and it was detrimental to the performance of the antenna within that frequency range. Consequently, the optimal Flare constant value of the suggested antenna is 76 mm which has the most optimal ratio between ultra-wideband operation, return loss and gain hence the most desired and suitable choice of antenna design.

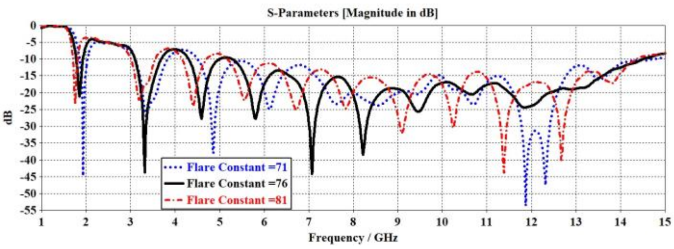


Figure 7. Flare constant effect on antenna performance

The efficiency of the proposed antenna was measured over a large operating frequency (2-13 GHz). The radiation efficiency and the total efficiency are indicated in Figure 8. As may be observed, the antenna has fairly high values of efficiency over most of the frequency range, between 82 and 84 % at lower frequencies (2 to 3.5 GHz), the capability of which the antenna has to radiate most of the power it receives on the feed line. An apparent decrease in overall efficiency occurs at the frequencies of about 4 GHz, to about 66 %, which can be due to the minor internal resonances brought about by the antenna geometry. This reduction is, however, only applied within a small frequency range after which efficiency again increases.

The efficiency starts to reduce gradually with the frequency to about 47 % at 13 GHz. This is credited to higher losses in the FR4 substrate material with higher frequencies besides dispersive effects. Nevertheless, the performance of the antenna is also good throughout most of its working range, thus it is more applicable to the usage of UWB communications.

In general, the efficiency values indicate that the suggested antenna is an efficient device in its radiation and total efficiency over the desired band, which also confirms its suitability to a broadband and high-frequency application.

Following the theoretical model design, numerical simulation, the proposed model was fabricated and experimentally tested in the Antennas Laboratory at Al-Nahrain University, Iraq, to confirm the accuracy of the theoretical model and their dependence on the real world as indicated in *figure 9.*

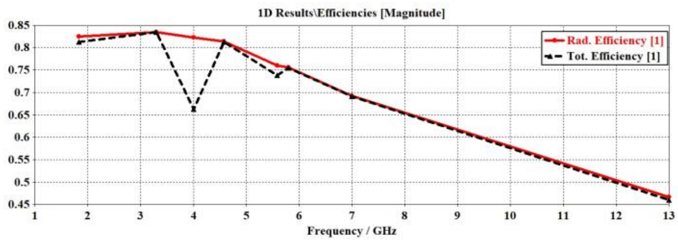
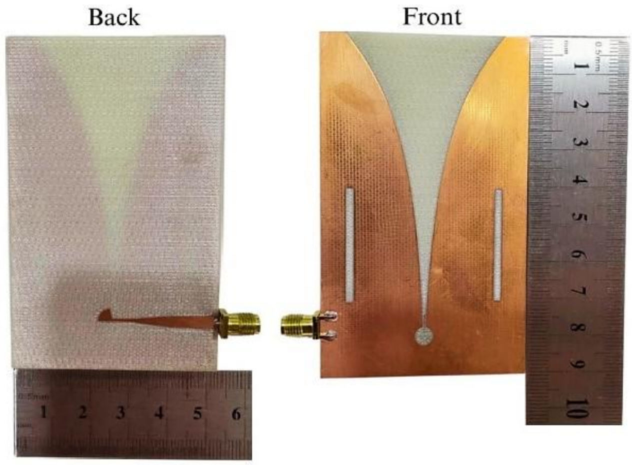
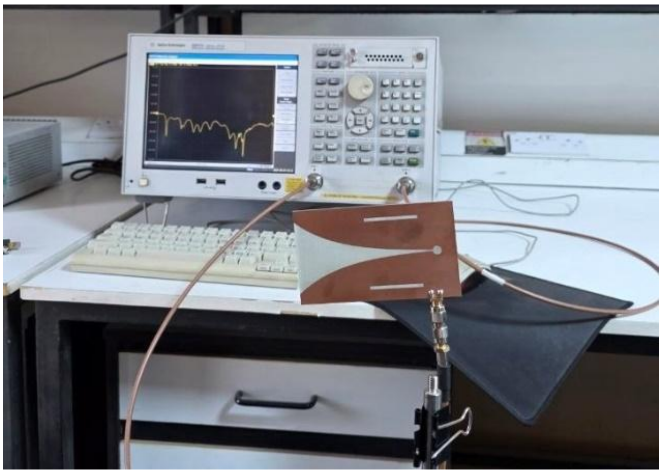


Figure 8. Efficiency performance of the antenna against the operating range (2-13 GHz)

The reflection coefficients (S_{11}) in the range of frequencies (1-12 GHz) were measured practically with the help of a VNA device. The experimental findings were well convergent with the findings obtained in the simulation as indicated in Figure 10. It has been determined that the calculated and measured values of S_{11} are lower than -10 dB at various frequency ranges, which indicates that the antenna may be utilized to attain good line alignment and minimize reflections. The fact that the results of the simulation are acceptable in comparison with the experimental measurements will indicate the strength and validity of the design and will confirm the ability of the proposed antenna to be efficient in a wide range of frequencies. This can be applied to a variety of applications including wireless communications, radars, sensor systems and 5G applications that demand large coverage and consistent performance. Moreover, this work shows that it is not only important to use high levels of simulation together with verification but also in attempting to come up with efficient antenna designs that can be trusted in practical applications. The suggested antenna has achieved a satisfactory performance in the UWB communication applications that demand a broad band as well as high radiation efficiency.



(a)



(b)

Figure 9. Proposed antenna design; (a) fabricated prototype; (b) measurement of the prototype

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The antenna was fabricated using FR4 substrate wherein the patch and ground plane consisted from a conductive copper layer. The substrate size was 90×53 mm^2. The signal was measured through an SMA connector. Measurements were conducted using an Agilent ENA-E5071C VNA device and the S-parameter values were tuned and calibrated properly. Port 1 of the VNA devise connected to the antenna using an SMA cable and the S-parameters measured to determine the frequency resonance loss. It was found that the measured S-parameter curve was slightly different than the simulated one: the simulation had a sharp resonance dip at 3.25 GHz whereas the experimental measurements had a broader response with slightly higher resonance loss, which indicated that there were minor differences in fabrication and measurements.

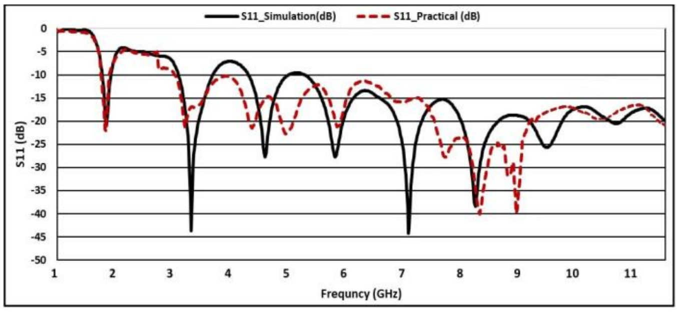

Figure 10. Reflection coefficient (S_{11}) of proposed antenna

Usually, in antenna fabrication and measurements, there should be small discrepancies between the results of the simulation and actual measurements. This is because of a number of practical considerations that cannot be precisely modeled in the simulation software. The most notable of them is a minor loss in the material of the substrate (FR4), the real electromagnetic properties of which might not be equal to the nominal theoretical values. These considerations also encompass the effects of the manufacturing processes and these include the accuracy of drilling, the copper thickness and the dimensions that do not match the values provided in the designs. The final results are also influenced by practical conditions of measurement like use of cables and other related equipment or other minor reflections in the laboratory. Despite these differences, the overall congruence between simulation and measurement results remains acceptable, confirming the validity and efficiency of the design.

Table 2. Comparison of proposed Vivaldi antenna specifications and performance parameters

Ref. No.	Size (mm)²	Material	Operating range (GHz)	Max gain (dB)
[25]	90 × 93.5	F4B	1.32-17	9.3
[26]	130 × 80	F4B	1.13-12	14
[27]	52.45 ×53	FR4	2.75-9.54	5.6
[28]	45 × 40	FR4	2.79-16.66	4.77
[29]	55 × 65	FR4	2.33-7.09	6.62
[30]	110 × 96	FR4	3 - 8 GHz	9
This work	90 × 53	FR4	1.77-1.93, and 3-12	8.37

Table 2 compares the suggested antenna's performance to that of previous works. Although the antenna [26] has a better gain, integrating it into mobile devices is made more difficult by its larger size. Researchers introduced a wideband antenna for medical imaging in [27]. The antenna's operational range was between 2.75 and 9.54 GHz; however, its gain was not very good. Although the antenna in [28] has a more complicated construction with parasitic components and covers a greater frequency range but it has low gain. Regarding the antenna [29], it uses dielectric lenses, which raise the design complexity and manufacturing costs even if it achieves a gain of 7.36 dB. In [30], a UWB Vivaldi antenna with a modified structure was presented for detection and imaging systems; however, the large size of the antenna limits its use in certain applications.

The proposed antenna achieves a more compact size compared to [25, 26, 30]. It provides higher gain across most of the band compared to [27, 28]. The fabrication process is simpler and cost-effective compared to the U-shaped slot antenna and confocal radar-based structure in [29]. Our design combines a wide operating bandwidth (3-12 GHz), high gain (8.37 dBi at higher frequencies), small size, and successful experimental validation. Few reported Vivaldi antennas achieve this balance of performance using a single-layer FR4 substrate, which we highlight as the key innovation.

A comparison between the simulated and measured performance of the designed Vivaldi antenna reveals both consistencies and differences. Regarding the operating frequency range, the prototype's working frequency range of 1.77-1.93 GHz and 3-12 GHz offers excellent performance in practical ultra-wideband operation. However, the sub-bands in the simulation results differed slightly: 1.77-1.93 GHz, 3-3.6 GHz, and 4.2-14.5 GHz. Regarding impedance matching, the simulation exhibited excellent matching across the entire design band. The measured results however indicated that there was a slight degradation in matching because of fabrication tolerances, material losses in the FR4 substrate and constraints in laboratory measurements. In spite of these variations, the radiation behavior of the prototype is near to the simulated results as shown in *table 3*.

Table 3. Comparison of proposed Vivaldi antenna specifications and performance parameters

Parameter	Simulated Results	Measured (Practical) Results	Comments
Operating Frequency Band (GHz)	1.77–1.93, 3–3.6, 4.2–14.5	1.77–1.93, 3–12	Measured bandwidth achieved UWB operation range in higher band.
Impedance Matching (S_{11})	Excellent across entire band	Slightly degraded	Degradation caused by substrate losses, fabrication tolerances, and lab measurement constraints.

4. CONCLUSIONS

In this work, an efficient ultra-wideband Vivaldi antenna is presented for various communication applications. The antenna has a good operating bandwidth of 3-12 GHz, with a return loss (S_{11}) value of less -10 dB across the entire operating band. Using an exponentially tapered slot on a 90×53 mm² FR4 substrate and two symmetrical slots added to the radiator to eliminate unwanted surface currents; the antenna achieves a radiation efficiency of 82% and 84% at lower frequencies (2–3.5 GHz). The results also show a maximum gain of approximately 8.37 dB at 7 GHz, which is very useful for long-range, high-data-rate communications such as 5G, radar, ground-penetrating radar, and microwave imaging. Thanks to the low cost FR4 substrate and its simple and compact design, a prototype was fabricated and measured. The measured results showed high agreement, yielding good simulation and experimental results, proving that the proposed Vivaldi antenna represents a stable and effective solution to current large-scale communication and sensing problems. Future research could expand this work and introduce metamaterials to achieve miniaturization and improve antenna performance by exploring arrays.

Acknowledgment: The authors are grateful for the support towards this research by the Communication Engineering College, University of Technology, Iraq.

Conflicts of Interest: Authors stated that no conflict of Interest.

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