RHOMBUS SHAPED ULTRA-WIDEBAND VIVALDI ANTENNA WITH ENHANCED GAIN FOR BRAIN TUMOR DETECTION

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Abstract:

In this article, a novel design for a compact Ultra-wideband Vivaldi antenna specifically designed for brain tumor detection. The antenna design incorporates a rhombus-shaped slots strategically positioned within the Vivaldi antenna, resulting in a compact form measuring 42.8×29.1×1.6 mm³. To accomplish this, the simulation and fabrication of the antenna utilized a cost-effective FR-4 substrate with a height of 1.6 mm was employed. The integration of these 1 mm side length rhombus-shaped slots enhances the antenna's gain and directivity, surpassing conventional designs. Comprehensive measurements were carried out, illustrating a return loss (S11) lower than -10 dB over a frequency spectrum spanning from 3.1 GHz to 10.6 GHz. The proposed Vivaldi antenna with rhombus shaped slots achieves the wide bandwith of 7.5 GHz and it provides the maximum fractional bandwidth of 109%. Moreover, the measured results showcase an enhanced gain of 5.8 dBi, emphasizing the efficacy of the proposed antenna design.

1 Introduction

Brain tumors constitute approximately 3% of all cancer cases and display a higher prevalence in men compared to women. Despite being among the top ten deadliest cancers, their occurrence rate remains relatively low. Various methods, such as ultrasound, radiography, CT scan, and MRI, are employed to detect intracranial tumors. Despite being one of the ten most lethal cancers, its occurrence rate is relatively low. Various methods are used to detect intracranial tumors, including ultrasound, radiography, CT scan, and MRI. Nevertheless, each of these methods presents its own set of limitations, which can include concerns related to high levels of ionizing radiation exposure, invasiveness, or extended monitoring durations. Antennas provide a solution to these limitations and can have a significant impact on image quality and performance. As cited in reference [1], microstrip patch antennas exemplify several desirable characteristics, such as integration, compactness, a straightforward geometric design, wide bandwidth, and high gain. However, it's important to note that while antennas have the potential to enhance medical imaging, there are various factors to consider when selecting the appropriate antenna for a particular application, including frequency range, sensitivity, and safety considerations. Therefore, further research is needed to determine the most suitable antenna for a given medical imaging application. Microwave imaging is a widely used technique for identifying hidden objects, especially in medical applications [2].

The technique uses electromagnetic waves in the microwave region, which ranges from 300 MHz to 300 GHz. Tumors have distinct electrical characteristics, such as higher dielectric permittivity and conductivity, compared to surrounding tissues [4]. As a result, microwave imaging is a promising technique for detecting brain tumors. To improve the image quality and performance of microwave brain stroke imaging systems, an antipodal Vivaldi antenna with high directivity is commonly used [5]. Ultra-wideband (UWB) antennas are

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also essential for cancer detection in medical applications [6–9]. However, many small UWB antennas have poor return loss and low gain properties [10]. To address these issues and enhance the image clarity of microwave imaging devices for the detection of brain cancer, moderate gain and improved return loss features are necessary. The Vivaldi antenna is widely recognized as a highly sought-after UWB antenna due to its ability to produce a directive radiation pattern that effectively minimizes the number of back-scattered signals resulting from obstructions present within or outside the phantom model's volume [11-16].

The antipodal Vivaldi antenna is commonly used to detect tumors, even in low-contrast scenarios, and is computationally fast. It is also much simpler and lighter than the contact liquid method, making it a popular choice for dry setup methods [17]. Tumor-induced brain models typically exhibit higher specific absorption rates (SAR) than healthy brain models. In [18], the authors proposed a reflector array antenna with high gain designed for the detection of human brain tumors using ultra-wideband technology. The antenna successfully detects brain tumors based on the specific absorption rate technique [19-21]. The absorption of energy and resulting SAR value were found to be higher in the human brain with a tumor compared to a normal healthy human brain. Utilizing a wideband of operation can offer benefits associated with both low and high ranges of operation [22]. A U-shaped slot Vivaldi antenna has been proposed for brain tumor identification in the frequency range from 2.33 GHz to 7.09 GHz [23]. In [24], a Vivaldi Tapered Slot Antenna (VTSA) with ultra-wideband capability has been developed by modifying its Transition from Microstrip to Slot line. Four different models (A-D) have been designed and analyzed to demonstrate the influence of transition shape on the dimensions and performance of the UWB VTSA. The three-layer structure of the UWB Vivaldi antenna outperforms a conventional two-layer antenna, and SAR analysis on tumor tissue demonstrates the significant potential of this antenna for future research in tumor detection [25]. The antenna is suitable for microwave imaging applications due to its reduced group delay and increased fidelity factor [26]. Various types of ground slots, including rectangular and elliptical slots, have been examined to increase radiation directivity, gain, and efficiency [27]. Metamaterial elements have been utilized in microwave tumor detection systems with the proposed antenna [28].

The Antipodal Vivaldi Antenna with a resonant parallel strip, as proposed in [29], operates over a frequency range of 2 to 9 GHz and offers enhanced gain, making it suitable for imaging applications. The ultra-wideband Vivaldi antenna [30] has been developed for imaging applications, with added corrugations in the flaring section to enhance its performance in terms of bandwidth and gain. The Antipodal Vivaldi antenna with two half-cut superstrates, proposed in [31], achieves wide bandwidth, making it suitable for head imaging applications. In this research paper, an innovative design is introduced for a compact ultra-wideband Vivaldi antenna specifically developed for brain tumor detection. The design incorporates strategically positioned rhombus-shaped slots within the Vivaldi antenna. The integration of these rhombus-shaped slots, with side lengths of 1 mm, significantly improves the antenna's gain and directivity compared to typical antenna designs. To evaluate the performance of the proposed antenna, extensive measurements were conducted. The results indicate an incredible return loss (S11) below -10 dB across the frequency range of 3.1 GHz to 10.6 GHz. Furthermore, the measurements validate the effectiveness of the proposed antenna design by revealing a monumental gain of 5.8 dBi. The remaining sections of this manuscript are organized as follows: Section II presents an analysis of the antenna's geometry, while Section III presents the outcomes and interpretations of the intended investigation. Finally, Section IV provides a conclusion for this research.

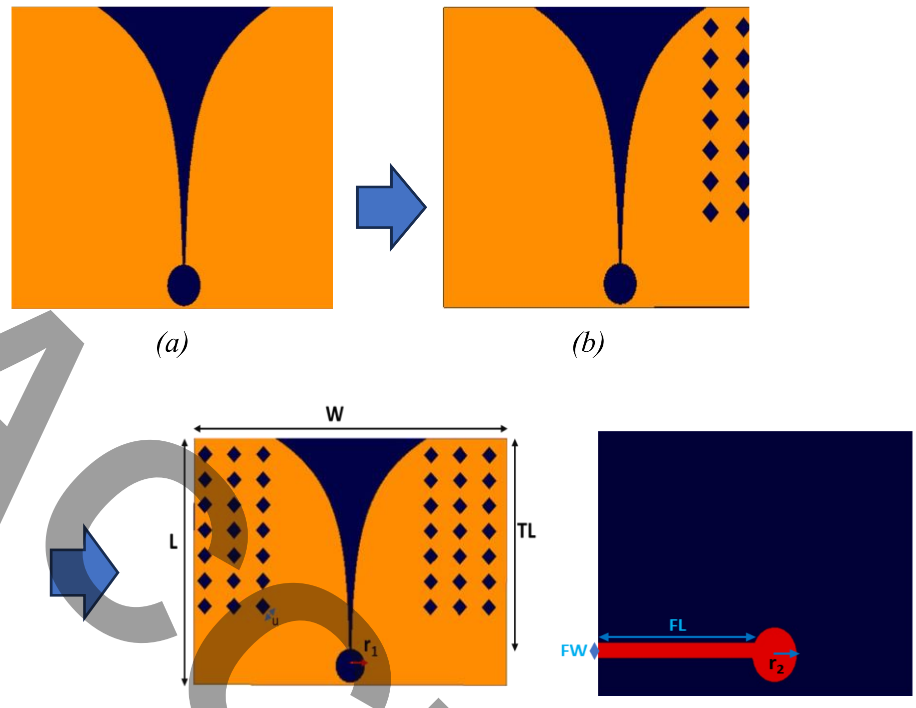
2 Geometry Analysis of Proposed Antenna

The initial design of the Vivaldi antenna as shown in Figure 1(a). On top of the substrate material, an exponentially tapered slot is constructed with one end creating a cavity in the shape of a circle and the other remaining open. The calculation of exponential tapered slot is,

$$\mathrm{Y} = C_1 e^{Rx} + C_2 \tag{1}$$

$$\mathrm{c}_1 = \frac{\mathrm{y}_2 - \mathrm{y}_1}{\mathrm{e}^{\mathrm{R}\mathrm{x}_2} - \mathrm{e}^{\mathrm{R}\mathrm{x}_1}} \tag{2}$$

$$\mathrm{c}_2 = \frac{\mathrm{y}_1 \mathrm{e}^{\mathrm{R}\mathrm{x}_2} - \mathrm{y}_2 \mathrm{e}^{\mathrm{R}\mathrm{x}_1}}{\mathrm{e}^{\mathrm{R}\mathrm{x}_2} - \mathrm{e}^{\mathrm{R}\mathrm{x}_1}} \tag{3}$$



(c)

Figure 1. Design steps of proposed antenna design: (a) Vivaldi antenna without slots (b) Vivaldi antenna with left side slots (c) Proposed Antenna with Bottom view.

It includes the operation in three frequency bands, namely 3.1-6.34 GHz ,6.9-9.29 GHz and 9.8-10.7 GHz. Rhombus- shaped slots are positioned in the left side of the tapered slot to increase impedance matching. It can be observed in Figure 1(b). These slots are strategically placed to enhance impedance matching. However, it is important to note that despite operating in the multiband, the antenna does not achieve the desired level of impedance matching. Then, to ensure that the wideband antenna for head imaging has the necessary properties, each antenna parameter was examined and validated, Rhombus shaped slots are aligned in two sides of the Vivaldi antenna. It is shown in Figure 1(c). The slots enable a more even distribution of current along the antenna, reducing impedance mismatch at the feed point and enhancing antenna gain.

The proposed ultra-wideband Vivaldi antenna is capable of transmitting and receiving signals within the frequency range of 3.1-10.6 GHz. The antenna is fabricated on a cost-effective FR4-epoxy substrate, characterized by a loss tangent of 0.02 and a dielectric constant of 4.4. Power is supplied to the antenna through a 50Ω microstrip line.S_{11} is the antenna- related parameter that is consistently mentioned. S_{11}, often referred to as the reflection coefficient, measures the amount of power is absorbed from the antenna. Figure 2. shows that the Vivaldi antenna design without any slots (i.e., Figure 1a) and with slots placed on the left side of the tapered slot (i.e., Figure 1b) provided a high reflection coefficient. It was determined that using rhombus-shaped slots on both sides of the tapered slot (i.e., Figure 1c) resulted in a low reflection coefficient, wide operational bandwidth, and higher gain, compared to the previously described structures.

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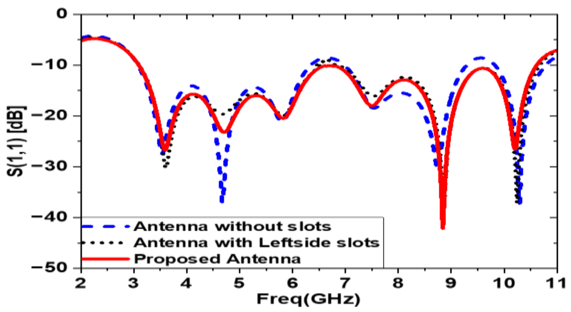

Figure 2. Comparison of Simulated Reflection coefficient (S_{11}) for with and without rhombus-shaped slots antenna design.

The position of the rhombus-shaped slots on either side of the tapered slot acts as a resistive loading, maintaining the intensity of the overall field in the slot region and increasing the radiation patterns, which significantly improves antenna gain. It can be observed from Figure 3. The proposed antenna's maximum gain among the three structures is 5.8 dBi.

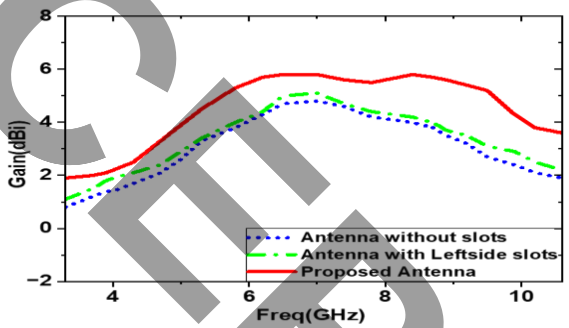

Figure 3. Comparison of Gain values for with and without rhombus-shaped slots antenna design.

Using the HFSS, the proposed antenna's performance has been reviewed and assessed. In accordance with the results of the simulation parameters, the design of the Vivaldi antenna loaded by the rhombus shaped slots are considered. For brain tumor detection applications, the proposed antenna provides the most effective parameters. Table 1 shows the parameters used to describe the proposed antenna structure. The proposed antenna design features an exponentially tapered patch that is terminated with a 3 mm radius circular cavity (r1) to achieve impedance matching. To increase antenna, gain and achieve a reflection coefficient of less than -10 dB, the final measurements for the length (L) and width (W) were set at 42.8 mm and 29.1 mm, respectively. The top surface of the substrate incorporates rhombus-shaped slots with a side length (u) of 1 mm, strategically designed to enhance the antenna's performance parameters.

Table 1. The Specifications of the Proposed Antenna.

Specification	Size (mm)	Specification	Size (mm)
L	42.8	FW	1.68
W	29.1	s	0.15
r_1	3	TL	35
r_2	3	h	1.6
FL	21.53	u	1

Through the optimization of gain, impedance bandwidth, and antenna efficiency using appropriate tuning techniques, the desired requirements were met. The microstrip feedline is 21.53 mm long (FL) and 1.68 mm wide (FW), connected to the patch through a lumped port. The connection is completed with a circular stub (r2) having a radius of 3 mm.

3 Results and Parametric Study

The proposed antenna uses a microstrip feeding technology with a circular stub positioned at the feedline's end. A summary of the effects of various circular stub sizes on the bottom side is presented in Figure 4. Further analysis shows that when the circular stub's radius is increased to 3.5 mm, its bandwidth is reduced and its reflection coefficient value will be increased slightly in the frequency range of 7.8 GHz to 8.2 GHz (i.e., above -10 dB). However, when the stub radius is decreased to 2.5 mm, the value of the reflection coefficient is reduced in the frequency range between 6.4 GHz and 7.1 GHz. On the other hand, the multi bands is produced for stub radius value of 2 mm, respectively. The proposed ultra-wideband frequency range of 3.1 GHz to 10.6 GHz is achieved when the stub radius is 3 mm, with a decrease in reflection loss.

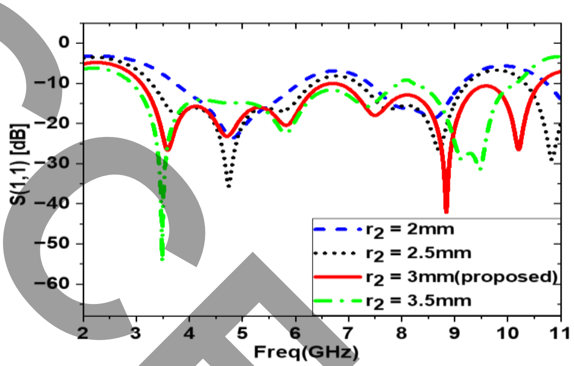

Figure 4. The impact of the reflection coefficient of the proposed antenna is observed with different circular stub radii: r_2 = 3 mm, r_2 = 3.5 mm, r_2 = 2.5 mm, and r_2 = 2 mm.

The proposed antenna employs microstrip feeding technology, and its performance with various feedline width sizes is summarized in Figure 5. Upon analysis, it is observed that increasing the feedline width to 2 mm results in a reduction in bandwidth and a slight increase in the reflection coefficient in the frequency range of 6.5 GHz to 6.8 GHz (i.e., above -10 dB). Conversely, when the feedline width is increased to 2.5 mm, the reflection coefficient value is decreased within the frequency range of 6.2-7 GHz and 9.4-9.7 GHz. Moreover, a multi-band response is obtained for a feedline width of 1 mm. However, for achieving an ultra-wideband frequency range of 3.1 GHz to 10.6 GHz with reduced reflection loss, the optimum feedline width of 1.68 mm is proposed.

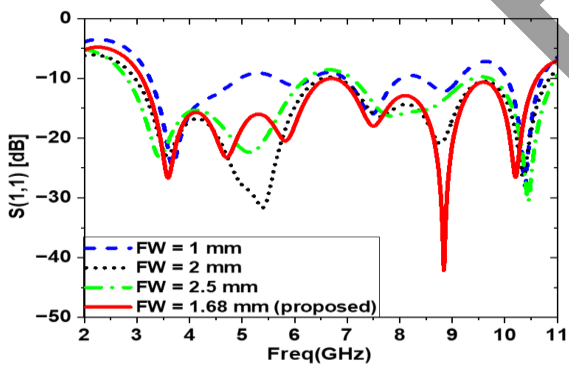

Figure 5. The impact of the reflection coefficient of the proposed antenna is observed with different feedline widths: FW = 1 mm, FW = 1.68 mm, FW = 2 mm, and FW = 2.5 mm.

The proposed antenna utilizes microstrip feeding technology, and an overview of the impacts of various feedline length sizes is presented in Figure 6. Further analysis reveals that increasing the length of the feedline to 22 mm leads to a reduction in bandwidth. Conversely, when the feedline length is decreased to 21 mm, the value of the reflection coefficient is reduced within the frequency range of 6.3- 7 GHz and 9.2-10.1 GHz, and it results in a multiband response. Additionally, a multi-band response is observed for a feedline length of 20.5 mm. For achieving an ultra-wideband frequency range of 3.1 GHz to 10.6 GHz with decreased reflection loss, the proposed optimal feedline length is 21.53 mm.

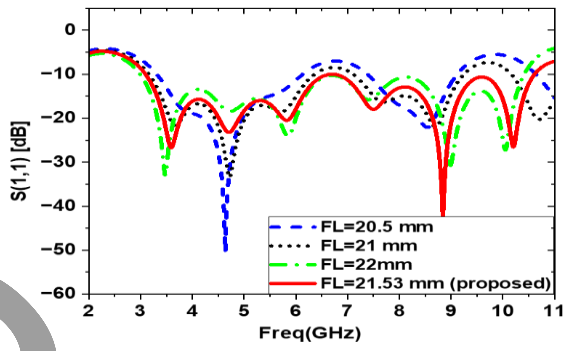

Figure 6. The impact of the reflection coefficient of the proposed antenna is observed with different feedline lengths: FL = 21.53 mm, FL = 22 mm, FL = 21 mm, and FL = 20.5 mm.

Figure 7. presents an overview of the effects of altering the distance between the rhombus-shaped slot columns placed in the radiating patch of the antenna. Upon further analysis, it is observed that decreasing the distance between the slot columns to 1 mm results in a reduction in bandwidth, and the reflection coefficient is also reduced in the frequency range of 6.5 GHz to 6.9 GHz. Conversely, increasing the distance to 3 mm leads to a reduction in the reflection coefficient within the frequency range of 6.5 GHz to 6.8 GHz, resulting in a multiband response. To achieve an ultra-wideband frequency range of 3.1 GHz to 10.6 GHz with reduced reflection loss, the proposed optimal distance between the slot columns is 2 mm.

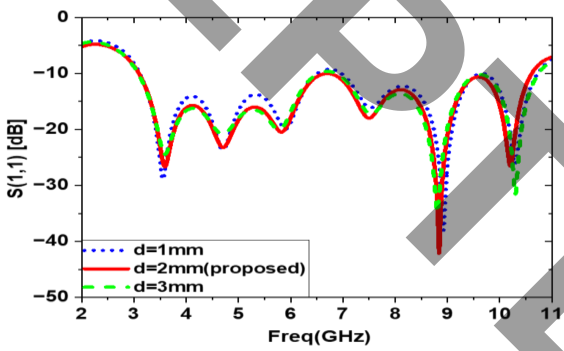

Figure 7. The impact of the reflection coefficient of the proposed antenna is observed with different distance between the rhombus-shaped slot columns: d = 1 mm, d = 2 mm, and d = 3 mm.

Furthermore, the prototype's reflection coefficient (S_{11}) has been evaluated using network analyzer. The designed antenna achieves -10dB impedance matching in the bandwidth of 7.5GHz (3.1 - 10.6 GHz). Figure 8(a). displays the fabricated model of the antenna and VNA measurement setup is illustrated in Figure 8(b).

(i) (ii)

Figure 8(a). Fabricated model of the Proposed antenna: (i) Top view (ii) Bottom view.

Figure 8(b). VNA Measurement setup for proposed work.

Figure 9. typically shows the measured and simulated S_{11} of the prototype, and it is observed that the measured and modelled return loss have a good correlation. The slight non-symmetry in S_{11} could be attributed to various factors such as reflections from the coaxial connection body, issues with the connecting device and soldering, and other manufacturing defects.

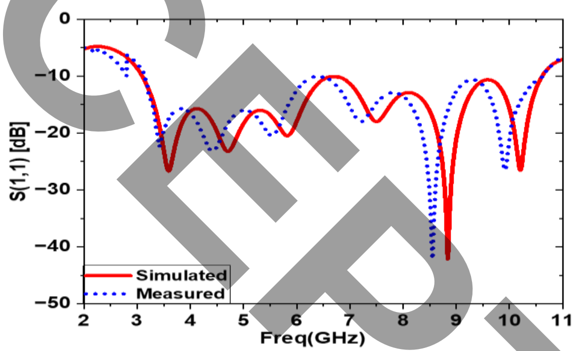

Figure 9. Simulated and Measured Reflection Coefficient(S_{11}) of the proposed antenna.

Consequently, the tapered slot antenna with rhombus-shaped slots provides better gain, making it especially suitable for head imaging due to its enhanced performance. The tapered slot antenna without any slots achieves a maximum gain of 4.8 dBi. By adding rhombus-shaped slots on both sides of the tapered slot, the maximum gain increases by 1 dB. The maximum gain achieved by the tapered slot antenna with rhombus shaped slots is 5.8 dBi. The simulated and measured gain values are shown in Figure 10.

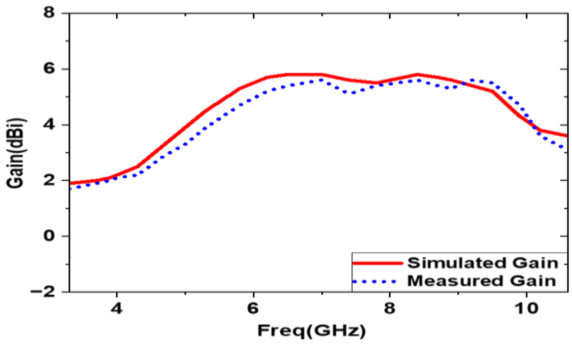

Figure 10. Simulated and Measured Gain of the proposed antenna.

The simulated and measured radiation efficiency of the tapered slot Vivaldi Antenna with rhombus shaped slots across various frequencies is depicted in Fig. 11. The figure indicates that the proposed prototype achieves an average radiation efficiency of approximately 70%, with a peak efficiency of 90% across the entire wideband, attributed to its maximum gain.

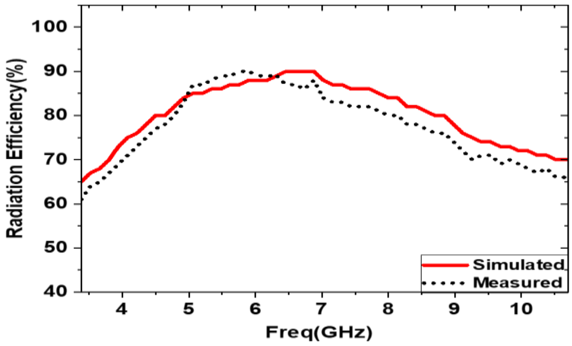

Figure 11. Simulated and Measured Radiation Efficiency of the proposed antenna.

3.1 Radiation Pattern

The computed 2-dimensional radiation pattern of the suggested antenna in the E plane and H plane is shown in Figure 12. The 3-dimensional radiation pattern, which displays the radiation characteristics of the antenna in both the E and H planes. The E-plane is perpendicular to the antenna's aperture, while the H-plane is parallel to it. The wideband antenna is essential in microwave head imaging systems because they have special traits like improved gain, efficiency, and directional radiation characteristics. The proposed Vivaldi antenna provides good gain and directed radiation properties over the operational frequency range. According to Figure 12, the backside lobe is decreased while the antenna's gain, directivity, radiation efficiency, and front-to-back ratio are all improved. As such, it follows that the proposed antenna needs to have antenna radiation properties that are greatly improved.

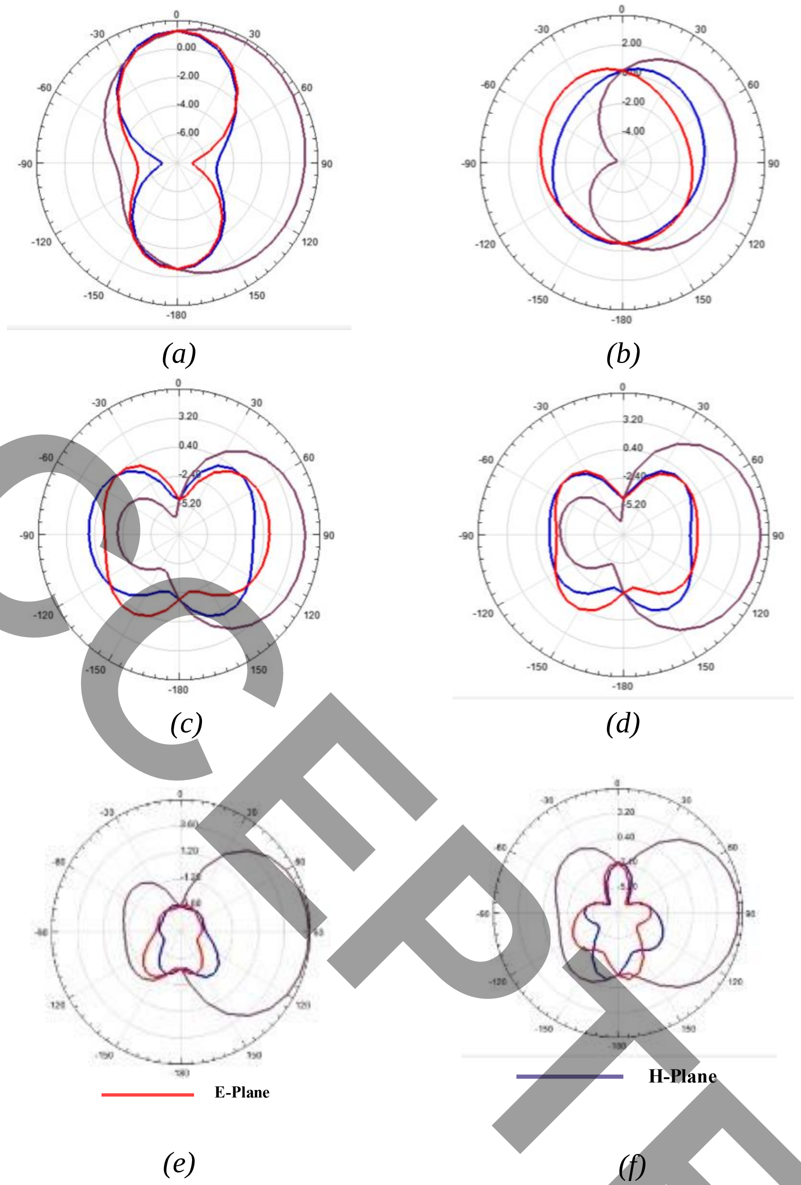

Figure 12. Simulated 2D radiation pattern of proposed antenna. (a) At 3GHz; (b) At 4GHz; (c) At 5GHz; (d) At 5.5GHz; (e) At 6.5GHz; (f) At 7GHz.

3.2 Surface Current Distribution

The surface current distribution at various frequencies is shown in Figure 13. The antenna's edges and slots are ultimately determining the current flow in the antenna. The electric and magnetic fields line up perpendicularly in regions where there are edges and slots, providing the most current. The surface current distribution map shows that the surface current is focused on the inner boundary of the exponential taper which enhance the antenna's gain.

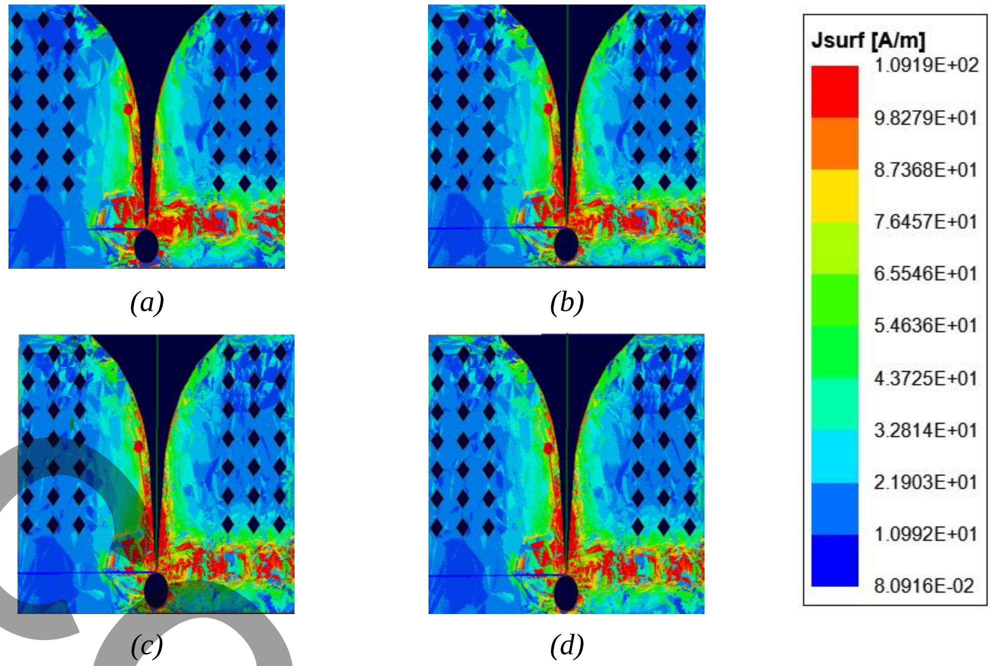

Figure 12. Surface current distribution of the proposed antenna at various frequencies (a)3.1GHz; (b)5.6GHz; (c)8.5GHZ; (d)10.1GHz.

Table 2 shows a comparison of the performance of the proposed rhombus-shaped slot antenna with relevant research, taking into account the antenna dimensions, operating frequency bandwidth, and gain. According to the results, the proposed Vivaldi Antenna with rhombus shaped slots offers a smaller size, higher efficiency, broader bandwidth and improved gain compared to the previously reported antennas.

Table 2. Comparative and Analysis of the Proposed Antenna with the observed Antennas.

Ref	Antenna Used	Dimension (mm)	Band Width (GHz)	Gain (dBi)
[5]	Antipodal Vivaldi antenna	50×60	2.06 – 2.61	2.45
[27]	Coplanar waveguide-based patch antenna	50×44	1.70 – 3.71	5.65
[28]	Metamaterial based antenna	22×22	2 – 12	4.8
[26]	Ellipse-shaped patch antenna	70×60	1.19 – 3.56	3.63
[29]	Antipodal Vivaldi antenna	104×100	2 – 9	6.5
[30]	Antipodal Vivaldi antenna	98×110	1.45 – 9.82	6.6
[31]	Antipodal Vivaldi antenna	30.2×44.4 30.32×60	2.65 – 4.2 1.9 – 5.4	5.2 5.5
Proposed	Rhombus Shaped Vivaldi Antenna	42.8×29	3.1 - 10.6	5.8

Novelty of the Proposed work:

1. The proposed antenna incorporated with simple rhombus shaped slots to improve the performance of the planar Vivaldi structure without increasing the complexity of the structure.

2. The designed Vivaldi antenna with rhombus shaped slots exhibit the size of 42.8×29, which is compact compared with [5], [26], [27], [29], and [30].
3. The developed antenna achieves fractional bandwidth of 109% which is greater than [5], [26-27], and [31].
4. The proposed antenna obtained enhanced gain of 5.8 dBi, rather than [5], [26-28], and [31].

4 Conclusion

A compact Vivaldi antenna with rhombus-shaped slots has been successfully designed and developed for brain tumor detection applications. The proposed antenna has been fabricated using FR-4 substrate, and simulation results have shown that it has adequate impedance matching with return losses under -10 dB throughout the operating band. By adding rhombus-shaped slots to the radiating patch, the performance of the Vivaldi antenna has been enhanced without augmenting the structural complexity. The rhombus shaped slotted Vivaldi antenna provides the wide band operating frequency range from 3.1 to 10.6 GHz and bandwidth of 7.5 GHz. Also, the proposed antenna obtained 109% of fractional bandwidth. Without adding the rhombus shaped slots on the tapered slot antenna, it provides the maximum gain of 4.8 dBi. After adding the slots on the radiating patch the gain has been increased by 1 dBi. The designed antenna has a gain of 5.8 dBi and is well-suited for brain tumor detection due to its enhanced performance characteristics. Overall, this research opens up new possibilities for improved antenna design in medical applications, particularly in brain tumor detection, where its enhanced performance can contribute to more accurate and reliable results. The successful implementation of the proposed antenna underscores its potential significance in advancing medical imaging and diagnostic technologies.

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