Gain enhancements of tapered slot Vivaldi antenna for radar imaging applications

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Abstract. in this paper, a gain enhancement of the UWB Tapered slot Vivaldi antenna (TSVA) for radar imaging application is presented. The proposed antenna has 41×48×1 mm³ dimensions. The proposed antenna operates from 2.7 GHz to more than 12 GHz. The antenna is printed on a 1 mm FR4 dielectric substrate thickness with an exponentially tapered slot shape. The suggested Vivaldi antenna is modified by inserting a polygon form dielectric lens and some periodic unequal lengths director elements consist of three metallic strips on the dielectric lens, which produces an improvement in gain significantly along with center frequency band about 2 dB. The radiation pattern of the proposed antenna has a stable variation with respect to frequency.

Keywords: directivity, end-fir, imaging applications, ultra-wideband, Vivaldi antenna.

1. Introduction
A Compact size UWB antenna with high gain and a stable radiation pattern is necessary for some applications such as UWB communication systems, radar, remote sensing, and microwave imaging. To achieve these requirements, tapered slot Vivaldi antenna (TSVA) is considered a good candidate owing to its performance. The (TSVA) provides high gain characteristics, wide bandwidth, and stable end-fire radiation. The UWB frequency range from 3.1 to 10.6GHz is allocated by The United States Federal Communications Commission (FCC). P. J. Gibson 1979 was the first to invent the Vivaldi antenna and then has been extensively deliberated in UWB antenna research due to its characteristics [1-5]. In order to improve the gain of the Vivaldi antenna and preserve its impedance bandwidth, an assortment of adjusted Vivaldi antennas have been deliberated by many researchers. An adjusted VA depends on the slotted edge loaded with lens structure is given in [9]. A tapered slot edge (TSE) structure for wide impedance bandwidth and good directive radiation patterns is proposed in [10]. In [11] the gain and directivity of VA are improved based on the inhomogeneous, and anisotropic IA zero-index meta-material ZIM. In [12-15] corrugation slots are used to enhance the radiation properties of VA. In this paper, a modified VA is presented to gain improvement based on the dielectric lens and metallic directors. The antenna is designed, simulated, and optimized based on Ansoft's High-Frequency Structure Simulator (HFSS) [16].

2. The Proposed Antenna Structure
The suggested antenna geometry is presented in (Fig. 1). The antenna is printed on low cost 41×48×1 mm³ FR4 substrate ( εr =4.4). The proposed tapered slot Vivaldi antennas (TSVA) based on an exponential tapered radiating slot, micro-strip-to-slot line transition structure, and a micro-strip feeding line on another side. The exponential radiating structure emphasizes theoretically unlimited bandwidth [12], that constrained by the taper dimensions, the transition from the feed line, and the slot line width. On the top of the substrate, the exponentially tapered slot is printed with a circular cavity slot while the other end is opened. The cavity reduces the reflections from the micro-strip line to slot-line transition which acts as an open circuit. The flaring shape and the circular cavity determine the main behavior and antenna properties. On the other side (backside) of the substrate, a linearly tapered micro-strip line is proposed. To supply feed to the TSVA, a micro-strip line to slot line transition is modelled to preserve the antenna matching over a large frequency band.
Figure 1. The proposed TSVA: (a) top view of TSVA, and (b) bottom view of TSVA.

The exponential tapered used in the proposed TSVA is given as:

\[ y(x) = c_1 e^{xR} + c_2 \]  \hspace{1cm} (1)
\[ y(x) = 9.19 e^{150x} + 0.134 \]  \hspace{1cm} (2)
\[ 11 \text{mm} \leq x \leq 41 \text{mm} \]

Where:

\[ c_1 = \frac{y_2 - y_1}{e^{(x_2\times R) - e^{(x_1\times R)}}} \]  \hspace{1cm} (3)
\[ c_2 = \frac{y_1 e^{(x_2\times R)} - y_2 e^{(x_1\times R)}}{e^{(x_2\times R)} - e^{(x_1\times R)}} \]  \hspace{1cm} (4)

R: is the opening rate.

The proposed TSVA parameters in (mm) are given in (Table 1).

Table 1. TSVA dimensions.

| W | L | T | Lg | Ws | Wu | Lt | Ls | Wf1 | Wf2 | Lf | Wfr | R |
|---|---|---|---|----|----|---|---|----|----|---|----|---|
| 48 | 41 | 1 | 4 | 4 | 0.8 | 3 | 30 | 1.9 | 0.8 | 4 | 24.4 | 150 |

3. Simulations:
The proposed TSVA is operating with frequency range from (2.5-12 GHz).

3.1 Reflection Coefficient Calculation:
The reflection coefficient S_{11} variations with a frequency are shown in (Fig. 2), for the proposed TSVA. It can be noticed that the reflection coefficient is below (-10 dB) for the frequency range from (2.7-12GHz) in the case of the proposed TSVA. Whereas it is observed that the S_{11} is below (-10dB) for the frequency range from (2.7-12GHz) when the flaring width is reduced to 40mm. However, it is noticed that the frequency range from (2.3-12GHz) when the circular cavity diameter is increased to 5mm, but S_{11} suffer mismatching in the frequency of (6.5GHz), and (9GHz).
3.2 3-D Radiation Patterns:

The gain patterns of the suggested Vivaldi Antenna at frequencies (3GHz, 6.77GHz, and 10GHz) are presented in (Fig. 3) respectively.
Figure 3. 3-D radiation patterns: (a) at 3GHz, (b) at 6.77GHz, and (c) at 10GHz.

The variation of the realized gain of the suggested TSVA is presented in (Fig.4). The gain in the centre frequency became maximum.

![Gain variation with frequency](image)

Figure 4. Gain variation with frequency

In order to improve the gain of the proposed TSVA further, two types of enhancement mechanisms are involved. Primarily, a dielectric lens with polygon shape is inserted at the flaring end of the Vivaldi antenna and secondly, three metallic rectangular directors are binned on the dielectric lens part of the TSVA in the orientation of antenna axis.

4. Modified TSVA Based on Dielectric Lens

The first technique to enhance the gain of the proposed TSVA a dielectric lens is inserted to the end of the TSVA. The dielectric lens is achieved by extending the substrate with a polygon shape that has the
same width as the substrate. The polygon shape dielectric lens focuses on energy at the aperture center of the TSVA, that’s the reason for the polygon shape of the dielectric lens instead of the Half-circular shaped lens because it’s not efficiently as some energy is dispersed off from aperture, mostly at higher frequencies. So, a proper form of a dielectric lens is necessary to supply efficient focusing, the proposed TSVA with a polygon lens is shown in (Fig.5).

![Figure 5](image)

**Figure 5.** TSVA: (a) TSVA, (b) TSVA with dielectric lens

The proposed TSVA with dielectric polygon shape lens parameters are $W_L=21.8$ mm, and $L_L=24$ mm. The proposed TSVA with dielectric polygon shape lens is operating with a frequency range from (2.5GHz) up to (12GHz)

4.1 Reflection coefficient:
The reflection coefficient (S11) variations with frequency are presented in (Fig. 6), for the proposed TSVA, and the proposed TSVA with dielectric polygon lens. It is observed that S11 is below (-10dB) for the frequency range from (2.5-12) GHz, however, in the case of the proposed TSVA with dielectric polygon lens S11 is also below (-10 dB) for the frequency range from (2.5-12) GHz.

![Figure 6](image)

**Figure 6.** TSVA with dielectric lens reflection coefficient

4.2 3-D Radiation Patterns:
The suggested TSVA and the suggested TSVA with dielectric polygon lens 3-D radiation patterns at the frequencies (3GHz, 6.77GHz, 10GHz ) are shown in (Fig. 7).
The modulation of the achieved gain with frequency of the suggested TSVA and the proposed TSVA with dielectric polygon lens are shown in (Fig. 8). It was noticed that the gain of the proposed Vivaldi antenna with polygon lens increased about (1dB). The lens affect the gain of the center frequency range.

Figure 7. 3-D Radiation Patterns: (a)3GHz, (b)6.77GHz, (c)10GHz.
5. Modified TSVA Based on metallic directors:

metallic directors are binned on the dielectric lens area of the TSVA, the grating elements composed of three different lengths, and different width metallic dipoles pinned in orientation of radiation, work as directive elements so that it assisted to enhance the radiation in the end-fire direction. The directors used to increase the gain in the center frequency. The proposed TSVA with dielectric polygon lens and directors is shown in (Fig.9).

The proposed TSVA with dielectric polygon shape lens and three different length and width metallic rectangular directors have diminutions listed in (Table 3), the TSVA with lens and directors operated at a frequency range from (2.7GHz) to more than (12 GHz).

|   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|
| $L_1$ | $W_1$ | $g_1$ | $g_2$ | $g_3$ | $g_{w1}$ | $g_{w2}$ | $g_{w3}$ |
| 24 | 21.8 | 8 | 10 | 12 | 1 | 1.5 | 2 |

5.1 The Reflection coefficient:
The modulation of $S_{11}$ with frequency for both the suggested TSVA and the TSVA with dielectric polygon lens and rectangular metallic directors, are presented in (Fig.10). It can be noticed that in the case of the suggested VA $S_{11}$ is below (-10dB) for the frequency range from (2.5-12GHz) whereas it is below (-10dB) for the frequency range from (2.7-12GHz) in the case of the TSVA with lens and directors.

![Figure 10. The reflection coefficient of TSVA with lens and directors](image)

5.2 3-D Radiation Patterns:
The suggested TSVA and the TSVA with dielectric polygon lens and the three metallic rectangular directors 3-D radiation patterns for the following frequencies (3GHz, 6.77GHz, and 10GHz) are presented in (Fig. 11). Both the suggested TSVA and the TSVA with dielectric polygon lens and the three metallic rectangular directors show a stable end-fire radiation pattern. Its noticed that the radiation of the proposed TSVA with lens and directors is more pointed and the side lobes are less than both, the proposed Vivaldi antenna and the proposed Vivaldi antenna with polygon lens and directors.

![3-D Radiation Patterns](image)
Figure 11. 3-D radiation pattern: (a) 3GHz, (b) 6.77GHz, (c) 10GHz
The modulation of the achieved gain with frequency of the suggested TSVA, and the TSVA with dielectric polygon lens and three metallic rectangular directors is shown in (Fig. 12). It is noticed that due to the extending the substrate to form a polygon lens and pinned three metallic rectangular directors the gain of the proposed TSVA enhanced manifestly during the operating frequency band. Because of the three metallic rectangular directors, the gain improving is great in the center frequency but it's very poor in the topmost range of the band. The TSVA with lens and directors with enhanced gain could be utilized for applications such as radars and microwave imaging.

Figure 12. gain modulation with frequency of the TSVA with lens and directors
6. CONCLUSION:
An UWB risen gain proposed tapered slot Vivaldi antenna with a polygon lens and three metallic rectangular directors was designed for radar and microwave imaging implementation. The suggested antenna total is slightly influenced by the mechanism utilized to improve the gain and enhance the radiation patterns of the suggested antenna, although, the total size of the antenna remains compact. The suggested antenna is UWB and has bandwidth range from (2.7GHz) to more than (12GHz). The radiation patterns and The reflection coefficient of the suggested antennas was plotted to realized the proposed antennas operating principles. The suggested antenna could be utilized for microwave imaging applications.

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