IEEE Open Journal of
Antennas and Propagation

Received 25 August 2021; revised 7 September 2021; accepted 10 September 2021. Date of publication 15 September 2021;
date of current version 20 September 2021.

Digital Object Identifier 10.1109/OJAP.2021.3112786

A Miniaturized Series Fed Tri-Slot Coplanar Vivaldi Antenna for RADAR Application With Reduced Ground Plane Effect

**JALIL UR REHMAN KAZIM [1], ZIA ULLAH KHAN [2] (Member, IEEE), JAMES RAINS [1],
HASAN T. ABBAS [1] (Senior Member, IEEE), MASOOD UR REHMAN [1] (Senior Member, IEEE),
AKRAM ALOMAINY [2] (Senior Member, IEEE), MUHAMMAD ALI IMRAN [1] (Senior Member, IEEE),
AND QAMMER H. ABBASI [1] (Senior Member, IEEE)**

[1] James Watt School of Engineering, University of Glasgow, Glasgow G12 8QQ, U.K.

[2] School of Electronic Engineering and Computer Science, Queens Mary University of London, London E1 4NS, U.K.

CORRESPONDING AUTHOR: J. UR REHMAN KAZIM (e-mail: j.kazim.1@research.gla.ac.uk)

This work was supported in part by the Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/R511705/1.

ABSTRACT In this article, a printed series fed tri-slot coplanar Vivaldi antenna is studied and investigated for RADAR application. The antenna consists of three exponentially tapered slots excited by a single microstrip line. The three slots are series fed simultaneously with a radial stub on the microstrip feed line for impedance matching. The proposed antenna covers a frequency of 7.8-11.8 GHz at -10 dB impedance bandwidth. The antenna gain varies from 7.5 dB at the lowest operating frequency and increases to around 9.5 dB at the center frequency of 10 GHz. A key versatility of the proposed design is the ability to modify the ground plane size without affecting the antenna impedance and gain. This makes the antenna suitable to incorporate RADAR transceiver components without modifying the existing antenna design. The proposed antenna is fabricated and measured results show good agreement with simulated results.

INDEX TERMS Vivaldi antenna, RADAR, slot antenna.

I. INTRODUCTION

THE FUTURE wireless communication standards such as beyond fifth-generation (B5G) technologies and sixth-generation (6G) will operate at extremely high frequencies to meet the demand for high data rates and link reliability. A key technology dedicated to defense applications such as RADAR is now being deployed in existing 5G and B5G networks, i.e., Phased array antennas. To obtain high directionality in phased arrays end-fire antennas are now explored over the broadside antennas.

Another potential area that is gaining significant attention using RADAR is in healthcare. Lately, contactless human activity detection is being performed using RADAR. The contactless human activity detection includes freezing of gait and vital sign monitoring, e.g., breathing and heart rate [1]–[4].

As RADAR systems deploy directional antennas, an important class of traveling wave, the end-fire antenna-Vivaldi antenna [5]–[7] has always remained an attractive solution for researchers. They are broadband, high gain, high efficiency and generate a stable radiation pattern. The antipodal Vivaldi antenna (AVA) [6] has mirror radiators on the top and bottom plane, generating a broader bandwidth than the conventional coplanar Vivaldi antenna (CVA) design [5], but it suffers from high cross-polarization. Due to the inherent unbalanced design of the CVA, the design was converted to a balanced CVA by [7] but at the cost of fabrication complexity with additional two layers.

Recently most researchers have presented various AVA designs [8]–[15] to enhance the bandwidth and the antenna gain. However, the proposed antennas are mainly designed to operate as stand alone antennas. The antenna is integrated with a PCB with a bigger ground plane to accommodate the components in practical scenarios. As a result, this degrades and/or requires changes to the antenna design [16]. For gain and bandwidth improvement, the CVA with corrugated slots has been proposed in [17]–[19]. Apart from that, no other method exists in the literature to improve the performance of the CVA.

In this article, we propose for the first time a concept of series fed exponentially tapered triple-slots on a common continuous ground plane applied to the CVA design. In previously published works, the traditional CVA bandwidth is widened by using a hollow cavity at the feed point. The proposed design introduces separate simultaneously excited slots to achieve the required bandwidth and additionally contributing to the antenna gain. To the extent of our knowledge, the proposed design has also achieved versatility as the ground plane could be extended along both length and width without affecting the impedance and gain of the proposed antenna. This makes it able to incorporate transceiver components without affecting the impedance matching and gain.

II. ANTENNA DESIGN

The optimization of the antenna is performed using CST MWS 2019. The antenna is fabricated on Rogers 4350B substrate having a dielectric constant of 3.48 and a loss tangent of 0.0037. The thickness of the dielectric substrate is taken as 0.8 mm. The proposed tri-slot antenna design consists of three separate radiators excited by a single microstrip feed line. This methodology adds to an improved gain of the proposed design. The inter-slot spacing is kept half wavelength at the center frequency, i.e., 10 GHz. As the radiation of the single slot is coupled to each other, this contributes to resonance altogether and the slots appear to each other as a two-element array. The proposed work has kept a common ground plane for all three slots. The total dimension of the proposed antenna is around 50×21 mm^2 which has 60% reduced volume as proposed in [19]. The complete layout of the antenna is given in Figure 1. The SMA connector is mounted at the bottom side and the pin is soldered perpendicular to the microstrip line. The stub on the top layer is carefully optimized to achieve 50Ω impedance matching when all three slots are excited together.

The exponentially tapered slots are designed using the equation from [20].

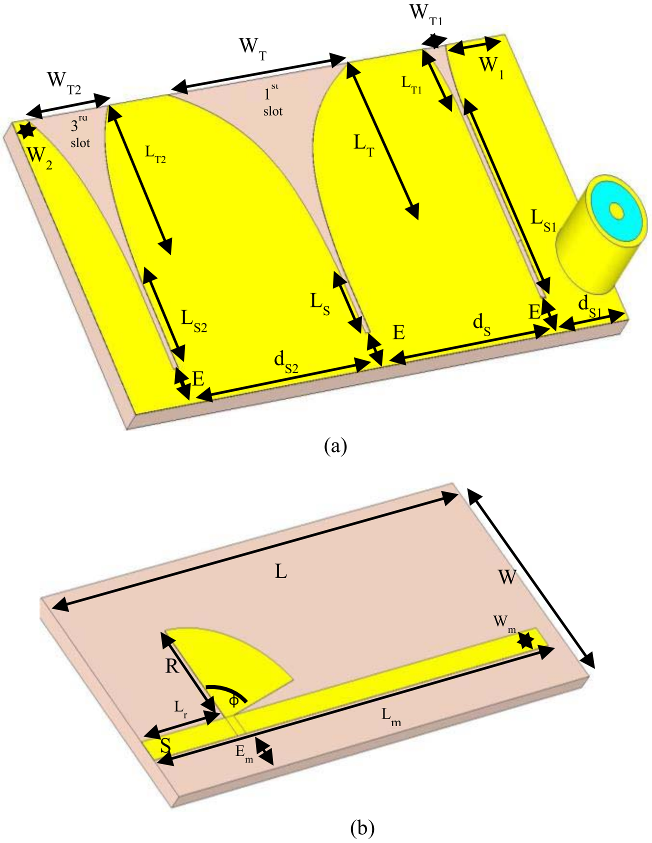
$$Y = \pm s e^{rx} \tag{1}$$

where ‘s’ represents the slot width at the feed point and ‘x’ the total antenna length from the feed point. The value of ‘r’ is important to determine the flare shape of the antenna, i.e., how the slot widens. The shape of the tapered slots in the proposed design is produced from the following values by optimizing in CST MWS.

$$Y_{1st} = \pm 0.08 e^{0.25x} \tag{2}$$

$$Y_{2nd} = \pm 0.001 e^{0.35x} \tag{3}$$

$$Y_{3rd} = \pm 0.22 e^{0.05x}. \tag{4}$$



(a)

(b)

FIGURE 1. The Geometry of the proposed Tri-slot Vivaldi antenna: a) Bottom view($W_2 = 1.42$ mm, $W_{T2} = 8.1$ mm, $L_{T2} = 12.6$ mm, $L_{S2} = 6.6$ mm, $d_{S2} = 18.75$ mm, $W_T = 18.49$ mm, $L_T = 14.5$ mm, $L_S = 4.95$ mm, $d_S = 17.5$ mm, $W_{T1} = 2.2$ mm, $L_{T1} = 4.2$ mm, $L_{S1} = 15.1$ mm, $d_{S1} = 7$ mm , $W1 = 6.15$ mm, $E = 1$ mm) and (b) Top view ($L = 50$ mm, $W = 21$ mm, $L_m = 47$ mm, $W_m = 1.2$ mm, $R = 10.8$ mm, $L_r = 10$ mm, $E_m = 3.4$ mm, $\varphi = 85°$).

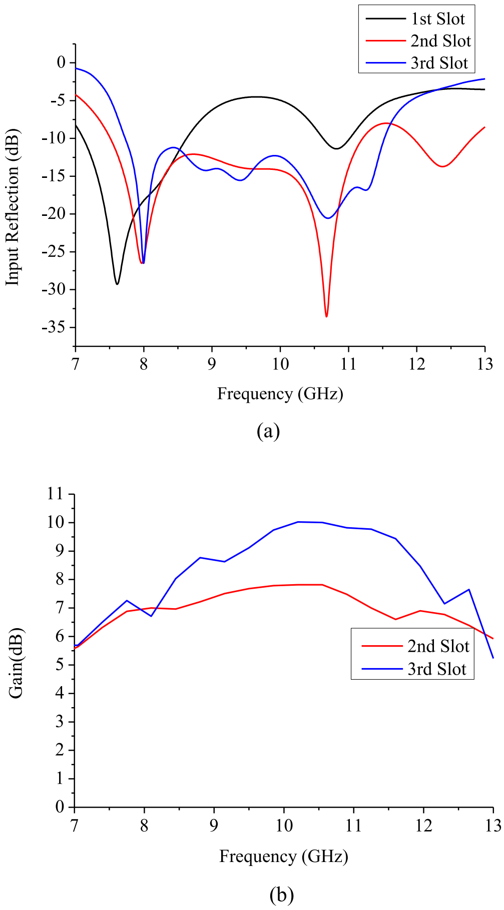
III. PARAMETRIC STUDY

The performance of the proposed antenna is dependent on the excitation of the slots. Instead of placing a hollow cavity at the radiator feed to achieve the impedance bandwidth, a novel approach is adopted. Three slots are simultaneously excited to achieve the required specification. While antennas are always integrated on PCB boards, an extension to the RF ground plane may affect the antenna performance. Hence, a parametric study is performed to analyze the inclusion of slots and extend the proposed antenna’s ground plane size.

A. EFFECT OF SLOTS ON IMPEDANCE MATCHING AND GAIN

The antenna is designed in three steps. In the first iteration, a single tapered slot is excited. The tapering is achieved from equation (1). The antenna resonates from 7.1 GHz to 8.5 GHz. Thus, the cutoff frequency of 7 GHz is established.

A second slot is placed near the feed point and tapering is achieved based on equation (2). Impressively, the bandwidth is extended from 7.5 GHz to 11 GHz. This can be seen in Figure 2a. The gain in the required band is around 7 dB. It is important to note that both the slots share a common ground plane.



(a)

(b)

FIGURE 2. Inclusion of slots in the proposed antenna (a) Simulated input reflection and (b) Simulated Gain.

TABLE 1. Performance metrics of proposed tri-slot antenna.

Slot	Width (W)	Length (L)	-10 dB bandwidth Frequency (GHz)	Simulated Gain (dB)
Single	35	21	7.5-8	4.5-6
Double	35	21	7.5-11	7-7.5
Triple	50	21	7.8-11.8	8-9.5

To improve the gain and impedance bandwidth for the RADAR application, a third slot is placed and designed using equation (3). With the placement of the third slot, a stub is also placed on the microstrip feed line to achieve impedance matching. It can be seen in Figure 2a that the impedance bandwidth is adjusted from 7.8-11.8 GHz and the gain is enhanced by around 2.5 dB. Hence, the average gain achieved is approximately 8.5 dB in the required band. The design steps of the proposed antenna are given in Table 1.

Table 1 shows the performance metrics achieved by the proposed tri-slot antenna. The versatility in terms of the profile of the antenna can be seen in Table 1. For a miniaturized case, a two-slot antenna has a very low footprint with acceptable operating bandwidth and moderate gain, which can be considered in small form factor devices. On the other hand, an extension in width of the antenna to include the third slot further enhances the gain.

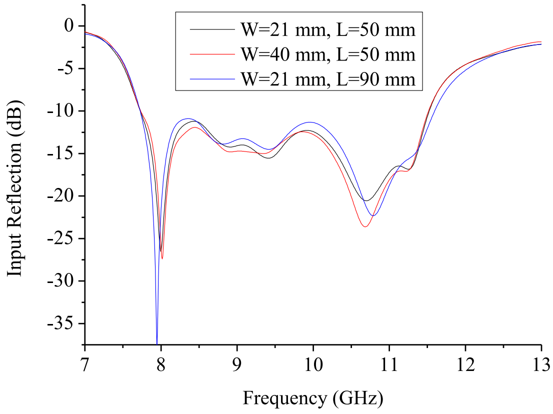


FIGURE 3. Effect on impedance matching due to the extension of the ground plane along the width and length.

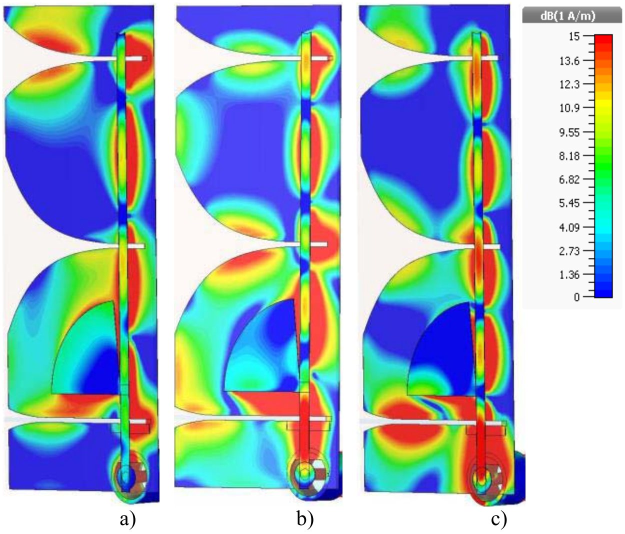
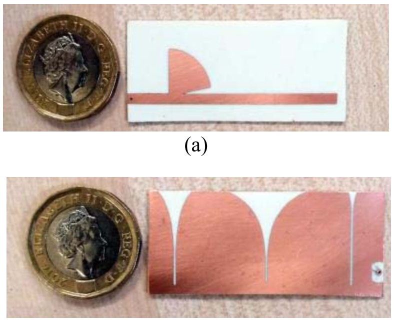


FIGURE 4. Simulated Current distribution (a) 7.5 GHz, (b) 9.5 GHz and c) 10.5 GHz.

B. EFFECT OF GROUND ON IMPEDANCE MATCHING

Contrary to the patch antenna, the ground plane of the CVA act as the main radiator. Energy is coupled from the microstrip line to the slot in the ground plane. Hence modification and/or extension to the ground plane can alter both impedance and gain of the CVA. The proposed antenna design can be considered as a ground-independent slot antenna. This feature has never been incorporated in any of the existing antenna designs. It is evident from Figure 3 that increasing the parameter ‘E_{4m}’ along length ‘L’ and/or ‘W_1’ along the width of the proposed tri-slot design, the impedance matching of the antenna is not affected at all. The length extension is performed from the edge of the third slot. This is useful in the case where the antenna needs to be integrated with the transceiver and an extension to the ground plane is imperative to accommodate various components.

The surface current distribution of the proposed antenna is shown in Figure 4. The red region offers higher


(a)

(b)

FIGURE 5. Fabricated: (a) Top view and (b) Bottom View.

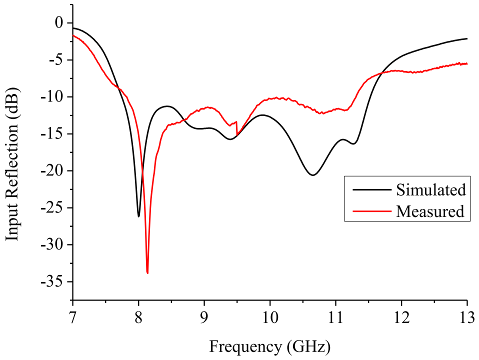


FIGURE 6. Reflection coefficient: Simulated and measured results of the proposed tri-slot Vivaldi antenna.

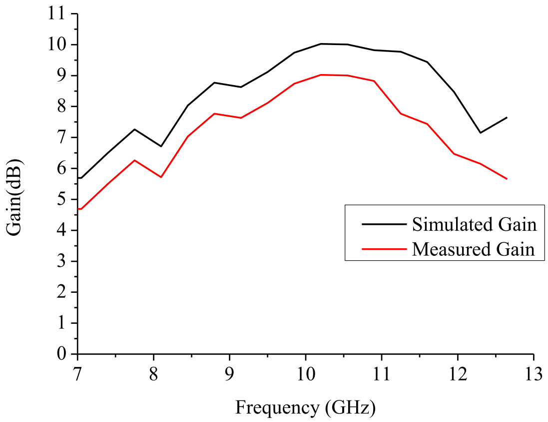
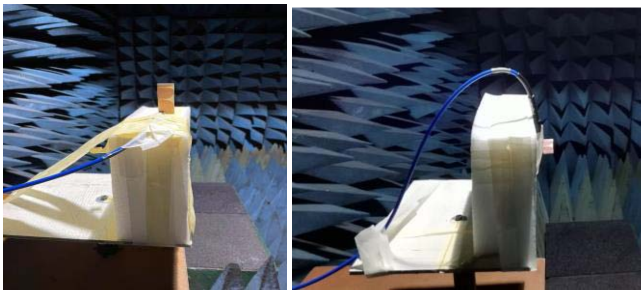
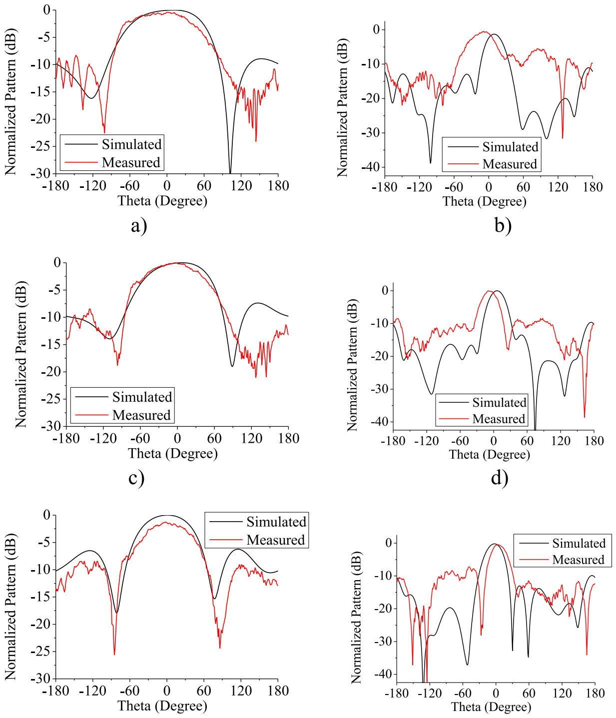


FIGURE 7. Gain of the proposed antenna.


a)

b)

FIGURE 8. Measurement setup of the proposed antenna: a) vertical polarized and b) horizontal polarized.



a)

b)

c)

d)

e)

f)

FIGURE 9. Normalized Radiation patterns of proposed antenna: a) Vertical co-polarized at 9 GHz, b) Horizontal co-polarized at 9 GHz, c) Vertical co-polarized at 10 GHz, d) Horizontal co-polarized at 10 GHz, e) Vertical co-polarized at 11 GHz and f) Horizontal co-polarized at 11 GHz.

current concentration areas. Each slot by itself acts as an independent radiator and contributes to various resonances. It can be seen in Figure 4a that the third slot is excited at the lower frequency band of 7.5 GHz while in Figure 4b, the middle slot generates the frequency band of 9.5 GHz. The second slot located near the feed point creates a resonance of 10.5 GHz. Thus, altogether a wider operating bandwidth is achieved.

IV. RESULTS AND DISCUSSION

Figure 5 shows the prototype of the proposed antenna. The measurement of the proposed antenna has been carried out using the N5230C vector network analyzer (VNA). The simulated and measured S-parameters of the proposed antenna are shown in Figure 6. As seen in the figure, a good agreement between the simulated and measured results has been obtained.

The simulated and measured gain of the proposed antenna is shown in Figure 7. The measured gain follows the simulated gain curve. Due to a minimum number of points, interpolation has been applied to smoothen the gain curve. The antenna mounting positions is illustrated in Figure 8. Further, Figure 9 shows the simulated and measured normalized gain pattern of the proposed antenna. The radiation patterns are along the end-fire direction. As discussed earlier, the directionality of the radiation pattern is due to the array behavior of the antenna due to inter-slot spacing of half-wavelength at the centre frequency of 10 GHz. Consequently, this results in an improvement in the overall gain.

V. CONCLUSION

This article presents the design, implementation and measurement of a tri-slot Vivaldi antenna for RADAR and RF sensing applications. The proposed antenna design is fed using a microstrip to slot line transition with a stub for impedance matching. The design is versatile and can be adapted for any form factor device. The ground plane extension does not affect the impedance and gain properties of the antenna. Additionally, the radiation pattern is also directional making it suitable to be used in Phased array applications. The antenna has a -10 dB impedance bandwidth of 4 GHz at the centre frequency of 10 GHz. The measured average gain of the antenna is around 8.5 dB in the required band.

REFERENCES

[1] X. Yang *et al.*, “Freezing of gait detection considering leaky wave cable,” *IEEE Trans. Antennas Propag.*, vol. 67, no. 1, pp. 554–561, Jan. 2019.

[2] C. Gouveia, C. Loss, Z. Raida, J. Lacik, P. Pinho, and J. Vieira, “Textile antenna array for bio-radar applications,” in *Proc. 23rd Int. Microw. Radar Conf. (MIKON)*, 2020, pp. 315–319.

[3] X. Yang *et al.*, “Contactless finger tapping detection at C-band,” *IEEE Sensors J.*, vol. 21, no. 4, pp. 5249–5258, Feb. 2021.

[4] S. A. Shah and F. Fioranelli, “RF sensing technologies for assisted daily living in healthcare: A comprehensive review,” *IEEE Aerosp. Electron. Syst. Mag.*, vol. 34, no. 11, pp. 26–44, Nov. 2019.

[5] P. J. Gibson, “Vivaldi aerial,” in *Proc. Eur. Microw. Conf.*, 1979, pp. 101–105.

[6] E. Gazit, “Improved design of the Vivaldi antenna,” *IEE Proc. H Microw. Antennas Propag.*, vol. 135, no. 2, pp. 89–92, 1988.

[7] J. D. S. Langley, P. S. Hall, and P. Newham, “Novel ultrawide-bandwidth Vivaldi antenna with low crosspolarisation,” *Electron. Lett.*, vol. 29, no. 23, pp. 2004–2005, 1993.

[8] X. Li, Y. Xu, H. Wang, Y. Zhang, and G. Lv, “Low cross-polarization antipodal tapered slot antenna with gain bandwidth enhancement for UWB application,” *J. Comput. Electron.*, vol. 17, no. 1, pp. 442–451, 2018.

[9] M. Moosazadeh, “High-gain antipodal Vivaldi antenna surrounded by dielectric for wideband applications,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 8, pp. 4349–4352, Aug. 2018.

[10] E. G. Tianang, M. A. Elmansouri, and D. S. Filipovic, “Ultra-wideband lossless cavity-backed Vivaldi antenna,” *IEEE Trans. Antennas Propag.*, vol. 66, no. 1, pp. 115–124, Jan. 2018.

[11] F. Wan, J. Chen, and B. Li, “A novel ultra-wideband antipodal Vivaldi antenna with trapezoidal dielectric substrate,” *Microw. Opt. Technol. Lett.*, vol. 60, no. 2, pp. 449–455, 2018.

[12] J. Eichenberger, E. Yetisir, and N. Ghalichechian, “High-gain antipodal Vivaldi antenna with pseudoelement and notched tapered slot operating at (2.5 to 57) GHz,” *IEEE Trans. Antennas Propag.*, vol. 67, no. 7, pp. 4357–4366, Jul. 2019.

[13] A. Karmakar, A. Bhattacharjee, A. Saha, and A. Bhawal, “Design of a fractal inspired antipodal Vivaldi antenna with enhanced radiation characteristics for wideband applications,” *IET Microw. Antennas Propag.*, vol. 13, no. 7, pp. 892–897, 2019.

[14] M. Sun, Z. N. Chen, and X. Qing, “Gain enhancement of 60-GHz antipodal tapered slot antenna using zero-index metamaterial,” *IEEE Trans. Antennas Propag.*, vol. 61, no. 4, pp. 1741–1746, Apr. 2013.

[15] M. Amiri, F. Tofigh, A. Ghafoorzadeh-Yazdi, and M. Abolhasan, “Exponential antipodal Vivaldi antenna with exponential dielectric lens,” *IEEE Antennas Wireless Propag. Lett.*, vol. 16, pp. 1792–1795, 2017.

[16] S. R. Best, “The significance of ground-plane size and antenna location in establishing the performance of ground-plane-dependent antennas,” *IEEE Antennas Propag. Mag.*, vol. 51, no. 6, pp. 29–43, Dec. 2009.

[17] M. Abbak, M. N. Akinci, M. Çayören, and I. Akduman, “Experimental microwave imaging with a novel corrugated Vivaldi antenna,” *IEEE Trans. Antennas Propag.*, vol. 65, no. 6, pp. 3302–3307, Jun. 2017.

[18] G. K. Pandey and M. K. Meshram, “A printed high gain UWB Vivaldi antenna design using tapered corrugation and grating elements,” *Int. J. RF Microw. Comput.-Aided Eng.*, vol. 25, no. 7, pp. 610–618, 2015. [Online]. Available: https://doi.org/10.1002/mmce.20899

[19] M. Farooq, S. Fatima, and H. M. Cheema, “A wideband miniaturized tapered slot Vivaldi antenna,” in *Proc. IEEE Int. Symp. Antennas Propag. North Amer. Radio Sci. Meeting*, 2020, pp. 597–598.

[20] K. S. Yngvesson, D. H. Schaubert, T. L. Korzeniowski, E. L. Kollberg, T. Thungren, and J. F. Johansson, “Endfire tapered slot antennas on dielectric substrates,” *IEEE Trans. Antennas Propag.*, vol. AP-33, no. 12, pp. 1392–1400, Dec. 1985.