High-gain UWB elliptical and circular slotted antipodal Vivaldi antenna for through wall detection

Sajjad Ahmed[1,2], Norshidah Katiran[1], Ariffuddin Joret[1,2], Shaharil Mohd Shah[1], Arslan Ahmed[1], Najwanisa Tusin[1,2]
[1]Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia
[2]Internet of Things Focus Group, Universiti Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia

Article Info

Article history:

Received Jan 25, 2024
Revised Feb 18, 2024
Accepted Mar 20, 2024

Keywords:

Antipodal Vivaldi
Elliptical and circular slotted
High gain
Through-wall detection systems
Ultra-wideband

ABSTRACT

The paper describes a high-gain ultra-wideband (UWB) elliptical and circular slotted antipodal Vivaldi antenna (ECS-AVA) that is designed for through-wall detection systems. The antenna flares are loaded with elliptical and circular slots to improve the gain and broaden the bandwidth. To validate the efficacy of the designed antenna, a prototype of ECS-AVA is fabricated and subjected to measurements. The experimental findings suggest that the designed antenna can handle signals effectively across a range from 3.1 GHz to 10.6 GHz, as shown by its measured impedance bandwidth, with $|S11| \leq -10$ dB. The obtained measurements results are consistent with the results of the CST simulation. The proposed antenna exhibits improved radiation patterns in the UWB band with peak gain values ranging from 4.8 dB to 11.9 dB.

Corresponding Author:

Norshidah Katiran
Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM)
Johor, Malaysia
Email: norshida@uthm.edu.my

1. INTRODUCTION

Ultra-wideband (UWB) is an advanced radio technology that transmits large data volumes over a wide frequency spectrum. In 1893, Hertz initiated the initial experiments on a UWB wireless communication system [1] and later it was authorized for commercial and research use by the FCC in 2002 [2]. The technology offers benefits such as high data rate, low power utilization, obstacle penetration, low cost-implementation, and time resolution [3], [4] making it a promising technology for various applications. UWB technology has gained popularity for use in through-wall detection systems [5], [6], which use electromagnetic (EM) waves to detect targets behind walls. These systems have wide applications in rescue, security, and surveillance [7]-[9]. The transmitter antenna transmits EM waves that penetrate the wall, causing the target to be struck and reflected back to the receiving antenna. Using signal processing techniques, the reflected energy is analyzed to generate an image of the target behind the walls. These systems are particularly useful for detecting metal-based explosive substances in busy public spaces [10].

Research on designing UWB antennas for through-wall detection systems is expanding, with the Vivaldi antenna being the preferred choice due to its small size, high gain, wide bandwidth, high directivity, low side lobes, and end-fire radiation [11], [12], making it a suitable solution for such applications. In 1979, Gibson [13] came up with the Vivaldi antenna, named after the famous violin composer Antonio Vivaldi. Vivaldi antennas can be categorized into Coplanar-VA, Antipodal-VA, and Balanced-AVA. The radiating structure and feed line are the main components. The AVA antenna, developed by Gazit [14] in 1988, offers minimal distortion, high gain, and high directivity. The two-layer structure, called the antipodal Vivaldi, provides high gain and directivity.

AVA utilizes slot structures with various shapes and sizes to enhance performance [15]. These structures restrict lower cut-off frequencies, minimize side lobe levels, and maximize main lobe levels [16]. Elliptical and circular slots improve gain, bandwidth, and return loss, and work as resistive loading, directing maximum field toward the slots, and enhancing radiation characteristics [17]. An AVA with an elliptical slot structure [18] was designed for UWB applications, achieving a peak gain of 11.04 dBi with a reflection coefficient exceeding -10 dB. Another high-gain UWB AVA with an elliptical slot structure was reported in [19], with symmetrical elliptical slots on the two patches, achieving a maximum gain of 11.3 dB. Muniyasamy and Rajakani [20] circular slots are loaded on flares of AVA to enhance the bandwidth.

In this paper, a high-gain UWB AVA antenna using elliptical and circular slots is proposed for through-wall detection systems. The antenna incorporates elliptical and circular slots on its flares to enhance gain and broaden bandwidth. The simulation results align with the measured results, indicating that the proposed antenna offers enhanced radiation properties in the frequency band of 3.1 GHz to 10.6 GHz.

2. ELLIPTICAL AND CIRCULAR SLOTTED ANTIPODAL VIVALDI ANTENNA (ECS-AVA) DESIGN

The AVA is constructed on Rogers 5880 material with an elliptical and circular slotted pattern. The radiating element features a thickness of 1.58 mm. The antenna's excitation port employs a microstrip line with a width (Wy) of 4.60 mm and an impedance of 50 Ω. The Rogers 5880 material is chosen for its tangential loss properties, contributing to high gain [21]. The ECS-AVA is constructed using two elliptical curvatures of identical dimensions as demonstrated in [22], [23]. The antenna is composed of two foundational components: the feed line, responsible for signal propagation, and the radiating flared wings, which facilitate the emission of EM waves. Theoretically, the Vivaldi antenna's infinitely broad high-frequency spectrum can be computed by applying (1) to (4) with consideration to its width and the effective dielectric constant (εeff), as elucidated in reference [22].

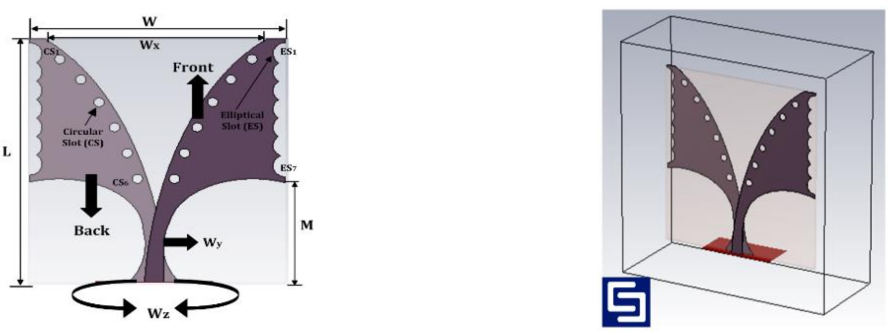
$$fmin = \frac{c}{2W\sqrt{\varepsilon_{eff}}} \tag{1}$$

$$z_o = \frac{60}{\sqrt{\varepsilon_{eff}}} ln\left(\frac{8h}{w} + \frac{w}{4h}\right) for \left(\frac{w}{h}\right) < 1 \tag{2}$$

$$z_o = \frac{60}{\sqrt{\varepsilon_{eff}}} ln\left(\frac{8h}{w} + \frac{w}{4h}\right) for \left(\frac{w}{h}\right) < 1 \tag{3}$$

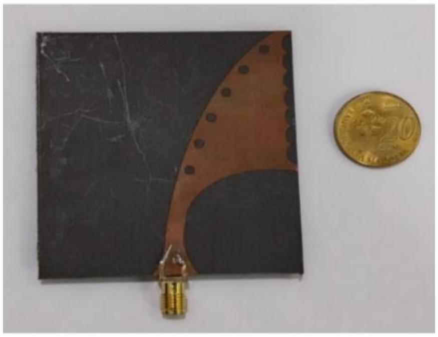
$$z_o = \frac{120\pi}{\sqrt{\varepsilon_{eff}}\left[\frac{w}{h} + 1.393 + \frac{2}{3}ln\left(\frac{w}{h} + 1.444\right)\right]} \quad for \left(\frac{w}{h}\right) \geq 1 \tag{4}$$

The slot structure is utilized in AVA to enhance the antenna's performance [17]. The AVA flares have six circular slots of the same size. Additionally, seven elliptical slots with variable dimensions are implemented on the AVA flares. The different layouts of the ECS-AVA are presented in Figure 1. Figure 1(a) illustrates the geometrical layout and Figure 1(b) illustrates the CST layout. Additionally, Figure 2 displays the fabricated ECS-AVA prototype, Figure 2(a) back view and Figure 2(b) front view. The optimized dimensions of the ECS-AVA antenna are presented in Table 1.

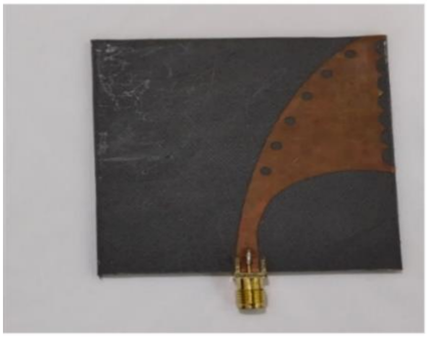


(a) (b)

Figure 1. ECS-AVA antenna layout (a) geometric layout and (b) CST layout



(a)



(b)

Figure 2. Fabricated ECS-AVA prototype (a) back and (b) front

Table 1. Dimensions of ECS-AVA

Parameters	Value (mm)
W	61
L	65.80
D	13.50
Wx	55
Wy	4.60
Wz	11.80
CS (1-6) (L & W)	2.50
ES (2-6) (W)	5
ES (1 & 7) (W)	5.80

3. MEASUREMENT AND SIMULATION RESULTS

The layout of this section is schematized as follows: subsection 3.1 describes the measured and simulated reflection coefficient and voltage standing wave ratio (VSWR) of ECS-AVA. Next, subsection 3.2 discusses the simulated polar and 3D radiation pattern of ECS-AVA. Continuing, subsection 3.3 investigates the simulated gain of ECS-AVA at UWB frequencies. Lastly, in subsection 3.4, we'll compare how well the proposed antenna performs compared to antennas discussed in the literature.

3.1. Reflection coefficient and VSWR

Figure 3 and Figure 4 display the measured and simulated results of the reflection coefficient (S_{11}) and VSWR, respectively, in the UWB frequency range of the designed antenna. The simulated reflection coefficient and simulated VSWR do not meet the specified standard levels between 4.1 GHz and 4.6 GHz. The measured results of S_{11} and VSWR were obtained using a vector network analyzer (VNA) R&S (ZNB20). Notably, irregularities in the S_{11} and VSWR patterns are observed between 9 GHz and 10.6 GHz, which are linked to issues with connectors and cables. The achieved measured results indicate S_{11} values surpassing -10 dB and VSWR values below 2.

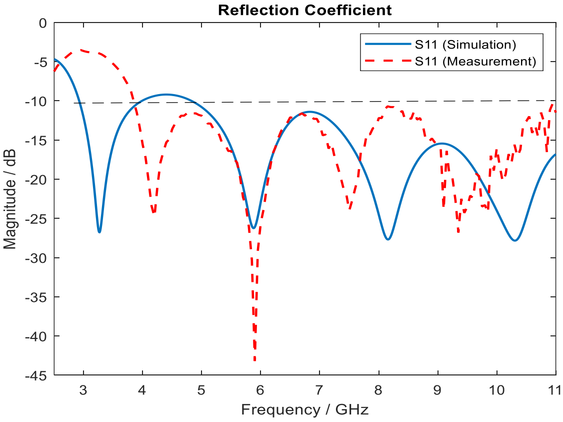


Figure 3. Simulated and measured S_{11}

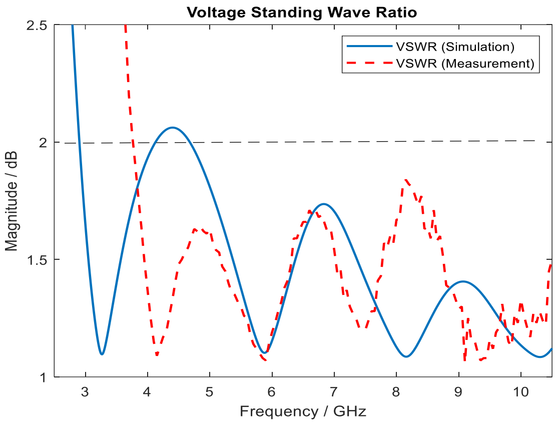


Figure 4. Simulated and measured VSWR

3.2. Polar and 3D far-field radiation patterns

Figure 5 illustrates the simulated polar patterns of ECS-AVA at frequencies; 4 GHz (Figure 5(a)), 6 GHz (Figure 5(b)), 8 GHz (Figure 5(c)), and 10 GHz (Figure 5(d)). At these specified frequencies, the designed antenna displays outstanding characteristics in terms of side lobe (SLL), angular width, and directivity in its polar pattern. Additionally, Figure 6 presents the three-dimensional far-field radiation pattern of ECS-AVA at frequencies; 4 GHz (Figure 6(a)), 6 GHz (Figure 6(b)), 8 GHz (Figure 6(c)), and 10 GHz (Figure 6(d)). The proposed antenna exhibits high gain at the mentioned frequencies, highlighting its capability to detect targets through walls.

3.3. Gain

Table 2 illustrates the gain of ECS-AVA from 3.5 GHz to 10.5 GHz. The antenna's performance was evaluated, revealing a maximum gain of 11.9 dB at 10 GHz, with a minimum gain of 4.8 dB. Figure 7 shows the simulated gain of ECS-AVA in the H-plane at 10 GHz, which is around 12 dB. Additionally, Figure 8 shows the simulated gain of ECS-AVA over the UWB band, which starts from 3.1 GHz to 10.6 GHz. It is observed that the proposed antenna gains increase between 7 GHz and 10.5 GHz frequencies. Further, the simulated peak gain is obtained at 10 GHz frequency, which is around 12 dB. Therefore, the proposed antenna has good radiation characteristics.

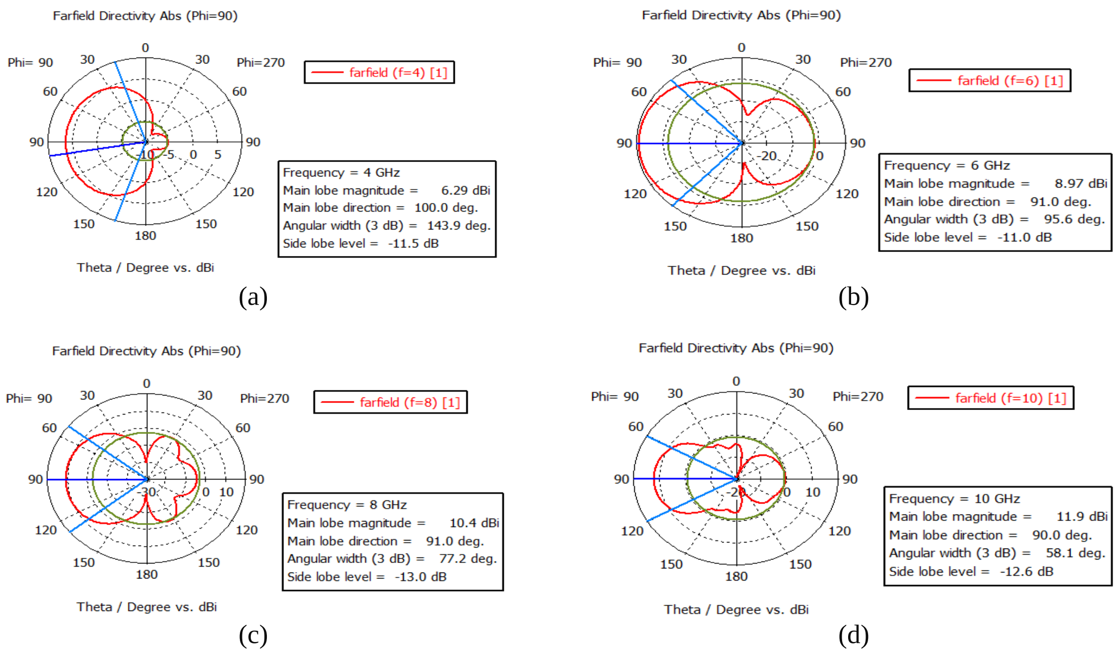
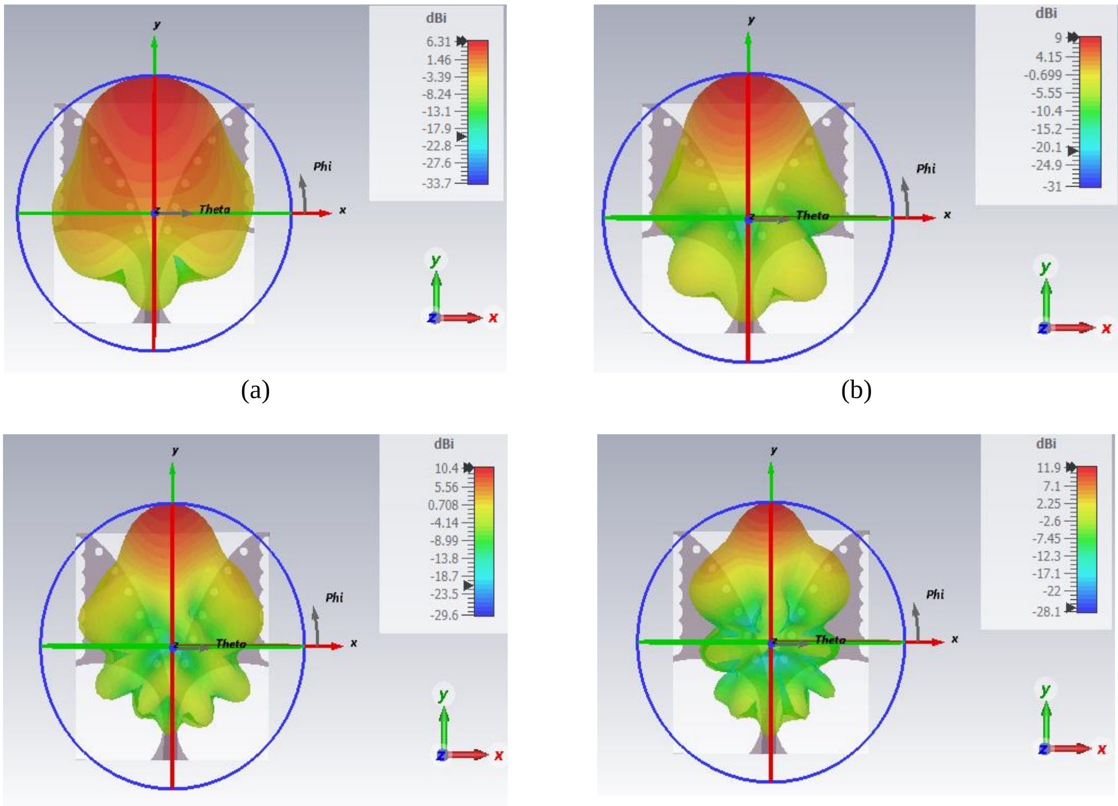


Figure 5. Polar radiation pattern of ECS-AVA, (a) 4 GHz, (b) 6 GHz, (c) 8 GHz, and (d) 10 GHz



(a) (b)

(c) (d)

Figure 6. 3D far-field radiation pattern of ECS-AVA, (a) 4 GHz, (b) 6 GHz, (c) 8 GHz, and (d) 10 GHz

Table 2. Gain of ECS-AVA

Frequency (GHz)	Gain (dB)
3.5	4.8
4	6.3
5	7.5
6	9
7	10.4
8	10.4
9	10.6
10	11.9
10.5	11.8

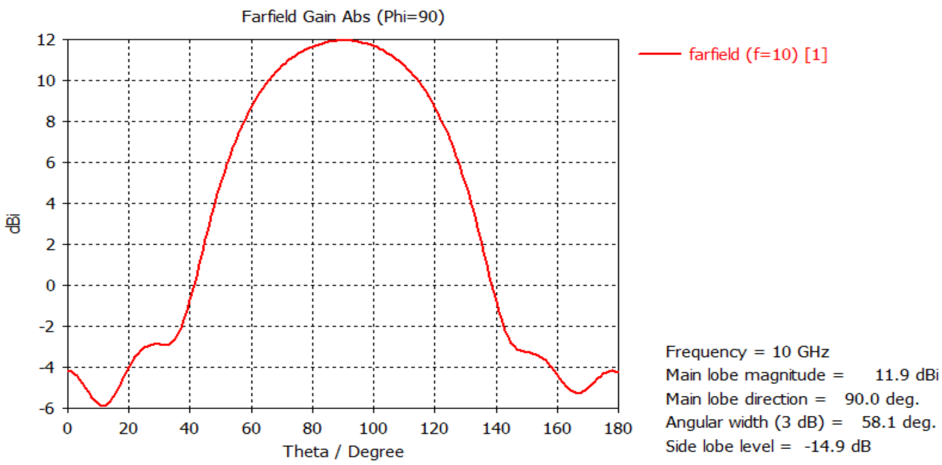


Figure 7. Simulated gain of ECS-AVA in H-plane at 10 GHz

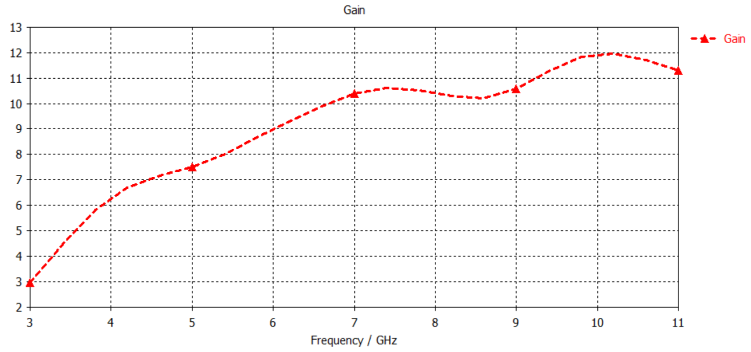


Figure 8. Simulated gain of ECS-AVA over UWB band

3.4. Comparative analysis

The consistent gain exhibited by the ECS-AVA antenna renders it valuable for through-wall detection systems. It operates in the UWB band, offering a wide range of frequencies and the ability to see through walls effectively. For better detection behind walls, the antenna needs to have less signal loss. The antenna performs well when the S_{11} value is -10 or less, resulting in increased gain and better penetration. Table 3 compares the Vivaldi antenna with other studies, considering antenna dimension, material, peak gain, working frequency, and how well it fits the proposed work. Table 3 indicates that the ECS-AVA has a better-reported gain when compared to studies conducted earlier.

Table 3. Contrasting the prior Vivaldi antenna studies with the newly proposed antenna design

Reference	Material	Peak gain (dB)	Frequency (GHz)	Dimensions	Application
[24]	Rogers RT6010	5.5	1-6	30.32×60×5.76 mm^3	Microwave imaging
[25]	Rogers 4003C	8	5-20	56×28×1.6 mm^3	RADAR systems
[26]	FR4	8.2	1.9 -12	128×70 mm^2	Through-wall radar (TWR)
[27]	FR4	7.66	1 - 4	91×108 mm^2	See through the wall
This work	Rogers 5880	11.9	3.1-10.6	66×60.80 mm^2	Through wall detection

4. CONCLUSION

In this paper, a UWB elliptical and circular slotted antipodal Vivaldi antenna (ECS-AVA) design for through-wall detection systems has been investigated. The incorporation of elliptical and circular slots on the arms of the proposed design has significantly enhanced its performance in key aspects such as gain, bandwidth, reflection coefficient, and VSWR. Experimental findings reveal that the proposed antenna achieves (S_{11}) of less than -10 dB and a VSWR value below 2 dB, with an impedance bandwidth spanning from 3.1 to 10.6 GHz. The obtained measurements align well with the simulated results. The designed antenna shows improved radiation patterns in the UWB band with a maximum simulated gain of around 12 dB. The simulated and measured results indicate that the proposed UWB (ECS-AVA) antenna could be a good candidate for through-wall detection systems.

ACKNOWLEDGEMENTS

Communication of this research is made possible through monetary assistance by Universiti Tun Hussein Onn Malaysia and the UTHM Publisher's Office via publication Fund E15216.

REFERENCES

[1] B. Allen *et al.*, "Ultra wideband: technology and future perspectives," *International Workshop on Convergent Technologies (IWCT)*, 2005.
[2] F. C. Commission, "Revision of Part 15 of the Commission's Rules Regarding Ultra-Wideband Transmission Systems," *First Report and Order in ET …*, no. FCC02-48, pp. 1–118, 2002, [Online]. Available: http://ci.nii.ac.jp/naid/10011635689/
[3] M. Elsanhoury *et al.*, "Precision Positioning for Smart Logistics Using Ultra-Wideband Technology-Based Indoor Navigation: A Review," *IEEE Access*, vol. 10, pp. 44413–44445, 2022, doi: 10.1109/ACCESS.2022.3169267.
[4] I. D. Saiful Bahri, Z. Zakaria, N. A. Shairi, and N. Edward, "A novel UWB reconfigurable filtering antenna design with triple band-notched characteristics by using u-shaped coppers," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 14, no. 1, pp. 267–275, Apr. 2019, doi: 10.11591/ijeecs.v14.i1.pp267-275.
[5] T. V. Hoang *et al.*, "Frequency Selective Computational Through Wall Imaging Using a Dynamically Reconfigurable Metasurface Aperture," *IEEE Open Journal of Antennas and Propagation*, vol. 3, pp. 353–362, 2022, doi: 10.1109/OJAP.2022.3161128.

[6] P. Thottempudi and V. Kumar, "Experimental study of through the wall imaging for the detection of vital life signs using SFWR," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 24, no. 2, pp. 825–830, Nov. 2021, doi: 10.11591/ijeecs.v24.i2.pp825-830.

[7] A. Randazzo *et al.*, "A Two-Step Inverse-Scattering Technique in Variable-Exponent Lebesgue Spaces for Through-the-Wall Microwave Imaging: Experimental Results," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 9, pp. 7189–7200, Sep. 2021, doi: 10.1109/TGRS.2021.3052608.

[8] K. Mu, T. H. Luan, L. Zhu, L. X. Cai, and L. Gao, "A Survey of Handy See-Through Wall Technology," *IEEE Access*, vol. 8, pp. 82951–82971, 2020, doi: 10.1109/ACCESS.2020.2991201.

[9] A. Fedeli, M. Pastorino, C. Ponti, A. Randazzo, and G. Schettini, "Through-the-Wall Microwave Imaging: Forward and Inverse Scattering Modeling," *Sensors*, vol. 20, no. 10, p. 2865, May 2020, doi: 10.3390/s20102865.

[10] J. Liu, K. Zhang, Z. Sun, Q. Wu, W. He, and H. Wang, "Concealed Object Detection and Recognition System Based on Millimeter Wave FMCW Radar," *Applied Sciences*, vol. 11, no. 19, p. 8926, Sep. 2021, doi: 10.3390/app11198926.

[11] S. Joof, S. Dogu, E. Bilgin, and M. Cayoren, "An Antipodal Vivaldi Antenna Design for Torso Imaging in a Coupling Medium," in *2021 15th European Conference on Antennas and Propagation (EuCAP)*, Mar. 2021, pp. 1–3, doi: 10.23919/EuCAP51087.2021.9411436.

[12] H. I. Hamd, I. H. Ali, and A. M. Ahmed, "Design and simulation double Ku-band Vivaldi antenna," *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 25, no. 1, pp. 396–403, Jan. 2022, doi: 10.11591/ijeecs.v25.i1.pp396-403.

[13] P. J. Gibson, "The Vivaldi Aerial," in *1979 9th European Microwave Conference*, Sep. 1979, pp. 101–105, doi: 10.1109/EUMA.1979.332681.

[14] E. Gazit, "Improved design of the Vivaldi antenna," *IEE Proceedings H Microwaves, Antennas and Propagation*, vol. 135, no. 2, p. 89, 1988, doi: 10.1049/ip-h-2.1988.0020.

[15] C.-F. Liang and C.-H. Cheng, "A Miniaturized Antipodal Vivaldi Antenna with Flat Gain for RF Energy Harvesting," in *2021 IEEE MTT-S International Wireless Symposium (IWS)*, May 2021, pp. 1–3, doi: 10.1109/IWS52775.2021.9499695.

[16] A. M. De Oliveira, M. B. Perotoni, S. T. Kofuji, and J. F. Justo, "A Palm Tree Antipodal Vivaldi Antenna With Exponential Slot Edge for Improved Radiation Pattern," *IEEE Antennas and Wireless Propagation Letters*, vol. 14, pp. 1334–1337, 2015, doi: 10.1109/LAWP.2015.2404875.

[17] A. Bhattacharjee, A. Bhawal, A. Karmakar, A. Saha, and D. Bhattacharya, "Vivaldi antennas: a historical review and current state of art," *International Journal of Microwave and Wireless Technologies*, vol. 13, no. 8, pp. 833–850, Oct. 2021, doi: 10.1017/S1759078720001415.

[18] Xiaole Kang and Zengrui Li, "A modified UWB antipodal Vivaldi antenna with improved radiation characteristics," in *2015 IEEE 6th International Symposium on Microwave, Antenna, Propagation, and EMC Technologies (MAPE)*, Oct. 2015, pp. 120–122, doi: 10.1109/MAPE.2015.7510279.

[19] Z.-F. Yin, X.-X. Yang, and T. Lou, "A High Gain UWB Vivaldi Antenna Loaded with Elliptical Slots," in *2018 International Applied Computational Electromagnetics Society Symposium - China (ACES)*, Jul. 2018, pp. 1–2, doi: 10.23919/ACESS.2018.8669383.

[20] A. Muniyasamy and K. Rajakani, "UWB radar cross section reduction in a compact antipodal Vivaldi antenna," *AEU - International Journal of Electronics and Communications*, vol. 99, pp. 369–375, Feb. 2019, doi: 10.1016/j.aeue.2018.12.020.

[21] J. G. Vera-Dimas, M. Tecpoyotl-Torres, V. Grimalsky, S. V. Koshevaya, and M. Torres-Cisneros, "Analysis of Equivalent Antennas in RT Duroid 5880 and 5870 for GPS Operation Frequency," in *2010 IEEE Electronics, Robotics and Automotive Mechanics Conference*, Sep. 2010, pp. 754–758, doi: 10.1109/CERMA.2010.133.

[22] C. B. Hien, H. Shirai, and D. N. Chien, "Analysis and design of antipodal Vivaldi antenna for UWB applications," in *2014 IEEE Fifth International Conference on Communications and Electronics (ICCE)*, Jul. 2014, pp. 391–394, doi: 10.1109/CCE.2014.6916735.

[23] K. Aravinda Reddy, S. Natarajamani, and S. K. Behera, "Antipodal Vivaldi antenna UWB antenna with 5.5GHz band-notch characteristics," in *2012 International Conference on Computing, Electronics and Electrical Technologies (ICCEET)*, Mar. 2012, pp. 821–824, doi: 10.1109/ICCEET.2012.6203866.

[24] F. Parveen and P. Wahid, "Design of Miniaturized Antipodal Vivaldi Antennas for Wideband Microwave Imaging of the Head," *Electronics*, vol. 11, no. 14, p. 2258, Jul. 2022, doi: 10.3390/electronics11142258.

[25] K. Premchand, H. Paik, and S. K. Mishra, "Stripline Fed Slotted Edge Balanced Antipodal Vivaldi Antenna for Advanced Radar Applications," *Progress in Electromagnetics Research Letters*, vol. 103, pp. 119–126, 2022, doi: 10.2528/PIERL22012806.

[26] A. Kuriakose, T. A. George, and A. S, "Improved High Gain Vivaldi Antenna Design for Through-wall Radar Applications," in *2020 International Symposium on Antennas & Propagation (APSYM)*, Dec. 2020, pp. 58–61, doi: 10.1109/APSYM50265.2020.9350711.

[27] V. P. Cam, S. Van Tran, and D. B. Nguyen, "An array of antipodal Vivaldi antenna with genetic optimization," in *2018 International Conference on Advanced Technologies for Communications (ATC)*, Oct. 2018, pp. 142–145, doi: 10.1109/ATC.2018.8587486.

BIOGRAPHIES OF AUTHORS

Sajjad Ahmed received a Master of Engineering in Telecommunication from Mehran University of Engineering and Technology Pakistan in 2017. Currently, he joined the Radio Communications and Antenna Design (RACAD) Laboratory, where he is working towards his PhD degree at Universiti Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia. His research interests include microwave through wall detection and imaging systems, antenna and communication device designing, internet of things (IoT) based systems, and radar system. He can be contacted at email: ge190065@student.uthm.edu.my.

Norshidah Katiran graduated from Universiti Teknologi Malaysia (UTM) with the degree of Bachelor of Electrical Engineering (Telecommunications) in 2001 and obtained her Ph.D. in Electrical Engineering in 2015 from the same university. Currently, she is serving as a senior lecturer at Universiti Tun Hussein Onn Malaysia (UTHM). She is a senior researcher at the Advanced Telecommunication Research Center (ATRC), Universiti Tun Hussein Onn Malaysia. Her research interests include resource allocation for wireless networks, cooperative communications, and MIMO networks. She can be contacted at email: norshida@uthm.edu.my.

Ariffuddin Joret is a senior lecturer at the Faculty of Electrical and Electronic Engineering (FKEE), Universiti Tun Hussein Onn Malaysia (UTHM). He received his first degree at Universiti Teknologi Mara (UiTM) in Electrical and Electronics Engineering. Then, he finished his study in master's degree at Universiti Sains Malaysia (USM) in 2006 with a Master of Science (Electrical and Electronics Engineering) in Neural Networks. In 2018, he graduated with his Ph.D. in the field of signal processing at UTHM. His current research interests include ground penetrating radar, and internet of things (IoT) system development and application. He can be contacted at email: ariff@uthm.edu.my.

Shaharil Mohd Shah obtained his B. Eng in Microwave and Communication from Multimedia University (MMU) in 2002. He received his M.Sc in Microwave Engineering and Wireless Subsystems Design from the University of Surrey, UK in 2004 and pursuing his Ph.D in Communication Engineering from the University of Birmingham, UK before graduating in 2016. He is currently a senior lecturer in the Department of Communication Engineering, Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM). His area of research includes, but not limited to, design of microwave devices, active antennas measurement and nonlinear characterization of active devices. He can be contacted at email: shaharil@uthm.edu.my.

Arslan Ahmed received his Bachelor of Engineering degree in Electronic Engineering from the Quaid-e-Awam University of Engineering, Science, and Technology, Nawabshah, Pakistan in 2015. He received his Master of Engineering degree from Sukkur IBA University, Pakistan in 2020. Currently, He is doing his Ph.D. Degree in Universiti Tun Hussein Onn Malaysia (UTHM), Johor, Malaysia. His current research interest is in THz waveguide characterization, antenna design, and material characterization. He can be contacted at email: arslansohoo33@gmail.com.

Najwanisa Binti Tusin is postgraduate student from Faculty of Electrical and Electronic Engineering (FKEE), UTHM. She obtained her bachelor's degree in Electronic Engineering from Universiti Teknikal Malaysia Melaka and is currently pursuing a Master's degree in Electrical Engineering at Universiti Tun Hussein Onn. Her current research focuses on wireless communication technologies which are related to visible light communication (VLC). She can be contacted at email: he210011@student.uthm.edu.my.