Wideband Antenna with UHF Sensor Applicability for HV Equipment in Smart Grid

S. M. Kayser Azam*
Department of Electrical Engineering, Universiti Malaya
Kuala Lumpur 50603, Malaysia†

Mohamadariff Bin Othman
Department of Electrical Engineering, Universiti Malaya
Kuala Lumpur 50603, Malaysia

Tarik Abdul Latef
Department of Electrical Engineering, Universiti Malaya
Kuala Lumpur 50603, Malaysia

H. A. Illias
Department of Electrical Engineering, Universiti Malaya
Kuala Lumpur 50603, Malaysia

Mohd Fadzil Ain
School of Electrical and Electronic Engineering, Universiti Sains Malaysia
Nibong Tebal 14300, Malaysia

Yazeed Qasaymeh
Department of Electrical Engineering, Majmaah University
Al-Majmaah, 11952, Saudi Arabia
E-mail: kaysereee2k8@gmail.com, mohamadariff@um.edu.my, tariqlatef@um.edu.my, h.illias@um.edu.my, eemfadzil@usm.my, y.qasaymeh@mu.edu.sa
www.um.edu.my

Abstract

Wideband antenna is proposed as an ultra-high frequency (UHF) sensor for high voltage equipment in smart grid. First, an antenna is designed in UHF range with wideband characteristics. Next, another antenna is designed from the first one to further improve its sensor applicability. Both antennas offer sufficient levels of realized gain and total efficiency while radiating with omni-directional patterns. Proposed antennas are compact and suitable to be applied as UHF sensors especially for the faulty-insulation detection in high voltage switchgears and power transformers.

Keywords: Wideband antenna, UHF sensor, partial discharge detection, smart grid.

1. Introduction

Antennas, apart from being the most fundamentally significant components in wireless communication systems, have emerging demands in many applications of next generation technologies. Other than communications, in the 5G-based systems, antennas are utilized for energy harvesting applications as per Ref. 1 and Ref. 2. Recently, antennas are having especial attentions from many researchers for their sensor applications on detecting the insulation faults in high voltage equipment e.g., cables, switchgears, power transformers etc[3-4]. Among the insulation faults, partial discharge (PD) is one of the most potentially dangerous phenomena in high voltage equipment. PD can be detected by many techniques that are mostly based on invasive and direct electrical connections. Since PD signals also appear as electromagnetic signals in the ultra-high frequency (UHF) range, antennas are employed as PD sensors that can detect the PD wirelessly which is highly required for the next generation smart grid system. As a result, instead of using antennas only for communication purposes, UHF antennas are being researched to improve their sensor applicability for detecting the PD[5] in high voltage equipment.

UHF antennas, as sensors for detecting the PD, are designed in a way so that they cover the UHF range as wide as possible and provide sufficient gain. In fact, an UHF antenna should provide more than 2 dBi gain so that weak PD signals are significantly detected[4]. For example, a bio-inspired monopole antenna is developed[5] to detect PD through wideband characteristics with sufficiently high gain. However, the antenna is quite large in physical dimensions which is a major limitation since UHF sensors for PD detection should be compact due to their expected portability or remote integration. A wideband antenna is proposed in Ref. 6 and compared with high frequency current transformer method for the PD detection. Nevertheless, since the antenna gain is not considered by Ref. 6, the antenna used a transmission line method i.e., direct electrical connections which does not fulfil the contactless method of PD detection. Recently, a bare patch antenna and its integrated design with filters are proposed[3] for PD detection. Being a microstrip patch type, antennas in Ref. 3 inherently have no wideband characteristics which is highly required for PD detection in the UHF range. Furthermore, Ref. 3 has not revealed antenna gain information in useful details while antenna radiation patterns in fact are worsened after the filter-antenna technique is applied. As a result, implications found from the Ref. 3 are not much convincing to detect PD sources on practical sites. Another recent work is found in Ref. 4 on wideband antenna design for PD detection. Although authors claimed that the antenna is a microstrip type with wideband and high gain characteristics, it is obvious from the highly distorted monopolar radiation patterns in higher frequency regions that the antenna actually works in the lower frequency region of its bandwidth. Consequently, the entire bandwidth may not accurately detect PD signals in higher frequency regions.

To overcome the major challenges described so far, wideband antenna is proposed by this work for detecting partial discharge in high voltage equipment. Two novel antennas have been introduced with wideband characteristics where both antennas have sufficiently high realized gain throughout their corresponding bandwidth. Purposes of designing two antennas are to first integrate with smart grid technology and then to separate communication bands from the UHF range. Next section of this paper is going to discuss design techniques of proposed antennas. Results obtained from the analysis will be discussed on section 3 before leaving a conclusion on section 4.

2. Design Techniques

Both the 1st antenna and 2nd antenna are designed on the commercial Rogers RT5880 substrate. Computer Simulation Technology (CST) software with 2021 version is utilized for design and simulation purposes. Partial ground plane (PGP) is method adopted for both antennas by applying the microstrip feeding technique[7],

$$w_f = \frac{7.48 \times h}{e^{\left(Z_0 \frac{\sqrt{\varepsilon_r + 1.41}}{87}\right)}} - 1.25 \times t. \quad (1)$$

Here, w_f is the feedline width, h is the substrate height (dielectric), t is the conductor thickness, Z_0 is the characteristic impedance, and ε_r is the relative permittivity of the dielectric substrate.

2.1. *1st Antenna*

Design of the 1st antenna is inspired from the four-leaf clover shape which is a unique variation in the nature.
The step-by-step design technique of the 1st antenna is illustrated in Fig. 1 where four conductive patch elements of circular shapes are utilized to mimic the four-leaf clover shape. Each circle has radius of 15 mm while connecting other three circles at its center to complete the radiating patch design. The substrate has a width (W) of 70 mm and a length (L) of 100 mm. The feedline of a length (l_f) of 50 mm connects the radiating patch from the bottom edge on the top plane. In the PGP, width is same as the substrate width, but the length (l_g) is 49.9 mm from the bottom edge of the ground plane.

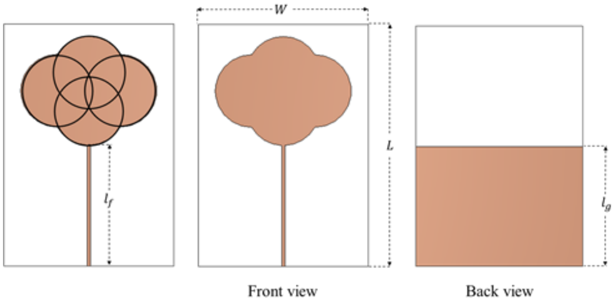


Fig. 1. Design technique (1st antenna).

Based on the design of the 1st antenna, a simulation is performed to observe its S-parameter (return loss) as shown in Fig. 2. Bandwidth ($S_{11} < -10$ dB) of the antenna is found wide due to its unconventional shaped radiating patch over the PGP. A sharp resonance is also found at 1.41 GHz with a return loss of 32.55 dB which is caused by the closest circle near the feedline.

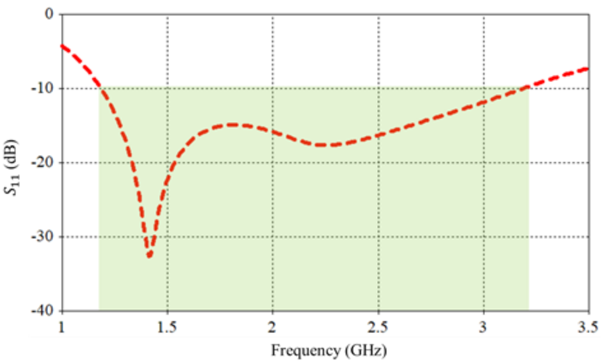
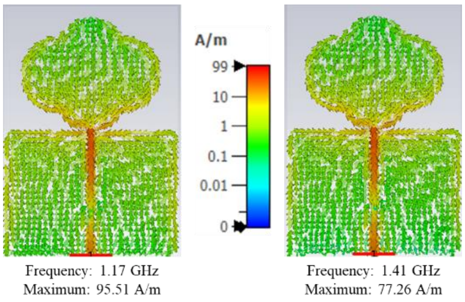
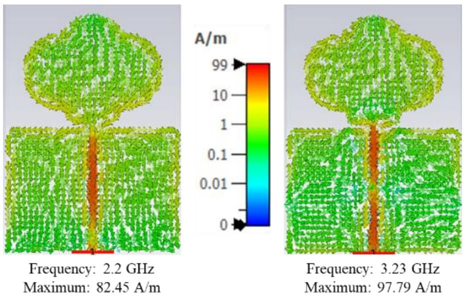


Fig. 2. S-parameter (1st antenna).

Since the S-parameter observation of the 1st antenna reveals that the antenna has a wide bandwidth by mostly covering the UHF range, it obtains the primary requirement of being used as an UHF sensor for PD detection. In Fig. 3, surface current distribution on the 1st antenna is observed where it is found that the closest circle to the feedline accumulates more current at lower frequencies of the UHF range.



(a)



(b)

Fig. 3. Surface current distribution (1st antenna).

2.2. *2nd Antenna*

The 2nd antenna is designed with the same dimensions as the first one except the PGP is truncated for separating the higher frequencies from the original antenna bandwidth. This is to separate the available communication bands i.e., GSM, 3G, Bluetooth, WLAN etc. that can highly affect the incoming PD signals. Fig. 4 shows the design technique of the 2nd antenna.

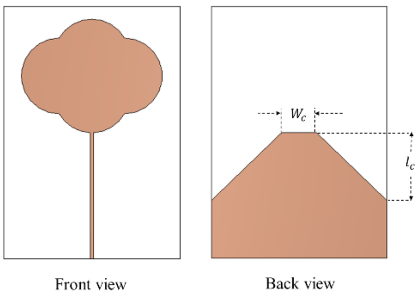


Fig. 4. Design technique (2nd antenna).

From the upper edge on the PGP, at a distance (l_c) of 27 mm, the ground plane is truncated as shown in Fig. 4 by leaving a width (W_c) of 14 mm on the upper edge. This truncated PGP technique greatly affects the bandwidth of the original antenna. As seen from Fig. 5, gradual slopes on both side of the truncated PGP gradually separates the higher frequencies the original bandwidth by leaving a decently wide bandwidth near between 1 GHz to 1.5 GHz. Because there are no commonly available communication bands within this frequency range, this bandwidth adds an extra applicability to the 2nd antenna of being utilized as a UHF sensor for PD detection. In fact, most of the PDs as electromagnetic signals appear within this range as well.

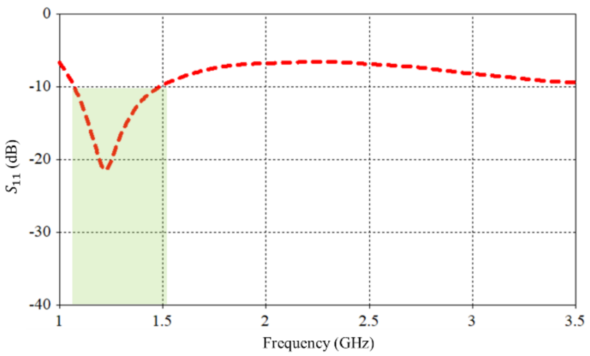


Fig. 5. S-parameter (2nd antenna).

In Fig. 6, surface current distribution of the 2nd antenna is presented, and it is seen that the truncated PGP prevents the current to be accumulated on upper parts of the patch.

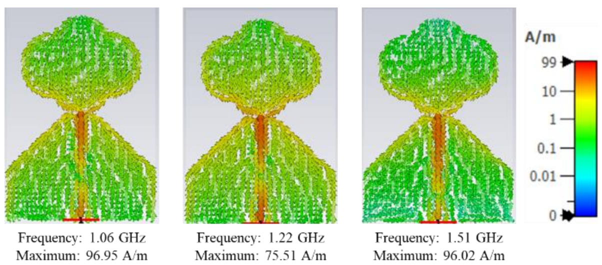


Fig. 6. Surface current distribution (2nd antenna).

3. Results and Discussion

3.1. *1st Antenna*

Based on the electromagnetic simulation on CST software with Hexahedral Transmission Line Method for the time domain solver, results are obtained for both antennas. The simulated results are presented for the VSWR (voltage standing wave ratio), realized gain, radiation pattern, and efficiency of the antenna. In Fig. 7, VSWR is presented for the 1st antenna. It is found that the commercial bandwidth (VSWR<2) of antenna is 2060 MHz from 1.17 GHz to 3.23 GHz frequencies. This largely covers the UHF range for sensing the PD in HV equipment.

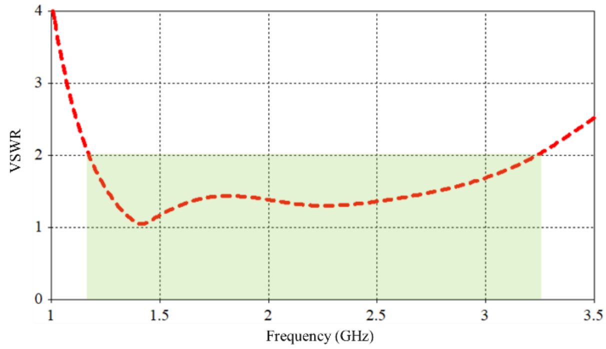
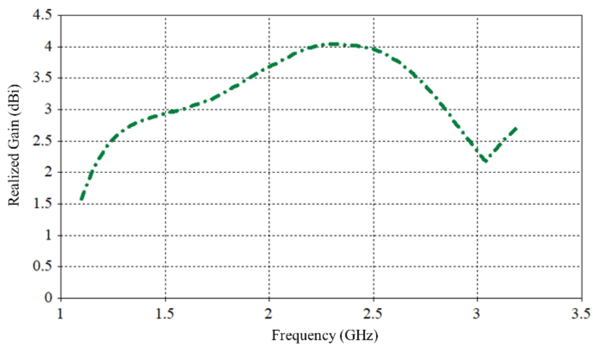
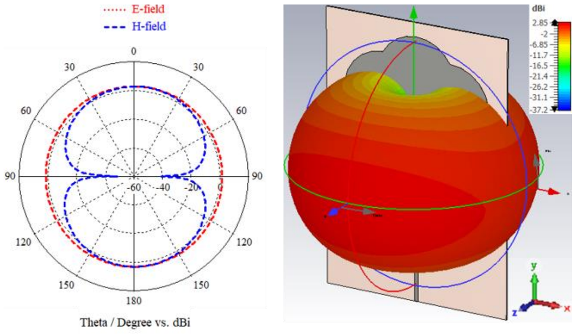


Fig. 7. VSWR (1st antenna).

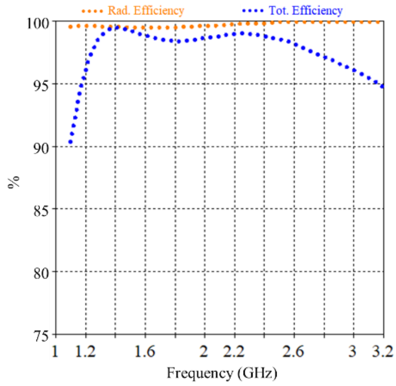
Realized gain is the most significant parameter to be observed prior to detecting PD with UHF antenna since it determines how much the amplitude of the received will be. Figure 8 illustrates the realized gain over frequency, radiation pattern, radiation efficiency, and total efficiency of the 1st antenna. For the 1st antenna, the average value of the realized gain is about 3.21 dBi throughout the entire bandwidth of 2060 MHz from 1.17 GHz to 3.23 GHz. It is clear that the average value of the realized gain for the 1st antenna is much above the expected 2 dBi gain to detect PD signals. The maximum realized gain obtained by the 1st antenna is 4.04 dBi at 2.31 GHz while minimum realized gain is obtained as 1.65 dBi at 1.06 GHz.



(a)



(b)



(c)

Fig. 8. 1st Antenna radiation analysis (a) realized gain over frequency (b) 2D and 3D radiation patterns (c) efficiency.

The antenna radiates with a typical monopolar omnidirectional pattern as shown in Fig. 8(b) where both the 2D and 3D plotted patterns are illustrated. Such a pattern is highly required for detecting PD in HV equipment since it can receive PD signal from all directions. Figure 8(c) shows the radiation efficiency and the total efficiency of the 1st antenna. It is found that the antenna, on average, has more than 99.5% radiation efficiency. The total efficiency finds the maximum value as 98.8% and the lowest value as 90%. This indicates that the antenna can receive PD signals with high accuracy.

3.2. *2nd Antenna*

The 2nd antenna is simulated and observed for its corresponding parameter in the same manner as before. The VSWR is presented in Fig. 9, and it is found that the 2nd antenna has a commercial bandwidth (VSWR<2) of 450 MHz from 1.06 GHz to 1.51 GHz. This is the prominent frequency range that a PD source is detected with its electromagnetic signals. Furthermore, there are no common band for communication systems within this range. Hence, the 2nd antenna achieves more precise applicability of being used as an UHF sensor for PD detection.

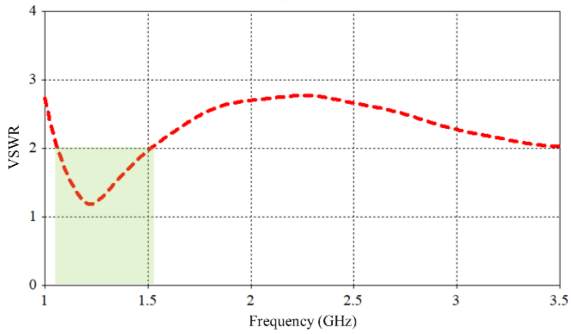
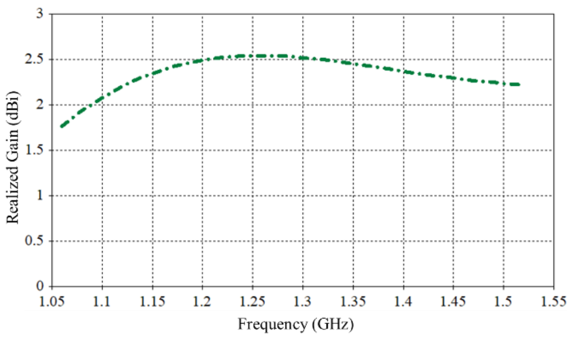
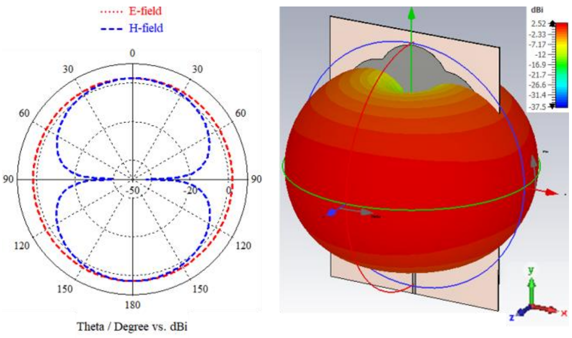


Fig. 9. S-parameter (2nd antenna).

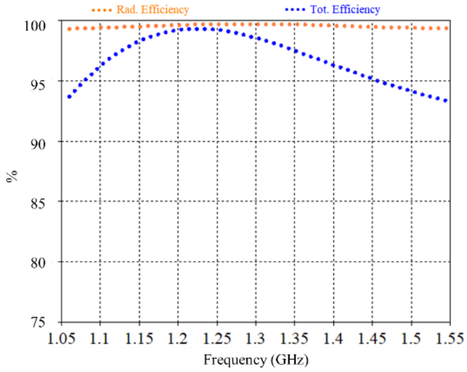
Figure 10 presents the realized gain over frequencies, radiation patterns, radiation efficiency, and total efficiency of the 2nd antenna. It is found that the 2nd antenna has an average realized gain of 2.33 dBi while having a maximum realized gain of 2.54 dBi at 1.26 GHz. This indicates that the 2nd antenna, throughout its entire bandwidth, maintains a consistently higher realized gain than the level of realized gain required for PD detection.



(a)



(b)



(c)

Fig. 10. 2nd antenna radiation analysis (a) realized gain over frequency (b) 2D and 3D radiation patterns (c) efficiency.

Radiation pattern in 2D and 3D plots are shown in Fig. 10 (b), and it is observed that the 2nd antenna radiates with a better monopolar omnidirectional pattern which is required for PD detection from all directions of HV equipment. As seen from Fig. 10(c), the average radiation efficiency for the 2nd antenna is found as 99.4%. The maximum value of the total efficiency is 98.6% and the minimum value of the total efficiency is 87.5% which enables the 2nd antenna to detect PD signals with higher accuracy as well. Table 1 presents the summarized results of both antennas and their comparison with recent works. It is found that both antennas are compact and compatible to be utilized as UHF sensors for partial discharge detection in high voltage equipment of smart grid.

Table 1. Proposed antenna results compared to recent works

Antenna	f_0 (GHz)	FBW (%)	$W \times L$ (mm^2)	Ga_{avg} (dBi)	ηR_{avg} (%)
in Ref. 3	1.55	12.85	–	–	–
in Ref. 4	2.09	68.00	80×100	–	–
1st	2.22	92.80	70×100	3.21	99.5
2nd	1.28	35.02	70×100	2.33	99.3

4. Conclusion

In this paper, two wideband antennas have been proposed for the applications of partial discharge detection in high voltage equipment. Partial ground technique is applied for designing both antennas whereas a truncated ground technique is applied only for the second antenna to separate the communication bands from the antenna bandwidth in terms of partial discharge detection requirements through UHF sensing method. From the analysis of results, it is obvious that both antennas have applicability of being utilized as UHF sensors in detecting partial discharge because of their consistently high realized gain over the wideband.

5. References

1. S. M. K. Azam, M. S. Islam, A. K. M. Z. Hossain, and M. Othman, "Monopole Antenna on Transparent Substrate and Rectifier for Energy Harvesting Applications in 5G," International Journal of Advanced Computer Science and Applications (IJACSA), Vol. 11, No. 8, pp. 84-89, September 2020.
2. A. K. M. Z. Hossain, N. B. Hassim, S. M. K. Azam, M. S. Islam, and M. K. Hasan, "A Planar Antenna on Flexible Substrate for Future 5G Energy Harvesting in Malaysia," International Journal of Advanced Computer Science and Applications (IJACSA), vol. 11, no. 10, pp. 151-155, November 2020.
3. Z. H. Bohari, M. Isa, A. Z. Abdullah, P. J. Soh, M. F. Sulaima, and S. N. M. Arshad, "Performance Assessment for Bare Patch Antenna and Integrated Filter-antenna Microstrip Patch Resonator Based for Partial Discharge Application in HV Equipment," 8th International Conference on Computer and Communication Engineering (ICCCE), pp. 294-298, 2021.
4. J. P. Uwiringiyimana, Suwarno, and U. Khayam, "Design of an Ultra-Wide Band Microstrip Patch Antenna for Partial Discharge Detection on Power Transformer," IEEE International Conference on the Properties and Applications of Dielectric Materials (ICPADM), pp. 242-245, 2021.
5. J. Cruz, A. Serres, A. de Oliveira, G. Xavier, C. de Albuquerque, E. da Costa, and R. Freire, "Bio-inspired Printed Monopole Antenna Applied to Partial Discharge Detection," Sensors, Vol. 19, No. 3, pp. 628, February 2019.
6. Z. Cui, S. Park, H. Choo, and K.-Y. Jung, "Wideband UHF Antenna for Partial Discharge Detection," Applied Sciences, Vol. 10, No. 5, pp. 1698, March 2020.

Acknowledgements

This work was supported by a university grant with the grant number of GPF032A-2019 from the Universiti Malaya, Malaysia.

Authors Introduction

S. M. Kayser Azam

He received his B.Sc. degree in electrical and electronic engineering from the Khulna University of Engineering and Technology, Bangladesh, in 2013. He obtained his M.Sc. research degree in electronics engineering from the International Islamic University Malaysia (IIUM), Malaysia, in 2019. He is currently a Ph.D. student and a Graduate Research Assistant in the Faculty of Engineering at the University of Malaya, Malaysia.

Dr. Mohamadariff Bin Othman

He received his B.Eng. (Hons.) degree in electronic engineering from Multimedia University, Malaysia, in 2006. He obtained his M.Sc. degree in RF and microwave, and the Ph.D. degree in antenna and propagation from Universiti Sains Malaysia (USM), Malaysia, in 2008 and 2015, respectively. He is now working at the Department of Electrical Engineering, Universiti Malaya, Malaysia, as a Senior Lecturer, since 2016. Prior to that, he served as a lecturer at the UCSI University, Malaysia for almost 1 and half year. His research interests include 5G antennas, dielectric characterization, dielectric resonator antenna design, and antenna design optimization. He is also a member in the Board of Engineers Malaysia (BEM).

Dr. Tarik Abdul Latef

He received his B.Sc. degree in electrical and electronic engineering from the University of Oita, Japan, in 1997, the M.Sc. degree in electrical engineering from the University of Leeds, and the Ph.D. degree from The University of Sheffield, U.K., in 2005 and 2011, respectively. Since 2011, he has been a Senior Lecturer with the Department of Electrical Engineering, Faculty of Engineering, University of Malaya, Malaysia. His research interests include circularly polarized antennas, conformal antennas, frequency independent antennas, array design, dielectric resonator antennas, superconducting metamaterial antennas, and RCS reduction mechanisms.

Assoc. Prof. Dr. H. A. Illias

He received the bachelor's degree in electrical engineering from the University of Malaya, Kuala Lumpur, Malaysia, in 2006, and the Ph.D. degree in electrical engineering from the University of Southampton, Southampton, U.K., in 2011.,He joined Freescale Semiconductors (M) Sdn. Bhd., as a Product Engineer in 2008. Since 2011, he has been an Academic Staff with the Department of Electrical Engineering, University of Malaya. He was the Secretary of the IEEE Dielectrics and Electrical Insulation Society (DEIS) Malaysia Chapter from 2015 to 2019. Since 2018, he has been the Counselor of the IEEE University of Malaya Student Branch. He is currently a member of Institution of Engineering and Technology, Corporate Member of Institution of Engineers Malaysia, a registered Chartered Engineer (C.Eng U.K.), and a Professional Engineer (P.Eng Mal).

Prof. Dr. Mohd Fadzil Ain

He received his B.S. degree in electronic engineering from Universiti Teknologi Malaysia, Johor Bahru, Malaysia, in 1997, the M.S. degree in radio frequency and microwave from Universiti Sains Malaysia (USM), Penang, Malaysia, in 1999, and the Ph.D. degree in radio frequency and microwave from the University of Birmingham, Birmingham, U.K., in 2003. Since 2003, he has been with the School of Electrical and Electronic Engineering, USM, Malaysia. He is also the Dean of the School of Electrical and Electronic Engineering, USM. His current research interests include wireless circuit design, low-temperature-cofired-ceramics-based antenna in package, rain propagation, microwave links, and dielectric resonator antennas.

Dr. Yazeed Qasaymeh

He is affiliated to Department of Electrical Engineering, University of Majmaah. He is currently providing services as Assiatant Profesor. He has published numerous publications in various national and international peer-reviewed journals and conference papers across the world. Because of the active association with different societies and academies as well as the contributions, he is been recognized by the subject experts around the world. His research interests include microstrip and dielectric resonator antennas, wireless communications hardware etc.