ISSN 2963-7511
Journal of Engineering Researcher and Lecturer, Vol.3, No. 1, pp. 1-17, 2024

Compact design of circularly polarised microstrip patch antenna with double slip ring resonator for vehicle-to-vehicle communication

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Abstract: The paper mainly focuses on the compact design of circularly polarised microstrip patch antenna for vehicle-to-vehicle communication. The charging time of electric vehicles is longer than that of traditional petrol vehicles. Charging is done at public charging stations. When the vehicles need to be recharged while driving, they communicate using the Dedicated Short Range Communications (DSRC) band to send the information to the nearest vehicles and receive information from the charging station. In addition, DSRC band is used in many application areas such as Intelligent Transportation System (ITS), Electronic Toll Collection (ETC), Collision Avoidance and Connected Vehicles. The research problem in this study is that when installing an antenna on a vehicle, it is important to have a compact size and achieve circular polarisation. The research solution for the problem statement in this study is emphasized on 45˚ inclined slot and corner trimmed is added in rectangular patch to make the current part longer and the impedance matching better, and to achieve circular polarization. Then Swiss roll structure CSRR is added in ground plane to improve the bandwidth. Finally, outer SRR is added in the ground plane to improve S11. The proposed design has been validated for car-to-car communication (5.85-5.925 GHZ).

Keywords: Instrumentation; Transmitter; Resonant Frequency; Polrization; FEKO Software

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Received: December 02nd 2023; Revised: January 27th 2024; Accepted: February 04th 2024
https://doi.org/10.58712/jerel.v3i1.122

Reference to this paper should be made as follows: Zaw, K. K., Khin, E. E., Oo, T., Pradhan, D., & Tun, H. M. (2024). Compact design of circularly polarised microstrip patch antenna with double slip ring resonator for vehicle-to-vehicle communication. *Journal of Engineering Researcher and Lecturer*, 3(1), 1–17. https://doi.org/10.58712/jerel.v3i1.122

1. Introduction

Wireless communication is very popular in the world. In a wireless communication system, the free space is used as the communication channel instead of wires and cables. So the transmitter needs to convert the electrical signals into the EM signals for propagation through the free space, and then the receiver needs to convert the EM signals back into electrical signals. The antenna, which converts electrical signals into EM signals and vice versa at the transmitter and receiver ends. The antenna is therefore a necessary component in wireless communication. Nowadays, the wireless devices are becoming more popular and compact in size and the number of applications in a single device is increasing. Therefore, the antenna design needs to be compact in size, light in weight, lower in cost and support multiple frequency band operation. The microstrip patch antenna can solve all of the above and more. It can be mounted directly on devices. In addition, these microstrip patch antennas have many advantages such as low power consumption, easy to manufacture, low cost and easy to manufacture in large quantities as well as low power consumption. Therefore, the microstrip patch antennas are highly suitable for applications such as WLAN, WiMAX, satellite communication, vehicle-to-vehicle communication and so on (Tyagi et al., 2020).

Vehicle-to-vehicle or car-to-car communication is a new technology approach that allows vehicles to communicate with each other based on the new IEEE 802.11p standard for WAVE. It refers to IEEE 802.11 base products marketed as Wi-Fi. It is required to support ITS in the permitted ITS band of 5.9 GHz. IEEE 802.11p standard has 7 channels of 10 MHz bandwidth in the 5.9 GHz band, this 10 MHz channel width is obtained from 75 MHz spectrum divided into seven intervals, ranging from 5.85 GHz to 5.925 GHz. In EVs, on-board units (OBUs) are used to communicate with the upcoming DSRC standard, and a Controlled Area Network (CAN) bus is connected to the charging port. The DSRC standard allows EVs to communicate with each other through their OBUs for safety purposes (Xinzhou Wu et al., 2013). It is expected that these two standards will be used in every vehicle after 2021 (Roberts et al., 2017).

A microstrip patch antenna configuration can be divided into a three layer sandwich structure, the first layer being the antenna patch, the second layer being the patch layer consisting of a dielectric substrate and the third layer being the ground plane. The conductor of the patch is usually made of copper and can sometimes be replaced by any conductive material depending on the antenna application. The shape of the radiating patch can be in various shapes such as square, circular, rectangular, elliptical or other irregular shapes. However, the most commonly used shapes are square, rectangular and circular (Rahayu et al., 2019).

The main advantage of the monopole antenna is its omnidirectional pattern in the horizontal plane (M. Bank & M. Haridim, 2009). For this reason, microstrip patch monopole is used in car-to-car communication. Because the receiver monopole microstrip patch antenna can receive all the signal from any direction in the horizontal (azimuth) plane.

In this research work, the double slip ring resonator such as SRR and CSRR are added in the ground plane of antenna to get circular polarisation and more improvement in S11. In addition, the bandwidth is good enough for DSRC band and the size of the antenna becomes a high level compact design by adding corner trimmed, slot and double slip ring resonator. The advantage of this study is to be used in vehicle to vehicle communication purposes very well.

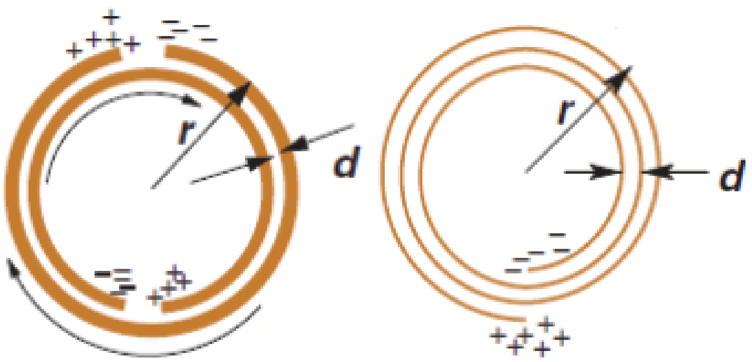
2. Material and methods

A microstrip antenna consists of three main parts such as ground, patch and substrate. In the ground layer, the material of the antenna is copper which is a conductive layer. In the second substrate layer, the FR4 substrate is used in this design which is 1.6mm thick. Generally, FR4 material is used in antenna designs (DEMIRBAS & AKAR, 2022).

Co-axial feed technique is a very common feeding technique for microstrip patch antenna design. In this technique, the SMA connector is penetrated through the substrate and welded to the radiating patch of the antenna. The main advantage of this feeding technique is that the feeding point can be changed at any point of the patch to achieve a better impedance matching between the coaxial cable and the antenna (Singal et al., 2020).

Split ring resonators (SRR) are defined as the realisation of an artificial negative permeability medium by using an array of tiny resonant metallic inclusions (Rajni & Marwaha, 2016). The use of metamaterials has helped antenna designers to reduce the overall size of the antenna without overtly compromising the performance. SRRs have been embedded in the patch to improve the performance of patch antennas. Another popular configuration of SRR is the complementary split ring resonator (CSRR), which is added to the ground plane of the antenna (Nornikman et al., 2012). These complementary structures exhibit inverse properties of an SRR, as verified by the Babinet principle. The aim of the CSRR is to reduce the size of the patch antenna and improve the impedance bandwidth (IBW) (Nornikman et al., 2016).

In addition, the SRR function is that the magnetic field of the electromagnetic radiation can drive a resonant LC circuit through the inductance. The induced currents flow in the directions indicated in; with charges accumulating at the gaps between the rings. The different capacitance effects of the split ring resonator and the Swiss roll structure are shown in Figure 1. The large gap in each ring prevents the current from flowing around a single ring and the circuit is completed across the small capacitive gap between the two rings (El Mrabet et al., 2013; Rao & Basarkod, 2020).



(a) (b)

Figure 1. (a) Split Ring Resonator (SRR) and (b) Complementary Swiss Roll Structure (CSRS)

2.1 Design formulas

The procedure assumes that the specified information includes the dielectric constant of the substrate (ε_r), the resonant frequency (f_r), and the height of the substrate h. For an efficient radiator, a practical width that gives good radiation efficiencies (Kai-Fong Lee & Kin-Fai Tong, 2012; Ramamoorthy et al., 2022; Sharma et al., 2017; Soh et al., 2007; Vaish et al., 2019).

$$W = \frac{1}{2f_r\sqrt{\mu_0\varepsilon_0}}\sqrt{\frac{2}{\varepsilon_r+1}} = \frac{v_0}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2}+\frac{\varepsilon_r-1}{2}[1+12\frac{h}{W}]^{-0.5}, \frac{W}{h}>1 \tag{2}$$

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Journal of Engineering Researcher and Lecturer, Vol.3, No. 1, pp. 1-17, 2024

$$\frac{\Delta L}{h} = 0.412 \frac{(\varepsilon_{reff} + 0.3)\left(\frac{W}{h} + 0.264\right)}{(\varepsilon_{reff} - 0.258)\left(\frac{W}{h} - 0.8\right)} \quad (3)$$

$$L_{eff} = L + 2\Delta L \quad (4)$$

$$L = \frac{1}{2f_r \sqrt{\varepsilon_{reff}} \sqrt{\mu_0 \varepsilon_0}} - 2\Delta L = \frac{v_0}{2f_r \sqrt{\varepsilon_{reff}}} - 2\Delta L \quad (5)$$

$$R_{in}(y = y_0) = \frac{1}{2(G_1 \pm G_{12})} \cos^2\left(\frac{\pi}{L} y_0\right) = R_{in}(y = 0)\cos^2\left(\frac{\pi}{L} y_0\right) \quad (6)$$

2.2 The Proped antennas

The design specifications of the proposed antennas are shown in Table 1. FR4 substrate is used in all proposed antennas. The unit of the proposed antenna is mm. The height of the substrate is 1.6 mm and the feed position is (6.0565,0,0) mm.

Table 1. The design specification of proposed antennas

Parameters		Antenna I	Antenna II	Antenna III
Width of Patch		11.4	11.2	11.2
Length of Patch		13	12.8	12.8
Position of Feed Point		(6.0565,0,0)	(6.0565,0,0)	(6.0565,0,0)
Width of Substrate		22.7	21.5	21.5
Length of Substrate		21.7	22.5	22.5
Width of Slot		1	1	1
Length of Slot		5	5	5
Hight of Substrate		1.6	1.6	1.6
Corner Trimmed Length		3	3	3
Swiss Roll Structure	Router Radius	-	3	3
	Inner Radius	-	1	1
	Width	-	0.1	0.1
Split Ring Resonator	Radius	-	-	10
	Width1	-	-	1
	Gap	-	-	1

In the proposed antenna I, a 3 mm long corner is trimmed and a 45˚ slot is added to obtain circular polarisation in a rectangular patch. The length and width of the slot are 5 mm and 1 mm respectively. The top view and bottom view of the proposed antenna I is shown in Fig. 2. In the proposed antenna II, the Swiss roll structure CSRR is added in the ground plane of antenna I to improve the impedance bandwidth. In CSRR, the outer radius is 3 mm, the inner radius is 1 mm and the width is 0.1 mm. The proposed antenna II is Swiss roll structure is added in the proposed antenna I. The top view and bottom view of the proposed antenna II is shown in Fig. 3. In proposed antenna III,

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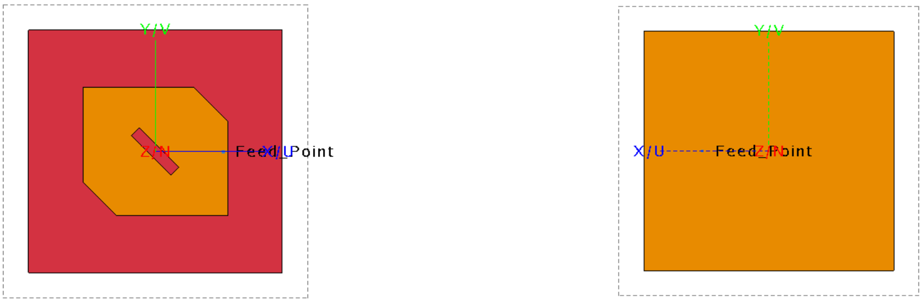
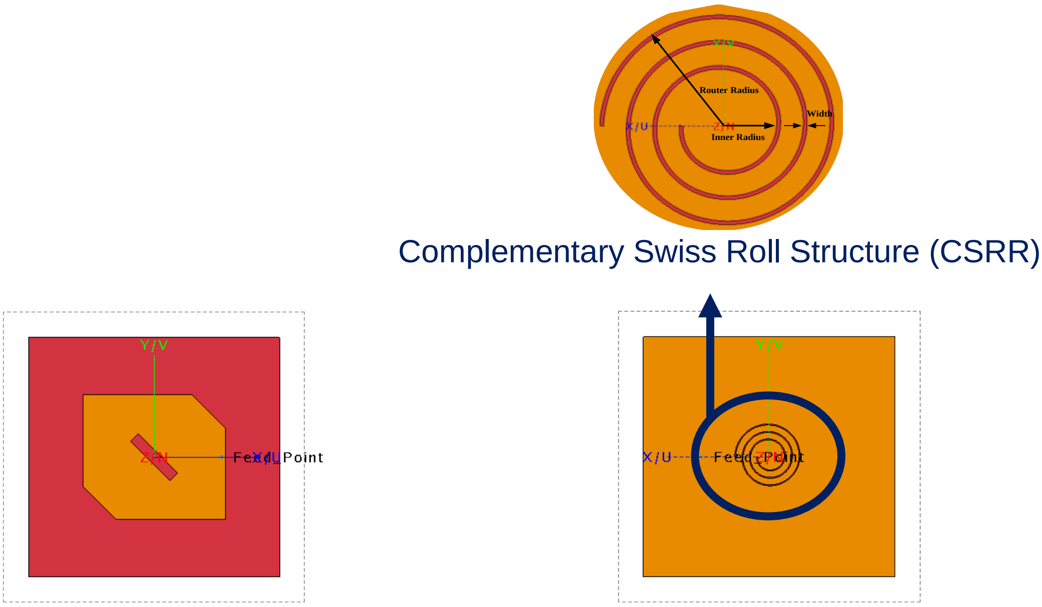
Journal of Engineering Researcher and Lecturer, Vol.3, No. 1, pp. 1-17, 2024

outer SRR is added in the ground plane of antenna II to obtain circular polarisation. The radius, width of 1 mm and gap of SRR are 10 mm, 1 mm and 1 mm respectively. The proposed antenna III is formed by adding the outer SRR in the proposed antenna II. The top view and bottom view of the proposed antenna III are shown in Fig. 4.



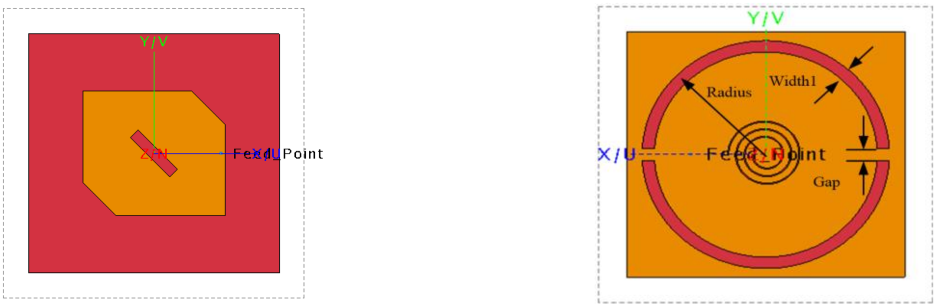
(a) (b)

Figure 2. Proposed antenna I. (a) Top view and (b) Bottom view



(a) (b)

Figure 3. Proposed antenna II. (a) Tip view and (b) Bottom view



(a) (b)

Figure 4. Proposed antenna III. (a) Tip view and (b) Bottom view

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Journal of Engineering Researcher and Lecturer, Vol.3, No. 1, pp. 1-17, 2024

2.3 Research procedure

The process of the system is shown in Figure 5. Firstly, the resonant frequency, height and dielectric constant of the substrate are selected for the V2V application. Then the dimension and feed point of the microstrip patch antenna is calculated to obtain the appropriate resonant frequency. The corner is trimmed and slit on the patch to achieve better impedance matching and circular polarisation. And then check the performance of the antenna by using the parameters such as reflection coefficient, bandwidth, realised gain and axial ratio which is suitable or not for V2V communication. If the results are sufficient, the design I is finished.

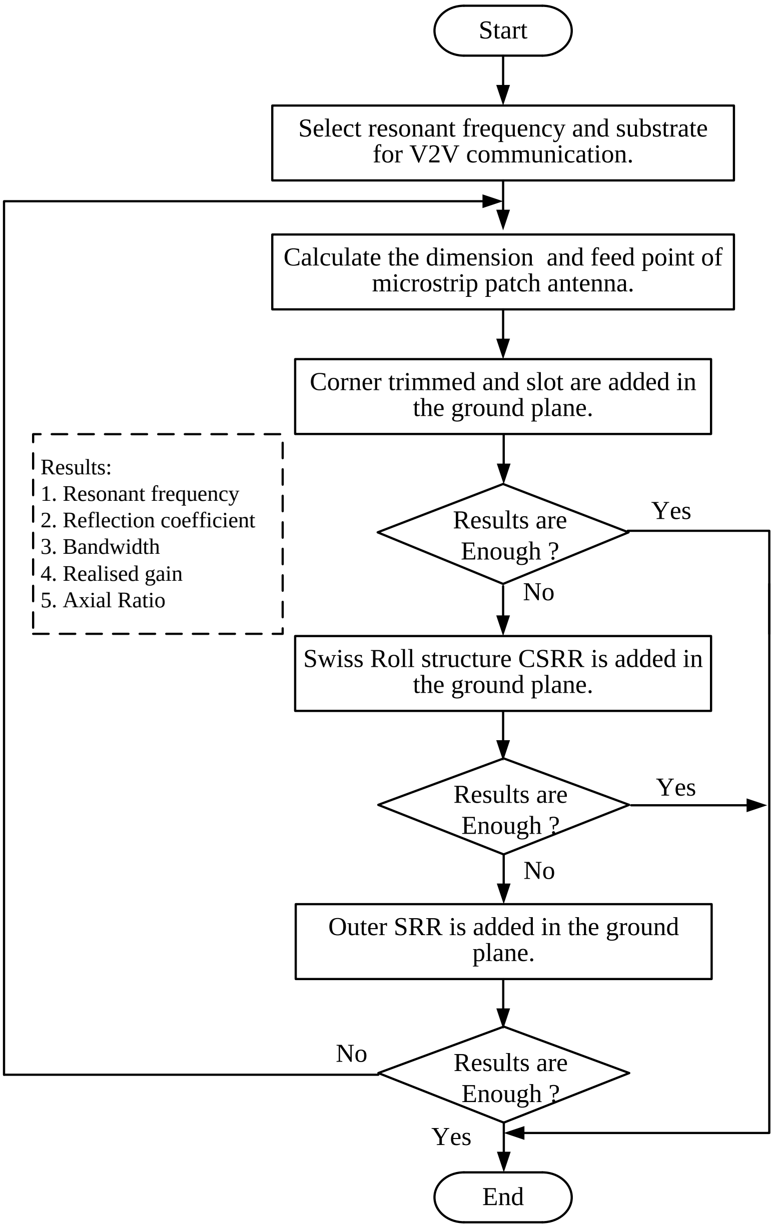

Figure 5. Procedure of the system

Secondly, the internal Swiss roll structure slip ring resonator is added to the ground plane to improve the bandwidth. And then, the performance of the antenna is checked

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Journal of Engineering Researcher and Lecturer, Vol.3, No. 1, pp. 1-17, 2024

using parameters such as resonant frequency, reflection coefficient, bandwidth, realised gain and axial ratio, which is suitable or not for V2V communication. If the results are sufficient, design II is completed. Finally, the outer slip ring resonator is added on the ground plane to improve the bandwidth and S11. And then, the performance of the antenna is checked by using the parameters such as resonant frequency, reflection coefficient, bandwidth, realised gain and axial ratio, which is suitable or not for V2V communication. When the results are sufficient, the design III is completed (Moe et al., 2023; Oo et al., 2022; Sarade & Ruikar, 2020; Tun et al., 2021, 2023).

3. Results and discussion

In this paper, a compact rectangular slot microstrip patch antenna is used for V2V communication. The proposed antenna consists of a square flame-retardant 4 (FR4) substrate. The corners of the patch are cut in order to minimise the patch size, increase the length of the current part and improve the impedance matching. Three designs are proposed in this research. In the first design, 45˚ slot and corner cut are added in rectangular patch to obtain resonant frequency for V2V communication and circular polarisation. In the second design, Swiss roll structure CSRR is added in ground plane to improve the bandwidth. In the final design, outer SRR is added in ground plane to improve S11. The performance of the antenna is measured using reflection coefficient, bandwidth and polarisation. The results and discussion are presented in the following sections.

3.1 Proposed antenna design I

In the proposed antenna I, a 3 mm long corner is trimmed and a 45˚ slot is added to obtain circular polarisation in a rectangular patch. The length and width of the slot are 5 mm and 1 mm respectively. According to the result, the impedance bandwidth of the antenna is 0.527 GHz. The minimum value of s11 is -41.2 dB at 5.71 GHz and -14.4 dB at 5.9 GHz. The realised gain of the antenna is 4.02 dBi at 5.9 GHz. The reflection coefficient and realised gain of the proposed antenna I are shown in Figure 6. The current distribution of the proposed antenna I is shown in Figure 7.

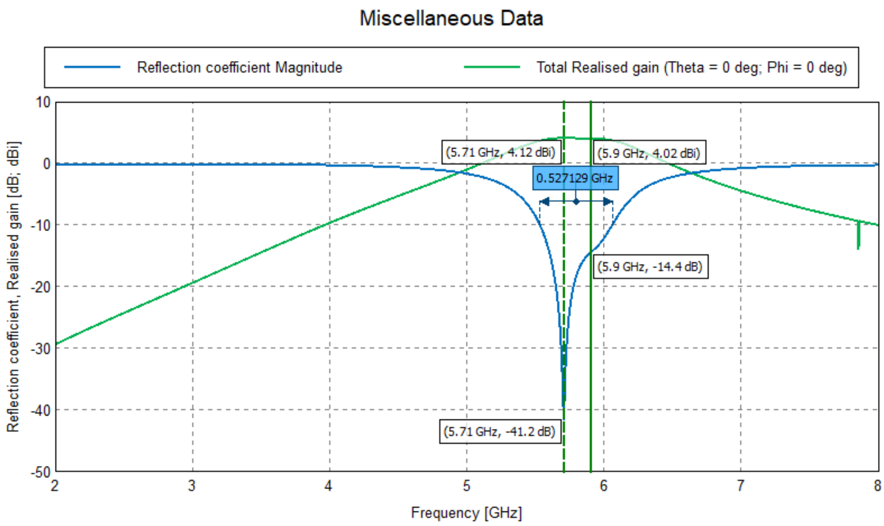
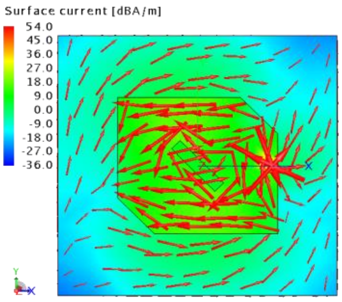
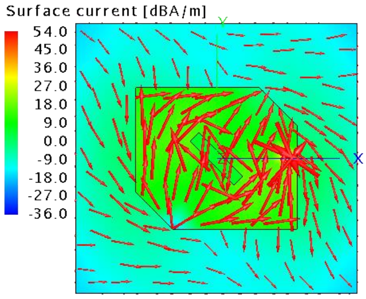


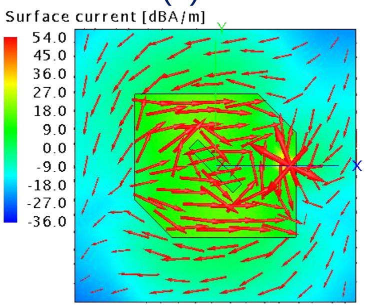
Figure 6. Reflection coefficient and realised gain of proposed antenna I



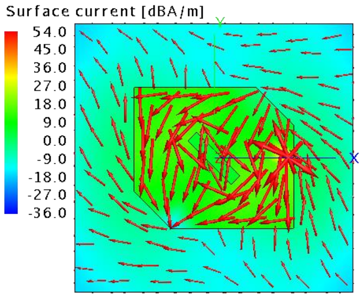
(a)



(b)



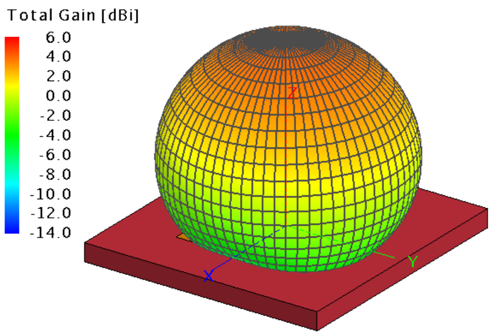
(c)



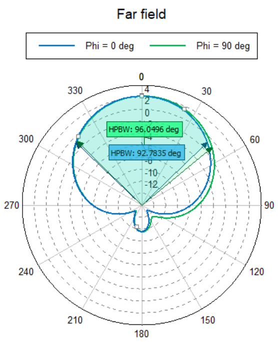
(d)

Figure 7. Current distribution of proposed antenna I. (a) at 0 Degree, (b) at 90 Degree, (c) at 180 Degree, and (d) at 270 Degree

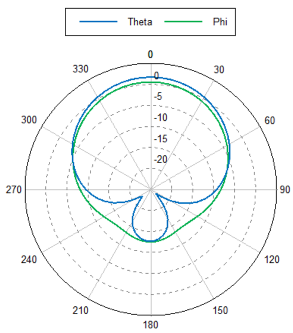
The maximum total gain of the antenna is 6 dBi at 5.9 GHz and the beamwidth of the antenna is 92.7835 degrees at phi = 0 degrees at 5.9 GHz and 96.0496 degrees at phi = 90 degrees at 5.9 GHz. The radiation pattern of the proposed antenna I is shown in Figure 8.



(a)



(b)



(c)

Figure 8. Radiation pattern of proposed antenna I at 5.9 GHz. (a) 3D Radiation pattern, (b) Polar form, and (c) at Theta and Phi

The polarisation of the antenna is circular polarisation because the axial ratio (AR) is less than 3dB between 5.828 GHz and 5.969 GHz. So the proposed antenna I have designed is very suitable for car-to-car communication (5.85-5.925 GHZ). The antenna can be easily fabricated at low cost. The axial ratio (AR) of the proposed antenna I is shown in Figure 9.

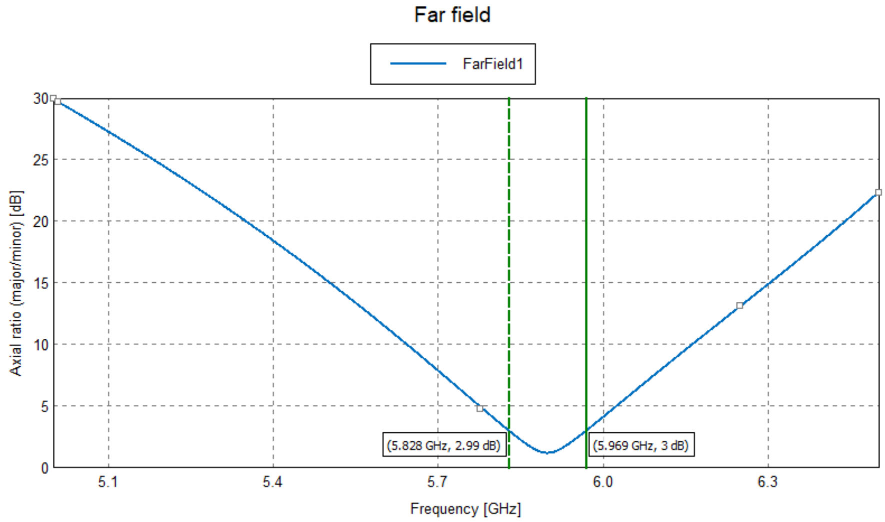


Figure 9. Axial ratio (AR) of proposed antenna I

3.2 Proposed antenna design II

In the proposed antenna I, the impedance bandwidth is narrow and the minimum value of s11 is small at 5.9 GHz. So the proposed antenna II is Swiss roll structure CSRR is added in the ground plane of proposed antenna I to improve the impedance bandwidth. In CSRR, the outer radius is 3 mm, the inner radius is 1 mm and the width is 0.1 mm. According to the result, the impedance bandwidth of the antenna is 0.68927 GHz. The minimum value of s11 is -20.73 dB at 5.48 GHz and -14.47 dB at 5.9 GHz. The realised gain of the antenna is 4.208 dBi at 5.9 GHz. The reflection coefficient and realised gain of the proposed antenna II are shown in Figure 10. The current distribution of the proposed antenna II is shown in Fig 11.

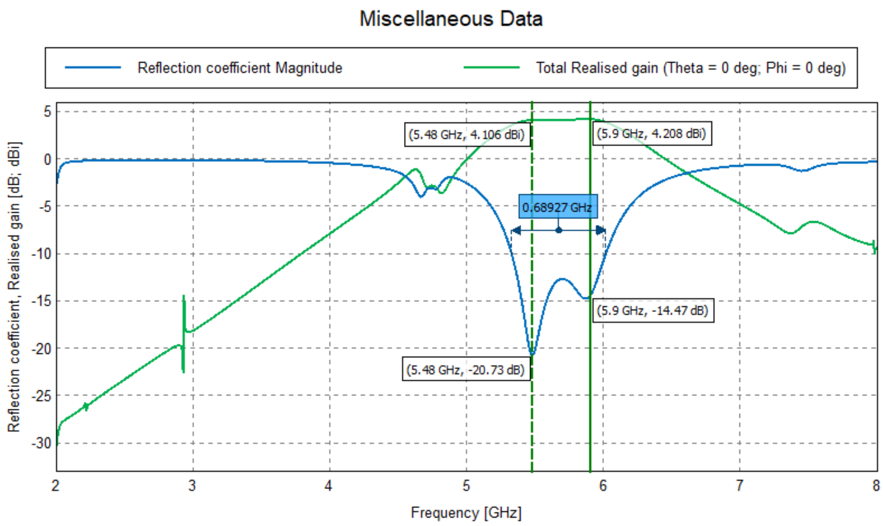


Figure 10. Reflection coefficient and realised gain of proposed antenna II

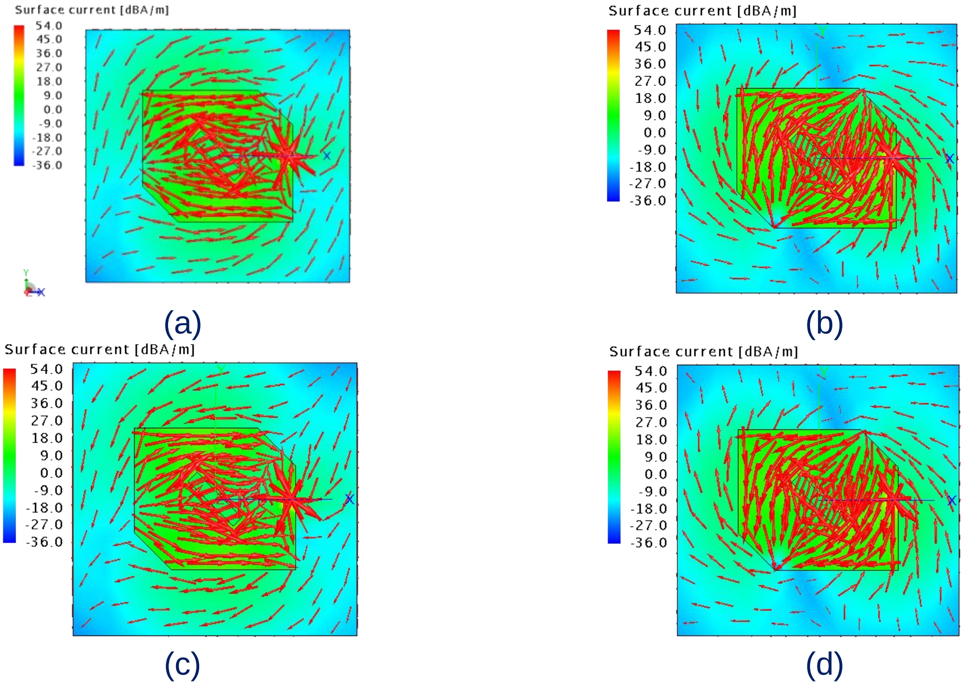


Figure 11. Current distribution of proposed antenna II. (a.) at 0 Degree, (b.) at 90 Degree, (c) at 180 Degree, and (d) at 270 Degree

The maximum total gain of the antenna is 5.25 dBi at 5.9 GHz and the beamwidth of the antenna is 92.7184 degrees at phi = 0 degrees at 5.9 GHz and 95.6664 degrees at phi = 90 degrees at 5.9 GHz. The radiation pattern of the proposed antenna II is shown in Figure 12. The polarisation of the antenna is linear polarisation. The impedance bandwidth and the realised gain of the proposed antenna II is slightly better than that of the proposed antenna I. Thus, the proposed antenna II design is very suitable for car-to-car communication (5.85-5.925 GHZ).

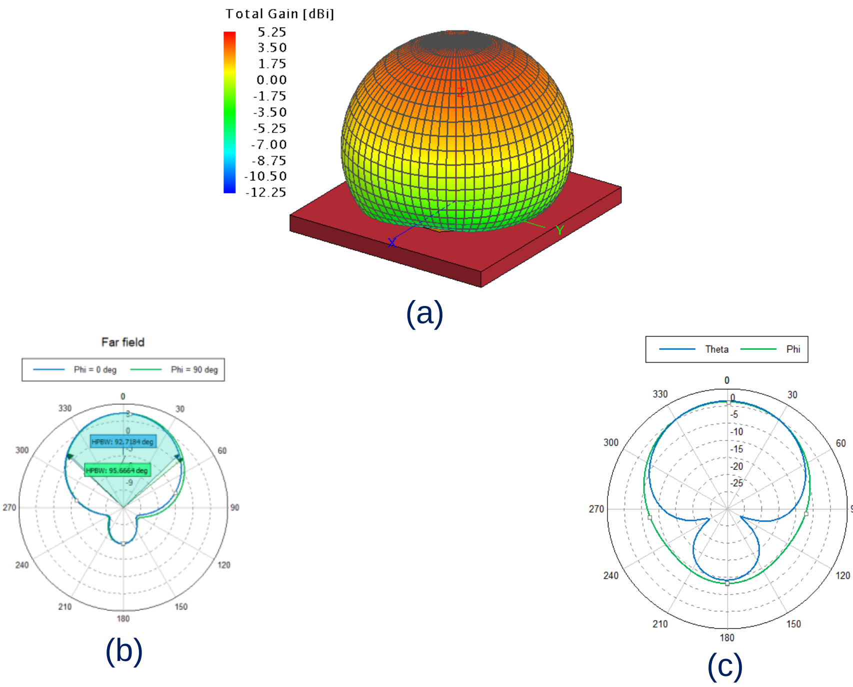


Figure 12. Radiation pattern of proposed antenna II at 5.9 GHz.

3.3 Proposed antenna design III

In the proposed antenna II, the polarisation of the antenna is linear. So the outer SRR is added in the ground plane of the proposed antenna II. Outer SRR is added in the ground plane of proposed antenna II to obtain circular polarisation. The radius, width of 1 mm and gap of SRR are 10 mm, 1 mm and 1 mm respectively. According to the result, the impedance bandwidth of the antenna is 0.67879 GHz. The minimum value of s11 is -12.8 dB at 5.51 GHz and -35.1 dB at 5.91 GHz. The realised gain of the antenna is 3.39 dBi at 5.91 GHz. The reflection coefficient and realised gain of the proposed antenna III are shown in Figure 13. The current distribution of the proposed antenna III is shown in Fig 14.

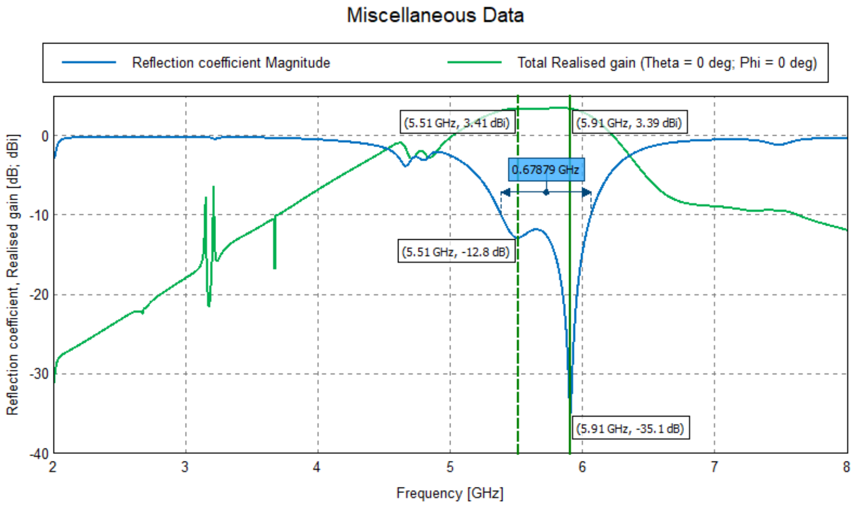


Figure 13. Reflection coefficient and realised gain of proposed antenna III

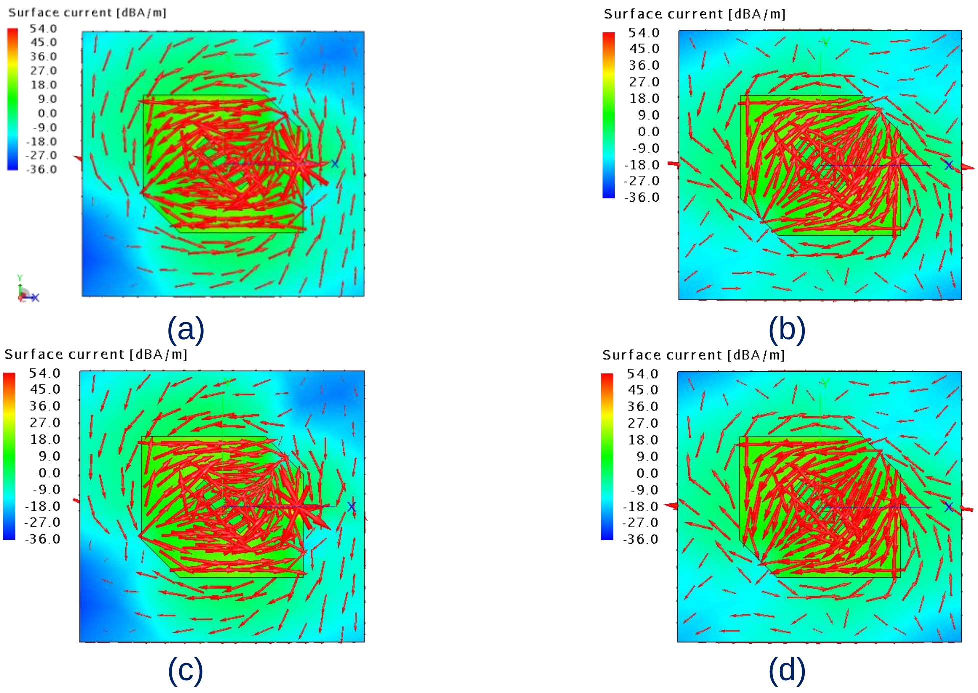


Figure 14. Current distribution of proposed antenna III. (a.) at 0 Degree, (b.) at 90 degree, (c) at 180 Degree, and (d.) at 270 degree

The polarisation of the antenna is circular polarisation because the axial ratio is less than 3dB between 5.773 GHz and 6.146 GHz. The axial ratio of the proposed antenna III is shown in Figure 16. This antenna design is more resonant than the other two at 5.9 GHz and the beamwidth is almost the same at phi = 0 and 90 degrees. Therefore, the proposed antenna design III is very suitable for car-to-car communication (5.85-5.925 GHZ). The antenna can be manufactured easily and at low cost.

The maximum total gain of the antenna is 3.5 dBi at 5.9 GHz and the beamwidth of the antenna is 94.3841 degrees at phi = 0 degrees at 5.9 GHz and 94.8863 degrees at phi = 90 degrees at 5.9 GHz. The radiation pattern of the proposed antenna III is shown in Figure 15.

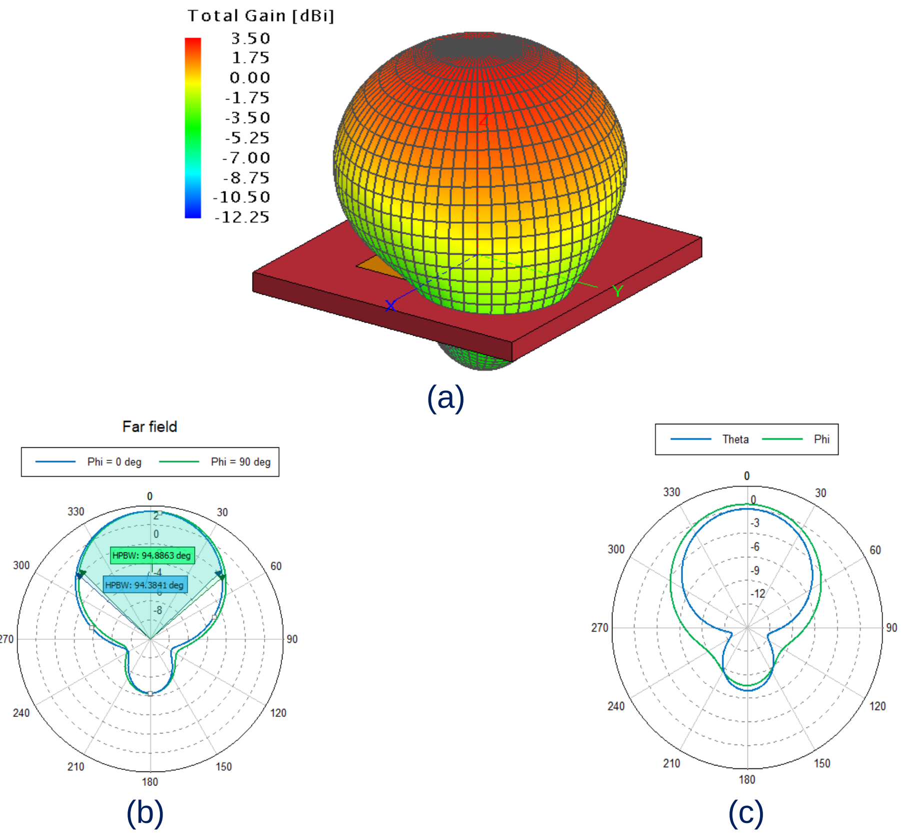


Figure 15. Radiation pattern of proposed antenna III at 5.9 GHz. (a) 3D radiation pattern, (b) Polar form, and (c) at Theta and Phi

The performance of the proposed structure compared to previously reported designs is shown in Table 2 (Ghosh et al., 2016). The radiation pattern of designs I, II and III is directional. Directional antennas are good for applications that require the available RF energy to be focused in a particular direction. The polarisation of the proposed antennas is linear and circular polarisation. Circular polarised microstrip patch antennas play an important role in wireless communications. They allow any signal polarisation of the receive antenna with respect to the transmit antenna. In linear polarisation, the transmitter and receiver must have the same polarisation and accurate alignment of the antennas (Nadeem et al., 2022).

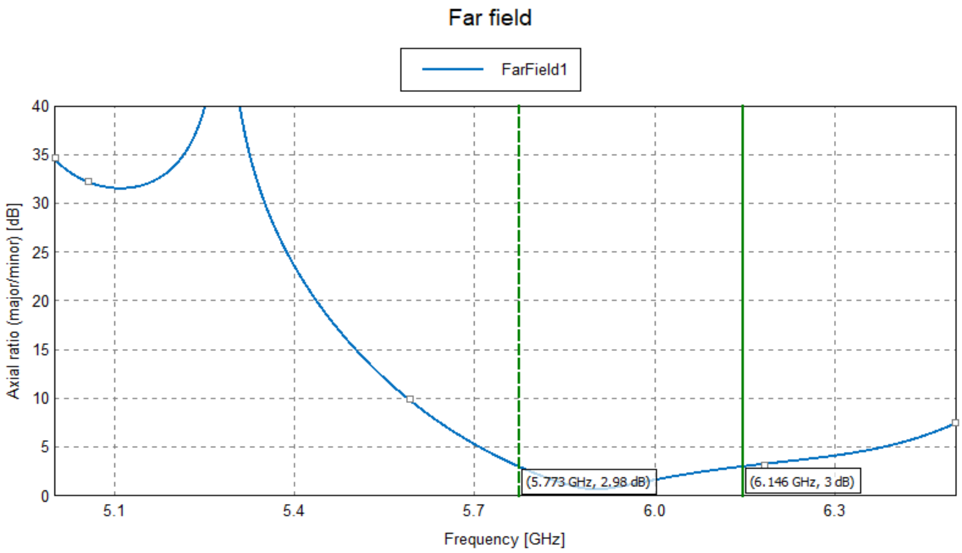


Figure 16. Axial ratio of proposed antenna III

Table 2. Performance of the proposed structure compared with previous reported designs

Technique	Resonant Frequency (GHz)	Dimension (mm^3)	Polarization	Ref.
Hexagonal shape with Cantor fractal	5.9	31 × 28 × 1.6	-	(Ez-Zaki et al., 2021)
Genetic Algorithm	5.9	20.2×24.1×1.6	-	(Renuga Kanni & Brinda, 2019)
Hexagonal Patch Antenna with Defective Ground Structure	5.9	20×1.6	-	(Singhal et al., 2020)
A single element microstrip transparent antenna	5.9	60×45×1.6	-	(Rahayu et al., 2019)
Corner Trimmed, Slot	5.71	22.7×21.7×1.6	Circular	Proposed Work (Design I)
Corner Trimmed, Slot, CSRR	5.9	21.5×22.5×1.6	Linear	Proposed Work (Design II)
Corner Trimmed, Slot, Double SRR	5.91	21.5×22.5×1.6	Circular	Proposed Work (Design III)

4. Conclusion

The proposed antenna has been simulated through various parametric studies using FEKO software. The proposed antenna consists of a square flame retardant 4 (FR4) substrate. The dimension of the antenna is $22.5\left(0.4425\,\lambda_0\right)\times 21.5\left(0.4228\,\lambda_0\right)\times 1.6$

$\left(0.0314\,\lambda_0\right)\mathrm{mm}^3$ (where λ_0 is the free-space wavelength of 5.9 GHz). The dimension of the antenna is $0.5\lambda_0$ (where is the free space wavelength of 5.9 GHz). In addition, when this antenna is installed on the car, the size of the antenna is very small compared to the size of the car body. Therefore, this design is a compact design. The performance of the antenna is checked by using the parameters such as reflection coefficient, bandwidth, realised gain and axial ratio, which is suitable or not for V2V communication. In the simulation results of the proposed design III, the impedance bandwidth of the antenna is 0.67879 GHz. The minimum value of S11 is -35.1 dB at 5.91 GHz. The realised gain is 3.39 dBi at 5.91 GHz. The beamwidth of the antenna is 94.3841 degrees at phi = 0 degrees at 5.9 GHz and 94.8863 degrees at phi = 90 degrees at 5.9 GHz. The proposed antenna II polarisation is linear. But the proposed antenna I and III is circular because the axial ratio (AR) is below the 3dB in (5.828-5.969) GHz and (5.773-6.146) GHz respectively. Thus, the proposed antenna design is very suitable for car-to-car communication (5.85-5.925 GHz). In this research work, a compact size antenna is developed by contributing to V2V communication. In the future, the antenna designer needs to make MIMO antenna for high speed transmission, antenna miniaturisation and bandwidth and gain enhancement.

Acknowledgements

The authors would like to thank many colleagues from the microstrip patch antenna research group of the Department of Electronic Engineering, Yangon Technological University. The author would especially like to thank all the teachers from the Department of Electronic Engineering, Yangon Technological University for their support, encouragement and invaluable guidance in the preparation of this research. The authors would like to express their gratitude to all the people who provided support during the preparation period of this research.

Declarations

Author contribution

Hla Myo Tun: Conceptualisation, formal analysis, funding acquisition, research, validation, visualisation, project management, resources, supervision, writing - original draft, writing - review & editing. Ko Ko Zaw and Ei Ei Khin: Conceptualisation, data curation, formal analysis, investigation, methodology, writing - original draft, writing - review & editing. Devasis Pradhan and Thandar Oo: Investigation, validation, visualisation.

Funding statement

The work was supported in part by the Japan International Cooperation Agency (JICA) for the Enhancement of Engineering Higher Education (EEHE) Project, and Grant-in-Aid for Scientific Research from the Government of the Republic of the Union of Myanmar (GB/D(18)/2021/2).

Conflict of interest

All authors have worked together for the sustainable development of antenna technology. The collaboration between all authors is very strong and concrete. They have published several research articles in scientific societies. The corresponding authors have received research grants from JICA Project for Enhancement of Engineering Higher Education in Myanmar and Grant-in-Aid for Scientific Research of the Government of the Republic of the Union of Myanmar.

Ethical clerance

There are no human subjects in this manuscript and informed consent is not applicable.

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