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Multibeam One-Third Radial Line Slot Array (RLSA) Antennas

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Abstract—This study aims to develop and evaluate the multibeam one-third Radial Line Slot Array (RLSA) antennas. The various techniques used include: a) slot implementation on the background surface for the design of multibeam, b) cutting the full circle of RLSAs for the simplification of the antenna size, and c) slot deletion for the formation of bandwidth. Approximately 40 multibeam one-third RLSA models were designed and simulated, with the best being fabricated and measured to verify the simulation. The results showed that the antenna had symmetrical beams regarding the gain, direction, and beamwidth at 9 dBi, 20° and 160°, as well as 38°, respectively. The antenna also had a low reflection of −22 dB at the centre frequency of 5.8 GHz, with a broad bandwidth of approximately 1.2 GHz, which was highly sufficient for Wi-Fi application. The gain of 9 dBi was 3 dB lower than that of a simulated single-beam antenna, which was suitable for the theory of splitting. Based on these findings, the agreement between measurement and simulation verified the design of the antenna.

1. INTRODUCTION

Radial Line Slot Array (RLSA) is a type of systematic cavity or wideguide antenna, initially developed for high gain applications, such as satellite broadcast links [1–4]. The successful development led to the subsequent modification, to be suitable for other applications at different frequencies, including Wi-Fi [5, 6]. Since the devices using this application require smaller size antenna, there is a need to develop small-sized RLSA. However, this process limited the number of slots, causing a high signal reflection that had been a problem for the past two decades [7]. During these periods of facing challenges, various studies attempted to develop several small RLSA antennas for Wi-Fi devices, while overcoming their high-signal reflection effects. In 1990 and 1997, Hirokawa et al. [8] and Akiyama et al. [9] separately initiated the development of these antennas, by implementing the matching slot technique to lower the reflected power, leading to the reduction of signal reflection. According to Bialkowski and Zagriatski (2004), small omnidirectional RLSA antennas were purposely developed for Wi-Fi [6], where unusual long slots were used to prevent the excessive remaining power at the antenna perimeter, therefore, reducing the signal reflections. The weakness of using long slots emphasized the acquisition of small gain, since the antennas only had a few slots.

Imran et al. (2007) also designed Wi-Fi point-to-point antennas with a radius of 325 mm, using the conventional beam squint technique [5]. These systems showed a good performance with a high gain of 26 dBi, although they were too bulky for Wi-Fi devices. Moreover, Islam et al. (2008) designed RLSA antennas using the several Flame Retardant (FR-4) layers bounded as a systematic cavity material [10]. Since the radius of the systems was only 75 mm (quite small), a negative performance was observed with a low gain and narrow bandwidth of 8 dB and 75 MHz, respectively. This was due to the incorrect design and utilization of slot overlapping and high-loss FR-4 material. In the study of Purnamirza and

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Rahman (2012), three different materials were proposed and used for the antenna cavity, namely two FR-4 layers at the top and bottom of the system, with only one polypropylene at the middle [11]. Despite the significant reduction of reflections, the antennas still had a disadvantage regarding the complexity of the cavity, which complicated the fabrication process. The study also reduced signal reflections successfully by proposing a high-value beam squint technique in designing the antenna slots [12]. Besides this, the technique was subsequently implemented to design small RLSAs for Wi-Fi functional needs [13].

Multibeam RLSA antennas using a phased shifter to produce beams were initially proposed by Takada et al. [14]. The research was conducted based on numerical calculations, without simulation or measurement, hence, it is regarded as an introduction of a technique enabling multibeam for RLSA antennas. Presently, there is no significant study on multibeam development. Therefore, this study aims to develop a special technique, different from the previous [14], in the design of multibeam RLSA antennas.

2. STRUCTURE OF BASIC SINGLE BEAM RLSA

Basic RLSA models are found to contain a copper layer at the top and bottom of the antenna, known as the radiating element and background, as well as a polypropylene cavity and SMA (Sub-miniature version A) feeder in the middle, as depicted in Fig. 1(a). Based on Fig. 1(b), a copper head disc was added to the feeder to convert coaxial TEM (transverse electromagnetic mode) into cavity mode signals, to ensure radial propagation. All the parameters of feeders are depicted in Fig. 1(c).

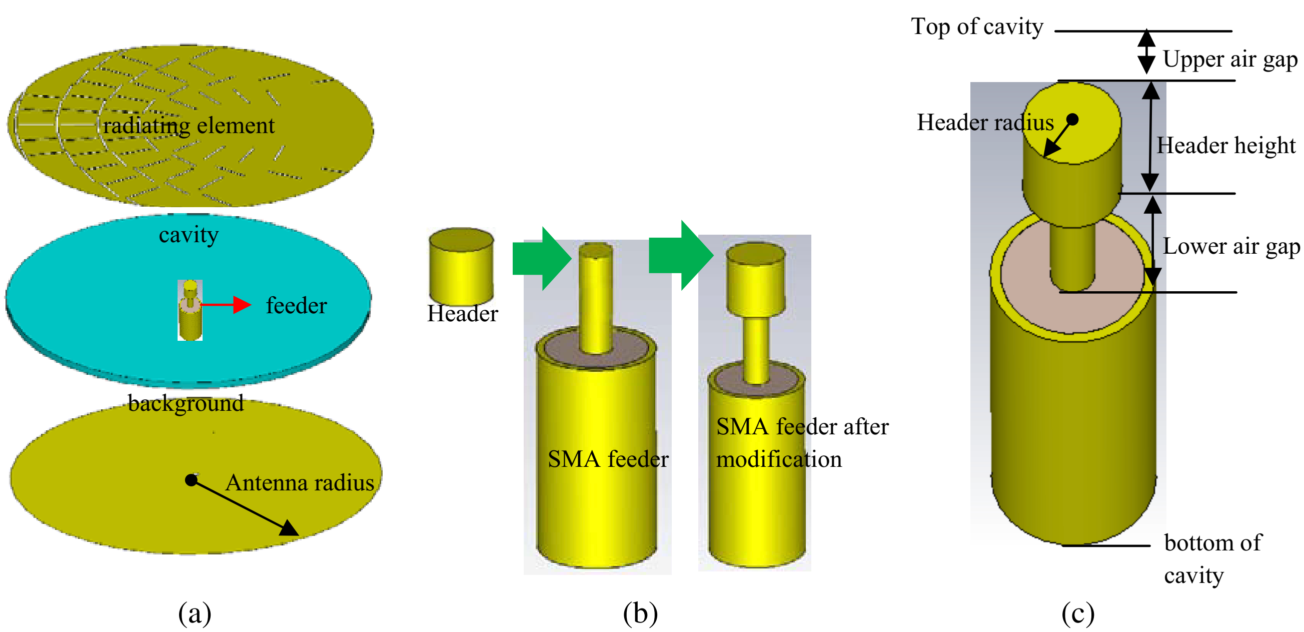


Figure 1. (a) Structure of basic RLSA antennas [11], (b) fabrication of feeder [12], and (c) parameters of feeder [12].

Typically, the radiating element consists of several slots, as depicted in Fig. 1(a). The shape of each slot has a unique position and inclination, which is calculated using Eqs. (1)–(7) [15]. The definitions of all slot parameters are shown in Table 1, with Fig. 2 depicting all the parameters.

$$\theta_1 = \frac{\pi}{4} + \frac{1}{2}\left\{\arctan\left(\frac{\cos(\theta_T)}{\tan(\emptyset_T)}\right) - (\emptyset - \emptyset_T)\right\} \tag{1}$$

$$\theta_2 = \frac{3\pi}{4} + \frac{1}{2}\left\{\arctan\left(\frac{\cos(\theta_T)}{\tan(\emptyset_T)}\right) - (\emptyset - \emptyset_T)\right\} \tag{2}$$

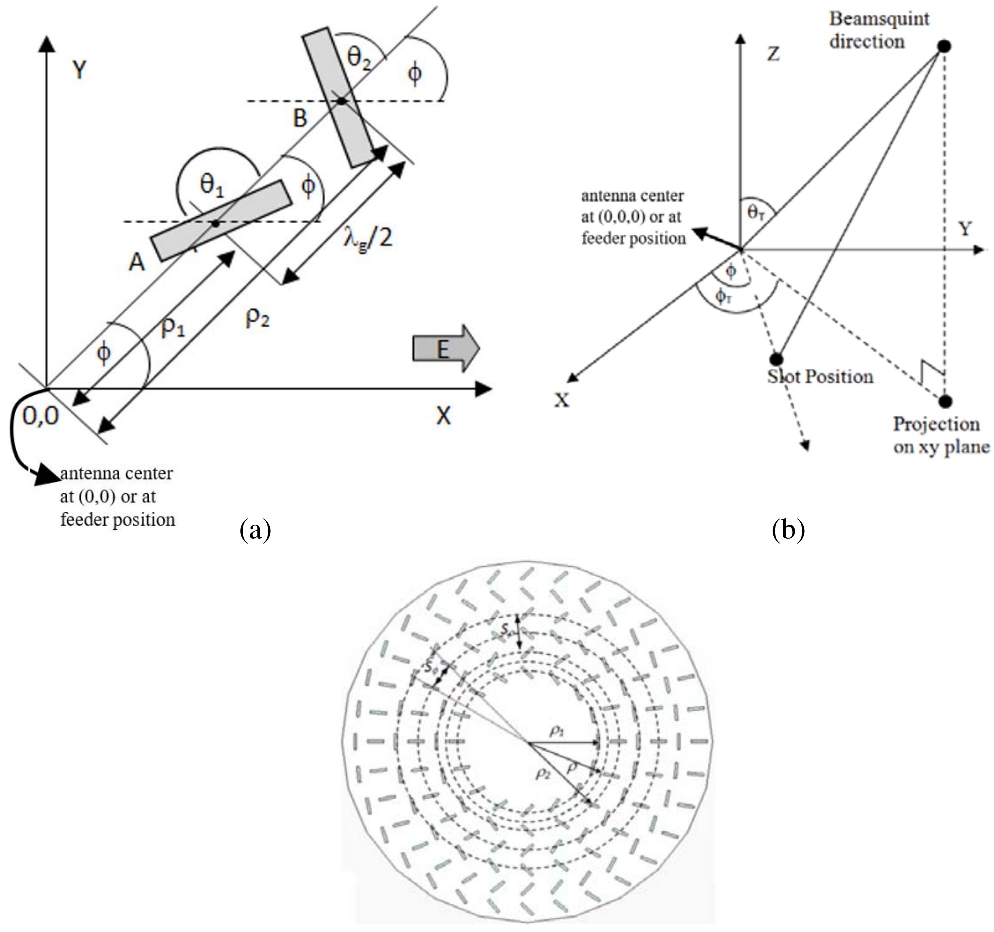


Figure 2. (a) Parameters of slots in the x-y plane, (b) slots' positions and their relationships in respect to the beam direction in x-y-z, and (c) distance between the slots in radial and azimuth directions [15].

$$\rho_1 = \frac{(n-1+q-0.25)\,\lambda_g}{1-\xi\sin\theta_T\cos(\phi-\phi_T)} \tag{3}$$

$$\rho_2 = \frac{(n-1+q+0.25)\,\lambda_g}{1-\xi\sin\theta_T\cos(\phi-\phi_T)} \tag{4}$$

where $\xi = \frac{1}{\sqrt{\varepsilon_{r_1}}}$

$$S_\rho = \frac{\lambda_g}{1-\xi\sin\theta_T\cos(\phi-\phi_T)} \tag{5}$$

$$S_\phi = \frac{2\pi\lambda_g}{\sqrt{1-\xi^2\sin\theta_T^2}}\frac{q}{p} \tag{6}$$

$$L_{rad} = \left(4.9876\times10^{-3}\rho\right)\frac{12.5\times10^9}{f_0} \tag{7}$$

3. PROPOSED TECHNIQUE FOR THE DESIGN OF MULTIBEAM RLSA

The design of multibeam began by creating a squinted beam to the desired direction, where a high beam squint value was used to develop related slots. This indicated that the slots produced were not

Table 1. The designed parameters of the slot pairs [15].

Parameters	Symbols
The inclination angle of Slot 1	θ_1
The inclination angle of Slot 2	θ_2
Beam squint angle in the elevation direction	θ_T
The azimuth angle of Slots 1 and 2 positions	ϕ
Beam squint angle in the azimuth direction	ϕ_T
Distance of Slot 1 from the centre of antennas	ρ_1
Distance of Slot 2 from the centre of antennas	ρ_2
Number of slot pairs in the first ring	N
Integer numbers (1, 2, 3...) expressing the distance of the innermost ring from the centre of antennas	q
Distance between two adjacent unit radiators located in two different rings (radial direction distance)	S_ρ
Distance between two adjacent unit radiators in the same ring (azimuth direction distance)	S_ϕ

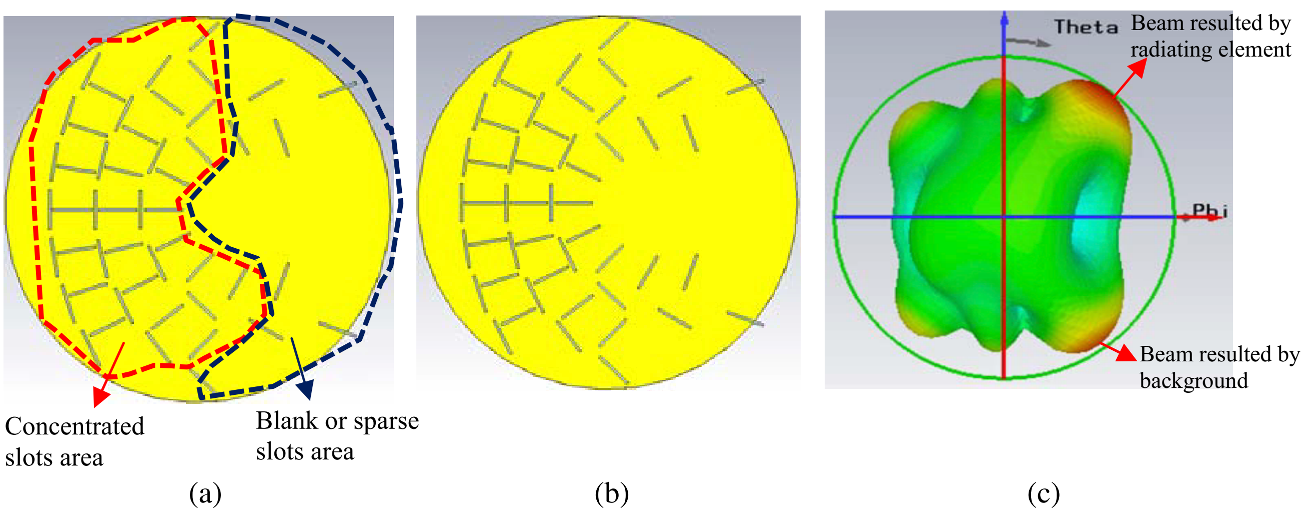


Figure 3. Slot distribution using high beam squint values on (a) the radiating element surface (b) background, and (c) the dual beams.

evenly distributed on the specific part of the antenna surface, as depicted in Fig. 3(a). To produce another identical beam, related slots were also designed and placed on the background surface as shown in Fig. 3(b). Meanwhile, Fig. 3(c) shows the dual-beams produced by the radiating element and the background.

Based on the background surface, unusual placement of the slots was observed due to the sole use of this component as a cavity barrier. This placement hindered the radial orientation of power flow within the antenna cavity (Figs. 4(a) and (b)), leading to the reduction of gains and beam pattern effects. Despite this, an advantage was still observed regarding the minimization of signal reflection, indicating that the antenna had more slots for high-power radiation when the background was used for placement. This helped to reduce the remaining reflected power from the antenna perimeter.

Since only a few slots contributed to the level of gain, the sparse areas of the antennas (Fig. 3(a))

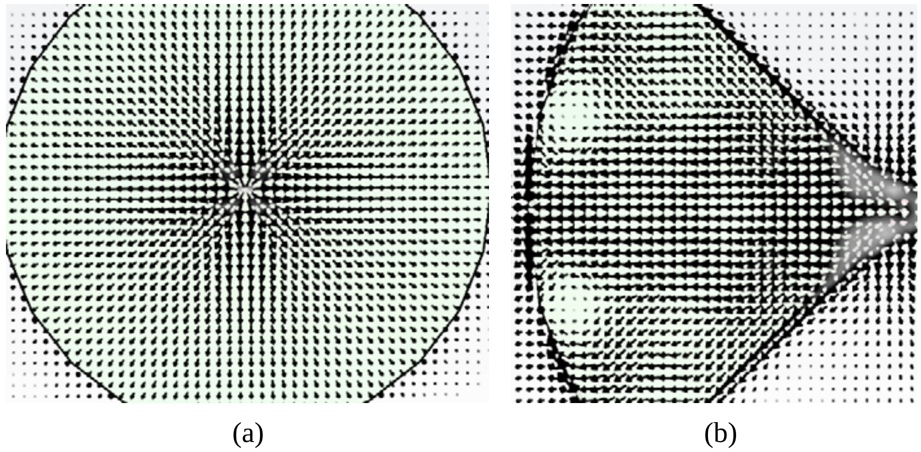


Figure 4. (a) Radially flowing power, (b) power that does not flow completely radially.

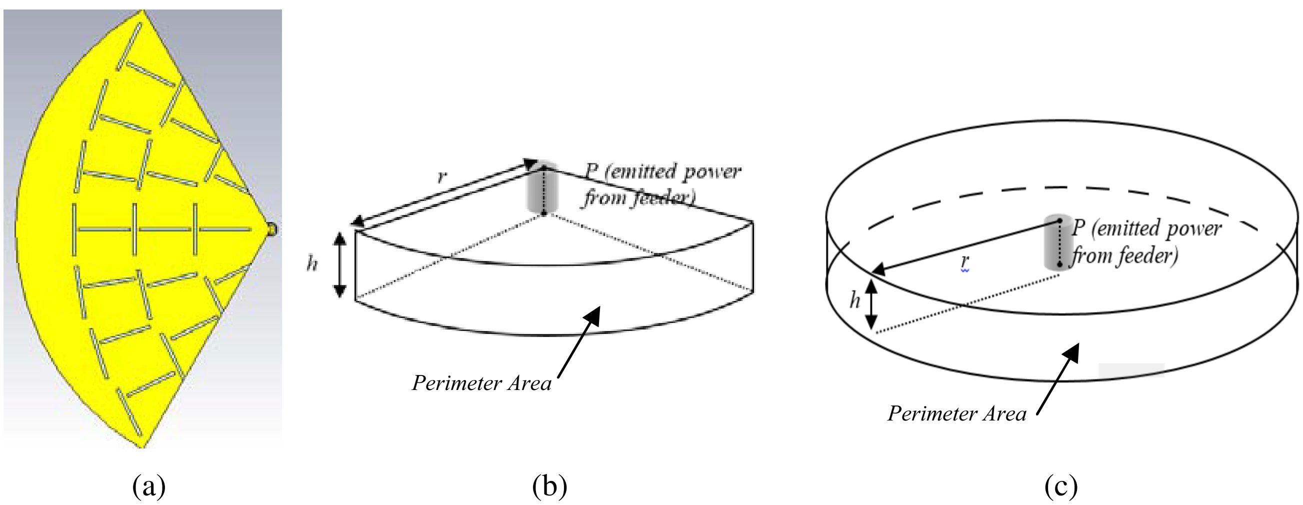


Figure 5. (a) One-third cut RLSA antennas, (b) perimeter area of one-third RLSA antennas, and (c) perimeter area of full circle RLSA antennas.

were considered insignificant. These areas were then cut out by one-third and separated to produce a new smaller antenna (Fig. 5(a)). The gain increased due to the additional power emitted by the slots, compared to those in the previous full circle system. This was because the perimeter cut areas were smaller than the previous types, indicating that the power density within the new cavity $\left({}^{3P}/_{(2\pi R \cdot h)}\right)$ was higher than those in the full circle system $\left({}^{P}/_{(2\pi R \cdot h)}\right)$, as shown in Figs. 5(b) and (c), respectively. Therefore, this cut neutralized the negative effect of the aforementioned background slot placements.

4. DESIGNED ANTENNAS MODELS

Compared to other antenna types that are simple and easy to draw, the shape of RLSA slots was very complicated. This is because each slot has a unique position and inclination, as discussed in the previous section. Using a mouse and the tools of Radio Frequency software, the manual drawings of these slots were difficult and time-consuming. This led to the development of a Visual Basic Application (VBA) computer program, which was embedded within the CST simulation software, to calculate the slots' position and inclination, as well as draw them rapidly and accurately. Using the computer program, all

Table 2. Parameters of the antenna models and feeders.

Symbol	Parameter	Value
θ_T	Beam squint angle	63° up to 89°
ε_{r1}	Cavity permittivity	2.33
d	Background thickness	0.35 mm
d_1	Cavity thickness	8 mm
d_2	Radiating element thickness	0.35 mm
f	Frequency centre	5.8 GHz
w	Slot width	1 mm
r	Antenna radius	85 mm
n	Number of slot pairs in the first ring	12, 14, 16
b_1	Lower air gap	4 mm
h	Header height	3 mm
r_a	Header radius	1.4 mm
b_2	Upper air gap	1 mm

the models were drawn with their design parameters and feeders as shown in Table 2.

Approximately 40 RLSA models were designed using different values of θ (beam squint values) and n (number of slots in the first ring). This diversification was performed to verify the application of the proposed technique in all cases. It was also used to obtain the best values for θ and n leading to the acquisition of a suitable model.

Based on previous assessments in Section 3, the designed systems were observed as dual-beam RLSAs (one third-circle antenna), due to the effects of the implemented technique, as shown in Figs. 6(a) and (b). This indicated that the designed slots, present in the radiating element, were similar to those observed in the background. However, a specific slot (red curved colour) was removed from the background to widen the antenna bandwidth, as well as balance the beam gains produced by the radiating element and the background.

All the models were also simulated towards obtaining several performance parameters, such as

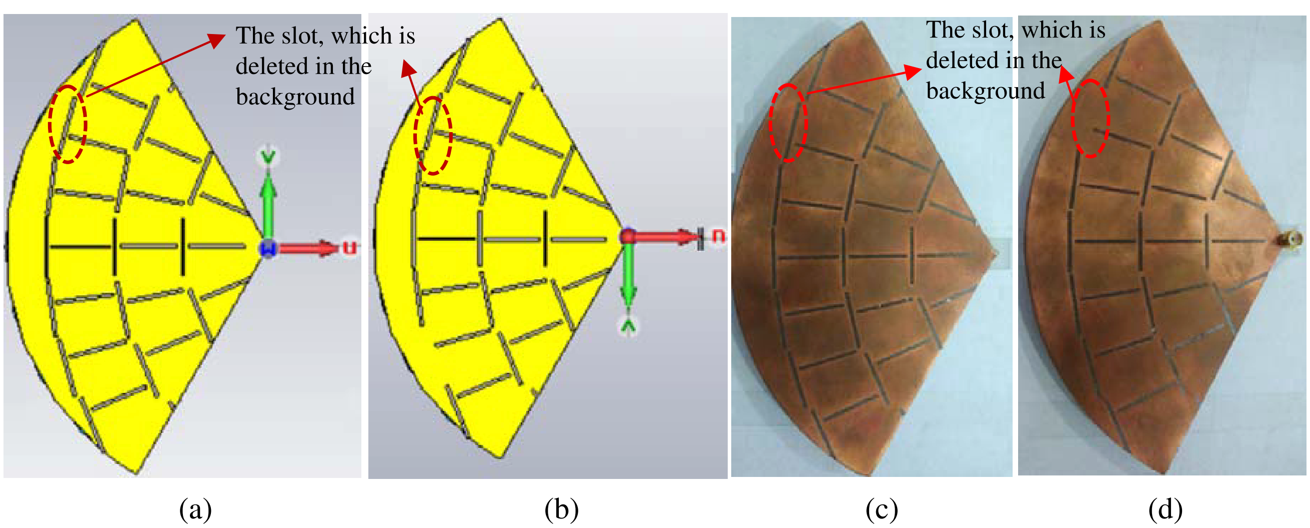
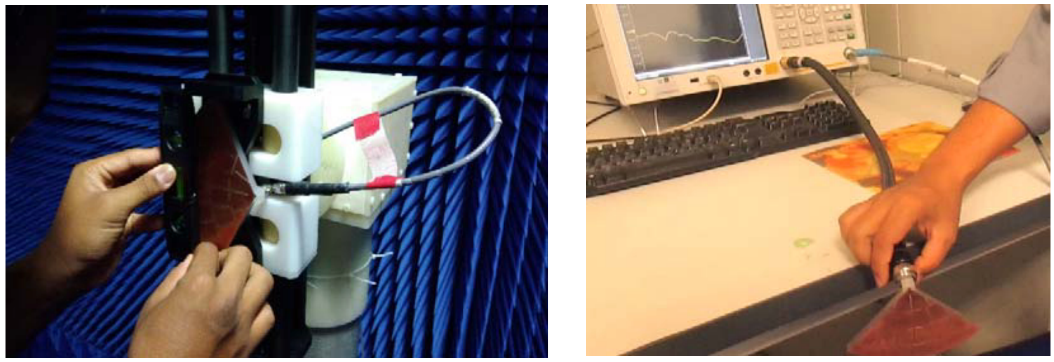


Figure 6. (a) The radiating element of the best model, (b) the background of the best model, (c) the radiating element of the prototype, and (d) the background of the prototype.



(a) (b)

Figure 7. The setup measurement of the prototype model using (a) anechoic chamber, and (b) network analyzer.

radiation pattern, gain, reflection coefficient, and bandwidth. This was then accompanied by the selection of the best model for fabrication. Figs. 6(c) and (d) show the fabricated prototype of the model, with Figs. 7(a) and (b) indicating the setup measurement through an anechoic chamber and Vector Network Analyzer.

5. RESULTS AND ANALYSIS

Figure 8 shows the reflection coefficient response of the best models (in redcolor), where the bandwidth was not achieved at a frequency of 5.8 GHz. This was due to a large amount of interference with the signal orientation in the cavity, regarding the placement of slots in the background elements. Based on these results, the technique for forming bandwidth was introduced through the removal of one or more background slots. To obtain the best reflection coefficient and bandwidth, the eliminated slot was determined through a deletion test in the background, as shown in Fig. 6. Subsequently, the related reflection coefficient response is observed in Fig. 8 (in green color), where the bandwidth increased to approximately 586 MHz after slot deletion. This was highly sufficient for Wi-Fi applications, therefore, showing the ability of the deletion technique in bandwidth formulation.

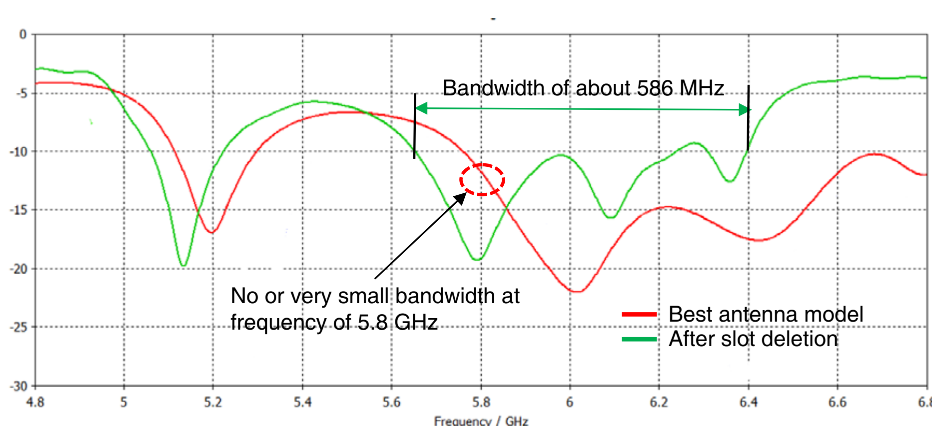


Figure 8. The reflection coefficient of the best antenna model and after the implementation of the slot deletion technique.

Figure 9 shows the agreement between the simulation and measurement of reflection coefficient (RC). The measurement indicated a better RC performance and wider bandwidth of approximately 1200 MHz than the simulation output.

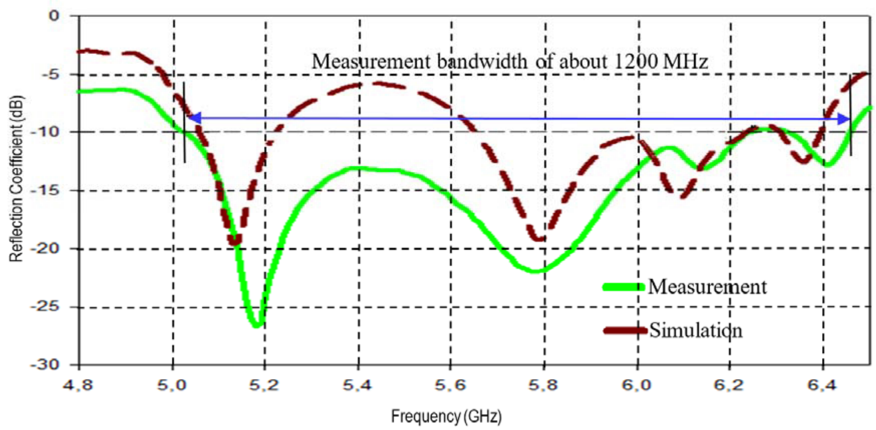
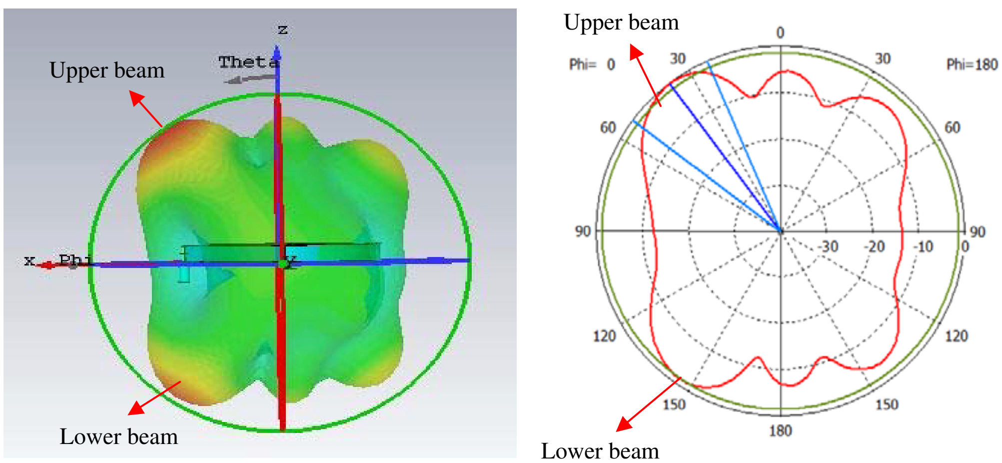
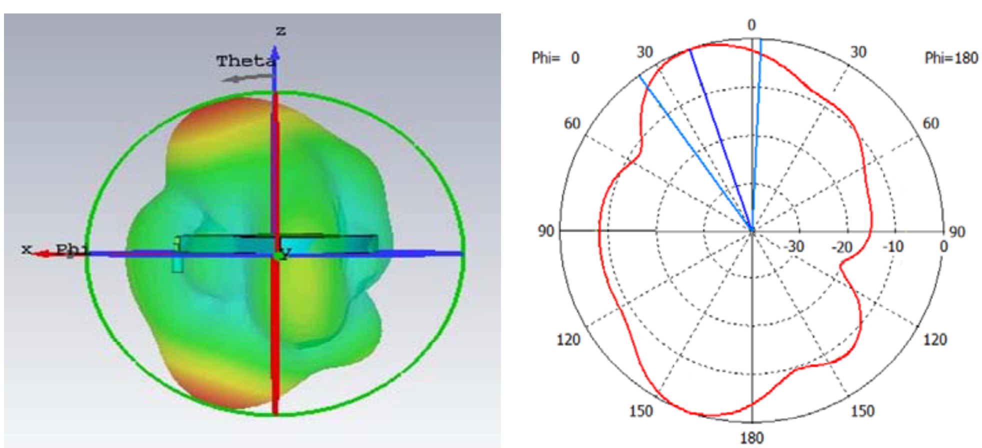


Figure 9. Comparison between simulation and measurement result for reflection coefficient.



(a) (b)

Figure 10. The radiation pattern of the antenna model before the slots deletion, (a) 3-dimension, (b) 2-dimension for Phi = 0° and Theta = 0–360°.



(a) (b)

Figure 11. The radiation pattern of the antenna model after the slots deletion, (a) 3-dimension, (b) 2-dimension for Phi = 0° and Theta = 0–360°.

Figure 10 shows the radiation pattern of the best model before the slots deletion, where the gain of the upper beam was higher than that of the lower one by approximately 2 dB, indicating an unbalanced condition. Based on Fig. 11, the radiation pattern of the best model was also observed after the slot deletion, indicating that two balanced beams had an identical gain, symmetrical directions, and beamwidth of 9 dB, 20°, and 160° (upper & lower beams), as well as 38°. This indicated that the slot deletion technique was successfully implemented in balancing the beams' patterns and gains. Fig. 12 also shows the agreement between the simulation and measurement outputs for the radiation pattern.

To show the efficiency of the introduced technique, a single beam antenna of a similar size to the dual beam system was designed and simulated as shown in Fig. 13. Analytically, the emitted power of the dual beam antenna is the same as the half of the single type. This is because in the dual-beam antenna, the power is emitted not only by the radiating element but also by the background. Since the

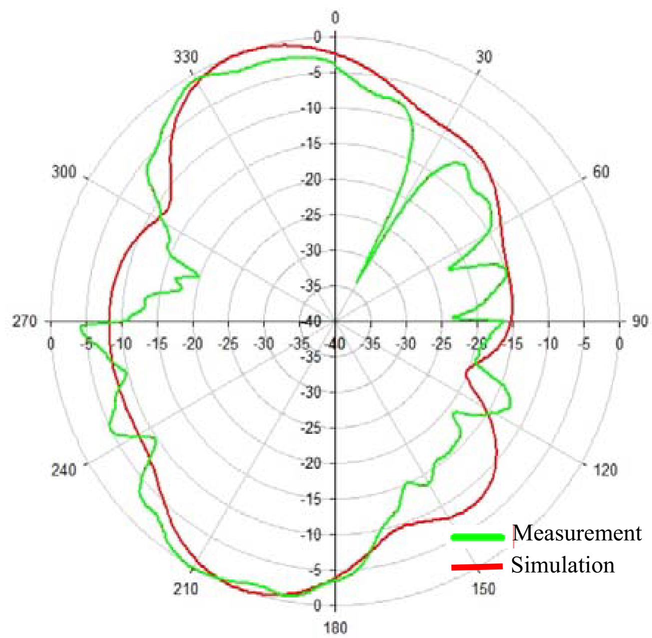
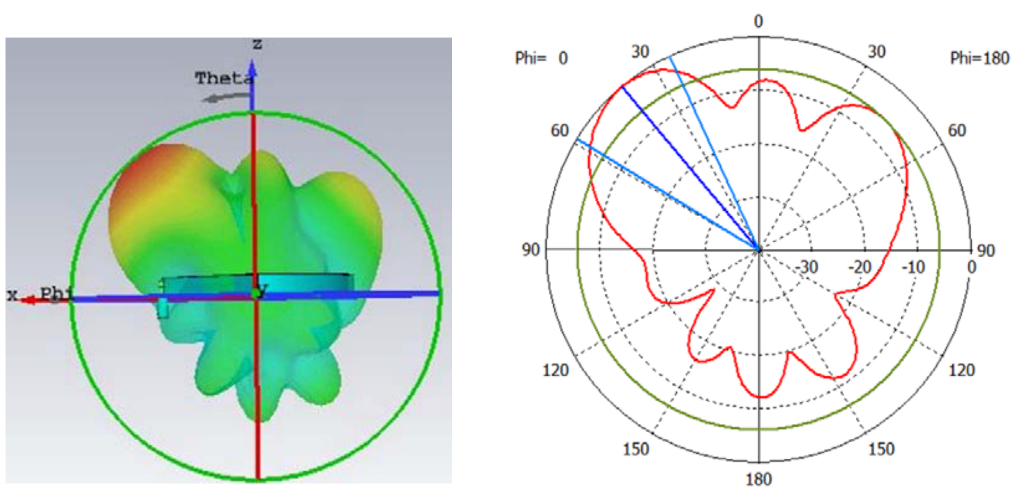


Figure 12. Radiation pattern for simulation and measurement.



(a) (b)

Figure 13. Radiation pattern of a single beam RLSA antenna.

emitted power is directly proportional to gain, the gain of a dual-beam antenna is expected to be twice of the single one. From the simulation result of the single beam, a gain of 11.88 dB was observed. This indicated that the dual-beam antenna had a gain that was 2.88 dB lower than that of the single-beam system. These results were in line with the beam splitting theory, where a reduction of about 3 dB should be observed.

Finally, Figs. 9 and 12 show that the simulation corresponds to the measurement results. The slight deviation in the measurement is due to errors that occurred in fabricating the prototypes, especially in printing the radiating element's design, drilling the antenna's feeder hole, and soldering the head disc at the correct position.

6. CONCLUSIONS

A multibeam one-third RLSA antenna was successfully designed using the proposed cut technique and the implementation of slots on the model's background surfaces. The slot deletion technique was also introduced to form bandwidth, as well as balance the radiation pattern and gain of the antenna beams. Based on the results, the designed system had a similar low profile to microstrip antennas, although it was better in gain and efficiency. This confirmed the possibility of being utilized as an alternative system for microstrip antennas. It is also recognized as a notable move towards the development of small multibeam RLSA antennas for various devices, such as point to multipoint bridges or routers. In the development of these systems, future development needs to be carried out to obtain more beams. Furthermore, beam-steering and beamforming RLSA antennas should be developed further by modifying the single feeder into a reconfigurable multi-feeder system, through various network connections, such as an RF combiner or divider.

REFERENCES

1. Ando, M., J. Takada, T. Numata, and N. Goto, "A linearly polarized radial line slot antenna," *IEEE Trans. Antennas Propag.*, Vol. 36, No. 12, 1675–1680, 1988, doi: 10.1109/8.14389.
2. Davis, P. W. and M. E. Bialkowski, "Experimental investigations into a linearly polarized radial slot antenna for DBS TV in Australia," *IEEE Trans. Antennas Propag.*, Vol. 45, No. 7, 1123–1129, 1997, doi: 10.1109/8.596903.
3. Koli, M. N. Y., M. U. Afzal, and K. P. Esselle, "Increasing the gain of beam-tilted circularly polarized radial-line slot array antennas," *IEEE Trans. Antennas Propag.*, 1, 2022, doi: 10.1109/TAP.2022.3140490.
4. Bray, M., "A spiral radial line slot array antenna for NASA's double asteroid redirection test (DART)," *2020 IEEE International Symposium on Antennas and Propagation and North American Radio Science Meeting*, 379–380, 2020, doi: 10.1109/IEEECONF35879.2020.9330400.
5. Imran, M. I., A. R. Tharek, and A. Hasnain, "An optimization of beam squinted radial line slot array antenna design at 5.8 GHz," *2008 IEEE International RF and Microwave Conference*, 139–142, 2008, doi: 10.1109/RFM.2008.4897411.
6. Bialkowski, K. S. and S. Zagriatski, "A dual band 2.4/5.2 GHz antenna including a radial line slot array and a patch," *IEEE Antennas and Propagation Society Symposium, 2004*, Vol. 3, 3095–3098, 2004, doi: 10.1109/APS.2004.1332033.
7. Takada, J., M. Ando, and N. Goto, "A reflection cancelling slot set in a linearly polarized radial line slot antenna," *IEEE Trans. Antennas Propag.*, Vol. 40, No. 4, 433–438, 1992, doi: 10.1109/8.138845.
8. Hirokawa, J., K. Sakurai, M. Ando, and N. Goto, "A matching slot pair for a circularly-polarized slotted waveguide array," *International Symposium on Antennas and Propagation Society, Merging Technologies for the 90's*, Vol. 2, 926–929, 1990, doi: 10.1109/APS.1990.115260.
9. Akiyama, A., T. Yamamoto, M. Ando, and N. Goto, "Numerical optimisation of slot parameters for a concentric array radial line slot antenna," *IEE Proc. Microwaves, Antennas Propag.*, Vol. 145, No. 3, 141–145, 1998, doi: 10.1049/ip-map:19981630.

10. Islam, M. R. U., L. Faisal, and T. A. Rahman, "Simple integrated system for wireless backhaul networks," *2008 International Conference on Computer and Communication Engineering*, 341–345, 2008, doi: 10.1109/ICCCE.2008.4580625.
11. Purnamirza, T. and T. A. Rahman, "A novel technique in simplifying the fabrication process and improving the reflection coefficient of the linear polarized radial line slot array (LP-RLSA) antennas," *Journal of Electromagnetic Waves and Applications*, Vol. 26, No. 4, 535–548, Jan. 2012, doi: 10.1163/156939312800030631.
12. Purnamirza, T., T. A. Rahman, and M. H. Jamaluddin, "The extreme beamsquint technique to minimize the reflection coefficient of very small aperture radial line slot array antennas," *Journal of Electromagnetic Waves and Applications*, Vol. 26, Nos. 17–18, 2267–2276, Dec. 2012, doi: 10.1080/09205071.2012.733491.
13. Purnamirza, T., M. Ralibi, I. Ibrahim, A. Fitri, D. Rahmi, and S. Sutoyo, "A design of radial line slot array antennas using the specification of panel antennas," *TELKOMNIKA (Telecommunication Comput. Electron. Control.*, Vol. 17, 3066, Dec. 2019, doi: 10.12928/telkomnika.v17i6.12679.
14. Takada, J., T. Yamamoto, M. Ando, and N. Goto, "An azimuthal multibeam radial line slot antenna for mobile satellite communication," *Proceedings of ICUPC '95 — 4th IEEE International Conference on Universal Personal Communications*, 571–574, 1995, doi: 10.1109/ICUPC.1995.497073.
15. Davis, P. W., "A linearly polarised radial line slot array antenna for direct broadcast satellite services," Thesis Report, University of Queensland, 2000.