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The Development of Multibeam Quarter-Cut Radial Line Slot Array (RLSA) Antennas

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ABSTRACT: This research aimed to introduce multibeam quarter-cut Radial Line Slot Array (RLSA) antennas for the first time. These antennas are distinct from the multibeam full-circle RLSA due to the use of quarter RLSA, making it suitable for small devices. To achieve beams directed to the backside, an unconventional approach was taken by placing slots on the antenna's background. A technique comprising the deletion of specific slot pairs in the radiating element was introduced to balance the gain and beam shape. Furthermore, thirty-six multibeam quarter RLSA models were designed and simulated. The best model was then fabricated and measured to validate the simulation results. Consequently, the results showed the possibility of designing multibeam antennas with symmetrical beams in terms of gain, direction, and beamwidth, which were 6.23 dBi, 37°, 145°, and 34°, respectively. The gain of 6.23 dBi was 3 dB less than the single-beam antennas, consistent with the theory of beam splitting. Additionally, antennas exhibited low reflection and a broad bandwidth suitable for Wi-Fi needs. Finally, the agreement between measurement and simulation validated the design of antennas.

1. INTRODUCTION

Large Radial Line Slot Array (RLSA) antennas, with diameters at least 600 mm, are successfully investigated and adopted for satellite broadcasting applications [1–4]. Following this success, antennas were investigated for other applications, such as for Wi-Fi devices [4–6]. However, Wi-Fi devices require significantly smaller antennas than those used for satellite applications, necessitating the development of small RLSA antennas. As opposed to large RLSA antennas, which have many slots, small RLSA antennas have much fewer slots, resulting in high reflection issues [7].

Research in previous decades has proposed multiple techniques to address the issue of high reflection in small RLSA antennas. These techniques include the canceling slot technique [8, 9], long slot technique [10], normal beamsquint technique [5], extreme beamsquint technique [11], and FR4 technique [12]. Based on the results, the extreme beamsquint technique was considered the most promising for mitigating high reflection. The technique was successfully implemented in designing small RLSA antennas that meet market demands with favorable reflection and gain characteristics [13–17]. Additionally, extreme beamsquint was effectively combined with the cutting technique to reduce the dimensions of RLSAs [18, 19]. The results of this minimization effort include half-cut, quarter, and one-third RLSA antennas.

Multibeam RLSA antennas [20, 21] and beamsteering [22] have both benefited from the use of extreme beamsquint. It was successfully possible to create twin and triple-beam antennas [20]. For the purposes of this study, the number of slot groups that match the required number of beams is designed in order to produce the beams. For instance, as Figure 1(a) illustrates, three slot groups result in three beams. By including slots on the background surface, as seen in Figure 1(b), the construction of multibeam antennas is improved even further [21]. Other latest researches of multibeam waveguide antennas are metallic waveguide transmitarray antennas (MWTAs) [23, 24].

The radial power flow within an antenna's cavity is disrupted when the background is used to form beams, which may result in a gain reduction [18]. The main goal of both [20] and [21] was the development of full-circle antennas for multibeam RLSA. Consequently, building based on the work described in [20] and [21], this research advances the construction of multibeam antennas. In contrast to other studies that employed full-circle antennas, the current study uses quarter RLSA antennas to create multibeam antennas. It is crucial to ensure that the design is suitable for small Wi-Fi devices. Moreover, this research presents a challenge because creating multibeam RLSA antennas in quarter-circle form disrupts the power flow orientation. This disruption arises from using the background as a radiating element and from the effects of antenna cutting [18, 19].

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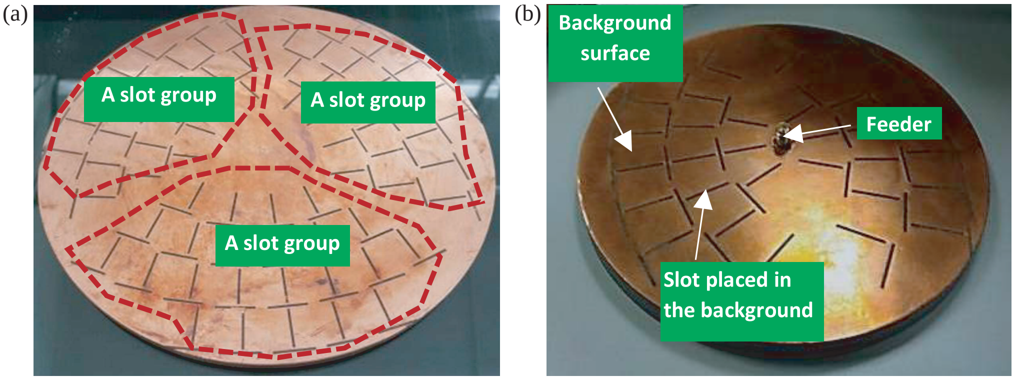

FIGURE 1. (a) Triple-beam RLSA consists of three slot groups [20]. (b) Background with installed slot [21].

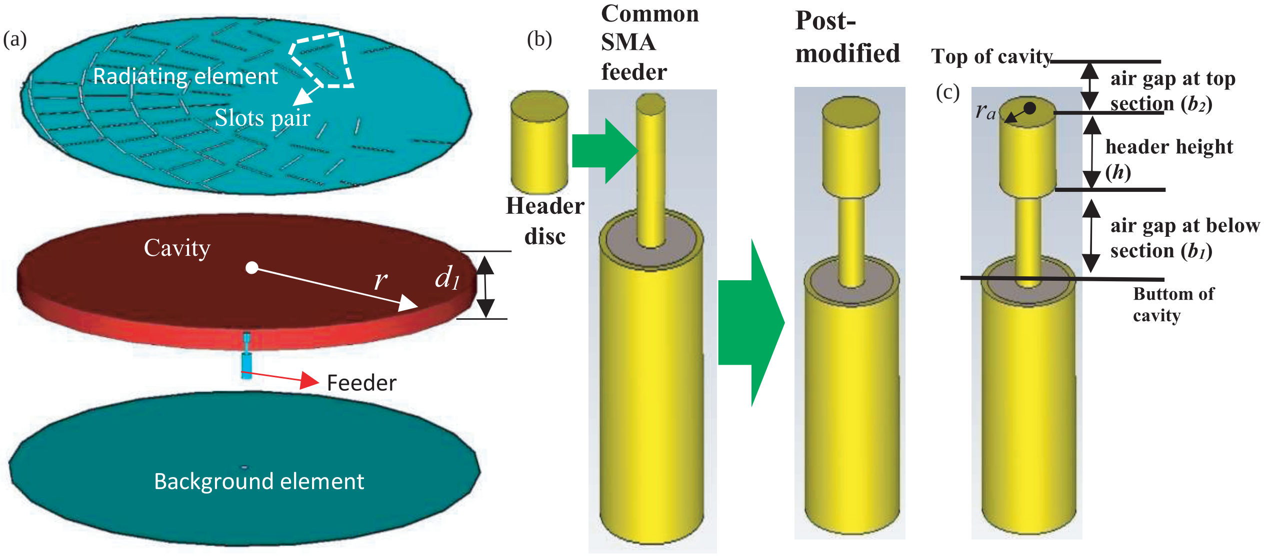

FIGURE 2. (a) RLSA antennas parts. (b) Process of header disc installations. (c) Parameters of feeder.

2. STRUCTURES, MODELS, AND PROTOTYPES OF ANTENNA

Typical RLSA antenna constructions were composed of three layers: a background, a polypropylene cavity, and a copper radiating element. As seen in Figure 2(a), the radiating component was made up of pairs of slots that released signals.

Every slot pair was specifically designed in terms of location and orientation. Hence, the signals they released complimented one another and increased gains. For this study, dozens of antennas, each with 10 slots, were required to be modeled. Because it was challenging to calculate and draw slots by hand, a Visual Basic Application (VBA) program integrated with CST simulation was created. This program's automated calculation and drawing of slots allowed for the quick design of dozens of antenna types.

The computer program was used to determine different slot parameters using the equations given below [1–3], together with the meanings of the parameters displayed in Table 1 as well as Figure 3 and the design parameters provided in Table 2. These characteristics comprised the length, distance, as well as inclination angle of the slot pairs and locations.

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

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

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

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

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

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

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

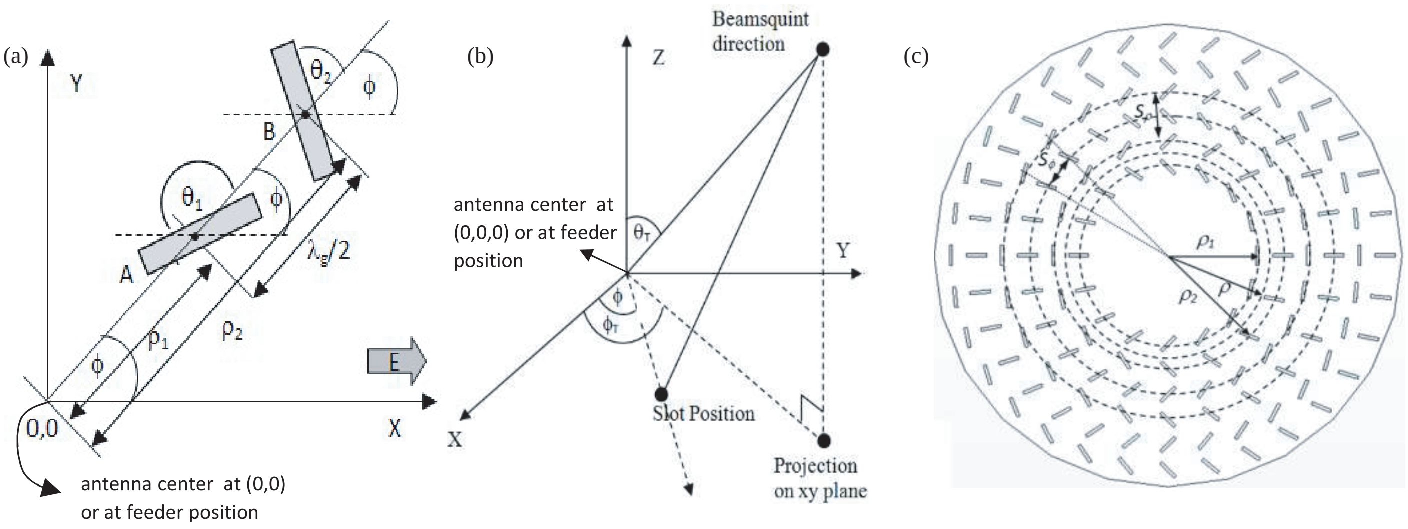

FIGURE 3. Figure 3 showed (a) parameters of slot pair (x-y plane), (b) parameters of slot position as well as its relation to the (x-y-z plane) beam direction, and (c) the lenght between two adjacent slot and unit radiator in radial and azimuthal directions [1–3].

TABLE 1. The slot pairs design parameters [1].

Parameters	Symbols
incline of first slot in degree	θ_1
incline of second slot in degree	θ_2
beamsquint in elevation in degree	θ_T
position of first and second slot in azimuth in degree	φ
beamsquint in azimuth in degree	φ_T
distance of a first slot to center of antennas	ρ_1
distance of a second slot to center of antennas	ρ_2
number of slot pairs in the first ring	n
integer numbers expressing the distance between innermost ring and center of antennas	q
distance in radial direction between adjacent unit radiators located in adjacent different rings	S_ρ
distance in azimuth direction between adjacent unit radiators located in adjacent different rings	S_ϕ

TABLE 2. The antennas models design parameters.

Parameters	Symbols	Values
permittivity of cavity	ε_{r1}	2.33
beamsquint in degree	θ_T	63 up to 90
thickness of cavity	d_1	8 mm
thickness of background	d	0.4 mm
thickness of radiating element	d_2	0.4 mm
center of frequency	f	5.8 GHz
width of slot	w	1 mm
radius of cavity	r	85 mm
area of antenna	L	5671.6 mm
number of slot pairs in first ring	n	12, 14, 16

TABLE 3. Feeders Design parameters [5].

Symbol	Parameter	Value
b_1	height of air gap at below section	4 mm
h	height of header disc	3 mm
r_a	radius of header disc	1.4 mm
b_2	height of air gap at top section	1 mm

$$L_{rad} = \left(4.9876 \times 10^{-3}\rho\right) \frac{12.5 \times 10^9}{f_0} \tag{7}$$

As seen in Figure 2(b), the antenna's feeder may be a typical Sub-Miniature Version-A (SMA) feeder with a copper header added to the top. After the alteration, the antenna and feeder impedance were 50 ohms. This also guarantees the antenna cavity's radial flow of electricity from the feeder. The feeder's characteristics, detailed in Figure 2(c), are displayed in Table 3.

Several designs were made and simulated in order to get the best antenna model. There were 36 models overall since these differed in p (the number of slots in the first ring, ranging from 12, 14, to 16) as well as θ_T (the beamsquint, ranging from 63° to 90° with increment of 3°), resulting in a total of 36 models. The background element surface was left with no slot by default because its only purpose was as waveguide layer to route the signal into the antenna cavity.

Identical slots for those in the radiating component were inserted in the background element to permit the backward-directed beam, as illustrated in Figures 4(a) and (b). This is because RLSA antennas were created to provide dual beams directed to the broadside and the rear. Furthermore, the antennas were cut using the cutting technique in order to produce quarter-cut antennas, according to Figures 4(c) and (d). Subsequently, the models were designed to have two beams, squinted at approximately 35° and 145° in elevation, as shown in Figures 5(a) and (b). The deletion of one slot pair in the radiating

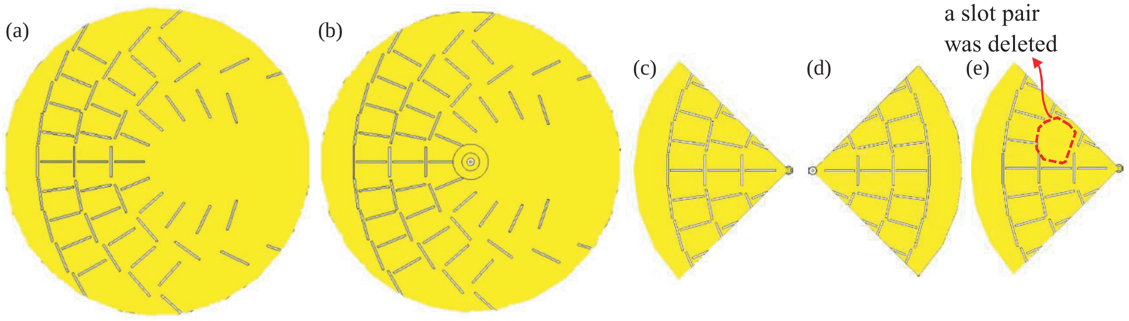

FIGURE 4. (a) Radiating element. (b) Background element. (c) Radiating element after cut. (d) Background element after cut. (e) Radiating element of Figure 4(c) after deleting a particular slot pair.

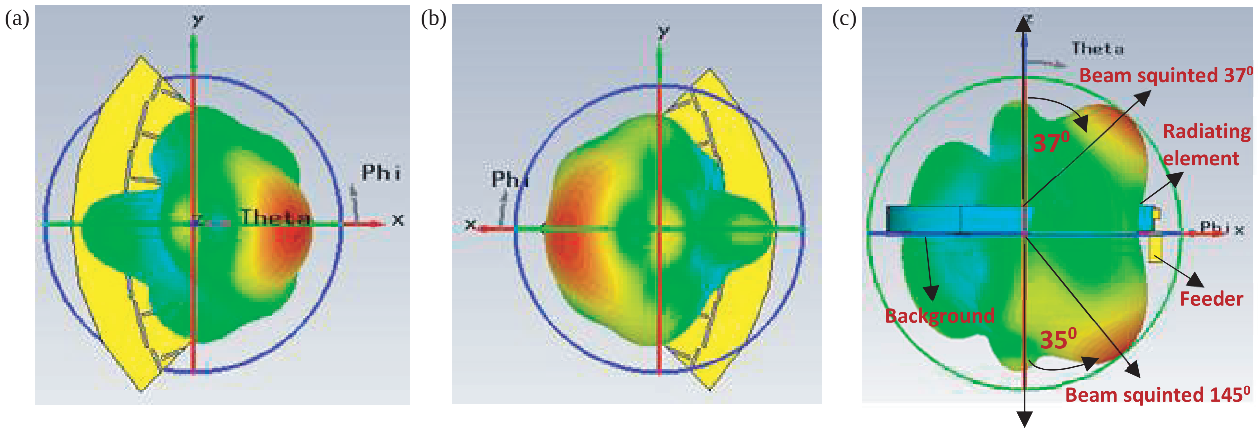

FIGURE 5. (a) Radiating element-produced upper beam. (b) Background element-produced lower beam. (c) Antenna model-generated dual beam.

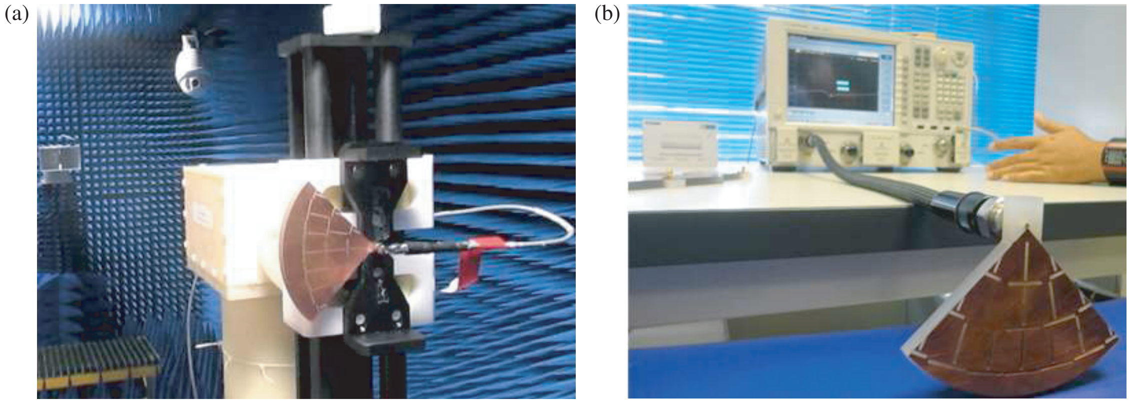

FIGURE 6. The prototype masurment utilized. (a) Anechoich chamber. (b) Vector network analyzer.

element was parameterized to balance the gain and shape of both beams. Typically, the most balanced and similar radiation pattern between the two beams was achieved by deleting slot in the second ring, illustrated in Figure 4(e). Subsequently, the resulting radiation design is shown in Figure 5(d).

After simulating all the models using CST software, the best was selected and fabricated, which has design parameter of $p_0 = 16$ and beamsquint of $73°$. The results of the simulation were then confirmed by measuring the constructed prototype. The measurement operations, whose results were covered in the next part, are displayed in Figure 6.

3. RESULTS AND DISCUSSION

Figure 7 displays the optimal antenna model's reflection coefficient for both simulation and measurement. A bandwidth around 1.5 GHz was demonstrated, which is rather wide for 5.8 GHz applications.

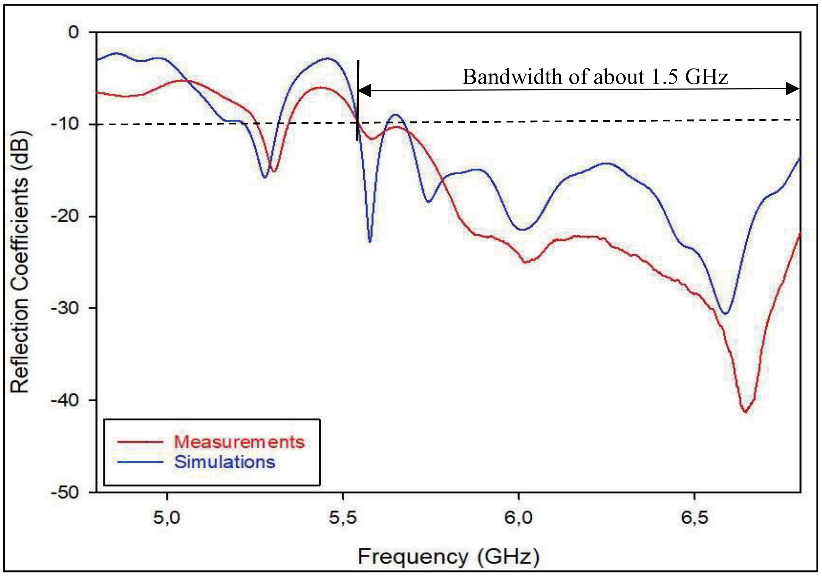

FIGURE 7. Reflection coefficient plot.

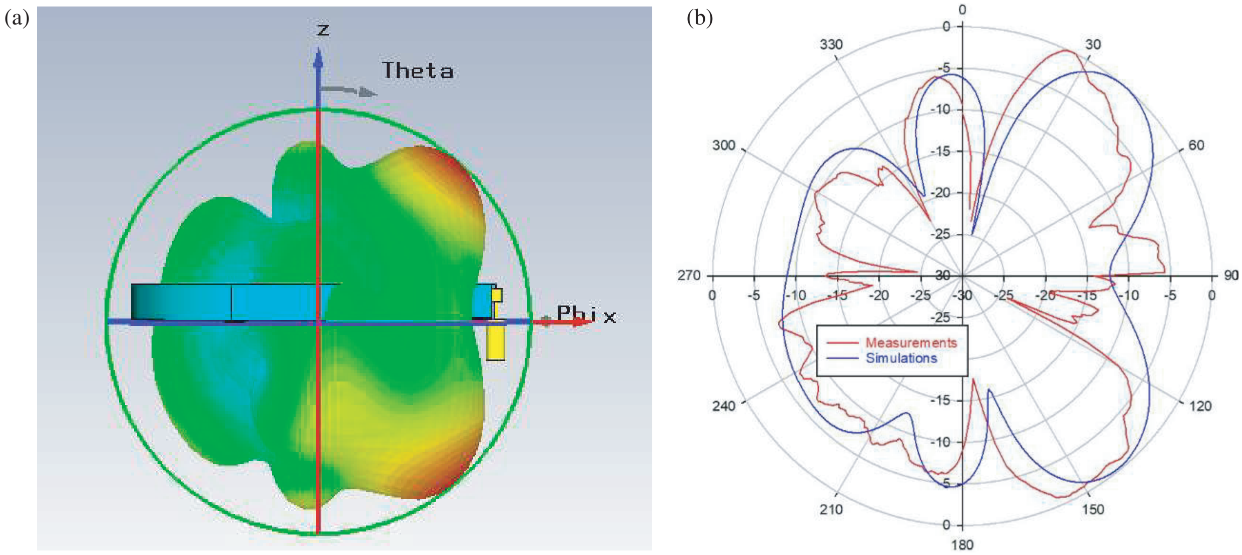

FIGURE 8. Radiation pattern. (a) Three-dimensional. (b) Two-dimensional.

Figure 8(a) displays antenna radiation patterns in 3D. In this context, the azimuth angle was indicated by Phi, and the elevation angle was represented by Theta. The 2D radiation pattern at Phi = 0°, with Theta spanning from 0° to 360°, was also depicted in Figure 8(b). From both Figures 8(a) and (b), it was observed that similar beams could be designed with beamwidth of approximately 34°. Additionally, the beams had considerable symmetry in elevation directions, approximately at 37° and 145°.

Similar beams were produced by giving each beam the same number and location of slots in its design. By altering the number of slots correspondingly, the beams can grow or decrease. There was good agreement between the simulation and measurement findings, with a gain of 7.68 dBi for simulation and 6.23 dBi for measurement.

To analyze the decrease in gain, single-beam antennas with a size twice as large as dual-beam antennas were designed. During simulation, single-beam antennas obtained a gain of 12.95 dBi. Theoretically, the gain of dual-beam antennas should be 6 dB lower than that of single-beam antennas. So the gain of 7.68 dBi for dual-beam antennas, which was around 5.7 dB less than the gain of 12.95 dBi for single-beam antennas, was in line with theory.

Columns 4 and 5 of Table 4 compare the area and gain of various small RLSAs to the dual-beam RLSA antenna. The gains of the other antennas (column 3 in Table 4) were lowered by 3 dB since they were single-beam before they were compared

TABLE 4. Comparison of other compact RLSA to dual beam antennas.

References	Radii (cm)/ areas (cm^2)	Gains after subtracted by 3 dB (dBi)	Comparison of areas of other small RLSA antennas to dual beam antennas (times)	Comparison of the gain of other small RLSA antennas to dual-beam antennas (times)
12	7.5/176.62	6	1.56	0.68
13	7.5/176.62	9	1.56	1.36
14	14/615.44	15.4	5.43	5.92
15	12.7/506.45	14	4.46	4.29
16	10.7/359.5	13.25	3.17	3.61
17	12.3/475	14.53	4.19	4.84
20	7.6/182.25	8	1.61	1.08

with the dual-beams. In general, dual-beam antennas outperformed other compact RLSA antennas in terms of gain. For example, antennas in [12] and [13] had areas 1.56 times larger than the area of dual-beam antennas. Since theoretical gains are proportional to the area, antennas described in [12] and [13] should have a gain that is 1.56 times higher than the dual-beam antenna. However, the gains were actually worse by 0.68 and 1.36 times, respectively. It is important to note that comparable outcomes were found in other studies.

The alignment between the simulation and measurement findings was demonstrated in Figures 7 and 8. However, the prototypes' fabrication flaws may cause a little variation in the measurement findings. Among these flaws were errors in soldering the head disc in the proper location, accurately drilling the feeder hole, and printing the radiating element's design.

4. CONCLUSIONS

In conclusion, this research successfully designed dual-beam quarter-cut RLSA antennas that used the background for beam radiation, showing good performance. Typically, the technique of deleting specific slot pair in the radiating element was introduced to balance the gain and shape of the beam. The successful design was expected to contribute to the development of small multibeam RLSA antennas for Wi-Fi multibeam devices. As opposed to the low profile-like patch antenna, the designed antenna had superior gain and efficiency, making it a viable alternative to patch antenna. Future research could focus on creating quarter-cut RLSA antennas with more beams. Additionally, enabling beam steering and beamforming capabilities in RLSA antennas could be achieved by modifying the single feeder used in this research into a reconfigurable multi-feeder connected to a beamforming network, such as an RF combiner or divider.

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