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The technique to design multibeam Radial Line Slot Array (RLSA) antennas

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ABSTRACT

The Technique, to design multibeam Radial Line Slot Array (RLSA) antennas optimally, was proposed in this study, using high beam squint values to produce more slots. This is necessary to maintain gain, which dropped due to the beam splitting. A gap was also incorporated between the slots group to overcome a coupling between adjacent beams which can lessen gains. RLSA models for 42 dual and 42 triple-beams were simulated after which a prototype for each was measured to verify the simulation. The results showed the possibility of obtaining multibeam antennas with similar symmetrical beams in terms of beamwidth, gain, and direction. The gains obtained were 13.5 dBi for the dual-beam and 10.5 dBi for the triple-beam, indicating a difference of 3 and 4.77 dB, respectively, with the single-beam antennas, thereby, making them suitable for the theory of beam splitting. The antennas also have sufficient bandwidth and a good reflection coefficient.

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KEYWORDS
Multibeam; Radial Line Slot Array (RLSA); high beamsquint

Introduction

Radial Line Slot Array (RLSA) antennas were originally intended, and successfully developed, for satellite broadcast applications, which are big [1,2]. Researchers then have tried implementing them in small antenna applications due to the success reported in [3–7]. This effort has, however, been constrained for years due to the high signal reflection problem in small RLSAs [7].

Several researchers have tried overcoming this problem, for example, Akiyama [8] and Hirokawa [9] introduced the matching slot technique to dispose remaining power at RLSA perimeters, while Zagriatski [6] used the long slot technique to maximize power radiation through slots targeted towards minimizing signal reflections. Purnamirza [10] used two-cavity layers to enable reflected signals to eliminate them and introduced the extreme beam squint technique to efficiently radiate power through slots [11], thereby significantly

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reducing signal reflections. Purnamirza [12–14] successfully implemented this technique to design several small Wi-Fi RLSAs for market needs. Meanwhile, Koli [15] recently investigated a small aperture RLSA for 11 GHz frequency.

Multibeam RLSA antennas were introduced by Takada [16], by using a phased shifter to result in four different azimuthal beams. This study was carried out using numerical calculations, without conducting either simulation using full electromagnetic software of a model or a measurement of its prototype. Hence, this paper is a kind of introduction of concept of how to enable multibeams for RLSA antennas. There was, however, no significant progress in the development of multibeam RLSAs till now. This paper, therefore, introduced the technique to develop multibeam RLSAs. Different from reference [16] that used a phase shifter to enable multibeams, this paper groups antenna slots into several groups, each of which generated a single beam, thus to enable multibeam.

Technique to enable multibeam in RLSA antennas

Normally, the slots in single-beam RLSA antennas are expected to be uniformly distributed, as depicted in Figure 1(a). It is possible to design antennas with multiple beams by ensuring that a slot group has beam heading in a certain direction, while others have them in other directions, as illustrated in Figure 1(b).

The division of the slots into two groups decreases the numbers available for each beam and this further leads to an experience of a quite significant drop in gain. It is, therefore, possible to design the distance between the slots as close as possible before dividing the slots into two groups to ensure the antennas have more slots and more gain. It is, however, impossible to achieve this using low beam squint values, which are lesser than 20° as the usual practice in a single-beam design. This paper, therefore, introduced the use of high beam squint value, which is higher than 60° to design the tight slots and the result is shown in Figure 2(a).

The figure shows the slots in the left area are tight and get sparser as they move closer to the right and this indicates they have a beam directing to the right. The sparse slots were deleted to provide a blank space for other slots group, as shown in Figure 2(b). Moreover, Figure 2(b,c) show the number of slots designed using high beam squint values to be greater than those designed using low beam squint values.

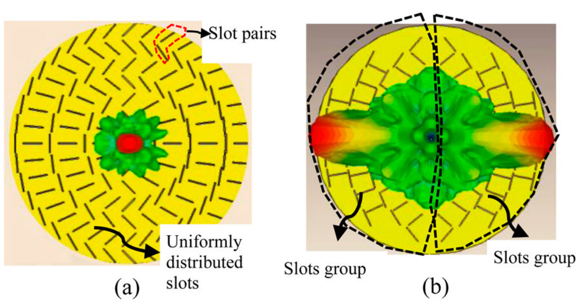


Figure 1. (a) uniformly distributed slots of single-beam RLSA (b) double-beam RLSA.

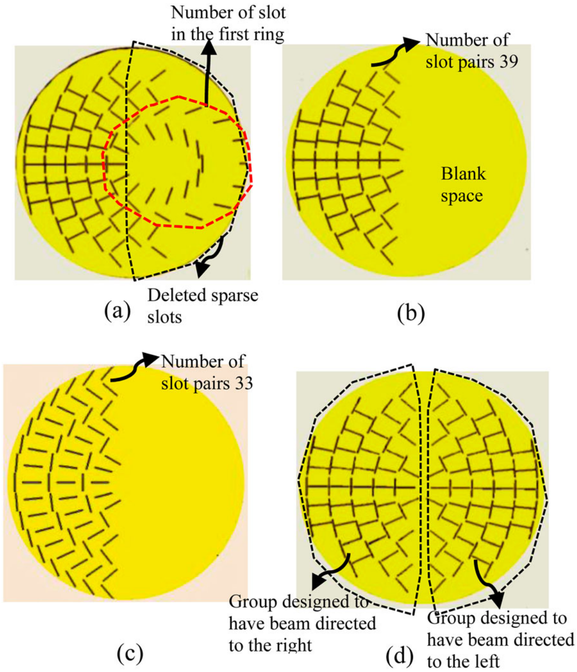


Figure 2. (a) Slots designed using high beam squint (b) The design after deleting the sparse slots (c) Slots designed using low beam squint (d) The final design with two slots groups.

Another slot group was added to the antenna of Figure 2(b) to direct the beam to the left and the image in Figure 2(d) was produced. This, therefore, means two slots groups were designed with the beams in the opposite direction.

It is very important to consider the interference between adjacent beams while designing the slots of multibeam antennas due to its ability to decrease the beam focus and the gain. This was, therefore, overcome by providing an optimum sufficient gap (see Figure 3(a,b)) between the slots groups to avoid interference between the beams using parameterization.

This research verifies the technique previously explained by designing and simulating several multiple beam RLSA models with different beam squint values, after which the best antenna model was selected and its prototype fabricated, as presented in Section 3. Moreover, Section 4 analyzed the results from the prototype measurement and those associated with the simulation of the model with the focus placed on indicators, such as radiation pattern, coefficient reflection, bandwidth, and gain. Finally, Section 5 concludes the overall results.

Antenna models and prototypes

The structure of antenna models consists of a copper radiating layer, a copper background layer, a polypropylene cavity, and a feeder, as shown in Figure 3(a). The difficulty in drawing the antenna structure manually, especially the slots, led to the development of a Basic computer program to ensure the models' structures are drawn faster and more accurately. Several equations, taken from [1,2] and design parameters listed in Table 1, were used in

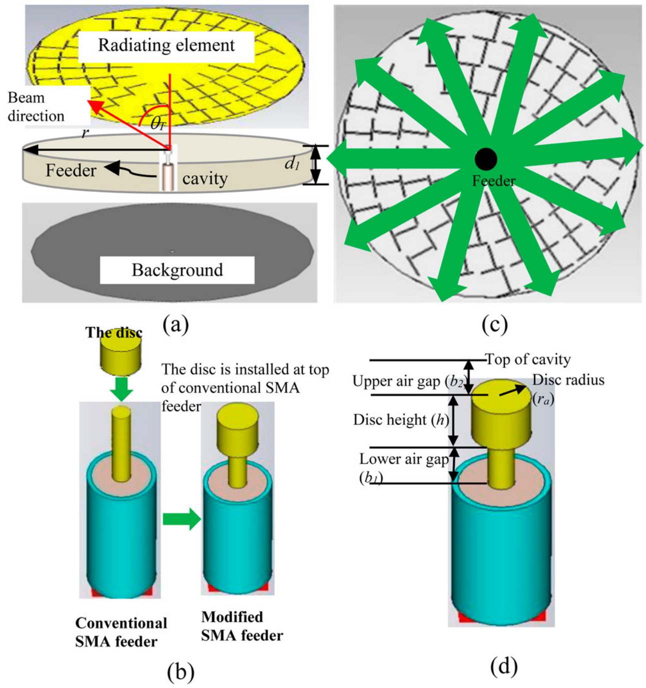


Figure 3. (a) Structure of RLSA (b) Installation of copper disk (c) Power flow from the feeder to antenna perimeter (d) Parameters of the feeder.

Table 1. Specification parameters for the antenna model [12–14].

Symbol	Parameter	Value
θ_T	Beam squint angle	60° up to 89°
d_1	cavity thickness	8 mm
d_2	radiating element thickness	0.1 mm
d	background thickness	0.1 mm
ε_{r1}	cavity permittivity	2.33
f	frequency	5.8 GHz
r	antenna radius	115 mm
n	number of slot pairs in the first ring	10, 12, 14, 16

the computer program to calculate several slots parameters, such as the inclination angle of the slots' pairs, their positions, the distance between them, and their length.

Furthermore, to produce the tight slots, as discussed in section II, the high beam squint angle values (θ_T) that range from 60° up to 89° were used. As an example, by substituting the $\xi = \frac{1}{\sqrt{\varepsilon_{r_1}}} = \frac{1}{\sqrt{2.33}} = 0.655$, $\lambda_g = 33.88$ mm, ϕ (azimuth angle of slots) $= 180°$, and $\phi_T = 0°$ into Equation (1) [1,2], we would get the distance between slot pairs for a low beam squint value (θ_T) of 20° = 27.8 mm, and for a high beam squint value (θ_T) of 80° = 21.9 mm, thus verifying how high beam squints produce more tight slots than low beam squints.

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

Table 2. Specification parameters of the feeder [17].

Symbol	Parameter	Value
b_1	lower air gap	4 mm
H	disk height	3 mm
r_a	disk radius	1.4 mm
b_2	upper air gap	1 mm

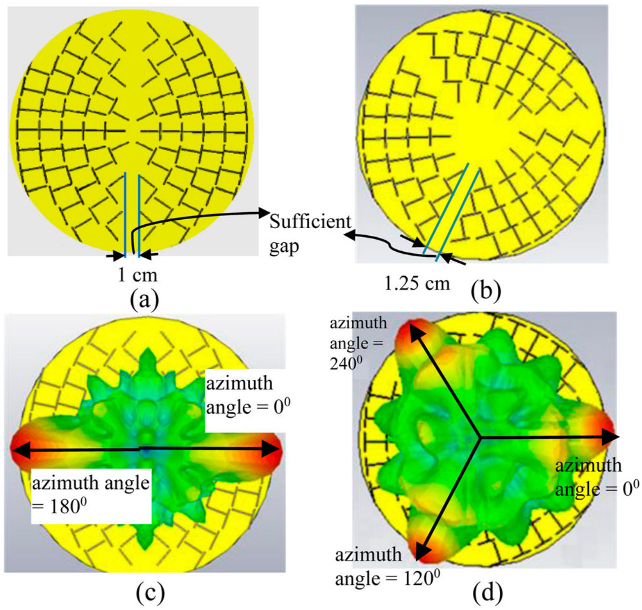
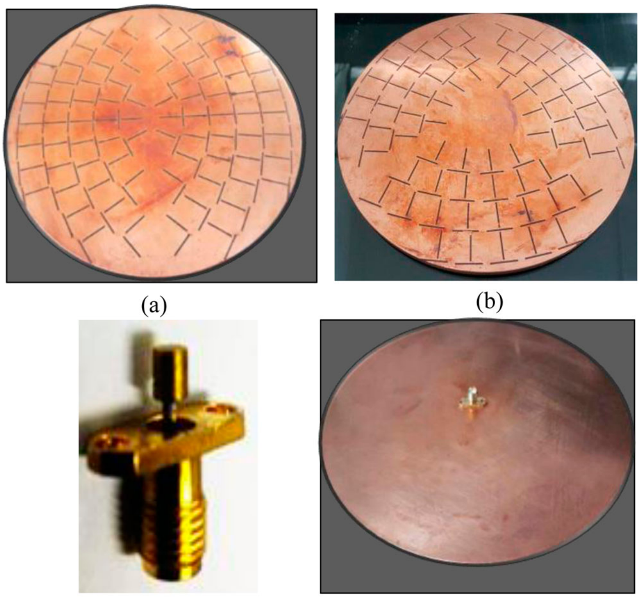


Figure 4. (a) Dual-beam design (b) Triple-beam design (c) Dual-beam pattern (d) Triple-beam pattern.

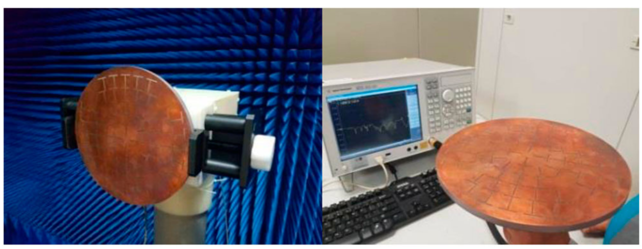
The feeder is an ordinary SMA feeder, which is modified by adding a copper disk, as shown by Figure 3(b). The copper disk is useful to make signals launched by the feeder to propagate radially within the cavity, as illustrated by green arrows in Figure 3(c). Table 2 lists the specifications of the feeder, as depicted in Figure 3(d). The feeder position, by default, is at the center of antenna models, as shown in Figure 3(a). The parameters of feeder in Table 2 were taken from reference [17], which determined them by conducting a parameterization using a C++ computer program.

Using the Basic computer program, a design of 42 dual and 42 triple-beams' RLSA models was made with different parameters, such as p_0, which is the number of slot pairs in the first ring and θ_T, which indicates the beam squint direction. These variations were to ensure the technique is applicable in different values of θ_T and p_0 as well as to obtain the optimum design. The models have two and three slot groups, which were used to obtain dual- and triple-beam antennas, as shown in Figure 4(a,b), respectively. The right group was designed to have a beam squinted to the left at azimuth angle $= 0^\circ$, while the beam on the left group squinted to the right at azimuth angle $= 180^\circ$ for the dual beams, as shown in Figure 4(c). Meanwhile, the triple-beam antennas were designed with each group having a beam squinted to azimuth angle $= 0^\circ$, 120°, and 240°, as shown in Figure 4(d).



(a) (b) (c) (d)

Figure 5. Fabricated models for (a) Dual-beam (b) Triple-beam (c) Feeder (d) Background and attached feeder.



(a) (b)

Figure 6. Measurement of the prototypes (a) in an anechoic chamber (b) using a network analyzer.

The best two models were selected and fabricated after simulation using the CST software. Figure 5 depicts the fabricated models for the dual-beam (a), triple-beam (b), their feeder (c) as well as the position of the feeder at the back of the antenna (d). The prototypes were measured to verify the simulation results (see Figure 6 for measurement activities).

Results and discussion

Figure 7(a,b) show the reflection coefficient for the simulated and measured triple- and dual-beam antenna. They were also both recorded to have bandwidths estimated at 400 and 625 MHz, respectively, which are quite broad for 5.8 GHz applications.

Figures 8(a) and 9(a) show the simulation of 3-dimensional antenna's radiation pattern for the dual and the triple-beam antennas with theta representing the elevation angle, while

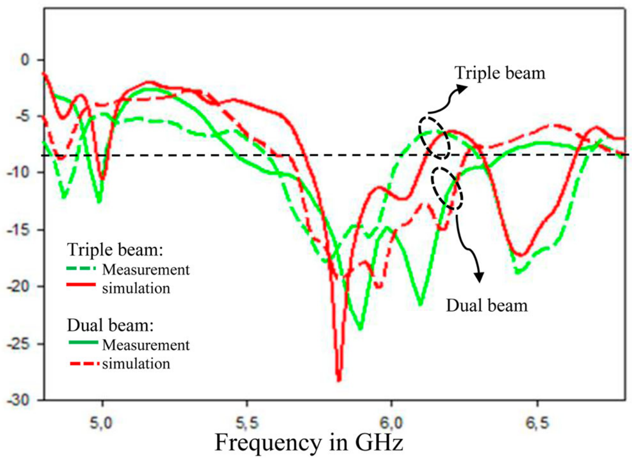


Figure 7. The reflection coefficient of triple-beam antenna and dual-beam antenna.

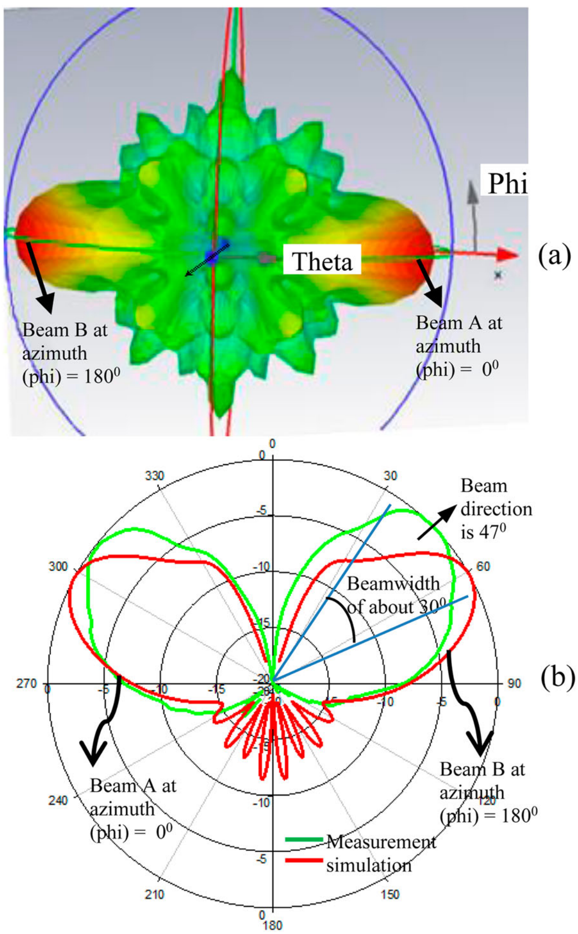


Figure 8. Radiation Pattern of dual-beam (a) 3-Dimension (b) 2-Dimension.

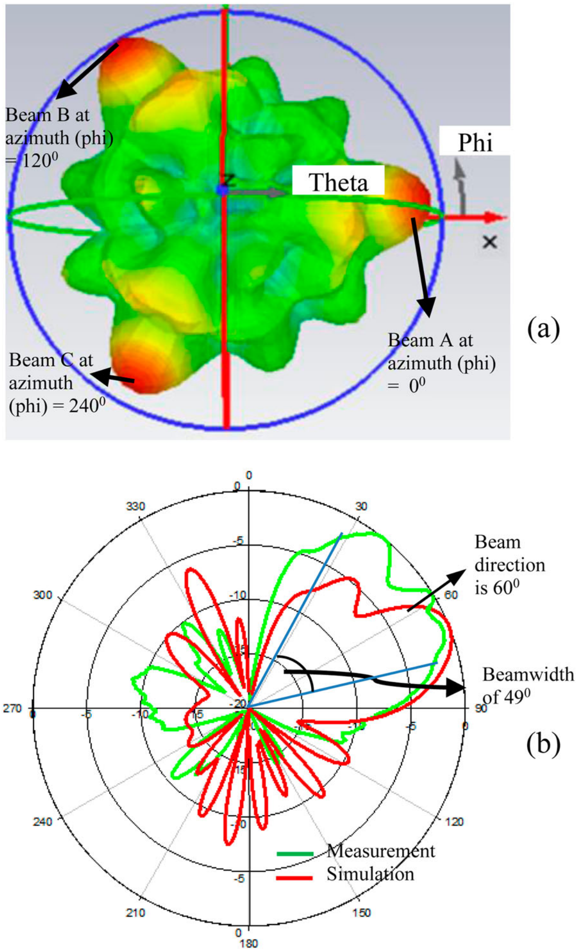


Figure 9. Radiation Pattern of triple-beam (a) 3-Dimension (b) 2-Dimension.

phi is the azimuth angle. Meanwhile, Figures 8(b) and 9(b) indicate the 2-dimensions with the Phi $= 0^{\circ}$, while theta is from 0° to 360°.

Figures 8 and 9 also show the possibility of designing similar beams in terms of beamwidth, which was estimated at 30° and 49° and quite symmetric in elevation directions at 47° and 60° for dual- and triple-beam, respectively as well as in azimuth directions at 0° and 180° for the dual and 0°, 120°, and 240° for the triple-beam.

It was possible to achieve similarity by designing the same number and position of slots for each beam. The beams could be adjusted to enlarge or shrink through an increase or reduction in the number of slots for the corresponding beams. Moreover, there is a need to prevent the coupling effect, which is the interference between adjacent beams with a possible effect on their pattern by providing a sufficient gap, as shown in Figure 4(a,b) between the slot groups. The gap should, however, not be too big to avoid a reduction in the gain and was determined in this research by conducting parameterization to obtain the optimum values of 1 and 1.25 cm for the dual- and triple-beam antennas, respectively.

Table 3. Comparison of other small RLSA antennas against the dual-beam antennas.

References	Radii (cm)/areas (cm^2)	Gains -3 (dBi)	Areas of other small RLSA antennas compared to the dual-beam antenna (times)	Gain of other small RLSA antennas compared to the dual-beam antenna (times)
[10]	7.5/176.62	6	0.42	0.18
[11]	7.5/176.62	9	0.42	0.35
[12]	14/615.44	15.4	1.48	1.54
[13]	12.7/506.45	14	1.22	1.12
[14]	10.7/359.5	13.25	0.86	0.94
[17]	32.5/3316.6	22	7.99	7.08
[18]	7.6/182.25	8	0.44	0.28

A gain value of 13.3 dBi was obtained from the simulations, while the measurement produced 13.5 dBi for the dual-beam antenna, while 10.4 and 10.5 dBi were, respectively, recorded for the triple-beam antenna. These values, however, indicate the agreement between the results from the two methods.

The dual-beam antenna has a gain of 13.5 and 13.4 dBi for beams A and B, respectively, while the triple-beam antenna has 10.41, 10.35, and 10.41 dBi for beams A, B, and C, respectively. This means both antennas have quite balanced gains.

A single-beam antenna was designed at the same size as the dual- and triple-beam antennas to analyze the decrease in the gain. The simulation has a gain of 15.56 dBi and this means the gain for dual- and triple-beams is theoretically expected to be 3 and 4.77 dB lower. Therefore, the antennas designed are able to fulfill the theory as observed from their respective values.

Comparisons of the area and the gain of other small RLSA antennas against the dual-beam RLSA antenna are listed in Table 3 column 4 and 5. Since the other RLSA antennas are single-beam, their gains (column 3 in the Table 3) are subtracted by 3 dB before compared to the dual-beam antenna. We observe that generally the gain of the dual beam is comparable with other small RLSA antennas, as can be seen from references 11, 13, and 14. Moreover, we also observe that the gain of dual beam is better. As an example, compared to the dual-beam antenna, the area of antenna in reference [10] is 0.42 times smaller. Since theoretically gains would decrease linearly by the decrease of areas, the gain of the antenna in reference [10] should be 0.42 times smaller, but the gain is 0.18 times smaller. We also observe the similar results for other comparisons.

Finally, Figures 7, 8, and 9 show the results from the simulation correspond with those from the measurement. The slight deviation observed from the measurement is associated with the imperfections in fabricating the prototypes, especially in printing the radiating element's design, drilling the antenna's feeder hole at the exact position, and soldering the head disk at the correct position.

Conclusions

The technique, to design multibeam antennas through high beam squint values toward optimizing the beams' gains, was introduced. It is, however, expected to be a significant step in developing small multibeam RLSA antennas with balance gains for multibeam devices such as point to multipoint Wi-Fi bridges. This technique also can develop beam-steering

RLSA antennas by modifying the single feeder into multiple feeders connected to a beam-steering network. The antennas designed in this research were low profile just like microstrip antennas but better due to their high gain and efficiency. It is, therefore, possible to use them as an alternative for multibeam microstrip antennas in multibeam devices with a 5.8 GHz frequency. Future investigation is required to determine the ability of this method to produce small multibeam RLSA antennas for other beams and directions.

Disclosure statement

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