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The Utilization of Backgrounds as Radiating Elements to Construct Multibeam Radial Line Slot Array (RLSA) Antennas

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Abstract *RLSA antennas normally have a single beam produced by slots installed on their radiating element. A technique was, therefore, introduced in this study to optimally design multibeam RLSA antennas. This involved the utilization of the antennas' background to radiate signals by installing slots on it just like the radiating element to ensure the creation of multibeam after which the effects of this method such as signal flow disturbances and gain reduction were discussed. Moreover, 105 multibeam RLSA models were designed and simulated to verify the technique developed after which a prototype of the best model was fabricated and measured to verify the simulation. The result showed it is possible to obtain multibeam antennas with similar symmetry in terms of beamwidth and directions. Furthermore, the gain recorded for beams 1, 2, 3, and 4 was 8.28 dBi, 6.28 dBi, 6.38 dBi, and 8.18 dBi respectively, and were averagely about 6 dB lower than the value for single beam RLSA antennas, therefore, they suit the theory of beam splitting. The antennas were also found to have more than enough bandwidth and good reflection coefficient and the technique's validity was verified by a strong agreement between the simulation and measurement results.*

Keywords*: RLSA antennas, multibeam antennas, antennas' background, radiating element*

I. Introduction

Radial Line Slot Array (RLSA) antennas were initially proposed in the 1950s by Kelly [1]. The feeding structure of these antennas was complex despite their ability to produce a pencil beam and this makes their fabrication to be costly. There was, however, no significant progress in their development up to the 1980s.

In 1988, Japan researchers started to develop RLSA antennas for satellite broadcasting applications at a frequency of 12 GHz. Ando proposed a linearly polarized RLSA (LP-RLSA) at a frequency of 12 GHz using slot arrangements technique to produce a uniform aperture distribution. This antenna has a double layer cavity and exhibits a 15 dB co-polarization level above the cross-polarization level. Moreover, a beam-tilt technique was also proposed to decrease high reflections in these antennas [2] after which another LP-RLSA antenna was further designed by applying slot coupling and reflection suppression technique and was reported to have an efficiency of 76% and a gain of 36 dB [3]. In 1990, Ando further introduced a Circularly Polarized RLSA (CP-RLSA) antenna using a single instead of a double layer cavity. This simpler cavity structure improves the complexity of RLSA fabrications and achieves a gain of 35.4 dBi and an efficiency of 65%. Ando used two techniques to improve antenna performance. The first involves varying the length and spacing of the slots to even out the aperture illuminations of the antenna while the second involves matching the spiral used to reduce the reflection at the antenna perimeter [4]. In 2019, Ando and Hirokawa reported the performance improvement of RLSA by utilizing the combination of dialectric and air cavity [5].

In 1992, Takada introduced a technique of canceling slots to reduce reflection from -2 dB to -10 dB [6] while Endo designed an optimum thickness of double layer RLSA antennas to realize the mass production of thinner models [7]. In 1991, Takashi proposed a technique to vary slots length and spacing and applied it to several high-efficiency single layer RLSA antennas with diameters ranging between 25 cm to 60 cm. These antennas were able to achieve efficiencies between 70% to 84% [8]. Furthermore, Takashi also produced and marketed a-78% efficiency, 32.6 dB gain, single-layered RLSA [9].

In 1997, Australian researchers continued with the works of Ando. For example, Davis developed RLSA antennas with the focus on low-cost materials and fabrications [10] and design a 60 cm diameter LP-RLSA prototype using the reflection canceling slot technique due to its ability to overcome high reflection coefficient. This researcher also successfully tested an RLSA antenna designed with the use of a reflection-canceling slot technique and a beamsquint value of 20^0 [11]. Furthermore, Davis investigated the LP-RLSA antennas which were using the beamsquint technique for several squint angles and the reflection coefficient was observed to have been reduced to under -25 dB [12]. Davis further integrated the report of [2, 6, 9, 10] to form a beam synthesis algorithm used to calculate the design parameter of LP-RLSA antennas [13]. In the last few years, several researchers improved RLSAs performance using variety of advance techniques [14-23]. RLSA antennas also have been tested and implemented on NASA's Double Asteroid Redirection Test (DART) mission [24-25].

The successful development of RLSA antennas for satellite broadcast applications inspired researchers to develop those compatible with small devices such as Wi-Fi. This effort was, however, constrained for years due to the high signal reflection problem in small RLSAs as the effect of a lesser number of slots [9, 26]. Several studies have been conducted in an attempt to overcome these problems. For example, Hirokawa [27] introduced a matching slot technique to dispose remaining power at RLSA perimeters while Zagriatski used long slots technique to maximize power radiation through slots in order to reduce signal reflections [28]. Moreover, Purnamirza used two-cavity layers to enable reflected signals eliminate each other [26] and also introduced extreme beamsquint technique in another study to efficiently radiate power through slots to achieve a significant reduction in signal reflections [29]. Purnamirza successfully implemented this technique to design several small Wi-Fi RLSAs for market needs [30-33]. The recent development of RLSA is a cutting technique which is designed to minimize the size of small RLSA antennas [34-35] and multibeam RLSA antennas [36].

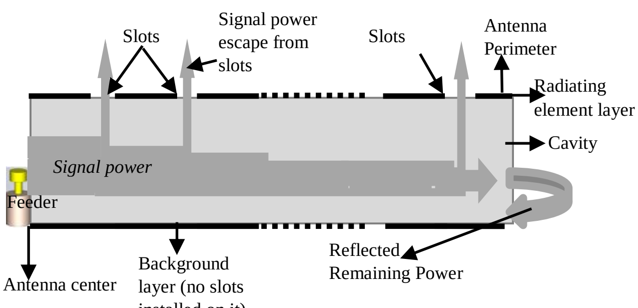
A technique was suggested to develop multibeam RLSA antennas in the future and this involves utilizing the background element of the antennas to radiate signals. This is considered not to be ordinary due to the fact that the background element normally functions only as a boundary waveguide, therefore, several effects are expected from this role conversion. Therefore, this research discusses the implementation of this technique and its effects on the performance of RLSA antennas in Section 2. Several multibeam RLSA models were designed and simulated to verify the technique and the best model was later selected for fabrication as discussed in Section 3. Moreover, the measurement results for the prototype and the simulation results for the model were analyzed with the focus on beamwidth, beam direction, coefficient reflection, bandwidth, and gain after which the overall results are presented in Section 4.

II. Effect of Using Backgrounds as Radiating Elements

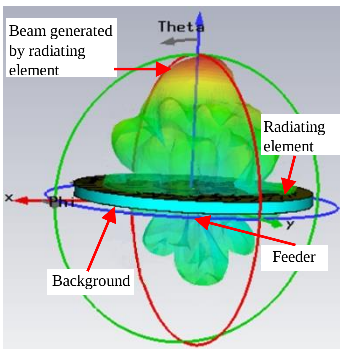
The background of an RLSA antenna with the radiating element normally serves as the waveguide to guide signal power from the feeder to the antenna perimeter as illustrated in Fig. 1(a). As the signals are traveling to the perimeter, they decrease because some portions have escaped through the slots on the radiating element. Meanwhile, the signals remaining in the antenna perimeter are reflected back to the feeder and this contributes to the increase in reflection coefficients.

Fig 1(a) shows there are no slots installed on the background layer and this means signals are radiated only by the radiating element to produce a single beam as depicted in Fig. 1(b). Therefore, slots were also constructed on the background surface to double the number of slots and obtain multibeam as illustrated in Fig. 2(a). Even though it is theoretically possible to produce multibeam as depicted in Fig. 2(b), this unusual technique has the ability to affect the performance of the antenna in several ways.

One of the effects is a signal flow disturbance as shown by the simulation in Fig. 3(a). The signals power, represented by the arrows, which are supposed to flow radially as shown in Fig. 3(b) were observed to have slightly changed directions and this has a possible effect on radiation pattern and gains.



(a)



(b)

Fig.1 (a) Signal power flow inside the cross-section of ordinary RLSA antennas (b) multibeam

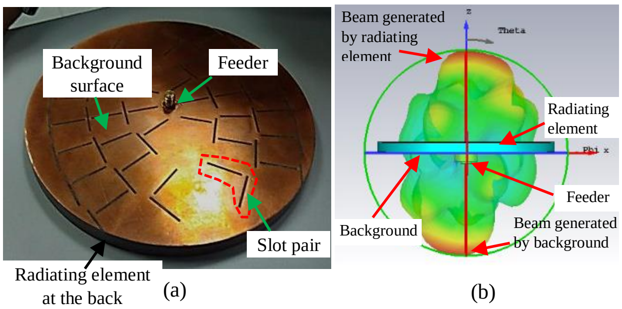


Fig.2 (a) Slots installed on background surface of RLSA antennas (b) Radiation pattern (cross-section view) with slots on the background

Another effect is the reduction in the gain of the antenna due to the split of the power from one beam to multibeam. Moreover, the reflection coefficient is also decreased as observed in the process illustrated in Fig. 4 which shows the number of slots is doubled compared to Fig 1(a) due to the presence of additional slots on the background layer. This means more power has escaped from the double slots, thereby, leaving less power in the antenna perimeter compared to Fig 1(a) and this shows it produces lesser reflection.

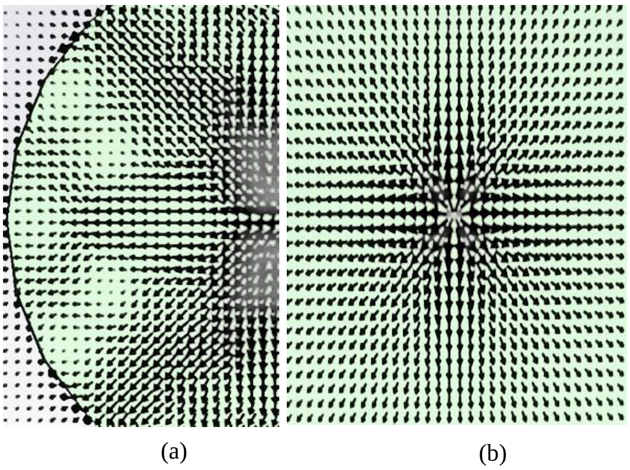


Fig.3 (a) Disturbed radial signal power (b) Undisturbed radial signals power

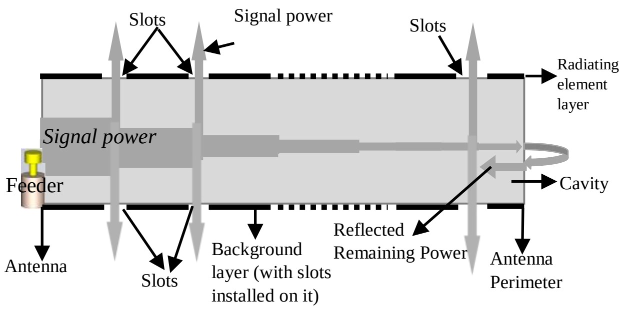
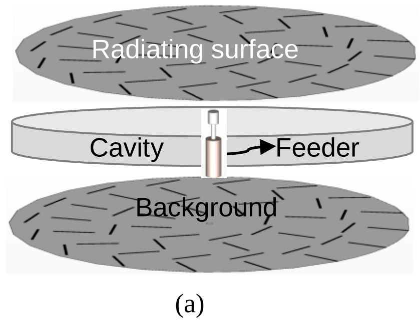


Fig.4 Signal power flow inside the cross-section of multibeam RLSA antennas

All these effects influence the performance of multibeam antennas. Therefore, the parameterizations of the models developed were conducted to obtain the best model due to the difficulty in calculating the effects manually.

III. Antenna Models and Prototypes

The models' structure has three layers as shown in Fig 5(a) and these include a radiating element made of copper at the top, a cavity made of polypropylene in the middle, a background made of copper on the back, and a feeder at the center. The feeder is, however, an ordinary Sub-Miniature version-A (SMA) feeder which is modified by adding a copper head as illustrated in Fig 5(b). The head converts transverse electromagnetic mode (TEM) coaxial mode into TEM cavity mode to ensure the signals fed by the feeder flow in a radial direction within the antenna cavity as shown in Fig.6.



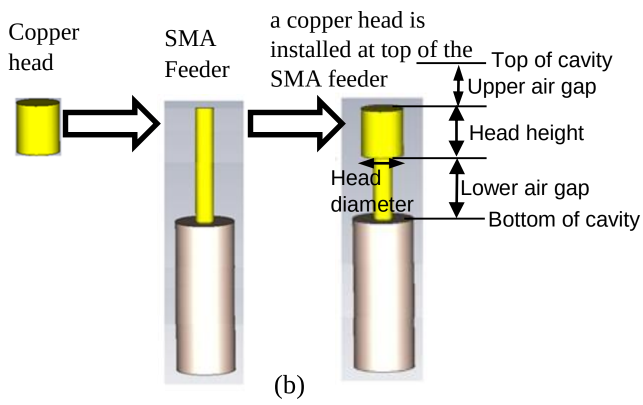


Fig. 5. (a) Antennas models' structure (b) Modification of SMA feeder [32]

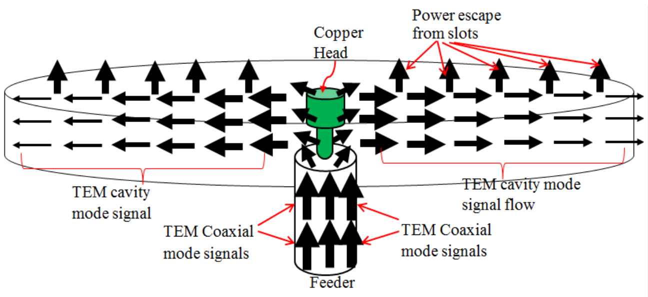


Fig. 6. Illustrations of TEM cavity and TEM coaxial mode signals' flow [32]

A computer program was developed to draw the models' structures faster and more accurately due to the difficulty associated with the drawing the antenna structure in CST, especially its slots, manually. All the design parameters embedded in the computer program are listed in Tables I for the antenna and the feeder, which the values are taken from several previous researches [26-29].

TABLE I
SPECIFICATION PARAMETERS OF THE ANTENNA MODELS AND FEEDERS [26-29]

Symbol	Parameter	Value
f	frequency	5.8 GHz
r	antenna radius	85 mm
n	number of slot pairs in the first ring	10, 11,12,13, 14, 15, 16
θ	beamsquint angle	60^0 up to 89^0 with an increment of 3^0
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
h	head height	3 mm
r_a	head radius	1.4 mm
b_1	lower air gap	4 mm
b_2	upper air gap	1 mm

Several equations were used in the computer program for the slots pairs design to calculate the inclination angle (Eq.1 and Eq.2), positions (Eq.3 and Eq.4), the distance between them (Eq.5 and Eq.6), and length (Eq.7) [1]. Moreover, Table II lists the definitions of the slot's pairs parameters in all the equations and they are illustrated in Fig. 7.

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

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

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

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

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

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

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

$$L_{rad} = (4.9876 \times 10^{-3}\rho)\frac{12.5\ x\ 10^9}{f_o} \quad (7)$$

TABLE II
DESIGN PARAMETERS OF THE SLOT PAIRS [2, 10, 13]

Parameters	Symbols
Inclination angle of Slot 1	θ_1
Inclination angle of Slot 2	θ_2
Beam squint angle in the elevation direction	θ_T
Azimuth angle of Slot 1 and Slot 2 position	ϕ
Beam squint angle in azimuth direction	ϕ_T
Distance of a slot 1 from the center point of antennas	ρ_1
Distance of a slot 2 from the center point of antennas	ρ_2
Integer numbers (1, 2, 3…) that express the distance of innermost ring from the center of antennas	q
Distance between two adjacent unit radiators located in two different rings (distance in the radial direction)	S_ρ
distance between two adjacent unit radiators in the same ring (distance in azimuth direction)	S_ϕ

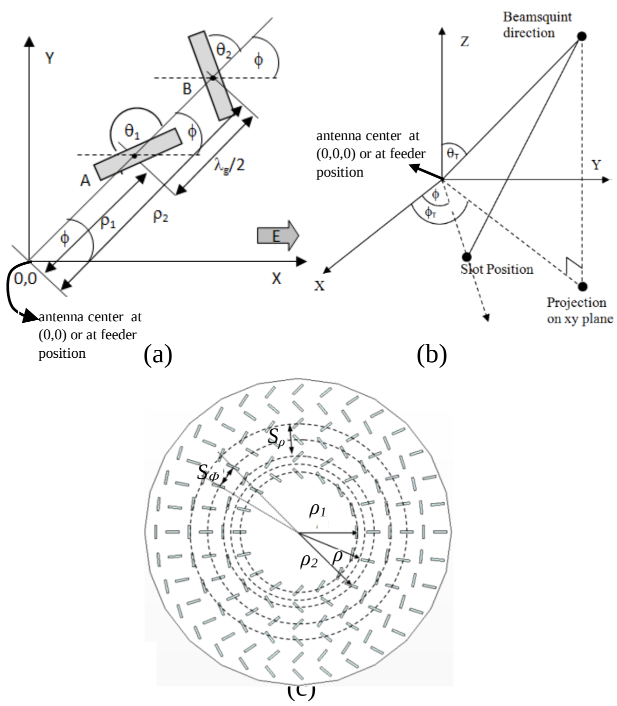


Fig. 7. (a) slots pairs along with all parameter in x-y plane (b) slots positions and their relations to beam direction in x-y-z (c) distance between slots in radial and azimuth directions [2,10]

One hundred and five RLSA antenna models were designed and simulated using CST software and they all consist of two slots groups in the background and two slots group in the radiating element as shown in Figs. 8(a) and (b). Each slot group produces one beam and this means the models have four different beams.

The models vary in terms of beamsquint values, θ, which are between 60^0 to 89^0 with an increment of 3^0 as well as the number of slots in the first ring, p_0, varied between 10, 11, 12, 13, 14, 15, and 16 to produce 105 models. The variations led to a slightly different configuration of slots and performance between the models. Therefore, the θ and p_0 values were varied to obtain the model with the best performance.

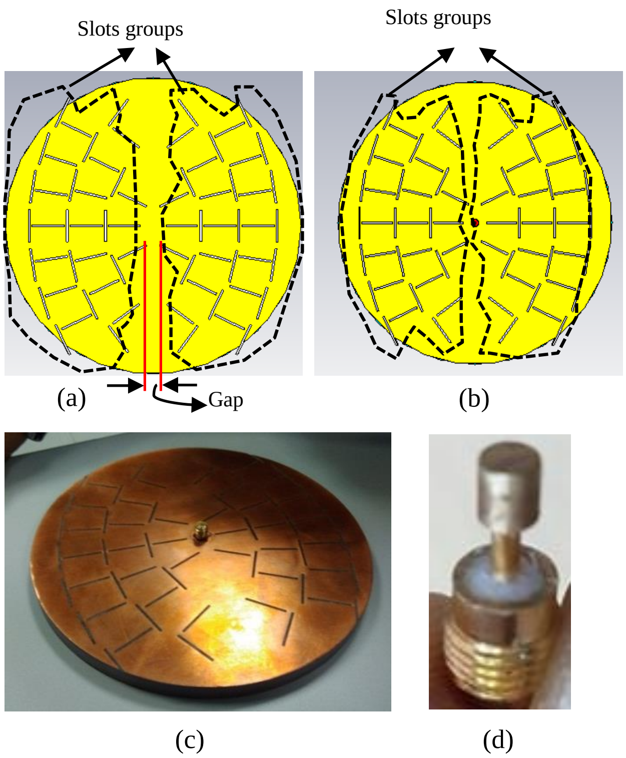


Fig.8. (a) Radiating element of the best model (b) Background element of the best model (c) Fabricated prototype of the best model (d) Fabricated feeder

The best model was obtained and fabricated after simulation and parameterization showed it has θ value of 75^0 and 73^0 for the radiating element and the background, respectively as well as a p_0 value of 14 for both of the elements. Fig. 8 shows the radiating element (a), background (b), fabricated model (c), as well as the fabricated feeder (d) of the best model. Moreover, the radiation pattern, gain, and reflection coefficient of the prototype was measured to verify the simulation results as shown in Fig 9.

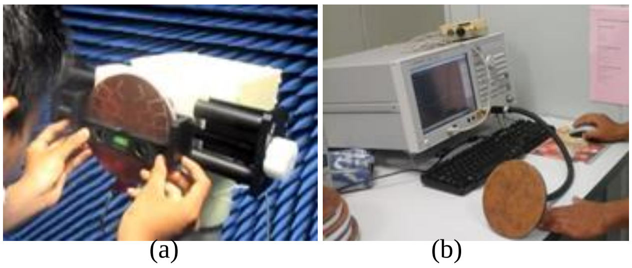


Fig. 9. Measurement of the prototypes (a) in an anechoic chamber, (b) using a network analyzer.

IV. Results and Discussion

The reflection coefficients obtained from the simulation and measurement are shown in Fig. 10 and the antenna was observed to have a bandwidth estimated between 5.3 and 6.7 GHz which are quite broad for 5.8 GHz applications.

The radiation pattern for simulated and measured multi-beam antenna and its 3-dimension are presented in Figs. 11(a) and (b) respectively. It was discovered that it is possible to produce similar beams in terms of beamwidth, which was estimated at 20^0 and quite symmetric in elevation directions of 50^0, 135^0, 230^0, and 310^0.

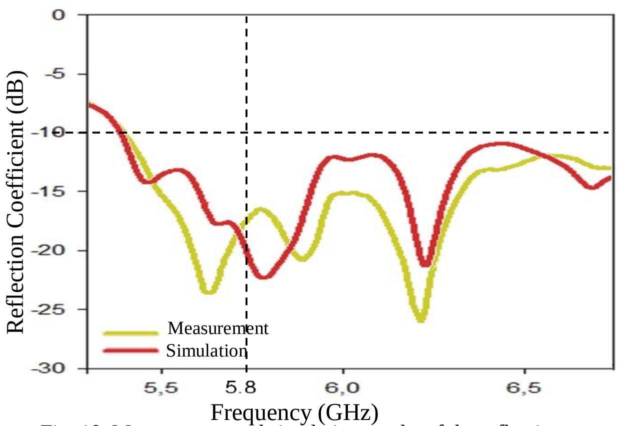
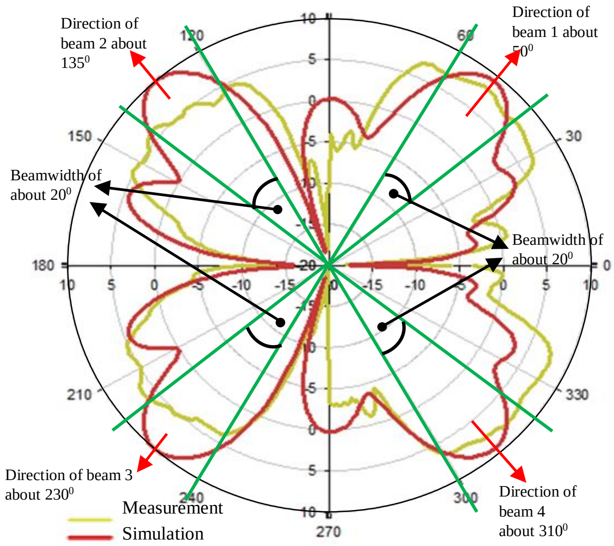
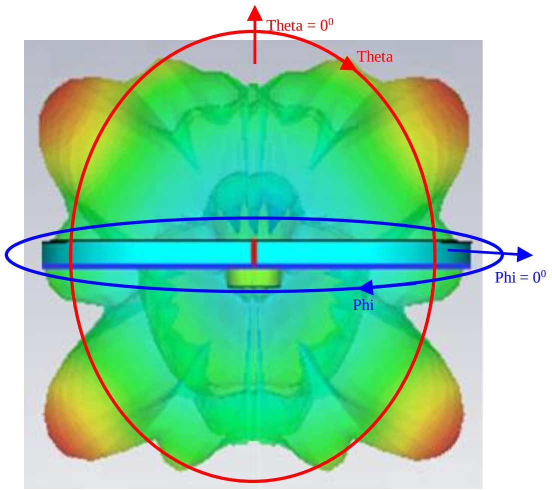


Fig. 10. Measurement and simulation results of the reflection coefficient



(a)



(b)

Fig. 11 (a) 2-Dimension radiation pattern at phi = 0⁰ (b) 3-Dimension radiation pattern

It is possible to obtain similar beams using the same number and same position of slots for each beam. Moreover, the beams are also adjustable to become enlarged or shrink by increasing or lessening the number of slots for the corresponding beams. It is, however, important to prevent the coupling effect, which is interference between adjacent beams influencing the beams pattern, to produce similar beams. This was achieved by providing a sufficient gap between the slot groups as shown in Fig 8(a). This gap should not be too big to avoid an increase in size. The sufficiency was determined in this research through the use of parameterization to obtain the optimum value which was found to be 1 cm.

The antenna gain of each beam was calculated from the measured received power shown in Fig. 12 as:

$$G = P_{r,RLSA} - P_{r,reference\ antenna} + G_{r,reference\ antenna}$$

The gain of beam 1 directed to 50^0 is:
$G_{beam1} = -40.3-(-31.3) + 17.28 = 8.28$ dBi

The gain of beam 2 directed to 135^0 is:
$G_{beam2} = -42.5-(-31.3) + 17.28 = 6.08$ dBi

The gain of beam 3 directed to 230^0 is:
$G_{beam3} = -42.2-(-31.3) + 17.28 = 6.38$ dBi

The gain of beam 4 directed to 310^0 is:
$G_{beam4} = -40.4-(-31.3) + 17.28 = 8.18$ dBi

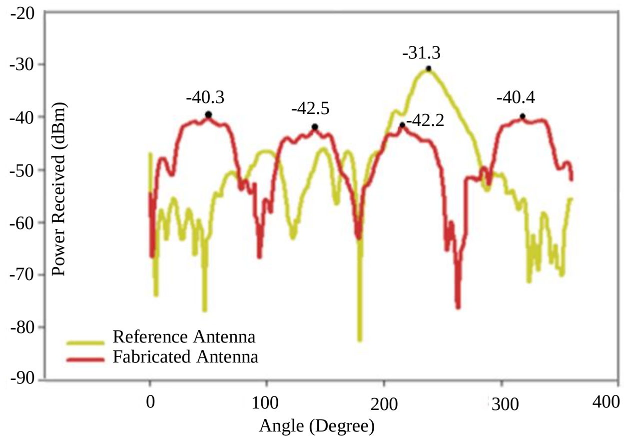


Fig. 12. Received Power Measurements

A single beam antenna having the same size as the multibeam antenna was designed to analyze the decrease in the gain of the multibeam. The simulation showed a gain of 13.15 dBi for a single beam antenna and the multi-beam antenna is theoretically expected to be 6 dB lower due to the fact that it is obtained by dividing the value of the single beam by four. Therefore, the gains of 8.28 dBi, 6.28 dBi, 6.38 dBi, and 8.18 dBi for beams 1, 2, 3, and 4 respectively fulfill the theory because they are averagely about 6 dB lower than 13.15 dBi obtained for the single beam.

Figs. 10 and 11 show the results of the simulation is comparable to the measurement with the difference observed to be due to several imperfections during the fabrication process of the antenna model. These were caused by the fact that, first, the radiating element, cavity, and background were separated elements and a slight shift from their correct position occurred when they were combined during the fabrication process. Second, the permittivity of the cavity slightly increased due to the use of glue in sticking the radiating element and background to the cavity. Third, there was an imperfection in soldering the head disc at the SMA feeder to the correct position.

V. Conclusions

This research discussed the technique to design multibeam antennas through the use of the background element of RLSA antennas as a radiating element at frequency of 5.8 GHz. It is demonstrated that the technique could develop a multibeam antenna with similar and simetry beams. This result is expected to be a significant step towards developing small multibeam RLSA antennas for multibeam devices such as point to multipoint routers. It also shows the potential to develop beamforming RLSA antennas by modifying a single feeder into multiple feeders connected to a beamforming network. Moreover, the antennas designed were low profile just like microstrip antennas but better due to their high gain and efficiency. Therefore, they can be used as an alternative for multibeam microstrip antennas in multibeam devices with a 5.8 GHz frequency. Future investigation is, however, required to determine the ability of this method to produce small multibeam RLSA antennas for other numbers of beams and directions.

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