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The Realization Study on the Reconfigurable Functions of Radial Line Slot Array (RLSA) Antennas

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Abstract—This paper thoroughly studies the realization of the reconfigurable function of RLSA antennas in terms of beamsteering at the frequency of 5.8 GHz. In the first step, the study on the characteristic of small RLSA antennas concludes that maximum beamsquint that can be achieved is around 70°. In the second step, in order to minimize the size of reconfigurable RLSA antennas, a new technique of cutting a small RLSA into sectors is introduced. The analysis on the quarter cut RLSA and the semi cut RLSA shows that their performances do not deviate too much from the full circle RLSA performance. In the third step, study on the most suitable method of realizing the reconfigurable function of RLSA antennas chooses the method of implementing antenna array as the most suitable method. Based on this method, a structure of reconfigurable RLSA antennas is proposed. In the last step, utilizing the proposed structure and four quarter cut RLSA elements, a novel reconfigurable RLSA antenna in terms of beamsteering is simulated and fabricated. To avoid significant coupling effect between the antenna elements, all elements are separated by 20 mm. The antenna has a directivity of 9.2 dB, an efficiency of 97.95%, a bandwidth about 1.5 GHz, the mainlobe direction (in elevation direction) of 45°, the beamwidth of 32.5°, and the sidelobe level −6.3 dB. The beam of the reconfigurable antenna can be steered into four different azimuth directions, which are 0°, 90°, 180°, and 270°. Furthermore, a similar radiation pattern and reflection coefficient between the measurement and simulation verifies the validity of the study.

1. INTRODUCTION

Researches on the reconfigurable antennas have drawn much attention in the development of wireless communication system recently. For reconfigurable antennas realization, microstrip antennas are the most recommended type of antennas since it is low profile and small [1]. However, it is well known that microstrip antennas have drawbacks such as low gain and low efficiency [1, 2]. The utilization of switches such as PIN diodes installed on the microstrip surface that function to enable the reconfigurable function further deteriorate the gain of the reconfigurable antennas [3, 4].

In order to improve the gain and efficiency of reconfigurable antennas, it is needed to explore other types of antennas which have good performances as well as small and low profile. For the high gain and high efficiency purpose, RLSA antennas might be a suitable candidate since RLSA antennas have high gain and high efficiency characteristics [5, 6]. The other distinction of the RLSA antennas is that RLSA antennas are in low profile and flat. Furthermore, the beamsquint technique — which is basically utilized to improve the reflection coefficient response of the RLSA antennas [7–11, 17] — can be theoretically utilized to design a reconfigurable RLSA antenna that can steer its beam to an arbitrary azimuth angle

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and an arbitrary elevation angle while maintaining the position of RLSA antenna still flat (elevation angle = 0°).

This paper thoroughly studies the realization of the reconfigurable functions of RLSA antennas in terms of beamsteering function. The frequency of 5.8 GHz is chosen as operating frequency since this frequency is one of the most fertile unlicensed frequencies. In outline, the study in this paper is divided into four main sections, which correspond to four main steps taken as the methods to realize the reconfigurable function of RLSA antennas. The four steps are as follows. The first step: the study is started by analyzing the characteristic of small RLSA antennas in terms of their performance and in terms of how much they can squint their beam from the boresight direction. The small aperture (radius less than 75 mm) is utilized since the size is the consideration as explained in the above paragraph. The high beamsquint (the beamsquint greater than 60°) is utilized since high beamsquint is needed in order to realize the beamsteering ability of RLSA antenna.

The second step: The utilization of full circle RLSA antennas as elements for reconfigurable antennas might produce bulky antennas. Therefore, in order to reduce the antenna size, this study analyzes a new approach to minimize the RLSA size. This approach is cutting full RLSA antennas into several sectors. In this study, a quarter cut RLSA and a semi cut RLSA are taken as examples to be analyzed. The characteristics of power flow inside the cavity of the quarter cut and the semi cut are analyzed to know how much their characteristics deviate from the characteristic of normal RLSA antennas.

The third step: The reconfigurable function of the antennas can be achieved through different methods such as altering the physical structure of the antennas, changing feeding methods, and implementing antennas arrays [1]. Therefore, this study analyzes and chooses the most suitable method to realize the reconfigurable function of small RLSA antennas.

The fourth step: Based on the previous discussion and result, a novel reconfigurable antenna in terms of beamsteering is designed, simulated, and fabricated. The simulation and measurement results in terms of reflection coefficient and radiation pattern are compared in order to verify the discussion result. To the authors' knowledge, this reconfigurable antenna is the first reconfigurable antenna that utilizes the original RLSA antenna technology.

2. SMALL RLSA ANTENNAS

This section discusses the ability of small RLSA antennas in resulting beamsquint that is squinted from the boresight direction in elevation direction (see Figure 1(a) for the illustration of beamsquint) and compares their performance characteristic with the performance characteristic of normal RLSA antennas. For this purpose, the small RLSAs and their feeder are designed and simulated utilizing the CST Microwave Studio for various beamsquint values. In order to observe the effect of the slots configuration, the simulations are also carried out for various numbers of slots in the first ring (n).

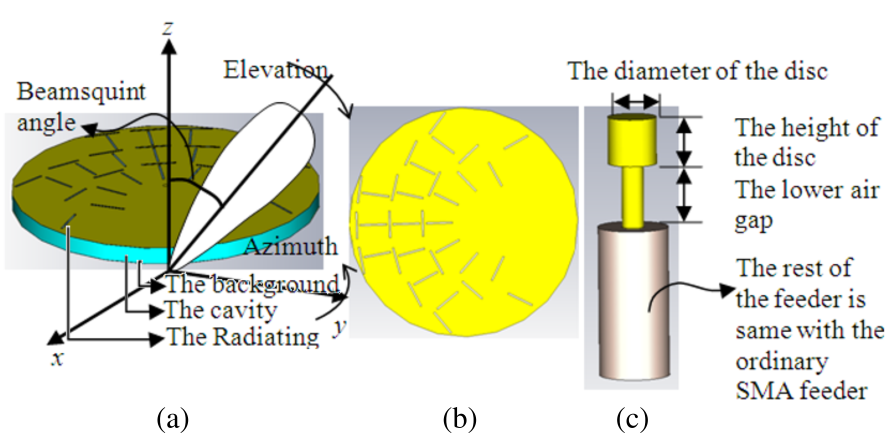


Figure 1. (a) Structure of small RLSA antennas models. (b) Slots configuration on the radiating element of small RLSA antennas models. (c) Feeder.

2.1. Structure and Parameters of Small RLSA Antennas

The structure of simulated small RLSA antennas models is shown in Figure 1(a). The structure consists of a radiating element (made of copper) where slots are placed on it, a cavity (made of polypropylene), a background (made of copper), and a feeder. The feeder is an ordinary SMA feeder, which is modified by adding a head disc. The head disc has the function to convert the signal from TEM coaxial mode into TEM cavity mode (the radial mode), so that the signal fed by the feeder will propagate in the TEM mode and in radial direction within the antenna cavity. The detailed specification of small RLSA antennas models and their feeder are listed in the Table 1 and Table 2, respectively.

Table 1. Specification parameters of small RLSA antennas models.

The Specification Parameters	The Symbol	The Value
Centre frequency	f	5.8 GHz
Wavelength inside the cavity	λ_g	33.88 mm
Slot length	l	$0.5\lambda_g$
Slot width	w	1 mm
Radius of antenna	r	75 mm
Cavity thickness	d_1	8 mm
The thickness of radiating element and background	d	0.1 mm
The permittivity of cavity	ε_{r1}	2.33
Cavity material	-	Polypropylene
The material of radiating element and the background	-	copper

Table 2. Specification parameters of feeder [12, 13].

The Specification Parameters	The Symbol	The Value
The height of disc	h	3 mm
The radius of disc	r_a	1.4 mm
The lower air gap	b_1	4 mm
The upper air gap	b_2	1 mm

The RLSA antennas slots were calculated and designed using Equations (1) to (7) below [14]. The definitions of variables in those equations are listed in Table 3 [14]. Since it is difficult to calculate and draw the slots manually, and there is a need to draw tens of antenna models, with each consisting tens of slots, hence a computer program using Visual Basic Application embedded within CST software was developed so that slots calculation and drawing could be done rapidly.

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

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

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

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

Table 3. Design parameters of the slot pairs [14].

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 centre point of antennas	ρ_1
Distance of a slot 2 from the centre point of antennas	ρ_2
Number of slot pairs in the first ring	n
Integer numbers (1, 2, 3...) that express the distance of innermost ring from the centre 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

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

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

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

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

2.2. Characteristic of Small RLSA Antennas

Figure 2(a) is the simulation result of small aperture RLSA antennas and shows the relationship between the designed beamsquint (less than 60°) and the achieved beamsquint for $n = 12$. The definition of designed beamsquint is the beamsquint direction that the antenna is designed for, and the definition of achieved beamsquint is the beamsquint direction that the designed antenna can result in. From Figure 2(a), it can be observed that the relationship between the designed beamsquint and achieved beamsquint is proportional as appropriate with the theory of RLSA antennas. However, the achieved beamsquints do not exactly match the designed beamsquints, because the simulated RLSA antennas have a small number of slots (less than 16 slot pairs) and long slot length ($0.5\lambda_g$), so that the beam does not too focus to the designed beam directions.

Figure 2(b) is the simulation result that shows the relationship between the designed beamsquint (greater than 60°) and the achieved beamsquint for several n values. From Figure 2(b), it can be observed that the maximum beamsquint direction that can be achieved is 70°, although the small RLSA antennas are designed for higher beamsquint directions (greater than 70°). This is due to the emergence of the grating lobes when the small RLSA antennas are designed for extreme beamsquints. The grating lobe will influence the direction of the mainlobe and deflect it from the designed direction. The amount of the grating lobe will increase proportionally with the increase of the designed beamsquint direction. The beamsquint direction (θ_T) that can produce the grating lobe is shown by Equation (8) below [14].

$$\theta_T = \sin^{-1}\left(\frac{\sqrt{\varepsilon_r}-1}{\cos(\emptyset-\emptyset_T)}\right) \tag{8}$$

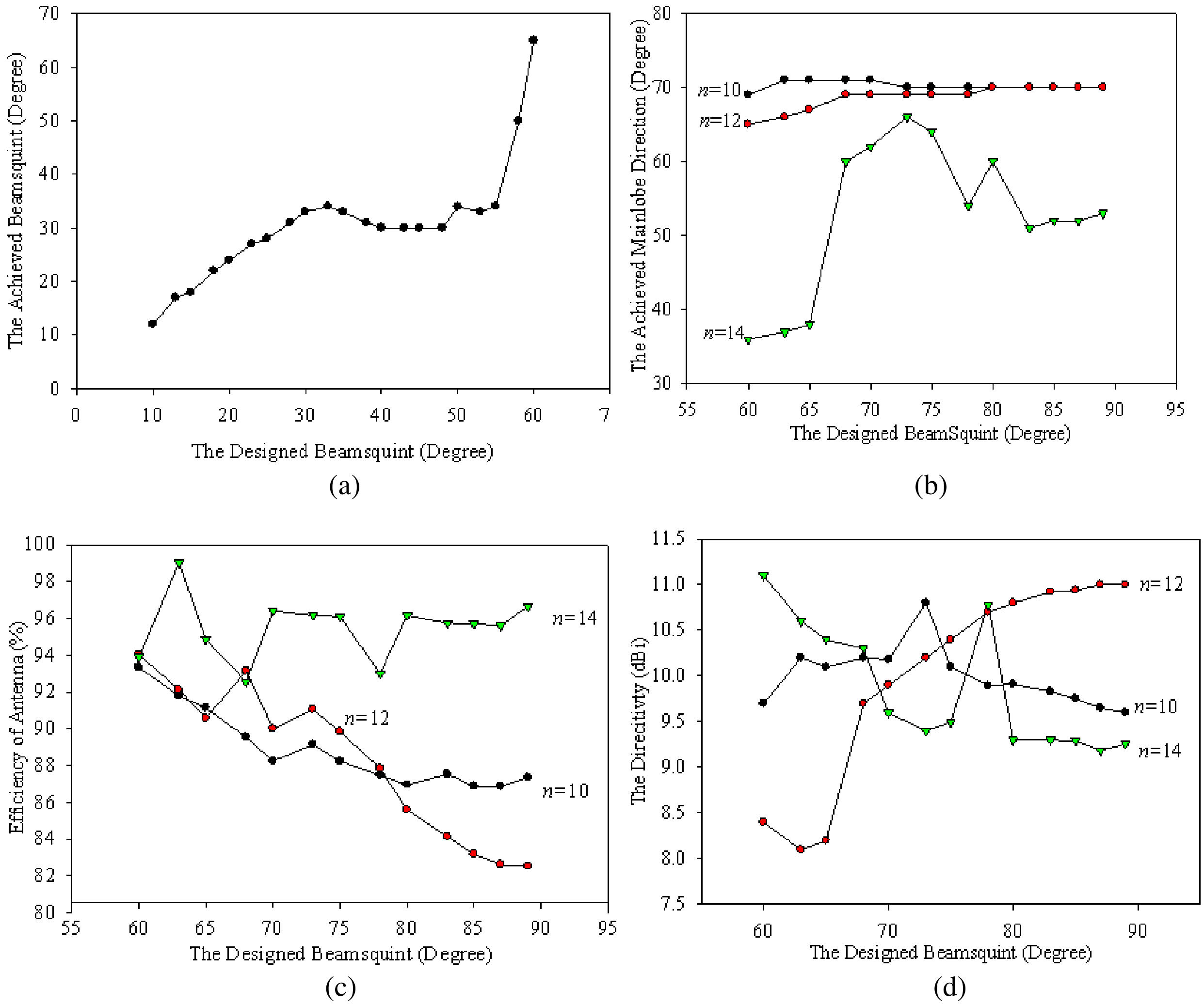


Figure 2. Simulation result of (a) achieved beamsquint for small designed beamsquint, (b) achieved beamsquint for large designed beamsquint, (c) efficiency, (d) directivity — versus the designed beamsquint of small RLSA antennas for various n values.

For this simulation case, the permittivity of the cavity (ε_r) is 2.33. The minimum θ_T that can make the slots of small RLSA antenna start to produce the grating lobe can be calculated by setting the beamsquint in azimuth direction ($\emptyset_T$) to be equal to 0° and the slot position in azimuth direction ($\emptyset$) to be equal to 0°. Hence, by utilizing Equation (8), we can get $\theta_T = 31.8°$. From Equation (8), it can also be observed that other slots at the respective $\emptyset$ will produce the grating lobe as the θ_T increases greater than 31.8°.

Figure 2(c) is the simulation result that shows the relationship between the designed beamsquint and the efficiency of small RLSA antennas. From this figure it can be observed that generally the efficiency of small RLSA antennas is high (above 80%) as it is well known for normal RLSA antennas [15]. It can also be observed from Figures 2(c) and 2(d) that the efficiency characteristic and directivity characteristic do not exactly proportionally relate to n (number of slots in the first ring) as also appropriate with the theory of normal RLSA antennas. This is because in a normal RLSA antenna, if the number of slots is too large, the directivity can decrease since the signal wavelength inside the cavity changes excessively [16]. If the number of slots is too small, the directivity can also decrease since the resulting array factor is too small. The too small number of slots also cannot radiate most of signals within the antenna cavity, hence there will be a significant amount of signal left at the antenna perimeter which will be reflected back to the feeder, thus increase the reflection coefficient and aggravate the efficiency. Therefore, the optimum number of slots is the number of slots that can result in the best antenna performance, which is too complex to be calculated mathematically.

Moreover, it can be observed from Figures 2(c) and 2(d) that the characteristic of directivity and characteristic of efficiency change with the change of designed beamsquint, because the different designed beamsquint results in different configurations of slots which will result in different antenna performances as explained in the previous paragraph.

From the above discussion and result, it can be concluded that the achieved beamsquint of small RLSA is quite extreme (up to 70°) so that it can be utilized to realize the beamsteering function of reconfigurable antenna. The characteristics of small RLSA antennas — including the beamsquint, efficiency, and directivity — are still appropriate with the characteristics of the normal RLSA antennas. This result gives a hope to continue and explore the characteristics of cut small RLSA antennas as elements for the reconfigurable RLSA antennas, which will be discussed in the next section.

3. CUT SMALL RLSA ANTENNAS

The utilization of full small RLSA antennas as an array element for reconfigurable antennas might produce bulky antennas. Therefore, in order to minimize the antennas size, this paper introduces a new approach in realizing smaller array elements for reconfigurable RLSA antennas. This approach is by cutting a full small RLSA antenna into several sectors. In this paper, a quarter sector and a semi sector will be discussed as examples.

3.1. Structure and Parameters of Cut Small RLSA Antennas

The structure of cut small RLSA antennas models is shown in Figures 3(e) and 3(f) for the quarter cut and semi cut RLSA, respectively. The structure and parameters of the cut RLSA antennas remain same with the structure and parameters of full circle RLSA as shown in Figure 1 and listed in Table 1 and Table 2.

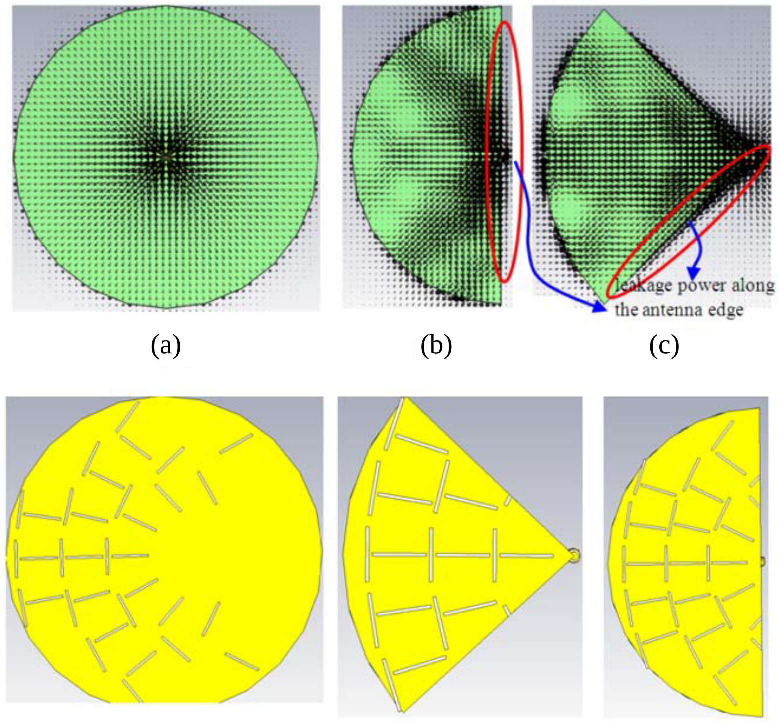
3.2. Characteristic of Power Flow inside the Cavity of Cut RLSA Antennas

This section discusses the characteristic of the power flow inside the cavity of semi cut RLSA antennas and quarter cut RLSA antennas. The characteristic of power flow is important to be observed since this characteristic influences the performance of cut RLSA antennas. From Figure 3(a), it can be observed that the power inside a full RLSA antenna flows in perfect radial direction as appropriate with the theory of RLSA antennas. It can also be observed that the power decreases uniformly as the power is away from the antenna centre as also appropriate with the theory of RLSA antennas.

From Figures 3(b) and 3(c), it can be observed that for some areas, the powers inside a semi cut RLSA antenna and a quarter cut RLSA antenna do not flow in a perfect radial direction. It can also be observed that for some areas the power does not decrease uniformly as the power is away from the antenna centre. The imperfect radial direction and imperfect uniform decrease of the power flow are due to the edge of both antennas that are no longer circular. However, most of the power still flows in the radial direction and still decreases uniformly as can be seen from Figure 3. The imperfect radial direction and imperfect uniform decrease of the power flow might affect the characteristic of semi cut RLSA antennas and quarter cut RLSA antennas, which will be discussed more in the next section.

3.3. Characteristic of Performance Parameters of Cut RLSA Antennas

Figure 4(a) is the simulation result that shows the relationship between the designed beamsquint and the achieved beamsquint for several n values for both the semi cut RLSA antennas and quarter cut RLSA antennas. From Figure 4(a), it can be observed that the maximum beamsquint direction that can be achieved is 50° which is smaller than the achieved beamsquint of full circle RLSA antennas (that is 70°). This is due to the emergence of leakage radiated power at the area around antennas feeder, as can be seen in Figures 3(b) and 3(c), and the effect of imperfect power flow as discussed in Section 3.2.



(a) (b) (c)

(d) (e) (f)

Figure 3. Power flow inside the cavity of (a) full circle RLSA antenna, (b) semi cut RLSA antenna, (c) slot configuration of full circle RLSA antenna, (d) slot configuration of quarter cut RLSA antenna, (e) slot configuration of semi cut RLSA antenna.

However, the values of efficiency and directivity of cut RLSA antennas are averagely not smaller than the values of full circle RLSA antennas as can be seen in Figures 4(b) and 4(c). Even, for $n = 14$, the directivity of semi cut RLSA antennas (12 dBi) is greater than the maximum directivity that can be achieved by the full circle RLSA antennas (11 dBi). This interesting result is because most of the slots are placed at the left hand side of the antennas as can be seen in Figure 3(d). Since the sector of cut RLSA is taken from this area, the directivity and efficiency of the cut RLSA antennas do not decrease too much.

Another interesting result is that the reflection coefficient and bandwidth of cut RLSA antennas are better than the reflection coefficient and bandwidth of full circle RLSA antennas as shown in Figure 4(d). These are because the whole area of cut RLSA antennas consists of slots (see Figures 3(e) and 3(f)) so that most of the power is radiated from the slots. Otherwise, in the full circle RLSA antennas, almost half of the antennas' area does not consist of slots (see Figure 3(d)) so that the power flow in this area cannot be radiated and reflected back to the feeder at antennas perimeter, thus contributing to the increase of reflection coefficient and the decrease of bandwidth.

As an example to show the characteristic of cut RLSA antennas, Figures 5(a) and 5(b) show the radiation pattern and reflection coefficient of a quarter cut RLSA antenna for designed beamsquint of $73°$ and $n = 15$ (dashed line), respectively. This antenna has the directivity of 10.1 dBi, beam direction of $40°$, beamwidth of $35°$, sidelobe level of -7.4 dB, and the total efficiency of -0.2103 dB (95%). As a comparison, in Figure 5, the radiation pattern and reflection coefficient of a full RLSA (solid line) are included. It can be observed from Figure 5 that the quarter cut RLSA has better characteristic (wider beamwidth, better sidelobe level, better efficiency, better sidelobe level, and better reflection coefficient) than the characteristic of the full RLSA antenna as appropriate with the discussion in previous paragraph. However, the gain and the achieved beamsquint of the quarter cut RLSA are lower than the full RLSA antenna as also appropriate with the discussion in the first paragraph of this section.

From the above analysis and discussion, it can be concluded that although the size of cut RLSA

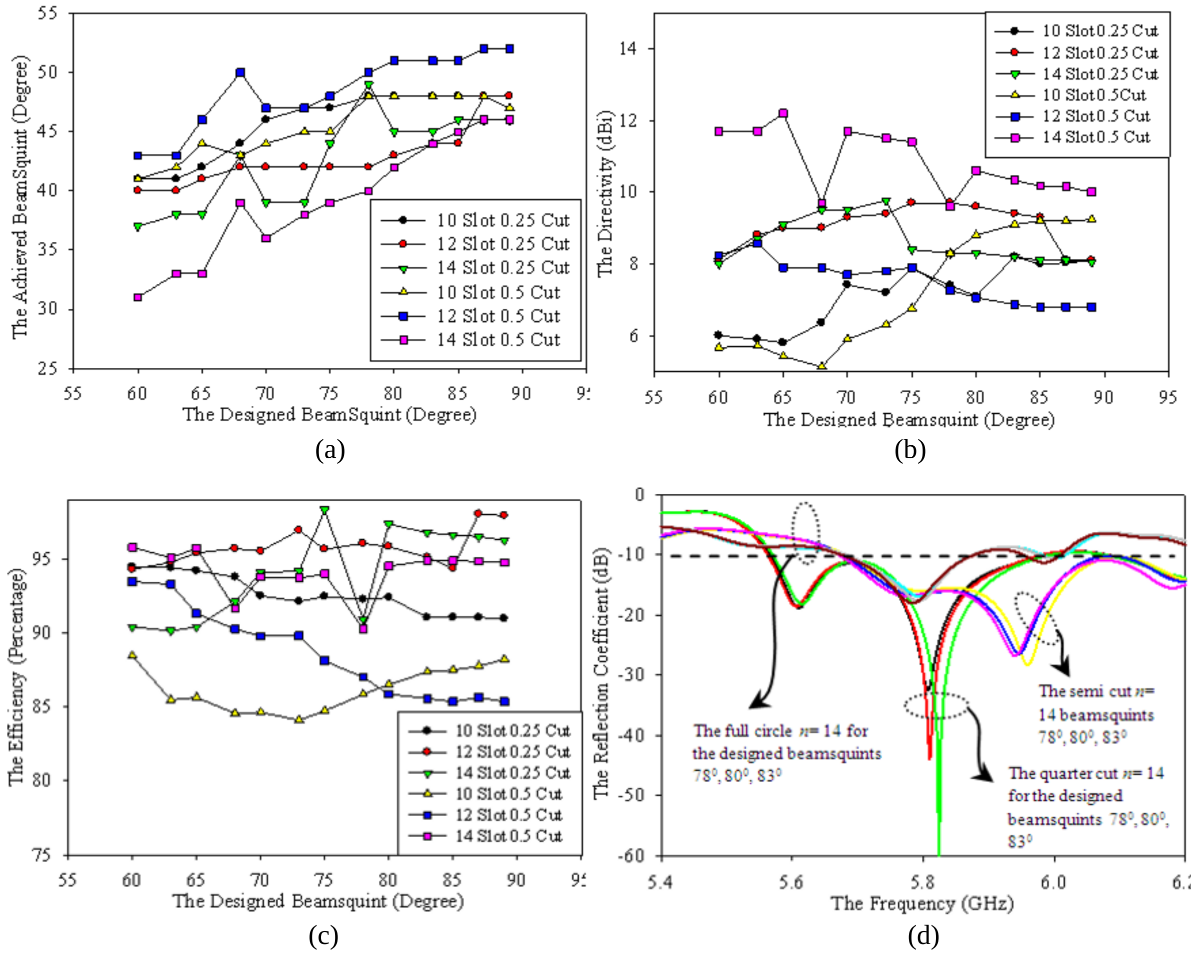


Figure 4. Simulation result of (a) achieved beamsquint, (b) directivity, (c) efficiency versus designed beamsquint of both semi cut RLSA and quarter cut RLSA for various n values, (d) reflection coefficient of full RLSA, semi cut RLSA and quarter cut RLSA for $n = 14$ and for beamsquint of 78°, 80°, 83°.

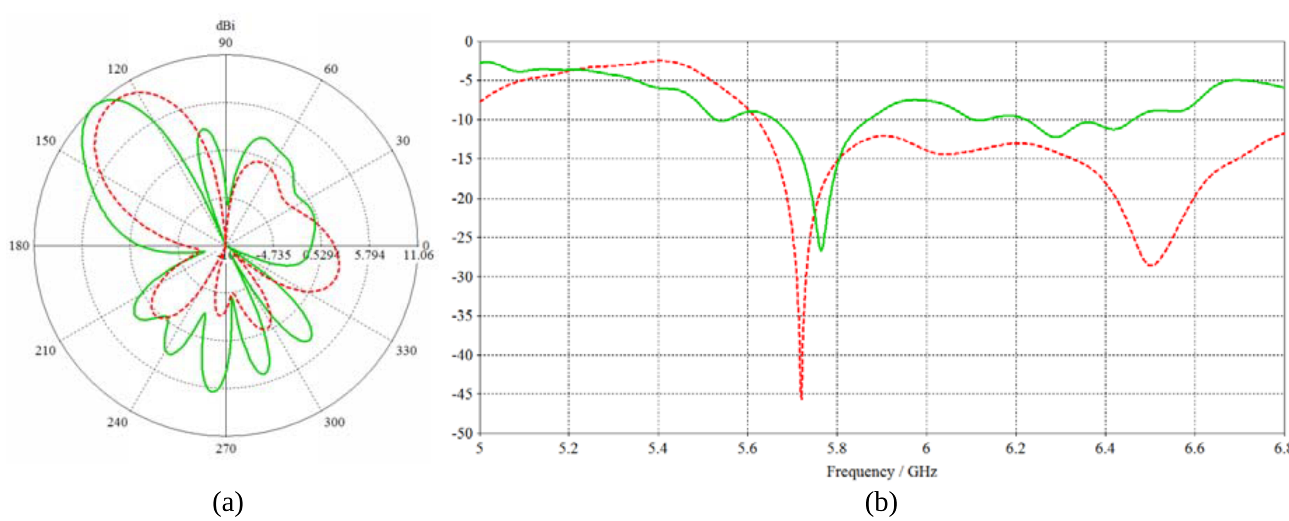


Figure 5. Simulation result of (a) radiation pattern, (b) reflection coefficient — of quarter cut RLSA antenna (dashed line) and full RLSA antenna (solid line) for designed beamsquint of 73° and $n = 15$.

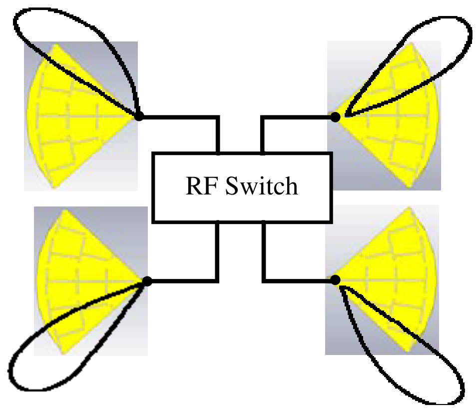


Figure 6. Illustration of reconfigurable (in term of beamsteering) RLSA antennas.

antennas is smaller than that of full RLSA antennas, their performances in terms of efficiency and directivity remain similar, even the reflection coefficient and bandwidth of cut RLSA antennas are better. This result ensures the capability of the cut RLSA antennas as a candidate for reconfigurable antennas, which will be confirmed in Section 5.

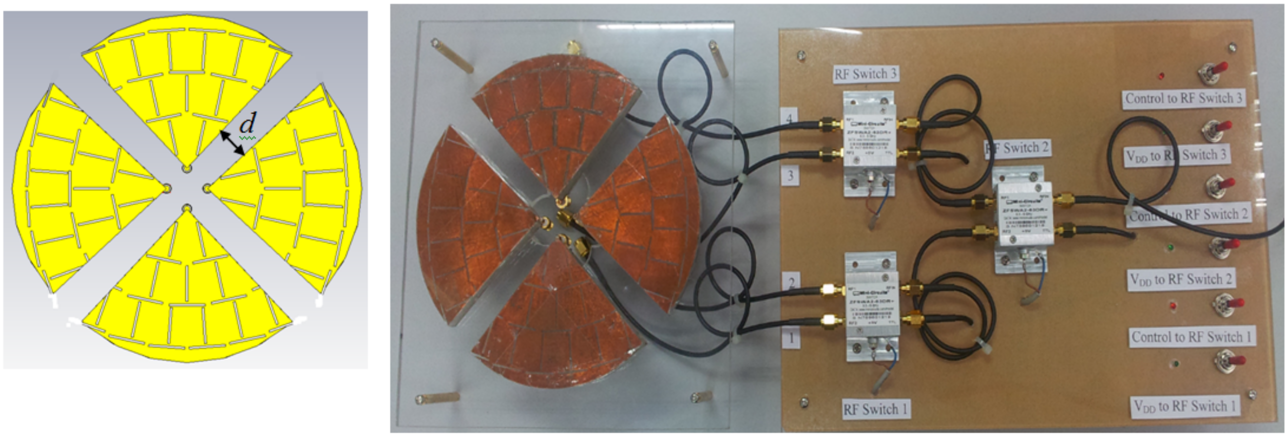
4. MOST SUITABLE METHOD IN REALIZING RECONFIGURABLE FUNCTION OF RLSA ANTENNAS

The reconfigurable function of antennas can be achieved through different methods such as altering the physical structure of antennas, changing feeding methods, and implementing antennas arrays [1]. The method of altering the physical structure might be not suitable for RLSA antennas since it will need many switches to cover the circular surface of RLSA antennas. This is different with the microstrip antenna. The microstrips antenna consists of narrow strips so that the microstrip needs only few switches to alter its physical structure. The method of changing the feeding method might also not be suitable for RLSAs since so far only the feeding method of disc ended coaxial probe that can result in the best performance of RLSAs [14]. The method of changing the feeding method also might change the wave propagation mechanism inside the antenna cavity, thus impair the performance of RLSAs. The method of implementing antenna array is the most likely method that can be utilized to realize the reconfigurable function of RLSA antennas. For this method, the reconfigurable function is realized by utilizing several cut RLSA antennas as the array element that has a different beam direction as shown by Figure 6. Every array element is connected to its own feeder, and all feeders are connected to an RF switch. The reconfigurable function in terms of beamsteering can be realized by setting "ON" one particular element, which has the beam direction the same as the desired direction and setting "OFF" the other elements.

5. RECONFIGURABLE (BEAMSTEERING) RLSA ANTENNAS

5.1. Antennas Structure

In this section, a reconfigurable antenna in terms of beamsteering is designed. The structure of designed model, the structure of fabricated prototype, and the fabricated feeder are shown in Figures 7(a), 7(b), and 7(c), respectively. The method of implementing antenna array as discussed in Section 4 is utilized to realize the reconfigurable function of the antenna. The quarter cut RLSA antenna is designed for beamsquint of 73°, and the n value of 15 is utilized for the array element of the reconfigurable antenna. This antenna consists of four array elements that have four different beam directions. Every element has its own feeder, and all feeders are connected to a commercial SP4T (single input four output) RF switch. By switching 'ON' one of the desired feeders and 'OFF' the others, the antenna beam can



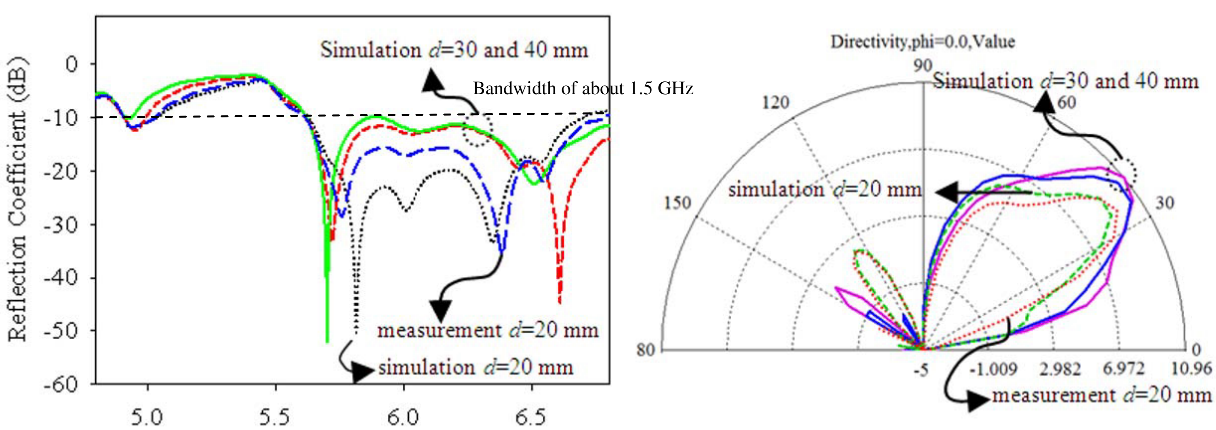
(a) (b)

Figure 7. Structure of reconfigurable RLSA antenna, (a) simulated model, (b) fabricated prototype.

be steered into one of the four directions, hence realizing the beamsteering function. The feeders and antenna elements are separated one to another in order to minimize the effect of 'OFF' element on the 'ON' element. The antenna parameter of the array element (the quarter cut) is same as the previous antenna parameter as listed in Table 1 and Table 2.

5.2. Result and Discussion

Figure 8(a) shows the reflection coefficient of the beamsteering RLSA antenna (consist of 4 element of the quarter cut) for several values of d (distance between the element feeders, see Figure 7(a) for the definition of d). From Figure 8(a), it can be observed that the reflection coefficient response of the beamsteering RLSA antenna varies with the value of d, because different d will cause different effects of the 'OFF' element on the 'ON' element. This is also the reason that the radiation pattern of beamsteering RLSA antenna varies with the value of d, as can be seen in Figure 8(b). The best d value that can give the best reflection coefficient and the best radiation pattern is determined by parametric study. In this simulation case, the best reflection coefficient and the best radiation pattern are given by the d of 20 mm.



(a) (b)

Figure 8. (a) Reflection coefficient. (b) Radiation pattern of beamsteering RLSA antenna for several values of d (in mm) for both simulation and measurement result.

For the d of 20 mm, the antenna beam has the directivity of 9.2 dB, the total efficiency of −0.08984 dB (97.95%), the mainlobe direction (in elevation direction) of 45°, the beamwidth (in elevation) of 32.5°, the bandwidth about 1.5 GHz, and the sidelobe level −6.3 dB. The reflection coefficient and radiation pattern of the antenna can be seen in Figures 8(a) and 8(b), respectively. Since all elements are identical, their beams are also identical. The only difference is that every beam has different directions in azimuth directions (0°, 90°, 180°, and 270°). As explained in Section 5.1, by setting "ON" one element and setting "OFF" the others, the antenna will be able to steer its beam to one of the four directions, thus realizing the beamsteering function.

The measurement result of reflection coefficient and the radiation pattern are also ploted in Figures 8(a) and 8(b), respectively. The slight deviation of the measurement result from the simulation one is due to the imperfection in fabricating the prototype especially in drilling a hole for the antenna feeder at exact position, aligning the radiating element, cavity, and background, and in soldering the head disc at SMA feeder at correct position.

6. CONCLUSIONS

The study on the realization of the reconfigurable function of RLSA antennas has been discussed in this paper. The study shows that in terms of performance, small RLSA antennas are suitable as a candidate for reconfigurable antennas. In order to minimize the size, the new method of cutting small RLSAs is proposed. The study moreover shows that the cut RLSAs are more suitable as a candidate for reconfigurable antennas than the full RLSAs since the cut RLSA antennas can significantly reduce the size of the RLSA antennas with slight performance decrease. The study also shows that the method of implementing array is the most suitable method in realizing the reconfigurable function of RLSA antennas. In order to verify the study, utilizing the quarter cut RLSAs as the array element, a novel reconfigurable RLSA antenna that can steer the beam into 4 different directions has been successfully designed, simulated, and fabricated. Future researches could be carried out for beamshaping by utilizing the cut RLSA as the array elements with no beamsquint design (the beam is in the boresight direction). Reconfigurability in frequency can also be realized by designing the slot for different interested frequency bands for different array elements.

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