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The extreme beamsquint technique to minimize the reflection coefficient of very small aperture radial line slot array antennas

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This paper proposes the utilization of extreme beamsquint technique to minimize the reflection coefficient of very small aperture radial line slot array (VSA-RLSA) antennas when the normal beamsquint technique is no longer able to do so. This technique utilizes very high beamsquint in order to obtain multiple rings on the radiating element of VSA-RLSA antennas, thus minimizes the reflection coefficient and improves the efficiency of VSA-RLSA antennas. The theoretical analysis on the generation procedure of signal reflections in the VSA-RLSA antennas, as well as the operational function of how extreme beamsquint technique can minimize the signal reflections, is explained. Various extreme beamsquint VSA-RLSA antennas and normal beamsquint VSA-RLSA antennas with radius of 75 mm are designed, simulated and fabricated. The good agreement between simulation and measurement results shows that the extreme beamsquint VSA-RLSA antennas have much lower reflection coefficient response and higher efficiency than the normal beamsquint VSA-RLSA antennas.

1. Introduction

Radial line slot array (RLSA) antennas have gained much attentions since the year 1985 [1]. Initially, the RLSA antennas were developed for satellite signal reception antenna and have an antenna diameter not less than 600 mm [2,3]. Due to the advantages of the RLSA antenna, such as high gain [1–4], the RLSA antennas are also developed for smaller antenna applications such as wireless LAN [5–13], milimetre wave [14–16] and mobile satellite [17]. Some of these applications utilize small aperture RLSA (SA-RLSA) antennas with the diameter less than 300 mm [5–17].

In contrast to the normal size RLSA antennas, SA-RLSA antennas have lower efficiency [18]. From the view of antenna theory, this is normal since smaller antennas will have smaller efficiency. The lower efficiency is due to insufficient number of slot pairs that the SA-RLSA antennas have. The insufficient number of slot pairs cannot radiate most of power coming from the feeder, so that there will be a significant amount of remaining power left at the perimeter of SA-RLSA antennas. This remaining power will be reflected back to the antenna feeder and increase the reflection coefficient of SA-RLSA antennas, thus lower the efficiency of SA-RLSA antennas. Normally, the utilization of longer slot length can minimize the

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remaining power at perimeter of SA-RLSA antennas since the longer slot length can increase the ability of slot in radiating the power [5,19].

For very small aperture RLSA antennas (VSA-RLSA) which have apertures smaller than SA-RLSA antennas (diameter less than 150 mm), the efficiency is lower than SA-RLSA antennas, hence the design becomes more difficult. In VSA-RLSA antennas, the reflection coefficient is not only the contribution of the remaining power at the perimeter like in the SA-RLSA antennas, but also the contribution of reflected signal from the slots. Hence, the utilization of longer slot, as explained in previous paragraph, is not sufficient to minimize the reflection coefficient of VSA-RLSA antennas. The technique of normal beamsquint in [20–22] – usually utilized to cancel the reflected signal from the slot in the normal size RLSA and in SA-RLSA – is no longer able to cancel the reflected signal from the slots, since the number of rings of VSA-RLSA antenna is insufficient.

This paper proposes a new technique to minimize the reflection coefficient of VSA-RLSA antennas using the extreme beamsquint technique. This technique utilizes very high beamsquint values (greater than 70°) to obtain more rings on the radiating element of VSA-RLSA antennas, thus decrease the reflection coefficient and increase the efficiency of VSA-RLSA antennas. This paper is organized as follows. First, the theoretical analysis on the generation procedure of signal reflections in the VSA-RLSA antennas and the operational function of how the extreme beamsquint technique can minimize the signal reflections are explained in Section 2. Then, in Section 3, several VSA-RLSA antennas with radius of 75 mm are designed at the frequency 5.8 GHz. The design uses the extreme beamsquint tehnique and normal beamsquint technique to observe how the extreme beamsquint technique can minimize the reflection coefficient of VSA-RLSA antennas. Two prototypes of VSA-RLSA antennas that utilize normal beamsquint technique and extreme beamsquint technique are fabricated and measured. The measurement and simulation results are discussed in Section 4. Finally, conclusions are drawn in Section 5.

2. The theoretical analysis

The signal reflection in RLSA antennas stems from two causes, those are: the signal reflection due to the power remaining at antenna perimeter and the signal reflection due to the reflected signal from the slots. In this paper, only the reflected signal from the slot is discussed since this kind of signal reflection is the one that the normal beamsquint technique fails to overcome in case of VSA-RLSA antenna. This section also explains the theory of how the normal beamsquint is no longer able to minimize the reflection coefficient once the number of rings is insufficient. Furthermore, this section discusses the analysis of how the extreme beamsquint technique can minimize the reflection coefficient response of VSA-RLSA antennas.

2.1. The signal reflection due to the slot

Figure 1 shows the front cut view of RLSA antenna and the signal flow within the cavity of RLSA antenna. The grey arrows represent the signal flow from the centre of RLSA antenna to the antenna perimeter, and the black arrows represent the reflected signal from the slots. Figure 1 shows that if the distance between the slots (d) is $\lambda_g/2$, the signal from slot “A” will travel for $\lambda_g/2$ to reach “B”. At “B”, some part of the signal will be reflected back and will travel for another $\lambda_g/2$ to reach “A”. Therefore, the reflected signal from the slots “A” and “B” will have a different phase of $\lambda_g/2 + \lambda_g/2 = \lambda_g$ or 360° (or can be said that there is no phase difference), so that they will strengthen each other and result in a high reflection coefficient.

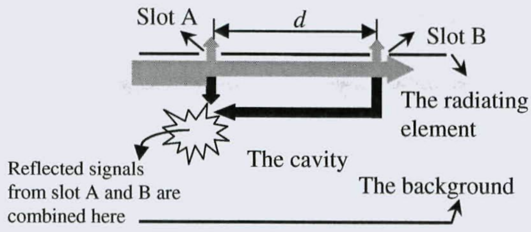

Figure 1. The illustration of reflected signal from the slot.

In normal RLSA antennas or SA-RLSA antennas, the effect of reflected signal from the slots can be minimized by utilizing the beamsquint technique. The effect of the beamsquint technique is that the distance between slots (d) is no longer $\lambda_g/2$, hence the reflected signal from slots "A" and "B" will have a different phase that is no longer λ_g or 360°, so that they will cancel out each other and lower the reflection coefficient.

The ability of beamsquint technique in minimizing the reflected signal from the slots depends on one condition that the number of rings must be sufficient. As an example, Figure 2(a) and (b) show the reflected signals of a three ring RLSA antenna and the reflected signals of a two ring RLSA antenna, respectively. Since every ring consists of two slots, there are six reflected signals for the three ring RLSA antenna and four reflected signals for the two ring RLSA antenna. It is assumed that the amplitude of all reflected signals is the same in order to simplify the analysis. From Figure 2(a), it can be observed that all the graph space is covered by the reflected signals, hence the combination of all reflected signals will cancel out each other, and the minimum signal reflection is obtained. In contrast, from Figure 2(b), it can be seen that not all the graph space (the area pointed by "A") is covered by the reflected signals, hence the combined signal will be greater than the combined signal in Figure 2(a).

From the example in the previous paragraph, it can be concluded that smaller number of rings will decrease the ability of beamsquint technique in cancelling the reflected signal, which is the reason that the reflection coefficient of VSA-RLSA antennas with fewer rings (less than two) is high and that the normal beamsquint technique fails to minimize the reflection coefficient of VSA-RLSA antennas. Next section will explain how the proposed extreme beamsquint technique can reduce the high reflection coefficient of VSA-RLSA antennas by increasing the number of rings.

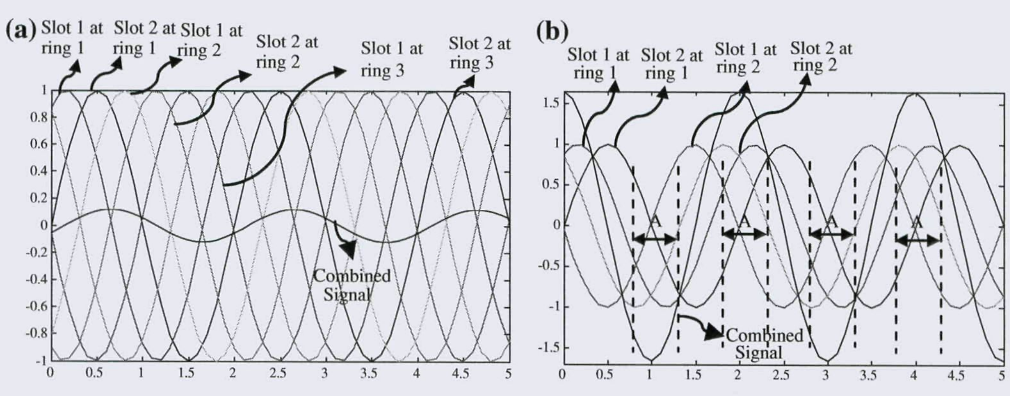

Figure 2. (a) The reflected signal of three ring RLSA antenna. (b) The reflected signal of two ring RLSA antenna.

2.2. *Extreme beamsquint technique to minimize the reflection coefficient of VSA-RLSA*

The position of the ring in radial direction (S_ρ) can be expressed by Equation (1) below [23]:

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

where, θ_T is the beamsquint angle, ϕ, the positions of slots in azimuth, ϕ_T is the azimuth angle of beamsquint and r is the ring number. The definition of all these parameters is illustrated in Figure 3(a).

Based on Equation (1), by utilizing $r = 1$, $\phi_T = 0$ and $\phi = 0$ to 360°, rings for beamsquint angles of 10°, 30° and 60° are plotted as shown in Figure 3(b), which illustrates that the beamsquint technique obtains the ring in an ellipse-like shape rather than circular shape. From Figure 3(b), it can be observed that the position of the ring at the left-hand side will

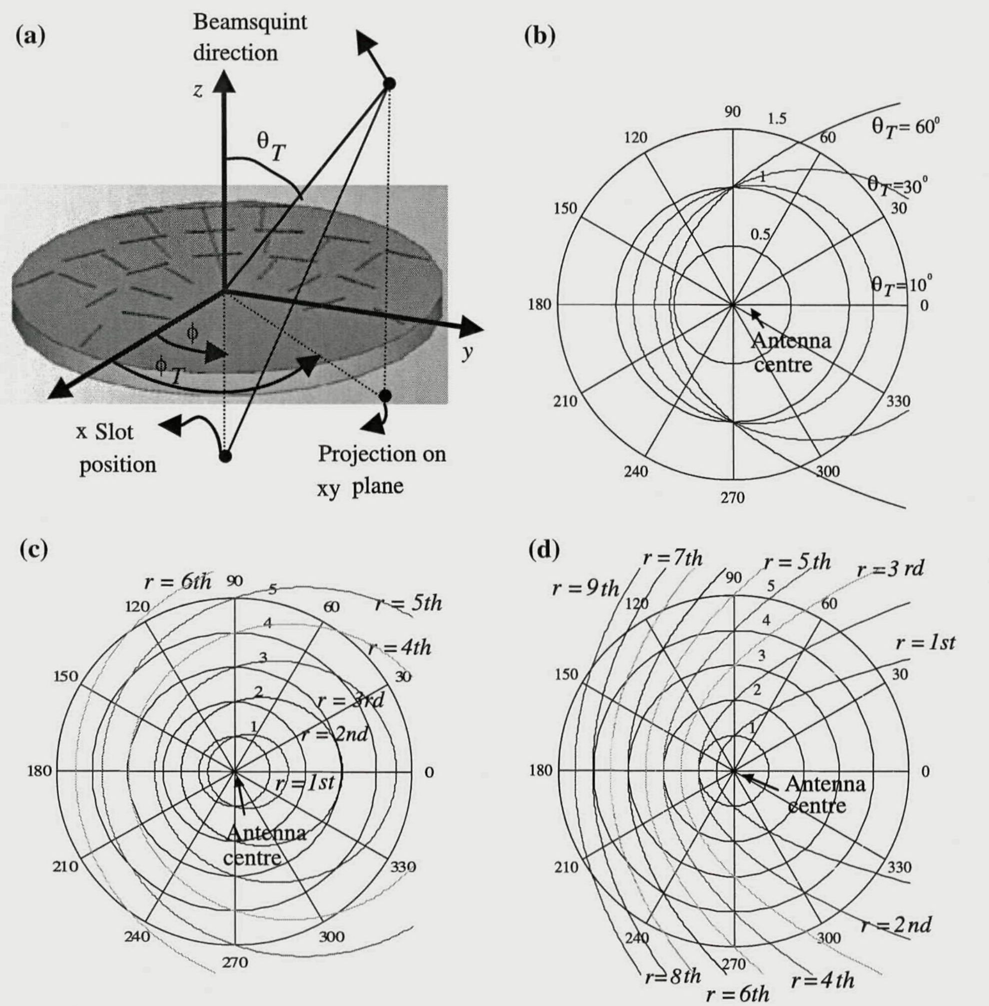

Figure 3. (a) The illustration of some parameters of ring position. (b) Plot of ring for beamsquint of 20°, 30° and 60°. (c) Plot of various ring numbers for beamsquint angle of 20°. (d) Plot of various ring numbers for beamsquint angle of 80°.

move closer to antenna centre as the beamsquint increases. In contrast, the position of the ring at the right-hand side will move farther from antenna centre as the beamsquint increases.

Still based on Equation (3), by utilizing $\phi_T = 0$ and $\phi = 0$ to 360°, the rings are plotted for various ring numbers for the beamsquint angles of both 20° and 80°, as shown in Figure 3 (c) and (d), respectively. From these figures, it can be observed that at the left-hand side, the distance between the rings for beamsquint angle of 80° is shorter than the distance between the rings for the beamsquint angle of 20°. Due to the shorter distance between the rings, the beamsquint angle of 80° has more rings (nine rings) that can be plotted in the antenna area than the beamsquint angle of 20° (six rings). Based on the previous examples and explanations, it can be concluded that a higher beamsquint angle can yield more rings. This fact is very useful to include additional rings for the VSA-RLSA antenna which originally has low number of rings (less than two). With the extra number of rings, the antenna will have better ability to minimize the reflection coefficient of VSA-RLSA antenna, as will be proven in Section 4.

3. The structure and the specification of the experimental antenna

The structure of VSA-RLSA antenna model, going to be simulated and measured in Section 4, is shown in Figure 4. The structure consists of a radiating element (made of copper), a cavity (made of polypropylene), a background (made of copper) and a feeder. The feeder is an ordinary SMA feeder, modified by adding a head disc. The head disc has the function to convert the signal from the 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 VSA-RLSA antenna model and its feeder are listed in Tables 1 and 2, respectively.

4. Results and discussion

In this section, various VSA-RLSA antennas are simulated for various beamsquint values. The same antenna parameters, as described in Section 3, are used in the simulations. The design of VSA-RLSA antennas using low beamsquint values (ranging from 3° up to 55°) obtains the VSA-RLSA antennas with two rings, as shown in Figure 5(a). In contrast, the

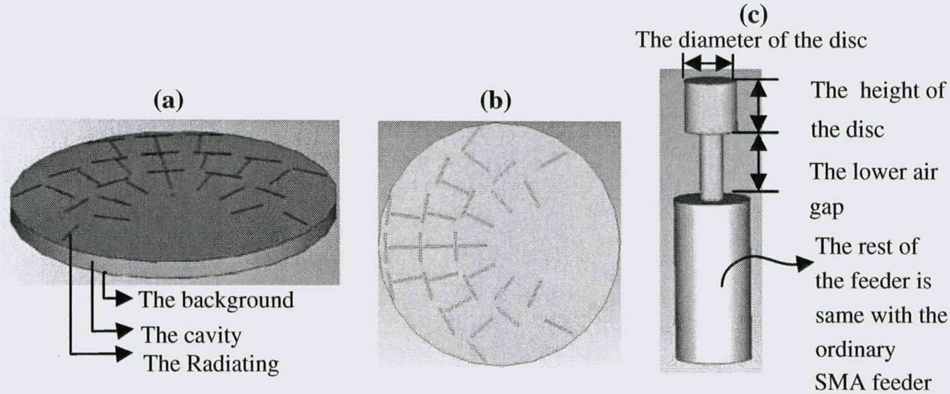

Figure 4. (a) The structure of VSA-RLSA antenna model. (b) The slot configuration on the radiating element of VSA-RLSA antenna model. (c) The feeder.

Table 1. The specification parameters of VSA-RLSA antenna model.

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
Number of slot pairs in first ring	n	14
Cavity thickness	d_1	8 mm
The thickness of radiating element and background	d	0.1 mm
The permittivity of cavity	ε_{r1}	2.47
Cavity material	–	Polypropylene
The material of radiating element and the background	–	Copper

Table 2. The specification parameters of feeder [24].

The specification parameters	The symbol	The value (mm)
Height of the disc	h	3
Radius of the disc	r_a	1.4
The lower air gap	b_1	4
The upper air gap	b_2	1

design of VSA-RLSA antennas using higher beamsquint values (raging from 58° up to 89°) results in the VSA-RLSA antennas with three rings, as shown in Figure 5(b).

Figure 5(c) presents the reflection coefficient response of VSA-RLSA antennas for various beamsquint values ranging from 3° up to 53°. Figure 5(c) shows that the reflection coefficient response around the centre frequency of 5.8 GHz averagely is above −10 dB. In contrast, in Figure 5(d), which shows the reflection coefficient response of VSA-RLSA antennas for various beamsquint ranging from 55° up to 89°, it can be observed that the reflection coefficient response around centre frequency of 5.8 GHz averagely is −18 dB, and a bandwidth of at least about 200 MHz is obtained. The better reflection coefficient of antennas in Figure 5(d) than the reflection coefficient of antennas in Figure 5(c) is due to the greater number of rings that the antennas in Figure 5(b) have, as the result of utilization of extreme beamsquint technique.

In Figure 6(a), it can be observed that the VSA-RLSA antennas designed for extreme beamsquint (greater than 60°) have higher efficiency (averagely above 90%) than the VSA-RLSA antennas designed for normal beamsquint (smaller than 60°). This result is the consequence of better reflection coefficient of the extreme beamsquint VSA-RLSA antennas, as discussed in the previous paragraph.

Figure 6(b) shows the gain of VSA-RLSA antenna for various beamsquint values. From this figure, it can be observed that higher beamsquint will result in lower gain, due to the emergence of grating lobes as the consequence of utilizing high beamsquint values [23]. The grating lobes will influence the directivity of VSA-RLSA antenna and, thus, lower the gain.

The beamsquint direction (θ_T) that can produce the grating lobes is expressed by Equation (2) below [23].

$$\theta_T = \sin^{-1}\left(\frac{\sqrt{\varepsilon_r} - 1}{\cos(\emptyset - \emptyset_T)}\right) \quad (2)$$

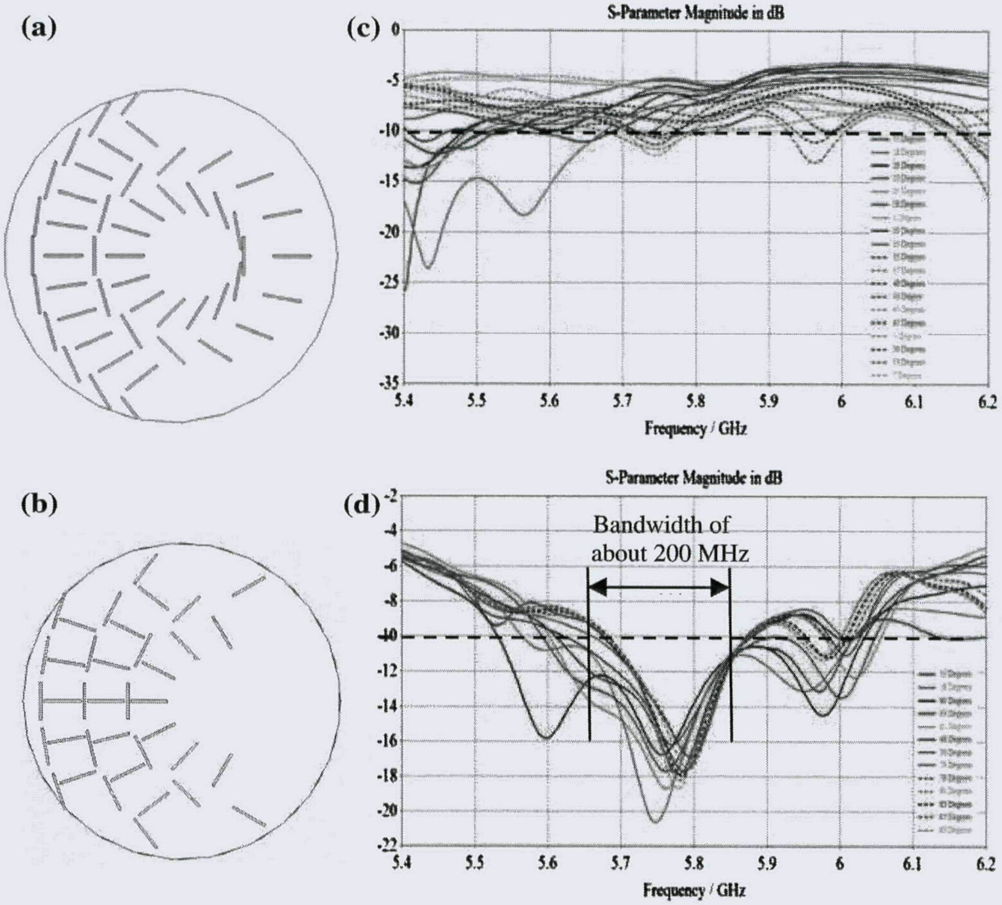

Figure 5. (a) The slot design for beamsquint of 20°. (b) The slot design for beamsquint of 85°. (c) The reflection coefficient response of VSA-RLSA antenna for low beamsquint. (d) The reflection coefficient response of VSA-RLSA antenna for high beamsquint.

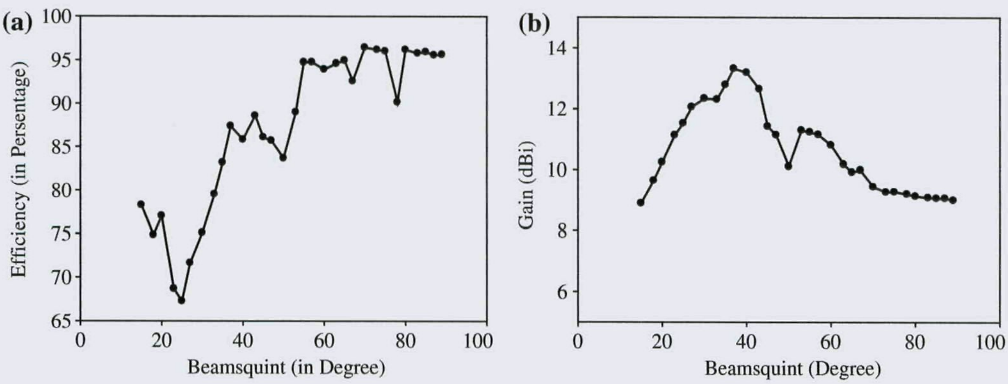

Figure 6. (a) The efficiency for various beamsquint. (b) The gain for various beamsquint.

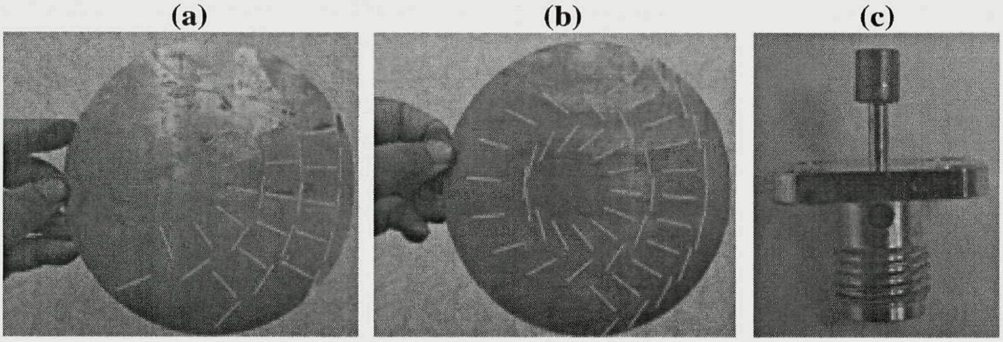

Figure 7. (a) The fabricated VSA-RLSA antenna for beamsquint of 87°. (b) The fabricated VSA-RLSA antenna for beamsquint of 20°. (c) The fabricated feeder.

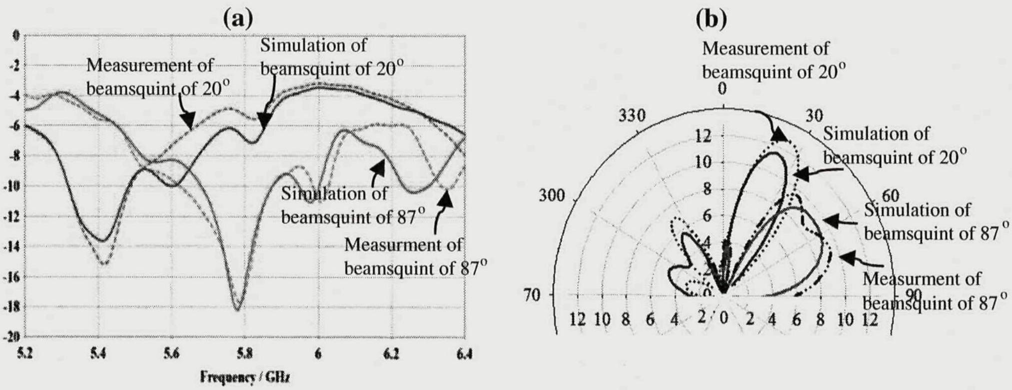

Figure 8. The measurement and the simulation result of VSA-RLSA antenna. (a) The reflection coefficient. (b) Radiation pattern.

For the simulation in this paper, the permittivity of the cavity (ε_r) is set equal to 2.471. The minimum θ_T ($\theta_{T\min}$) that can make the slots of VSA-RLSA antenna start to produce grating lobes 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 (2), we can get $\theta_{T\min} = 31.8°$. From Equation (2), it can also be observed that other slots at the respective $\emptyset$ will start to produce grating lobes as θ_T increases to greater than 34.89°, which means that the number of grating lobes increases proportionally with the increase of the designed beamsquint angle, which is why the gain in Figure 6(b) decreases as the beamsquint increases.

In order to verify the theoretical and simulated results, two prototypes of VSA-RLSA antenna are fabricated, as shown in Figure 7(a) and (b). The first VSA-RLSA antenna utilizes the normal beamsquint technique (the beamsquint of 20°) and the second VSA-RLSA antenna utilizes the extreme beamsquint technique (the beamsquint of 87°). The antennas' parameters are the same as the parameters tabulated in Tables 1 and 2 in Section 2.

Figure 8(a) and (b) show the reflection coefficient response and the radiation pattern of both VSA-RLSA antennas, respectively. From Figure 8(a), it can be observed that the first VSA-RLSA antenna utilizing normal beamsquint has worse reflection coefficient than the second VSA-RLSA antenna utilizing the extreme beamsquint, as appropriate to the explained theory in Section 3. From Figure 8(b) it can be observed that the directivity of the first VSA-RLSA antenna is higher than the directivity of the second VSA-RLSA antenna, as also appropriate to the explained theory in Section 3.

It also can be observed from Figure 8(a) and (b) that a good agreement is shown between the measurement and the simulation results. A slight deviation of the measurement result from the simulation one is due to the imperfection in fabricating the prototype, especially in drilling the hole for the antenna feeder at the exact position, aligning the radiating element, cavity and background and soldering the head disc at the SMA feeder at a correct position.

5. Conclusions

The extreme beamsquint technique utilized to minimize the reflection coefficient of VSA-RLSA antennas has been explained theoretically and implemented for both the simulation model and the prototype model of VSA-RLSA antennas. The analysis of the simulation and measurement results concludes that the implementation of the extreme beamsquint technique has successfully minimized the reflection coefficient from averagely above −10 dB to averagely −18 dB and formed the bandwidth not less than 200 MHz. Furthermore, it is also concluded that the efficiency of VSA-RLSA antenna has been improved up to averagely 90%. The ability of this technique in minimizing the reflection coefficient response, forming the bandwidth and improving the efficiency of VSA-RLSA antenna would be a great step in realizing the development of RLSA technology for small antenna applications.

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