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A NOVEL TECHNIQUE IN SIMPLIFYING THE FABRICATION PROCESS AND IMPROVING THE REFLECTION COEFFICIENT OF THE LINEAR POLARIZED RADIAL LINE SLOT ARRAY (LP-RLSA) ANTENNAS

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Abstract—A novel technique in simplifying the fabrication process of LP-RLSA antenna as well as improving the reflection coefficient of LP-RLSA antenna is proposed in this paper. This technique utilizes a FR4 board added on the top of the normal LP-RLSA antenna. Theoretically, FR4 dielectric material is able to reduce antenna reflection coefficient since it produces the signal that has a different phase with the propagating signal within the antenna cavity. Moreover, by utilizing the copper part of the FR4 board as the radiating element, the fabrication process can be simplified since the antenna slots can be cut utilizing the simple low cost etching process. In this paper, the theory about how the utilization of the FR4 board can improve the reflection coefficient response is explained. The parameters that influence the capability of FR4 board in improving the reflection coefficient response are also discussed. A LP-RLSA antenna with FR4 board and a LP-RLSA antenna without FR4 board are designed and simulated at frequency of 5.8 GHz. The simulation result shows that the thickness and permittivity values of FR4 board influence the reflection coefficient response and the antenna gain. The best values of the permittivity and thickness of the FR4 board are 4.3 and 1.6, respectively. The simulation result shows that these values can improve antenna gain up to 2.45 dB. They can also improve reflection coefficient response significantly from −3 dB to −25 dB. It is discovered

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that the LP-RLSA with FR4 board also produces the beamsquint effect from -10° up to 10° from the boresight direction. The prototype of the designed antennas is fabricated and measured. The measurement and simulation results show that the LP-RLSA with FR4 board has a better gain and better reflection coefficient than the LP-RLSA without FR4 board, thus prove the concept of the novel technique.

1. INTRODUCTION

The main problem of the Linearly Polarized Radial Line Slot Array (LP-RLSA) antenna is its poor reflection coefficient response [1]. To overcome this problem, the techniques of beamsquint and cancelling slot are normally utilized [2–7]. These two techniques have slight weaknesses. Firstly, the technique of beamsquint produces an oval ring of slots instead of a circle ring of slots, so there is an amount area of antenna radiating element that cannot be utilized to cut the slots, hence the design becomes not optimum, especially for the antenna that is small with long slot length. Secondly, the technique of cancelling slot needs to cut more slots on the radiating element or on the background of the antenna, hence it increases the fabrication cost of the antenna.

The other LP-RLSA antenna problem is that the fabrication process of LP-RLSA antenna is not simple compared to microstrip antennas, due to the need of special fabrication tools such as a large plotter used to cut the slots on the antenna radiating element [8]. To simplify the fabrication process of LP-RLSA antennas, several researches reported the utilization of a cheap FR4 material with simple etching process as the material for the LP-RLSA antenna [9–13]. However, in those researches, the utilization of several FR4 boards as the antenna cavity reduces the performance of LP-RLSA antennas, because of the presence of air gap and poor electrical performance of the FR4 board.

This paper proposes a novel technique to overcome both of above problems (the poor reflection coefficient and fabrication process). This technique is named FR4 board technique. In this technique, a FR4 board is added on the top of the LP-RLSA antenna. The copper material of the FR4 board is utilized as the radiating element of the LP-RLSA antenna, which can simplify the fabrication process since the slots on the radiating element can be cut by utilizing the simple etching process.

Furthermore, the dielectric part of the FR4 board is able to reduce the reflection coefficient of the LP-RLSA antenna. Different from the researches in [9–13], the dielectric part of the FR4 board is not utilized as the LP-RLSA antenna cavity, but as the other dielectric material that has a different permittivity. This different permittivity results in a different phase between the reflected signal within the FR4 dielectric material and the reflected signal within the antenna cavity. Hence, these two signals will not strengthen each other when they meet, thus improve the reflection coefficient response.

2. THE THEORY OF HOW THE FR4 BOARD REDUCES THE REFLECTION COEFFICIENT

The high reflection coefficient response of the LP-RLSA antenna is normal due to the distance of $\lambda_g/2$ between two neighbouring slots in a same ring. λ_g is the wavelength of the signal within the antenna cavity. It is shown in Figure 1(a) below. Because the distance between slots A and B is $\lambda_g/2$, the reflected signals from the slots at A and at B will have the same phase at C, so that they will strengthen each other while they are propagating toward the feeder, hence increase the reflection coefficient response.

Figure 1(b) describes the process of how the FR4 board can reduce the reflection coefficient value in the LP-RLSA antenna. The equation of the two signals at C reflected from two neighbouring slots (A and B) can be written as below:

$$\begin{aligned} E_A &= X_A \cos\left(wt - k_1 z_1\right) \\ E_B &= X_B \cos\left(wt - k_2 z_2\right) \end{aligned} \quad (1)$$

In Equation (1), the magnitudes of signals E_A and E_B (that

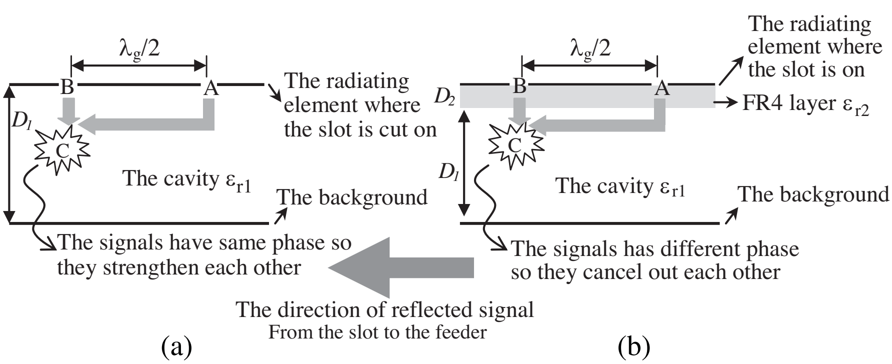

Figure 1. (a) The mechanism of generating the high reflection coefficient in the normal LP-RLSA antenna. (b) The mechanism of reducing the reflection coefficient in the LP-RLSA antenna with the FR4 board.

are X_A and X_B) are assumed same to simplify the analysis. The wavevectors k_1 and k_2 can be written in detail as shown in Equation (2) below:

$$\begin{aligned} k_1 &= {}^{2\pi}\!/_{\lambda_{g1}} = {}^{2\pi}\!/\!\left(\lambda_0/\sqrt{\varepsilon_{r1}}\right) = \frac{2\pi\sqrt{\varepsilon_{r1}}}{\lambda_0} \\ k_2 &= {}^{2\pi}\!/_{\lambda_{g2}} = {}^{2\pi}\!/\!\left(\lambda_0/\sqrt{\varepsilon_{r2}}\right) = \frac{2\pi\sqrt{\varepsilon_{r2}}}{\lambda_0} \end{aligned} \tag{2}$$

Equation (2) is substituted into Equation (1) and results in Equation (3) as below:

$$\begin{aligned} E_A &= X_A \cos\left(wt - \frac{2\pi\sqrt{\varepsilon_{r1}}}{\lambda_0} z_1\right) \\ E_B &= X_B \cos\left(wt - \frac{2\pi\sqrt{\varepsilon_{r2}}}{\lambda_0} z_2\right) \end{aligned} \tag{3}$$

From Equation (3), it can be seen that signals E_A and E_B have the same frequency and different phases. The phase difference is determined by different signal positions in the cavity (z_1 and z_2) and permittivity of dielectric $\sqrt{\varepsilon_{r1}}$ and $\sqrt{\varepsilon_{r2}}$. Since the reflected signals from the slot at A and B have a different phase at C, they will cancel out each other while they are propagating toward the feeder, thus decrease the reflection coefficient of the LP-RLSA antenna.

In order to get the minimum reflection coefficient, the sum of signals E_A and E_B at all positions along the cavity (z_1 and z_2 values) and during the operating time (so called t_1 to t_2) should be minimum. This condition can be expressed by Equation (4) below:

$$\begin{aligned} &\int_{z_1}^{z_2}\int_{t_1}^{t_2} (E_A + E_B)\, dt dz = \text{minimum} \\ &\int_{z_1}^{z_2}\int_{t_1}^{t_2} \left(X_A \cos\left(wt - \frac{2\pi\sqrt{\varepsilon_{r1}}}{\lambda_0} z_1\right) + X_B \cos\left(wt - \frac{2\pi\sqrt{\varepsilon_{r2}}}{\lambda_0} z_2\right)\right) dt dz = \text{minimum} \end{aligned} \tag{4}$$

The minimum condition in Equation (4) can be achieved by setting the phase difference between signals E_A and E_B equal to π radian or 180°. The parameters that can be modified for this purpose are $\sqrt{\varepsilon_{r1}}$, $\sqrt{\varepsilon_{r2}}$, z_1 and z_2. However, the appropriate values for $\sqrt{\varepsilon_{r1}}$, $\sqrt{\varepsilon_{r2}}$, z_1 and z_2 are too complex and difficult to be calculated mathematically, because signals E_A and E_B have changeable phase differences over different positions (z_1 and z_2) in the cavity. As an example, Figure 2 below shows the plot of signals E_A and E_B over different positions

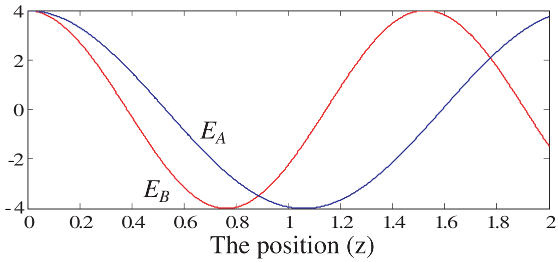

Figure 2. The signal of E_A and E_B along different position (z).

(for $X_A = X_B = 4$, $f = 5.8\,\mathrm{GHz}$, $\varepsilon_{r1} = 2.33$ and $\varepsilon_{r2} = 4.3$). From Figure 2, it can be observed that signals E_A and E_B have different phase differences for different positions. The other reason that they are difficult to be calculated mathematically is that the signal component $\sqrt{\varepsilon_{r2}}$ of E_B will gradually change into $\sqrt{\varepsilon_{r1}}$ as signal E_B exits from material layer 2 (FR4 board), enters material layer 1 (polypropylene), and propagates along this layer.

The other parameter that influences the reflection coefficient is the thickness of the FR4 board (D_2), because the thickness of FR4 board determines the volume of FR4 board, thus determines the amount of signal E_B that propagates within the FR4 board. However, similarly with $\sqrt{\varepsilon_{r1}}$ and $\sqrt{\varepsilon_{r2}}$, the most appropriate thickness of the FR4 board that can fulfil the minimum condition in Equation (4) is too complex to be calculated mathematically for the same reason as the above.

Since $\sqrt{\varepsilon_{r1}}$, $\sqrt{\varepsilon_{r2}}$ and D_2 are too complex and difficult to be calculated mathematically, the only way to find the appropriate value for them is by conducting a parametric study using an antenna simulation software, which will be discussed in Sections 3 and 4.

3. THE STRUCTURES AND SPESIFICATIONS OF THE DESIGNED ANTENNAS

3.1. The Designed Antenna for Parametric Study

In order to determine appropriate permittivity and thickness value of the FR4 board as discussed in Section 2, a LP-RLSA with FR4 board is designed and simulated for various FR4 permittivities and FR4 thicknesses at frequency of 5.8 GHz. The antenna structure of the LP-RLSA with FR4 board, LP-RLSA without FR4 board and its feeder are designed utilizing CST MWS 2010 simulator, shown in Figure 3.

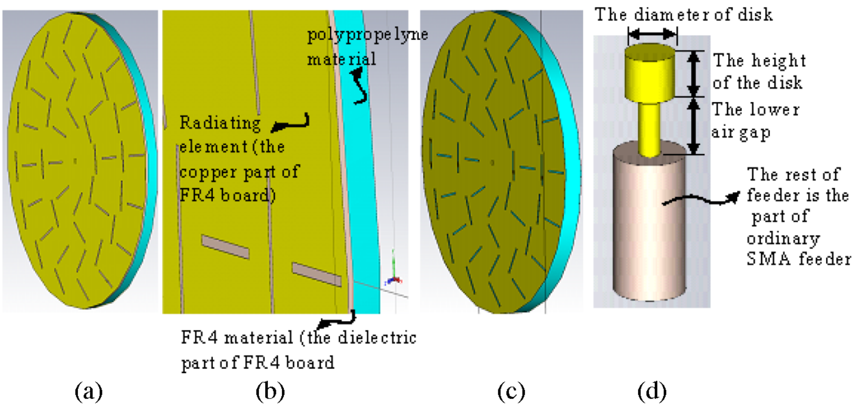

Figure 3. (a) The structure of LP-RLSA antenna with the FR4 board. (b) The zoom of Figure 3(a). (c) The structure of LP-RLSA without FR4 board. (d) The antenna feeder.

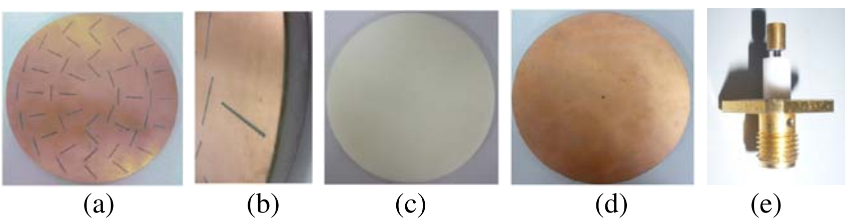

Figure 4. (a) The antenna prototype structure of LP-RLSA with and without the FR4 board. (b) The radiating element of the LP-RLSA. (c) (a) is seen from the side. (d) The cavity (polypropylene) of the LP-RLSA. The background of the LP-RLSA (e) the fabricated antenna feeder.

3.2. The Prototype Antenna Design

After the appropriate permittivity and thickness value of FR4 board have been determined, they are utilized to fabricate the prototypes of LP-RLSAs with and without FR4 board. Figure 4 shows the antenna prototype structure of the LP-RLSAs with and without FR4 board and their feeder.

The antenna structure of the LP-RLSA without FR4 board consists of radiating element (made of copper), cavity (made of polypropylene), background (made of copper) and feeder. The antenna structure of the LP-RLSA with FR4 board consists of radiating element (the copper part of the FR4 board), dielectric part of the FR4 board, cavity (made of polypropylene), the background (made of copper) and 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 the TEM coaxial mode into the TEM cavity mode (radial mode), so that the signal fed by the feeder will propagate in the TEM mode in radial direction within the antenna cavity. The detail specification of both antennas and their feeders are listed in Table 1 and Table 2, respectively below:

Table 1. The specification parameters of the LP-RLSA antenna.

Specification Parameters	**Symbol**	**Value**
Frequency	f	5.8 GHz
Wavelength inside the cavity	λ_g	33.88 mm
Slot length	L	0.5λ
Slot width	W	1 mm
Spacing between unit radiators in radial direction	S_ρ	$\lambda/2$ mm
Number of ring	N	2 rings
Number of slot pair in the first ring	z	8 pairs
Number of slot	N	48 slots
Diameter of antenna	R	85 mm
Cavity material	–	Polypropylene
Cavity thickness	D_1	8 mm
Permittivity of the cavity	ε_{r1}	2.33
The thickness of FR4 layer	D_2	1.6 mm
The permittivity of FR4 layer	ε_{r2}	4.3

Table 2. The specification parameters of antenna feeder.

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

4. THE RESULT AND DISCUSSION

4.1. The Parametric Study to Determine the Appropriate Permittivity and Thickness

The reflection coefficient of the LP-RLSA antenna for various permittivity values of the FR4 board (thickness = 1.6 mm) and for various thickness values of the FR4 board (permittivity = 4.3) are shown in Figures 5(a) and 5(b), respectively. In Figure 5(a), it can be observed that the permittivity influences the antenna reflection coefficient response, because the permittivity is the parameter that determines the signal phase within the FR4 board as explained in Section 2. In Figure 5(b), it can also be observed that the thickness influences antenna reflection coefficient response, because different thicknesses will have different capacities in changing the signal phase within FR4 board as also explained in Section 2.

It can be observed in Figures 5(a) and 5(b) that the most appropriate permittivity and thickness are 4.3 and 1.6 mm, respectively, because these values can result in a reflection coefficient that has the deepest valley at 5.8 GHz. Fortunately, the FR4 board with a thickness of 1.6 mm and permittivity of 4.3 is available in the market, so the prototype of this antenna can be fabricated and measured.

The antenna gains for various permittivities of the FR4 board (thickness = 1.6) and various thicknesses of the FR4 board (permittivity = 4.3) are shown in Figures 6(a) and 6(b), respectively. In Figure 6(a), it can be observed that various permittivities result in different antenna gains. The antenna with 3.2 up to 4.4 of permittivity of the FR4 board can achieve a gain higher than the gain of antenna without FR4 board (12.92 dBi). The highest gain of 14 dBi can be achieved by using a permittivity of 4.0. In Figure 6(b), it can be observed that various thicknesses of the FR4 board influence the antenna gain. The antenna with 0.2 up to 2.2 of thickness of the FR4

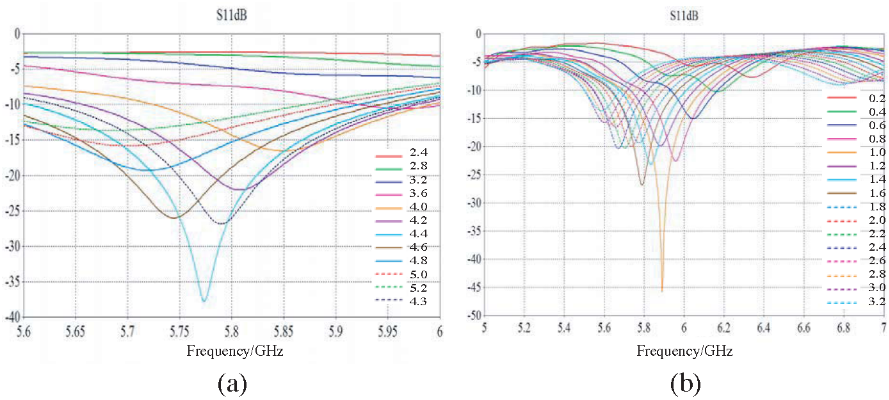

Figure 5. (a) The response of reflection coefficient for various permittivity of the FR4 board (the thickness = 1.3 mm). (b) The response of reflection coefficient for various thickness of the FR4 board (the permittivity 4.3).

board can achieve a gain higher than the gain of antenna without the FR4 board (12.92 dBi). The highest gain of 14.37 dBi can be achieved by using a thickness of 0.8. The gain improvement in the LP-RLSA with FR4 board is achieved due to the significant improvement of reflection coefficient response, which then improves the efficiency and gain of the antenna.

The other effect of adding the FR4 board is beamsquint, which is the deviation of the antenna mainbeam from the boresight direction. The beamsquint for various permittivities of FR4 board (thickness = 1.6) and various thicknesses of FR4 board (permittivity = 4.3) are shown in Figures 6(c) and 6(d), respectively. It can be observed in Figure 6(c) and 6(d) that various permittivities and thicknesses of FR4 board have various beamsquint degrees ranging from 10° to −10°. This beamsquint effect is because the signal propagates not only within the cavity but also within the FR4 board. Since the slots position and slots orientation are designed for the cavity permittivity, the signal that propagates within the FR4 board - which has the permittivity different from the permittivity of the cavity - will result in the beamsquint effect. However, this beamsquint does not affect the antenna performance.

4.2. The Designed Antenna Utilizing the Appropriate Permittivity and Thickness

Figures 7(a) and 7(b) show the characteristic of reflection coefficient and radiation pattern (in term of gain) of the LP-RLSAs with and

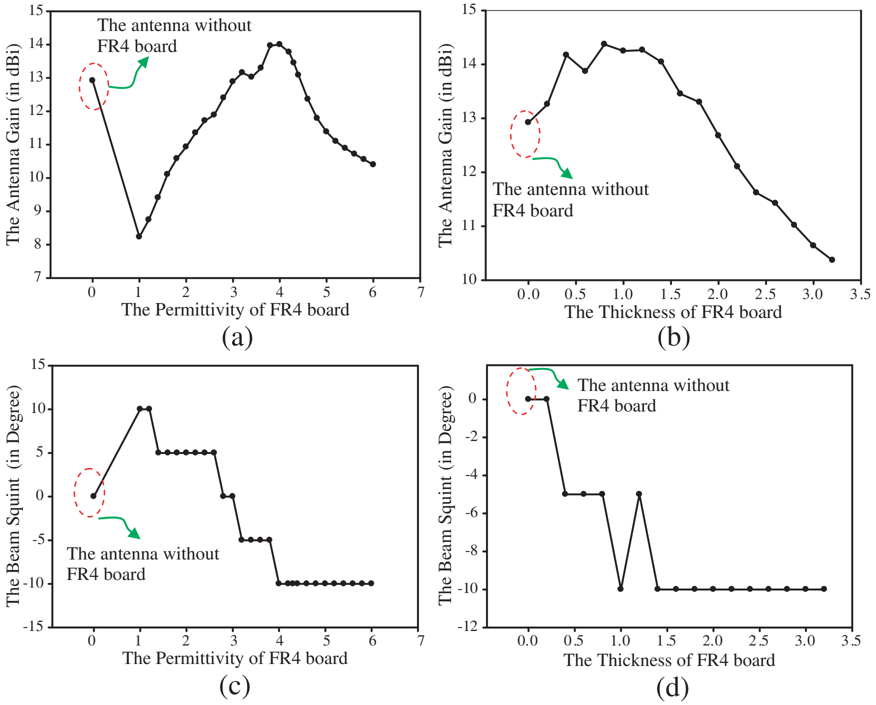

Figure 6. (a) The antenna gain for various permittivity of the FR4 board (the thickness = 1.3 mm). (b) The antenna gain for various thickness of the FR4 board (the permittivity = 4.3). (c) The beamsquint angle for various permittivity of the FR4 board (the thickness = 1.3 mm). (d) The beamsquint angle for various thickness of the FR4 board (the permittivity = 4.3).

without FR4 board, respectively. Both of these antennas utilize the parameters listed in Section 3. The thickness and permittivity of the FR4 board are 1.6 mm and 4.3. The reasons of utilizing these values are as follows. Firstly, these values are the most appropriate ones to get the best reflection coefficient at 5.8 GHz as discussed at the beginning of this section. Secondly, the FR4 material that has these specifications is available on the market. The deviation of the measurement result from the simulation result is due to the material imperfection of cheap FR4 board and slight lack of accuracy in fabricating the antenna prototype.

In Figure 7(a), both simulation and measurement results show that the LP-RLSA with FR4 board is able to improve the reflection coefficient response significantly, that is from about −3 dB to −25 dB at frequency of about 5.8 GHz. From Figures 7(b) and 7(c), it can be observed that the LP-RLSA with FR4 board has both inductive and reactive impedances over the test frequency (5.6–6 GHz) since some of the impedance curve lies above and below the equator of the Smith Chart. The resonant frequencies of LP-RLSA with FR4 board are 5.792 and 5.871 GHz for the simulation and measurement results, respectively. These resonant frequencies are also the frequencies that have the smallest reflection coefficient since they are the closest points to the centre of the Smith Chart. From Figures 7(a), (b), (c), it can also be observed that the reflection coefficients of the LP-RLSA without FR4 board for both the simulation and measurement results are high as predicted by the LP-RLSA theory. The reflection coefficient lies around 1–3 dB along the test frequency. The impedance plot shows that the impedance of the LP-RLSA without FR4 board is inductive since it lies above the equator of the Smith chart. Its position is also far from the centre of the Smith chart that confirm the high reflection coefficient.

Figure 8(a) shows the polarization radiation pattern of the LP-

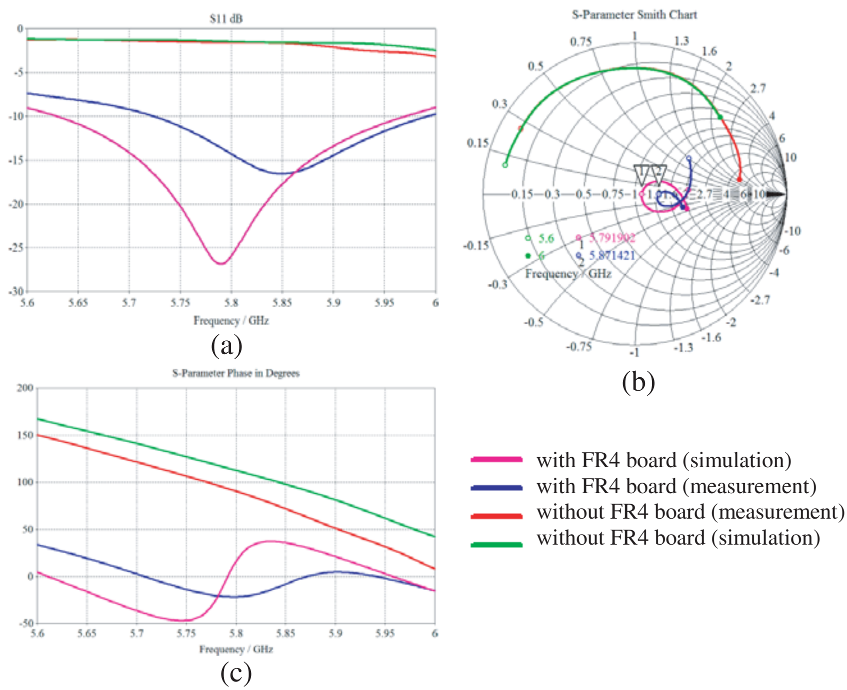

Figure 7. (a) The Reflection coefficient of LP-RLSA with and without FR4 board (simulation and measurement result). (b) The impedance plot. (c) The phase plot.

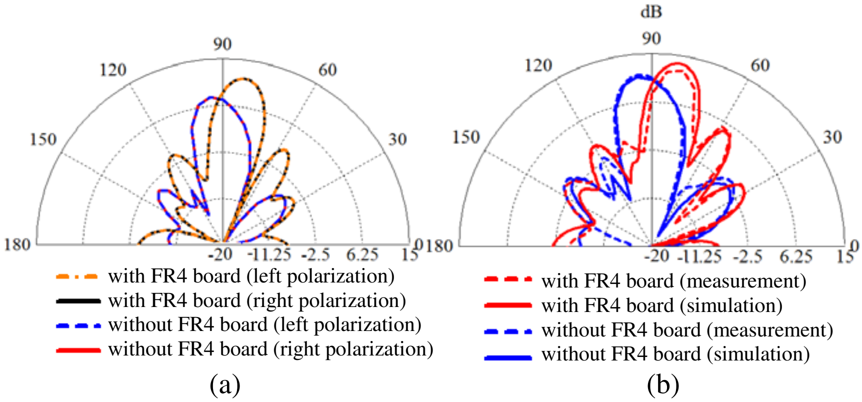

Figure 8. (a) The Simulation result of polarization radiation pattern (in term of gain in dBi) of LP-RLSA antenna. (b) The Radiation Pattern of LP-RLSA (in term of gain in dBi) of LP-RLSA with and without FR4 board (simulation and measurement result).

RLSA antenna. It can be observed from the figure that the radiation patterns of the left and right polarizations coincide each other. The gain of each polarization is half of the gain of the LP-RLSA antenna. This means that the signal radiated by the antenna is equally divided into the left and right polarizations. This result confirms the perfect linear polarization of the antenna.

Figure 8(b) shows the radiation patterns of the LP-RLSA with and without FR4 board both for measurement and simulation. In Figure 8(b), the simulation and measurement results show that the LP-RLSA with FR4 board has a better gain about 2.45 dB than that without FR4 board. The gain improvement in the LP-RLSA with FR4 board is achieved due to the significant improvement of reflection coefficient response, which then improves the efficiency and gain of the antenna. The LP-RLSA with FR4 board has beamsquint effect about 10° deviating from the boresight (90°).

Finally, the above result and analysis of the reflection coefficient and gain of the LP-RLSA antenna verify and prove the concept and theory explained in Section 2.

5. CONCLUSION

A novel technique that aims to improve the reflection coefficient of LP-RLSA antenna as well as to simplify its fabrication process is introduced and discussed in this paper. This technique utilizes a FR4 board as an additional layer to the normal LP-RLSA antenna. The fabrication process of the LP-RLSA with FR4 board becomes simple since the slots on the copper part of FR4 board can be cut simply utilizing the photolithography etching process. On the other hand, the FR4 dielectric material can reduce LP-RLSA reflection coefficient significantly since the FR4 dielectric can change the phase of the signal reflected from the antenna slot. In order to observe the effect of the FR4 board, several antennas were simulated and parameterized. Based on the discussion in Section 4, we draw the following conclusion. Firstly, the thickness and permittivity of the FR4 board influence its ability to improve reflection coefficient response and antenna gain. For the antenna designed in this paper, the most appropriate values of the permittivity and thickness are 4.3 and 1.6 mm, respectively. Secondly, the addition of the FR4 board can improve the reflection coefficient response significantly from about -3 dB to -25 dB at frequency of 5.8 GHz. Thirdly, in this research, the addition of the FR4 board can improve the gain about 2.45 dB. Fourthly, the addition of the FR4 board results in the antenna beam deviating from the boresight direction about -10° up to 10°. In order to prove the concept of the novel technique, LP-RLSAs with and without FR4 board are fabricated and measured. The measurement and simulation results show that the LP-RLSA with FR4 board has a better gain and reflection coefficient than the LP-RLSA without FR4 board, thus prove the concept of the novel technique. This proposed novel technique would be a great step in simplifying the fabrication process and realizing the mass production of the LP-RLSA antenna.

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