A Study of Different Substrate Material on Air Gap Radial Line Slot Array (RLSA) Antenna at 28 GHz

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***Abstract*— This paper compared the performance of the conventional Radial line slot array (RLSA) antenna structure. Two different substrates of RLSA antennas were used: The FR4 with the relative permittivity (ε_r) value of 4.5 and the Duroid/RT5880 with the relative permittivity (ε_r) value of 2.2. Both substrates had their own thickness, where the Rogers RT Duroid 5880 was thinner with the value of 0.254 mm compared to FR4 which was 1.600 mm. There were two antenna cavities, which were the FR4 hybrid with air gap and the Duroid/RT5880 hybrid with air gap. Based on different substrate, this RLSA antenna was simulated using the CST Microwave Studio simulation software and measured using the Vector Network Analyzer (VNA) equipment that can measure the frequency range (10.0 MHz to 50.0 GHz). Moreover, this RLSA antenna was presented, experimented and measured for millimeter wave frequency, which is within the frequency range (24.0 GHz to 32.0 GHz). In the middle of the rectangular, slots on radiating plate, located with fed coated of 50 Ω SSMA connector as a coaxial to waveguide transition frequency reconfigurable millimeter-wave antenna for 5G networks is presented. The results of the simulation and measurement of this RLSA antenna with different substrates show the S_{11} and wider value of impedance bandwidth performance in millimeter wave frequency.**

***Index Terms*—5G; Air Gap Cavity Structure; Radial Line Slot Array Antenna; Sub-millimeter Wave.**

I. Introduction

Radial line slot array (RLSA) antenna was first introduced for direct broadcast from satellite (DBS) receiver at a frequency of 12 GHz [1,2,3] and satellite on the move (SOTM) [4] which operates in the range of Ku-band. This paper focuses on designing the RLSA antenna using FR4 and Rogers RT Duroid 5880 substrates with the working frequency at (24 GHz to 32 GHz). The proposed antenna is in the range of frequency Ka-band, suitable for space usage, similar to the design of RLSA antenna by some researchers [5,6]. As mentioned in [3,6,8,9], the epsilon value chosen to be tested by researchers is mostly the FR4 as it is convenient and low cost with the values (ε_r=4.7) [7] and (ε_r=5.4). The combination of brass act as conductor and air as cavity in [9]. I.M. Ibrahim et. al used the value of epsilon (ε_r=1.06), while several researchers used the Rogers RT Duroid 5880 with value of (ε_r=2.20) [10,11] and Purnamirza used the combination of polyproperlen with air gap (ε_r=2.47) [12].

Consequently, RLSA antenna is good for producing the three polarize such as linear, circular and elliptically polarization [10]. It is also well-known as an excellent radiator and reciever for transferring the microwave signal from one point to one point or one point to multi points communication application [3,9,10,13,14].

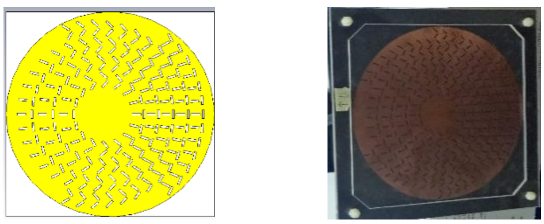
II. Antenna Design

A radial line slot array antenna is proposed as a simple planar structure, and it requires one sided copper cladding only, which consists of dielectric substrate sandwiched by copper plates. Figure 1 shows the side view of the antenna, where the ‘a’ is the coppers as the radiating surface and the ground plane, while the ‘b’ is the substrate. A cavity, which is the combination of substrate and air gap, is located in between the copper cladding on the single sided on the substrate and copper plate.

The radius of the radiating surface is 50 mm along the x-axis and the thickness of the cavity or also known as the height of the antenna *h* along the y-axis is located on the surface of a grounded dielectric substrate.

The three essential parameters for the design of RLSA antenna are frequency of operation (f_o), dielectric permittivity of the substrate (ε_r) and the height of the substrate (h). The dielectric substrate material (ε_r) selected for this design is the FR4 and Air Gap. This combination produces a new equivalent dielectric value of 1.13, while the value of the dielectric substrate material (ε_r) for Rogers RT Duroid 5880 and Air Gap is 1.07.

Figure 1: Basic layer of antenna prototype



(a) Simulated (b) Fabricated

Figure 2: The antenna structure

Figure 1 illustrates the prototype of the antenna design. Slots, which are holes as shown in Figure 1 (a) were allocated on the radiating surface of the antenna in order to get the shape of the rectangular slot array. It needs the equation to get the value of the slot length by using λ_g [14] from equation (1) and (2). Figure 1 (b) shows the ground of the RLSA antenna with coaxial waveguide as a feeder.

Figure 2 shows the proposed antenna structure for the RLSA. The value of *h* is tuned to provide an optimum impedance bandwidth [7,8].

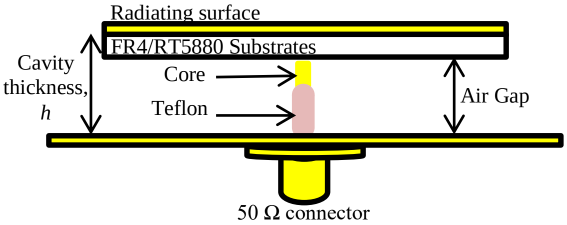


Figure 3: Illustration structure the feeder inside the cavity [4, 10]

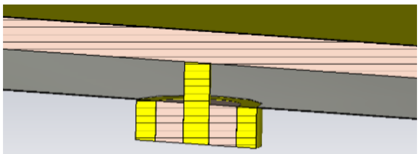


Figure 4: The side view structure of the antenna cavity proposed

The RLSA antenna using Rogers RT Duroid 5880 with high frequency laminated with a disk ended of 50 Ω dielectric coated SSMA probe was reported in [15]. In this paper, the idea was extended to include a disk ended of 50 Ω dielectric coated SSMA probe with FR4 as the substrate. Technically, the rectangular shape is proposed as the air gap at the top of the radiating surface on the circular shape board.

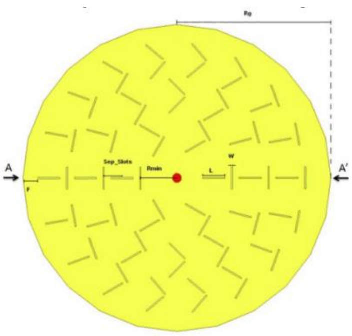


Figure 5: The location of the SMA port [16]

J. Cardenas and C. I. Paez located the coaxial feeder at the centre between the rectangular slots onto the radiating plates. The FR4 with permittivity (ε_r) value is 4.4 and it used different technique on point the SSMA coaxial port, as show in Figure 6.

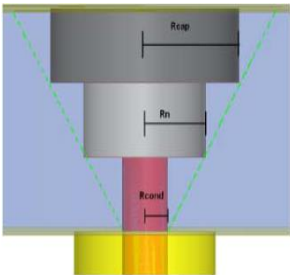


Figure 6: The inside 50Ω SSMA coaxial port [16]

The equation below is used to calculate the value of the resonant wavelength ($\boldsymbol{\lambda}_g$), resonant frequency (f_r), *c* is the speed of light and (ε_r) is relative permittivity value and it depends on the substrate is chose[17].

$$\boldsymbol{\lambda}_R = \frac{c}{\sqrt{\varepsilon r}\ \mathrm{fr}} \tag{1}$$

This research proposed a simpler feed probe design as shown in Figure 3 and Figure 4. The radial waveguide is fulfilled with a dielectric material of suitable relative permittivity (ε_r), where in the space of cavity thickness is known as *d*, hence *d* has a relation to the ε_r.

$$d < \frac{\lambda_g}{2} \tag{2}$$

$$\lambda_g = \frac{c}{\sqrt{\mu_r \varepsilon_r}} \tag{3}$$

where: $\boldsymbol{\lambda}_g$ = Wavelength in the guide
C = Speed of light
$\boldsymbol{\mu}_r$ = Relative permeability
d = *h* value which is the thickness of the cavity

The value of ε_r must be greater than 1 to prevent the grating lobes from being present in the radiation pattern. The dielectric material performance is to create a slow wave in the cavity, resulting in $\boldsymbol{\lambda}$g > $\boldsymbol{\lambda}$o (free space wavelength).

$$c = \varepsilon\ \frac{A}{d} \tag{4}$$

where: c = Capacitor
ε = Dielectric value
A = Area of slot
D = Slot thickness

The capacitance is influenced by dielectric permittivity, the size and the slot thickness. In this study, the slot length is already fixed to half wavelength. The dielectric relative permittivity is 1 since it is an air gap. Figure 5 shows the radiating slot shape of the radiating surfaces.

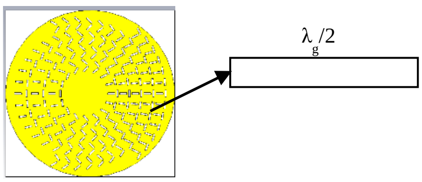


Figure 7: The shape of radiating

S. Huang stated that frequency dependent is a loss tangent, while both of the dielectric constants (ε_r) and loss tangent (tan δ) are known as lossy material in microwave engineering [18]. From the data sheet, the loss tangent for FR4 is 0.009 [19] and the loss tangent for RT5880 is 0.0009 [20].

$$\tan\delta = 2\pi f c + \varepsilon \quad (5)$$

where: tan δ = Tangent loss
f = Frequency resonate
c = Capacitance value
ε = Permittivity value

As the value of permittivity is different, both the FR4 and RT5880 used the air gap techniques, hence the value of permittivity value is smaller than the real value of permittivity. When the value of permittivity is small, the correlation value of capacitance and tangent loss will be small also.

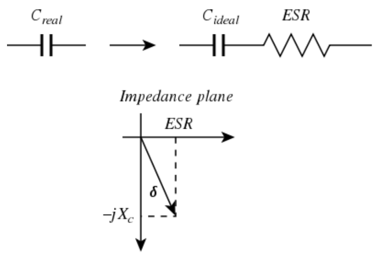


Figure 8: A lumped element model of a losses ideal capacitor in series with an equivalent series resistance (ESR)

III. Result And Discussion

The proposed design was simulated and measured using the CST software. Table 1 shows the specification for the two substrates of the parameter used to design the RLSA antenna.

Table 1
Design Specification

Parameter	Value
Center frequency, f_o	28 GHz
Radius of antenna	50 mm
No. of slots in first ring	16
Cavity of thickness (Maximum)	3.6 mm
Cavity of thickness (Minimum)	2.254 mm
Thickness of radiating surface (copper)	0.035 mm
Thickness of ground (copper)	0.035 mm
Relative permittivity of FR4	5.4
Relative permittivity of RT5880	2.2
Slot width	1.0 mm
Slot length	5.0 mm

Figure 9 and 10 show the comparison of the return loss resulting from the simulation and measurement as the optimization of the proposed design. The cavity thickness shows the result for the substrate FR4 and RT5880 using air gap techniques.

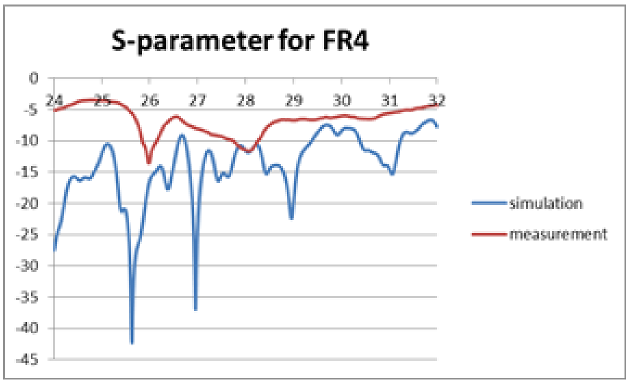


Figure 9: Return loss of the performance of the FR4 substrate

Figure 9 shows the best performance obtained when the FR4 hybrid with the air gap were simulated at the low resonate frequency of 26.950 GHz with the value of $|S_{11}|$ is -50.860 dB, while the measurement value of the low resonate frequency is at 25.980 GHz which has the value of $|S_{11}|$ is -13.610 dB. On other hand, the value of $|S_{11}|$ at 28 GHz is slightly different when the simulation value is -11.507 dB compared to measurement value, which is -11.495 dB.

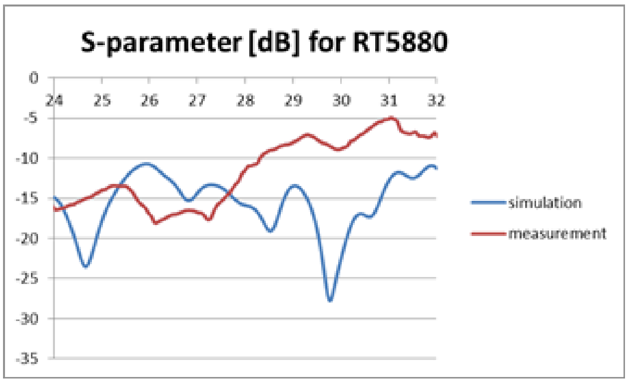


Figure 10: Return loss performance of the RT5880 substrate

Table 10 shows the best performance obtained resulting from the simulation that involved the Rogers RT Duroid 5880 hybrids with the air gap, which has the lowest frequency resonate at a frequency of 29.800 GHz at value of $|S_{11}|$ is -27.580 dB. While the measurement result for the low frequency resonates at a frequency of 26.110 GHz with the value $|S_{11}|$ is -18.06 dB from the range of frequency 24.000 GHz to 28.260 GHz. This structure has a cavity thickness of 2.254 mm. At frequency of 28 GHz the simulation result is -15.883 dB while there is a gap value for measurement which is -11.008 dB.

Table 2
Exemplification of S_{11} Value between FR4 with RT5880 for Simulation and Measurement Results at 28 GHz

Substrate	Simulation	Measurement
FR4 (ε_r=5.4)	-11.507 dB	-11.495 dB
RT5880 (ε_r=2.2)	-15.883 dB	-11.008 dB

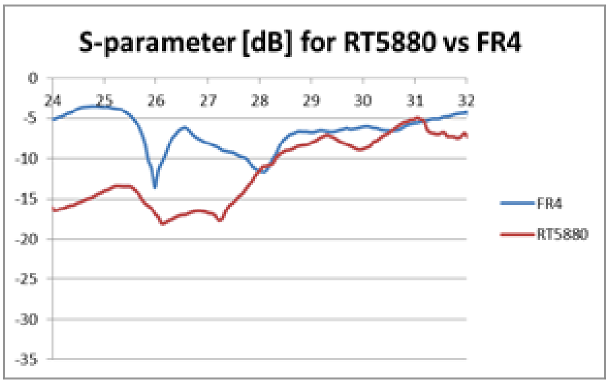


Figure 11: Comparison of return loss performance between FR4 and RT5880 at 28 GHz

Figure 12 and 13 show the simulation results on the illustration of radiation pattern for phi 0 and phi 90 as the air gap techniques was applied on FR4 and RT5880 at the frequency of 28 GHz.

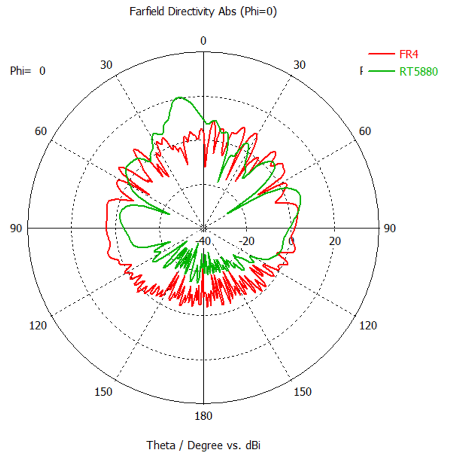


Figure 12: Radiation pattern phi 90 (E-plane) for simulation result at 28 GHz

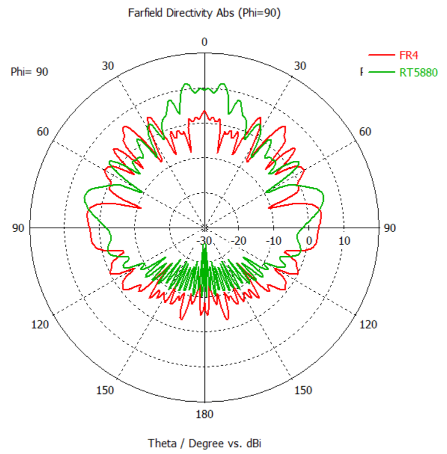


Figure 13: Radiation pattern phi 0 (H-plane) for simulation result at 28 GHz

Table 3 shows the center frequency chosen, in which 28 GHz is for radiation pattern performance on the simulation results for both such FR4 and RT5880. The directivity for RT5880 is higher compared to FR4, which are 20.160 dBi and 11.220 dBi. The value realized gain performance RT5880 is good, which is 19.750 dB compared to FR4 is 7.909 dB. The lowest side lobe level (SLL) for FR4 phi0 is -0.600 dB, while RT5880 phi 90 is -1.800 dB.

Table 3
Correlation Radiation Pattern of FR4 with RT5880 on Simulation Results

Substrate		Side Lobe Level (dB)	Angular Width (3dB)	Main Lobe Magnitude (dBi)	Realized Gain (dB)	Directivity (dBi)
FR4	Phi 0	-0.600	3.700	9.390	7.909	11.22
	Phi 90	-1.500	6.800	6.980		
RT5880	Phi 0	-11.100	8.700	20.200	19.750	20.16
	Phi 90	-1.800	5.900	11.700		

Basically, the technique of air gap can reduce the value of dielectric cavity of the substrate chosen. Therefore, it can be used at high frequency which is 28 GHz. In reality, the FR4 is not convenient at high frequency, hence it is proven that the radiation pattern performance occurrence is not suitable to be used for point to point communication in 5G applications.

However, the results of simulation and measurement shifted and quite different between them. This is obtainable from the contact of 50 Ω dielectric coated SSMA coaxial feeder with the copper plate act as a ground using metallic screw. In millimetre wave frequency for 5G applications, there will be an effect with the type of material used on the result measured.

IV. CONCLUSION

The proposed RLSA antenna is compact, light and simple to fabricate. This antenna with a hybrid of FR4 or Rogers RT Duroid 5880 and Air Gap cavity is used in a millimetre-wave for 5G communication applications. The cavity thickness of the RLSA antenna for Rogers RT Duroid 5880 with 2.254 mm produces a good radiation pattern performance for point to point communication compared to FR4 with a thickness of cavity of 3.600 mm. This work does not compare the radiation pattern result on measurement part. Thus, for future work, a measurement of radiation pattern for both designs should be compared with the results derived from the simulation.

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