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Design and simulation of dual-band rectangular microstrip patch array antenna for millimeter-wave

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ABSTRACT

Microstrip array antennas are essentially for radar and communications systems. They are used to get a needed pattern that cannot be realized with a single element. This paper aims to design and simulate of rectangular microstrip patch array antenna 1 patch (1×1), 2 patches (1×2), and 4 patches (1×4) and improve the performance results. The proposed antenna is simulated by using electromagnetic simulation, computer software technology Microwave studio (CST) printed on Rogers RT5880 (lossy) substrate with dielectric constant 2.2, 0.0009 loss tangent, and thickness 0.1 mm. The simulation results show that the small patch antenna size (1.57 mm × 2 mm) for three designs works at dual bandwidth. The major target of this work is to accomplish an unusual directivity with improved gain for three antenna array designs.

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1. INTRODUCTION

With the rapid improvement in radio telecommunication and wireless systems, antenna design has always been a challenging topic to improve the characteristics of antenna such as size, reflection coefficient, different bandwidths, VSWR, gain, and directivity. This condition leads to several proposals to achieve adjustments between proposal, high gain, antenna dimension, large bandwidth, and low cost [1]-[5]. To fulfill multi-band there are three types of antenna: slot antenna, a monopole antenna, and patch antenna [6]-[15]. The technology of 5G that holds the millimeter wave is involved to overcome current limits like slow data transmission rate and spectrum shortage. The 5G technology also propositions better analysis as matched to that of earlier generations [16], [17]. Millimeter waves have an unemployed range 3-300 GHz to satisfy the novel generation's requests. The application of the 5G range is (20 GHz-90 GHz) [18].

In various radar and communications systems, microstrip array antennas are deeply favorite. They are used, to produce a required pattern that a single element cannot be realized. The array antenna system is used to augment the directivity, gain and perform different other purposes which would be complex with any single element [19]. D. Imran *et al.* [20], a simple microstrip patch antenna (1×1) and (1×4) RMSPAA is designed with patch size (2 mm×2 mm). Microstrip patch antenna (1×1) gives dual-band at 38 GHz and 54 GHz frequencies and array (1×4) gives 38.6 GHz, 47.7 GHz, and 54 GHz frequencies. Research by Dheyab and Qasem [21] shows three designs (1×1, 1×2, and 1×4 RMSPAA) at patch dimension (1.62 mm×2 mm). The three array antenna works at frequency 60 GHz. (1×1, 1×2, and 1×4 RMSPAA) with patch size (9.31 mm×11.86 mm) is designed to work at frequency 10 GHz [22]. Research by Prakasam *et al.* [23], simple microstrip patch antenna (1×2) and (1×4) RMSPAA is designed to work at frequency 2.45 GHz with patch dimension (27.62 mm×35.79 mm).

In this paper, a tiny and simple structure dual-band microstrip patch array antenna is estimated. Rogers RT5880 (lossy) substrate with dielectric constant 2.2, 0.0009 loss tangent, and thickness 0.1 mm is used. The patch sizes are 1.57 mm x 2 mm x 0.035 mm with a quarter-wave transmission line. This paper proposed an array antenna with good performance, gain, directivity, VSWR, return loss, and bandwidth. The organization of this paper is summarized as; section 2 displays the design and geometry of RMSPAA, section 3, displays simulation results of three arrays and comparison, and in section 4, the results of this research have been discussed.

2. METHOD OF DESIGN AND GEOMETRY OF RMSPAA

The constructions and geometry of the single patch (1×1), 2 patches (1×2), and 4 patchs (1×4) array antenna are presented.

2.1. Single element RMSPA

The process of any MSPA design involves the design of the patch, the feedline, and the matching component. There are three main parameters necessary to design any microstrip antenna: the first one is the dielectric of a substrate (εr), the second is the substrate height (h), and the last is the resonant frequency (fr) [24]. Table 1 presentations the necessary factors selected for this project.

Table 1. Parameter values of MSPA

Parameters	Value
Operating frequency (fr)	60 GHz
Constant of substrate dielectric (εr)	2.2
Height of substrate (h)	0.1 mm
Input impedance (Rin)	50 Ω

The dimensions of any design antenna are computed using the distinguished microstrip patch antenna formulas as specified [24], [25]:

$$W = \frac{c}{2f_r}\sqrt{\frac{2}{\varepsilon_r+1}} \tag{1}$$

where: W is the width of the patch, c is 3×10^8, and εr is the substrate dielectric constant of Rogers RT5880 with loss tangent 0.0009.

$$\varepsilon_{reff} = \frac{\varepsilon_r+1}{2} + \frac{\varepsilon_r-1}{2}\frac{1}{\sqrt{1+12\frac{h}{w}}} \tag{2}$$

where: ε_{reff} is the effective dielectric constant of MSPA.

$$\Delta L = 0.412\ h\ \frac{(\varepsilon_{reff}+0.3)\left(\frac{W}{h}+0.264\right)}{(\varepsilon_{reff}-0.258)\left(\frac{W}{h}+0.8\right)} \tag{3}$$

where: ΔL is the extension length.

$$L = \frac{c}{2f_r\sqrt{\varepsilon_{reff}}} - 2\Delta L \tag{4}$$

where L is the actual length.

$$W_S = W * 2 \tag{5}$$

where: W_S is the width of the substrate.

$$L_S = L * 2 \tag{6}$$

where: L_S is the length of the substrate.

$$L_f = 3.96 * W_f \tag{7}$$

where: L_f is the length of the feed line and W_f is the width of the feed line

$$W_f = \frac{2h}{\pi}\left\{B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2\varepsilon_r}\left[\ln(B - 1) + 0.39 - \left(\frac{0.61}{\varepsilon_r}\right)\right]\right\} \quad (8)$$

$$B = \frac{377\pi}{2Z_0\sqrt{\varepsilon_r}} \quad (9)$$

The quarter wave transformer is a microstrip line spent as a proper matching method. The quarter wave transformer is spent among the microstrip line and midpoint along the width of the rectangular patch element for matching their impedances.

$$L_T = \frac{\lambda_0}{4\sqrt{\varepsilon_R}} \quad (10)$$

where: L_T is the length of the quarter-wave transformer and λ_0 is the wavelength.

$$Z_T = \sqrt{Z_0 Z_P} \quad (11)$$

where: Z_T is the impedance of the quarter-wave transformer, Z_0 is the feedline impedance (50 Ω), and Z_P impedance attainable by the patch at the midpoint along the width of the patch. The input impedance at the midpoint along the width is [24].

$$Z_P = \frac{1}{2G_1} \quad (12)$$

where

$$G_1 = \begin{cases} \frac{1}{90}\left(\frac{W}{\lambda_0}\right)^2 & W \ll \lambda_0 \\ \frac{1}{120}\left(\frac{W}{\lambda_0}\right) & W \gg \lambda_0 \end{cases} \quad (13)$$

Table 2 shows the dimensions which were calculated using the equations and optimized for a rectangular MPA. Figure 1 shows a single element RMSPA.

Table 2. Calculated and optimized RMSPA parameters

Parameter	Calculated	Optimized
Patch width (W)	1.97 mm	2 mm
Patch length (L)	1.63 mm	1.57 mm
Substrate width (W_S)	3.94 mm	2.5 mm
Substrate length (L_S)	3.26 mm	3 mm
Feedline width (W_f)	0.308 mm	0.308 mm
Feedline length (L_f)	1.21968 mm	0.465 mm
Transmission line width (W_T)	0.089 mm	0.089 mm
Transmission line length (L_T)	0. 843 mm	0.84 mm

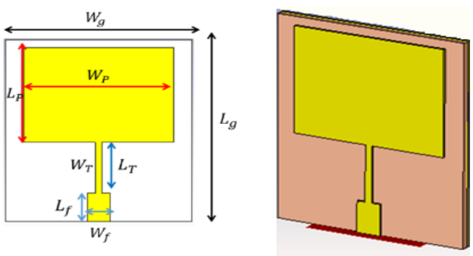


Figure 1. Single element RMSPA

2.2. 1×2 and 1×4 RMSPA antenna design

Figure 2 shows 1×2, and 1×4 RMSPA array. The dimensions used to design the single patch antenna are the same as those used for the array antenna design and the substrate used the same type as mentioned above. The overall sizes of the ground and the substrate are equal to 5×6 mm. The spacing between the rectangular patch array elements is equal to $\lambda_g/2$, where λ_g is the guided wavelength determined applying the equations offered in [21]. A corporate feeding network is resolved from mathematical equations related in [22]. Three different values of microstrip lines are 50 *Ω*, 70.7 *Ω*, and 100 *Ω* the dimension of each feeding shows in Table 3.

Table 3. Dimension of the corporate feeding network

L_1	W_1	L_2	W_2	L_3	W_3	L_4	W_4
0.089 mm	1.047 mm	0.46 mm	0.176 mm	0.465 mm	0.308 mm	0.47 mm	0.089 mm

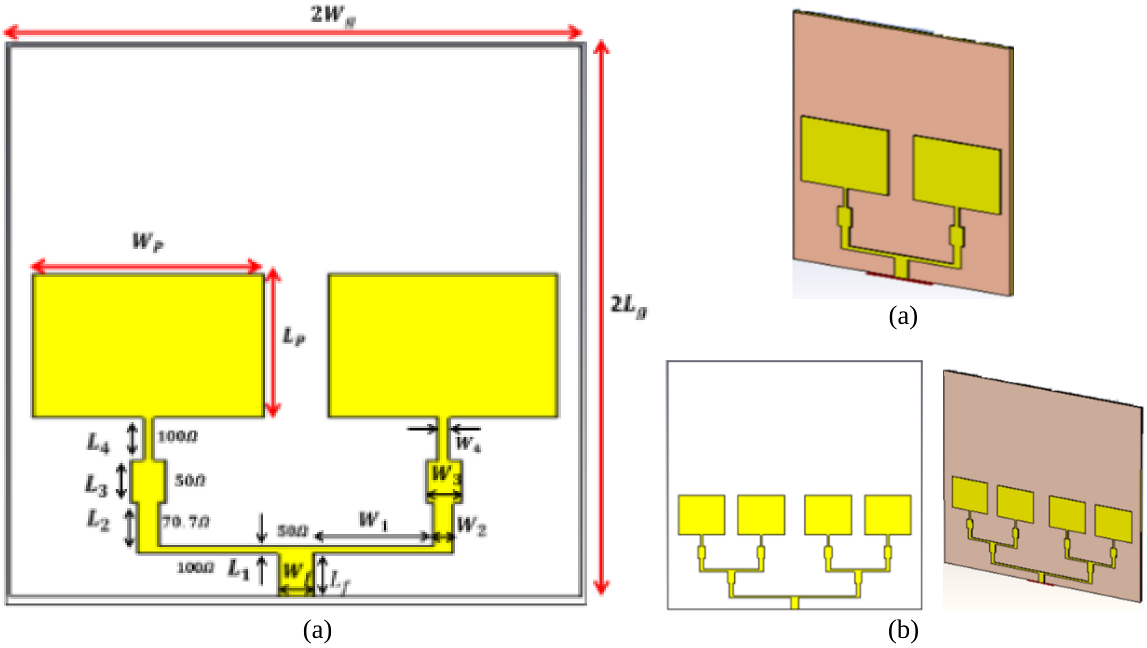


Figure 2. Design of RMSPA array (a) 1×2 RMSPAA and (b) 1×4 RMSPAA

3. SIMULATION RESULTS OF THREE ARRAYS AND ANALYSIS

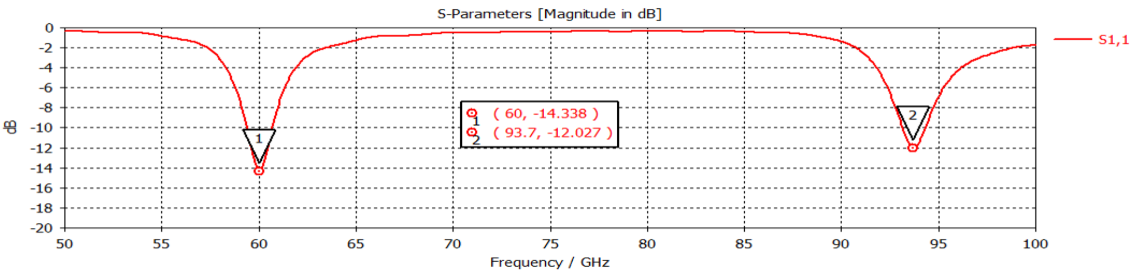
In this section, the results and simulation obtained by using the CST STUDIO SUITE Version 2019 will be explained. VSWR, bandwidth, return loss, gain, directivity, and the current surface for each 1×1, 1×2, and 1×4 element array antenna will be displayed. Theoretically, the return loss amount should be less than -10 dB, and the VSWR amount varies from 1 to 2.

3.1. Result of the single element

The result of the 1×1 element appears the design work with dual-band (60 GHz with bandwidth 1.2 GHz), and (93.7 GHz with a bandwidth equal to 1.1 GHz). Table 4 shows the result of the 1×1 element at each frequency. Figure 3 shows return loss and VSWR equal 1.475 at 60 GHz and it's equal to 1.6682 at 93.7 GHz. From Figure 4 directivity is equal to (7.493 dBi at 60 GHz) and (7.376 dBi at 93.7 GHz). The gain at frequency 60 GHz is 6.673 dBi and at 93.7 GHz is 6.833 dBi as shown in Figure 5. The maximum surface current for 60 GHz is 844.371 A/m and for 93.7 GHz is 669.894 A/m as shown in Figure 6.

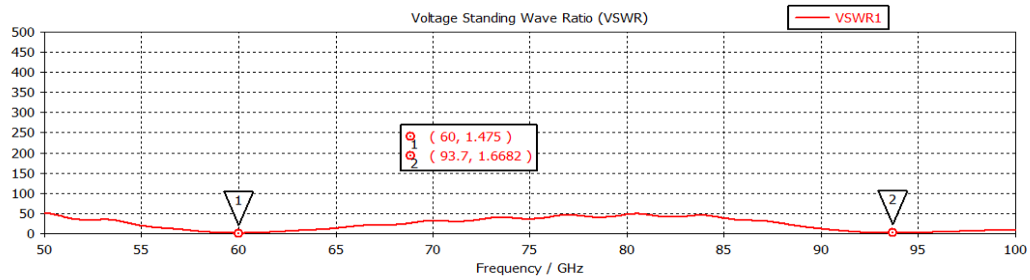
Table 4. Result of the single element of RMSP array antenna

Frequency (GHz)	Return loss (dB)	VSWR	Bandwidth (GHz)	Directivity (dBi)	Gain (dBi)
60	-14.338	1.475	1.2	7.493	6.673
93.7	-12.027	1.6682	1.1	7.376	6.833



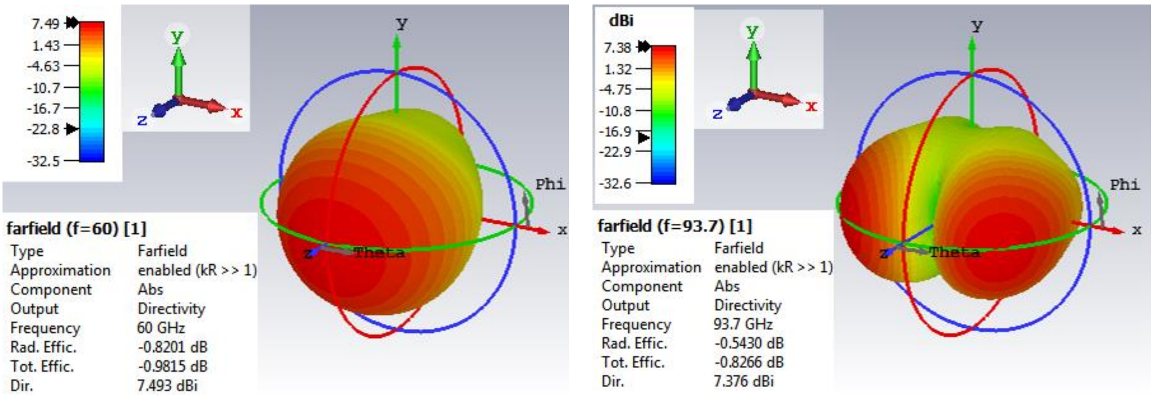
(a)

Figure 3. Dual-band of a single element (a) return loss



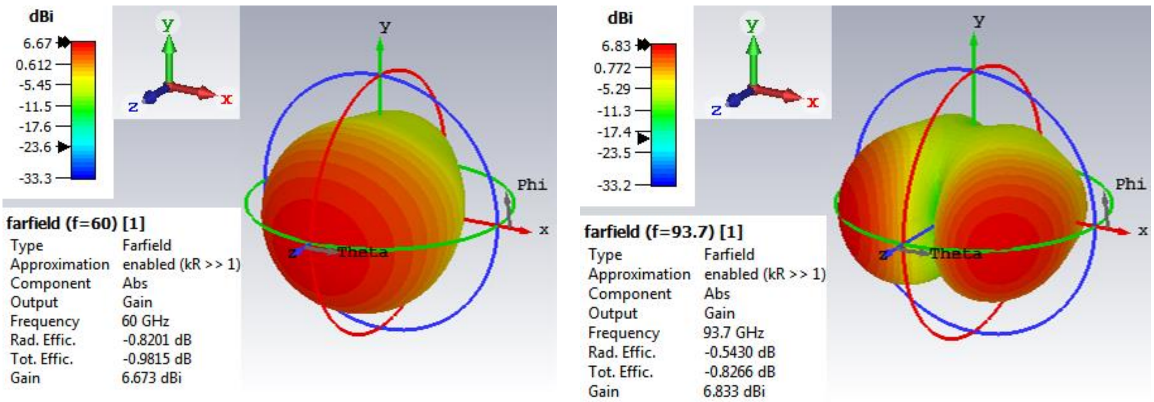
(b)

Figure 3. Dual-band of a single element (b) VSWR *(continue)*



(a) (b)

Figure 4. Directivity of the single element at (a) 60 GHz and (b) 93.7 GHz

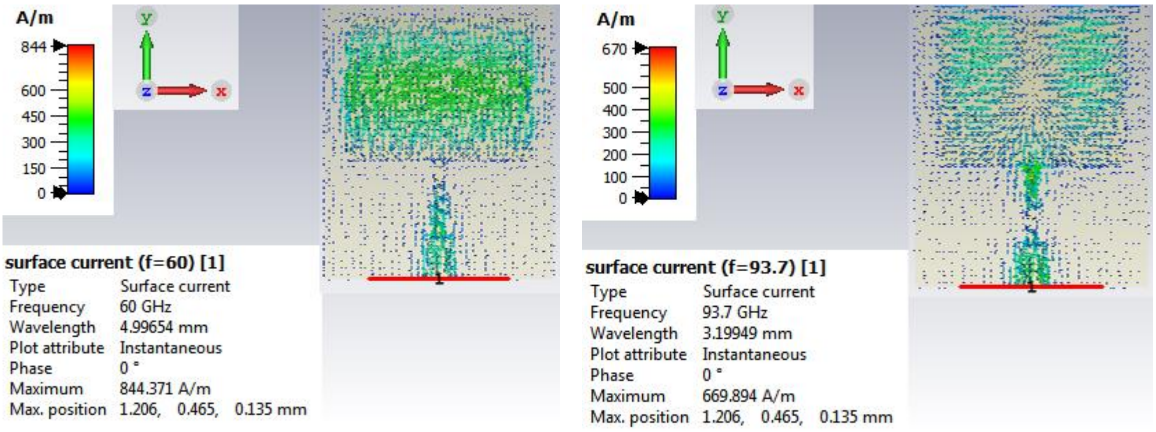


(a) (b)

Figure 5. Gain of the single element at (a) 60 GHz and (b) 93.7 GHz

3.2. Result of the 1×2 RMSP array antenna

Design 2 patches (1×2) array element of RMSPA appears its work with dual-band (60 GHz and 94.4 GHz) as displayed in Table 5. The results of the (1×2) array antenna show there is an enhancement compared to the results of the single element at frequency 60 GHz. The other frequency shifts up to 94.4 GHz with -19.669 dB return loss, 1.2319 VSWR, and bandwidth equal to1.8 GHz as shown in Figure 7. The results of the directivity appear enhancement at 60 GHz equal to 8.616 dBi, and at 94.4 GHz equal to 6.425 dBi as shown in Figure 8. The gain at frequency 60 GHz is 8.125 dBi and at 94.4 is 5.431 dBi as shown in Figure 9. Figure 10 appear that the maximum surface current for 60 GHz is 612.533 A/m and for 94.4 is 510.42 A/m. The results show that the performance of 2 patches (1×2) is best than the performance of 1 patch (1×1).

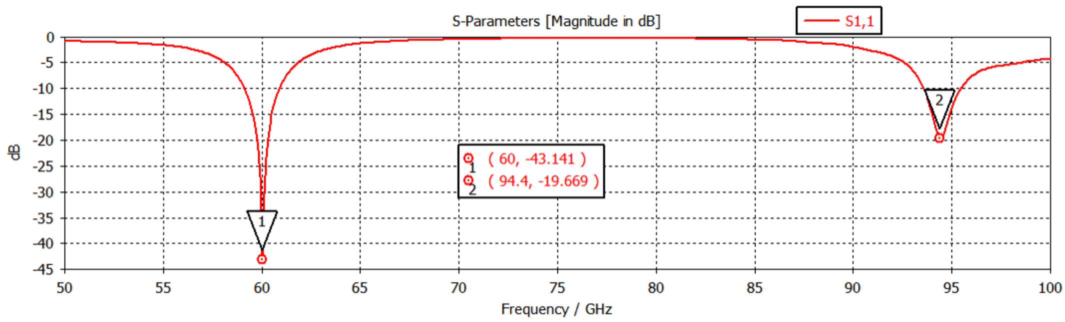


(a) (b)

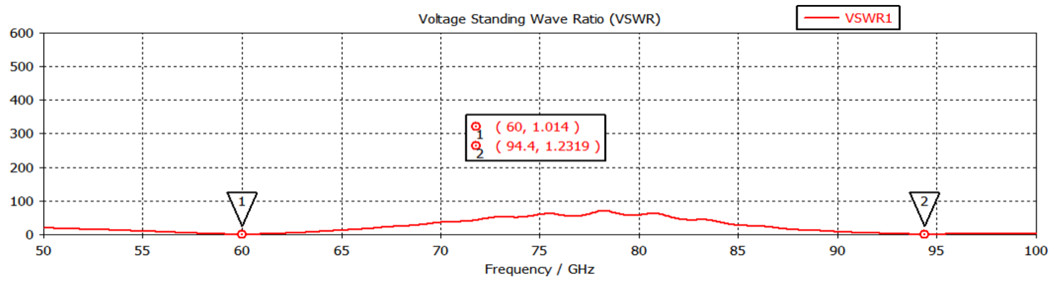
Figure 6. Current surface of the single element at (a) 60 GHz and (b) 93.7 GHz

Table 5. Result of the (1×2) RMSPA antenna

Frequency (GHz)	Return loss	VSWR	Bandwidth (GHz)	Directivity (dBi)	Gain (dBi)
60	-43.141(dB)	1.014	1.7	8.616	8.125
94.4	-19.669(dB)	1.2319	1.8	6.425	5.431



(a)

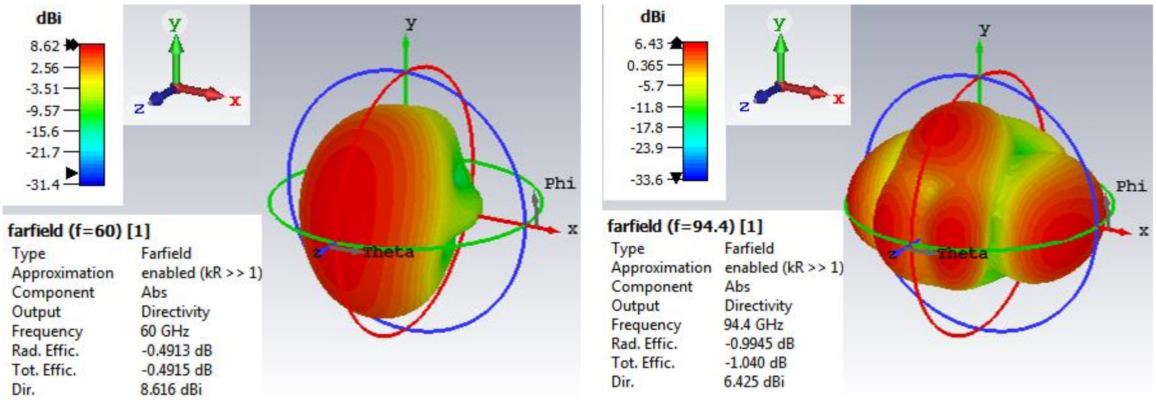


(b)

Figure 7. Dual-band of a 2patches (1×2) array antenna (a) return loss and (b) VSWR

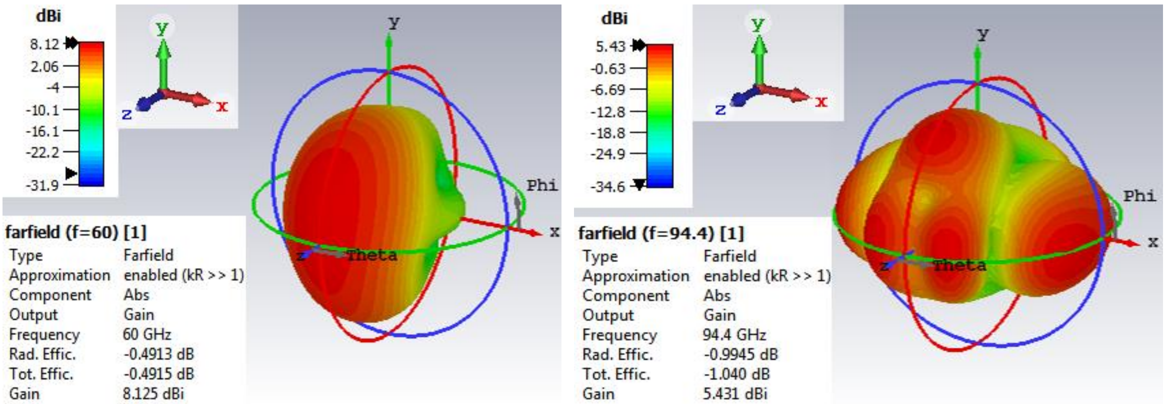
3.3. Result of the 1×4 array RMSPA

Dual bandwidth (60 GHz and 92.8 GHz) operates with a 1×4 array antenna. Table 6 shows that the frequency 60 GHz works at 1.0879 VSWR, -27.512 dB return loss, and bandwidth equal to at 1.7 GHz as shown in Figure 11. The gain (11.01 dBi) and directivity (11.54 dBi) of 1×4 array at 60 GHz show an improvement over comparing with 1×1, and 1×2 array. The frequency (92.2 GHz) have directivity equal to (10.50 dBi) and gain equal to (9.211 dBi) as shown in Figure 12 and 13. According to Figure 14, the maximum surface current for 60 GHz is 546.161 A/m and for 94.4 is 5210.973 A/m. The results show that the performance of 4 patches (1×4) is best than the performance of both 1 patch (1×1) and 2 patches (1×2).



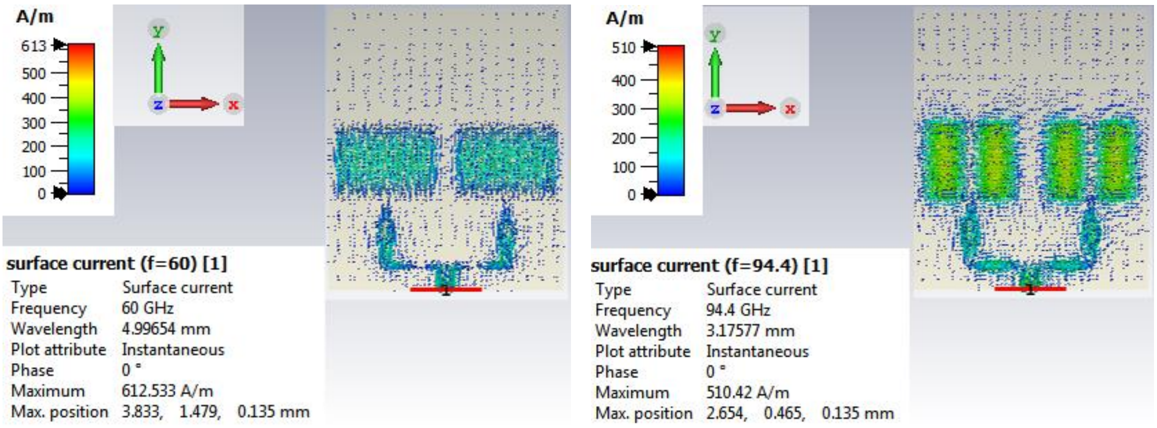
(a (b)

Figure 8. Directivity of 1×2 array at (a) 60 GHZ and (b) 94.4 GHz



(a) (b)

Figure 9. Gain of 1×2 array at (a) 60 GHz and (b) 94.4 GHz

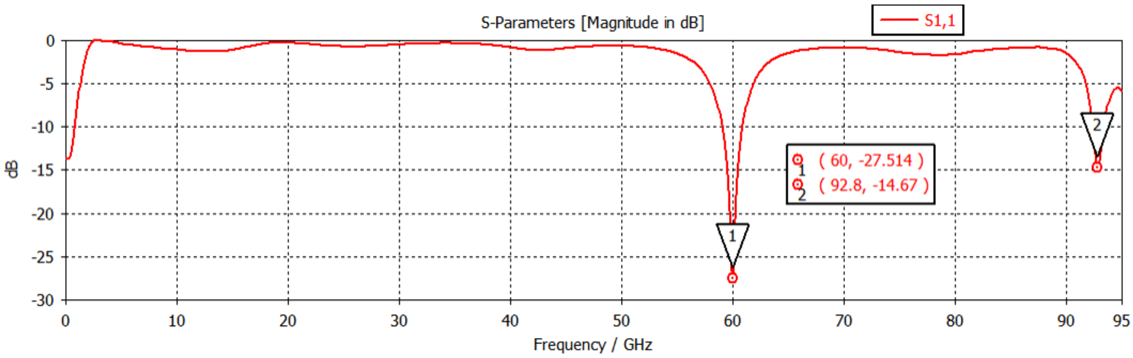


(a) (b)

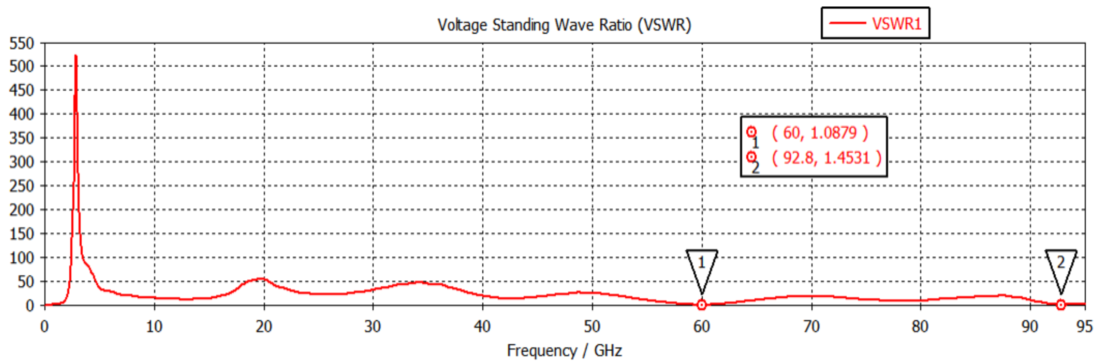
Figure 10. Current surface of 1×2 array at (a) 60 GHz and (b) 94.4 GHz

Table 6. Result of the (1×2) RMSPA antenna

Frequency (GHz)	Return loss	VSWR	Bandwidth (GHz)	Directivity (dBi)	Gain (dBi)
60	-27.514(dB)	1.0879	1.7	11.54	11.01
92.8	-14.67(dB)	1.4531	0.9	10.50	9.211

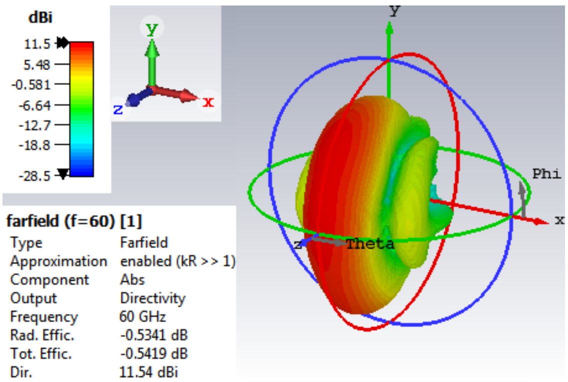


(a)

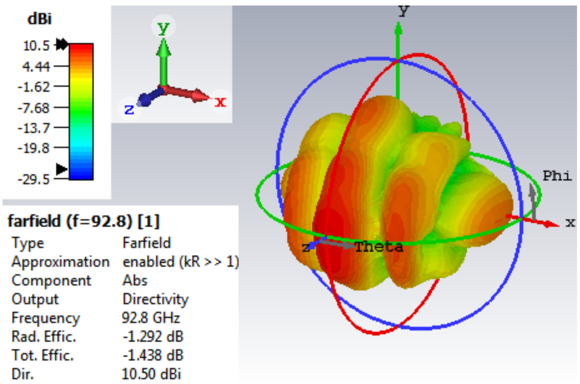


(b)

Figure 11. Dual-band of a 4patches (1×4) array antenna (a) return loss and (b) VSWR of d



(a)

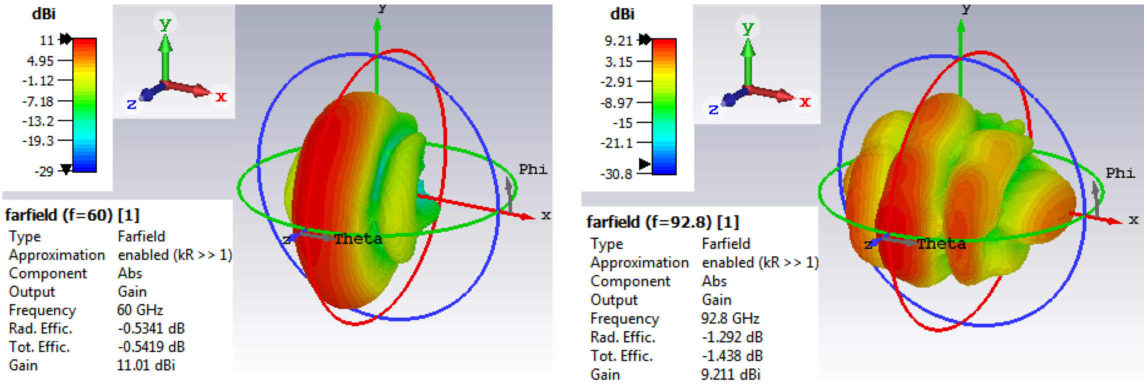


(b)

Figure 12. Directivity of 1×4 array at (a) 60 GHz and (b) 92.8 GHz

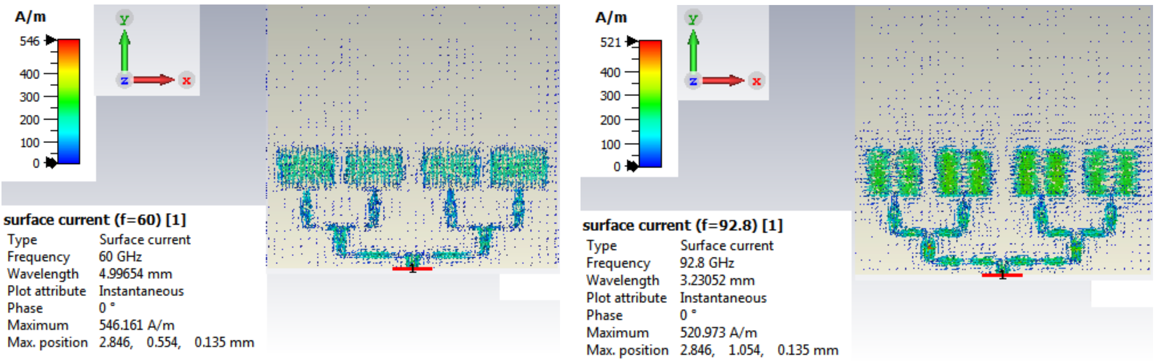
3.3. Comparison result of three design antenna implementation with other works

The comparison between the results of three arrays in this research and other results of other researches is shown in Table 7. The results of this research can be summarized as: firstly, the size of the patch (1.57 mm×2 mm) is the smallest RMSPA antenna that works on millimeter waves. Secondly, the three designs RMSPA antenna works with the dual bandwidth. Third, the performance for the three designs gives higher efficiency than the other work. Finally, the performance results for the directivity and power gain show that the best design is the 4 patches (1×4) compared with the 1 patch (1×1) and 2 patches (1×2).



(a) (b)

Figure 13. Gain of 1×4 array at (a) 60 GHz and (b) 92.8 GHz



(a) (b)

Figure 14. Current surface of 1×4 array at (a) 60 GHz and (b) 92.8 GHz

Table 7. A comparison between other published and this our work

	[Ref]	Size	Resonance frequency	Return loss(dB)	VSWR	Bandwidth	Directivity (dBi)	Gain (dBi)
1×1 element array RMSPA	[20]	2 mm×2 mm	38 GHz 54 GHz	-15.5 -12	1.3 1.64	1.94 GHz 2 GHz	7.2 8.2	6.9 7.4
	[21]	1.62 mm×2 mm	60 GHz	-22	1.173	1.375 GHz	Not reported	7.27
	[22]	9.31 mm×11.86 mm	10.6 GHz	-14.33	1.47	Not reported	8.89	8.53
	This work	1.57 mm×2 mm	60 93.7	-14.338 -12.027	1.475 1.6682	1.2 GHz 1.1 GHz	7.493 7.376	6.673 6.833
1×2 element array RMSPA	[21]	1.62 mm×2 mm	60 GHz	-22.85	1.15	1.15 GHz	Not reported	10.7
	[22]	9.31 mm×11.86 mm	10.45 GHz	-38.91	Not reported	Not reported	10.19	9.93
	[23]	27.62 mm×35.97 mm	2.45 GHz	-11.211	1.7588	29.3 MHz	9.633	9.225
	This work	1.57 mm×2 mm	60 GHz 94.4 GHz	-43.141 -19.669	1.014 1.2319	1.7 GHz 1.8 GHz	8.616 6.425	8.125 5.431
1×4 element array RMSPA	[20]	2 mm×2 mm	38 GHz 47.7 GHz 54 GHz	-13.5 -22.5 -18	1.55 1.16 1.2	3.5 GHz 2.5 GHz 1.3 GHz	12.2 11.6 12.4	12.2 11.6 12.1
	[21]	1.62 mm×2 mm	60 GHz	-32.7	1.047	1.3 GHz	Not reported	13.5
	[22]	9.31 mm×11.86 mm	10.45 GHz	-33.69	1.04	Not reported	13.18	12.85
	[23]	27.62 mm×35.97 mm	2.45 GHz	-12.741	1.5995	35.5 MHz	11.79	11.73
	This work	1.57 mm×2 mm	60 GHz 92.8 GHz	-27.514 -14.67	1.0879 1.4531	1.7 0.9	11.54 10.50	11.01 9.211

4. CONCLUSION

In this paper, three rectangular microstrip patch array antenna ((1×1), (1×2), and (1×4)) are presented with simple and small structures. The proposed antenna is simulated by using electromagnetic simulation, computer software technology Microwave studio (CST) printed on Rogers RT5880 (lossy) substrate with dielectric constant 2.2, 0.0009 loss tangent, and thickness 0.1 mm. The size of the patch for three designs of microstrip patch array antenna MSPAA is (1.57 mm×2 mm) and it works at dual-band. The good performance results in return loss, VSWR, directivity, and gain for the three designs necessary for many applications basically radar and communication. The three design results show that the best performance for the directivity and gain obtained by a 4 patchs (1×4) array.

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