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Evaluation of Gain Enhancement in Improved Size Microstrip Antenna Arrays for Millimetre-wave Applications

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Abstract: A number of microstrip antenna arrays have been designed based on the improved size patch elements with different substrate heights to evaluate the gain enhancement in practical measurements. Initially, microstrip patch antenna arrays (MPAAs) have been designed, analysed and tested at 10GHz frequency and then the optimized high gain (~21dBi) array is fabricated and tested at 60GHz-band frequencies. It has been found that the loss emergence due to the long feeding transmission line (TL) network severely degrades the antenna gain in large MPAAs on the thicker substrates. However, the gain can be significantly enhanced in large MPAAs by employing relatively thinner substrate but it shrinks the return loss (S11) bandwidth (BW) and increases the side lob level (SLL).

1. Introduction

In the modern point to point wireless communications, it is very common to enhance the gain of microstrip antennas by constituting arrays of multiple patch elements due to the simplicity and cost effectiveness of this approach [1-13]. However, at microwave and lower frequencies (<30GHz) this technique is limited by the exceptionally large antenna size acquired for high gain (>20dBi) arrays [6]. On the other hand, at mm-wave frequencies high gain MPAAs can

fit within a small footprint due to the small form factor [7-15]. However, at mm-wave frequencies this approach is restricted by the declined antenna efficiency and gain due to the substantial power losses commenced by the extended feeding line network which is vital to deliver matched electrical signal to each of the radiating elements [1-2]. Theoretically, the microstrip array output (Y) of N_p number of patch elements is expressed as [3].

$$Y = R(\theta, \varphi) \sum_i^{N_p} w_i e^{-jk r_i} \quad (1)$$

Where $R(\theta, \varphi)$ is the radiation pattern of single element in spherical coordinate system, w is the weighting factor, r is the radial distance and k is wave number. In eq. (1), it is assumed that the signal in all of the radiating elements is exited in phase with negligibly small mutual coupling effect. However, in practice these assumptions may deviate to some extend due to several reasons including imperfections in the dielectric material, discontinuities in the patch and feeding structures, impedance matching, etc. These peculiarities usually degrade the antenna array's measured radiation results from the expected ones. Nevertheless, for far-field response of a microstrip antenna array of symmetrical patch elements fed with equal signal level, eq. (1) turns into:

$$Y = N_p \cdot R(\theta, \varphi) \cdot w \cdot e^{-jk r} \quad (2)$$

Equation (2) can be written in terms of decibel (dB) units as:

$$Y = N_p \cdot (\text{dB}) + R(\theta, \varphi) \cdot w \cdot e^{-jk r} (\text{dB}) \quad (3)$$

Equation (2) reveals the fact that doubling the number of patch elements in microstrip array should add up 3dB in the gain output in ideal case. But at mm-wave frequencies this

relationship does not satisfy even for the first doubling of patch elements due to the substantive power loss contribution of the feeding line network [12].

Several MPAAAs have been reported in the literature but most of them are individually designed for a specific application [1, 2, 5-15]. In [6], the performance of two microstrip antenna arrays at 10GHz frequency has been studied in computer simulation environment. The first array presented in [6] was consisted of four patches which yielded 12.56dBi gain, 75% efficiency and -14.84dB SLL. In the second array reported in [6], the number of patch elements was doubled to 8 which slightly improved the gain to 13.9dBi but dropped the antenna efficiency down to 63.2% and increased the SLL to -11.58dB. However, there is a gap in the literature regarding the gain evaluation and performance analysis of large MPAA prototypes and their applicability at mm-wave frequencies.

Therefore, in the present work a study has been carried out to evaluate the MPAAAs gain enhancement with multiple patch elements to figure out a reasonable trade-off between the arrays' gain and size. Also, the effect of the substrate thickness, which is a major source of the losses in the associated microstrip TL networks, on the MPAAAs gain performance is investigated. Moreover, low impedance TLs have been proposed for the feeding and matching network to keep the lines sufficiently wide to fabricate with the cost-effective PCB etching method especially at mm-wave frequencies.

2. MPAA Design at 10GHz

2.1 Antenna Arrays on Substrate Thickness of 1.57mm

Initially, 3 MPAAAs i.e. with 2×1 (2-elements), 4×2 (8-elements) and 4×4 (16-elements) patches, are designed at 10GHz frequency on RT/Duroid5880 material with substrate thickness ' h ' = 1.57mm. Figs. 1(a), (b) and (c) show the geometries of 2-elements, 8-elements

and 16-elements arrays, respectively. The patch width 'W' and length 'L' are calculated by the following equations based on the size improvement method as explained in [1, 2] to improve the fabrication tolerance:

$$W = \frac{(2M+1)}{\sqrt{\frac{\epsilon_r + 1}{2}}} \times (\lambda_0/2) \quad (4)$$

$$L = \frac{(2N+1)}{\sqrt{\epsilon_{\text{eff}}}} \times (\lambda/2) - 2\Delta L \quad (5)$$

Where M and N are integers (for the present design M=1 and N=0), λ_0 and λ are free space and operating wavelengths, respectively, ϵ_r and ϵ_{eff} are the relative and effective dielectric constants, respectively, and ΔL is patch length extension due to the fringing field effect [3]

The antenna input impedance $Z_a = 59.8 \lambda_0 / nW$, where n is the number of series fed patch elements in a column (see Fig. 1), is matched to the standard 50Ω impedance through the impedance transformers of length ' L_{T1} ' as shown in Fig. 1. The rest of the feeding TL network in 8-elements and 16-elements arrays consists of the horizontal 50Ω lines with width W_{T3} and the vertical 35Ω lines with width W_{T1} (see Fig. 1). The vertical 35Ω lines work as impedance transformer to match the 25Ω resultant impedance, at the T-junction on the 50Ω horizontal lines, with the lower stage 50Ω line (i.e. $\sqrt{50\Omega \times 25\Omega} = 35.35\Omega$).

The general equations used to calculate the impedance transformer length ' L_{T1} ' and transmission line width ' W_T ' are as follows [13]:

$$L_{T1} = (2P+1) \times \frac{\lambda}{4} \quad (6)$$

$$W_T = \frac{7.475 h}{e^x} - 1.25t \quad (7)$$

Where P is an integer (we chose P=1 in our design), $x_1 = (Z_{01}\sqrt{\epsilon_r + 1.41}/87)$, and h and t are the substrate thickness and copper cladding, respectively (Fig.1). In the case of 2-element antenna array, W_{T2} is set to be equal to $W_{T1}/2$ to minimize the side lob level (SLL) (see Figs. 1(a)) [2]. The separations ' L_{T2} ' and ' S ' between the series and parallel patch elements are given by [12]:

$$L_{T1} = (2K + 1) \times \frac{\lambda}{2} + 2\Delta L \quad (8)$$

$$S = (2Q + 1) \times \frac{\lambda}{2} \quad (9)$$

Where K and Q are integers (K=Q=0 in our designs). The arrays' final dimensions (eqs. (4)-(9)) are optimized by CST Microwave Studio for the best antenna response.

Table 1 shows the dimensions of the three MPAAAs designed on PCB thickness of 1.57mm. The separation ' S ' between the parallel patch elements is optimised to be 10mm. Figs. 2-4 depict the experiment results of 2-elements, 8-elements and 16-elements MPAAAs, respectively, where (a), (b), (c) and (d) illustrate the fabricated prototype, S11 response, 2-dimensional (2-D) far-field radiation patterns (FRP) and 3-dimensional (3-D) simulation FRP, respectively. Table 2 summarises the performance parameters of these three MPAAAs where it can be noticed that increasing the number of patch elements from 2 to 8 (both in series and parallel) improved the antenna gain only by about 1.8dB. However, further doubling the patch elements to 16 enhanced the gain by 2dB yielding a maximum gain to 17.7dBi. It can also be seen that increasing the patch elements has reduced the S11 BW and increased the SLL.

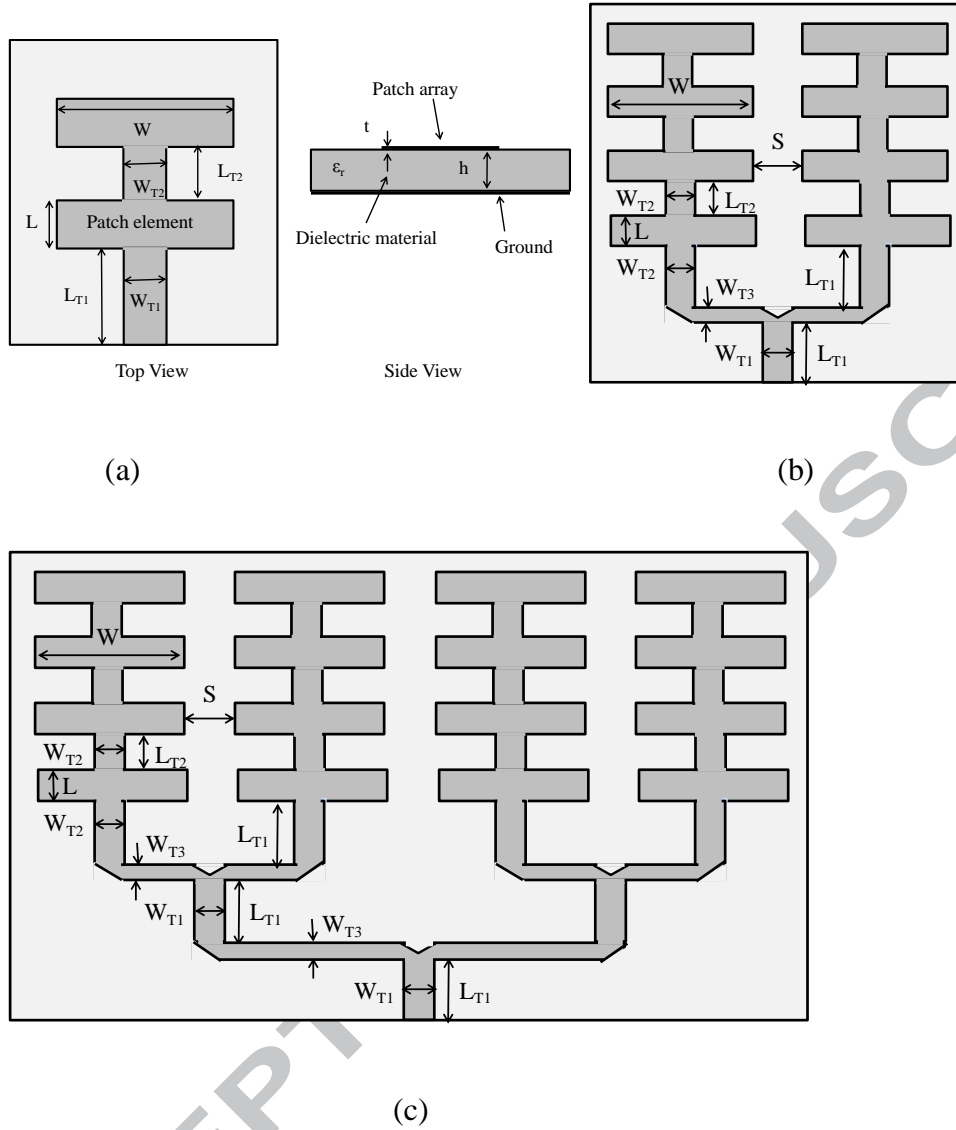


Fig. 1. Geometry of (a) 2-elements, (b) 8-elements and (c) 16-elements MPAAAs

Table 1. Dimensions in mm of MPAAAs with $h=1.57\text{mm}$

MPAA	L	W	L_{T1}	W_{T1}	L_{T2}	W_{T2}	W_{T3}
2-elements	8.66	34.45	14.89	7.79	8.66	3.9	-
8-elements	8.66	32	15.63	5.11	9	3.33	3.63
16-elements	8.66	33	15.63	6	9	3	3.63

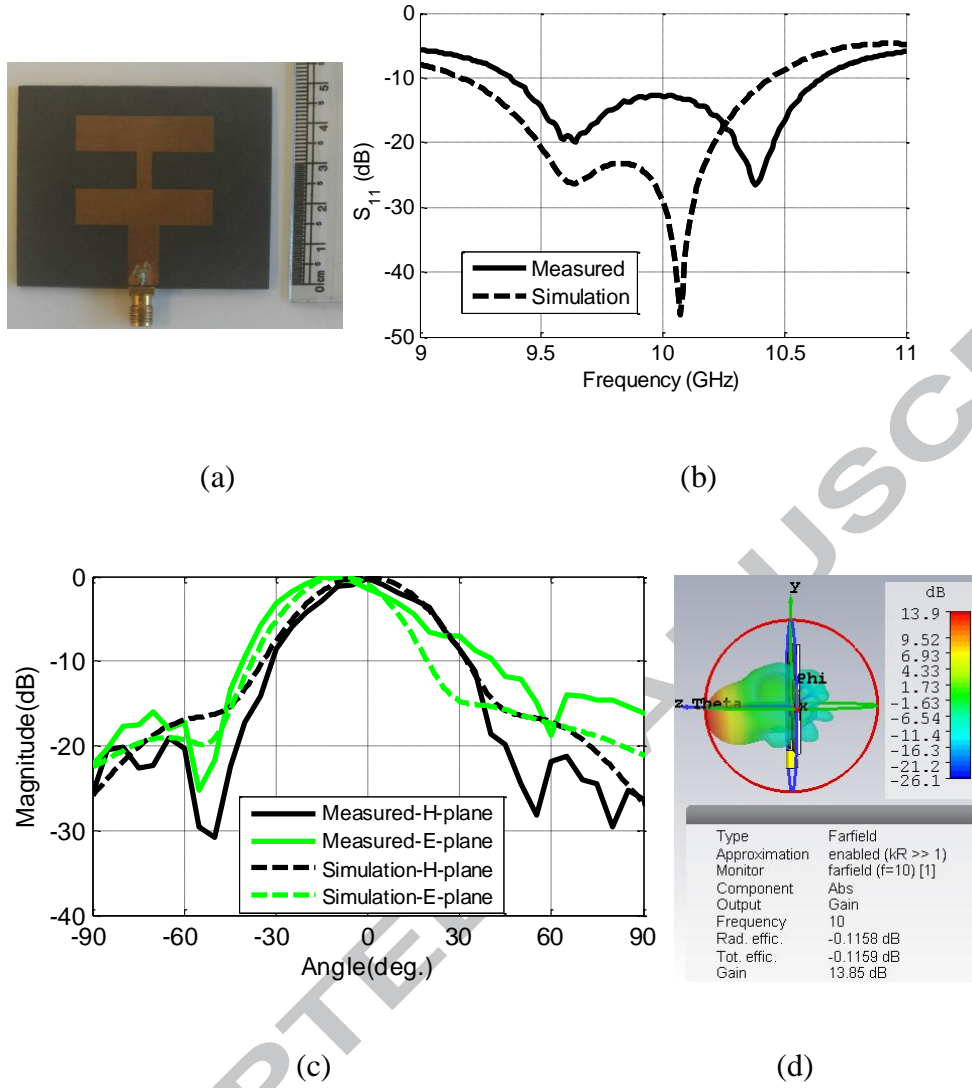


Fig. 2. Experiment results of 2-elements MPAA designed at 1.57mm thick PCB. (a)

Fabricated prototype, (b) S₁₁, (c) 2-D FRP and (d) 3-D simulation FRP

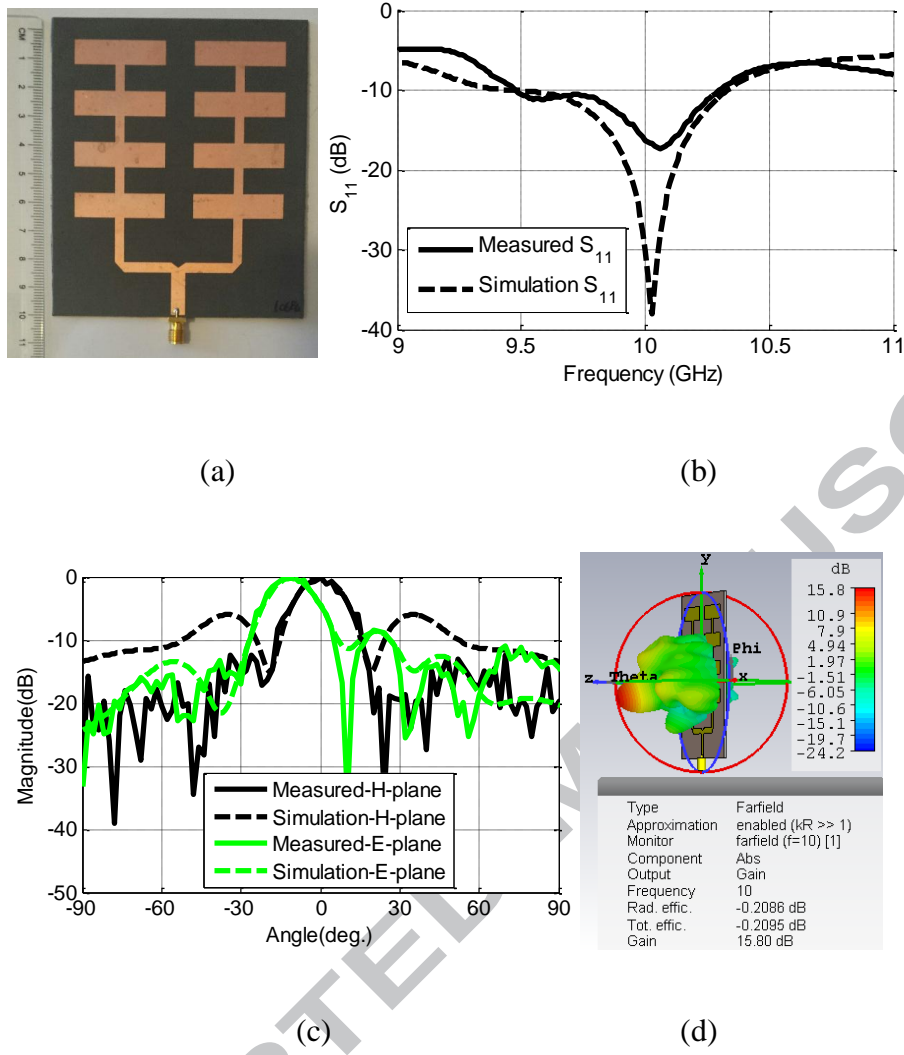
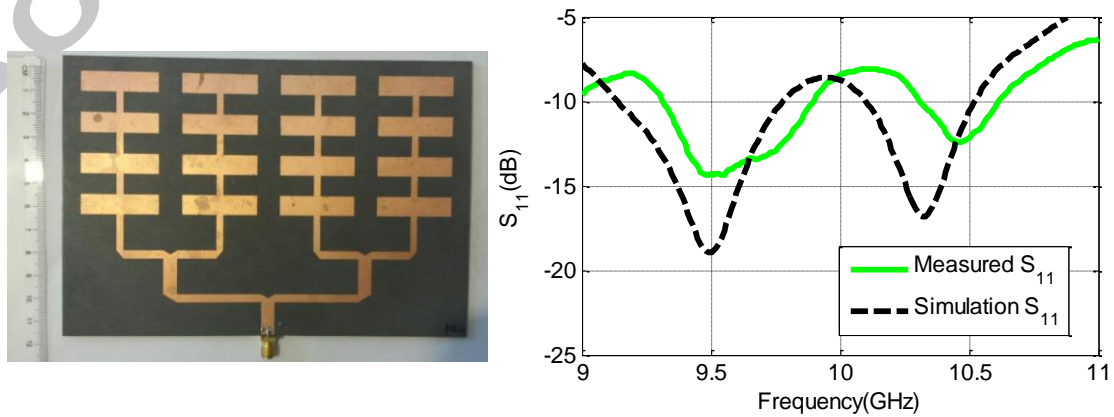


Fig. 3. Experiment results of 8-elements MPAA designed at 1.57mm thick PCB. (a) Fabricated prototype, (b) S_{11} , (c) 2-D FRP and (d) 3-D simulation FRP



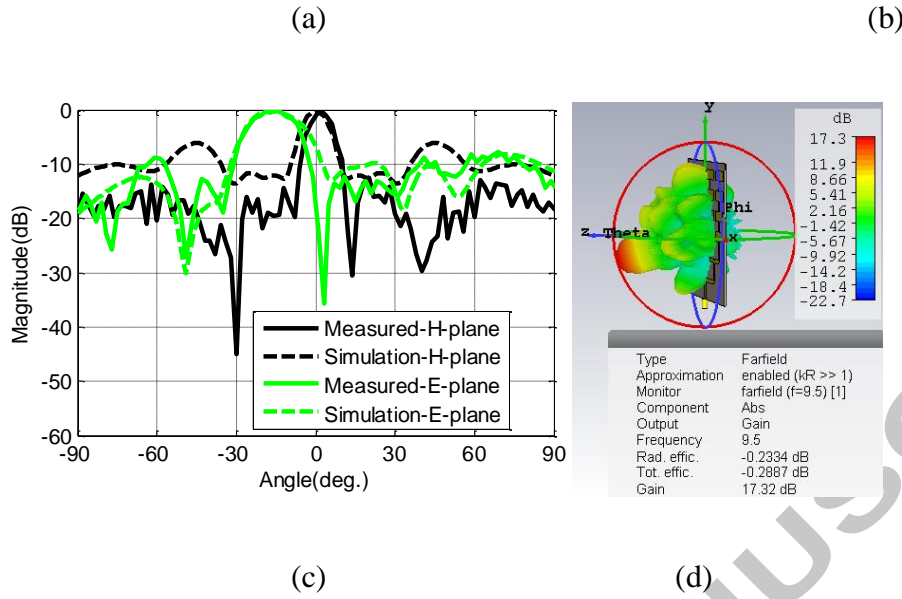


Fig. 4. Experiment results of 16-elements MPAA designed at 1.57mm thick PCB.

(a) Fabricated prototype, (b) S11, (c) 2-D FRP and (d) 3-D simulation FRP

Table 2. Performance of MPAAAs with $h=1.57\text{mm}$

MPAA	BW (MHz)		Gain (dBi)		SLL(dB)	
	Simu.	Meas.	Simu.	Meas.	Simu.	Meas.
2-elements	1250	1228	13.85	13.93	-19	-14.02
8-elements	400	823	15.8	15.68	-6	-8.29
16-elements	640	586	17.32	17.7	-7.91	-7.3

2.2 Antenna Arrays on Substrate Thickness of 0.508mm

Table 3 shows the dimensions of the 10GHz MPAAAs designed on the PCB thickness of

0.508mm. The separation between the parallel patch elements $S=9.73\text{mm}$. Figs. 5-7

demonstrate the experiment results of these 2-elements, 8-elements and 16-elements MPAAAs,

respectively, where (a), (b), (c) and (d) present the fabricated prototype, S11 response, 2-D

FRP and 3-D simulation FRP, respectively. Table 4 shows the performance parameters of

these three MPAAAs where it is clear that increasing the number of patch elements from 2 to 8

improved the gain by about 4.66dB and further doubling the patch elements to 16 boosted the

antenna gain by 3.1dB yielding the maximum gain of 21.1dBi. Comparing Table 4 with Table 2, it can be concluded that the thinner substrate is more suitable to obtain high gain in large MPAA. However, S_{11} BW of the larger MPAA with thinner substrate becomes even narrower.

Table 3. Dimensions in mm of MPAA with $h=0.508$ mm

MPAA	L	W	L_{T1}	W_{T1}	L_{T2}	W_{T2}	W_{T3}
2-elements	9.46	36	14.46	3	9.46	1.5	-
8-elements	9.19	32.25	14.59	1.73	9.19	2.18	1.27
16-elements	9.19	31.5	14.6	1.75	9	2.18	1.28

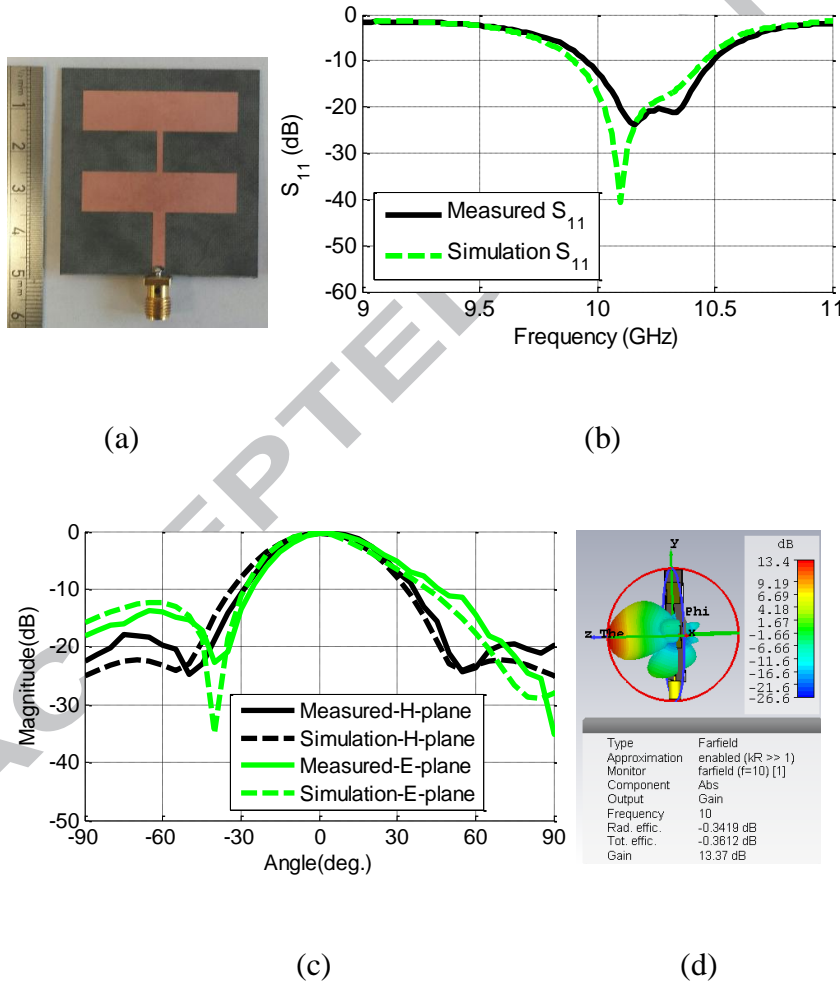


Fig. 5. Experiment results of 2-elements MPAA designed at 0.508mm thick PCB. (a)

Fabricated prototype, (b) S_{11} , (c) 2-D FRP and (d) 3-D simulation FRP

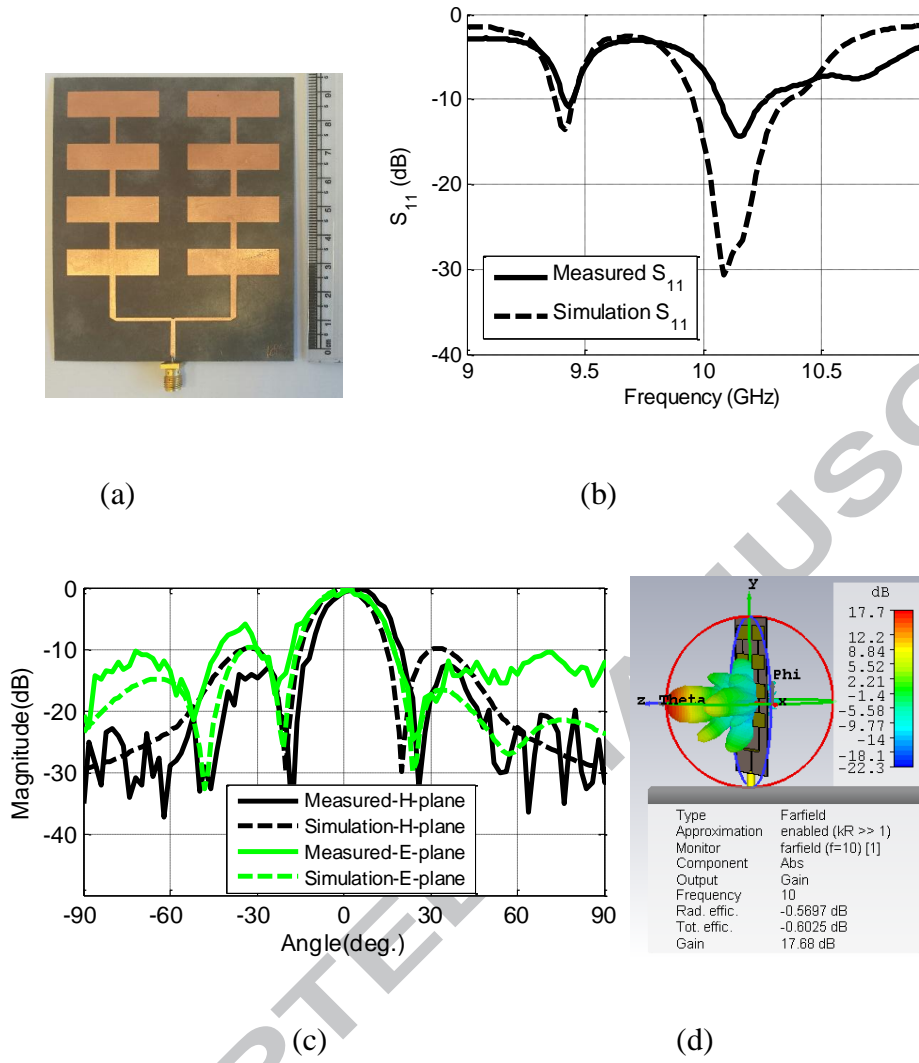
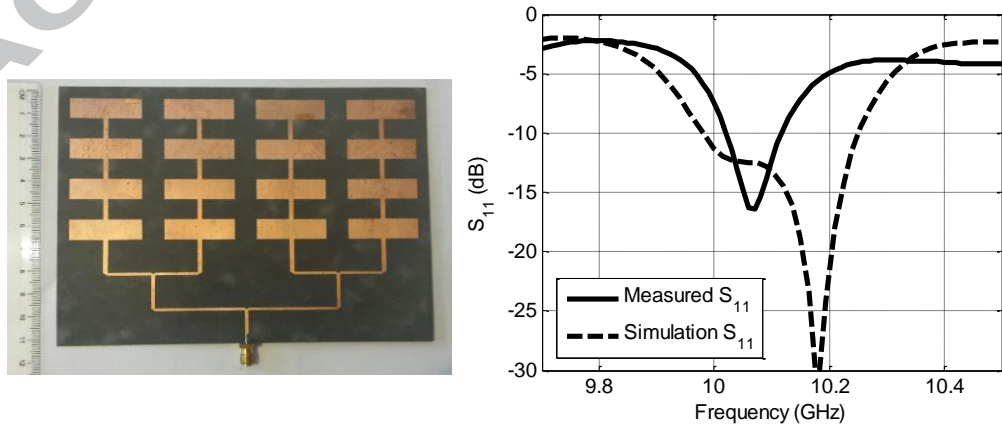


Fig. 6. Experiment results of 8-elements MPAA designed at 0.508mm thick PCB. (a)

Fabricated prototype, (b) S_{11} , (c) 2-D FRP and (d) 3-D simulation FRP



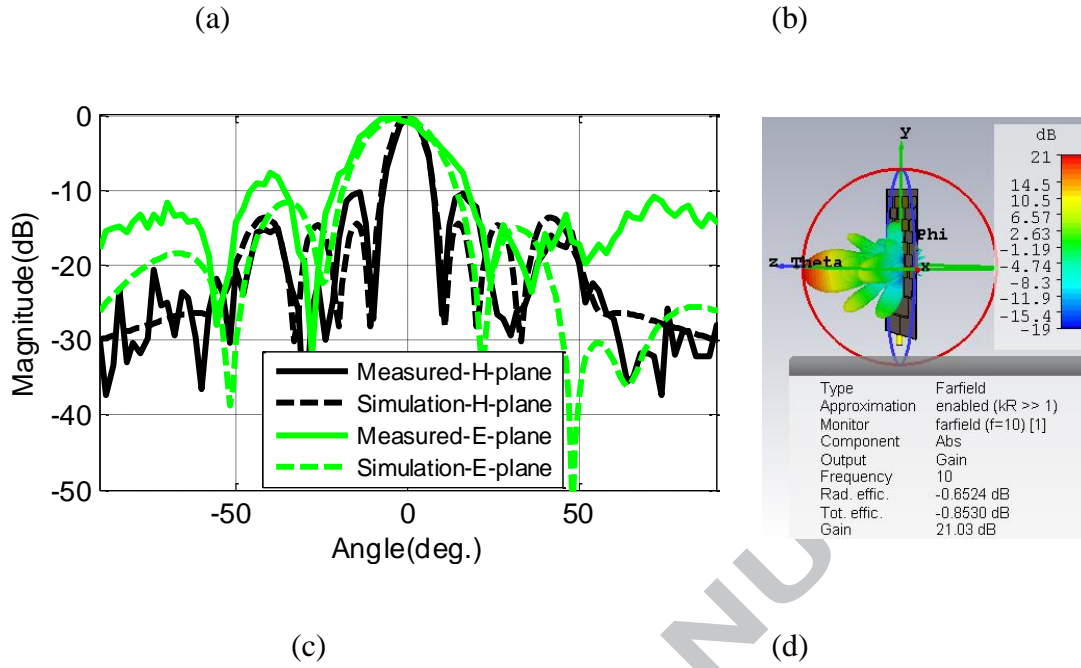


Fig. 7. Experiments results of 16-elements MPAA designed at 0.508mm thick PCB. (a)

Fabricated prototype, (b) S11, (c) 2-D FRP and (d) 3-D simulation FRP

Table 4. Performance of MPAA with $h=0.508\text{mm}$

MPAA	BW (MHz)		Gain (dBi)		SLL (dB)	
	Simu.	Meas.	Simu.	Meas.	Simu.	Meas.
2-elements	560	537	13.37	13.33	-12.26	-13.83
8-elements	450	200	17.68	17.99	-9.8	-5.8
16-elements	310	230	21.03	21.1	-10.29	-7.75

In the next stage, based on the conclusion described in the last paragraph, a large MPAA is

designed at 10GHz with 32-elements on the PCB thickness of 0.508mm. Fig. 8 shows the

geometry of 32-elements MPAA and Table 5 presents its optimised dimensions. Fig. 9

demonstrate the experiment results of 32-elements 10GHz MPAA where (a), (b), (c) and (d)

show the fabricated prototype, S11 response, 2-D FRP and 3-D simulation FRP at the central

resonance frequency of 10.03GHz, respectively. Table 6 shows the performance parameters

of this array. Comparing these results with 16-elements MPAA results presented in Table 4 it

is apparent that further doubling the patch elements to 32 improved the measured antenna

gain by 1.17dB to 22.27dBi but the S11 BW is shrunk down to 80MHz and the SLL is increased to -4.88dB.

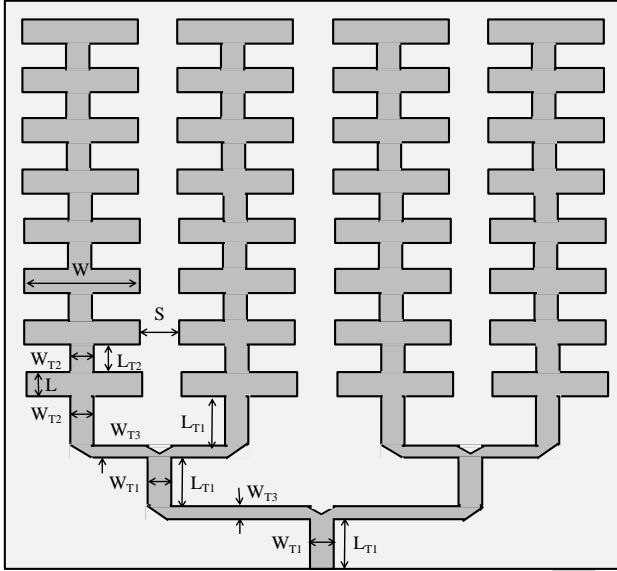
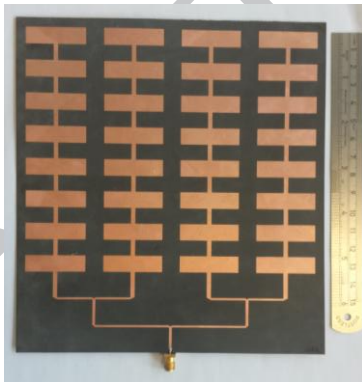


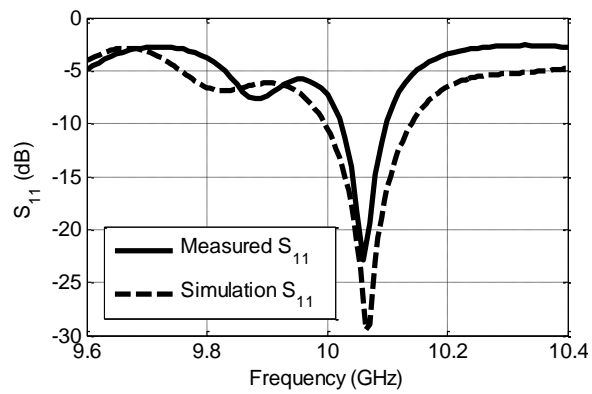
Fig. 8. Geometry of 32-elements MPAA

Table 5. Dimensions in mm of 32-elements 10GHz MPAA with $h=0.508\text{mm}$

L	W	L_{T1}	W_{T1}	L_{T2}	W_{T2}	W_{T3}	S
9.19	33	14	1.75	8.67	2.56	1.28	9.73



(a)



(b)

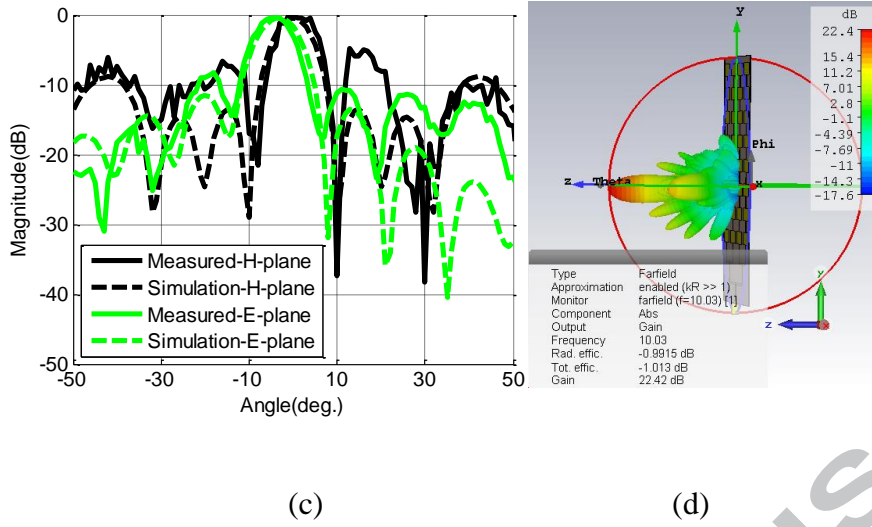


Fig. 9. Experiment results of 32-elements 10GHz MPAA designed at 0.508mm thick PCB. (a) Fabricated prototype, (b) S11, (c) 2-D FRP and (d) 3-D simulation FRP

Table 6. Performance of 32-elements 10GHz array with $h=0.508\text{mm}$

BW (MHz)		Gain (dBi)		SLL (dB)	
Simu.	Meas.	Simu.	Meas.	Simu.	Meas.
150	80	22.42	22.27	-8.83	-4.88

3. Microstrip Patch Antenna Array Design at 60GHz

The 32-elements MPAA design presented in the last section is redesigned at 60GHz frequency on the same material but with $h=0.127\text{mm}$. Table 7 shows the optimised dimensions of the 60GHz MPAA where it is clear that the antenna dimensions are well above the PCB etching limit of 0.152mm track width/gap [3]. Fig. 10 demonstrates the experiment results of 60GHz MPAA where (a), (b), (c) and (d) reveal the fabricated prototype, S11 response, 2-D FRP and 3-D simulation FRP at the central resonant frequency of 60.5GHz, respectively. As seen from Fig. 10, the measured and simulation results show a close agreement. Table 8 summarises the antenna's overall performance parameters. The measured -10dB S11 BW and maximum gain at 60.5GHz of this array are 2.39GHz and 20.5dBi,

respectively. The measured gain is relatively lower than that of the 32-element array at 10GHz due to the fact that the substrate's thickness of 0.127mm at 60GHz is relatively thicker (i.e. $h/\lambda_0=0.0254$) than 0.508mm at 10GHz (i.e. $h/\lambda_0=0.0169$). Also, about a 12° angle beam squint in the main radiation lobe has been observed which is due to successively lower signal weight ('w', see eq. 1) because of the additional power losses along the series feeding of the patch elements at 60GHz-band frequencies. However, the beam squint angle may be reduced by reducing the losses encountered due to the long TL path. This may be accomplished by (i) designing the antenna on even thinner substrate, (ii) employing a substrate material with slightly higher dielectric constant, and (iii) using more incorporate feeding sections instead of very long series feed.

The other factors which may influence the antenna's performance at mm-wave frequencies include mechanical strength of the thin PCB board, impact of the antenna integration with the testing fixture/other components, and the tolerance levels in fabrication and measurements. However, in the current 60GHz antenna design, 0.127mm thick PCB substrate with copper cladding of 17.5 μ m on both sides provided reasonable mechanical strength to the antenna prototype to remain straight without any external support. Additionally, the fabrication, soldering, assembling and measurements have been carried out with extra cautions to mitigate the relevant inaccuracies (see Fig. 10).

Table 7. Dimensions in mm of 60GHz MPAA with $h=0.127$ mm

L	W	L _{T1}	W _{T1}	L _{T2}	W _{T2}	W _{T3}	S
1.45	5	2.8	0.42	1.45	0.62	0.3	1.58

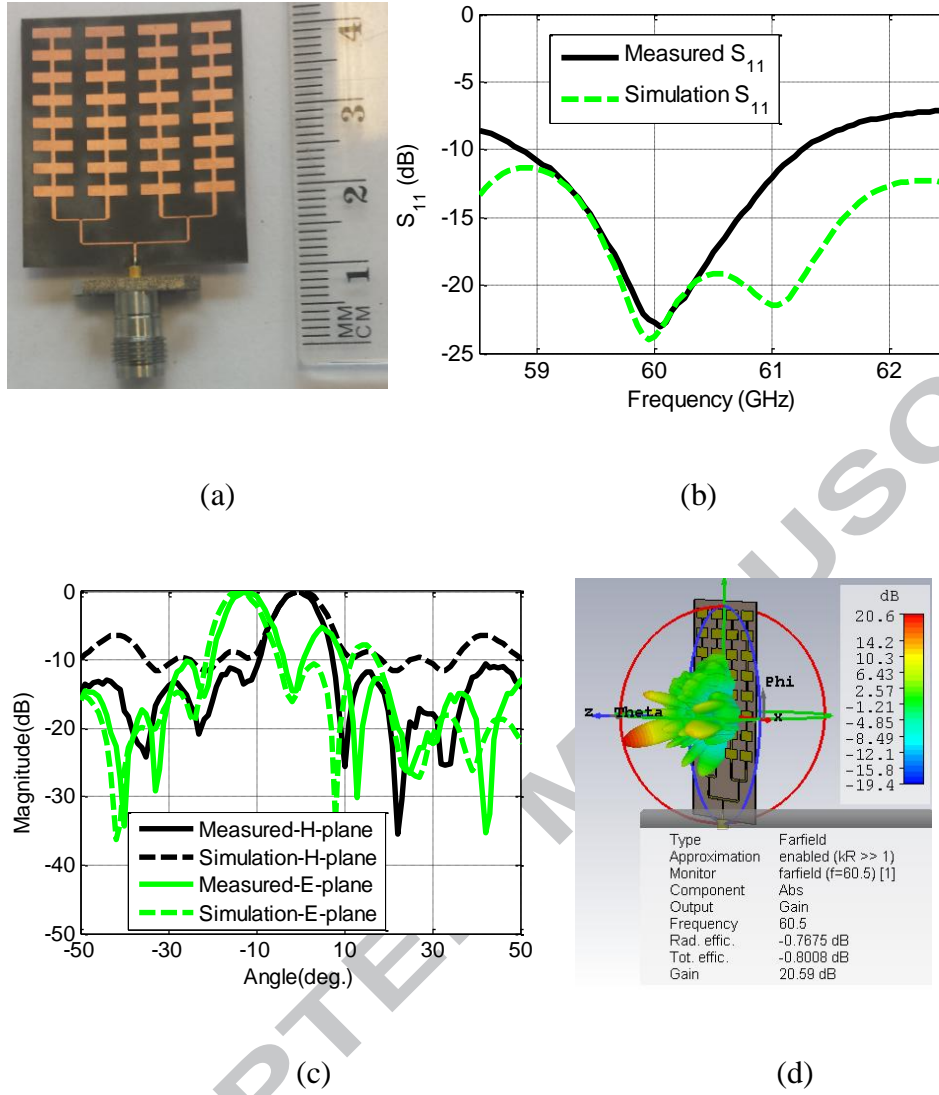


Fig. 10. Experiments results of 32-elements 60GHz MPAA designed at 0.127mm thick PCB.

(a) Fabricated prototype, (b) S11, (c) 2-D FRP and (d) 3-D simulation FRP

Table 8. Performance of 60GHz array with $h=0.127\text{mm}$

BW (GHz)		Gain (dBi)		SLL (dB)	
Simu.	Meas.	Simu.	Meas.	Simu.	Meas.
3.31	2.39	20.59	20.50	-6.41	-5.32
(S11<-12dB)					

4. Conclusion

The performance of improved size microstrip antenna arrays has been studied at 10GHz frequencies by designing and testing several prototypes with various number of patch elements on two different substrate thickness i.e. 1.57mm and 0.508mm. It has been found that thin PCB substrate is desirable for high gain large MPAA designs. Subsequently, high gain antenna arrays have been designed with 32 patch elements on relatively thinner substrates and tested at 10GHz and 60GHz frequencies and maximum measured gain of 22.27dB and 20.5dBi have been achieved at 10GHz and 60GHz, respectively. Also, about a 12° beam squint in the main radiation lobe has been observed in case of the presented 60GHz array due to the long series feeding of the patch elements. Furthermore, the SLL is increased in the large MPAA's which may be minimised by applying lobe grating methods as discussed in [3]. The designing approach may be particularly useful to make microstrip antenna arrays at even higher frequencies of mm-wave and THz (0.3-3THz) bands by employing even thinner substrates. In addition, the possibility of beam reconfiguration may be exploited on the proposed MPAA design by using one of the exiting techniques i.e. by weighting the power level to each of the radiating element series or by introducing switched delay lines in the feeding paths for a gradual phase shift across the parallel antenna elements.

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