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Original Article

Design and Analysis of Stacked 4×4 Array Antenna for Applications in the S and C Bands

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Abstract - *Patch antenna arrays are renowned for their low profile and compact form factor. This paper introduces a dual-layer stacked 4x4 microstrip patch antenna array is intended to achieve high gain and multiband response. The array is constructed using a cost-effective FR-4 epoxy substrate. The single patch antenna's performance is compared with that of a 2×2 array, a 4×4 array, and a dual-layer stacked array. Performance metrics analyzed include the reflection coefficient, gain, radiation pattern, and surface current density. The dual-layer stacked array demonstrates a gain of 18.6 dBi at 3.95 GHz and 18.8 dBi at 6.71 GHz, showcasing its multiband capability. The bandwidth of the stacked array at 3.95 GHz and 6.71 GHz is 150MHz and 2750MHz, respectively. The array effectively operates across multiple frequencies within the S and C bands, making it suitable for various applications in communication systems. Additionally, the enhanced design of the dual-layer stacked array offers significant improvements in gain and bandwidth compared to traditional single-layer arrays. This makes it an excellent candidate for advanced wireless communication technologies where high performance and multiband operation are critical. The use of FR-4 epoxy not only reduces the cost but also maintains the structural integrity and performance of the antenna array.*

Keywords - *Arrays, Bandwidth, Microstrip patch, Stacked arrays, S and C bands.*

1. Introduction

Microstrip patch antennas have emerged as the preferred choice for antenna design due to their characteristics tailored for commercial wireless applications. These antennas, characterized by their smaller size, lightweight nature, and versatility in rectangular, square, and triangular shapes, play a pivotal role in supporting high-density packaging. Moreover, their cost-effectiveness adds to their appeal. The versatility of patch antennas extends to supporting various feed techniques and the development of arrays to improve gain and achieve desired pattern requirements.

The easy feed technique, a notable characteristic of microstrip patch antennas, allows for various feeding techniques, ranging from single lines to complex networks. The literature has witnessed the presentation of innovative microstrip patch designs and various feeding techniques.

The planar arrays, such as a wideband patch array with modified unequal arms [1] and a 5G antenna featuring a sectoral disk to serve as a radiating surface along with a circular-shaped slot [2, 3] on it, are successfully excited through the probe-feed technique. A four-element dual-band printed slot antenna array and E-shaped patch array [4] for 5G applications have been fed using a modified Wilkinson power divider and folded patch feed that serves as examples of intricate feeding techniques. In contrast to intricate feed, microstrip array antenna for 5G networks at 28GHz [5] presents a simple series feed network comprising a continuous transmission line progressively coupling energy between the elements of a 4x4 planar antenna array. Furthermore, a modified 3x3 series-fed patch array antenna for beam steering antenna for millimetre-wave applications has been presented [6].

Antenna feeding that involves equally splitting power at each junction of the MPA is referred to as the corporate feed technique to ensure uniform distribution. A16-element MPA for 5G applications using corporate feed network can achieve bandwidth greater than 300MHz [7].

Researchers have explored combining series and corporate feed techniques [6] to achieve desired antenna performance even at 28 GHz 5G applications. The inset feed that provides good impedance matching is employed for patch arrays [8]. To implement four configurable states of vertical and horizontal linear polarization, right hand and left hand circular polarization, which is composed of a wide band stacked patch antenna array [9]. The broadband antenna that provides applications like Wi-Fi, GSM 1800,3G,4G,5G and an operating frequency range from 1.7 to 2.5GHz was designed in the broadband antenna, which also provides high gain with enhanced efficiency [10].

In their study, K. Ghorbani [11] et al. developed a printed antenna with wide-band characteristics expressing dual-polarization features, which was devised and built. It incorporated a dual-layered feeding method in union with an aperture stacking patch architecture, which produced dual-polarized radiation. It also reported a 52% rise in bandwidth with a return loss of 10 dB. Further, it expressed excellent isolation above 30 dB and uniformly over the entire operating spectrum. The gain is reported to be 7.4dBi with a possible variation of 0.4dB. The cross-shaped reflectors can nullify specific issues associated with the aperture-excitation. The works discussed in this paper include the design of staked arrays with corporate feed.

A dual polarised stacked patch antenna with L-Probe was studied by K. L. Lau [12] et al. in their research work, which operates between 0.808 and 0986 GHz in the frequency range. The antenna array, operated at those frequencies, produced an excellent result of 14-dB return loss with a bandwidth enhancement of 19.8% with excellent isolation of 30db and an average gain of 10.5dBi throughout the bandwidth. The radiation pattern is shown in two principal planes with cross-polarization with a maximum level of 15dB within the 3-db beam widths across the passband of the antenna. These qualities of the antenna make it work appreciably in the outdoor base stations, covering the bandwidths of the operating range for both CDMA800 and GSM900 mobile communications applications.

A Circularly Polarized planar antenna is proposed with multi-stacking by Kwok L. Chung [13] et al., which expressed enhanced efficiency. The stacked antenna operated along with its subarray at X-band frequency. The antenna subarray bandwidths were measured at 25.6 % and 23.5%, respectively, by achieving 10dB antenna impedance and 3dB axial ratio. Individually, the antenna achieved 20.2% and 8.0% in the case of a single ingredient. The mutual coupling of the elements is very low compared to any stacked patch antennas, and this got a gain of 10dB with a bandwidth of 23.50%. The antenna efficiency is calculated as 89% around the centre frequency with an increase of 10dB for a single element, but the stacked patch subarray antenna has an antenna efficiency of 71% with a gain of 15dB over 21% of bandwidth.

B. Nandgaonkar et al. [14] proposed an antenna design method to provide excellent impedance bandwidth. The design is a two-layered geometry in which the coupling ensures an electro-magnetic technique. In this study, the operating band expressed 90% radiation efficiency. The designed antenna covers the 2.40 GHz frequency range and is circularly polarised in the right hand. The Agilent Vector Network Analyzer, E5062A, was used for experimental verification after the proposed structure was first optimised using IE3D software.

For a wide working bandwidth and good gain, a two-fold Electromagnetic Band Gap (EBG) reflector was presented by Pui-Yi LAU et al. [15]. The design has the EBG layer serving as a reflector. The radiating patch is positioned at the center of this reflector and serves as a source of excitation. As a result, approximately 2GHZ BW is repeated, which is calculated to be 44.40%.

Xueyao Ren et al. [16] utilised Giuseppe Peano fractal-shaped patches for a novel microstrip array antenna design. The design incorporated a layered stack structure, which achieved high gain characteristics along with wideband within the targeted frequency range. This antenna is subjected to a parametric study to adopt arbitrary changes in the fractal elements' proportions and maintain the aperture efficiency at high. A 2 X 2 and 4 X 4 prototype fractal patches have been designed, fabricated, measured, and compared with the simulated results, maintaining excellent trade-off. The performance of the wideband, high directivity and high aperture efficiency have been studied in this work.

The paper's organisation includes an introduction to arrays and different feeding techniques followed by literature. The second section provides antenna design, and the third includes the results and discussions.

2. Antenna Design

In this section, the details of the antenna design are presented as follows. An FR-4 substrate which has a permittivity of 44 is considered due to its obvious advantages. Further, multiple antenna designs are presented sequentially in this work and design criteria are progressive. The critical design is a single element antenna, which is later extended to an array configuration. The single element radiating system is designed to operate at 2.4GHZ. The geometry of it is given in Figure 1, while the design specifications are listed in Table 1 below.

Table 1. Design specifications

Design Specifications	Dimension (in mm)
Patch Length	29.4
Patch Width	38
Substrate height	1.6
Substrate Dimensions	50×50
Air Gap between layer	50
Ground Dimensions	50×50

The antenna is excited using microstrip line feeding. Further, a 2×2 array is formed with a spacing of 50 mm for the optimised radiation pattern shown in Figure 2(a). The 2×2 array is fed using corporate feeding to deliver maximum excitation to all the elements. Furtherly. A corporate fed 4×4 array antenna is designed for multiband applications, as shown in Figure 2(b). The designed 2×2 array and 4×4 array are shown in the figure. A stacked array was also developed to enhance the effectiveness of the array. The 4×4 antenna array is stacked on the ground plane with the height λ/10, as indicated in Figure 2.

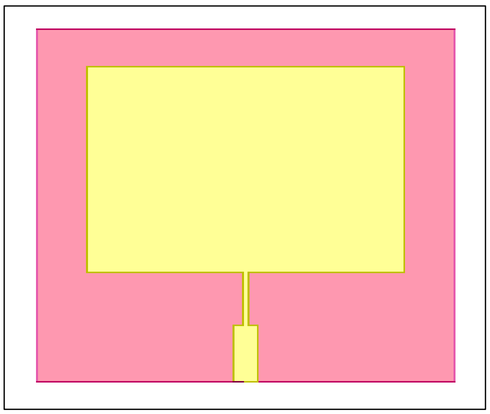
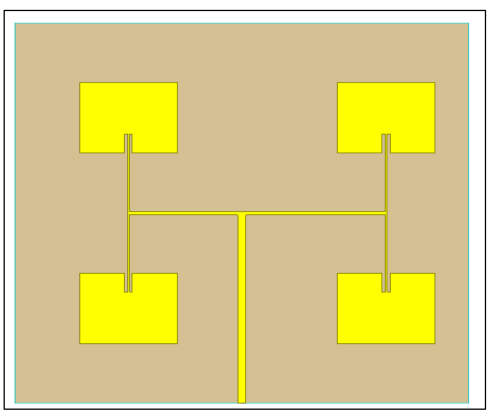
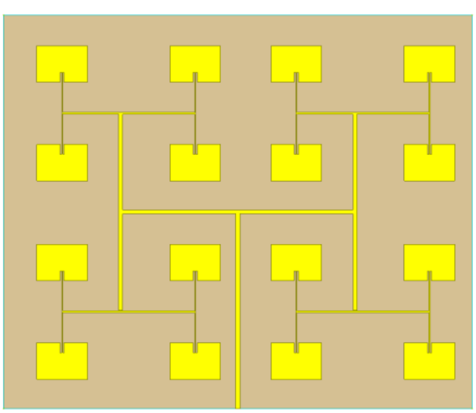


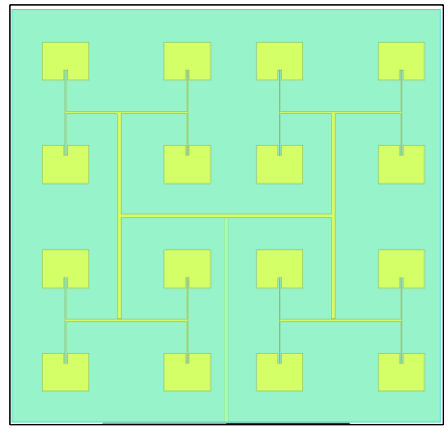
Fig. 1 The rectangular patch antenna



(a)



(b)



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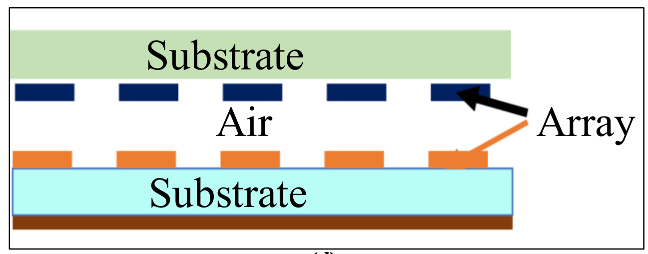


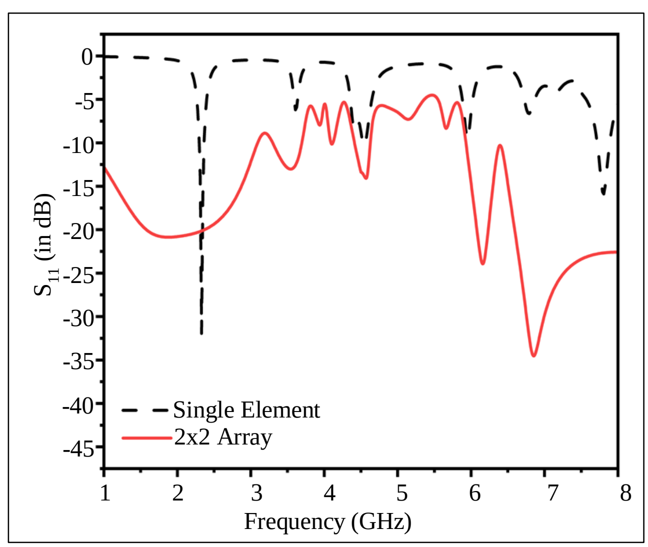
(d)

Fig. 2(a)The 2×2 antenna array, (b) 4×4 antenna, (c) The stacked 4×4 patch antenna array, and (d) Cross-section view of stacked antenna array.

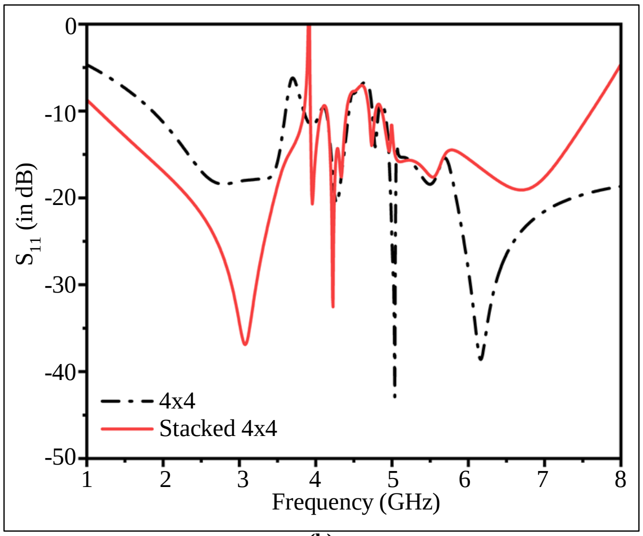
3. Results

The designed rectangular patch antenna and the 2×2 array antenna, the 4×4 array antenna and the stacked 4×4 array antenna are simulated and analysed for parameters.

A single element's reflection coefficient element of the antenna and the 2×2 array antenna is shown in Figure 3(a). The single element has centre resonating frequencies at 2.32 GHz and 4.5425 GHz, having dips at -22.42 dB and 11.6 dB



(a)



(b)

Fig. 3 The reflection coefficient plot (a) Single element and 2×2 array, and (b) 4×4 and stacked ×4.

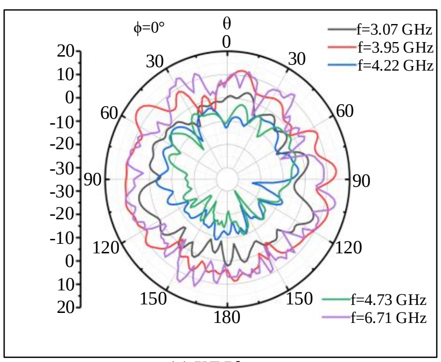
The 2×2 array antenna has centre resonating frequencies at 2, 3.54, 4.57, 6.16 and 6.85 GHz, having dips at -20.79 dB, -13.02 dB, -14.03 dB, -23.92 dB, and -34.53dB. The response shows that it has a dual-band response at bands.

The 4×4 array antenna has centre resonating frequencies at 2.78, 4.57, 5.03 and 6.16 GHz, having dips at -18.40 dB, -20.63 dB, -42.89 dB and -38.59 dB. When the antennas are stacked, it has resonant frequencies at 4.2, 3.07, 4.33 and 6.68 GHz, having dips at -32.54 dB, -36.88 dB, -17.59 dB and -19.09 dB. The resonant frequencies for good performance are observed for the reflection coefficients well below -10dB.

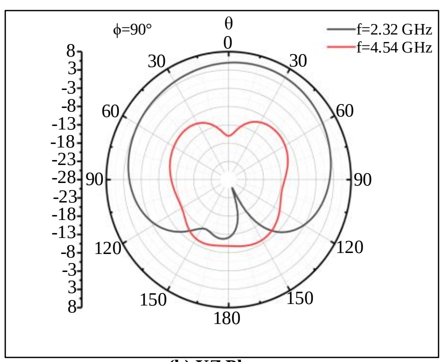
The radiation pattern is a two-dimensional plot representing the radiation from the antenna in the elevation and azimuth plane. Figure 4(a-c) shows the radiation pattern of the single element at all its resonant frequencies. It has a uniform pattern along the broadside and low radiation below the ground plane.

The radiation patterns are simulated for the 2×2 array at all resonant frequencies, as shown in Figure 4(d-f). It has a uniform pattern along the broadside and has low radiation below the ground plane. However, multiple sidelobes are found. The array has a similar pattern at all resonant frequencies with variable gains. Similarly, the patterns are also simulated for the 4×4 arrays and presented in Figure 4(g-i). It has a uniform pattern along the broadside and has low radiation below the ground plane. However, multiple sidelobes are found. The array has a similar pattern at all resonant frequencies with variable gains. The array has a similar pattern at all resonant frequencies with variable gains.

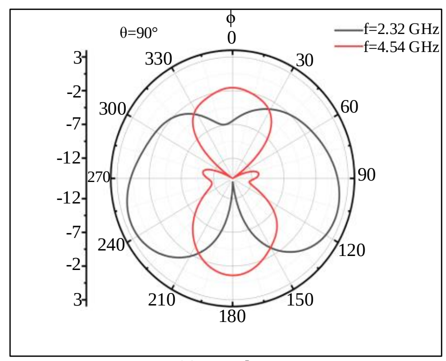
The radiation pattern of the stacked 4×4 array at frequencies is shown in Figure 4 (j-l). It has a uniform pattern along the broadside and has low radiation below the ground plane. However, multiple sidelobes are found. The array has a similar pattern at all resonant frequencies with variable gains.



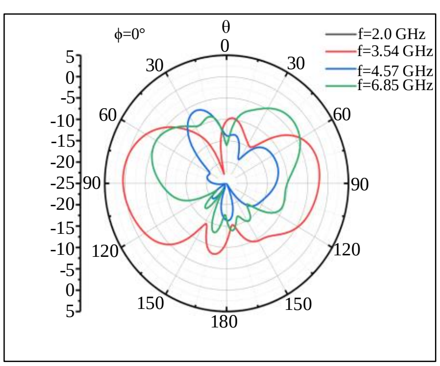
(a) XZ Plane



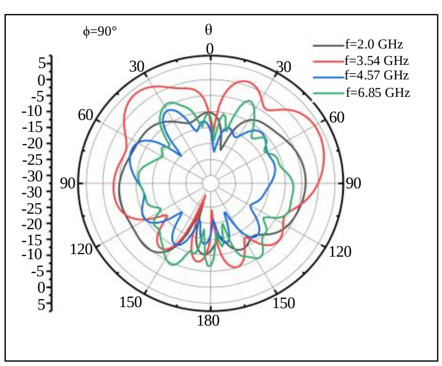
(b) YZ Plane



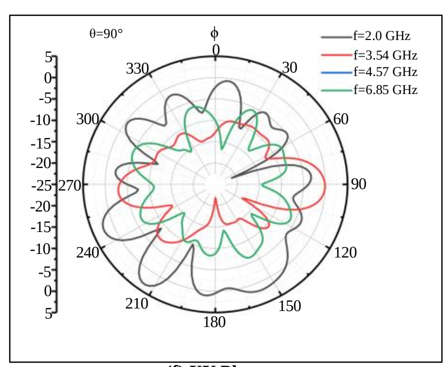
(c) XY Plane



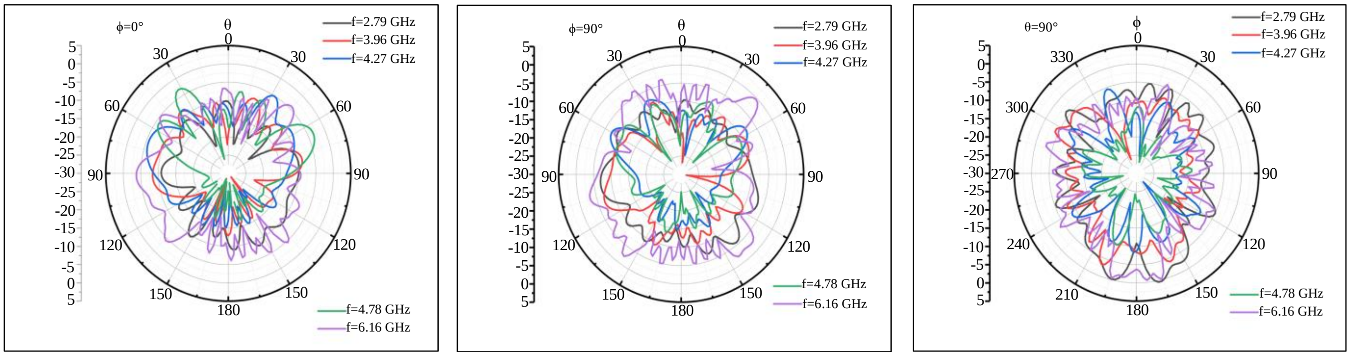
(d) XZ Plane



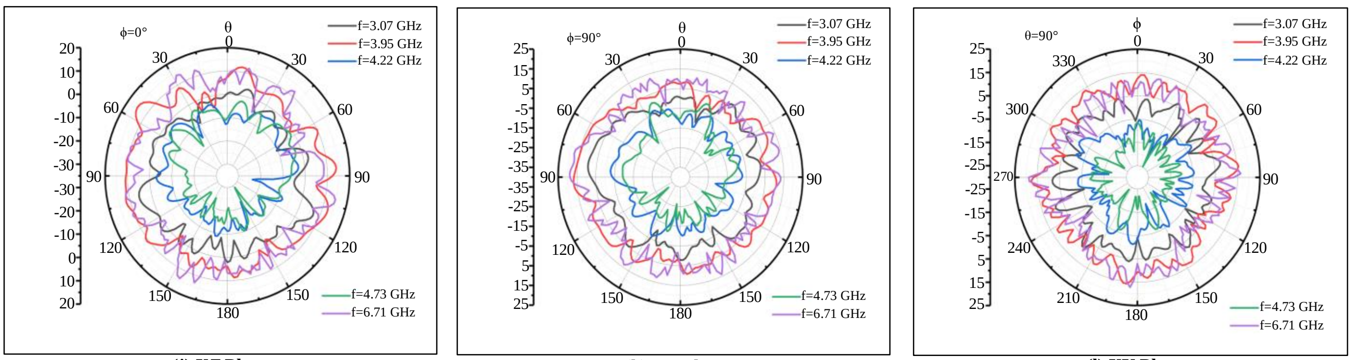
(e) YZ Plane



(f) XY Plane



(g) XZ Plane **(h) YZ Plane** **(i) XY Plane**



(j) XZ Plane **(k) YZ Plane** **(l) XY Plane**

Fig. 4 Radiation Pattern (a-c) Single element, (d-f) 2×2 array, (g-i) 4×4 array, and (j-l) The stacked 4×4 array.

Table 2. The S_{11} < -10dB bandwidth

Antenna Design	f_c (In GHz)	f_L (In GHz)	f_H (In GHz)	Bandwidth (In GHz)	S_{11} (In dB)	Peak Gain (In dB)
Single Antenna	2.34	2.30	2.37	0.07	-23.8	3.8
	4.54	4.52	4.58	0.06	-11.41	3.4
2×2 Antenna	2.0	0.56	3.9	3.34	-20.79	1.3
	3.54	3.30	3.70	0.3	-13.02	2.9
	4.57	4.41	4.63	0.22	-14.09	1.2
	6.85	5.93	8.0	2.07	-34.52	5.1
4×4 Antenna	2.79	1.86	3.61	1.75	-18.40	1.45
	3.96	3.84	4.07	0.23	-11.67	2.6
	4.27	4.14	4.44	0.30	-20.63	1.4
	4.78	4.73	4.83	0.10	-14.11	3.0
	6.16	4.91	8.00	3.09	-38.59	16.8
Stacked 4X4 Antenna	3.07	1.15	3.85	2.7	-36.88	10.6
	3.95	3.93	4.08	0.15	-20.6	18.6
	4.22	4.14	4.40	0.26	-32.54	1.7
	4.73	4.70	4.79	0.09	-13.98	1.3
	6.71	4.87	7.62	2.75	-19.08	18.8

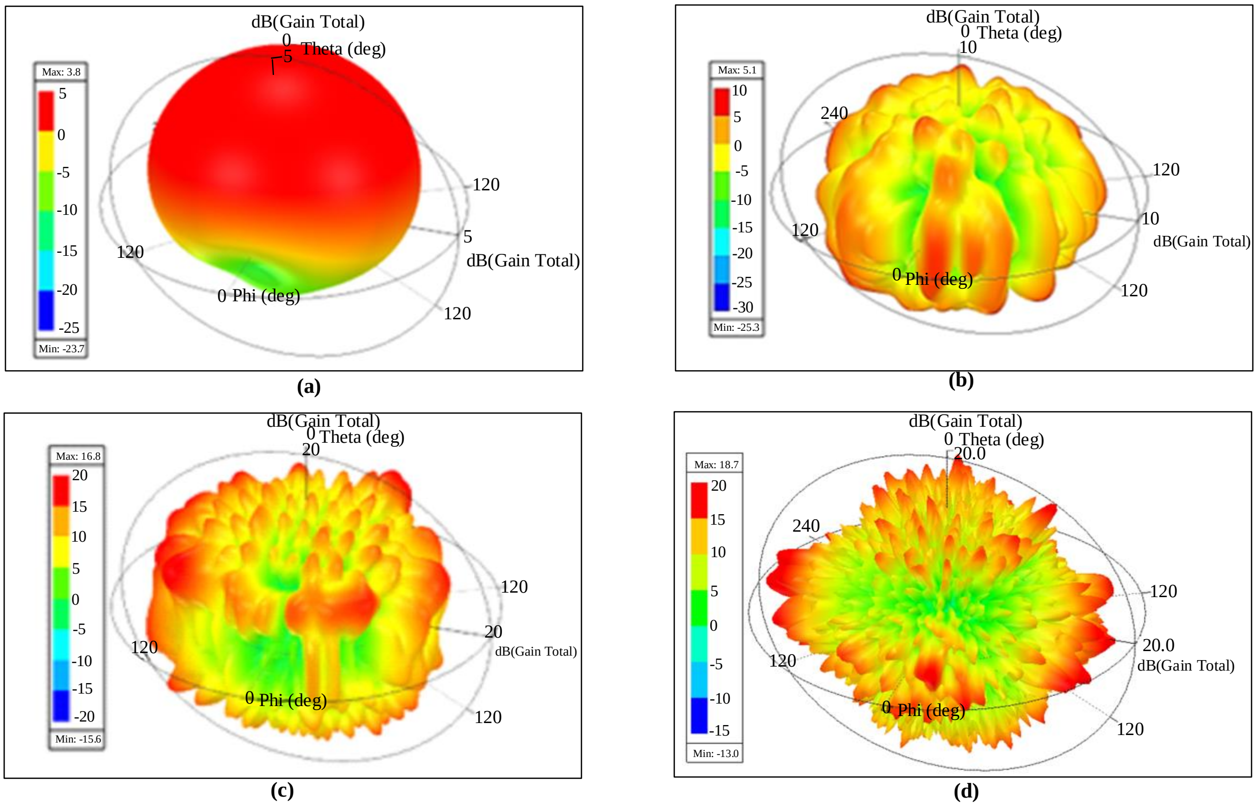


Fig. 5 The gain 3-D polar plots (a) single rectangular patch, (b) The 2×2 array, (c) The 4×4 antenna, and (d) The stacked 4×4 array antenna.

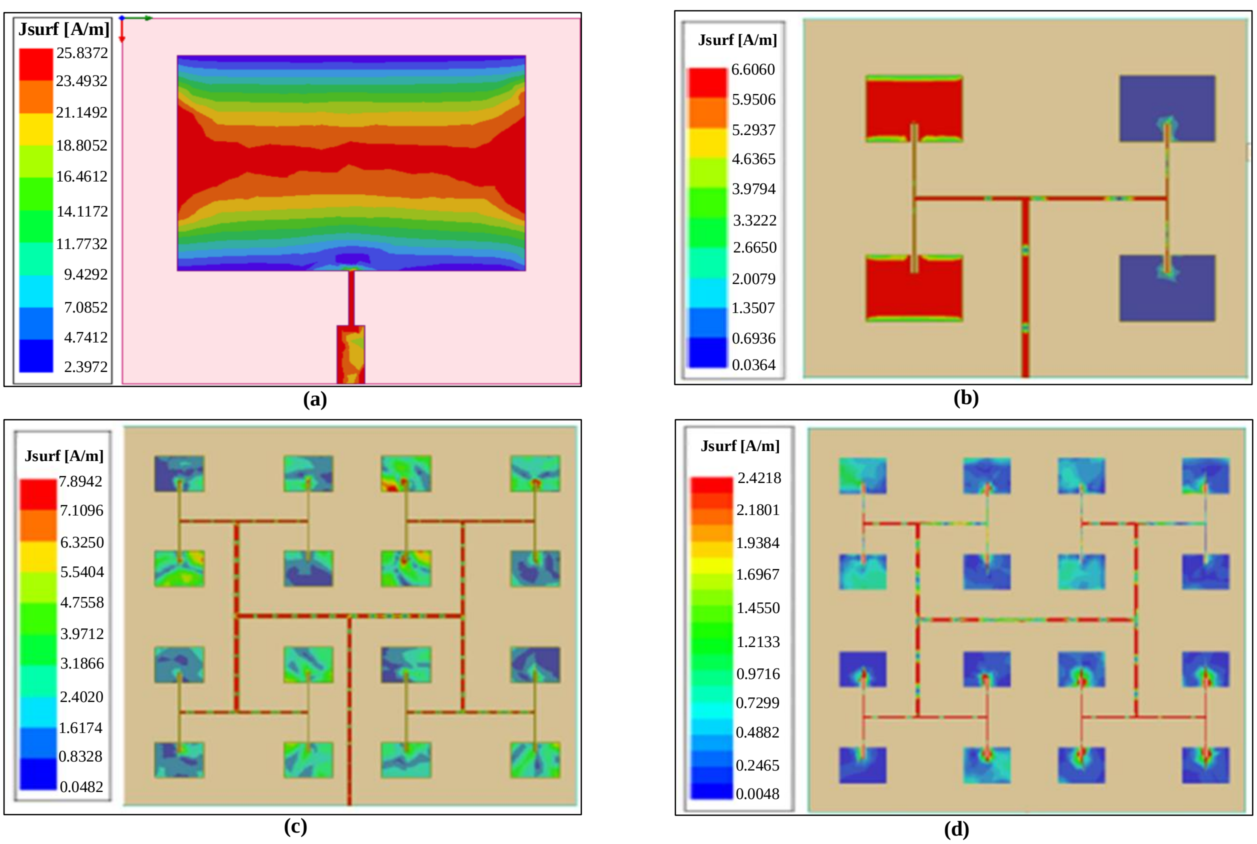


Fig. 6 The surface current density (a) Single patch antenna array, (b) 2×2 Array, (c) 4×4 Array, and (d) 4×4 Stacked array.

The gain 3D polar plots of single patch, 2×2 array, 4×4 and stacked array antenna are shown in Figure 5. The gain plot of a single antenna has a gain of 3.8 dBi and uniform gain over the upper sphere. For the 2×2 array, the gain increased to 5.1 dBi, and side lobes are observed. The possible reason for spiky radiation surface is the mutual coupling between elements.

Similarly, for the 4×4 array, the gain increased to 16.1 dBi, and side lobes are observed for the same reason. The single patch antenna surface current density, 2×2 array, 4×4 array and stacked 4×4 array are shown in Figure 6. For a single element, it is perceptible from the surface current distribution plot that the concentration decreases from the center to the edges.

The 2×2 array has maximum current density over the feed line and the patch. The 4×4 array has maximum current density over the feed line and over the patch. Similarly, stacked antennas have a maximum current density over the feedline and decrease over the patch surface.

4. Conclusion

The work presented a stacked array antenna for applications in the S and C bands. The initial stages of design include the design of a single patch antenna followed by 2×2 array and 4×4array. The antenna stacking is conceived by elevating the parasitic array over the base antenna array. FR-4 material is used for both base and parasitic patches for stable performance.

The antenna gains with an increase in no.of array elements. The stacked antenna has resonant frequencies at 3GHz, 3.95GHz, 4.22GHz, 4.73GHz and 6.71GHz and has gains of 10.6 dBi, 18.6 dBi, 1.7dBi, 1.3dBi, 18.8 dBi. The antenna array also maintained a good front-to-back ratio of over 20 dB. The surface current density plots show an even distribution of surface currents over the array elements.

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