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High Gain Beam Steering Antenna Arrays with Low Scan Loss for mmWave Applications

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ABSTRACT

In millimeter-wave (mmWave) communications, the antenna gain is a crucial parameter to overcome path loss and atmospheric attenuation. This work presents the design of two cylindrical conformal antenna arrays, made of modified rectangular microstrip patch antenna as a radiating element, working at 28 GHz for mmWave applications providing high gain and beam steering capability. The microstrip patch antenna element uses Rogers RO4232 substrate with a thickness of 0.5 mm and surface area of 5.8 mm × 5.8 mm. The individual antenna element provides a gain of 6.9 dBi with return loss bandwidth of 5.12 GHz. The first antenna array, made by using five conformal antenna elements, achieves a uniform gain of approximately 12 dBi with minimal scan loss for extensive scan angles. In the second antenna array, a dielectric superstrate using Rogers TMM (10i) was used to modify the first antenna array. It enhanced the gain to approximately 16 dBi while still maintaining low scan loss for wide angles. The proposed array design method is very robust and can be applied to any conformal surface. The mathematical equations are also provided to derive the array design, and both array designs are verified by using full-wave simulations.

Keywords: Microstrip antenna; Conformal antenna array; Phased array; Superstrate; Beam steering; Beam scanning

1. INTRODUCTION

In antenna arrays[1], multiple antennas are used to increase the gain in the desired direction instead of a single antenna. While antenna elements radiate individually but form constructive interference when placed in an array configuration at an optimised location and fed with proper phases. In this way, the radiations from all the elements sum up to form the beam in the desired direction with high gain and provide better performance with minimum losses. There are two types of antenna arrays, i.e., planar antenna arrays and conformal antenna arrays. Due to the inability to scan in all directions by a planar array, conformal antenna arrays have received broad interest in recent years because of their various advantages such as lower aerodynamic drag, reduced radar cross-section (RCS), enhanced angular coverage, and potentially lower installation costs. Low-profile microstrip patch antenna (MPA) elements are used as array elements as they can be easily mounted on a conformal surface using 3D printing technology. MPA arrays, conformal to curved surfaces viz. aerodynamic surfaces like supersonic aircraft or missiles, can be modelled approximately in the shape of a cylinder. Conformal antenna arrays fitted to the surface of a non-planar part of a modern aircraft, vehicles, or ships are considered an attractive alternative for specific applications where planar arrays or reflector antennas have definite drawbacks. The potential advantages of the conformal arrays are improved aerodynamics, increased payload, large field of view (LFOV), and low observability (LO). However, the usage of conformal array technology in commercial applications is still comparably rare. The circular cylindrical designs of recent antenna arrays on curved apertures in[2] and mostly exhibit a weak degree of curvature.

Nowadays, high data rate connections such as multimedia applications over a short-range drive interest in the mmWave range. The mmWaves correspond to a frequency range of 30 to 300 GHz. The mmWaves can propagate relatively short distances and do not propagate through solid obstacles. Nevertheless, mmWaves provide better spectrum utilisation[2]. The World Radio Communications Conference (WRC-15) identified frequency range from 24 GHz to 86 GHz for 5G studies[3]. Global researchers are showing their interest in the frequency spectrum of 28 GHz, 38 GHz, 60 GHz, and 73 GHz for usage in 5G systems[4]. These frequencies bands are used in the high-speed mobile communications, automotive radar, and 5G applications[5]. Several related antennas are developed in[6-10]. In[11], a 3×3 rectangular microstrip patch antenna array is described in which a rectangular patch is used and it achieved S_{11} bandwidth of ~2 GHz. In[12], an 4×4 E-shaped patch antenna array with a bandwidth of approximately 150 MHz is proposed at a frequency of 2.45 GHz. A dual-polarised dual-mode orbital angular momentum (OAM) microstrip antenna array is presented in[13] with bandwidth of 0.2 GHz.

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Two conformal five-element antenna arrays are presented in this manuscript. One of these two arrays has a superstrate to enhance the overall gain of the antenna array. Both of the designs can scan the beams up to 30° with low scan loss. In the following sections, first, we discuss a systematic study of antenna element design for these arrays which will help the readers to design similar arrays to an even wider scanning range. Next, we show how to calculate phase values for individual elements when arranged on the conformal surface. In the end, we conclude this work with results and concluding remarks.

2. ANTENNA CONFIGURATION

The design of radiating elements is one of the essential aspects of antenna array designs. The radiating element design starts with the selection of central frequency of the desired frequency range. Here, we took 28 GHz as the frequency of interest. Then, using[14], the dimensions of a typical rectangular microstrip antenna is calculated. However, a typical rectangular microstrip antenna has low impedance bandwidth. So, to increase the bandwidth of the rectangular microstrip antenna, the antenna shape is changed to square using the length of the rectangular antenna as the side of the square. But, even that does not provide the needed bandwidth. Next, we cut two notches near the corners for wide bandwidth. By cutting these notches, optimizing the whole square microstrip patch dimensions, and moving the feed at the optimised position, the modified rectangular microstrip patch antenna (MRMPA) is created as shown in Fig. 1. This modified radiating antenna element, also called as MRMPA, provides the required bandwidth.

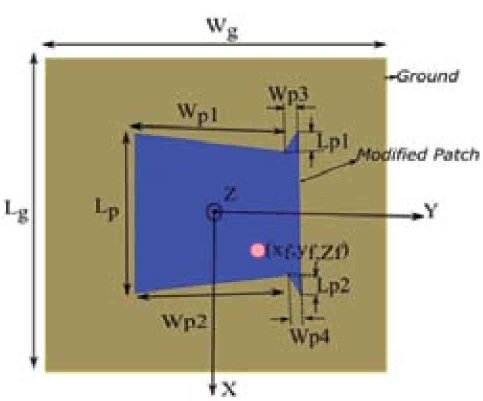

Figure 1. MRMPA antenna element.

The MRMPA is designed on a Rogers R04232 substrate with relative permittivity of 3.2 and tanδ of 0.0018 with a dimension of $L_g \times W_g \times h$ and a ground plane of $L_g \times W_g$. The antenna is excited using a coaxial probe feed at the location (x_f, y_f, z_f) as shown in Fig. 1. The numerical values of MRMPA are provided in Table 1.

The variation of W_{p1} yields $S_{11} = -10\,dB$ at $25.01\,GHz$ and the variation of W_{p2} along y-axis is responsible for the upper band of frequency of $S_{11} = -10\,dB$ at 30.12 GHz resulting in a total bandwidth of $5.12\,GHz$ as shown in Fig. 4. The designed antenna element has been working with $|S_{11}| \leq -10\,dB$ at a central frequency of 28 GHz with a bandwidth of 5.12 GHz

Table 1. MRMPA element dimensions

Parameter	Value (mm)	Parameter	Value(mm)
Lp	2.9	Wp4	0.12
Lp1	0.49	Lg=(Wg)	5.8
Lp2	0.49	h	0.5
Wp1	2.8	x_f	0.6
Wp2	2.78	y_f	0.6
Wp3	0.1	Z_f	0.5

3. PHASE CALCULATION FOR ARRAY ELEMENTS

In antenna arrays, each element's spatial distribution, phases, and magnitudes decide the array performance, so these should be optimally selected. It becomes even more important to take care of these parameters in the case of conformal arrays as spatial distribution depends upon the curvature of the conformal surface. Hence, to scan a beam of an array antenna placed on a curved surface, it is necessary to calculate optical path length from each antenna element to an aperture plane, the so-called 'equi-phase front'. To calculate phases of different array elements, we calculate the element positions on which the MRMPA antenna elements are mounted according to the geometrical approach. In this work, the array of antenna elements are placed on the periphery of cylindrical shape, as shown in Fig. 2. Five microstrip antenna elements are placed on locations L_2, L_1, C, R_1, and R_2 on the periphery of the cylindrical surface to form a five-element array. Using geometrical theory[15], we can derive the following equations:

$$(x_c, y_c, z_c) = (0, 0, R) \tag{1}$$

$$(x_{R1}, y_{R1}, z_{R1}) = (0, d/_2 + d/_2 \cos(\theta_{p1}), R - d/_2 \sin(\theta_{p1})) \tag{2}$$

$$(x_{R2}, y_{R2}, Z_{R2}) = (0, y_{R1} + d/_2 \cos(\theta_{p1}) + d/_2 \cos(\theta_{p2}), z_{R1} - d/_2 \sin(\theta_{p1}) - d/_2 \sin(\theta_{p2})) \tag{3}$$

$$(x_{L1}, y_{L1}, z_{L1}) = (0, -y_{R1}, z_{R1}) \tag{4}$$

$$(x_{L2,} y_{L2}, z_{L2}) = (0, -y_{R2}, z_{R2}) \tag{5}$$

where $d = \lambda/_2$ and R = radius of the circle, which can be calculated using the formula $R = \dfrac{d/_2}{\tan(\theta_p/_2)}$.

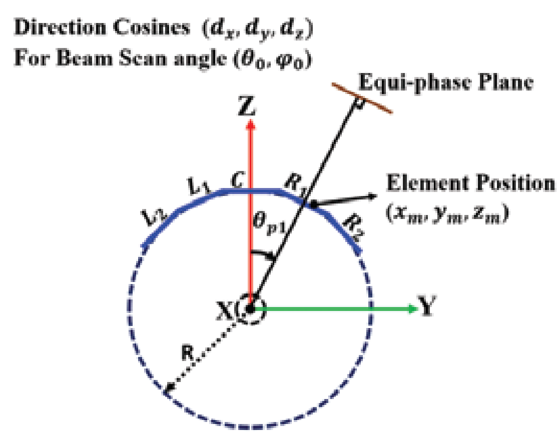

Figure 2. Geometry of MRMPA antenna array.

For further analysis, we consider an arbitrary conformal surface as mentioned in[15]. We express coordinates of antenna elements by (x_m, y_m, z_m), where m is the number of the corresponding elements. As shown in Fig. 2, the beam scanning direction is defined by (θ_0, φ_0) in spherical coordinate system. Therefore, the direction-cosines (d_x, d_y, d_z) are described as:

$$d_x = \sin\theta_0 \cos\varphi_0 \quad (6)$$

$$d_y = \sin\theta_0 \sin\varphi_0 \quad (7)$$

$$d_z = \cos\theta_0 \quad (8)$$

where (d_x, d_y, d_z) are the angles measured from the axis of rectangular coordinates (x, y, z), respectively.

Using these relations, an expression for a plane that is perpendicular to the beam direction, also called the equi-phase front S_0, is derived as:

$$d_x x + d_y y + d_z z = P_0 \quad (9)$$

where P_0 is the distance between the phase-front and coordinate origin. Using this relationship, path-length between the equi-phase plane and element position (x_m, y_m, z_m) is derived as:

$$P_m = \sin\theta_0 \cos\varphi_0 x_m + \sin\theta_0 \sin\varphi_0 y_m + \cos\theta_0 z_m \quad (10)$$

This length is obtained for a given array surface, and the phase for each element can be derived depending on the beam direction (θ_0, φ_0). For a cylindrical case, shown in Fig. 2, elements at locations L_2, L_1, C, R_1, and R_2 are placed at $\varphi = 90°$, i.e., along the y-axis at a radius R. So, the path difference can be expressed as:

$$p_d = d_x x_m + d_y y_m + d_z z_m - p_0 \quad (11)$$

Using the above equations, we can calculate the position of the elements. Next, using direction cosines, path length for each element radiation can be calculated. This calculated path length gives the particular phase values for each element when multiplied with wavenumber $(k = 2\pi/\lambda)$. For constructive interference where the array gives high gain, these phase values are appropriately selected.

4. ANTENNA ARRAY CONFIGURATIONS

To check the validity of the method described in section 3, a cylindrical five-element array is designed and simulated in Ansys HFSS full-wave simulator. Figure 3 shows the isometric view of the simulated structure. The central element is placed on the origin and all the other remaining four elements are placed along the y-axis, on either side of center elements along the y-axis, on either side of center elements at angles of $\pm 15°$, and $\pm 30°$ respectively. Each element is excited using a coaxial feed similar to Fig. 1. Each antenna element is spaced at a distance of $\lambda/2$ to avoid the grating lobes and ensure good isolation between antenna elements. The S-parameters of the single MRMPA element and five-element antenna array are presented in Fig. 4. It is evident from the figure that the bandwidth offered by the MRMPA antenna element is 5.12 GHz while it is 4.56 GHz for the five-element antenna array.

The mutual coupling between the center element C and element R_1 is provided in Fig. 4, which is less than -15 dB. For this array, a gain of 12.91 dBi, 12.63 dBi, and 12.22 dBi are achieved at the scan angles of 0°, 15°, and 30°, respectively as shown in Fig. 5. The remaining response parameters of the antenna array are presented in Table 2.

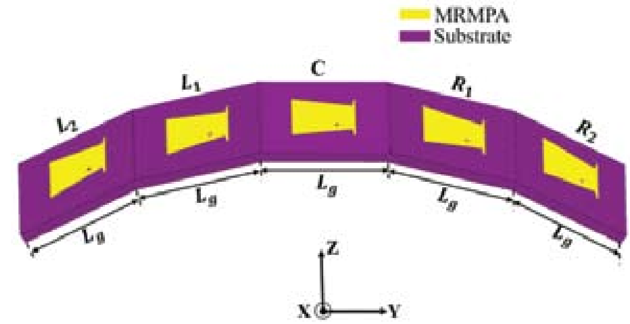

Figure 3. Five-element antenna array.

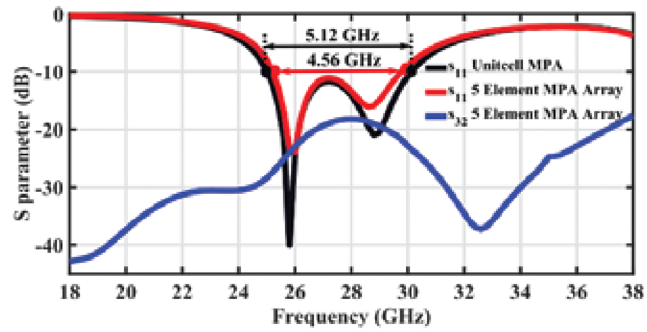

Figure 4. S-parameters for different structures.

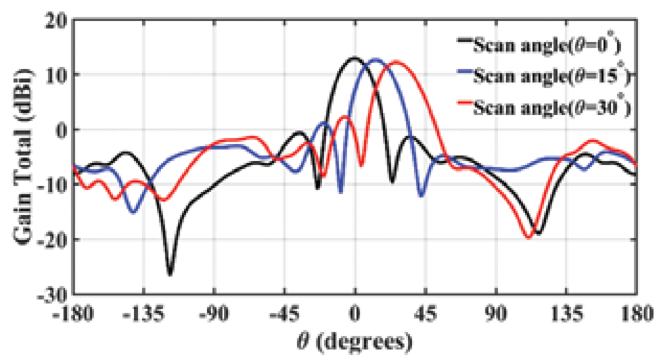

Figure 5. Beam scanning of a five-element array.

Table 2. Radiation properties of 5-element antenna array

Scan angle (deg)	Position of main lobe (deg)	Magnitude of main lobe (dBi)	Sidelobe level (dB)	3 dB beamwidth (deg)
0°	0°	12.91	13.54	20.19°
15°	13°	12.63	11.5	21.16°
30°	25°	12.22	9.94	22.85°

5. GAIN ENHANCEMENT OF FIVE ELEMENT ANTENNA ARRAY WITH SUPERSTRATE

The superstrate placement is a well-established theory defined by the Fabry–Pérot principle[10] to increase the antenna gain. However, it is mostly used for planar superstrate. In our case, we use the preliminary guiding principles of Fabry–Pérot design and later optimise it for conformal superstate. Like any design, simulations with optometric variations are run and the desired result (here gain) is tracked. Once the desired results are achieved, the particular design parameters for those results is selected. Next, we look into the gain enhancement by introduction of the superstrate.

The five-element antenna array is formed along $\varphi = 90°$ i.e., along the y-axis and each MRMPA element is placed at the positions at an angle of 0°, ±15°, and ±30° with a center element at 0° as shown in Fig. 6. The Rogers TMM (10i) dielectric, which has $\varepsilon_r = 9.8$ and loss tangent of 0.002 is used as a superstate at an optimised height of h_s =5.4 mm from the surface of the antenna array with a thickness of th_s =1.7 mm. Figure 7 shows the scanning behaviour of this array. The gain values of 16.10 dBi, 15.81 dBi, and 15.06 dBi are achieved at the scan angles of 0°, 15°, 30°, respectively, as shown in Fig. 7.

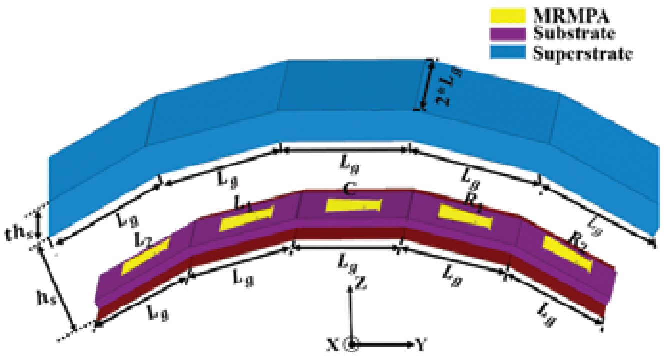

Figure 6. Five-element array with superstate.

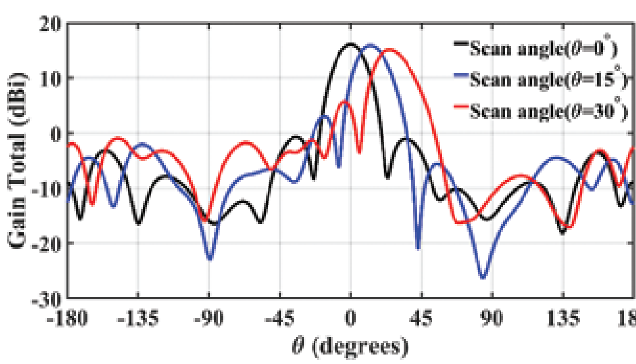

Figure 7. Beam scanning of a five element array with super state.

In this way, it is evident that the array yields a high gain with shallow scan loss up to 30°. So, there is a gain improvement of approximately 3 dB for an array with a superstrate as compared to a similar array without a superstrate. Other parameters such as main lobe level, side lobe level, 3 dB beamwidth are listed in Table 4.

Table 4. Radiation properties of 5-element antenna array with superstrate

Scan angle (deg)	Position of main lobe (deg)	Magnitude of main lobe (dBi)	Side lobe level (dB)	3 dB beamwidth (deg)
0°	0°	16.02	16.71	18.55°
15°	13°	15.81	12.78	19.13°
30°	25°	15.06	9.50	17.53°

Table 3. Comparison with the existing works

Ref.	S_{11} Bandwidth (GHz)	Area (L×W) mm²	No. of Elements	Gain (dB)
[11]	2	9.1×6.7	3×3	17.29
[12]	0.15	29.1×29.1	4×4	12.01
[13]	0.2	120×112	2×2	9.5
[16]	2	30×30	2×2	5.5
[17]	2.5	30×30	2×2	7.5
[18]	2.3	70×63.5	1×8	13.97
[19]	0.5	18×26.5	1×4	12
[20]	3	26.9×19.5	1×4	10.3
This work	**4.56**	5.8×29	1×5	**12.91 and 16.71 (with superstrate)**

6. RESULTS AND DISCUSSION

Both five-element antenna arrays presented in the previous sections show low scan loss for scan up to ±30°. The antenna array without superstrate shows a scan loss of ~0.7 dB, while the one with the superstrate shows scan loss of ~1 dB. The array with low gain, i.e., array without superstrate, also showed wider beamwidth as compared to the antenna array with superstrate (see Table 2 and Table 4). It is also important to note that the theoretical values of beam steering angles match well with the simulated main beam within an error of 5°. It is also evident from Tables 2 and 4 that the sidelobe level increases for wider scan angles. Overall, both arrays have good performance and can be used for modern applications such as 5G, where beam steering principles are used. Table 3 presents the comparison of the proposed work with the existing work reported in the literature. The suggested antenna array has minimal size when compared to the ones that have been published, and it has a very excellent bandwidth and gain. In summary, the main novelty of the proposed work is the simultaneous achievement of wide-bandwidth (4.56 GHz), more than 12 dBi gain, with low sidelobes in the radiation pattern, which qualifies our proposed design as a competent candidate for future 5G applications based on mmWaves.

7. CONCLUSION

Two five-element antenna arrays conformal to cylindrical surfaces were presented. The first antenna array provides gain of approximately 12 dBi while another array, with superstrate, provides gain of approximately 16 dBi. Both the arrays have low scan loss. The theoretical design methodology of both the arrays was provided and verified with full-wave simulations.

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Contribution in the current study, he verified the methods and results and involved in results discussion.