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Series Fed Designs of Planar Circular and Hexagonal Microstrip Antenna Arrays for High Gain and Reduced First Side Lobe Level Radiation

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***Abstract*— To achieve a high gain and low first side-lobe level, variants of linear and planar series fed circular and hexagonal microstrip antenna arrays using the binomial distribution, are proposed around 3000 MHz frequency band, on thinner Arlon substrate (h ~ $0.027\lambda_g$). The linear 7 × 1 array of circular patches, yields first side-lobe level of -25 dB with a gain of 12.7 dBi, whereas using hexagonal patches, respective values are, -28 dB and 12.9 dBi. The planar 5 × 3 and 5 × 5 arrays using half wavelength and wavelength spacing are presented. An optimum response is obtained in 5 × 5 array for the wavelength inter-element spacing. Here, using circular patches, first side lobe level in the E and H-planes is -29 and -14 dB, respectively, with a peak gain of 17.6 dBi, whereas that using hexagonal patches, the respective first side lobe level in the E and H-planes is -26 and -17 dB, with a peak broadside gain of nearly 19 dBi. Thus using a thinner substrate, proposed series feed binomial planar arrays offer a gain of more than 15 dBi with a lower first side lobe level.**

***Index Terms* —** Microstrip Antenna Array, Binomial Distribution, First Side Lobe Level, Circular Microstrip Antenna, Hexagonal Microstrip Antenna.

I. Introduction

In modern day communication systems, series fed microstrip antenna (MSA) array finds its place in many applications such as airborne radar, microwave link, satellite communication, etc. The series fed MSA array has the advantages such as low profile, ease of integration with RF circuits and compact size due to the simple series feeding technique. In the array designs, first side lobe level (FSLL) parameter plays an important role in reducing the interference from the nearby communication channel. One of the techniques to lower the FSLL is the current amplitude tapering. Generally, it is realized by applying appropriate input power according to the pre-defined amplitude weighting function to the antenna array elements [1]-[2]. A series fed tapered MSA array is designed with a recessed microstrip-line feed to the terminal element, to provide improved VSWR characteristics and FSLL of -14 dB [3]. The FSLL reduction is also achieved by employing unequally spaced array elements [4]-[6]. However, this technique requires a high accuracy complex algorithm to find the

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inter-element spacing. A series fed eight-slot MSA array designed by adjusting the impedance of the series fed line in between the slots, offers a gain of 10.9 dBi and FSLL of -19 dB [7]. A planar MSA array with a series-parallel slot coupled feeding network is proposed with FSLL of -17 and -23 dB in E and H-planes, respectively [8]. A 2 × 8 MSA array is realized by using the slot coupler-based three-way power divider fed linear array, offering FSLL of -15 and -12 dB in the E and H-planes, respectively [9]. A corporate feed 8 × 4 planar array is implemented with sub arrays of 2 x 2 corporate fed array using the Dolph Tchebysheff amplitude distribution to yield FSLL of -19 and -17 dB in the E and H-planes, respectively [10]. A stacked series fed MSA array is presented with a T-shape and inter-digital microstrip transmission lines to provide a gain and FSLL of 13.5 dBi and -20 dB respectively [11]. A 3 × 3 parasitically coupled array of identical rectangular patches with microstrip lines for further coupling of patches is designed to provide FSLL of -13 dB [12]. In [13], an 8 × 8 microstrip array is designed to obtain FSLL of -20 dB in the E and H-planes using eight 8 x 1 sub arrays and parallel unequal power dividers. A series fed planar array is designed to provide FSLL of less than -23 dB in the E and H-planes using the tapered patch width array elements and an impedance matching stub [14]. An 8 × 6 corporate fed planar array is designed using six element series fed sub array with Taylor distribution to provide -20 dB and -15 dB of FSLL in the E and H-planes, respectively [15]. A series and corner fed planar microstrip array is proposed for the broadside radiation pattern with FSLL of -14 dB in the E and H-planes [16]. In [17], cosine-square distribution over the pedestal distribution is used to realize amplitude tapering in the E and H planes, giving FSLL of -18 dB and -15 dB, respectively. Series fed Binomial array using non-identical rectangular MSAs is designed to yield FSLL of -28 dB in both the principal planes with broadside gain of 12.8 dBi [18]. In [19], 16 × 32 comb-line fed microstrip antenna array is designed using the Chebyshev window function. This structure provides a broadside gain of 24.6 dBi with FSLL of -20.8 dB and -16.4 dB in E and H-planes respectively. Thus, various combinations of series fed array designs are reported using non-uniform distribution, but they offer either higher gain or lower side lobe levels. Design featuring both the parameters optimized together is not widely discussed. Thus, there is a need for simpler array designs that offer reduced FSLL with a higher gain, without much increase in the antenna size.

In this paper, various series fed linear and planar circular MSA (CMSA) and hexagonal MSA (HMSA) array designs to achieve lower FSLL with relatively higher gain are presented. The array configurations are discussed around the single patch resonance frequency of 3000 MHz using Arlon substrate (ε_r = 3, h = 0.153 cm, tan δ = 0.002). A binomial distribution is realized in CMSA and HMSA array elements by truncating the top and bottom portions of the patches according to the array element weight. To keep the overall array size smaller, linear binomial series fed CMSA and HMSA arrays are designed using series U-shape microstrip line feeds. In the linear design, on a thinner substrate, an optimum response is obtained in 7 × 1 array. Using the circular patches, FSLL here is -25 dB with a gain of 12.7 dBi, whereas using hexagonal patches, respective values are, -28 dB and 12.9 dBi.

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Further series fed planar binomial CMSA and HMSA arrays are designed by using U-shape series feeds along the E-plane and microstrip line feeds of either half wavelength ($\lambda_g/2$) or wavelength (λ_g) in length, along the H plane. In the planar designs, 5 × 3 and 5 × 5 arrays are investigated. Due to the larger aperture area, optimum results are obtained in 5 × 5 array using a wavelength spacing. In 5 × 5 array using circular patches, FSLL of -29 dB and -14 dB in the E and H-planes is obtained with a broadside peak gain of 17.6 dBi. The 5 × 5 array design using hexagonal patches provides FSLL of -26 dB and -17 dB in the E and H-planes, respectively. It yields a broadside peak gain of 18.9 dBi. Thus, in terms of realized FSLL and peak gain, proposed array designs optimized on thinner single substrate offers better results as compared with the reported series fed variations. A detailed comparison highlighting the same is presented further in the paper. The MSA arrays presented in this paper are first simulated using CST software for different antenna parameters [23]. Antennas are fed using SMA panel type connector with 0.12 cm inner wire diameter. The experimental validation for the proposed designs was carried out inside the Antenna Lab using high frequency instruments namely, ZVH–8, FSC 6 and SMB–100A. For the pattern and gain measurements, reference wideband Horn Antennas were used. The gain is measured using the three-antenna method for better accuracy. A close matching between the simulated and measured results is obtained in all the binomial array variants.

II. LINEAR AND PLANAR SERIES FED CMSA ARRAYS USING BINOMIAL DISTRIBUTION

In antenna, a Fourier transform relation exists between the radiation pattern and the spatial current (aperture) distribution. The fundamental property of the Fourier Transform points out that any sudden change in the function or derivatives, introduces a significant ripple in the transform domain. In the case of a uniform distribution array, sudden change in the current at the ends results in the side lobe in the radiation pattern plot. The reduction in the abruptness in the current distribution thus can reduce the side lobe level. For the spatial current distribution across various patches in the array design, various amplitude distribution window functions such as triangular and binomial are used. The present paper applies the binomial distribution approach. A series fed linear CMSA array is designed using the binomial distribution window function around the TM_{11} mode frequency of 3000 MHz on Arlon substrate, as shown in Fig. 1(a). For this frequency, initially the central patch radius (r) is calculated [20]. The binomial CMSA array is realized by evaluating the normalized coefficients to design each array element using binomial expansion function $(1+x)^{m-1}$ as given in equation (1) [21]. Here ‘m’ is the number of array elements. Three array variations, 3 × 1, 5 × 1 and 7 × 1, have been studied for the gain and FSLL optimization. For each array order, the total number of array elements using the binomial distribution coefficients is calculated separately.

$$(1+x)^{m-1}=1+\frac{(m-1)x}{1!}+\frac{(m-1)(m-2)x^2}{2!}+\dots \tag{1}$$

The central array element is designed to operate at the maximum gain. The gain of the adjoining elements is reduced as per the binomial distribution. For m = 7, i.e., 7 × 1 array, the array element

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width w_j (j = 1, 2, 3) of the CMSAs have been varied to realize array elements whose gains are proportional to the normalized binomial distribution coefficients, 0.05, 0.3, 0.75, 1.0, 0.75, 0.3, 0.05. Here 1 is for the coaxially fed central element. The variation in w_j alters the gain of each element. To obtain this width tapering as per the above coefficients, the top and bottom portions of the series fed CMSAs are cut horizontally. As each CMSA array element is truncated symmetrically, their resonance frequency decreases. This frequency reduction is attributed to more amount of fringing fields from the patch boundaries. Therefore, the radius of truncated CMSA array elements is tuned further to radiate all the elements at the same operating frequency as that of the central element. All the array elements are needed to be excited in the same phase to get the broadside radiation pattern. As the CMSA exhibits 180^0 phase shift between the diametrically opposite points along the coaxial feed axis, the array elements are series fed using U-shape microstrip lines which are a half wave in length. The dimensions of U-shape microstrip line (w_h, l_1, l_3) are calculated by noting the edge impedance of every patch and the operating frequency. Here instead of a straight line, U-shape lines are employed, which makes the linear array compact in size. The 90^0 step turn in U-shape line can affect its impedance, but this effect is taken into consideration while doing impedance optimization.

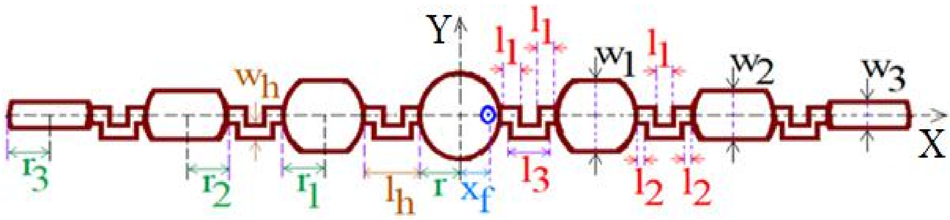

Fig. 1. Linear series fed 7 × 1 binomial CMSA array (dimensions in mm).

The total U-shape feed line length is 21 mm corresponding to the $\lambda_g/2$ at the operating frequency. Starting with a single patch, 3 × 1, 5 × 1 and 7 × 1 linear series fed arrays are studied for the gain and FSLL. The results for these arrays using linear and binomial distributions are compared in Table I. At the cost of gain reduction, the binomial distribution array offers lower FSLL. Also, FSLL decreases with an increase in the number of the binomial array elements. An optimum result is obtained in 7 × 1 array for the antenna dimensions as, $r = 16$, $r_1 = 15.5$, $r_2 = 15$, $r_3 = 14.75$, $w_1 = 25$, $w_2 = 17$, $w_3 = 8$, $l_1 = 7$, $l_2 = 3$, $l_3 = 15$, $w_h = 4$, $l_h = 21$, $x_f = 8$. The antenna dimensions mentioned in this paper are in mm and frequency is in MHz. The simulated peak gain and FSLL in the 7 × 1 array are 12.7 dBi and -25 dB. The measured values of the gain and FSLL are in close agreement with the simulated values. In the binomial distribution, the normalized binomial coefficients value is very small for the fourth element to realize a 9 × 1 array, where it becomes much lesser than the U-shape line width. Hence that array design is not considered in the present study.

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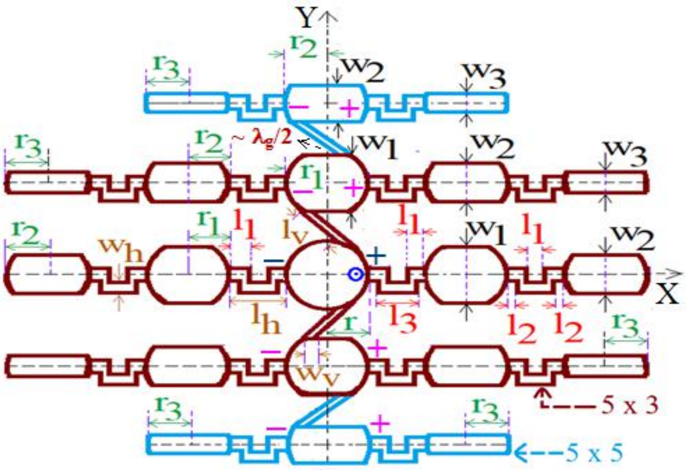
TABLE I. COMPARISON FOR SERIES FED CMSA ARRAYS FOR LINEAR AND BINOMIAL DISTRIBUTION

Configuration	Amplitude Distribution	Peak gain (dBi)	FSLL (dB)
3 × 1	Linear	10.8	-13
3 × 1	Binomial	10.6	-14
5 × 1	Linear	12.8	-13
5 × 1	Binomial	11.6	-22
7 × 1	Linear	14.0	-14
7 × 1	Binomial	12.7	-25

In order to increase the gain with lower FSLL in the principle planes, planar binomial CMSA arrays are studied. In the planar arrays, the amplitude tapering is to be realized along both the axis. As the fourth element size as per binomial distribution is not realizable, to realize various planar arrays, the central linear sub array is taken as 5 × 1. The planar CMSA arrays are designed using either half wavelength or wavelength spacing in between the linear sub arrays placed along the Y-axis. This spacing is selected since the mutual coupling is smaller for these spacing values. The series feed excitation method is used in both E and H-planes. The planar binomial array realized by connecting U-shape feed lines in the E-plane (X-axis), and nearly half wavelength microstrip lines in the H-plane (Y-axis), is shown in Fig. 2 (a).



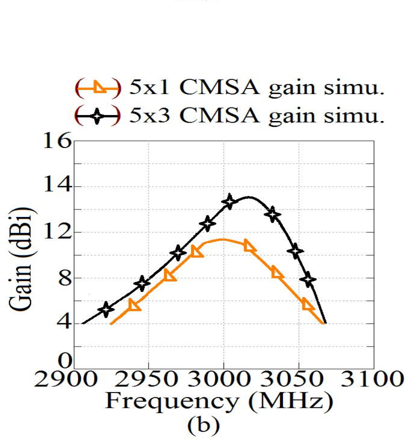


Fig. 2. (a) Planar binomial CMSA array with '$\lambda_g/2$' spacing, (b) gain plots for 5 × 1 and 5 × 3 CMSA array.

In 5 × 1 array, amongst the five elements, the normalized binomial distribution coefficients are selected as 0.16, 0.66, 1, 0.66, 0.16, to keep the gain of array elements with respect to the central element. These distribution coefficients are different as compared to the above linear array as 5 elements are present in the planar case as against 7 in the linear array. The length of U-shape line and half wavelength microstrip line (l_v) along the two axes is 21 and 28 mm, respectively. The length l_v excites upper and lower linear sub arrays. The zigzag connection of the line l_v ensures the same polarity of the TM_{11} mode fields on all the patches connected along Y-axis [18]. The dimensions of the microstrip line along the Y-axis are calculated as per the edge impedance present at the connecting point on the patch and the operating frequency. This planar array is optimized for two variations, 5 × 3 and 5 × 5. In 5 × 5 array, three elements are present in the top and bottom sub arrays as shown in Fig. 2(a), as for the last element in them, the binomial amplitude coefficient value for the patch width w_4 is very small and thus not realizable. The dimensions in optimized 5 × 3 array are; $r = 16$, $r_1 = 15.5$, $r_2 = 15$, $r_3 = 14.75$, $w_1 = 24$, $w_2 = 13.5$, $w_3 = 8$, $l_1 = 7$, $l_2 = 3$, $l_3 = 15$, $w_h = 4$, $w_v = 4$, $l_v = 28$, $x_f = 13$. The simulated and measured BW for 5 × 3 array are 23 MHz and 20 MHz, respectively. It gives a simulated peak gain of 15.2 dBi as shown in Fig. 2 (b), with FSLL of -21 and -14.5 dB in E and H-plane respectively. The measurement has been carried out to validate the simulated result, which shows close agreement. As compared with the 5 × 3 array, optimized variation of 5 × 5 planar array contains additional sub array. The simulated and measured return loss (S_{11}) plots, gain variation over the frequencies and the radiation pattern at the center frequencies, is shown in Figs. 3 and 4.

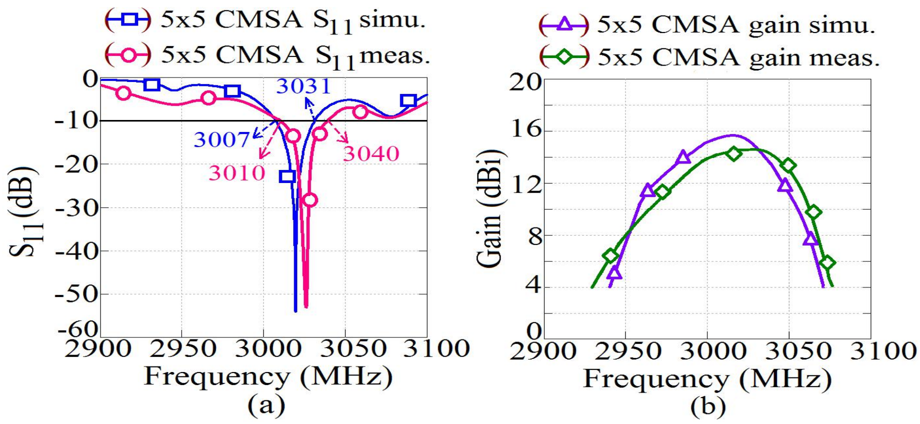


Fig. 3. (a) Reflection coefficient plots for the planar binomial CMSA array with $\lambda_g/2$ spacing and its (b) gain plots.

The simulated and measured BW for $S_{11} \leq -10$ dB are 24 MHz and 30 MHz, respectively. The simulated and measured values of the peak gain in 5 × 5 planar binomial CMSA array are, 15.6 and 14.8 dBi, respectively. The simulated and measured the radiation pattern plots at the center frequencies shows simulated and measured FSLL in E and H-planes as -26 dB, -22 dB and -24 dB, -21 dB, respectively. The 5 × 5 array shows a broadside radiation pattern with half power beam width (HPBW) of 20° and 35° in E and H-planes, respectively. Thus 5 × 5 planar array yields higher gain with lower FSLL.

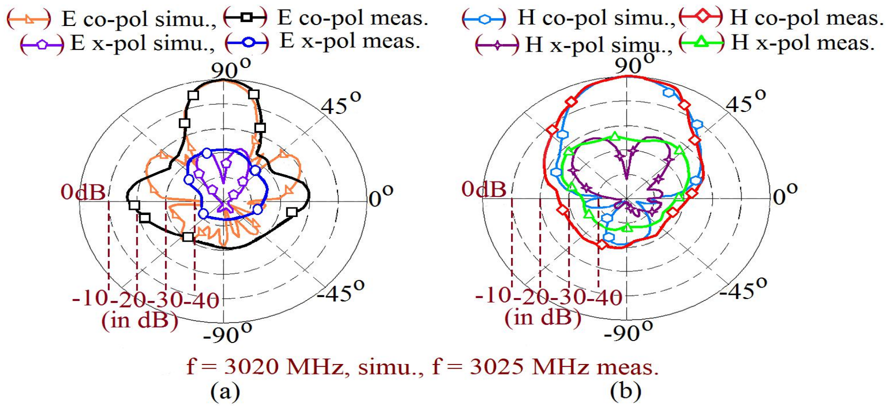


Fig. 4. (a), (b) Radiation pattern at the center frequency of the BW for 5 × 5 planar binomial CMSA array with $\lambda_g/2$ spacing.

Further similar planar array configuration is investigated for wavelength λ_g spacing in between the sub arrays as shown in Fig. 5 (a). In this design, length (l_v) and width (w_v) of the microstrip lines feeding the sub arrays along the Y-axis is 56 mm and 4 mm respectively. The 5 × 3 and 5 × 5 arrays using λ_g spacing is optimized for the broadside gain and FSLL. All the antenna dimensions except the microstrip line length along the Y-axis of the array, are the same to that present in 5 × 5 and 5 × 3 array designs using $\lambda_g/2$ spacing.

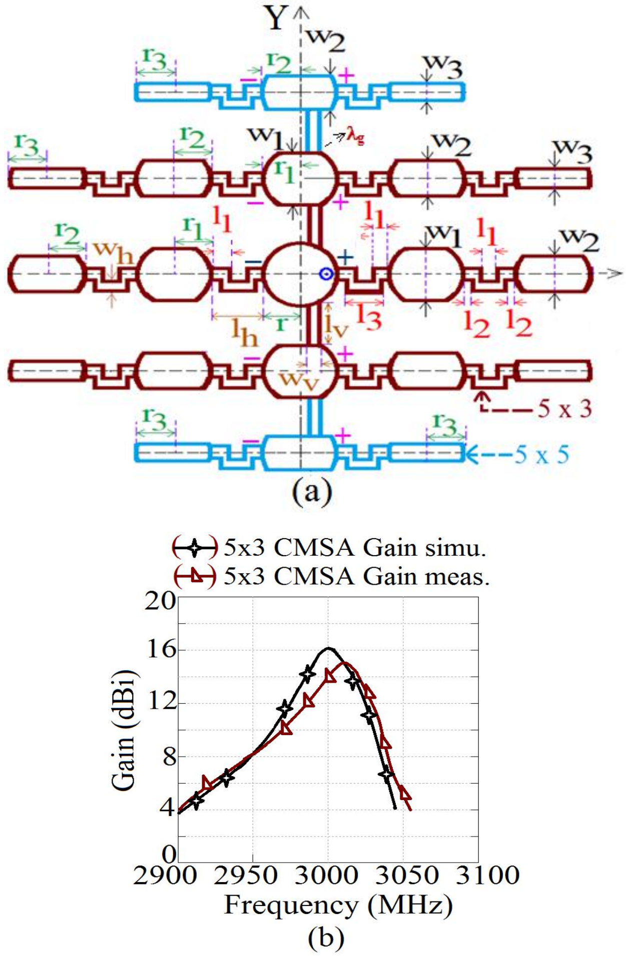


Fig. 5. (a) Planar CMSA array using λ_g spacing and (b) gain plots with λ_g spacing for 5 × 3 CMSA array.

The simulated and measured gain variation over the BW for 5 × 5 CMSA array and S_{11} plots are shown in Fig. 6 (a) and (b). In 5 × 3 and 5 × 5 arrays, simulated and measured BW for $S_{11} \leq -10$ dB, is around 15 MHz and 13 MHz respectively.

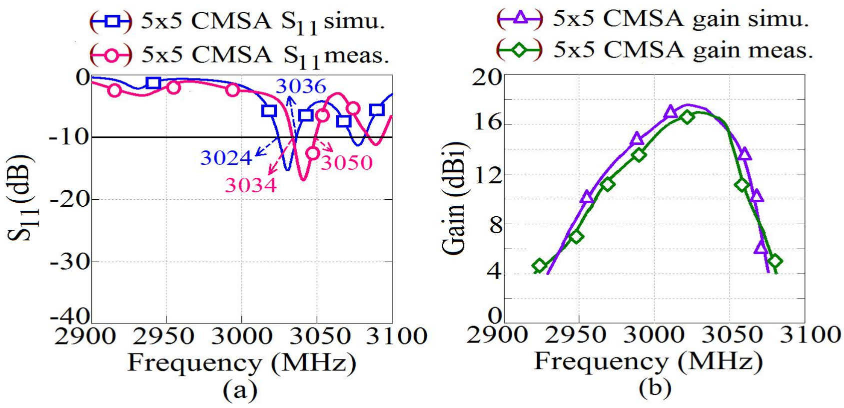


Fig. 6. (a) S_{11} with λ_g spacing for 5 x 5 CMSA array and its (b) gain plots.

The simulated and measured radiation pattern plots at the center frequency of BW, for 5 × 3 and 5 × 5 CMSA arrays are shown in Fig. 7(a)–(d). The radiation pattern in both the cases is in the broadside direction with E and H-planes aligned along with $\Phi = 0^0$ and 90^0, respectively.

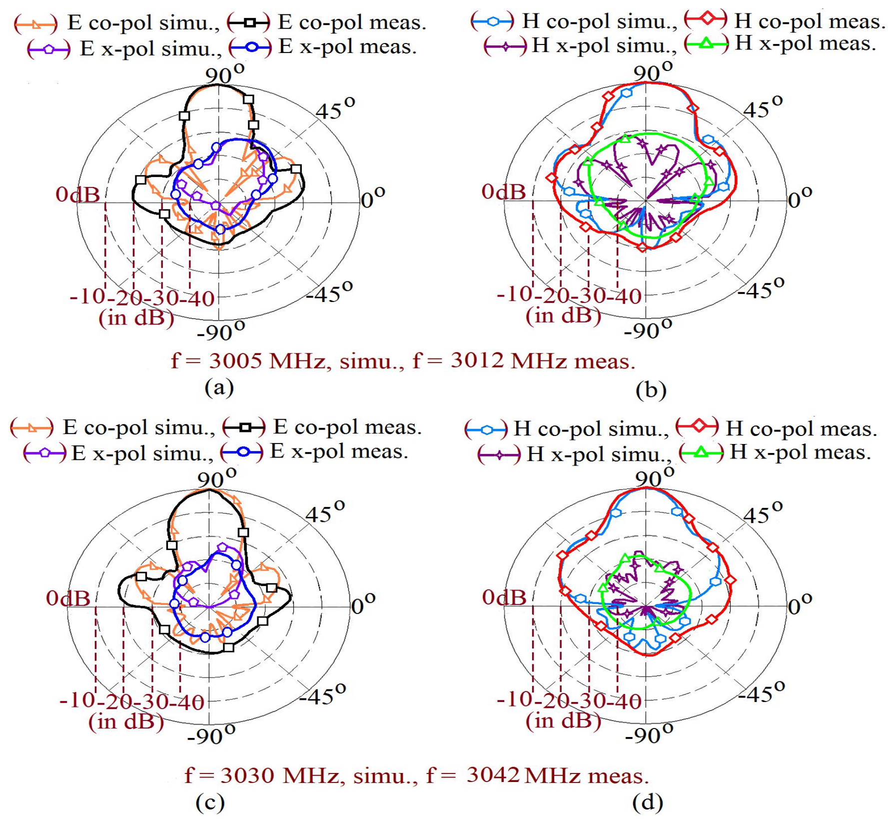


Fig. 7. (a), (b) Radiation pattern at the center frequency of BW for 5 × 3 and (c), (d) for 5 × 5 CMSA arrays.

The broadside simulated and measured gain realized in 5 × 5 CMSA array is 17.7 dBi and 17 dBi, respectively. Since only one additional sub array on either side is introduced in 5 × 5 array as against

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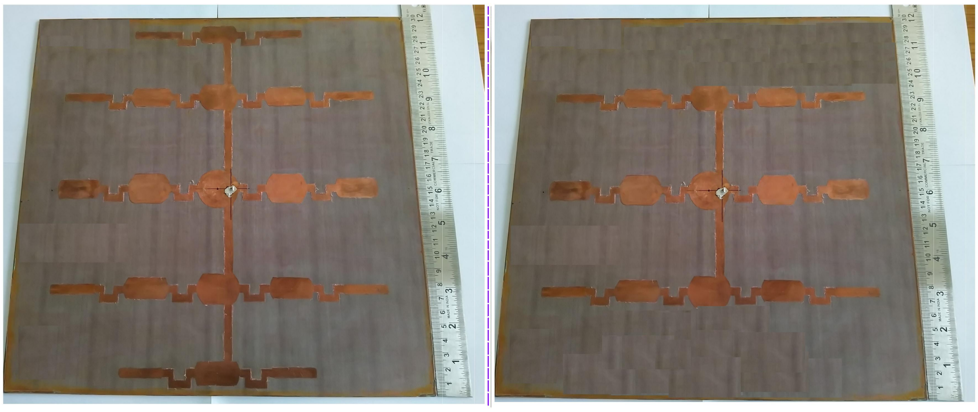
5 × 3 array, increase in the gain is only by 1 dBi. However, with reference to the half wavelength spacing between sub arrays, this array design offers higher gain. The fabricated antenna prototypes using wavelength spacing sub arrays in 5 × 3 and 5 × 5 designs are shown in Fig. 8(a) and (b).



5 x 5 CMSA array
(a)

5 x 3 CMSA array
(b)

Fig. 8. Fabricated prototype of (a) 5 × 5 and (b) 5 × 3 CMSA arrays.

III. LINEAR AND PLANAR SERIES FED HMSA ARRAYS USING BINOMIAL DISTRIBUTION

The resonant modes in HMSA are similar in variations to the resonant modes present in CMSA [22]. Therefore, linear series fed variations of HMSA using binomial distribution are studied. On Arlon substrate, dimensions of single regular HMSA, *i.e.*, its side length S and length L are optimized for the fundamental mode frequency of 3000 MHz. For this frequency, S is found to be 17.32 mm and L equals 30 mm. Starting with this single element, 3 × 1, 5 × 1 and 7 × 1 linear series fed variations are realized by employing the binomial distribution. The 7 × 1 configuration is shown in Fig. 9. All the array elements are excited in the same phase by using U-shape microstrip lines of length $\lambda_g/2$. The central HMSA is designed to offer maximum gain.

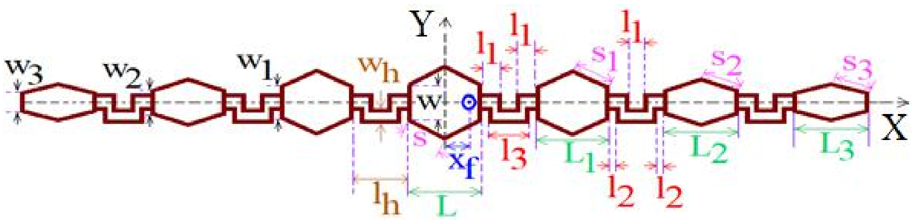


Fig. 9. Linear series fed 7 × 1 binomial HMSA array.

To obtain the required tapering across the array elements in terms of the element gain, width w_j of the series fed HMSAs is modified. As the 7 × 1 array yields optimum gain in the linear array design, the parametric optimization procedure is explained here for the same. Similar to the CMSA design, in 7 x 1 design, array elements are designed such that their gains are proportional to the normalized binomial distribution coefficients, 0.05, 0.3, 0.75, 1, 0.75, 0.3, and 0.05. These coefficients are calculated for m= 7, using (1). Since the width of HMSAs (w_j) is tapered according to the binomial distribution coefficients, respective patch frequency changes. Therefore, to ensure the same operating frequency across all the array elements, length of the HMSAs in a series fed array is adjusted to radiate all the elements in the same phase and frequency. This optimization procedure leads to the design of 7 × 1 array, which consists of regular HMSA as the fed element, and irregular HMSA (where six side lengths and their subtended angle are not the same) as the series fed elements. The various antenna dimensions in the optimized design of 7 × 1 array are, $L = 30$, $L_1 = 30.5$, $L_2 = 31.5$, $L_3 = 32$, $w = 17.32$, $w_1 = 16$, $w_2 = 9$, $w_3 = 6$, $S = 17.32$, $S_1 = 17.22$, $S_2 = 16.38$, $S_3 = 16.3$, $l_1 = 7$, $l_2 = 3$, $l_3 = 15$, $w_h = 4$, $x_f = 8$. This optimized 7 × 1 linear binomial HMSA array yields a peak gain of 12.9 dBi with FSLL -28 dB. These values are better as compared to that observed in 7 × 1 array design using CMSA. Further, in the binomial distribution, the next value of the normalized binomial distribution coefficient is very small hence, other higher order linear arrays are not considered in the present study. To realize an increase in the gain with reduced FSLL, planar binomial HMSA arrays are designed. Similar to the planar CMSA arrays, 5 × 1 linear binomial array as the central sub array is selected. The linear sub arrays along the Y-axis i.e. along the H-plane are inter-connected using microstrip line of length l_v, which is either $\lambda_g/2$ or λ_g in length. Along the X-axis i.e. along E-plane, U-shape feed lines are employed to inter-connect the array elements. For the 5 × 1 array, normalized binomial distribution coefficients are 0.16, 0.66, 1, 0.66, 0.16. These coefficients realize varying gain amongst array elements with reference to the central element. The Fig. 10 shows the design of 5 × 3 series fed binomial HMSA array.

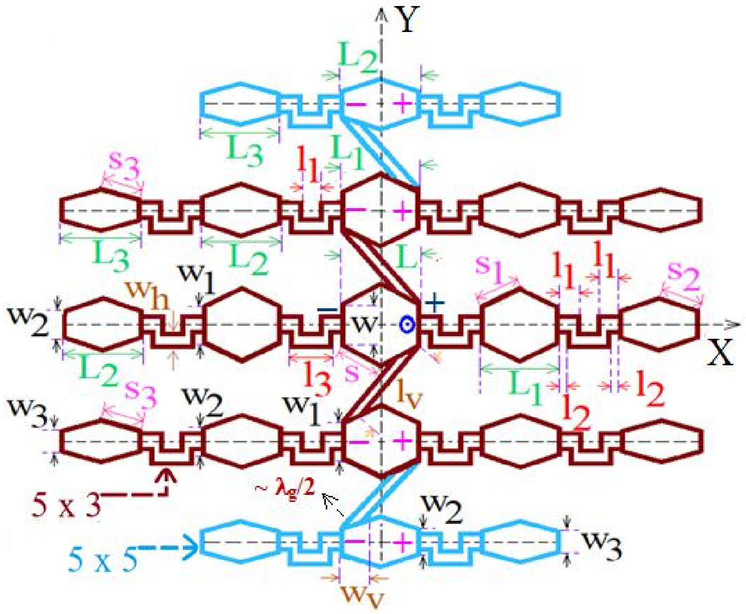


Fig. 10. Planar binomial HMSA array employed with $\lambda_g/2$ spacing along the H-plane.

An optimum simulated response for the 5 × 3 planar binomial array with $\lambda_g/2$ spacing is obtained for $L = 30$, $L_1 = 30.5$, $L_2 = 31.5$, $L_3 = 32$, $w = 17.32$, $w_1 = 14$, $w_2 = 8$, $w_3 = 6$, $s = 17.32$, $s_1 = 16.77$, $s_2 = 16.52$, $s_3 = 16.27$, $w = 4$, $w_v = 4$, $l_v = 28$, $x_f = 12$. The simulated values of the gain and FSLL for the

5 × 3 planar binomial array are 14.9 dBi and -24 dB yields, respectively. Respective measured values are in close agreement with the simulated results. Further to enhance the gain with lower FSLL, the array order is increased and 5 × 5 series fed planar binomial HMSA array with $\lambda_g/2$ length spacing is studied as shown in Fig. 10. While realizing the 5 × 5 array, an additional sub array is placed at $\lambda_g/2$ spacing as shown in the figure. The order of the additional sub array is 3 × 1. The S_{11} and gain plots for 5 × 5 HMSA array is shown in Fig. 11 (b), (c). The simulated and measured BW's for $S_{11} \leq -10$ dB are 30 MHz and 34 MHz, respectively. This array yields simulated and measured peak gain of 16.5 dBi and 15.8 dBi, respectively.

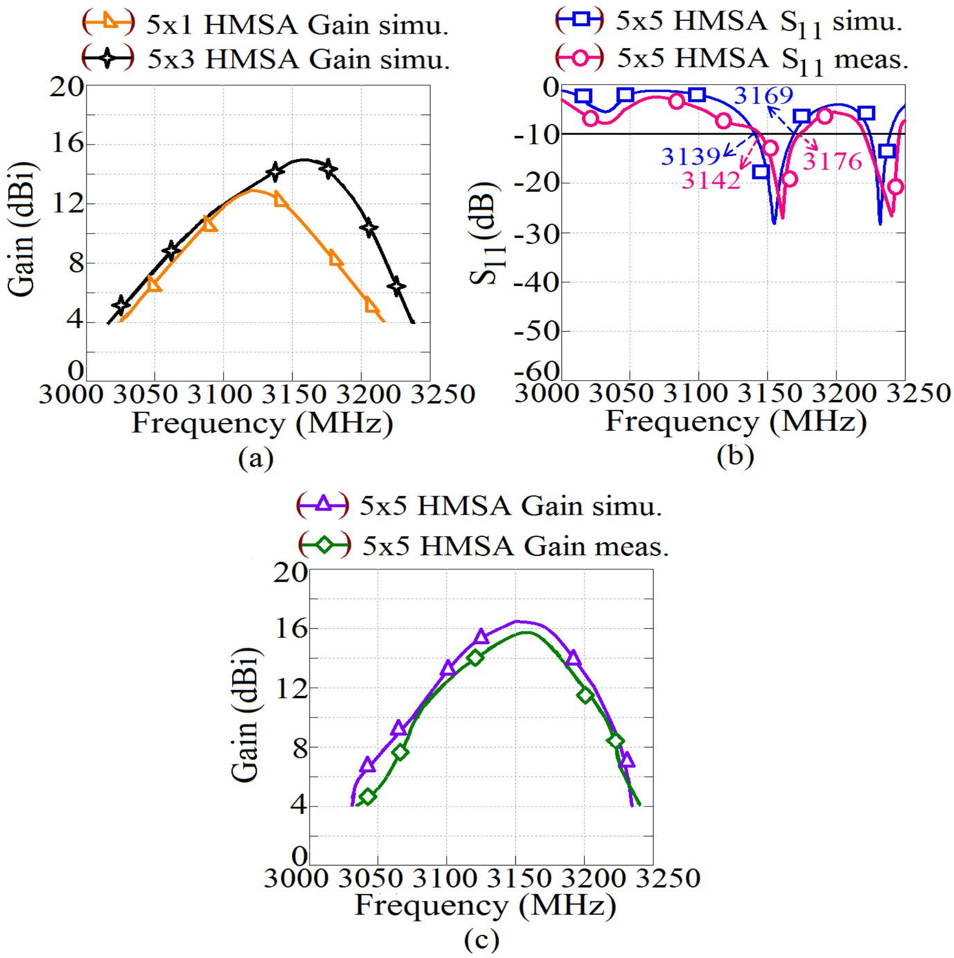


Fig. 11. (a) Gain plots for 5 × 1 and 5 × 3 binomial HMSA array with $\lambda_g/2$ spacing (b), (c) S_{11} and gain plots for 5 × 5 planar binomial HMSA array with $\lambda_g/2$ spacing .

The simulated and measured radiation pattern at the center frequency for the 5 × 5 array is shown in Fig. 12 (a), (b). The 5 × 5 HMSA array exhibits a broadside radiation pattern with HPBW of 22° and 31° in the E and H-planes, respectively. The simulated and measured values of FSLL with $\lambda_g/2$ spacing in the E and H-planes are -20 dB, -27 dB and -21 dB, -26 dB, respectively. As compared with the linear 7 × 1 array, it shows improvement in the gain with a smaller improvement in the FSLL.

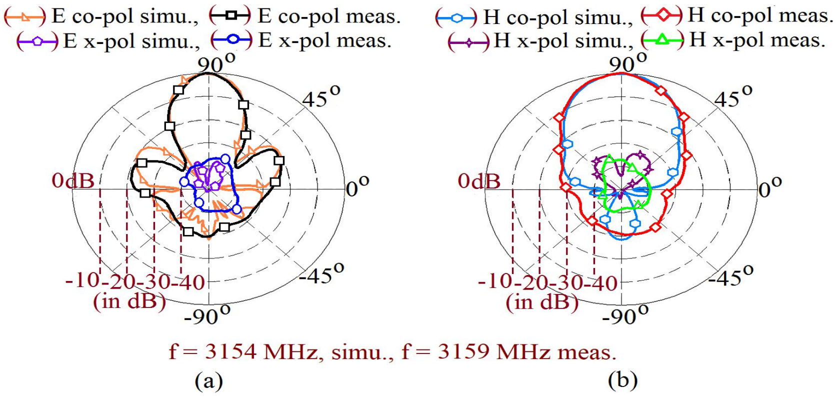


Fig. 12. (a), (b) Radiation pattern plots for 5 x 5 planar binomial HMSA array with $\lambda_g/2$ spacing.

Further 5 × 3 and 5 × 5 array designs with λ_g spacing between the respective sub arrays is studied as shown in Fig. 13 (a). Microstrip line of length l_v = 56 and width w_v= 4 mm are used to interconnect the HMSA linear sub arrays. The position of the microstrip line along the length of HMSA and connecting the two sub arrays along the Y-axis as shown in Fig. 13 (a) is selected as per the required impedance matching for the complete array structure.

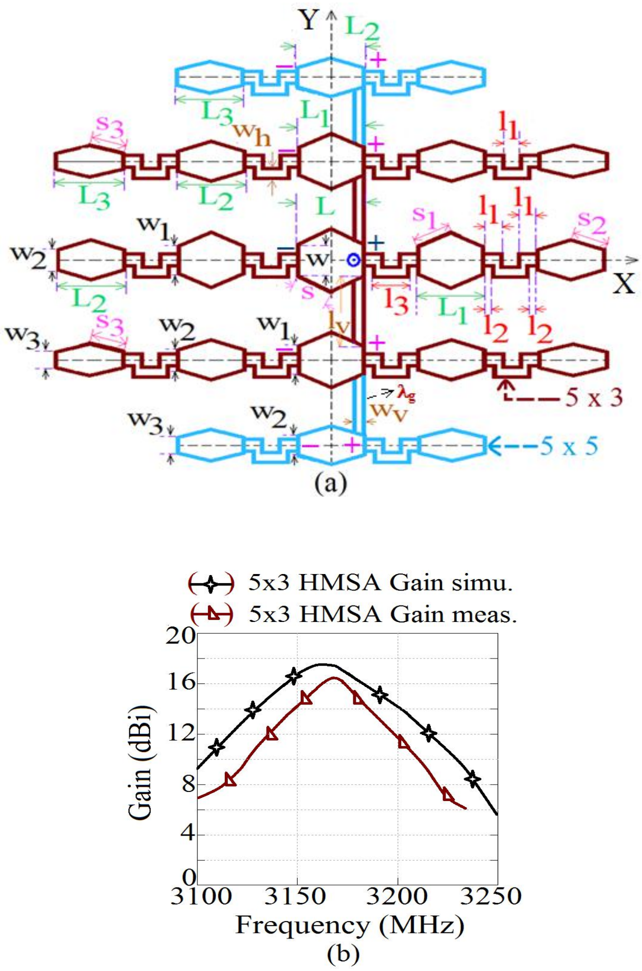


Fig. 13. (a) Planar HMSA array using λ_g spacing (b) gain plots with λ_g spacing for 5 × 3 HMSA array.

The simulated and measured resonance frequencies for the 5 × 3 HMSA array are 3157 MHz and 3160 MHz with a BW of 17 MHz and 14 MHz respectively. Respective values of the simulated and

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measured broadside gain in 5 × 3 array are 17.4 dBi and 16.5 dBi, as shown in Fig. 13 (b). The simulated and measured resonance frequencies for 5 × 5 HMSA array are 3178 MHz and 3190 MHz with a bandwidth of 15 MHz and 14 MHz respectively. This antenna shows the simulated and measured gain of 18.9 dBi and 17.8 dBi, respectively as shown in Fig. 14 (b). This gain is maximum amongst all the array configurations, proposed in this paper.

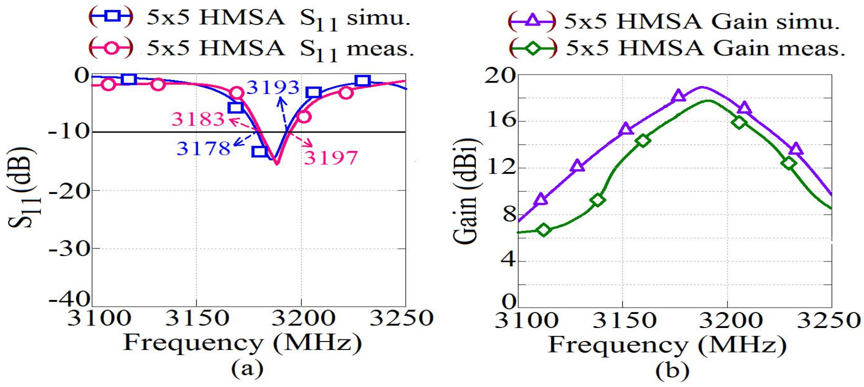

Fig. 14. (a) S_{11} plots for 5 x 5 HMSA array with λ_g spacing and its (b) gain plots.

The radiation pattern for 5 × 3 HMSA array with λ_g spacing is in the broadside direction with HPBW of 20° and 24° in the E and H-planes, respectively as shown in Fig 15(a), (b). The 5 × 3 array provides the simulated and measured FSLL of -22 dB, -23 dB and -20 dB, -22 dB in the E and H-planes, respectively. Similarly, 5 × 5 array of HMSAs using wavelength spacing is optimized for the gain and FSLL and their results are shown in Fig. 14 (b) and 15 (c) and (d).

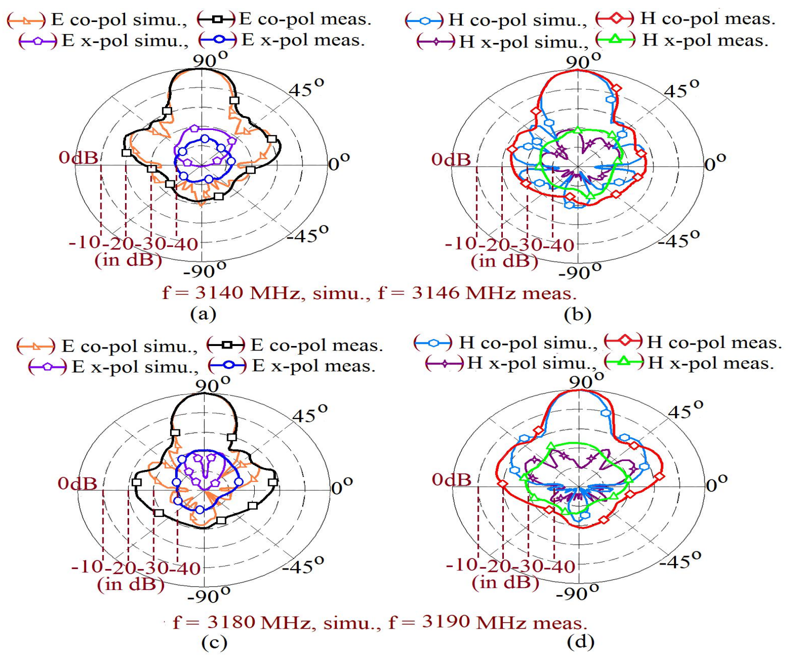

Fig. 15. (a), (b) Radiation pattern at the center frequency of the impedance BW for 5 × 3 and (c), (d) for 5 × 5 planar HMSA binomial array.

The fabricated antenna prototype for the 5 × 5 and 5 × 3 HMSA array using wavelength spacing are

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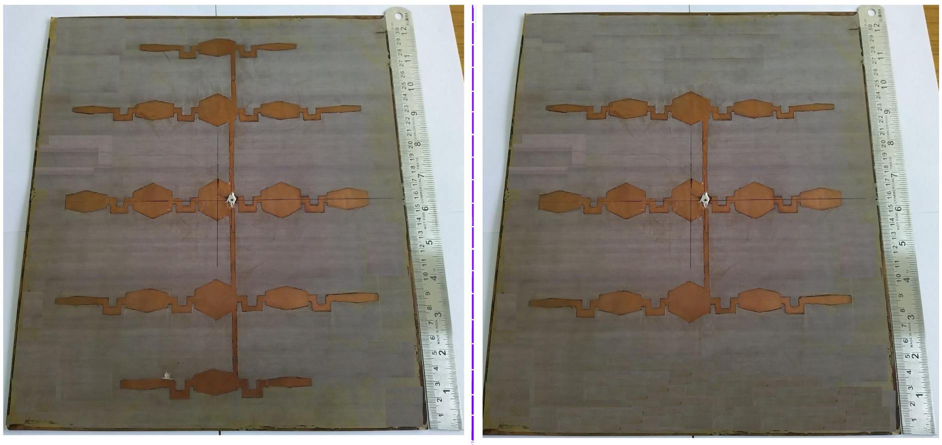
shown in Fig. 16 (a) and (b).



5 x 5 HMSA array
(a)

5 x 3 HMSA array
(b)

Fig. 16. Fabricated prototype of (a) 5 × 5 and (b) 5 × 3 HMSA arrays

In the present work, measurements have been carried out for all the optimum results as obtained in linear 7 × 1 array and planar 5 × 3 and 5 × 5 planar arrays. To avoid repeatability, results are only shown for the 5 × 5 array, which are optimum in terms of the gain and FSLL. Since the arrays were designed on thinner substrate, VSWR BW is in the range of 20 to 30 MHz. In the radiation pattern of proposed arrays, the cross polar component is less than 25 dB as compared with the co-polar component. The input impedance, radiation pattern and broadside gain measurements have been carried out inside the Antenna Lab. In the pattern and gain measurements, minimum far field distance between the reference antenna and antenna under test (i.e. linear and planar CMSA and HMSA arrays) was maintained. A broadband Horn antenna was used as the reference antenna. The broadside gain was measured using three antenna method for better accuracy. The results for all the planar array designs using CMSAs and HMSAs are summarized in Table II.

TABLE II. COMPARISON AMONGST ALL SERIES FED PLANAR BINOMIAL CMSA AND HMSA ARRAYS

Configuration	Spacing along H-plane	Gain (dBi)	E-plane FSLL (dB)	H- plane FSLL (dB)
5 × 3 CMSA	$\lambda_g/2$	15.2	-21	-14.5
5 × 5 CMSA	$\lambda_g/2$	15.6	-26	-22
5 × 3 CMSA	λ_g	16.2	-24	-16
5 × 5 CMSA	λ_g	17.7	-29	-14
5 × 3 HMSA	$\lambda_g/2$	14.9	-24	-14
5 × 5 HMSA	$\lambda_g/2$	16.4	-20	-27
5 × 3 HMSA	λ_g	17.4	-22	-23
5 × 5 HMSA	λ_g	18.9	-26	-17

As can be seen from Table II that with a 5 × 5 array, gain increases but FSLL also increases. The increase in FSLL in the 5 × 5 array is attributed to the use of only three elements in the last linear sub array as against the five elements present in the other linear sub arrays. This variation in the number of elements does not optimally realize the binomial distribution across the complete aperture, which

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increases the FSLL in the H-plane. In the initial linear array design, 7 × 1 array was optimized. Later, 5 x 1 array was considered for realizing the planar arrays. Here if along with 7 × 1 array, the planar array would have been developed, then in those configurations, decreasing number of sub array elements would have been present along the Y-axis. This would have resulted in more un-asymmetrical distribution of the aperture deviating more from the binomial case. This is also one of the reasons for selection of 5 × 1 array in developing the planar arrays. In this selection, asymmetry only exist in 5 × 5 case but not in 5 × 3 configuration. As against the CMSA, HMSA arrays offer higher gain. This is attributed to the larger amount of uni-directional current on the hexagonal patch against the circular patch, at the fundamental TM_{11} mode. In the 5 × 5 array, total of five linear sub arrays are present with the central linear sub array containing the five elements. Due to this, although the last sub array does not contain five elements, but the order of the array is referred to as 5 × 5. Against the reported configurations, performance comparison for the planar 5 × 5 array is presented in Table III.

TABLE III. COMPARISON OF PLANAR 5 × 5 HMSA ARRAY AGAINST REPORTED CONFIGURATIONS

Reference	**Frequency (MHz)**	**Array elements**	**Gain (dBi)**	**E- plane FSLL (dB)**	**H- plane FSLL (dB)**
[7]	3500	8 × 1	10.86	-19	-
[8]	24150	8 × 8	18	-17	-23
[9]	10500	2 × 8	14.5	-15	-12
[12]	20000	3 × 3	14.1	-17	-17
[13]	24000	8 × 8	20.9	-20	-20
[14]	24500	8 × 6	19.9	-23	-23
[15]	77000	6 × 8	-	-20	-15
[16]	5800	9 × 9	22.2	-15	-15
[17]	10100	5 × 5	-	-18	-15
[18]	5760	3 × 3	12.8	-28	-28
[19]	77000	32 × 16	24.6	-20.8	-16.4
Fig. 13(a)	**3180**	**5 × 5**	**18.9**	**-26**	**-17**

In terms of the gain and FSLL, 5 × 5 binomial HMSA array using wavelength spacing yields optimum result. Hence that design is used for comparison purpose. The 8 × 1 array as reported in [7] consist of patches backed by slot cut ground plane. Against the same, proposed 7 × 1 linear array design using CMSA and HMSA yields better results in terms of gain and FSLL, on electrically thinner substrate. In the design reported in [8], a multilayer, complex feeding structure is used to realize higher gain and lower FSLL. The MSA array presented in [9] involves complex feeding network and provides lesser gain with high FSLL as against the proposed configurations. The configuration reported in [11] is a two-layer stacked series fed MSA array which offers lesser gain as compared to the proposed designs. The configuration reported [13] is a non-planar two substrate MSA array and it provides the higher gain than the design presented in this paper. However, design in [13] suffers from higher feeding losses which are attributed to several unequal power dividers, which are used for feeding the array elements. In the array design given in [14], higher gain with comparable FSLL as compared with the proposed design is realized. However that array requires more number of elements and involves complex matching stubs for the impedance matching purpose. Series and corner fed configurations reported in [16] provides more gain due to larger number of array elements but has poor performance in terms FSLL. The array design reported in [18] yields lower FSLL but it has lesser gain as against the proposed designs. Comb-line fed array reported in [19] provides higher gain with higher FSLL values. Thus, as compare with the reported papers proposed work presents several configuration of HMSA and CMSA array on thinner substrates, which make the design low profile and planar. In addition, realized gain and FSLL are better as compared with the reported configurations for the same array order. Thus to summarize, simpler thinner substrate designs of HMSA and CMSA arrays using binomial distribution function for higher gain and lower FSLL, is the new technical contribution in the proposed study.

The CMSA and HMSA were originally designed for the fundamental mode frequency of 3000 MHz. However, as seen from the above results, an optimum response in respective arrays is obtained at a slightly higher frequency (by 150 to 180 MHz). This frequency shift is attributed to the loading effects of all the array elements. Thus with the shift in frequency from 3000 to 3150 MHz, as observed in various array configurations, the antenna characteristics like BW, radiation pattern and gain will marginally change, as over this frequency range the effective substrate thickness (h/λ_g) of Arlong changes from $0.026\lambda_g$ to $0.027\lambda_g$, which is marginal. Thus although the center frequency of different array designs changes, still they can be compared within themself, as electric substrate thickness remains almost constant.

IV. CONCLUSIONS

Linear series fed designs of CMSA and HMSA arrays using binomial distribution are proposed. In the binomial amplitude distribution window functions, tapering is comparatively more as compared to the other amplitude distribution functions; hence the same is used in the proposed study for FSLL reduction. Amongst the linear array designs, 7 × 1 arrays offer maximum gain and lower FSLL. Further, the design using HMSA provide better results in terms of the gain and FSLL. Various series fed planar binomial distribution CMSA and HMSA arrays with a spacing of 'λ_g' and '$\lambda_g/2$' in between each linear sub arrays are proposed to enhance the gain and with lower FSLL. Amongst all the variants, the design of 5 × 5 array using HMSA with wavelength spacing, yields optimum result in terms of the gain and FSLL, together. It yields a broadside gain of 19 dBi with FSLL of better than -25 dB. As compared with the reported designs, results obtained in the proposed optimum design are better in terms of gain and FSLL with a smaller number of elements and by using thinner microwave substrate. Proposed single substrates with high gain and low FSLL planar arrays can find applications in S-band radar applications.

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