

Antenna Array Using Non-Identical Truncated Circular Elements for FSSL Reduction

Bharati Singh^{1, *}, Nisha P. Sarwade¹, and Kamla P. Ray²

Abstract—Resonance frequency of a Circular Microstrip Antenna (CMSA) depends on its diameter. Hence when CMSA is truncated or sectored into smaller elements, keeping the diameter same, it resonates at almost the same frequency. An analysis of the new antenna arrays designed using these truncated non-identical CMSA elements to realize an amplitude distribution over pedestals leading to a desired first side lobe level (FSSL) has been presented. Truncated elements are designed as non-identical elements based on their gain variation with respect to the standard normalized aperture distribution coefficients. Experimental verification to validate the proposed concept and simulated results has been carried out using an antenna array with eight non-identical elements. There is good agreement between simulated and measured results at 1.76 GHz.

1. INTRODUCTION

In an array radiation pattern, reduction of the First Side Lobe Level (FSSL) has gained increased importance in the wireless communication systems in order to facilitate reduction of interference near the direction of arrival. Implementation of tapering in antenna arrays is one of the well-known methods used for FSSL reduction. Recently, for linear arrays, the minimum number of elements required for the given amplitude distribution, to achieve a desired FSSL has been discussed in [1]. For a desired FSSL, the number of elements also depends on the sharpness of aperture distributions used to obtain tapering [1]. Many ways are possible to realize tapering for the antenna array. One traditional method is to realize the desired distribution by an unequal power division with identical antenna elements. This necessitates the design of a complicated feed network for appropriate power division which is rather difficult to realize [2–4].

Another method to realize amplitude tapering is to use non-identical elements in the antenna array with equal division of power requiring simple design of the feed network. The concept of width variation of Rectangular Microstrip Antenna (RMSA) has been used in antenna arrays to realize tapering and to suppress FSSL [5–7]. The amplitude tapering is achieved by varying both the width of the patch and feed of microstrip line in [5], but the work mainly concentrated on impedance matching. In this work, reasonable impedance matching is obtained for a 5 element array but FSSL of only -14 dB was achieved. The radiation conductance of each element is varied according to Chebyshev distribution coefficients for a desired FSSL in [6] but only simulation results are given. Reference [7] presents a dual frequency series fed array, in which both variation in width of patch and feed line is obtained with respect to Chebyshev amplitude coefficients. The method of extraction of amplitudes from resistance of the circuit model, used in this paper, is not suitable for patch width tapering as compared to line width tapering [7]. The Chebyshev distribution used in [6, 7] presents problems with edge effects and mutual coupling for large number of elements and for side lobe levels below -22 dB [1]. Complex weighted

Received 20 November 2017, Accepted 24 January 2018, Scheduled 4 February 2018

* Corresponding author: Bharati Singh (bhartisingh@somaiya.edu).

¹ Department of Electronics, VJTI Mumbai, Mumbai 400 019, India. ² EE Department, DIAT, DRDO, Ministry of Defense, Girinagar, Pune 4110 25, India.

excitations with digitally controlled attenuators and phase shifters with discrete attenuation and phase states have been discussed and used in active phased arrays to realize low sidelobe levels [8]. In this case too, only simulation results are presented. All these above-mentioned works use non-identical RMSAs in series fed antenna arrays. Design procedures of series and corporate fed antenna arrays have been discussed in [9]. None of the work so far has reported the use of CMSA as non-identical elements in an array to realize amplitude tapering for FSLR reduction.

A semicircular Circular Microstrip Antenna (SCMSA), with the same diameter and thus half the area of the CMSA, has the same resonance frequency as that of a CMSA [10, 11]. Using this concept, in this paper, a new technique has been proposed to obtain amplitude tapering in uniformly spaced antenna arrays using non-identical elements of CMSA and its derivatives. The non-identical elements with same diameter have different sizes and hence different gains which is made proportional to the standard aperture distributions coefficients. In the present case, for nearly the same resonant frequency, the diameter has been kept the same, therefore, the smallest element is the SCMSA. Thus, the amplitude distribution/tapering over pedestal has been chosen. Keeping the diameters the same, CMSAs have been truncated systematically up to the SCMSA, thereby obtaining variation in gain of these elements, leading to amplitude tapering in the E -plane. The design of CMSA and its derivatives of non-identical truncated elements is initially discussed. These elements are used in the design of arrays with different numbers of elements based on three different standard amplitude distribution functions with pedestal. The three distribution functions used are the cosine, cosine-square, and triangular amplitude distribution functions as they have different tapering natures and are separately suitable for different numbers of elements [12]. An analysis has been carried out with respect to number of elements using the design of nine such arrays to establish suitability of an amplitude distribution over the pedestal. The non-identical CMSA elements are fed with a simple corporate feed with equal power division to verify the concept in transmit mode and experimentally verified for an array with eight elements at 1.76 GHz with a reasonably good agreement.

2. CMSA AND ITS DERIVATIVES

The CMSA is a widely used configuration of microstrip antenna due to its symmetrical geometry and ability to suppress harmonics generated by the transmitter [10]. The accurate formula of resonance frequency of a CMSA is given as [10]

$$f_{nm} = \frac{K_{nm}c}{2\pi a_e \sqrt{\epsilon_e}} \quad (1)$$

where K_{nm} is the m th zero of the derivative of Bessel functions of order n , and parameters c , a_e , and ϵ_e are the speed of light, effective radius and effective dielectric constant of a CMSA, respectively [10]. K_{nm} is 1.84118 for the fundamental TM_{11} mode.

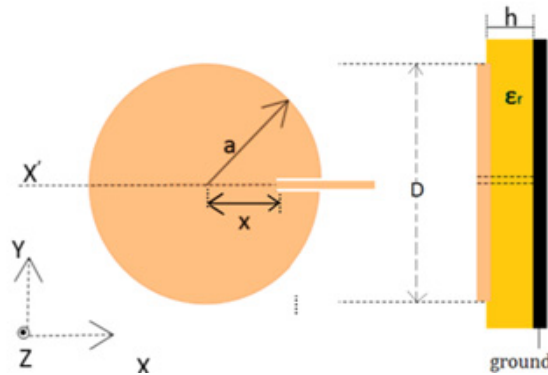


Figure 1. A CMSA configuration.

For the analysis, the CMSA with diameter D and inset feed position x is designed at a frequency of 1.8 GHz on glass epoxy substrate with dielectric constant $\epsilon_r = 4.3$, loss tangent 0.01 and thickness $h = 1.59$ mm using design equations in [10, 11, 13], as depicted in Figure 1. This basic CMSA is truncated to realize non-identical CMSA elements as explained below.

Figure 2(a) gives some of the truncation levels used to convert an inset fed CMSA to various truncated elements up to a Semi-Circular Microstrip Antenna (SCMSA), and Figure 2(b) gives the layout of the inset fed single CMSA element at the truncated level of -1.9 cm as an example. The initial truncation level (i.e., no truncation = CMSA) is equal to the radius of the CMSA equal to 2.32 cm at 1.8 GHz. The next step involves the systematic conversion of a CMSA to the SCMSA by increasing the truncation levels from 1 to 2 and further as indicated in Figure 2(a). In this work, the truncation level 1 is greater in magnitude than level 2 and so on. The minimum truncation level is the one at which the SCMSA is obtained. Truncation here implies deleting off systematically the parts of the original CMSA in its lower half and hence its area (and gain) reduces and approaches the SCMSA. As the CMSA is systematically reduced to SCMSA, a unique behavior in the resonant frequency of the elements generated is observed. This is depicted in Figure 3 which presents the variation in resonant frequency of the CMSA against the percentage reduction of radius (in the lower half) as the truncation level. The realized frequency for a few of the levels and simulated gains of those truncated elements are depicted in Table 1. For the analysis, the CMSA with zero % reduction of truncation level is designed at 1.800 GHz with radius of 2.32 cm, and the SCMSA (with 100% reduction) has a frequency of 1.835 GHz.

Table 1. Percentage change in frequency for truncated CMSA elements with radius of 2.32 cm.

Shape of element	% reduction of radius as truncation level	New Obtained frequency (GHz)	% change in frequency	Gain of the elements (dBi)
CMSA	0	1.800	0	3.90
Truncated CMSA	5	1.792	-0.44	3.79
Truncated CMSA	10	1.784	-0.89	3.68
Truncated CMSA	30	1.746	-3.0	3.19
Truncated CMSA	50	1.738	-3.444	2.65
Truncated CMSA	70	1.744	-3.12	2.03
Truncated CMSA	90	1.794	-0.33	1.30
SCMSA	100	1.835	+1.944	0.90

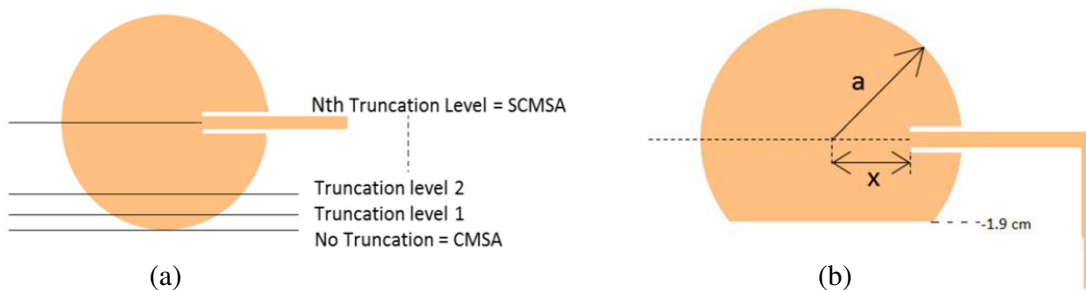


Figure 2. (a) Truncation levels of the designed inset fed CMSA. (b) CMSA at truncation level -1.9 cm with inset feed.

The change in resonant frequency is primarily because of modification of surface current path and the variation in effective dielectric constant. As depicted in Figure 3, initially as the truncation level increases, the resonant frequency of the CMSA decreases linearly from 1.8 GHz to 1.738 GHz, and the

maximum percentage reduction of the resonant frequency for CMSA of frequency 1.8 GHz is 3.4444%. This reduction is because the minor change in current path available now though the diameter remains the same. This reduces the total circumference length and hence the length available for the existence of the complete TM_{11} mode. Moreover, the straight edge available in the lower half of CMSA adds to the fringing fields. For a further few truncations, the total length of the outer periphery of the truncated element becomes equal to the original circumference, hence there is no further change in frequency for these truncated elements. For this case, the resonant frequency remains at the minimum value of 1.738 GHz as observed in Figure 3. With further truncations, the size of the element reduces significantly, reducing the effective dielectric constant, which in turn increases the frequency. Thus, the resonant frequency increases to the original value of 1.8 GHz at truncation level 0.25 cm. This truncated CMSA (with a truncation level of 0.25 cm) is slightly larger in area than the SCMSA (10.6837%). Further on, the SCMSA has resonant frequency of 1.835 GHz, thus having a 1.9444% increase of frequency as compared to the original design frequency.

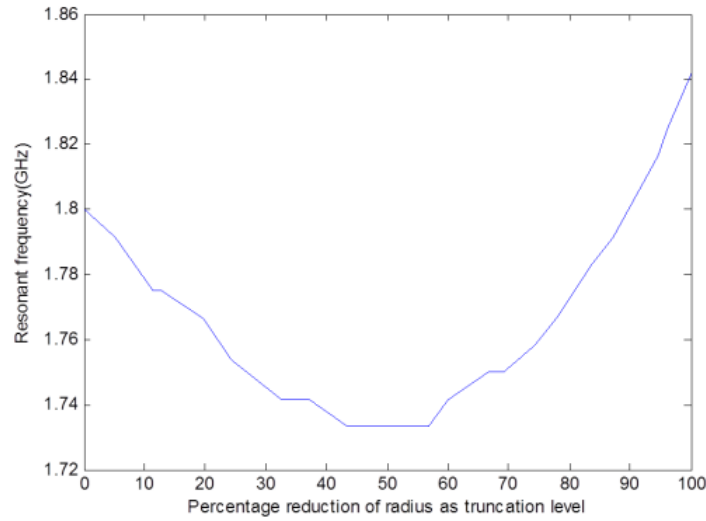


Figure 3. Change in resonant frequency of CMSA (1.8 GHz) versus truncation levels.

3. DESIGN AND ANALYSIS OF THE CMSA ARRAY

To prove the concept, a corporate feed is used since all elements are needed to be fed with equal amplitude and equal length of microstrip lines (for equal input amplitude distribution) and thus in phase. Simple corporate feed network has been designed in transmit mode, which has to be suitably redesigned with isolating resistors for the receiving mode.

The significant feature here in the CMSA arrays designed for a desired FSLL is that the gain of the non-identical elements is based on normalized coefficients over pedestals of standard amplitude tapering (window functions). For the corporate feed, the inset feed for the $50\ \Omega$ input impedance, as shown in Figure 2(b), has been used to feed the CMSA and its derivatives. This concept was used to design various truncated non-identical elements of the CMSA (example in Figure 2(b)) with different gains at the average frequency of 1.76 GHz. Each CMSA element has a different truncation level, and hence effective dielectric constant (ϵ_r) is slightly different for each one of them. Thus, the diameter of each truncated CMSA was fine-tuned so that the truncated element now resonates at the same frequency. Designs of the non-identical elements are such that the gains of the elements are proportional to the normalized aperture distribution coefficients over pedestals obtained using MATLAB. The height of the pedestal is approximately corresponding to the gain of the SCMSA. The arrays using four, eight and sixteen CMSA elements were designed for three aperture distributions, namely cosine, cosine-square and triangular over pedestal. The central elements of the array are the complete CMSAs and other

elements in the arrays are the truncated elements whose size reduces as per the normalized coefficients. Since the elements are inset fed, the edge element normalized gain coefficients have to be large enough to accommodate the smallest possible truncated inset fed CMSA element which is slightly larger than the SCMSA. Hence, for the design of the arrays, the maximum % reduction of truncation level is taken as 90% and the pedestal height adjusted to 0.69 to appropriately realize the inset feed for the smallest derivative of the CMSA.

Analysis of the CMSA arrays designed according to above mentioned procedure is given in Table 2(a). It tabulates the desired FSL with respect to number of elements in the array for all the 3 distributions with a pedestal of 0.69 obtained using MATLAB and corresponding realized (simulated) FSL obtained using Method of Moment based IE3D software [14]. It also presents the difference (in dB) between the desired and obtained FSL values. For a lower number of elements in the array ($N = 4$ and 8), it is noted that the difference between desired and obtained value of FSL is minimum for the sharpest distribution, i.e., the cosine-square over pedestal distribution. As compared to $N = 8$, this difference for the cosine-square distribution is more for $N = 4$. This is because the minimum number of elements required for the original cosine-square distribution coefficients to work appropriately as weighting coefficients for an antenna array is 6 [1]. However, as depicted in Table 2(a), the amplitude distribution coefficients on addition of pedestals works reasonably well for a smaller number of elements ($N = 4$ in this case) with difference of 1.0592 dB for $N = 4$ as compared to 0.2335 dB for $N = 8$ [15]. For still fewer number of elements ($N = 2$ or 3), the desired distribution is not realized as there is no formation of null in the radiation pattern. As the number of elements increase to 16, the array with triangular distribution has the minimum error difference between desired FSL and the one obtained from IE3D. Also, it is observed in Table 2(a) that as the number of elements increase (from $N = 4$ to 16), the obtained difference between desired FSL and designed arrays (IE3D) reduces for the cosine distribution, clearly indicating that the smooth cosine distribution is more suitable for still larger number of elements. The overall analysis concludes that minimum difference in FSL depends on both the number of elements and the amplitude tapering over pedestal. Figure 4 presents the simulated far-field radiation patterns in the E -plane of all the three distributions for $N = 8$. It is clearly observed that the FSL degrades as the amplitude tapering reduces (cosine) for $N = 8$. Table 2(b) presents the normalized aperture distribution coefficients (amplitude tapering) over pedestal of 0.69 of the three considered distribution functions for $N = 8$ and the simulated gain of the corresponding truncated elements. From these tabulated coefficients, it is noted that the cosine-square coefficients have a sharper nature of tapering than the triangular function, whereas, the cosine distribution function coefficients vary in a smooth manner.

Table 2. (a) Variation between desired and obtained FSL with No. of elements of elements in the array for a corporate fed CMSA array for three amplitude distribution with pedestal height of 0.69.

N	Distribution matched to	Desired FSL (dB) for distribution over pedestal of 0.69	Obtained FSL (dB) using IE3D	Difference between the desired FSL with pedestal and obtained simulated FSL (dB)
4	Cosine-square	-15.1218	-16.181	1.0592
	Triangular	-13.5582	-14.9144	1.3562
	Cosine	-15.7391	-13.753	1.9861
8	Cosine-square	-17.2209	-16.9874	0.2335
	Triangular	-16.5715	-15.8485	0.7230
	Cosine	-16.0558	-15.1528	0.9030
16	Cosine-square	-17.1766	-16.28	0.8966
	Triangular	-15.9639	-15.4557	0.5082
	Cosine	-15.9141	-14.5729	1.3412

Table 2. (b) Normalized aperture distribution coefficients over pedestal of 0.69 of the three considered distribution functions for $N = 8$ and the simulated gain of the corresponding truncated elements.

Distribution	Weighted Normalized Coefficients over pedestal of 0.69 for $N = 8$ (from center element to edge element)	Simulated gain of the truncated elements (dBi)
Cosine-square	1	3.90
	0.880	3.35
	0.748	2.64
	0.690	2.29
Triangular	1	3.90
	0.896	3.42
	0.791	2.88
	0.690	2.29
Cosine	1	3.90
	0.938	3.62
	0.826	3.07
	0.690	2.29

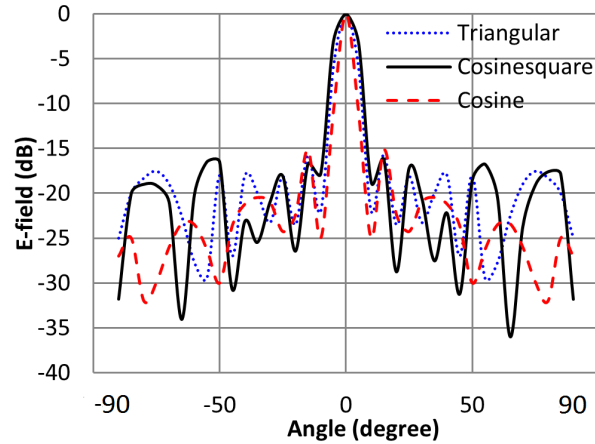


Figure 4. Far field radiation patterns for the three distributions with $N = 8$ in the E -plane.

4. EXPERIMENTAL VERIFICATION

A prototype of the CMSA array with 8 elements at 1.76 GHz with elements' gain proportional to the normalized coefficients of cosine-square distribution over pedestal of 0.69, based on the procedure as outlined in Section 3, was fabricated. For 8 elements the difference between the desired FSL and simulated FSL is minimum for this case as observed in Table 2(a). The normalized coefficients for the cosine-square distribution over 0.69 pedestal for $N = 8$ are 0.690, 0.748, 0.880, 1, 1, 0.880, 0.748 and 0.690, and the corresponding simulated gains (in dBi) for these gain varying truncated CMSA elements are 2.29, 2.64, 3.35, 3.90, 3.90, 3.35, 2.64 and 2.29. A CMSA and its derived elements have been designed with central element having maximum gain and remaining having gain as per above amplitude coefficients. Inter-element spacing between elements is kept as 0.7λ to avoid mutual coupling and formation of grating lobes [2, 16]. Figure 5 presents the layout of the array in IE3D, and Figure 6 gives a picture of the fabricated array. Measurements on the fabricated CMSA antenna array are

carried out using ANRITSU Vector Network Analyzer (No. MS2026C). Figure 7 gives the simulated and measured VSWR plots of the antenna array which are in agreement. The simulated resonance frequency is 1.766 GHz, whereas the measured value is 1.762 GHz. Figure 8 and Figure 9 compare simulated and measured radiation co-polar and cross-polar patterns in the E and H planes, respectively. Table 3 presents the comparative values of resonance frequency, FSL, VSWR and Beamwidth for the simulated and fabricated CMSA antenna array. Reasonable agreements between the measured and simulated responses are observed. Slight discrepancies in the simulated and measured plots in Figure 7 can be attributed to the lossy glass epoxy material used for fabrication and fabrication/measurement errors.

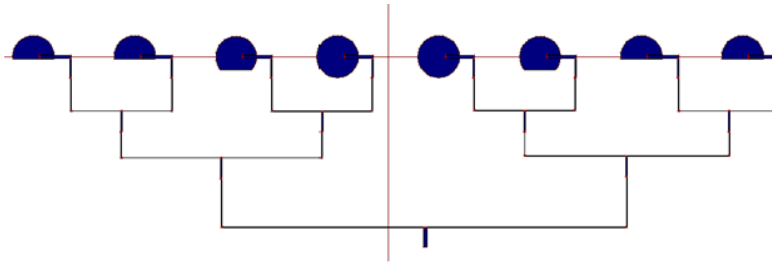


Figure 5. CMSA Tapered antenna array layout with 8 elements and corporate feed.

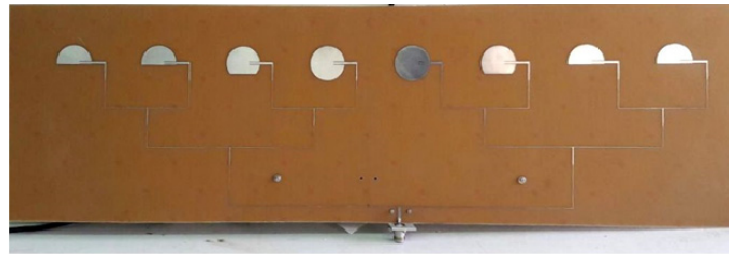


Figure 6. Fabricated antenna array with cosine-square amplitude distribution using non-identical CMSA element.

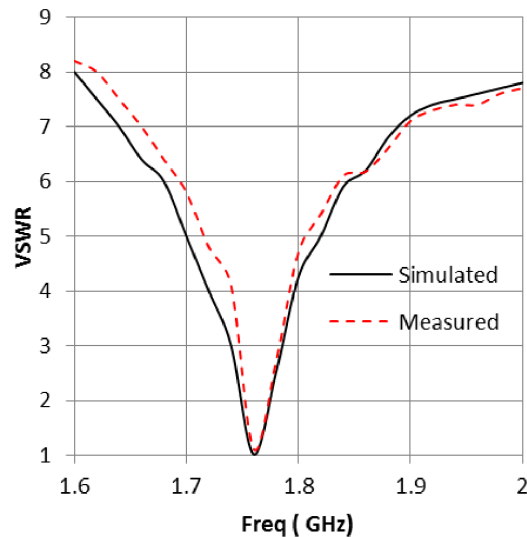


Figure 7. Simulated and measured VSWR plots of a 8-elements tapered array.

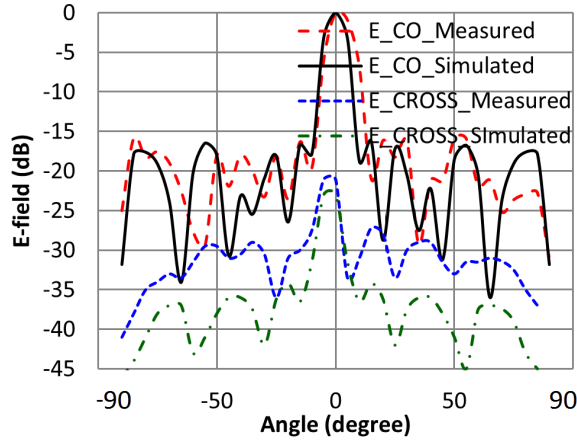


Figure 8. Simulated and measured E plane radiation patterns of an 8-elements tapered array.

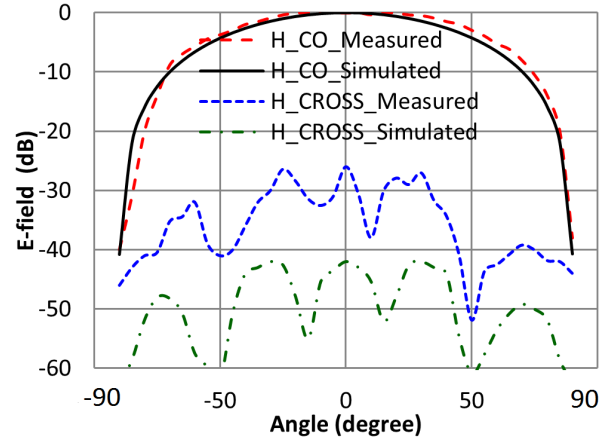


Figure 9. Simulated and measured H plane radiation patterns of an 8-elements tapered array.

Table 3. Simulated and measured parameters of the proposed tapered CMSA antenna array with 8 elements.

Antenna Parameter	Resonant Frequency (GHz)	FSL (E-plane) (dB)	VSWR	Beamwidth (E-plane) (degree)	S_{11} (dB)
Simulated	1.766	-16.9874	1.023	10.12	-38.88
Measured	1.762	-16.321	1.120	11.50	-24.94

The measured and theoretical values of FSL are very close to each other. A reasonably good impedance matching is also obtained at the resonant frequency. The half power simulated and measured beamwidths are in good agreement with each other. The cross polar in E -plane is less than 20 dB down with respect to main lobe, and the H -plane co-polar plots are equal to that of a single CMSA. The slight asymmetrical radiation pattern is due to the inset feed used for all the elements because of which the symmetry of the patch radiator is destroyed.

5. CONCLUSIONS

Truncated CMSA elements resonating at approximately same frequency have been proposed and effectively used in the design of a tapered antenna array. Suitability of using these non-identical elements to realize amplitude tapering over pedestal for a desired FSL reduction is clearly brought about. Analysis with respect to number of elements in the array is carried out to establish the suitability of amplitude tapering of cosine-square over pedestal for lower number of elements. The proposed concept has been experimentally verified using a tapered antenna array with 8 elements at 1.76 GHz. The measured radiation pattern and SWR agree reasonably well with the simulated results. Though the concept has been demonstrated for a 8-element linear array, it can be used to design a planar array for wireless systems.

ACKNOWLEDGMENT

Authors acknowledge SAMEER, MeitY, Govt. of India, Mumbai and VJTI, Mumbai managements for providing facility for experimentation and encouragement.

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