Bunny Ear Combline Antennas for Compact Wide-Band Dual-Polarized Aperture Array

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***Abstract*—A bunny ear shaped combline element for compact aperture arrays is presented which provides relatively low-profile and low level cross polarization over wide bandwidth. The radiation flares are corrugated along the outer edges between the elements. The aim is to suppress the current along the longitudinal direction due to the higher-order modes propagation. This produces nearly linear polarized waves in the principle planes. The cross polarization is lower than -10 dB over the entire scan volume. Previous generations of the Vivaldi-type antennas have been reviewed and the advantages of the new design are highlighted. The elements can be simply manufactured by water-cutting two separate metal sheets, forming a tapered slotline. Hence the cost is low and the cross-polar element can be arranged by crossing the co-polar element at its mutual axes accross the slotline to share the same phase centre, or by joining at the outer edge where it is half lattice spacing to the centre of the element. The performance for both configurations are investigated.**

***Index Terms*—Aperture array, bunny ear, dual polarization, cross polarization, phased array.**

I. INTRODUCTION

WIDE band dual-polarized phased arrays are increasingly desired for many applications. Many system functions have well defined polarization requirements. Generally, low cross polarization is desired across the whole bandwidth. For Square Kilometre Array (SKA) radio telescope [1], cross polarization of -30 dB after calibration is required within the full field of view over a scan volume of $\pm 45^\circ$. There are a large variety of existing microwave antenna designs. The prime example is the Vivaldi or tapered slot. One of the example is the THousand Element Array (THEA) developed by ASTRON [2]. The cross polarization properties of such antennas over the wide scan volume need more investigations [3].

The Vivaldi or tapered slot antenna (TSA) array was first introduced in 1974 by Lewis et al. [4]. It has been indicated in [5] that a single Vivaldi is optimum when the length of the slot-line is over one wavelength and the width of the aperture is more than half a wavelength. However, the antenna element in an array is much smaller than the isolated antenna in order to avoid grating lobes in the visible range. For the SKA application where the mid-frequency close-packed aperture array operates between 300 MHz and 1 GHz with a maximum 45° scan angle, it is theoretically required that the maximum element spacing is 175 mm, i.e. about one-sixth free-space wavelength at the lowest frequency. Mutual coupling between the radiating elements then becomes highly significant in determining the array performance. The low cross polarization requirement presents a challenge to antenna design engineers, especially when the TSA arrays are used, the mutual coupling is complex and unable to be precisely controlled.

A dual-polarized wide-band and wide-angle scanning TSA array was reported in [6]. Its bandwidth is in the order of 4.5:1 over a scan volume of $\pm 45^\circ$. One disadvantage of such antenna arrays is the impedance anomalies principally in the H-plane scan. Vias along the slotline and the slotline cavity were introduced to eliminate impedance anomalies (or resonances) [7]. However, no detail information regarding the cross polarization performance has been revealed.

The conventional Vivaldi antennas exhibit low cross polarization characteristics in the principle planes, however in the diagonal-(D-) plane, the cross polarization becomes increasingly higher as the arrays being scanned to wider angles [8]. It is indicated in [8] that these high cross-polar components mainly stem from extensive surface currents flowing in the longitudinal direction along the long tapered slots, and partly from unbalanced feed ports. The excessive surface current produces major impacts on the performance of an antenna array causing impedance mismatch and scan blindness.

A Fermi-type tapering has been used in [9] and [10] to improve the radiation pattern with a lower side lobe level, especially in the H-plane. A "corrugation structure" which consists of slits along the two sides of the Fermi antenna is used to reduce the width of tapered slot antenna for the design of compact arrays without a degradation of the radiation pattern. The Fermi antenna has a high directivity and it is inappropriate for array applications where wide scan angles are desired. For such arrays, a more compact geometry is required. In this paper we introduce comblines (or "corrugation structure") into a compact "bunny ear" type of element used in electronic scanning arrays.

In a compact aperture array element, there are two desired benefits from the combline approach: First, the combline design is to increase the overvall active impedance bandwidth and improve the impedance stability (that is reduce blindness effects); Secondly, the cross polarization performance is improved due to the suppression mechanism for the higher propagating modes by the comblines between tapered slots.

The bunny ear antenna can achieve better cross-polarization performance by tapering the outer edge of the conducting plate at the back end [11], and as a result, the element depth can be significantly shorter compared to the conventional Vivaldi antennas to obtain the same frequency bandwidth. For

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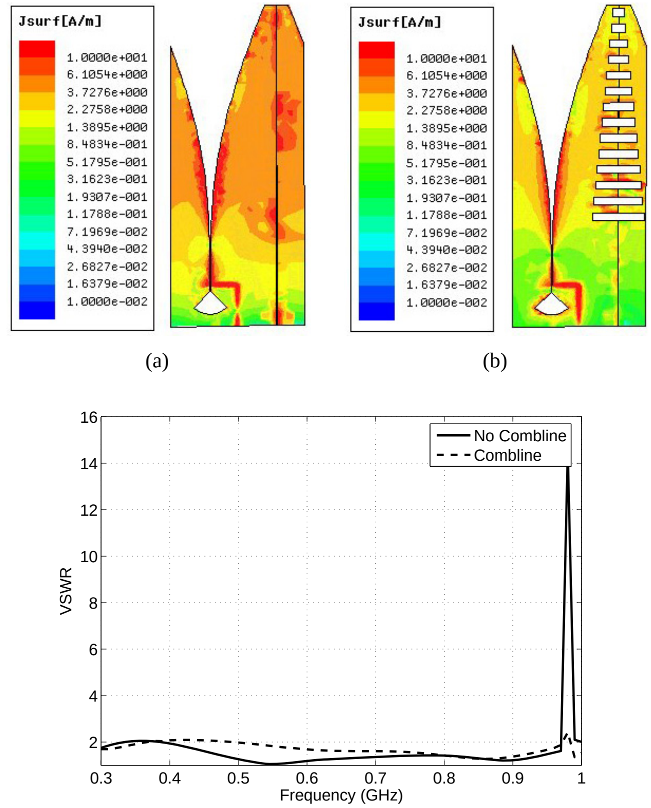
a conventional Vivaldi antenna and related structure, the ratio of the element depth to the element spacing is approximately proportional to the desired operating bandwidth [12], and therefore the element depth can be large, for example four wavelengths for Fermi antennas [9]. The shorter element depth of the bunny ear significantly reduces the possibility of producing complex propagation modes.

The bunny ear conducting flares are corrugated along the outer edge to form a combline shape. Such an antenna is named as Bunny Ear Combline Antenna (BECA). The current along the tapered conductors can be controlled by the physical dimensions of the comblines. In addition, the bunny ear is a balanced structure and ideal for a differential feeding mechanism, although it was reported that a coaxial cable was successfully used for feeding directly [11]. The cable feeding scheme needs an impedance transformer changing the characteristic impedance of the slot (i.e. 150 ohms in this case) to the impedance of the cable (i.e. 50 ohms).

The common "eggcrate" structure for dual polarized applications is easiest to implement by using the TSAs, but the phase centres of the orthogonally polarized element pair are not conincident, which may be problematic for certain applications [13]. The BECA design allows a flexible accommodation of an orthogonally polarized element. The two elements can cross either at their mutual axis or at the outer edges. The system analysis for both scenarios are presented in this paper.

This paper is organized as follows: In Section II, the variation versions of Vivaldis and "bunny ear" antennas are introduced. Section III discusses the methods to accommodate the orthogonally polarized element. Cross polarization characteristics of Vivaldi-type antennas and the proposed BECA are described in Section IV. The measured radiation patterns for the fabricated finite BECA array are presented in Section V. Section VI concludes the paper.



(c)

Fig. 1. The analysis for the element of dual-polarized Vivaldi array antenna with a single slotline. The element separation is 170mm and the depth of the element is 410mm. The surface current shown is based on the infinite array simulation when the array is scanned to 45° in the H-plane, (a) The surface current for the Vivaldi element when the array is scanned to 45° scan in the H-plane at 0.98 GHz without comblines, (b) The surface current for 45° scan in the H-plane at 0.98 GHz for the element with comblines, (c) VSWR for the Vivaldi of a single slotline with and without comblines in an infinite array, the direction of the scan is 45° scan in the H-plane.

II. Vivaldis and Bunny Ear Combline Antennas

A. Vivaldis with a Single Slotline

The Vivaldi TSA antenna with a bilateral slotline is known to produce resonances in the design frequency band. These resonances show some dependence on the presence of dielectric in the antenna structure if a triplate construction is applied. To reduce the dielectric region, a single tapered slotline structure is presented here by coupling into a feeding microstripline. The array shows a performance of Voltage Standing Wave Ratio (VSWR) less than 2 from 300 MHz to 1 GHz for broadside scan and 45° in the E-plane. However, for high angle scans in the H-plane, a resonance appears at 0.98 GHz for scan over 35° in the H-plane caused by the complex mutual coupling in the array. The surface current at 0.98 GHz for 45° scan in the H-plane is shown in Fig. 1(a). A strong surface current can be observed in the region between the adjacent elements, caused by higher modes propagation along the conducting plates. This is a well known phenomenon with this type of structures [12].

The higher modes along the plates contribute to a higher cross polarization and deteriorations of the radiation patterns with a high VSWR for the affected frequencies. By corrugating the edge of the element it is possible to suppress the surface current along the longitudinal direction and reduce the resulting resonance. The surface current at the same frequency for the single slotline Vivaldi with comblines is shown in Fig. 1(b), the combline fingers being formed along the outer edge of the conducting plate. The VSWR performance of the Vivaldi of a single slotline for 45° scan in the H-plane is shown in Fig. 1(c). The VSWR performance of the array elements with comblines is smoother than that of the conventional solid conducting plate, for example, the resonance occurring at 0.98 GHz for high angle scanning in the H-plane becomes significantly less pronounced and VSWR is reduced from above 10 to less than 2.

B. Bunny Ear Combline Antenna

As is reported elsewhere, high cross polarization performance of Vivaldi antennas is due to two primary sources: the excessive current flows along the longitude direction and the unbalanced feeding scheme [8]. Bunny ear type antennas can achieve better cross-polarization performance by tapering the outer edges of the conductor close to the ground plane, hence the current along the conductor plate can be suppressed. In

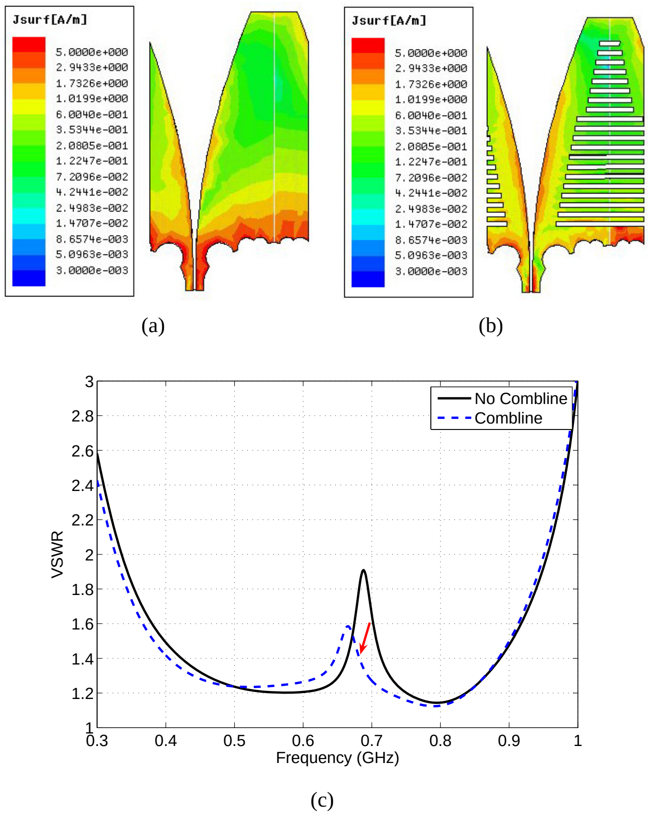


Fig. 2. The analysis for the element of dual-polarized bunny ear array antenna and bunny ear combline array antenna, the element separation is 170mm, the element depth is 280mm, the surface current is based on infinite array simulations, (a) Bunny ear antenna for 45° scan in the E-plane at 0.69 GHz, (b) Bunny ear combline antenna for 45° scan in the E-plane at 0.67 GHz, (c) VSWR for bunny ear antennas with and without combline in an infinite array, the direction of the scan is 45° in the E-plane.

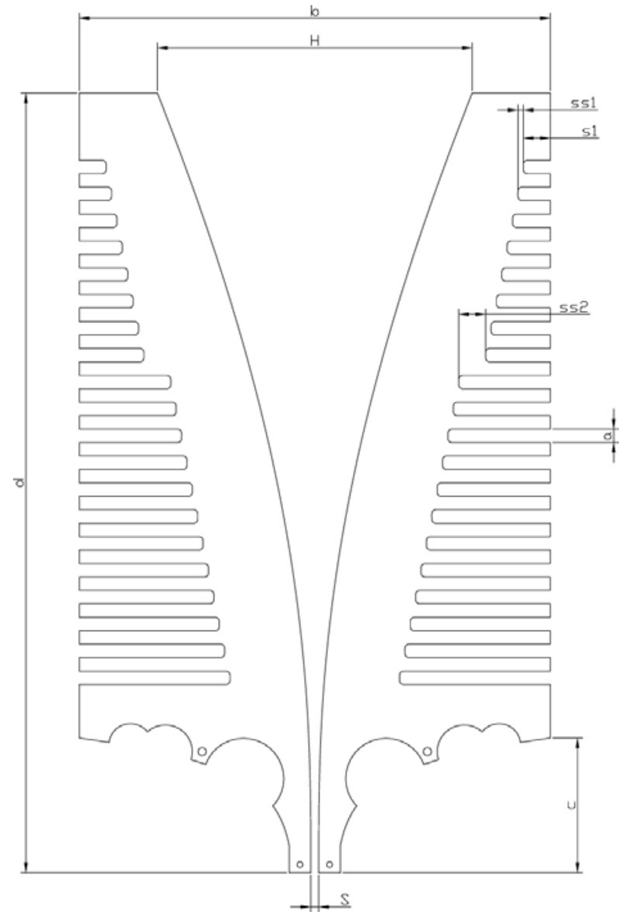


Fig. 3. The outline profile for the proposed BECA antenna, the width of the slotline at the end for feeding $S = 3$mm, the thickness of the conducting plate is 1.5 mm in the paper and therefore the characteristic impedance of the slotline at the feed point is 150 ohms. The characteristic input impedance can be tuned by changing the width of the slot and the thickness of the conducting plate

the BECA antennas, the performance is further improved by applying corrugation along the edge of the flares to form a combline shape. For these elements, the E-plane scan shows worse performance over the scan volume instead of the H-plane for the Vivaldi antennas. The E-plane scan performance for the BECA antenna of 170mm element separation with and without combline is shown in Fig. 2. The depth of the element is 280 mm. It is indicated that the infinite "bunny ear" antenna array element has a resonance at 690 MHz for large angle scans in the E-plane. The combline along the edges moves the resonance to 670 MHz and the VSWR is improved. The outline profile for the proposed BECA is shown in Fig. 3. The parameters related to the BECA design are as follows:
S width of the slotline at the end for feeding;
d depth of the element;
b height of the element;
H width of the opening aperture;
c height of the tapering at the outer edge;
a width of the branch of the combline;
sl length of the first combline;
$ss1$ length of the step for the first level combline;
$ss2$ length of the step for the second level combline.

The curve to build the tapered slotline is given as following:

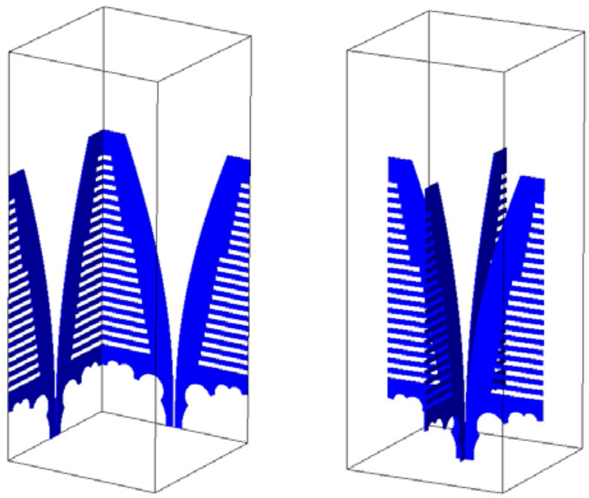
$$x = (1 - e^{-\alpha z})^p \quad (1)$$

where x is the transverse distance starting from the slot line edge, z is the longitudinal distance along the slot line. Here $\alpha = 0.5$, $p = 2.5$ is used to build the profile in the proposed design. It is noted that the flares of the BECA are shorter than a Vivaldi antenna to achieve the same bandwidth (less than one wavelength at the highest frequency). The BECA antenna is a balanced structure and the slotline is directly fed through a differential line. The antenna in Fig. 3 is fed via a balun with a 3:1 impedance transformer ratio (150 to 50 ohms) [14]. It is noted that the entire balun is below the ground plane with small holes in the ground plane for the tapered slotline of the antenna at the end for feeding passing through.

III. X or L Configuration

A dual-polarized array needs to consider the arrangement of the orthogonally polarized elements. The orthogonal elements can intersect either along their mutual axes or the outer edge of each element. These arrangements are called X configuration and L configuration respectively and the corresponding unit cells are shown in Fig. 4.

It has been noted that the scans in the E-plane show the worst performance for BECA arrays over the entire scan



(a) (b)

Fig. 4. The dual-polarized BECA unit cell for infinite arrays, (a) L configuration, the intersection is half the lattice spacing to the slotline, (b) X configuration, both elements share the same mutual axes and it is in the centre of the slotlines for both elements.

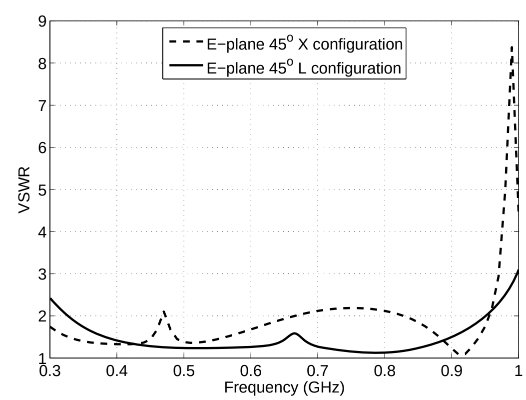


Fig. 5. The 45° in the E-plane scan performane for the dual polarized BECA array with a L and X configuration; The element spacing is 170mm, the depth of the element $d = 280$mm.

volume. The 45° scan in the E-plane for the BECA array with the L configuration and X configuration is shown in Fig. 5. The BECA aperture array with a L configuration shows an overall better performance than the dual-polarized BECA array with an X configuration. It is noticed that there is a weak resonance at 670 MHz for high scan angles in the E-plane. The surface current analysis for 45° scan has been shown in Fig. 2b.

IV. Cross Polarization

The Ludwig third definition of cross polarization is used in this paper [15]. Three designs are compared based on infinite array simulations: the Vivaldi with a triplate structure, a single slotline Vivaldi and the BECA. It is pointed out that the TSA arrays exhibit worse cross polarziation performance for the high frequency than the low frequency in the operational band. The cross polarization comparision in the D-plane scans for three typical designs is shown in Fig. 6. The cross polarization

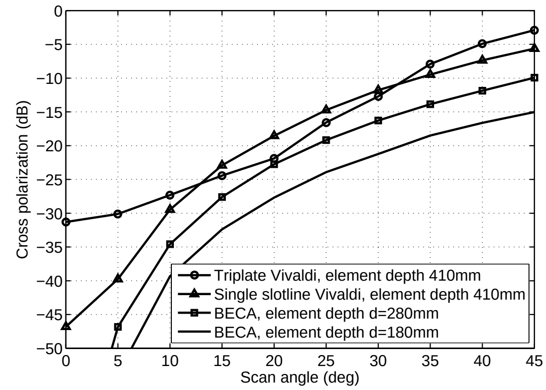


Fig. 6. The cross polarization performance comparison for scans in the D-plane at 1 GHz, it is based on infinite array simulation for dual polarized arrays, the elements for the three dual-polarized arrays share the same element spacing of 170mm, the element depth for Vivaldis is 410mm, the element depth for BECA is 280mm and 180mm.

in infinite arrays at the highest operating frequency of 1 GHz has been shown. The same element spacing of 170 mm is used for three arrays. The element depth is different for the arrays to operate between 300 MHz and 1 GHz with 410 mm for the Vivaldis and 280 mm for BECA. The Vivaldi antennas provide low cross polarization in the principal planes with an average value of -30 dB; however it suffers high cross polarization for large scan angles in the D-plane. The cross polarization component can be as high as the co-polarization component at 45° in the D-plane.

For Vivaldis with a single slotline, the cross polarization is lower than -40 dB in the E- and H-plane. It is -6 dB in the worst case at 45° in the D-plane. For the BECA antenna, the cross polarization is lower than -40 dB in the E- and H-plane over $\pm 45^\circ$ scan volume; in the D-plane, when the element depth is 280 mm, the cross polarization is close to -10 dB for $\pm 45^\circ$ scan at 1 GHz. The cross polarization can be as low as -15 dB for $\pm 45^\circ$ scan at 1 GHz with a shorter element depth of 180 mm. This indicates that the Vivaldi or BECA array element with a shorter element depth can produce a better cross polarization performacne. The total back-wall-to-aperture array depth is required to be as small as half a wavelength to achieve the cross polarization of better than -15dB over the entire scan volume. In conclusion, the BECA array produces an improved cross polarization performance over Vivaldis due to its low profile structures. This leads to easier and more precise polarization calibration in some applications such as radio astronomy.

V. Element Patterns

A dual-polarized 16×16 BECA array with the L configuration has been built and measured. The fabricated array in the anechoic chamber during measurement is shown in Fig. 7. The element is a laser cut aluminium sheet with 1.5 mm in thickness. The element width $d = 173.5$ mm with 1.5 mm extra spacing for the orthogonally-polarized element and therefore the element separation is 175mm. The depth of the element $d = 280$ mm, the depth of the side tapering

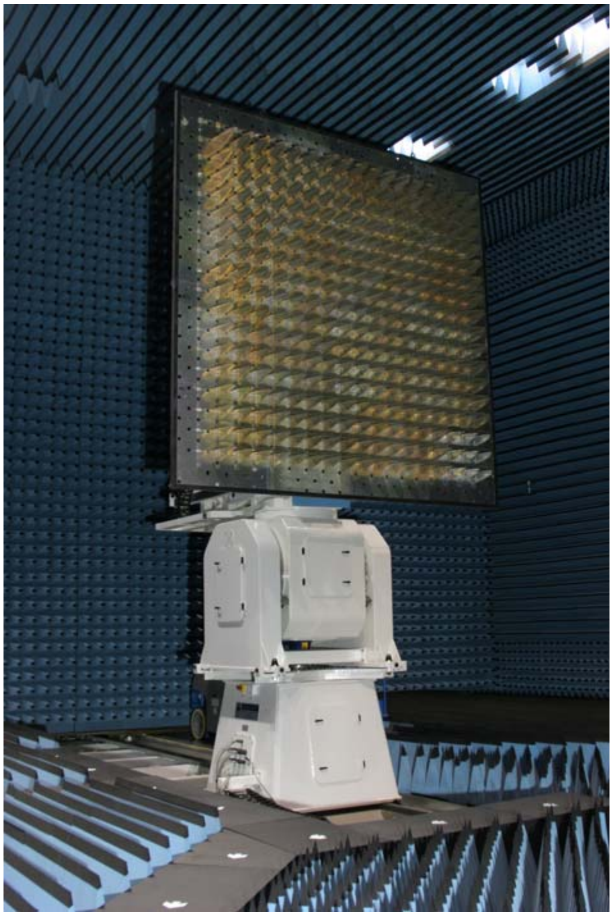
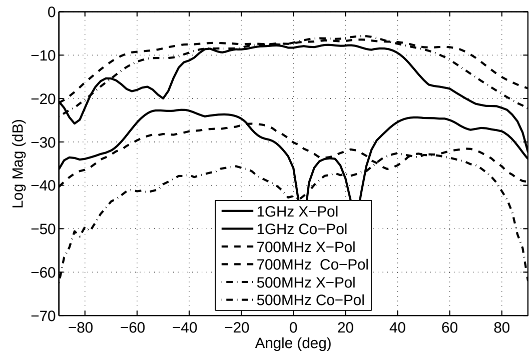


Fig. 7. The fabricated dual polarized 16×16 BECA array, the dimension for the element is: $b = 173.5$mm, $d = 280$mm, $S = 3$mm, $c = 40$mm, $H = 117$mm, $a = 5$mm, $sl = 10$mm, $ss1 = 2$mm, $ss2 = 10$mm, the thickness of the conducting plate is 1.5 mm and therefore the element separation is 175 mm.

$c = 40$ mm. The radiation pattern of the centre element is measured with the rest elements terminated with resistors of 150 ohms.The radiation patterns at three typical frequencies for the centre element of the finite array is shown in Fig. 8. It is indicated that the cross-polarization is below -10 dB over the $45°$ scan range. The ripples shown in the radiation patterns for high frequencies may be cause by the limited size of the finite array.

A subarray of 8×8 elements has been scanned to three directions of broadside, $45°$ in the E-plane and $45°$ in the H-plane. The elements of the subarray are fed through power splitters connected with phase stepped cables. The surrounding elements are terminated with 150 ohms loads. The scanned array co-pol patterns of 1 GHz at three directions are shown in Fig. 9. The loss of gain with scans from broadside to $45°$ in the E-plane is 5.21 dB and it is 3.14 dB when the array is scanned from broadside to $45°$ in the H-plane. We recall that the gain roll-off of the radiation pattern for the centre element in presense of the surrounding elements from broadside to $45°$ in the E- and H-plane is 4.45dB and 1.1dB respectively as shown in Fig. 8. The loss of gain with scans for the finite array is the total loss caused by the element radiation and the reduction of the aperture size when the array is scanned to



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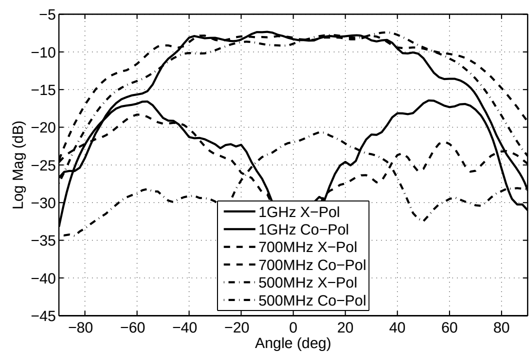

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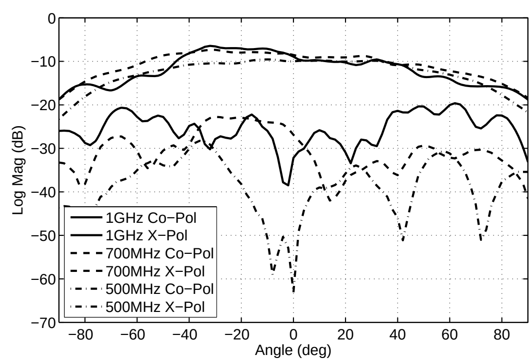

(c)

Fig. 8. The radiation patterns for the centre element in the 16×16 dual polarized finite BECA array (a) E-plane; (b) D-plane; (c) H-plane.

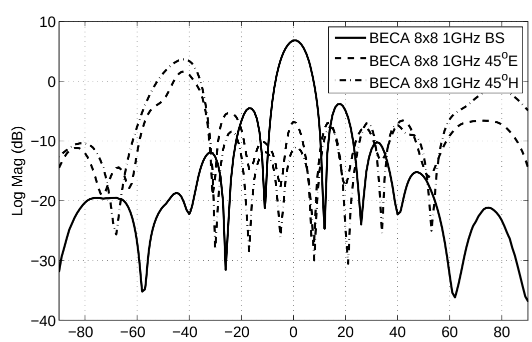

Fig. 9. The scanned array patterns of the 8×8 subarray at 1 GHz in three directions: broadside, $45°$ in the E-plane and $45°$ in the H-plane.

angles off the Zenith.

VI. Conclusions

The elements with taper slot architecture for aperture array systems are investigated. The proposed array with BECA elements provides a somewhat lower level of cross polarization than the basic Vivaldi antennas array due to the low profile and the balanced symmetrical structure. It allows improved control of the impedance resonance effects. The array element can be shorter than one wavelength at the high end of the frequency band for a 3.3:1 frequency bandwidth with the scan volume of $\pm 45^\circ$. The orthogonal elements are arranged in X and L configuration to study the array performance. L configuration for BECA provides an overall better performance. The cross polarization in the worst case of D-plane at 45° scan is lower than -10 dB with better than -40 dB in the principle planes. A lower cross polarization performance can be obtained by using a shorter element depth. The cross polarization over the entire scan volume can be as low as -15 dB with half a wavelength for the total back-wall-to-aperture depth of the array.

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