Study on Impact of Mutual Coupling on Performance of Dual Polarized Phased Array Antenna

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ABSTRACT This study involves the determination of the impact of mutual coupling between antenna elements on the performance of a dual-polarized, wide-angle scanning, phased array antenna for weather radar applications. Weather radars require dual linearly polarized antennas with low cross-polarization, and a narrow beam phased array for wide scanning angle. For this simulation-based study, a microstrip dual linearly polarized 2x20 phased array antenna operating at S-band (2.65 to 3.0 GHz) is designed. This antenna has been designed to have a cross-polarization level less than -45 dB at both polarizations and for the scan angle range of -55^o to 55^o, which is better than most of the existing dual-pol phased array antennas. This antenna has been used to analyze the impact of mutual coupling on cross-polarization, beamwidth, and antenna gain at various scan angles. Mutual coupling is studied in terms of antenna active element pattern and the corresponding cross-polarization value as well as the active reflection coefficient and impedance values for inter-element spacings of 0.4λ and 0.5λ. It has been found in this study that cross-polarization levels of the whole array (at various scan angles) are affected significantly because of mutual coupling between elements.

INDEX TERMS cross-polarization, dual-polarization, mutual coupling, phased array antenna, weather radars

I. INTRODUCTION

POLARIMETRIC weather radars have started using phased array antennas due to the low volume scan time. A planar phased array antenna can sample a given volume in less than two minutes which is much less than the time taken by a mechanically steered antenna. Although phased array antenna can perform measurements with high temporal and spatial resolution, their design and operation are affected due to various non-idealities. Some of them are the geometrically induced cross-polarisation and the mutual coupling between elements [1]. Cross-pol reduces the accuracy of the polarimetric variables. Mutual coupling due to the proximity of various elements cause design issues like non-uniformity in gain, cross-polarization and scan angle range limitation as well as a mismatch in intended and actual scan angles. Thus, the characterization and analysis of mutual coupling on cross-polarization, gain and scan angle range are important to alleviate the effect of these problems during phased array antenna design or calculation of polarimetric variables.

A lot of research has been done on the cross-polarization performance improvement of dual-pol phased array antennas. Granholm et. al. [2] presented a dual-polarized, probe-fed, stacked patch antenna for an operating frequency of 1.2-1.3 GHz with mirrored element pairs arranged in a subarray for cross-polarization suppression. It had a cross-polarization level of -40 dB and isolation between two ports was around 50 dB.

Saeidi et.al. [3] proposed a dual-polarized aperture coupled phased array antenna operating in the frequency band of 2.7-3.0 GHz. The aperture for each polarization was H-shaped and was excited using a microstrip feed line. The antenna used a subarray configuration with four elements where adjacent elements were rotated by 180^o and were fed 180^o out of phase. The array achieved a cross-polarization level of -35 dB for the scan range of $\pm 35^o$. A similar phased array configuration having a single element antenna with a slightly different excitation mechanism was proposed by Saedi et. al. [4]. Both an aperture coupled and a differential probe feed were used for exciting the patch. The horizontal polarization was fed by an H-shaped aperture and the vertical polarization was fed by the differential feed method. Using the subarray technique explained above, the phased array achieved a reduced cross-polarization of -37 dB for scan angle range of $\pm 45^o$.

Zhang et. al. proposed a cylindrical configuration for polarimetric phased-array radar where dual-polarized antenna elements were arranged in a cylindrical shape [5]. The cylinder had multiple sectors that formed simultaneous beams at the center of each sector. Fulton et. al. fabricated a cylindrical phased array working in the frequency range of 2.7-3.1 GHz

[6] [7] with cross-polarization level of -45 dB.

For the above discussed large arrays, mutual coupling between elements causes a change in the input impedance and radiation pattern with scan angle. This is because the change in the input impedance leads to an increase in the reflection coefficient of array elements that limits the scan range as well as the array performance [8]. The mutual coupling has been studied and these effects were characterized in detail [9] and different techniques have been employed to limit the impact of mutual coupling and the resultant surface wave excitation. The impact of mutual coupling have been reduced by placing a varactor or shorting post beneath the patch, substrate modification, defected ground structures (DGS), electromagnetic bandgap structures (EBG), and metamaterial structures between the patches. Kiani et. al. [10] suggested that placing an optimized rectangular slot structure between antenna elements reduced mutual coupling maintaining back lobe and cross-polarization similar to the normal array. Chen et. al. [11] proposed a new method of reducing the mutual coupling by altering the orientation each of the square patch.

Many mutual coupling reduction techniques have been developed but most of them are for single polarization. In addition, most of the analyses that have been performed to determine the impact of mutual coupling on single-polarization antennas are not suitable to use with dual-pol antennas. Considering the above, a theoretical and simulation-based study has been undertaken to understand the impact of mutual coupling between antenna elements on phased array antenna gain, scan angle range, scan angle accuracy, and cross-polarization. A microstrip phased array dual-polarization antenna with 2X20 elements operating at 2.65 to 3.0 GHz has been designed for low cross-polarization of -48 dB in the scan angle range of -55^o to 55^o (in azimuth) as discussed in Sections 2 & 3. Additionally, the mutual coupling effects on cross-polarization levels have been thoroughly analyzed and characterized in Section 4. The active element pattern, active impedance, and active reflection coefficient of the elements in the array have also been studied. Section 5 is the discussion on the findings of this research work as well as the conclusions.

II. DUAL POLARIZATION SINGLE ELEMENT DESIGN

The antenna element used in the array has been designed as a dual-polarized patch antenna and the expanded view of the aperture coupled single antenna element [12] is shown in Figure 1. The antenna has two stacked patches that have substrates below them. The radiating square patches of width 24.4 mm and 27.2 mm are laid on the substrate Taconic TLX with (ϵ_{r2} = ϵ_{r3} = 2.55, h2 = 1.62 mm, h3 = 4.95 mm). This dielectric constant ensures optimum radiation and wide bandwidth of the antenna [13]. Stacking of patches and optimization of the dimensions of the radiating and parasitic patches is done to obtain the required bandwidth [14]. The antenna patches are coupled to feedline using two dumbbell-shaped apertures on the ground plane. The two feedlines for signal transmission are at the bottom substrate Taconic RF-41 with ϵ_{r1}=4.1 and h1=0.78 mm as in Figures 2a and 2b.

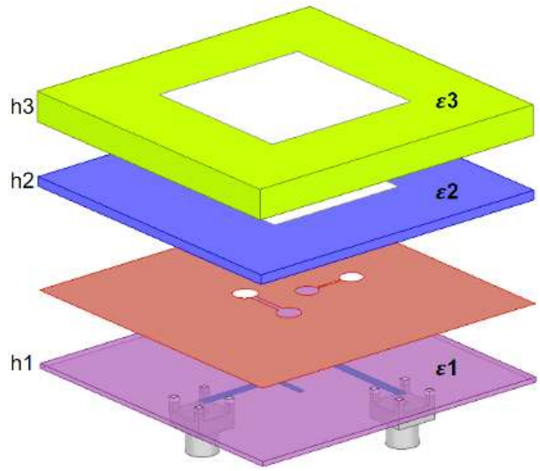
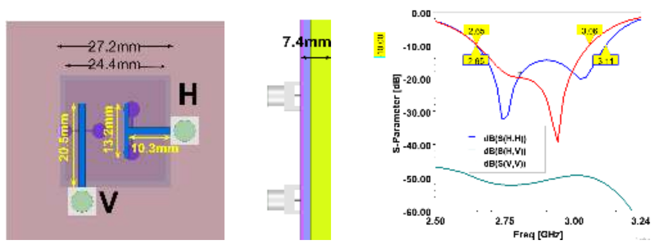


FIGURE 1: Expanded view of the antenna element

The feeding mechanism used here is the aperture coupled feeding technique [15] and has many advantages over other patch antenna feeding techniques. These include reduction of spurious radiations from feed, independent choice of substrates for patch and feed, and increase in bandwidth by using thick substrate while having the least cross-polarization [16] [17].

The two dumbbell-shaped apertures are arranged in T-shape to increase isolation between them. Dimensions and dumbbell shape of the aperture are chosen to obtain the required uniform coupling and cross-polarization suppression. The two feed lines corresponding to H and V polarization aperture are optimized to achieve the required isolation and matching.

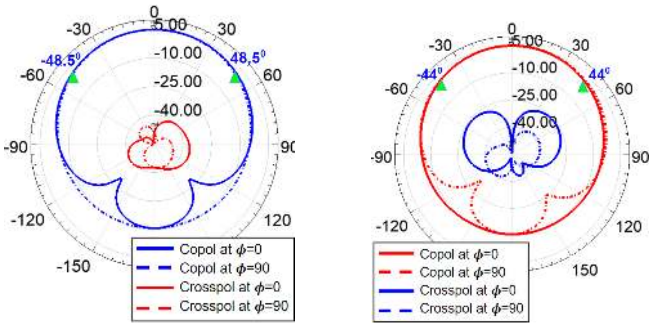


(a) (b) (c)

FIGURE 2: (a) Bottom view of the antenna element (b) Side view of antenna element (c) S-parameter plot

High-Frequency Structure Simulator (HFSS) is used for the simulation. The simulated return loss is less than -15 dB for both H and V ports while the isolation between the ports is more than 50 dB for the frequency range of 2.65 to 3.0 GHz as shown in Figure 2c.

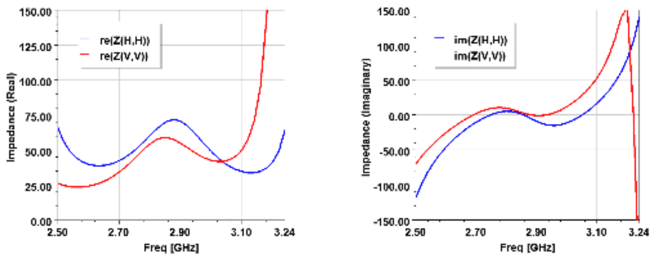
The co-pol and cross-pol gain patterns of the single element for horizontal and vertical polarizations at 2.8 GHz are given in Figure 3a and 3b. At 2.8 GHz, gain is 5 dB and cross-polarization levels in the broadside direction ($\theta = 0^o$)



(a) (b)

FIGURE 3: Gain pattern with (a) H port excited and (b) V port excited

are -53.85 dB and -55.92 dB for H and V polarizations, respectively. The -3 dB beamwidth is approximately 97.8^o and 87.2^o for H and V polarizations. Impedance v/s frequency plots of the single element are also given in Figure 4a and 4b. Real part of the impedance remains between 40 Ω to 70 Ω and the imaginary part is approximately -10 Ω to 10 Ω for the frequency range 2.65 to 3.0 GHz.



(a) (b)

FIGURE 4: (a) Real and (b) Imaginary Impedance plots of single element

III. DUAL POLARIZATION PHASED ARRAY ANTENNA

The single antenna element discussed in the previous section is arranged into a 2X20 array with inter-element spacing of 0.5λ The truncated view of the array is shown in Figure 5. The excitation of the elements is done with progressive phase shifts being applied to each element along with Taylor tapering weights so as to reduce the sidelobe level [13].

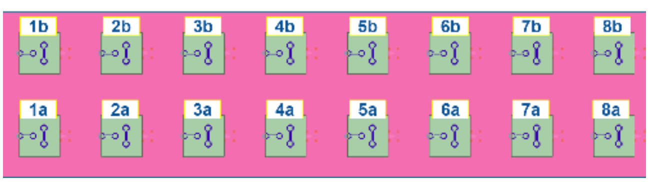
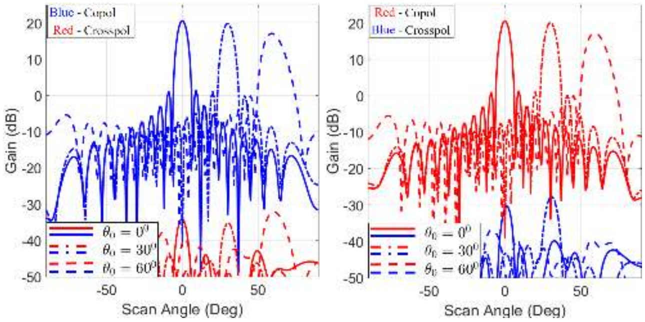


FIGURE 5: Truncated view of the 2X20 array

The gain patterns of the 2X20 element phased array antenna for H and V polarizations at different scan angles ($\theta = 0^o$, $\theta = 30^o$ and $\theta = 55^o$) are given in Figures 6a and 6b, respectively. It can be observed that the gain of the array is 20.5 dB at scan angle 0^o and reduces to 17.5 dB at scan angle 55^o for H and 18 dB for V-polarization as shown in Figure 7. On the other hand, beamwidth broadening at scan angles away from broadside direction is approximately similar for both polarizations. At scan angle $\theta = 0^o$, beamwidth is 5.7^o and increases to 11^o at $\theta = 55^o$ as seen in Figure 7. In



(a) (b)

FIGURE 6: Gain pattern for a 2X20 array with (a) H and (b) V polarization and spacing= 0.5λ

addition, for both H and V polarizations, sidelobe level at scan angle 0^o is around -20 dB, and sidelobe level increases to -17.5 dB at scan angle 55^o. One of the most important antenna characteristics in this work is the cross-polarization level range from -51 dB to -48 dB as the beam is steered from 0^o to 55^o for H-pol. The grating lobes are do not affect the antenna performance at a scan angle of 0 to 55^o. However, the grating lobe values increase with an increase in scan angle beyond 55^o. The grating lobe becomes significant when the scan angle is increased beyond 60^o.

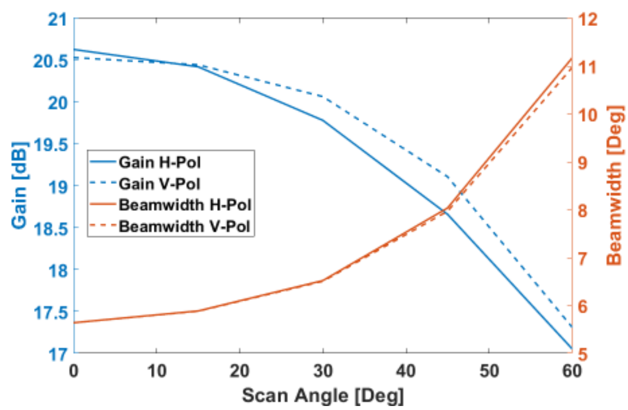


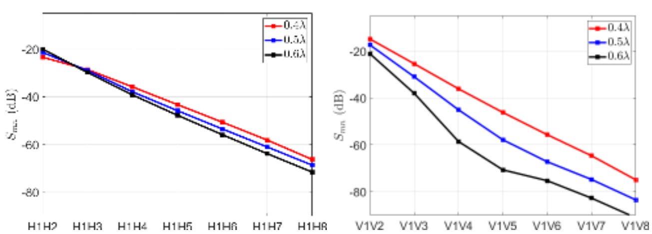
FIGURE 7: Variation in gain and beamwidth of the 2X20 array with scan angle

Grating lobes reduction can be achieved for wide angle scanning by using lower inter-element spacing. However, reducing the inter-element spacing lower than 0.5λ has the impact of increasing the mutual coupling between elements, which in turn increases scan blindness because of higher reflection coefficient at higher scan angles. Thus, the scanning angle cannot be increased beyond 55^o for this particular design.

IV. MUTUAL COUPLING EFFECTS ON ANTENNA CHARACTERISTICS

When two antennas elements are close to each other, some of the energy from one ends up getting coupled to the other [13]. Thus, the current developed in each antenna element is a combination of its excitation and also that coupled from the adjacent antenna element. The amount of coupling is determined by the radiation characteristics of each element, separation between the elements as well as the orientation of the elements to each other. This coupling of energy occurs in microstrip antenna primarily due to surface waves and radiation coupling. This interchange of energy is known as mutual coupling and makes the analysis and design of a phased array antenna very difficult to optimize.

The mutual coupling between various elements of the 2X20 element array (discussed in Section III) is characterized here based on S-parameter values. The S-parameter values are determined between edge element (H1) and other elements (H2 to H8) in the array for inter-element spacing of 0.5λ for both polarizations. The results are shown in Figure 8a and 8b and it can be observed from Figure 8a (for horizontal polarization ports) that the S-parameter values between the linearly placed elements (H1 to H8) decrease from -20 to -70 dB. When the inter-element spacing is changed, the S-parameter between H1 and H3 is -38 dB for 0.4λ and -40 dB for 0.6λ. However, the S-parameter between H1 and H8 is -66 dB for 0.4λ and -70 dB for 0.6λ. Thus, the decrease in S-parameters value with change in inter-element spacing is more for 0.6λ than for 0.4λ. For V-ports (inter-element spacing of 0.5λ), S-parameter values decrease more significantly (-20 dB to -85 dB) from V1 to V8 than for H-polarization. When the inter-element spacing is 0.6λ for V-polarization, the S-parameter between V1 and V8 decreases from (-20 to -90 dB) Also, an increase of 0.1λ in the inter element spacing decreases the S-parameter values by approximately 10 dB for V-polarization and about 3 dB for H-polarization. Thus, the mutual coupling is different for H and V polarization elements.



(a) (b)

FIGURE 8: Mutual coupling effects for (a) H and (b) V Ports for 2X20 Array at 2.8 GHz at d=0.4λ, d=0.5λ and d=0.6λ

Thus mutual coupling is inversely proportional to the spacing between antenna elements. Mutual coupling impact can be characterized based on active element pattern, active impedance, active reflection coefficients as well as the analysis of the impact on the cross-polarization level. These analyses have been performed and have been explained in the next few subsections.

A. ACTIVE REFLECTION COEFFICIENT

Active reflection coefficient at the element ports of a phased array antenna is depended on the matching of the input port to the antenna as well as to the excitation of the surrounding array elements and it varies as a function of scan angle [18]. The feed ports of a phased array can be characterized by an N x N scattering matrix using

$$S_{mn} = \frac{V_m^-}{V_n^+}\Big|_{V_k^+=0 \text{ for } k\neq 0} \tag{1}$$

where V_m^+ and V_m^- are the incident and reflected voltage wave amplitudes at the mth element.

The active reflection coefficient at the mth element is,

$$\Gamma_m(\theta_0) = \frac{V_m^-}{V_m^+} = e^{jkmd\sin\theta_0}\sum_{n=1}^{N} S_{mn}e^{-jnd\sin\theta_0} \tag{2}$$

where θ_0 is the angle to which the array is steered to.

Active reflection parameter tends to increase with an increase in scan angle and also increases as the distance between elements decreases. It can seen from Equation (2) that $\Gamma_m(\theta)$ does not depend on scan angle only if $S_{mn} = 0$ for all $m \neq n$. i. e., if there is no mutual coupling between ports. Thus, it is important to analyze the Γ_m for various scan angles at different inter element spacing.

Let the first row of the 2X10 array be denoted by a and second row by b as in Figure 5. For the edge element 1 of the first row (denoted by $1a$), active reflection coefficient can be written as,

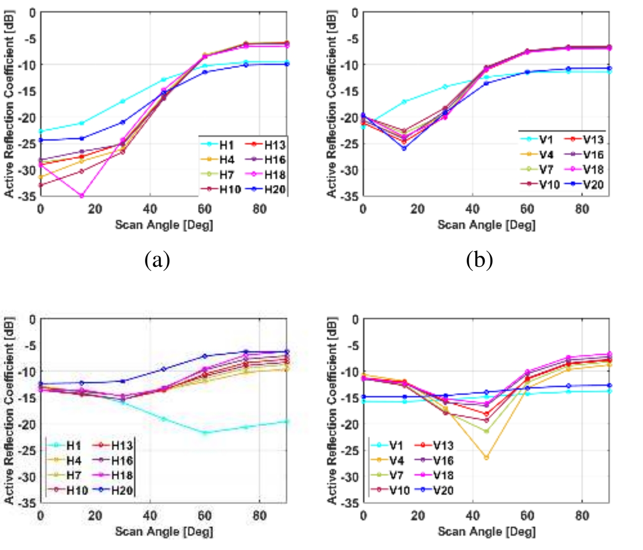
$$\begin{aligned}\Gamma_{1a}(\theta_0) = e^{jk(1a)d\sin\theta_0}[&S_{1a1a}e^{-j(1a)d\sin\theta_0}+\\ &S_{1a2a}e^{-j(2a)d\sin\theta_0}+\\ &S_{1a1b}e^{-j(1b)d\sin\theta_0}+...]\end{aligned} \tag{3}$$

where S_{1a2a} is the S-parameter value between ports $1a$ and $2a$ and so on. Active reflection coefficient of a central element of the first row (denoted by $10a$) can be shown as,

$$\begin{aligned}\Gamma_{10a}(\theta_0) = e^{jk(10a)d\sin\theta_0}[&S_{10a10a}e^{-j(10a)d\sin\theta_0}+\\ &S_{10a9a}e^{-j(9a)d\sin\theta_0}+\\ &S_{10a10b}e^{-j(10b)d\sin\theta_0}+\\ &S_{10a11a}e^{-j(11a)d\sin\theta_0}+...]\end{aligned} \tag{4}$$

Active reflection coefficient for edge element determined using (3) shows that it is impacted primarily by two elements while the active reflection coefficient for center element determined using (4) shows that it is impacted primarily by three elements. Thus, the mutual coupling effect for edge element is lower than that of the center element.

The active reflection coefficient of H and V-ports (for various element locations) for element spacing of 0.5λ for a range of scan angles is simulated and shown in Figure 9a and 9b. The active reflection coefficient is between -20 to -35 dB for all elements at scan angles between 0 to 20^o for both polarizations. As the scan angles change from 20^o to 40^o the coefficients ranges from -15 to -20 dB. However, it can be observed that for both the polarization, the active reflection coefficient is below -10 dB for scan angles above 55^o. These reflection coefficient values restrict the scan angle range up to $\pm 55^o$.



(c) (d)

FIGURE 9: Active S-Parameters for some of the (a) H and (b) V Ports at d=0.5λ and for (c) H and (d) V Ports at d=0.4λ of a 2X20 Array at 2.8GHz

In continuation, another analysis has been performed to determine the impact of mutual coupling on the active reflection coefficient for inter-element spacing of 0.4λ and the analysis is shown in Figure 9c and 9d. The active reflection coefficient is in the range of -10 to -15 dB for the scan angle of 0 to 20^o for both polarizations. It is in the range of -15 to -25 dB for the scan angle range of 20^o to 50^o for both polarizations. However, it can be observed that the active reflection coefficient from 0^o to 50^o is higher for element spacing 0.4λ than those of 0.5λ. This increase in reflection coefficient is due to mutual coupling which usually leads to scan blindness and limits the scan angle range of the phased array antenna at scan angle of 55^o and above.

It can also be observed that the edge elements of the 2X20 array show a trend different from those shown by other elements in the array. The first (H1 and V1) and last (H20 and V20) elements active reflection coefficient show values lower than -10 dB for scan angles range 0 to 80^o. This is because of the mutual coupling between edge elements and two elements while non-edge elements are affected primarily by three surrounding elements and this is confirmed by (3) and (4). Thus, the scan angle range is dependent on active reflection coefficient of all elements and not just the center elements.

B. ACTIVE ELEMENT PATTERN

Active element pattern plays an important role in determining the performance of the overall phased array pattern (for large array), the maximum gain in a particular scan direction and cross-polarization. The active element pattern is obtained by exciting a single radiating element and matching all other elements as shown in Figure 10. This co- and cross-pol pattern will be different from the isolated element pattern because of the mutual coupling with the adjacent elements [18] [8] [19].

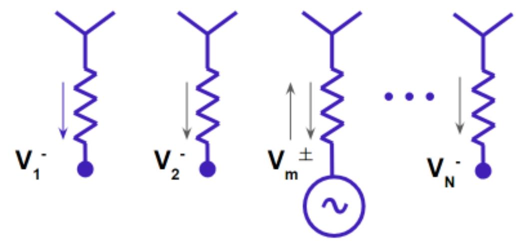


FIGURE 10: Schematic view of array of N elements with only m^{th} element excited

The radiated electric and magnetic fields for the array where the mth element is driven with voltage V_0 and all others are terminated are [18],

$$\begin{aligned} E_m^e(\theta) &= E_0(\theta)\sum_{n=1}^{N} V_n e^{-jknd\sin\theta} \\ &= V_0 f_0(\theta)[1+e^{jkmd\sin\theta}\Gamma_m(-\theta)]\frac{e^{-jkr}}{r} \end{aligned} \tag{5}$$

$$\begin{aligned} H_m^e(\theta) &= H_0(\theta)\sum_{n=1}^{N} I_n e^{-jknd\sin\theta} \\ &= \frac{V_0 f_0(\theta)}{\eta_0}[1-e^{jkmd\sin\theta}\Gamma_m(-\theta)]\frac{e^{-jkr}}{r} \end{aligned} \tag{6}$$

where $f_0(\theta)$ is the isolated pattern of the single element and V_n is the total voltage at nth element. The gain of the fully excited array for $\theta = \theta_0$ is [18],

$$\begin{aligned} G_m^e(\theta_0) &= \frac{4\pi r^2}{P_{inc}} Re(E_m^e H_m^{e*}) \\ &= \frac{4\pi f_0^2(\theta_0)}{N\eta_0}\left[N^2 - \left|\sum_{n=1}^{N}\Gamma_n(\theta_0))\right|^2\right] \end{aligned} \tag{7}$$

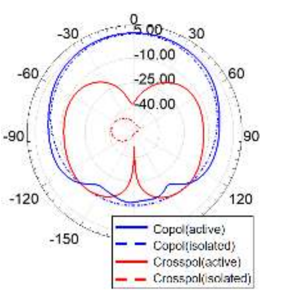
where P_{inc} is the incident power, N is the number of elements and η_0 is the intrinsic impedance of free space. The active element pattern is directly related to the active reflection coefficient magnitude of the fully excited phased array.

If the array is finite, only the elements at the center will have similar active element patterns. Active element pattern is determined for centre element and is compared with the isolated element pattern. Figures 11a and 11b show the comparison of both H and V polarization of the 2X20 phased array with 0.5λ inter-element spacing. The main beam width of isolated element is 86^o and 96^o for H and V polarizations and increases to 98^o and 100^o in their active element pattern, respectively. It has to be noted that cross polarization level of the isolated element is -53 dB and -55 dB for H and V polarizations while for the active element pattern of the central element, it is -43 dB and -49 dB. This clearly shows that the mutual coupling increases beamwidth and degrades cross-polarization level of a dual polarized antenna.

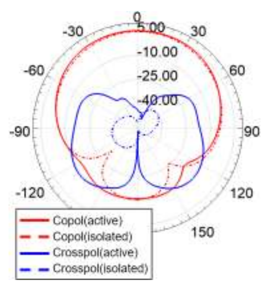
The next analysis is to compare the active element patterns of central elements when inter-element spacings are 0.4λ and 0.5λ and the results shown in Figures 12a and 12b. Figure 12a shows that the cross-polarization of H-polarization for 0.4λ spacing deteriorates by 7.5 dB in comparison to 0.5λ spacing. Similarly, for V-polarization, cross-polarization level for 0.4λ spacing is 5.9 dB higher than that of 0.5λ spacing. Thus, it is clear that as the elements are brought closer in a phased array, there is a considerable degradation in the cross-polarization level. In addition, beamwidth of the active element pattern is another characteristic that has to be analyzed. Here the H-polarization at $\phi = 90^o$ increases from 105^o to 123^o as the inter-element spacing is decreased from 0.5λ to 0.4λ. Also, the beam width for V-polarization increases from 104^o to 111^o as the inter-element spacing is changed from 0.5λ to 0.4λ. In addition, gain at $\theta = 0^o$ decreases from 5.25 dB to 3.21 dB for H-polarization and 5.21 dB to 3.05 dB for V-polarization as the spacing is changed from 0.5λ to 0.4λ. Thus, active element pattern characteristics get significantly affected as a result of the inter-element spacing variation. In addition, cross-polarization of active elements can be related to the cross-polarization of full array at various angles.

C. ACTIVE IMPEDANCE

Active impedance is the impedance looking into a single element of an array considering the effect of excitation of all other elements in the array. It depends on layout of the array, spacing between elements, and the steering angle. Impedance varies as a function of scan angle due to mutual coupling

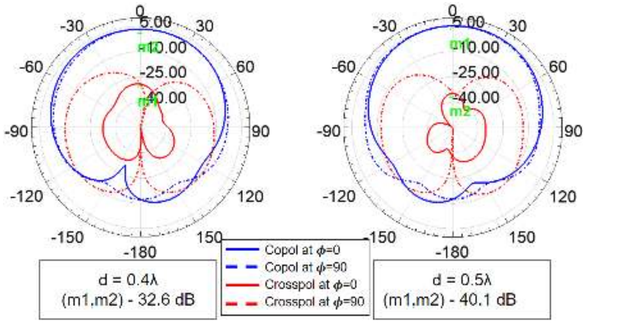


(a)

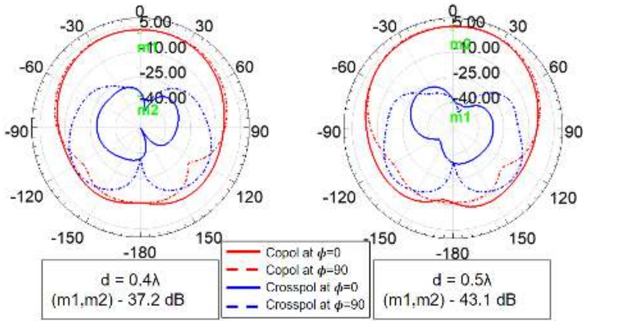


(b)

FIGURE 11: Active element patterns and isolated element patterns for (a) H and (b) V-polarization



(a)



(b)

FIGURE 12: Active element patterns for 0.4λ and 0.5λ spacing for (a) H and (b) V polar izations

between elements. The active input impedance at the mth element at a scan angle θ_0 is given as,

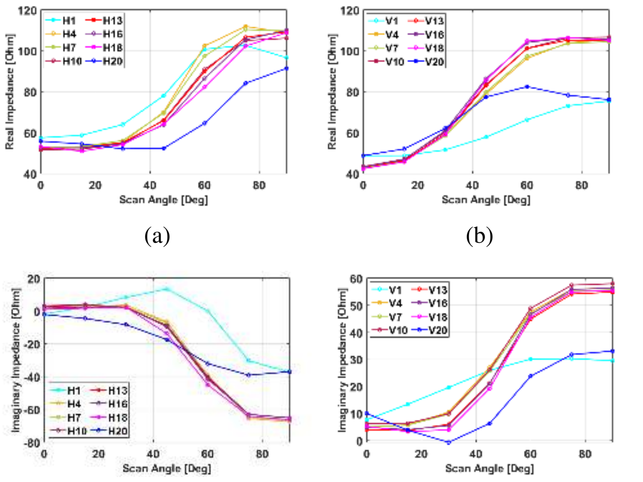
$$Z_{in}^m(-\theta_0) = Z_0 \frac{1 + \Gamma_m(-\theta_0)}{1 - \Gamma_m(-\theta_0)} \tag{8}$$

where $\Gamma_m(-\theta_0)$ is defined in (2). For large arrays, active impedance is related to active element pattern [19]. Figure 13 shows the variation in real and imaginary impedance values with scan angle.

The real part of impedance (resistance) remains at 50 Ω at angles near broadside. It deviates from 50 Ω as the elements are excited with phase shifts for higher scan angles above 50^o. At scan angle 60^o, the impedance value of different ports is in the range of 80-100 Ω for H-polarization. For V-polarization, it is higher than 100 Ω for scan angles above 60^o. The imaginary part of the impedance deviates from 0 Ω at higher scan angles. For H-polarization ports, the imaginary value decreases to -40 Ω at scan angle 60^o and tends to show capacitive nature. Whereas, impedance values of V-ports seem to become more inductive and increases up to 50 Ω at scan angle 60^o.

D. VARIATION OF GAIN DUE TO MUTUAL COUPLING

As already shown in Section IV.B the reduction in inter-element spacing reduces the level of gain of active element pattern. In addition, mutual coupling also impacts the overall phased array gain as already shown in Equation (7). It also shows that gain of the array at an angle is proportional to the



(a) (b)

(c) (d)

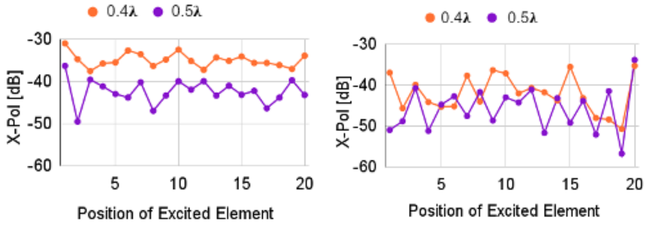
FIGURE 13: Active Z-Parameters for some of the (a) real (Z) H and (b) real (Z) V (a) imag (Z) H and (c) imag (Z) V of 2X20 Array at 2.8 GHz and d=0.5λ

active element pattern gain in that direction. This relation is verified based on simulation results of 2X20 antenna arrays with 0.4λ and 0.5λ inter-element spacing while steered to 0^o and 30^o. Gain of the 2X20 array at scan angle 0^o with 0.5λ inter-element spacing is 20.62 dB and 20.53 dB for H and V polarizations, respectively. When spacing is reduced to 0.4λ, gain at scan angle 0^o is reduced to 18.8 dB and 18.5 dB for H and V polarizations, respectively. At scan angle 30^o, gain of the array with 0.5λ is to 19.78 dB and 20.06 dB for H and V polarizations. Also, for spacing of 0.4λ, the gain of the array is to 17.92 dB and 18.08 dB for H and V polarizations.

E. IMPACT OF MUTUAL COUPLING ON CROSS-POLARIZATION OF ELEMENTS

Considering the variation of active element cross-polarization with change in inter-element spacing, it is important to analyze the cross-polarization of active element based on location in the array.

The aim is to determine the cross-polarization for the active element pattern of each of the 2X20 array elements. Figure 14 shows the cross-polarization level of the active element patterns of the elements at different positions in the 2X20 array for varying inter-element spacings (0.5λ and 0.4λ). As the position of the element changes, the cross-pol changes. The cross-pol for H-polarized element with spacing 0.5λ is below -45 dB for all elements except the one on the edge. The cross-pol for H-polarized 0.4λ separated elements is in the range of -30 dB to -40 dB. The edge element consistently shows high cross-polarization. The cross-pol level for V-polarization elements for 0.5λ spacing is below -45 dB. However, it can be seen that the cross-pol level for the array with spacing 0.4λ is higher for most of the elements as in Figure 14b. So, both H- and V-polarization elements have a better cross-pol level for elements spacing of 0.5λ than 0.4λ.



(a) (b)

FIGURE 14: Cross-polarization level of active element patterns at different positions in the array for (a) H and (b) V polarizations

F. VARIATION OF CROSS-POLARIZATION OF A PHASED ARRAY WITH CHANGE IN THE NUMBER OF ELEMENTS

To complement the above analysis the cross-polarization was determined for the whole array of 2XN elements where N is the number of columns. Figure 15 shows the variation of the cross-polarization level at the main beam direction ($\theta_0 = 0^o$ and $\theta_0 = 30^o$) for arrays with different numbers of elements. Variation of cross-polarization for both H and V polarizations is analyzed and presented in the Figure. It can be seen that the cross-polarization level is inversely related to the number of elements for H-polarization while it increases with the number of elements for V-polarization. For both the polarizations, cross-polarization level increases when the beam is steered to scan angle $\theta_0 = 30^o$. There is about a 4 dB difference in the cross-polarization level of scan angle $\theta_0 = 0^o$ and $\theta_0 = 30^o$ for V-polarization.

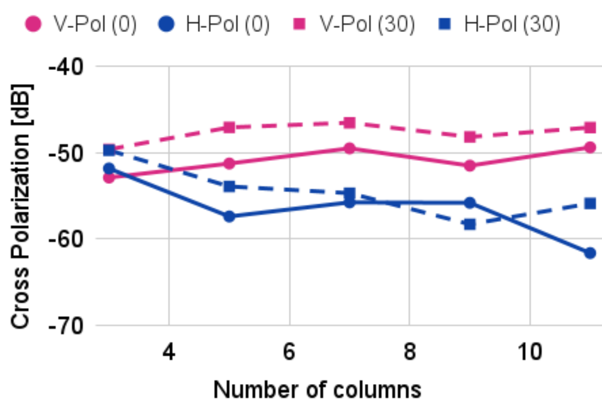


FIGURE 15: Cross-polarization level for different scan angles for the 2X20 array

V. CONCLUSIONS AND DISCUSSION

The performance of phased array antenna is known to be affected because of mutual coupling between array elements. The antenna parameters that are impacted are gain, beamwidth and scan angle range that are studied in detail in this work. However, in this study the impact of mutual coupling on cross-polarization values of antennas is also analyzed.

For this study, a stacked aperture coupled patch antenna operating in the frequency range of 2.65 to 3.0 GHz was used to design a low cross-polarization phased array that scans from -55^o to $+55^o$. Stacking of two patches was done to improve the bandwidth of the antenna. The aperture in the ground plane is chosen to have a dumb-bell shape that has better cross-polarization levels than any other shape. Simulation results show that the cross-polarization level of the isolated single element is -53.85 dB and -55.92 dB for H and V polarizations, respectively. The single element was arranged into a 2X20 array with Taylor tapering weights applied at the ports to control the side-lode level. Gain patterns of the array at different scan angles were simulated and both H and V polarizations had a cross-pol level below -48 dB for all scan angles from -55^o to $+55^o$.

The initial analysis involves determining the extent of mutual coupling based on variation of S-parameters with distance. S-parameters are determined for different element spacings of 0.4λ, 0.5λ, and 0.6λ. The S-parameter values for H-pol linearly placed elements (H1 to H8) decrease from -20 to -70 dB for all inter-element spacing considered here. For the V-pol the S-parameter values reduce from -20 to -85 dB. However, the S-parameter gradient for V-pol are -10 dB, -15 dB, -20 dB for 0.4λ, 0.5λ and 0.6λ, respectively. Thus, the mutual coupling is highest for 0.4λ and least for 0.6λ. Mutual coupling effects are characterized using active reflection coefficient, active impedance, and active element pattern. The active reflection coefficients for various ports in the array for 0.4λ and 0.5λ spacings were observed to increase significantly with scan angle (away from broadside direction) and with a decrease in distance between elements. The active reflection coefficient is higher than -10 dB for scan angles above $+55^o$. This increase in the reflection coefficient affects array gain pattern adversely by reducing the gain from 5 to 3.2 dB for both polarizations. Active impedance analysis is performed and it is observed that the active impedance real part values of various ports increase above 50 Ω and imaginary values changes from 0 Ω when the scan angles become higher than $+55^o$.

The most significant findings of the study are the impact of mutual coupling on cross-polarization performance of phased array antennas. The cross-polarization of active element pattern is observed to degrade with decrease in distance between elements. The degradation is approximately 5-10 dB in the broadside direction and gets worse at higher scan angles for both polarizations. The variation in cross-polarization of active element with change in location of the element in the array is also tested and the results are presented. It has been observed that the cross-polar performance varies in the range of -35 to -45 dB at all locations for both polarizations. The overall array performance in terms of cross-polarization (scan angles of interest) degrades due to mutual coupling and the degradation is close to 3 to 5 dB. Thus, mutual coupling effects on the cross-polarization values are analyzed for the first time and this analysis is comprehensive and will be very useful for phased array antenna design aspects.

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