0.1 Hybrid Feed Microstrip Patch Antenna Array; Balanced Probe-Feed and Symmetric Aperture Coupling Method

This section presents the design, fabrication and characterization of a high-isolation, low cross-polarization dual-polarized hybrid-fed patch antenna arrays for Multi-Function Phased Array Radar (MPAR) applications. Its hybrid feed design has been implemented, and the vertical and horizontal polarizations are excited by a balanced-probe feed and a slot-coupled feed, respectively. The presented Simulations and measurements in **??** have demonstrated an input isolation of 45 dB and 43 dB between the horizontal and vertical ports respectively for the designed single element. In this section, for further improvement in the cross-polarization level, the image feed method is also implemented, and a 2×2-element array made up of designed elements with image configuration has been fabricated. The simulated and measured S-parameter and radiation patterns of the horizontal and vertical polarizations of the designed 2×2-element array are presented and the measured cross-polarization level of less than -37 dB is achieved. To examine the performance of the designed element in an array, a 3×3-element array of designed 2×2-element subarray is fabricated and tested. In the 6×6-element measurements, -35.4 dB and -36 dB cross-polarization levels for horizontal and vertical polarizations are achieved respectively. Also, using the measured embedded element patterns, the cross-polarization level lower than -36 dB for scan angles up to 45°is achieved.

0.2 2×2-element array configuration

For further improvement on the cross-polarization level, the image feed method is applied to the 2×2-element array of the designed single element **woelder1997cross**, **rahmat2006novel**. In this configuration, the upper right and lower left elements in the 2×2-element array are mirrored with respect to the vertical plane. In this configuration, the phase of the copolarization pattern of mirrored element will be 180°out of phase compared to the original element. On the other hand, the phase of cross-polarization pattern won't change by mirroring the element. To compensate for the 180°phase shift in the copolarization pattern, the mirrored elements are excited with a 180°phase shift. Consequently, the copolarization pattern of two elements will be in phase and the cross-polarization patterns will be 180°out of phase, so the cross-polarization pattern will be canceled, especially in the principal planes.

Chapters/Ch4_Figs/Fab2.pdf

(a)

Chapters/Ch4_Figs/Fab1.pdf

(b)

Figure 1: Geometry of fabricated 2×2-element array of designed single element with image configuration. (a) Top view, (b) Bottom view.

The geometry of the fabricated 2×2-element array antenna is shown in Fig. 1. The fabricated array antenna is tested in the far-field anechoic chamber of

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(a)

Chapters/Ch4_Figs/Meas2x2/Hphi0_s.pdf

(b)

Chapters/Ch4_Figs/Meas2x2/Vphi0_s.pdf

(c)

Chapters/Ch4_Figs/Meas2x2/Vphi90_s.pdf

(d)

Figure 2: Measured normalized radiation pattern of 2×2-element array of designed single element with image configuration. (a) H-Pol, $\varphi = 0°$; (b) H-Pol, $\varphi = 90°$; (c) V-Pol, $\varphi = 0°$; (d) V-Pol, $\varphi = 90°$

the Advanced Radar Research Center (ARRC) and the measured results at 2.7 GHz, 2.8 GHz, and 2.9 GHz are presented in Fig. 2. Also, not shown here, the simulated cross-polarization level of the 2×2-element array with image configuration is below -80 dB for horizontal polarization and below -56 dB for vertical polarization. As shown in Fig. 2 the maximum measured cross-polarization level in the whole bandwidth is below -40 dB above the ground plane ($\theta = -90°$ to $\theta = 90°$) for both polarizations in the $\varphi = 0°$ plane. In the $\varphi = 90°$ plane the cross-polarization level is below -37 dB.

Although there is a gap between the maximum measured and simulated cross-polarization levels, it should be noted that the difference between -56 dB and -40 dB is less than 10^{-4}. Therefore, small backscattering from the cable and pedestal could increase the cross polarization to -40 dB. Also, the cross-polarization level of the standard transmitter antenna in the test will increase the measured cross-polarization level.

0.3 6×6-Element Array

A 6×6-element array of proposed dual-polarized hybrid feed patch antenna has been designed and fabricated to validate the radiation characteristics of the 2×2-element subarray, especially its low cross-polarization level. As shown in Fig. 3 the fabricated 6×6-element array is made of 9, 2×2-element subarrays, mounted on a fixture made of Polycarbonate and Acrylic.

The radiation pattern of the fabricated 6×6-element array is measured in the far-field anechoic chamber of ARRC. Fig. 4 shows the array antenna horizontal and vertical polarizations' radiation patterns at 2.7 GHz, and 2.8 GHz, and 2.9 GHz. In the $\varphi = 0°$ plane the cross-polarization level is below -35.4 dB and -36.1 dB for horizontal and vertical polarization respectively. As shown in Fig. 4 in $\varphi = 90°$ plane the cross-polarization level for horizontal polarization is below -35.5 and for the vertical polarization it is below -36 dB.

The 6×6-element array is used to predict the co and cross-polarization level of large arrays by using its measured embedded element pattern. Since the elements in the center 2×2-element subarray are not identical, each element in the center 2×2-element subarray is separately excited while all other elements

Chapters/Ch4_Figs/array_back.pdf

(a)

Chapters/Ch4_Figs/array_front.pdf

(b)

Figure 3: Geometry of fabricated 6×6-element array of designed single element with image configuration. (a) Back view, (b) Front view.

are terminated. Accordingly, the four measured embedded element patterns are used to characterize a large array radiation pattern. The measured embedded element patterns have been used to calculate the radiation pattern of a 20×20-element array. The horizontal and vertical polarizations radiation patterns of the 20×20-element array in $\varphi = 0°$ and $\varphi = 90°$ planes at 0°, 15°, 30°, and 45° scan angles are shown in Fig. 5 and Fig. 6. For horizontal polarization in $\varphi = 0°$ and $\varphi = 90°$ planes the maximum cross-polarization level at broadside is below -38.55 dB and cross-polarization level remains under -36 dB across the scanning to 45°. For the vertical polarization in $\varphi = 0°$ and $\varphi = 0°$ planes the cross-polarization level at broadside is below -38 dB and it remains below -36dB while the main beam direction is steered to 45°.

In this section, the design, simulation, and measurement results of a 2×2-element array of low cross-polarization, high-isolation hybrid feed dual-polarized microstrip patch antenna are presented. An input isolation of better than 45 dB and 43 dB are achieved in simulation and measurement respectively. The

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(a)

Chapters/Ch4_Figs/Measured6x6/A_Phi90.pdf

(b)

Chapters/Ch4_Figs/Measured6x6/A_Phi0.pdf

(c)

Chapters/Ch4_Figs/Measured6x6/B_Phi90.pdf

(d)

Figure 4: Measured radiation pattern of 3×3-element array of designed 2×2-element subarray (6×6-element array) at 2.7 GHz, 2.8 GHz, and 2.9 GHz; (a) H-Pol, $\varphi = 0°$, (b) H-Pol, $\varphi = 90°$, (c) V-Pol, $\varphi = 0°$, (d) V-Pol, $\varphi = 90°$.

elements in 2×2-element array is arranged in image configuration and -56 dB maximum cross-polarization level is achieved in simulations. The radiation pattern of the 2×2-element array was measured in the ARRC far field anechoic chamber and showed a -37 dB maximum cross-polarization level. Also, the cross-polarization level of less than -40 dB at the location of the co-polarization peak is achieved which shows that the proposed element could

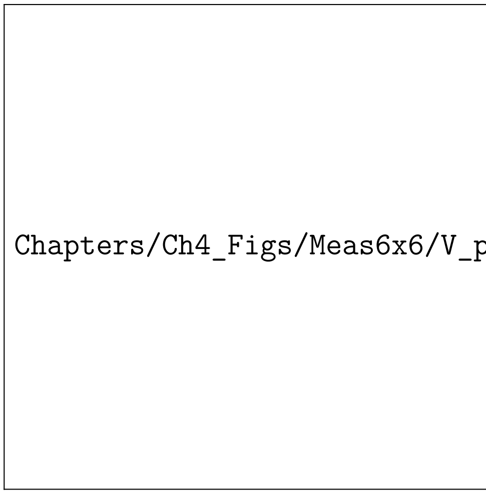
Chapters/Ch4_Figs/Meas6x6/H_phi0_v2.pdf Chapters/Ch4_Figs/Meas6x6/H_phi90_v2.pdf

(a) (b)

Figure 5: **Measured radiation pattern of 3×3-element array of designed 2×2-element subarray (6×6-element array) at 2.7 GHz, 2.8 GHz, and 2.9 GHz; (a) H-Pol, $\varphi = 0°$, (b) H-Pol, $\varphi = 90°$.**

be an ideal choice for the weather and MPAR applications.

To examine the co and cross-polarization radiation pattern characteristics of the designed 2×2-element subarray at the scan angles, a 3×3-element array of 2×2-element subarray is fabricated and tested. The radiation pattern of the 6×6-element array is measured and the cross-polarization levels of -35.4 dB for horizontal polarization and -36 dB for vertical polarization are achieved. Also, the radiation pattern of each element in the center 2×2-element subarray is measured and the measured embedded element patterns are used for calculating the radiation pattern of 20×20-element array at four scan angles from $\theta = 0°$ to $\theta = 45°$ in $\varphi = 0°$ and $\varphi = 90°$ planes and the cross-polarization level of lower than -36 dB is achieved.



(a)

(b)

Figure 6: **Measured radiation pattern of 3×3-element array of designed 2×2-element subarray (6×6-element array) at 2.7 GHz, 2.8 GHz, and 2.9 GHz; (a) V-Pol, $\varphi = 0°$, (c) V-Pol, $\varphi = 90°$.**

0.4 Hybrid Feed Microstrip Patch Antenna Array; Balanced and Symmetric Aperture Coupling Method

In this section, the radiation characteristics of a dual-polarization, aperture coupled hybrid feed microstrip patch antenna is presented. As mentioned in **??**, single element the horizontal and vertical polarization are excited using aperture coupling method. The measured cross-polarization level of lower than -30 dB and input isolation of better than 50 dB are achieved for the designed single element. To achieve a better cross-polarization level, the $2\times$ 2-element array of the designed single element while the horizontal polarization ports are mirrored with respect to the vertical plane is designed and fabricated. Using the cross-polarization suppression methods, the cross-polarization level of better than -39 dB is achieved in the measurement results. Finally, to characterize the scan performance of the designed element and subarray, a 4×10-element array of proposed hybrid feed element is fabricated and the cross-polarization level of lower than -45 dB is achieved while scanning up to 45°.

0.5 2×2-element array configuration

Cross-polarization suppression in dual-linear polarization array antenna is studied in many papers**woelder1997cross**, **saeidi2017cross**. Any dual-polarized antenna requires two individual ports for exciting orthogonal polarizations, and more or less in dual-polarized antennas it is desired to achieve low cross-polarization level. An ideal dual-polarized patch antenna can be designed while each polarization is excited with two 180° out phase ports which is called ideal differential feed patch antenna. The advantage of using ideal differential feed patch antenna is its extremely low cross-polarization level, especially in the principal planes. However, an ideal differential feed requires external 180° phase shifters. In a large array antenna, the increased number of connectors, cables, and phase shifters would significantly increase fabrication costs. An alternative solution for reducing cross-polarization level is to arrange the elements of the array into the groups of 2×2-element identical subarray in which the horizontal polarization ports are mirrored with respect to vertical planes. This method of improving cross-polarization level is implemented in this design. The geometry of fabricated 2×2-element subarray of the designed single element with the image configuration is shown in Fig. **??**. Similar to an ideal differential feed antenna the mirrored ports are excited with a 180° phase shift.

The measured radiation pattern of the fabricated 2×2-element subarray of the designed single element is shown in Fig. 8 and Fig. 9. As seen from Fig. 8 and Fig. 9, the cross-polarization level for both polarizations in the $\varphi = 0°$ and $\varphi = 90°$ planes in the entire frequency band is around -40 dB. At 2.8 GHz, Chapters/Ch5_Figs/pic/FAB2X22.pdf

Figure 7: Fabricated 2×2-element subarray with the image configuration.

the horizontal polarization cross-polarization level is better than -40 dB and -41 dB in $\varphi = 0°$ and $\varphi = 90°$ planes, respectively. For vertical polarization at 2.8 GHz, the maximum measured cross-polarization level is below -37 dB in $\varphi = 0°$ planes and less than -41 dB in $\varphi = 90°$ plane. Also not shown here, the simulated cross-polarization level in both principal planes is below -50 dB. The discrepancy between simulated and measured cross-polarization level is the result of unideal measurement environment such as the cross-polarization

Chapters/Ch5_Figs/pic/Meas2x2/H_phi0_2x2.pdf

(a)

Chapters/Ch5_Figs/pic/Meas2x2/H_phi90_2x2.pdf

(b)

Figure 8: Measured radiation pattern of the 2×2-element subarray with image configuration at 2.7 GHz, 2.8 GHz, and 2.9 GHz; (a) H-pol, $\varphi = 0°$; (b) H-pol, $\varphi = 90°$.

Chapters/Ch5_Figs/pic/Meas2x2/V_phi0_2x2.pdf

(a)

Chapters/Ch5_Figs/pic/Meas2x2/V_phi90_2x2.pdf

(b)

Figure 9: Measured radiation pattern of the 2×2-element subarray with image configuration at 2.7 GHz, 2.8 GHz, and 2.9 GHz; (a) V-pol, $\varphi = 0°$; (b) V-pol, $\varphi = 90°$.

level of the transmitter antenna and backscattering of the antenna cable and positioner and possible fabrication errors.

0.6 Array Design

To characterize the scan performance of the designed single element and subarray, a 2×5-element array of the 2×2-element subarray is fabricated. Fig. **??** shows the geometry of the fabricated 4×10-element array which is for characterizing the co- and cross-polarization radiation pattern of the horizontal and vertical polarizations at different scan angles in the $\varphi = 0°$ plane. For measuring low cross-polarization levels, the alignment of the antenna under test (AUT) with transmitter antenna, plays a key role. Considering perfect condition in the anechoic chamber, any misalignment between AUT and transmitter antenna will result in measuring the cross-polarization level in off principle planes. For a perfect alignment between AUT and the transmitter antenna, the 2×2-element subarrays are mounted on a fixture which is made from polycarbonate and plexiglass. The polycarbonate and plexiglass components of the antenna fixture are precisely processed by a laser cutting machine. The two white components of this fixture are made from ABS by using a 3-D printer. As seen from Fig. **??**, to measure the radiation pattern and characterize its scanning performance in $\varphi = 90°$ plane, the 2×2-element subarrays are rotated 90°.

Although a 4×10-element array antenna is fabricated for characterizing the performance of the designed single element, for MAPR applications final array dimensions could be as large as a cylindrical array antenna with 10 m diameter. Therefore, to reduce the edge effects on the array radiation pattern, one element form each side is terminated and the radiation pattern of the central 2×8-element array is measured. Also, it is worth noting that, in cylindrical geometry, beam steering is only required on principle planes and since the radiation pattern of the elements in a large cylindrical array antenna is similar to the planar array antenna, the antenna is tested while the element and subarrays are arranged as a 4×10-element array configuration. The radiation pattern of the 4×10-element array of the designed subarray (2×8-element array) is shown in Fig. 11. Fig. **??** and Fig. **??** show the horizontal and vertical polarization radiation pattern of the first array antenna in $\varphi = 0°$ plane. As seen from Fig. **??** and Fig. **??**, the cross-polarization level at 2.8 GHz is below -44dB and -39 dB for horizontal and vertical polarization respectively. The radiation pattern of the central 2×8-element array antenna in the $\varphi = 90°$ plane is measured by using the array antenna shown in Fig. **??**. According to the measurements results in $\varphi = 90°$ plane, the cross-polarization level for horizontal antenna vertical polarization at 2.8 GHz is better than -44 dB and -41 dB, respectively. It should be mentioned that the measured cross-polarization level at main beam area for the horizontal and vertical polarization are below -44 dB and -48 dB respectively.

The radiation pattern of the central 2×8-element array antenna is measured according to Unit Excitation Active Element Pattern (UEAEP) method **pozarmeas**, **volakismeas**. In this method, the radiation pattern of each element is measured while all other elements were terminated. The amplitude and phase of all measured active element patterns are imported into Matlab and the required phase shift between elements is applied to steer the array radiation pattern. It has not escaped our notice that while measuring the active element pattern, the active reflection coefficient magnitude of the fully excited array at the scan angles is contributing to the measured realized gain.

Therefore, measuring the active element pattern for characterizing the array scanning performance can be used to reduce the cost and risk of the system failure in the measurements of the prototypes.

Following the UEAEP method, the measured normalized scanning patterns of the array antenna in $\varphi = 0°$ and $\varphi = 90°$ planes at 2.8 GHz are shown in Fig. 13 and Fig. 14. Also, 25 dB Taylor amplitude tapering is applied to reduce the sidelobe level. For horizontal polarization, the cross-polarization level while scanning up to 45° in $\varphi = 0°$ and $\varphi = 90°$ planes, stays below -40 dB and -44 dB, respectively. For the vertical polarization, the cross-polarization level of better than -40 dB and -39 dB is achieved in scanning up to 45° in $\varphi = 0°$ and $\varphi = 90°$ planes respectively. It should be mentioned that the reported cross-polarization level is the peak of the cross-polar pattern at 2.8 GHz above the ground plane ($-90° < \theta < 90°$). In the main beam area, the cross-polarization level for the scanning up to 20°, which is the maximum required beam steering for cylindrical geometry, the cross-polarization level is mostly below -45 dB. This level of the cross-polarization level could satisfy the MPAR requirements.

(a)(b)

Figure 10: Fabricated 4×10-element array for characterizing the antenna performance; (a) in $\varphi = 0^\circ$ plane; (b) in $\varphi = 90^\circ$ plane.

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(a)

Chapters/Ch5_Figs/pic/4x10/V_phi0_Array.pdf

Chapters/Ch5_Figs/pic/4x10/H_phi90_Array.pdf

(a)

Chapters/Ch5_Figs/pic/4x10/V_phi90_Array.pdf

(b)

Figure 12: Measured radiation pattern of the central 2×8-element array in the fabricated 4×10-element array at 2.7 GHz, 2.8 GHz, and 2.9 GHz; (a) H-pol, $\varphi = 90°$; (b) V-pol, $\varphi = 90°$.

Chapters/Ch5_Figs/pic/4x10/H_phi0_Scanning.pdf

(a)

Chapters/Ch5_Figs/pic/4x10/H_phi90_Scanning.pdf

Chapters/Ch5_Figs/pic/4x10/V_phi0_Scanning.pdf

(a)

Chapters/Ch5_Figs/pic/4x10/V_phi90_Scanning.pdf