IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 23, 2018, accepted November 22, 2018, date of publication December 24, 2018, date of current version January 11, 2019.

*Digital Object Identifier 10.1109/ACCESS.2018.2889599*

# Low Cross-Polarization, High-Isolation Microstrip Patch Antenna Array for Multi-Mission Applications

**HADI SAEIDI-MANESH[1], (Student Member, IEEE), AND GUIFU ZHANG[2,3], (Senior Member, IEEE)**

[1]Advanced Radar Research Center, School of Electrical and Computer Engineering, The University of Oklahoma, Norman, OK 73019, USA
[2]School of Meteorology, The University of Oklahoma, Norman, OK 73019, USA
[3]Advanced Radar Research Center, School of Electrical and Computer Engineering, The University of Oklahoma, Norman, OK 73019, USA

Corresponding author: Hadi Saeidi-Manesh (hadi.saeidimanesh@ou.edu)

This work was supported by the National Oceanic and Atmospheric Administration (NOAA) under Grant NA11OAR4320072 and Grant NA16OAR4320115.

**ABSTRACT** The design and development of a high-performance, dual-polarization, hybrid aperture-coupled microstrip patch antenna are presented. In the presented design, the horizontal and vertical polarizations are excited using the aperture coupling method. The isolation level of better than 51 dB and cross-polarization level of less than −30 dB are achieved from the measurement results of the designed single element. To achieve better cross-polarization levels, the 2 × 2 element subarrays of the proposed unit cell, while the horizontal polarization ports are mirrored, are designed and fabricated, and a lower than −39-dB cross-polarization level is achieved in the measurement results. Finally, to characterize the scan performance of the unit cell and subarray, a 4 × 10 element array of the proposed single element is fabricated and a better than −45-dB cross-polarization level is observed while scanning up to 45°.

**INDEX TERMS** Dual-polarized, aperture coupled, high isolation, array antenna, differential feed, phased array radar, cross-polarization suppression, image arrangement.

## I. INTRODUCTION

There is an interest and practical value in utilizing polarization diversity for a radar to obtain more target information or for a communication system to carry more signal information without occupying more frequency band. This is because frequency bands are getting crowded in microwave frequencies due to the recent advancement in cellular communications. For example, the Spectrum Efficient National Surveillance Radar Program (SENSR) is started to study the feasibility of replacing the four radar networks that service the U.S with a single network of Multifunction Phased Array Radar (MPAR) [1]–[3].

Candidates being considered for future MPAR include Cylindrical Polarimetric Phased Array Radar (CPPAR) [4], [5], and Planar Polarimetric Phased Array Radar (PPPAR) [6]. To have desired accurate weather measurements with a PPPAR or CPPAR, a high-performance phased array antenna with dual-polarization capability is required. The array antenna is required to possess matched main beams, high input isolation, and low cross-polarization level at broadside and scan angles up to 45° [7]. The beam mismatch should be within 5% of the beamwidth, the input isolation needs to be better than 40 dB, and the cross-polarization level needs to be lower than −20 dB and −40 dB for alternate and simultaneous transmission, respectively [7]. These are a very stringent requirement for antenna design and development.

The required antenna performance can be realized through different designs in which the microstrip patch antenna is the most popular choice due to its low profile and fabrication cost [8]. Also, other microwave components, such as filters, can be readily integrated into the antenna array structure [9]. Different methods for exciting two orthogonal polarizations using microstrip patch antennas are proposed. Dual-polarized hybrid feed antennas [10]–[17] with high polarization purity could be an ideal choice for MPAR applications. One of the advantage of using hybrid feed technique to excite the single element include increasing the geometrical symmetry of the antenna without having a complicated multilayer design [10]. Although with proper design the coupling between two

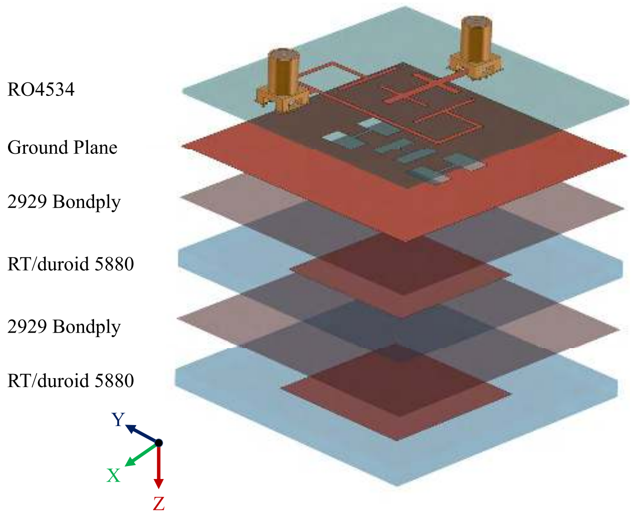



**FIGURE 1.** Layer stack up of the designed unit cell.

**TABLE 1.** Parameters and values of the proposed antenna.

| Parameter | Value | Parameter | Value | Parameter | Value |
|---|---|---|---|---|---|
| $l_1$ | 7.9 $mm$ | $w_1$ | 1.7 $mm$ | $l_{11}$ | 4.5 $mm$ |
| $l_2$ | 5.56 $mm$ | $w_2$ | 0.95 $mm$ | $l_{12}$ | 7 $mm$ |
| $l_3$ | 11.45 $mm$ | $w_3$ | 0.76 $mm$ | $l_{13}$ | 4 $mm$ |
| $l_4$ | 8.85 $mm$ | $w_4$ | 0.6 $mm$ | $l_{14}$ | 2.7 $mm$ |
| $l_5$ | 14.5 $mm$ | $w_5$ | 1.8 $mm$ | $l_{15}$ | 8.4 $mm$ |
| $l_6$ | 29.85 $mm$ | $w_6$ | 0.9 $mm$ | $h_{sub1}$ | 0.813 $mm$ |
| $l_7$ | 4.6 $mm$ | $w_7$ | 3.1 $mm$ | $h_{sub2}$ | 3.175 $mm$ |
| $l_8$ | 4.2 $mm$ | $w_8$ | 1.5 $mm$ | $h_{sub3}$ | 3.175 $mm$ |
| $l_9$ | 7.4 $mm$ | $w_9$ | 27.7 $mm$ | $h_{bondply}$ | 0.076 $mm$ |
| $l_{10}$ | 9.5 $mm$ | $w_{10}$ | 28.9 $mm$ | $w_{antenna}$ | 55 $mm$ |

polarizations and cross-polarization of the antennas excited with this method are very low, this type of patch antenna has a very compact design. Numerous methods are previously proposed for improving the antenna pattern and increasing the isolation of between array elements [18]. Also, it is possible to further improve the polarization purity of antenna radiation pattern using image configuration [19], [20].

Also, it is worth noting that, the antenna performance and the accuracy of weather measurement could be affected by radome conditions (e.g., wet radome) and several investigations have been conducted to illustrate these effects on antenna radiation pattern and the polarimetric biases [21]–[23].

Section II discusses the structure of the proposed unit cell and all design parameters. In section III, the subarray configuration is presented and simulated, and the measured results are provided. In section IV, the 4 × 10-element array radiation pattern at broadside and different scan angles are presented. Finally, the summary and conclusion of this work are given in Section V.

## II. SINGLE ELEMENT DESIGN

The layer stack up and the design parameters of the proposed unit cell are presented in Fig. 1 and Fig. 2. On the front side of the first laminate, the feed lines for both horizontal and vertical polarizations are laid. To achieve the maximum bandwidth and to have the minimum surface wave effect, it is always desired to implement a material with low dielectric constant. However, using materials with a low relative permittivity will increase the unit cell dimensions. Also, since materials with low relative permittivity, for instance, Rogers 5880, are based on PTFE composites, special treatment for metalized holes is required. In this design, a RO4534 laminate with the relative permittivity of 3.4 and a thickness of 0.813 mm is chosen for the first substrate which contains feed lines and metalized holes for connectors. The ground plane which includes three slots is located on the back side of the Rogers 4534 laminate. The radiating and parasitic patches are located on the back side of the second and third laminates which are 3.175 mm thick Rogers 5880. In the proposed design, a low dielectric material (Rogers 5880) is used to achieve the required bandwidth for multifunction applications, and Rogers 4534 with the higher dielectric material is used for reducing the size of the transmission lines and ease of fabrication [13].

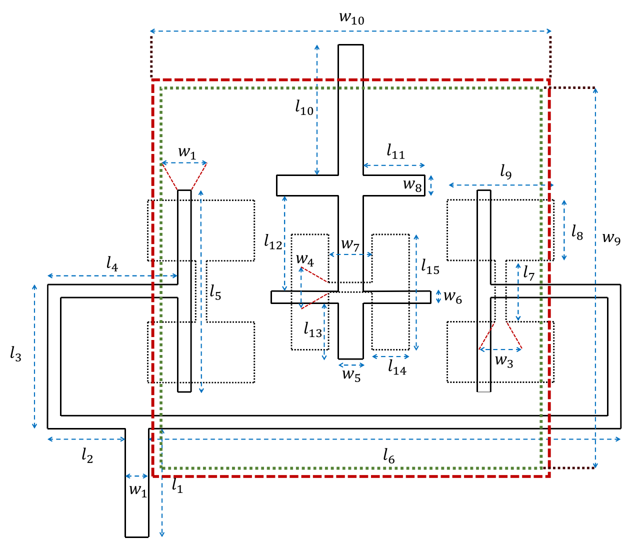



**FIGURE 2.** Parameters of the proposed antenna.

As seen in Fig. 2, the horizontal polarization feed line, and the corresponding H-shaped slot are placed in the middle of the antenna. The horizontal polarization slot is symmetric with respect to horizontal and vertical planes, and it is positioned in the middle of the ground plane.

One of the key points in the design and development of the low cross-polarization and high-isolation patch antennas is to increase the symmetry of design. As mentioned above, the horizontal polarization slot is designed to be in the middle of the ground plane. Therefore the only way to maintain the symmetry of the design without having a complicated multilayer design is to excite the vertical polarization through differential feed method. To implement the differential feeding method, two similar H-shaped slots are placed beside the horizontal polarization slot. In the presented differential feed method, to suppress the higher order modes and reduce the cross-polarization level, the two slots are excited with 180° phase shift. As seen in Fig. 1, the required 180° phase shift for differential feed method is produced through the length difference of the two branches of vertical polarization excitation feed line.

The allocated bandwidth for MPAR operation when replacing Airport Surveillance Radar (ASR) and Terminal Doppler Weather Radar (TDWR) is 2.7-2.9 GHz [10]. The typical bandwidth of microstrip patch antennas is 3% percent. Different bandwidth enhancement methods have been proposed, and the multilayer configuration approach is implemented in this design [24]. In the proposed design, a parasitic patch is placed on top of the radiating square patch. For bonding three different laminates, a 0.076 mm thick Rogers 2929 Bondply is utilized. The photograph of the fabricated unit cell is shown in Fig. 3 and the simulated and measured S-parameters are provided in Fig. 4. Fig. 4 demonstrates a perfect agreement between the simulation and measurement results.

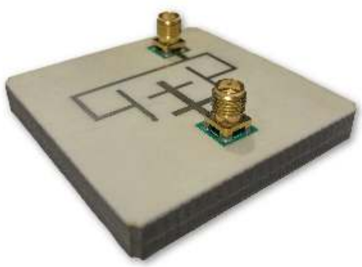


**FIGURE 3.** Photograph of the fabricated unit cell.

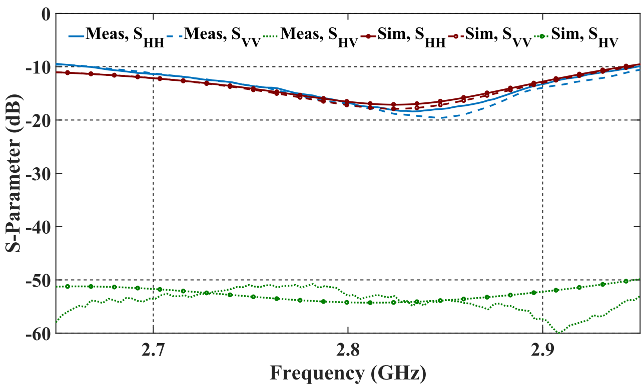



**FIGURE 4.** Simulated and measured S-parameters of the proposed antenna.

For horizontal and vertical polarizations, below −12.1 dB return loss has been achieved from simulated and measured results in the entire bandwidth (2.7-2.9 GHz). Also, it is worth noting that the horizontal and vertical polarization return loss results are pretty similar, which decreases the gain mismatch between the two polarizations. As seen in Fig. 4, the isolation between polarizations is better than 52 dB in simulations. To measure such low coupling between ports, the S-parameter measurements are conducted in shielded anechoic chambers designed for S-parameter measurements. As seen in Fig. 4, we managed to measure a higher than 51 dB input isolation in the entire bandwidth.

In phased array antennas, scan blindness could result in limited scanning angle range. One explanation for the scan blindness is the presence of dielectric or metallic material in the antenna plan which can support surface waves. The exact location of the occurrence of scan blindness depends on the spacing between elements, array configurations, and element design. Using high dielectric constant material, increasing the spacing between elements or using subarrays could move the blind angle towered the broadside [25], [26].

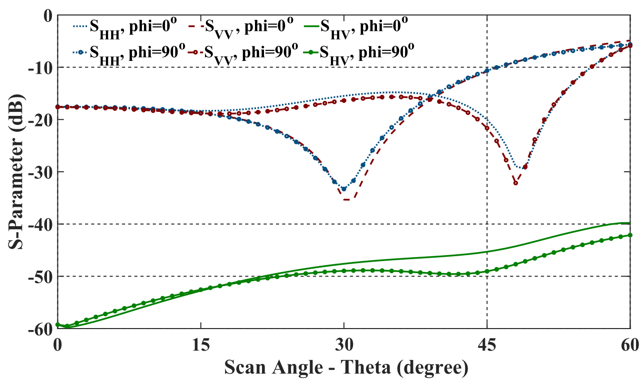



**FIGURE 5.** Simulated active S-parameters of the proposed patch antenna under periodic boundary conditions.

Fig. 5 shows the S-parameters versus scan angles in $\varphi = 0°$ and $\varphi = 90°$ planes. As seen in Fig. 5, at the MPAR operating frequency, the simulated return loss results stay below −10 dB while scanning up to 45° in both principal planes. The isolation between two orthogonal polarization in the required scanning range is better than 45 dB.

The measured radiation pattern of the fabricated hybrid feed patch antenna is provided in Fig. 6. The antenna radiation patterns are measured in the far field chamber of Advanced Radar Research Center (ARRC). The measured cross-polarization patterns of horizontal polarization in principle planes are presented in Fig. 6a and Fig. 6b. For the horizontal polarization, the single element cross-polarization level at 2.8 GHz is below −36 dB in $\varphi = 0°$ plane and better than −35 dB in $\varphi = 90°$ plane. As seen from Fig. 6c and Fig. 6d, the measured cross-polarization level while vertical polarization is excited at 2.8 GHz is better than −30 dB in $\varphi = 0°$ plane and less than −36 dB in $\varphi = 90°$ plane. Although this level of cross-polarization is very low,

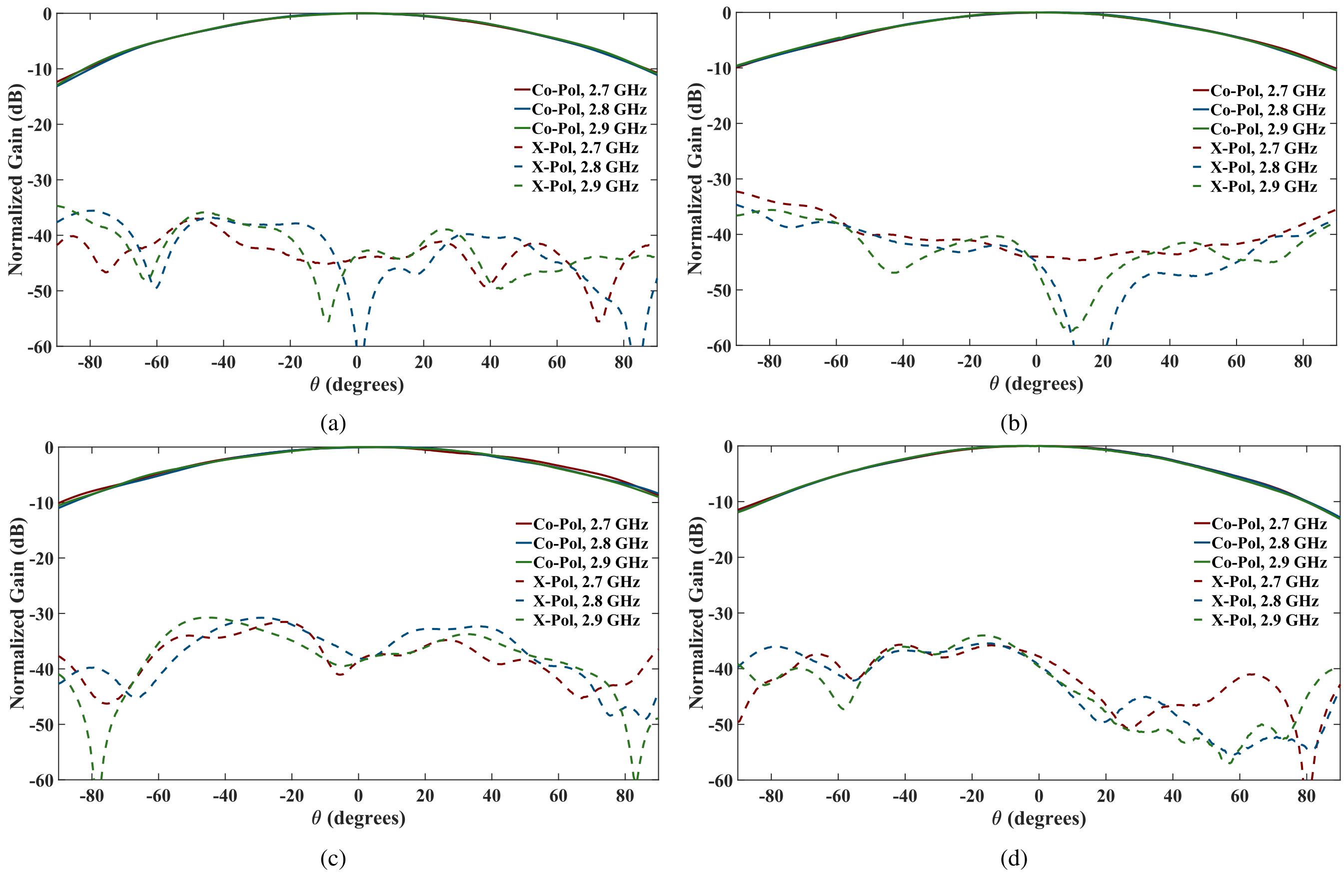



**FIGURE 6. Measured radiation pattern of the proposed unit cell in (a) $\varphi = 0°$ plane, H-pol, (b) $\varphi = 90°$ plane, H-pol, (c) $\varphi = 0°$ plane, V-pol, (d) $\varphi = 90°$ plane, V-pol.**

to satisfy MPAR requirements, polarization purity of higher than −40 dB is required.

## III. CROSS-POLARIZATION SUPPRESSION AND SUBARRAY DESIGN

Any dual-polarized antenna requires two individual ports for exciting orthogonal polarizations, and more or less in any dual-polarized antenna, the low cross-polarization level is desired. A microstrip patch antenna with dual polarization functionality can be realized while each polarization is excited with two 180° out phase ports which is called ideal differential feed patch antenna. The advantage of using the 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 phased array radar, the increased quantity 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 subarrays in which the horizontal polarization ports are mirrored [19]. In the presented design, this method of improving the cross-polarization level is implemented. The photograph of designed subarray configured according to the image configuration is shown in Fig. 7. Similar to an ideal differential feed antenna a 180° phase difference will be applied for exciting the mirrored ports.

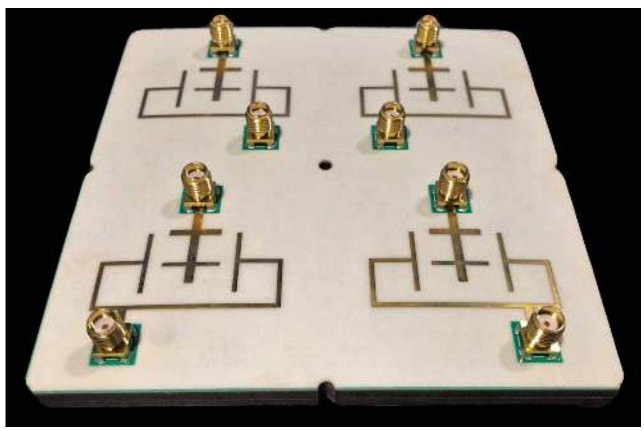


**FIGURE 7. Fabricated 2 × 2-element subarray.**

The measured radiation patterns of the fabricated 2 × 2-element subarray of the designed unit cell are shown in Fig. 8. According to the measurement results, for both polarizations in the E-plane and H-plane form 2.7 GHz to

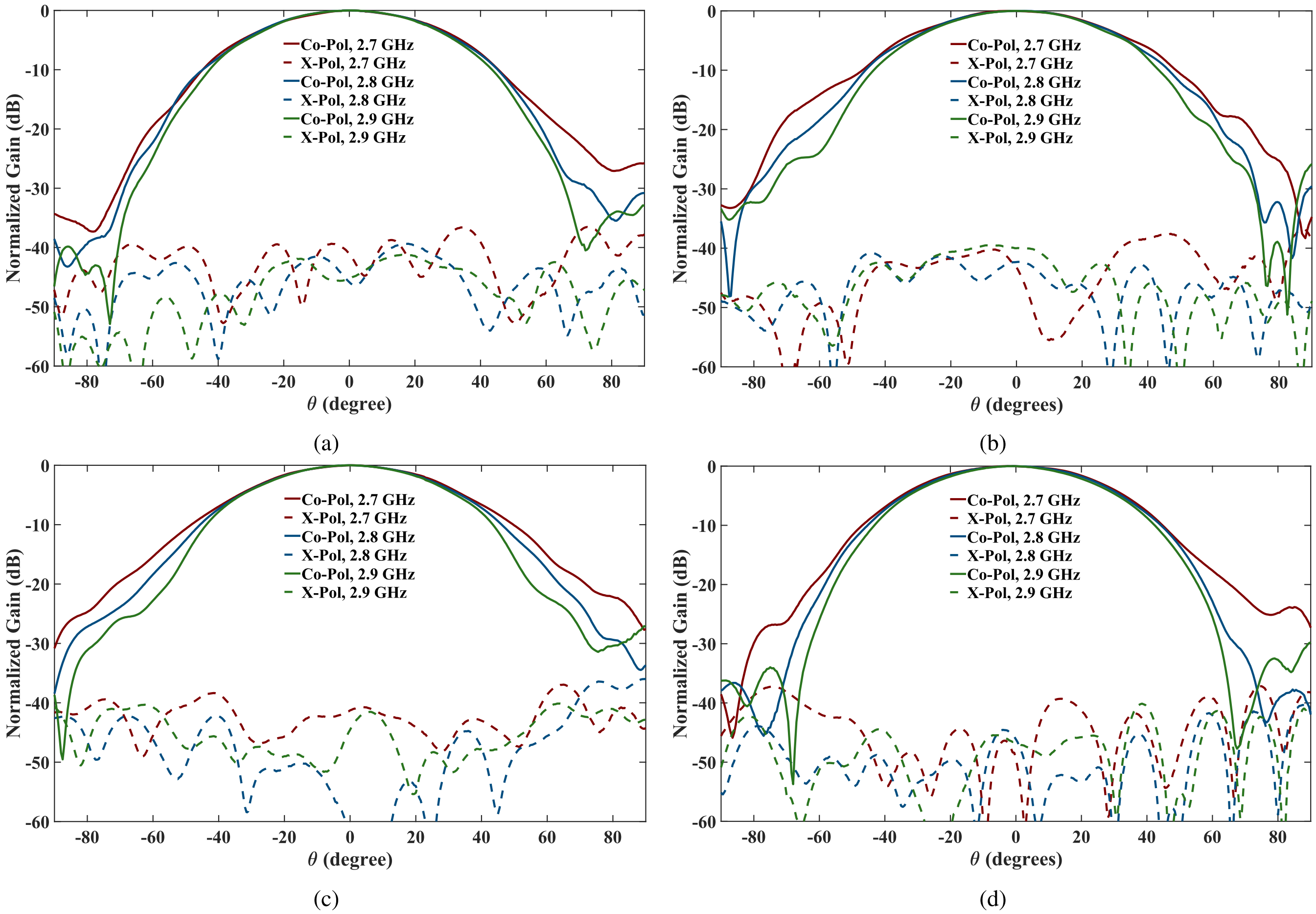


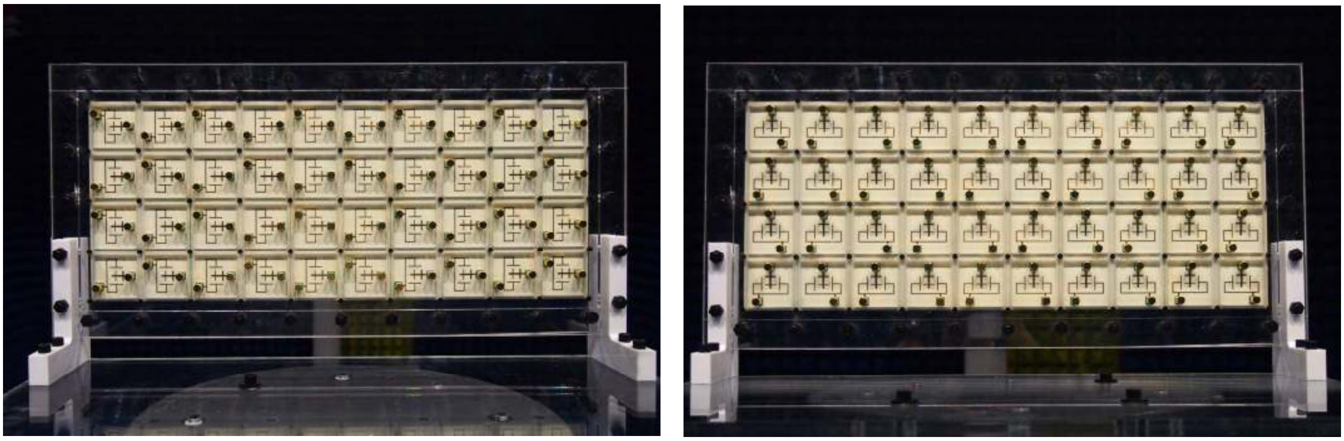

**FIGURE 8.** Measured radiation patterns of the designed 2 × 2-element subarray in (a) $\varphi = 0°$ plane, H-pol, (b) $\varphi = 90°$ plane, H-pol, (c) $\varphi = 0°$ plane, V-pol, (d) $\varphi = 90°$ plane, V-pol.

2.9 GHz, the cross-polarization level is around −40 dB. At the center frequency, with H-pol excitation cross-polarization level is better than −40 dB in $\varphi = 0°$ and less than −41 dB in $\varphi = 90°$ plane. For vertical polarization at 2.8 GHz, the maximum cross-polarization level is less −37 dB in $\varphi = 0°$ planes and less than −41 dB in $\varphi = 90°$ plane. Also, not presented here, the simulated cross-polarization level for both principal planes is better than −51 dB. The discrepancy between simulated and measured cross-polarization level is the result of unideal measurement environments such as cross-polarization of the transmitting antenna and backscattering of the antenna cable and positioner and possible fabrication errors.

## IV. ARRAY DESIGN

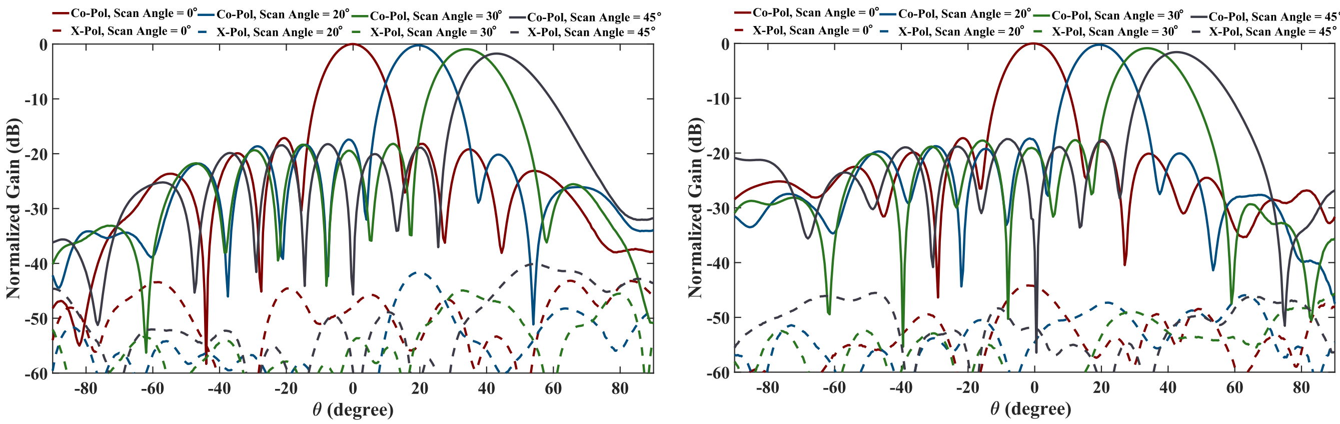
To characterize the scan radiation pattern of the proposed unit cell and subarray, a 2 × 5-element array of the presented subarray is fabricated. The geometry of the fabricated 4 × 10-element array which is made for characterizing the scan characteristics of the proposed unit cell at different scan angles in the $\varphi = 0°$ plane, is shown in Fig. 9a. For measuring low cross-polarization levels, the alignment of the antenna under test (AUT) with a 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 antennas are installed on the fixture which is fabricated from plexiglass. These 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 in Fig. 9b, to characterize the array 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 decrease the edge elements effect on the array radiation characteristics, one element from each side is terminated. It is worth noting that the simulated realized gain of the proposed unit cell at 2.8 GHz is 6.7 dB and 6.8 dB with the H-pol and V-pol excitations, respectively. With the 2 × 8-element array configuration,



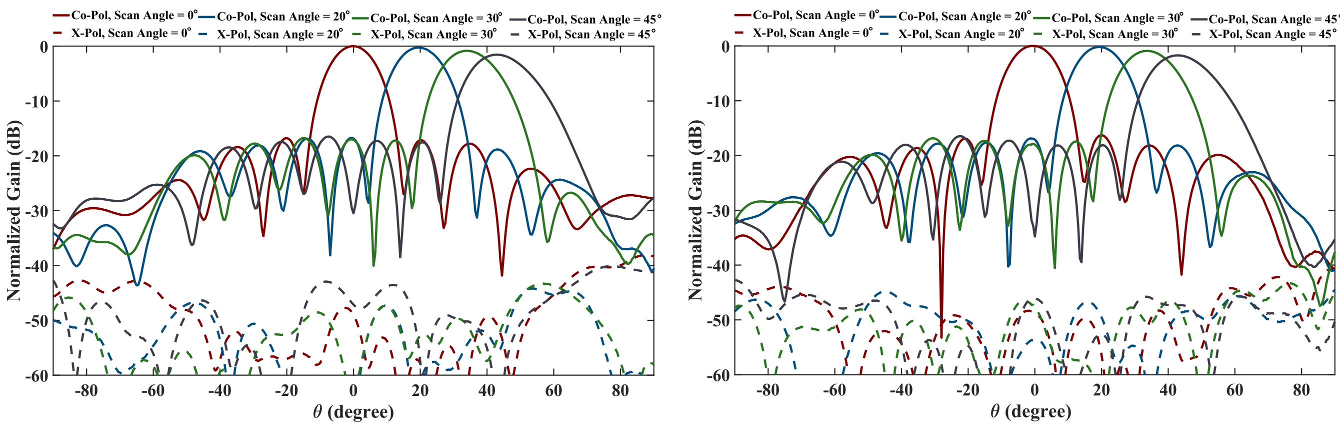
(a) (b)

**FIGURE 9.** Fabricated 4 × 10-element array for characterizing the antenna performance; (a) in $\varphi = 0°$ plane; (b) in $\varphi = 90°$ plane.




(a) (b)

**FIGURE 10.** Measured scan 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, $\varphi = 0°$; (b) H-pol, $\varphi = 90°$.




(a) (b)

**FIGURE 11.** Measured scan 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) V-pol, $\varphi = 0°$; (b) V-pol, $\varphi = 90°$.

the simulated realized gain will be increased to 17.26 dB and 16.88 dB for horizontal and vertical polarizations, respectively.

The array antenna radiation patterns are measured according to Unit Excitation Active Element Pattern (UEAEP) method [27], [28]. In this method, every element pattern is measured separately while all other remaining elements were terminated. The magnitude and phase of all the 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 the active reflection coefficient magnitude of the entirely excited antenna array at the steering angles is contributing to the measured realized gain while measuring the active element pattern. Therefore, using UEAEP method for characterizing the array scan radiation pattern can be used to decrease the cost and risk of failure in the measurements of the prototypes.

Following the UEAEP method, the array antenna measured scan pattern in principle planes at MPAR operating frequency are shown in Fig. 10 and Fig. 11. Also, the array elements excitation amplitude is adjusted according to 25 dB Taylor amplitude tapering to decrease the sidelobe level. With the H-pol excitation, the array cross-polarization level while scanning up 45° remains less than −40 dB in $\varphi = 0°$ plane. Also, the cross-polarization level of less than −44 dB is achieved in the $\varphi = 90°$ plane with the H-pol excitation. It is seen that the cross-polarization levels of V-pol excitation, are better than −40 dB in $\varphi = 0°$ and −39 dB in $\varphi = 90°$ planes with scanning up to 45°. The reported cross-polarization values are the peak of the cross-polarization at 2.8 GHz from $(-90° < \theta < 90°)$. For the scanning up to 20°, which is the maximum required beam steering for cylindrical geometry, the cross-polarization levels in the main beam area are mostly below −45 dB. This level of the cross-polarization pattern could satisfy the MPAR requirements.

## V. CONCLUSION

Design and development of a dual-polarized microstrip patch antenna array for multifunction radar application are presented. A higher than 51 dB horizontal to vertical ports isolation and a better than −30 dB cross-polarization level is achieved form the fabricated single element measurements. To improve the cross-polarization level, a $2 \times 2$-element subarray, which is configured according to image feed method, is designed and fabricated and a better than −39 dB cross-polarization level is observed from measurements results. The return loss and coupling between horizontal and vertical port are simulated using periodic boundary conditions in CST Microwave Studio. The simulation results showed that the return loss of H and V ports stay below −10 dB while scanning up to 45° and a less than −45 dB horizontal to vertical port coupling is achieved at 45° scan angle. Using UEAEP method, the $4 \times 10$-element array antenna radiation pattern is measured at 4 different scan angles and in the main beam area, better than −45 dB cross-polarization level is achieved with H-pol and V-pol excitations in both principal planes while scanning up 45°.

## REFERENCES


[1] M. E. Weber, J. Y. Cho, J. S. Herd, J. M. Flavin, W. E. Benner, and G. S. Torok, ''The next-generation multimission U.S. Surveillance radar network,'' *Bull. Amer. Meteorol. Soc.*, vol. 88, no. 11, pp. 1739–1751, 2007.

[2] D. Zrnic *et al.*, ''Agile-beam phased array radar for weather observations,'' *Bull. Amer. Meteorol. Soc.*, vol. 88, no. 11, pp. 1753–1766, 2007.

[3] M.-H. Golbon-Haghighi, H. Saeidi-Manesh, G. Zhang, and Y. Zhang, ''Pattern synthesis for the cylindrical polarimetric phased array radar (CPPAR),'' *Prog. Electromagn. Res.*, vol. 66, pp. 87–98, 2018.

[4] G. Zhang, R. J. Doviak, D. S. Zrnić, R. Palmer, L. Lei, and Y. Al-Rashid, ''Polarimetric phased-array radar for weather measurement: A planar or cylindrical configuration?'' *J. Atmos. Ocean. Technol.*, vol. 28, no. 1, pp. 63–73, 2011.

[5] H. Saeidi-Manesh, M. Mirmozafari, and G. Zhang, ''Low cross-polarisation high-isolation frequency scanning aperture coupled microstrip patch antenna array with matched dual-polarisation radiation patterns,'' *Electron. Lett.*, vol. 53, no. 14, pp. 901–902, 2017.

[6] G. Zhang, R. J. Doviak, D. S. Zrnic, J. Crain, D. Staiman, and Y. Al-Rashid, ''Phased array radar polarimetry for weather sensing: A theoretical formulation for bias corrections,'' *IEEE Trans. Geosci. Remote Sens.*, vol. 47, no. 11, pp. 3679–3689, Nov. 2009.

[7] G. Zhang, *Weather Radar Polarimetry*. Boca Raton, FL, USA: CRC Press, 2016.

[8] A. B. Constantine *et al.*, ''Antenna theory: Analysis and design,'' in *Microstrip Antennas*, 3rd ed. Hoboken, NJ, USA: Wiley, 2005.

[9] S. Saeedi and H. H. Sigmarsson, ''Miniaturized evanescent-mode cavity siw bandpass filter with spurious suppression,'' in *Proc. IEEE Radio Wireless Symp. (RWS)*, Jan. 2018, pp. 234–236.

[10] H. Saeidi-Manesh and G. Zhang, ''High-isolation, low cross-polarization, dual- polarization, hybrid feed microstrip patch array antenna for MPAR application,'' *IEEE Trans. Antennas Propag.*, vol. 66, no. 5, pp. 2326–2332, May 2018.

[11] K.-L. Wong and T.-W. Chiou, ''Broadband dual-polarized patch antennas fed by capacitively coupled feed and slot-coupled feed,'' *IEEE Trans. Antennas Propag.*, vol. 50, no. 3, pp. 346–351, Mar. 2002.

[12] T.-W. Chiou and K.-L. Wong, ''Broad-band dual-polarized single microstrip patch antenna with high isolation and low cross polarization,'' *IEEE Trans. Antennas Propag.*, vol. 50, no. 3, pp. 399–401, Mar. 2002.

[13] H. Saeidi-Manesh and G. Zhang, ''Dual-polarised hybrid feed microstrip patch antenna for multifunction application,'' *Electron. Lett.*, to be published.

[14] K. Luo, W.-P. Ding, Y.-J. Hu, and W.-Q. Cao, ''Design of dual-feed dual-polarized microstrip antenna with high isolation and low cross polarization,'' *Prog. Electromagn. Res.*, vol. 36, pp. 31–40, 2013.

[15] S.-G. Zhou and T.-H. Chio, ''Dual linear polarization patch antenna array with high isolation and low cross-polarization,'' in *Proc. IEEE Int. Symp. Antennas Propag. (APSURSI)*, Jul. 2011, pp. 588–590.

[16] Z. Sun, S.-S. Zhong, X.-R. Tang, and J.-J. Liu, ''C-band dual-polarized stacked-patch antenna with low cross-polarization and high isolation,'' in *Proc. 3rd Eur. Conf. Antennas Propag. (EuCAP)*, 2009, pp. 2994–2997.

[17] X. R. Tang, S. S. Zhong, L. B. Kuang, and Z. Sun, ''Dual-polarised dielectric resonator antenna with high isolation and low cross-polarisation,'' *Electron. Lett.*, vol. 45, no. 14, pp. 719–720, Jul. 2009.

[18] M. Alibakhshikenari *et al.*, ''Meta-surface wall suppression of mutual coupling between microstrip patch antenna arrays for THz-band applications,'' *Prog. Electromagn. Res.*, vol. 75, pp. 105–111, 2018.

[19] K. Woelder and J. Granholm, ''Cross-polarization and sidelobe suppression in dual linear polarization antenna arrays,'' *IEEE Trans. Antennas Propag.*, vol. 45, no. 12, pp. 1727–1740, Dec. 1997.

[20] Y. Rahmat-Samii *et al.*, ''A novel lightweight dual-frequency dual-polarized sixteen-element stacked patch microstrip array antenna for soil-moisture and sea-surface-salinity missions,'' *IEEE Antennas Propag. Mag.*, vol. 48, no. 6, pp. 33–46, Dec. 2006.

[21] A. Mancini, J. L. Salazar, R. M. Lebrón, and B. L. Cheong, ''A novel technique to characterize the effect of rain over a radome for radar applications,'' in *Proc. IEEE Radar Conf. (RadarConf)*, May 2017, pp. 0470–0475.

[22] A. Mancini, J. L. Salazar, R. M. Lebrón, and B. L. Cheong, ''A novel instrument for real-time measurement of attenuation of weather radar radome including its outer surface. Part II: Applications,'' *J. Atmos. Ocean. Technol.*, vol. 35, no. 5, pp. 975–991, 2018.

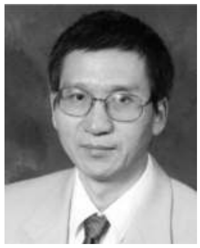
[23] A. Mancini, J. L. Salazar, R. M. Lebrón, and B. L. Cheong, ''A novel instrument for real-time measurement of attenuation of weather radar radome including its outer surface. Part I: The concept,'' *J. Atmos. Ocean. Technol.*, vol. 35, no. 5, pp. 953–973, 2018.

[24] R. Garg, *Microstrip Antenna Design Handbook*. Norwood, MA, USA: Artech House, 2001.

[25] D. M. Pozar and D. H. Schaubert, "Scan blindness in infinite phased arrays of printed dipoles," *IEEE Trans. Antennas Propag.*, vol. 32, no. 6, pp. 602–610, Jun. 1984.
[26] D. M. Pozar, "Scanning characteristics of infinite arrays of printed antenna subarrays," *IEEE Trans. Antennas Propag.*, vol. 40, no. 6, pp. 666–674, Jun. 1992.
[27] D. M. Pozar, "The active element pattern," *IEEE Trans. Antennas Propag.*, vol. 42, no. 8, pp. 1176–1178, Sep. 1994.
[28] D. K. Papantonis and J. L. Volakis, "Dual-polarized tightly coupled array with substrate loading," *IEEE Antennas Wireless Propag. Lett.*, vol. 15, pp. 325–328, 2015.

**HADI SAEIDI-MANESH** (S'16) received the B.S. and M.S. degrees in electrical engineering (electromagnetics) from the K.N. Toosi University of Technology, Tehran, Iran, in 2010 and 2012, respectively. He is currently pursuing the Ph.D. degree in electrical and computer engineering (electromagnetics) with The University of Oklahoma, Norman, OK, USA.

He is also a member of the Advanced Radar Research Center, The University of Oklahoma. His current research interests include the area of antenna arrays, polarimetric phased array radars, and reflector antennas. He is a member of the IEEE Antenna and Propagation Society.



**GUIFU ZHANG** received the B.S. degree in physics from Anhui University, in 1982, the M.S. degree in radio physics from Wuhan University, in 1985, and the Ph.D. degree in electrical engineering from the University of Washington, in 1998.

He was an Assistant and Associate Professor with the Space Physics Department, Wuhan University, from 1985 to 1993. In 1989, he was a Visiting Scholar with the Communication Research Laboratory, Japan. From 1993 to 1998, he worked and studied at the Department of Electrical Engineering, University of Washington, where he was first a Visiting Scientist and later a Ph.D. student. He was a Scientist with the National Center for Atmospheric Research, from 1998 to 2005. In 2005, he joined the School of Meteorology, The University of Oklahoma, where he is currently a Professor. He formulated theories of weather radar interferometry and phased array radar polarimetry. He led the development of advanced signal processing algorithm to improve the weather radar data quality and of the polarimetric radar data simulators to bridge the gap between radar meteorology and numerical weather prediction. Among his current projects, he is working on topics such as the optimal use of polarimetric radar data in quantitative precipitation estimation and quantitative precipitation forecast and the research and development of polarimetric phased array radars for weather measurements and multi-mission capability.

He is the author of *Weather Radar Polarimetry*, and he holds four U.S. patent awards, filed over 10 intellectual property disclosures, and has published over 100 journal publications on his research work in radar theory/technology and signal processing and applications. He also received several research and excellent paper awards.