Ultra-Compact Universal Polarization X-band Unit Cell for High-Performance Active Phased Array Radar

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***Abstract*—This paper describes the design of a high-performance X-band antenna array for a tileable dual-linear and circularly-polarized active phased array antenna. A 4x4 unit cell prototype was built and integrated with state-of-the-art T/R modules conforming to an active tile array. The use of cross patches as a stacked configuration add polarization purity while maintaining high bandwidth. The antenna is fed with four probes to implement a balanced differential feeding network in order to create a 180° phase delay between the opposing probes. This provides high polarization purity while maintaining the ability to do quadrature feeding for circular polarization. Preliminary results using uncalibrated patterns show promise for the potential implementation of the active array for circular and linear polarization based on an ultra-compact tile architecture.**

***Keywords*—Dual-polarized, balanced feeding, microstrip antenna, active phased array, T/R modules, circular polarization, tile active array, and probe-fed.**

I. INTRODUCTION

Recent advancements in radar applications have generated interest in the use of low-cost and high-performance antennas that meet polarimetric requirements for accurate weather measurements. The use of phased array radars is highly desired for providing weather information as well as single target detection due to their fast scanning rates and multifunction capabilities [1]. High polarization isolation is a necessary requirement for polarimetric measurements in dual-polarized radars [2]. Certain weather particles, such as electrically aligned ice crystals, can also be detected with circular polarized transmissions [3]. As an economical approach, single feed points in microstrip patch antennas (MPAs) with the necessary quadrature feeding can provide circular polarization. However, these have narrowband axial ratios often less than 1 %. Implementations of this type of antenna include slightly off-squared patches, patches with notches, and patches with slots. The disadvantage of these designs is that symmetry is compromised, affecting the performance of the dual-linear polarization.

In [4] a patch antenna supporting two orthogonal modes is presented to demonstrate the ability of polarization control that can be obtained with MPAs. There are three main types of single fed circularly polarized MPAs shown in [5]. These types include antennas that are diagonal-fed, nearly squared, squared with truncated corners, and squared with a diagonal slot. However, these designs show narrow axial ratio bandwidth and high cross-polarization when used as linearly polarized radiators. Aperture coupled antennas have been proven to have better cross-polarization levels and axial ratio bandwidth [6], [7]. Two orthogonally placed slots beneath a square patch makes it resonate in a single direction. These can be fed in quadrature, resulting in circular polarized radiation.

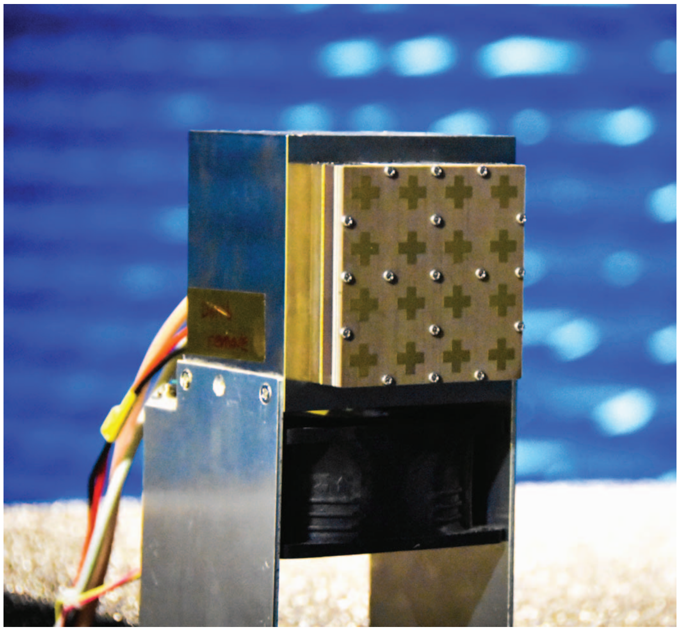

Fig. 1: Photo of the 4x4 tile dual-polarized active array antenna with RFcore T/R modules housed in the Near Field Chamber in the ARRC, at The University of Oklahoma in Norman (June 26, 2016).

A new approach to improve the isolation of two orthogonal modes is the use of crossed patches [8], [9]. MPAs can reach optimal cross-polarization levels when there is an effective ratio between both dimensions (L and W) of the patch [10]. When there is an effective ratio in the dimensions of the

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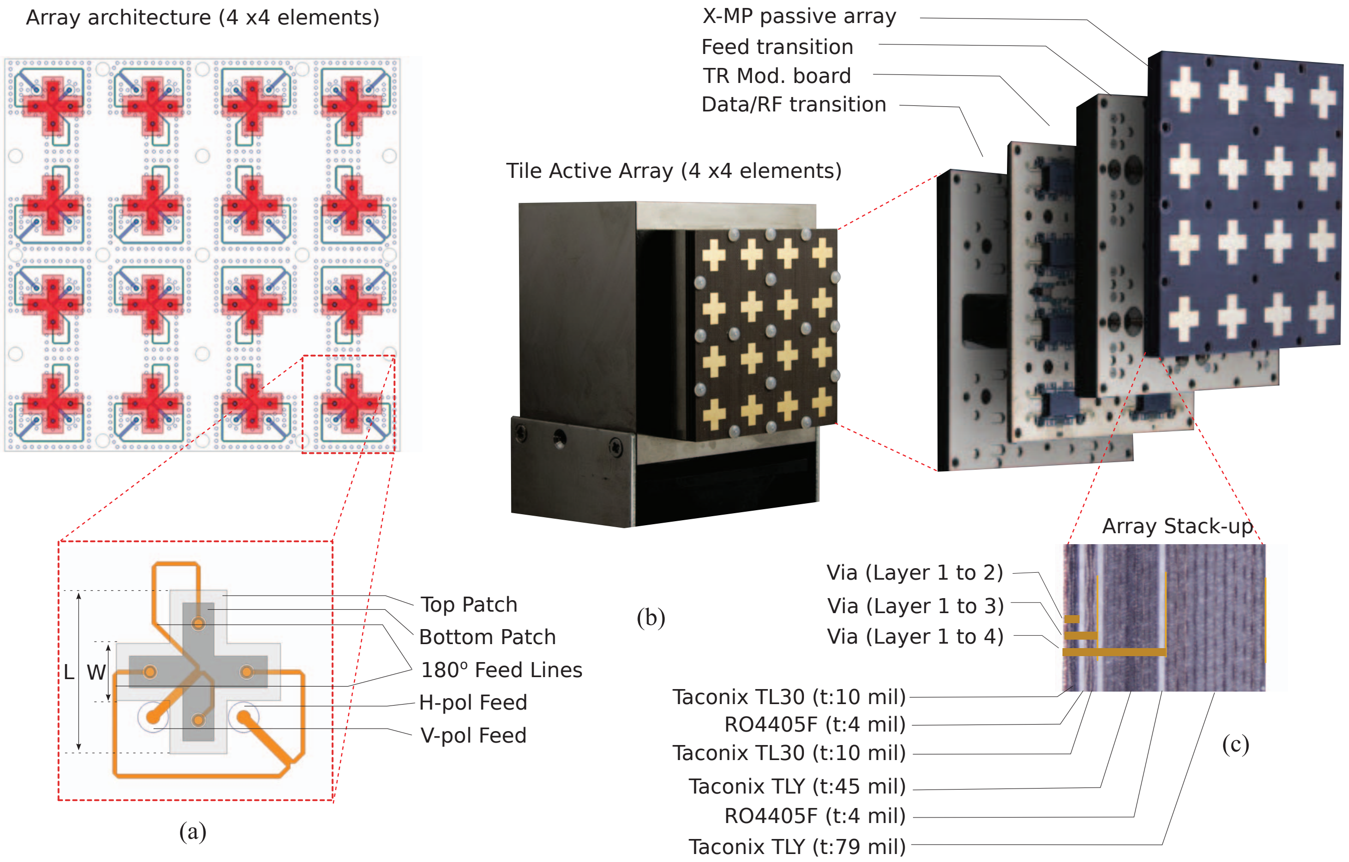
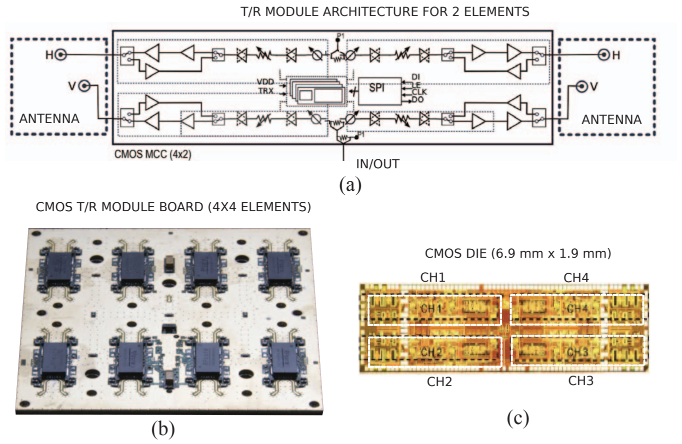


(a) (b) (c)

Fig. 2: Description of (a) Single antenna element description, where L_{Top} = 9.5 mm, W_{Top} = 3.3 mm, L_{Bottom} = 8 mm, and W_{Bottom} = 1.8 mm, (b) Active array tile configuration based on RFcore T/R modules, and (c) Stack-up.



(a) (b) (c)

Fig. 3: RFcore T/R modules for the active array antenna. a) Block diagram b) T/R module board and c) CMOS IC die.

patch, the radiating elements show improvements of cross-polarization levels in the principal planes to -30 dB. With the use of aperture coupling techniques, these cross-polarization levels can be reduced even more. Another technique employed in the work presented here was the use of four probes to excite the radiating element [11]. Commonly, probe-fed MPAs are known and used for their low-cost and ease of fabrication. This paper discusses the implementation of a four-probe technique applied to the stacked cross-patch antenna array shown in Fig. 1 and 2. With correct phase feeding, this element is capable of having linear cross-polarization levels of less than -40 dB in principal planes and -30 dB in diagonal planes. Also, the proposed configuration provides an axial ratio of less than 0.5 dB along the whole band and excellent scanning range for circular polarization.

II. SYSTEM DESCRIPTION

The active phased array, shown in Fig. 1, is designed for linear and circular polarization isolation, bandwidth, axial ratio, and beam scanning requirements for weather and surveillance.

A. Array Unit Cell Element

The array unit cell is composed of 16 elements, configured in a 4x4 square lattice array that provides spacing between elements of $\lambda/2$ in both dimensions. The elements are fed using

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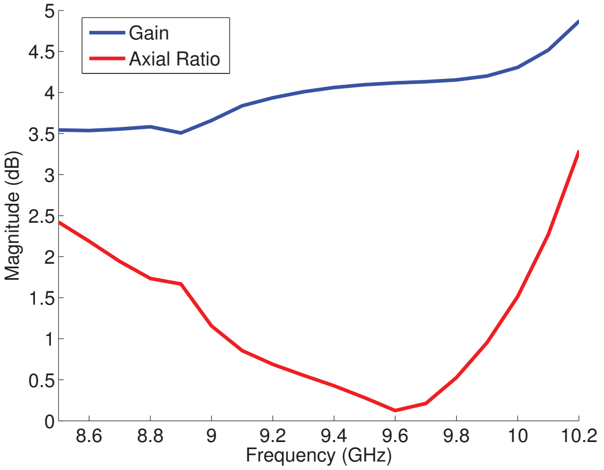

Fig. 4: Simulated single element gain and axial ratio bandwidth at boresight ($\theta = 0°$).

a balanced probe-feeding technique. The antenna contains H and V polarization ports that divide into a "T" transmission line network, as seen in Fig. 2a. The opposite end of the MPA is fed with the other end of the feeding network in order to excite the opposing radiating edge with a 180° phase shifted signal. This technique provides improved isolation between the two orthogonal modes for vertical and horizontal polarizations, as well as bandwidth widening [12], [13]. Orthogonal mode isolation provides low axial ratios when operating in circular polarizations with wide scanning capabilities. In addition to the feeding network, a crossed patch geometry was implemented to provide more isolation between modes while maintaining wide bandwidth performance. Another layer with a parasitic coupled patch, using the same geometry, was incorporated to increase bandwidth and scanning capabilities without compromising the size of the patch in lateral dimensions. The single element design, including the feeding network, as shown in Fig. 2a, can maintain the antenna gain and desired low axial ratio levels across frequency as shown in Fig. 4.

B. T/R Modules

Low-profile, low-weight and low-mass are critical requirements in antennas for space and airborne radar systems [14]. Furthermore, weather radars ideally require high precision in the co-polar matching of about ± 0.1 dB as a maximum mismatch between H and V co-polar patterns. In addition, they require high polarization purity of 40 dB or more (for simultaneous transmit and receive) for the entire scanning range. To achieve such purity, the radiating element requires perfect symmetry in the electric fields in the antenna and maximum flexibility in the control of the amplitude and phase in the excitation ports. Having independent T/R modules for H and V with 6-bits of control in the phase shifters, and 5-bits of control in the attenuators, makes this antenna unique to satisfy these stated requirements.

In this active array antenna prototype, the T/R modules only contain a four-channel X-band CMOS core chip fabricated by RFcore. It should be noted that the front-end integrated circuit (FEC) that provides high power and a T/R switch for high isolation was not incorporated in this prototype because the goal was to evaluate the performance of the CMOS core IC and the physical RF connection between the antenna and the T/R module board and effectiveness of the radiating array antenna.

The T/R module was fabricated using the CMOS process and contains a 6-bit phase shifter, a 5-bit attenuator, 6-bit tuning circuits, bidirectional gain blocks (BDGB), a low dropout regulator (LDO), and a serial to parallel interface (SPI). The phase shifters have a range of 360° with a 5.625° step of phase shifting, and an attenuation range of 31 dB with a 1.25 dB step. This architecture provides software with the capability of introducing the desired phase and attenuation values for each port. However, due to the structure of the design, the ports are all active in transmitting or receiving when operating in any linear polarization, limiting the isolation between H and V ports to 31 dB. Due to this limitation, the cross polarization isolations can not be better than -31 dB. This limitation can be mitigated using some calibration techniques and field cancellations with the opposing orthogonal fields of the transmitted signals.

Each module is connected to the two ports (H- and V-pol) of the two elements. Therefore, there is a total of 8 modules for this 4x4 subarray unit cell and a total of 32 ports for both H and V polarizations.

C. Active Phased Array

This ultra-compact design is composed of the array front panel backed by a metal layer that separates the array from the T/R module core chips and another metal transition that connects the TR module board and power and computer interface connectors with the heatsink. The connectors are vertically affixed to the back of the array module with a low-profile communication card to assimilate a brick module configuration that provides a compact feature [15]. The size of the array unit cell is 63.4 mm x 63.4 mm and the height of the T/R modules with the metal heatsink layers is 17.1 mm. The tile design is stacked with thick conductive layers in order to improve heat dissipation, which mitigates thermal expansion, phase errors, and component errors found in the T/R modules performance [14].

III. PRELIMINARY RESULTS

The initial measurements for the active array were taken from a setup placed in the Near-Field Chamber. For effective near-field to far-field transformations, the front-end of the active array should be placed four times the wavelength away from the probe. A power supply of 12 VDC is connected to the communication board on the T/R modules at the back of the tile, and is also connected to the fan that provides cooling to the system. The modules are then configured using a computer interface that can be easily operated with a laptop via a USB connection.

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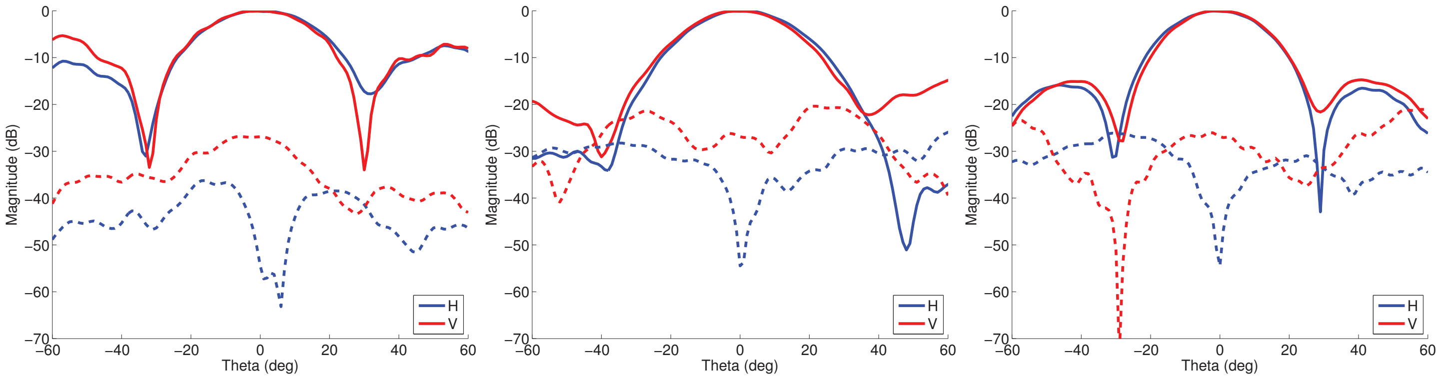

(a)

(b)

(c)

Fig. 5: Measured uncalibrated broadside antenna patterns for H- and V-pol for (a) E-plane, (b) D-plane, and (c) H-plane of the active array at the ARRC Near-Field chamber at 9.2 GHz. Solid (—) and dashed (- -) lines refer to co- and cross-polarization components, respectively.

The preliminary results presented show the performance of the array antenna with a limited capacity in the RF modules. These results were obtained without any calibration of the amplitude and phase in the 32 channels of the total 16 elements, due to the fact that there is no full control to turn off one of the channels when the other was transmitting. In other words, when transmitting in H-pol, V-pol is not completely turned off.

Fig. 5 shows the uncalibrated antenna measurements for the fabricated unit cell array with the functioning T/R modules. In all planes, patterns with cross polarization levels of under -31 dB and -25 dB for V- and H- polarization were obtained. For the antenna patterns that were scanned ± 30° in the E-, H- and D- planes respectively (see Fig. 6), results showed limited cross-polarization isolation because the CMOS core IC module must have independent channels in this specific IC architecture. The four channels are active and the only way to shut down one polarization while the other is active is by setting the 6-bit attenuator to 31 dB. This prototype was originally proposed only to evaluate the RF performance of the CMOS at 0.13 μm and the physical interconnection of the antenna and TR module board. For future measurements, a high-end calibration of random attenuation and phase values will be made in order to characterize each element of the subarray. This will provide better insight as to how the elements should be individually fed in order to achieve the best possible patterns. The estimated cross-pol values should be as low as -50 dB in all planes. Axial ratio values should also be improved to about 1 dB or less across the whole frequency and in beam scanning.

IV. CONCLUSION

A low-profile 4x4 element dual-polarized X-band antenna for a tileable active array antenna was designed and tested. The prototype was integrated with state-of-the-art T/R modules from RFcore to prove the feasibility of using CMOS technology and the antenna array performance without calibration. The results presented, which do not include any type of calibration, indicate that modules in CMOS and the proposed array antenna can offer very acceptable performance for a dual-polarized array. This is the first stage of the tile active array. In the near future, a second prototype will include an FEC module composed of high power amplifiers (4 W to 10 W per element), a high-isolation T/R switch, and an LNA.

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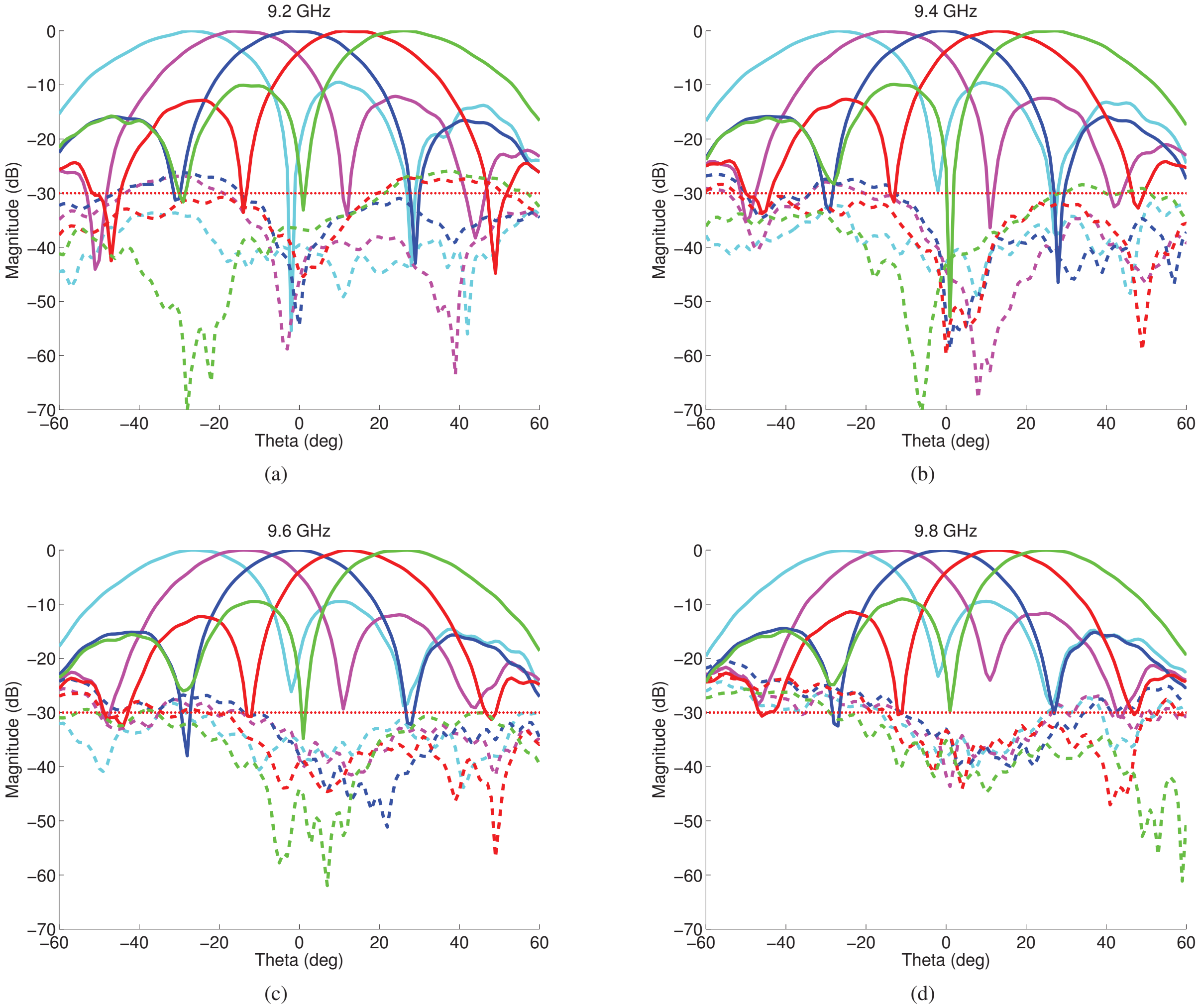

(a) (b) (c) (d)

Fig. 6: Measurements of uncalibrated H-pol scanned antenna patterns of the active array at (a) 9.2, (b) 9.4, (c) 9.6, and (d) 9.8 GHz. Solid (—) and dashed (- -) lines refer to co- and cross-polarization components, respectively.

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