# PHASE-TILT ARRAY ANTENNA DESIGN FOR DENSE DISTRIBUTED RADAR NETWORKS FOR WEATHER SENSING

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## ABSTRACT

This paper describes the design of a dual-polarized microstrip series-fed linear array as part of the phase-tilt active planar array antenna being designed for weather sensing for the CASA Engineering Research Center. The dual-polarized planar array antenna is composed of 64 linear array columns, each one formed by 32 aperture coupled patch antenna elements in cascade and excited by a 2 W solid state transmit and receive (TR) module. A straightforward synthesis method is used in order to achieve the desired amplitude and phase excitation of each linear array. Radiation patterns computed using method of moments (MoM) and measured in a compact range system are presented in order to validate the synthesis method proposed.

***Index Terms*—**Dual-polarized array antenna, series-fed, aperture coupled patch antenna, solid state radar weather radar, CASA radar.

## 1. INTRODUCTION

A new weather radar design concept is currently being investigated by the NSF Engineering Research Center for Collaborative Adaptive Sensing of the Atmosphere (CASA). The concept involves the use of dense networks of X-band radars [1], that defeat the blockage effect of earth's curvature by limiting the operating range of each radar to a few tens of kilometers. Such networks would be arranged in deployments comprised of tens (urban environment), hundreds (regional deployment), or potentially thousands of radar nodes (e.g. covering a nation the size of the contiguous US) for comprehensive sampling of the entire troposphere including the boundary layer. This dense radar network requires that each radar node be low cost that would be practical and cost effective to deploy in large networks.

Among the approaches, CASA is investigating a one dimensional-scanning planar array that performs phase steering in azimuth while mechanically steering (tilting) the antenna in elevation.

This work was primarily supported by the Engineering Research Center Program of the National Science Foundation under NSF Award Number 0313747. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect of the National Science Foundation

A conceptual drawing of the phase-tilt array antenna and possible installation options are shown in the Figure 1.

This paper addresses the design of the front-end of the solid state radar, emphasizing on the synthesis method for designing the dual-polarized linear array, using co-polar patterns with low sidelobe, matched main beam patterns and high cross-polarization levels, which represents essentials parameters to improve the accuracy of the rainfall estimation in polarimetric radar systems [2] [3].

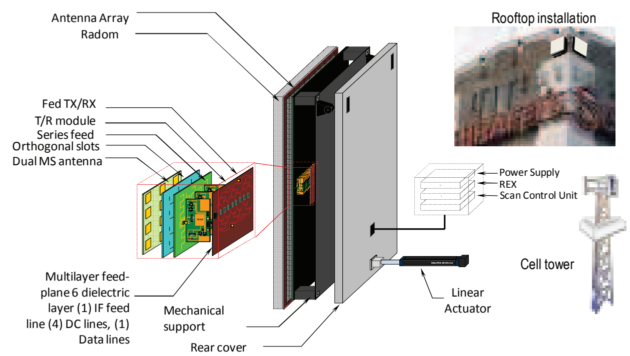



Fig. 1. Phase-tilt antenna concept

## 2. ARRAY ANTENNA CONFIGURATION

The phase-tilt array antenna is composed of 64 columns of dual polarized aperture coupled linear arrays. Each column is fed by a TR module that can be switched between polarizations as is shown in figure 2.

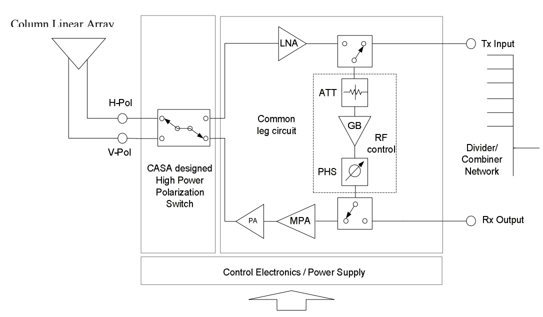



Fig 2. Block diagram of the TR module

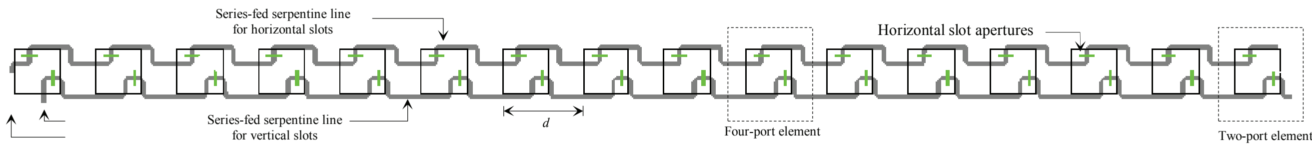



Fig 3. Geometry of one half linear arrays using dual-polarized aperture coupled microstrip patch antenna. The slots width is 0.4 *mm*, slot length from 2.2 *mm* to 3.18 *mm*, square path size is 9.88 *mm*, and the element spacing is 17 *mm* (0.54 $\lambda_o$)

The TR module uses commercial surface mount devices and has a common leg control circuit which features 360 *degrees* of phase control with 5.6 *degrees* resolution, and 31.5 *dB* of amplitude control with 0.5 *dB* of resolution. The TR modules uses 2W power amplifiers that deliver ~1W to the antenna columns. Commercial SMT switches that can handle the power level of the module are not currently available, so a TR polarization switch using discrete PIN diodes was designed and tested. Additional specifications of the system are given in table 1.

TABLE 1. Antenna array specifications

| Parameter | Specifications |
|---|---|
| Operation Frequency | 9.6 *GHz* |
| Antenna Gain | ~36 *dB* |
| Peak SLL | -20 *dB* |
| Elevation Beamwidth | ~3.4 degrees |
| Azimuth Beamwidth | ~2-3 degrees over scan range |
| Azimuth plane scan range | 90 degrees (± 45 *deg*) |
| Elevation plane scan range | 20 *deg* Mechanically |
| Polarization | Dual Linear-polarized |
| Cross-polarization level | 20 *dB* minimum |
| Isolation port level | Better than 25 *dB* |
| Power per panel (peak) | 128 *W* |
| Power out per T/R module | 2 *W* (peak) |

The array antenna is designed at 9.6 *GHz* and is realized on a multilayer substrate structure made of Rogers 5880 (εr= 2.2). The top layer of 20 *mil* thickness is used for the radiating elements and the bottom layer of 31 *mil* is used for ground plane where the aperture slots and also feed network are placed. A drawing geometry of half of the linear array of 32 elements, with the patches, feeds and slots apertures are shown in figure 3. In order to minimize the effects of beam squinting caused by errors in the progressive phase along the array, a symmetric center feed composed of a T-junction power divider with quarter-wavelength sections matched to 100 *Ohm* serpentine microstrip lines is used. Because the left and right halves of the array are mirror images, the vertical polarization T-junction requires an additional 180 degrees phase shift. This configuration suppresses the higher order modes in the patch antennas reducing the cross polarization fields and also minimizes the beam scanning with frequency. A reflector ground plane is placed 10 *cm* from the rear apart of the antenna in order to eliminate the backward radiation pattern of the antenna and also to provide the space and physical support required for each TR module.

## 3. DESIGN PROCEDURE

The design procedure for linear array antenna was developed using an equivalent circuit model of an *N*-element series-fed linear array, where each element can be represented as impedance interconnected in series for a serpentine transmission line, each one spaced one-half dielectric wavelength apart. This model and their respective parameters are represented in Figure 4.

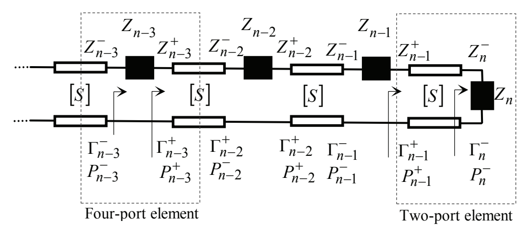



Fig 4. Equivalent circuit for the series-fed linear array antenna

Each inner section represents a four-port dual-polarized aperture patch antenna with the exception at the ends where a two-port dual-polarized aperture patch antenna is used as terminal element. $Z_o$ represents the characteristic impedance of the microstrip serpentine lines. For this design, 100 *Ohms* impedance and electric length of $\lambda_g/2$ is used for the feed networks for each polarization. The superscripts + and – indicate the quantity at the outgoing and incoming sides of the each antenna section along the linear array antenna.

An isolated dual-polarized aperture coupled patch antenna was designed and then optimized to obtain a lower imaginary part in the antenna impedance, high port isolation (better than 25 *dB*) and high cross-polarization levels (better than 20 *dB*). Then, a set of four-port aperture coupled patch antenna are used to characterize the antenna impedance (real and imaginary part) as function of the slot length. The range of slot length was limited by the cross-polarization, port isolation levels and also the space required arranging the two orthogonal slots and the respective feeds.

Once characterized the four and two–port antenna element, the iterative synthesis starts defining the slot length of the last element according to the required power radiated which is defined for the voltages or currents coefficients for a given aperture illumination. The next step is substitute the antenna impedance in equation (1) to calculate the incoming input reflection coefficient of *n*-element of the array. With the previous calculation and the *s*-parameters of the serpentine line, equation (2) and (3) provide the outgoing impedance of each section of the linear array.

$$\Gamma_n^- = \frac{Z_n^- - Z_o}{Z_n^- + Z_o}\ , \quad n=N,\ N\text{-}1,\ \ldots,1. \qquad (1)$$

$$M_n = \frac{S_{12}.S_{21}.\Gamma_n^-}{1 - S_{22}.\Gamma_n^-}\ , \quad n=N,\ N\text{-}1,\ldots,1. \qquad (2)$$

$$Z_{n-1}^- = -Z_o\frac{\left(S_{11} + M_n + 1\right)}{\left(S_{11} + M_n - 1\right)}\ , \quad n=N,\ N\text{-}1,\ldots,1. \qquad (3)$$

The incoming power for the *n*-element $P_n^-$ is calculated by equation (4) which represents the summation of the radiated power by each element ($P_n \cong a_n^2$, where $a_n$ represents the excitation coefficients for each element), and the out coming power of each section. $P_n^+$ is determined using expression (5), where $\Gamma_n^+$ can be calculated using equation (1) replacing $Z_n^-$ by $Z_n^+$.

$$P_n^- = P_n + P_n^+\ , \quad n=N,\ N\text{-}1,\ldots,1. \qquad (4)$$

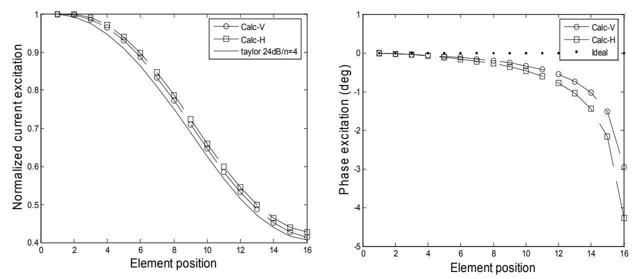
$$P_{n-1}^+ = P_n^-\frac{\left(1 - \left|\Gamma_{n-1}^+\right|^2\right).\left|1 - S_{22}\Gamma_n^-\right|^2}{\left|S_{21}\right|^2.\left|1 - \Gamma_n^-\right|^2}\ , \quad n=N,\ N\text{-}1,\ldots,1. \qquad (5)$$

Once obtained the values of: $Z_{n-1}^+$ and $P_{n-1}^+$ the antenna impedance is calculated for each section using expression (6). Then a fit polynomial expression that relate the impedance of the antennas as a function of the slot length can be used to calculate the respective slot length for each antenna section.

$$Z_{n-1} = \frac{Z_{n-1}^+ P_{n-1}}{P_{n-1}^+}\ , \quad n=N,\ N\text{-}1,\ldots,1. \qquad (6)$$

## 4. RESULTS

A dual polarized series-fed linear array composed by 32 aperture coupled patch antennas, was designed using MoM, and then fabricated to obtain measured values in order to check the effectiveness of the outline approach. The design, performed in the multilayer RF substrate, discussed previously in section 2, use an element spacing of d=17 *mm* (0.54 $\lambda_o$) to avoid grating lobes in the elevation plane pattern. Then, currents excitation according with Taylor distribution for -24 *dB* sidelobes (*n=4*), and an initial impedance of two-port terminated element and their respective slot length is used as input information for the synthesis program. Figure 5 (a) shows together, the ideal and calculated normalized current excitation for each element of half dual-polarized linear array antenna (16x1). Small discrepancies between the coefficients for V and H polarizations are essentially due to the fact of small differences in the s-parameters of the serpentine lines, and the antenna impedance characterization of each polarization. Figure 5 (b) shows the excitation phase for each element referenced to the first element. This undesirable non linear phase in each element, is because a non linear reactive part of the antenna impedance for different sloth length according with the taper distribution.




a) b)

Fig 5 (a). Current normalized excitation for each elemnt of half of the dual-polarized linear array antenna 32x1. (b) Estimated phase exitation of half linear array antenna for H and V polarization of a linear array of 32x1.

The no linear phase excitation produces small scanning of the main beam in opposite directions for each half of the array. When small scanning angles are produced (less than 0.125 *degrees*) adverse effect in the total main beam pattern can be negligible. Nevertheless, for greater scanning angles than 0.125 *degrees*, the first sidelobes can be affected in more than 1 *dB* with respect to the desired sidelobe level specified.

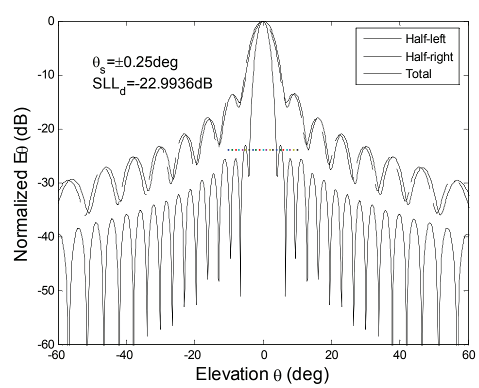



Fig 6. Calculated radiation patterns for a vertical polarized series-fed array antenna composed by the two halfs (left and right) arrays sections composed by 16 elements each.

Figure 6, shows the radiation patterns for the halves (left and right) of the 32x1 linear array, and the total radiation array pattern, which is obtained by superposing of the patterns of each half array. About ± 0.25 *degrees* scanning in the main beam for each half-array is observed which degraded the first side lobe levels in 1 *dB*.

Simulated broadside patterns at 9.6 *GHz* for a linear array of 32 elements in both polarizations are depicted in the Figure 7. For this design, chip resistors at the end of each half array were used instead of terminated radiating element. Also step discontinuities in the serpentine lines were introduced in order to reduce the inductive part of the antenna impedance. Matched co-polar main beam patterns compare favorably with the ideal patterns. Cross-polarization levels below -22 *dB* and -27 *dB* for the vertical and horizontal polarizations respectively. The antenna gain for the vertical and horizontal polarization results in 19.3 *dB* and 18.1 *dB* with a total radiation efficiency of 79 *%* and 70 *%* for each polarization. The computed return loss for both polarizations is about -22 *dB* and -20 *dB* at 9.6 *GHz*.

Measured co-polar main beam and cross-polarization patterns of the first series-fed linear array antenna of 32 elements, embedded in planar array of 20 columns are shown in Figure 8.

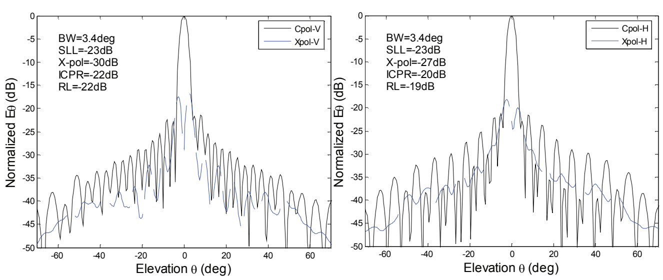



Fig 7. Simulated copolar and cross-polar radiattion patterns of vertical and horizontal polarized series-fed array antenna composed for 32 coupled patch antenna elements.

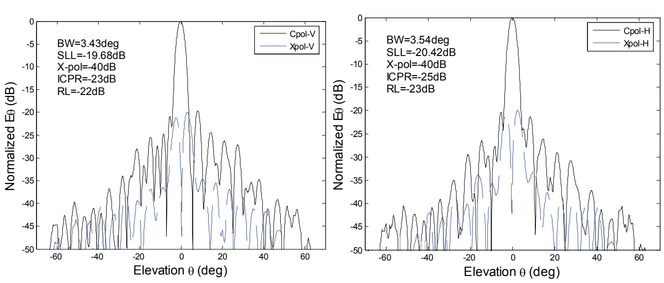



Fig 8. Measured copolar and cross-polar radiattion patterns of vertical and horizontal polarized series-fed array antenna composed for 32 coupled patch antenna elements.

The measured return loss for vertical and horizontal polarization is about -22 *dB* and -23 *dB* at 9.6 *GHz*. The cross-polarization at broadside is below -35 *dB* for both polarizations. Degradation of 2 *dB* in the first sidelobes with respect to the values obtained in simulations is observed. The differences can be attributed to the resolution of the mesh used in the simulation, the fabrication process for multilayer substrate and difficulties with the terminating resistors. Additionally, a broadside measured pattern at 9.64 GHz (see right plot in Figure 8), which corresponds to the upper frequency of the operating bandwidth, shows that the main beam is still pointed at broadside, even supposing, a scanned beam can be occurred with frequency.

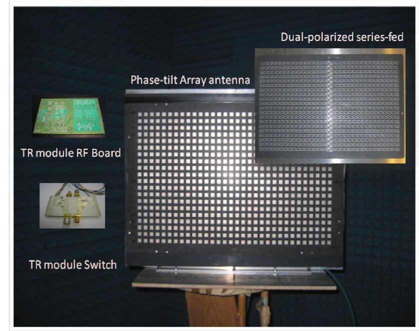



Fig 9. Pictures of phase-tilt planar array antenna used as first prototype. In the left, the RF part of the TR Module, and board of the customized transfer switch implemented.

A new design of 32 elements linear array antenna that substitutes the chip resistor with a radiating antenna element is currently designed. This second prototype and the functional TR module will be promptly tested in order to have a measured radiation patterns for elevation and azimuth planes.

## 5. CONCLUSIONS

A simple and effective synthesis method to design a dual-polarized series-fed coupled aperture patch antenna linear arrays is presented. The design and fabricated linear array having 32 coupled patches using low dielectric constant substrates has been considered. Indeed, small inaccuracies in the first sidelobes, this approach provides very good matched co-polar patterns with high cross-polarization levels.

## 6. REFERENCES

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