A Study of Mutual Coupling in a 7-Element Phased Uniform Patch Array

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***Abstract*—This work investigates design methods for reducing variation in the active VSWR over scan angle of a patch array. The unit cell is stacked patch microstrip antenna. It is validated and compared to previously published results. Next, the computation of a uniformly spaced and uniformly excited seven-element linear array radiation pattern from an infinite cell array is validated with the full-wave HFSS simulation. A parametric study is then performed on the distribution of spacing between the antenna elements as well as on cell wall elements inserted between unit cells to prevent near field coupling. The resultant array at 10 GHz has a realized gain of 14.9 dB or more across a 50 degree scan width, with a VSWR of 2 or less.**

***Index Terms*—Microstrip antenna arrays, beam steering**

I. Introduction

PHASED arrays are championed in radar systems, and increasing in automotive systems, for their electronic steering abilities and conformal shape. At the cost of adding control electronics and phase shifters (or whichever delay mechanism is used), the restraints of mechanical steering are greatly loosened. However, whereas conventional arrays assume that a unit element of an array performs the same as its neighboring elements, phased arrays must account for mutual coupling between the cells. With phased arrays providing beam steering advantages, mutual coupling bounds its operation in terms of maximum scan angle and bandwidth of operation. Coupling between elements can change with near-field loading and scan angle, which decreases the effective area of the antenna as the target approaches the edge of the array.

Usually at extreme scan angles or wide element spacing, coupling can yield a phenomena called scan blindness, which occurs when energy incident on the antenna is coupled into surface waves that propagate through the substrate [1]. For an antenna whose input is connected to the output of a power amplifier, this results not only in a high-magnitude reflection coefficient, causing low realized gain of the antenna, but furthermore poses the risk of destabilizing the amplifier and reflecting all power back into the transistor output.

This work presents parametric studies on reducing variation in the active input S_{11} parameter over scan angle of a seven-element uniformly spaced and uniformly excited microstrip patch array.

II. Unit Cell Structure and Validation

The unit cell is a stacked patch antenna, polarized linearly along the same axis of its microstrip feed, and designed to operate at 10 GHz, with a second upper substrate patch added to increase the bandwidth of the patch. The modified cell is shown in Fig. 1; the version validated through measurements in [2] has a second microstrip feed on an adjacent side of the patch. To ensure proper simulation set up, the unit cell was modified to match the dual-linearized version, previously validated through measurement (see Fig. 2) in [2], and simulated with ANSYS HFSS. The s-parameters shown in Fig. 3 show good agreement. As a standalone patch antenna, this antenna displays a gain of 8.88 dB, or 8.75 dB realized gain to account for impedance mismatch.

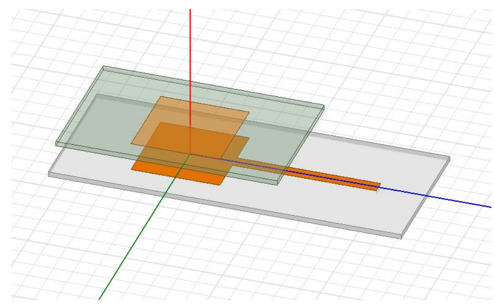


Fig. 1. The patches measure 9.1 mm to a side and are center-fed with 1.4mm 50 Ω. The substrate used is ULTRALAM 2000 with a thickness of 0.508 mm and a relative dielectric constant of 2.5. The upper patch is spaced 3 millimeters above the lower patch with air in between (created in implementation with nylon spacers).

III. Array Validation

In the interest of computational time and efficiency, a parametric study is intended upon a unit cell of the finite array. To validate the accuracy of the simulation, three methods of computing or approximating far field radiation patterns are implemented:

1) (Single element on infinite ground plane) x [Array Factor]
2) Pattern multiplication: [Single element within infinite linear array] x [Array Factor]
3) HFSS full-wave simulation of complete array

As the complexity of each method increases, so does its computational time and the nonlinearities accounted for. As discussed in [3], pattern multiplication of a single element placed in infinite array takes into account coupling effects from neighboring elements, which have the most impact, while disregarding edge effects and assuming a uniform input impedance for each element. The full-wave simulation takes more computational time but fully solves for edge effects and the coupling at each excitation port.

As HFSS shows only single element behavior when plotting the far field radiation of an infinitely periodic element, the fields were exported and processed in MATLAB to obtain

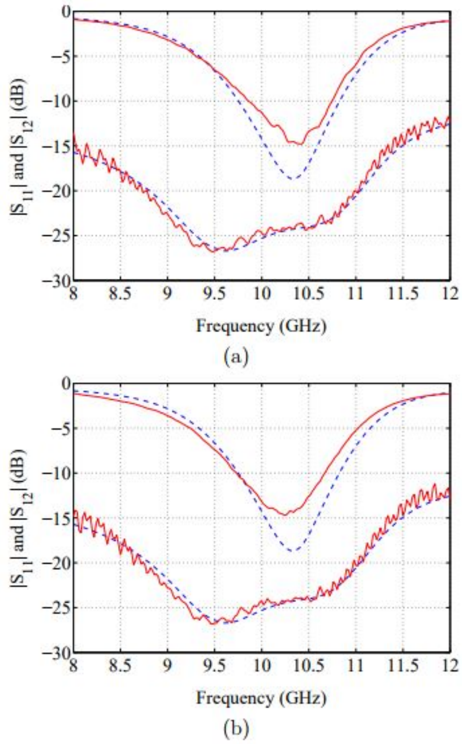


Fig. 2. Measured (red solid lines) and simulated (blue dashed lines) two-port unit cell s-parameters, where the ports correspond to orthogonally polarized feeds [2].

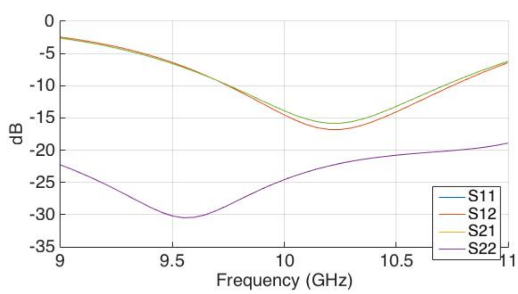
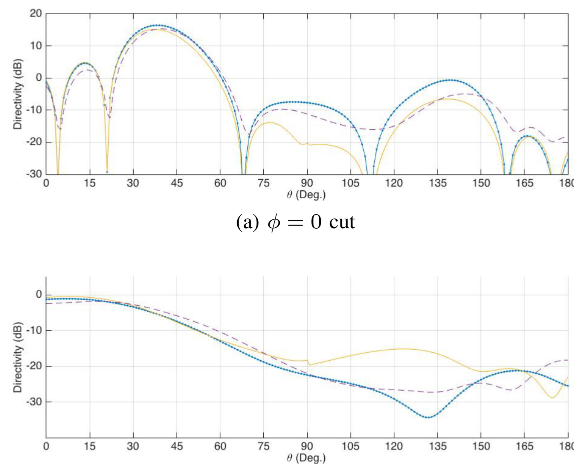


Fig. 3. Reproduction of previously published s-parameters for the antenna array unit cell in Fig. 1 for simulation validation.

N-element finite array behavior. Fig. 4 shows the overlay of radiation patterns at $\phi = 0$ and $\phi = 90$ using three methods of solving. Their agreement shows that the unit cell in a linear, one dimensional array can be tuned and modified for faster solve time in a good approximation of a seven-element finite array. Fig. 5 shows active VSWR for two different methods of solving the array. At scan angles above 60 degrees, the discrepancies between the two curves can be explained in that the infinite array unit cell pattern multiplication approximates the finite array by ignoring edge effects in the computational domain which are present in the full-wave simulation.

IV. Parametric Studies and Tuning of Infinite Array Cell

The distance of element spacing was swept around half a wavelength of separation. As expected, as elements are moved



(a) $\phi = 0$ cut

(b) $\phi = 90$ cut

Fig. 4. Validation in two ϕ-cut planes of the infinite element pattern multiplication results (dotted) as compared with the simpler, single element pattern multiplied (solid) and the more complex full-wave EM simulation (dashed).

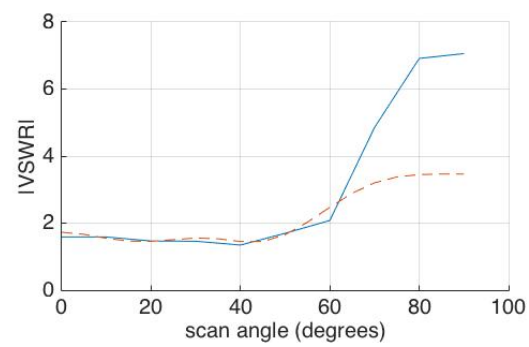


Fig. 5. VSWR comparison of two methods of solving the array - pattern multiplication with an infinite array element (solid) and full-wave finite array solving (dashed).

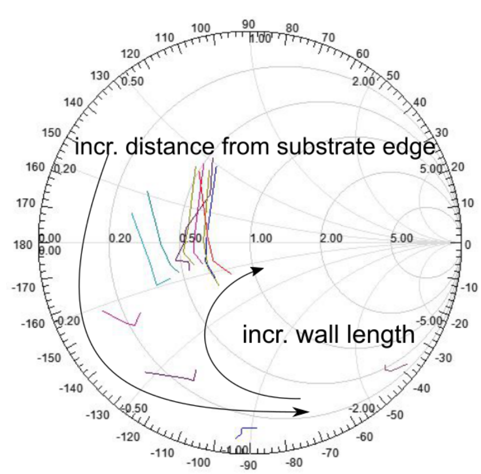


Fig. 6. A high reflection coefficient, suggesting scan blindness and lower realized gain, can be seen with a cell wall located closer to the edge of the patch than the edge of the substrate.

wider apart, they couple less across increasing scan angle. To investigate the possibility of reducing element-to-element coupling, a fin 0.4mm thick is added to either side of the radiating element. This cell wall height was swept between 0.3 to 2.7mm, the length between 7.23mm to 21.7mm centered in alignment with the patch, and the location of the wall was varied from 65% to 95% to the edge of the substrate.

The patch geometry's length was swept, but found to have insignificant effect on gain and VSWR variation. To reduce the number of simulations, the parametric sweeps were conducted in three dimensions at a time, sweeping scan angle and two dimensions of the cell wall (e.g. height and location or location and length). The nominal value of the cell wall length was 12.05 mm, the wall location was .95% of the element spacing, and the height was 1.5mm. An example of resulting trends is in Fig. 6, where it can be seen that increasing the length of the cell wall and decreasing the distance from the unit cell edge together reduces the magnitude of VSWR.

V. Final Design and Simulated Full-wave Performance

The unit cell of the final design is shown in Fig. 7, with element spacing determined to be 17mm, providing a trade-off between both flattening the VSWR and maintaining consistent gain across scan. The cell wall measures 1.5mm by 12.05mm, and each is located 7.05mm away from the edges of the patch. The performance of the array is solved in the full-wave finite 7-element configuration. As shown in Fig. 8, the VSWR of the modified design, measured at the central fourth element of the array, remains around or below 2 across the entire 90 degree scan range, as compared to the initial array configuration where the VSWR increased significantly after 45 degrees and reached a magnitude of 3.5. The realized gain is at or above 14.9 dB between scan angles of 0 and 50.

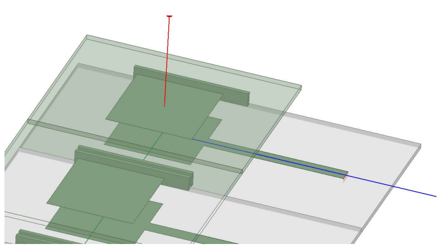


Fig. 7. The final modified unit cell is spaced 2mm farther apart than the starting half-wavelength design, and includes cell walls to reduce element-to-element coupling.

When examined across frequency (shown in Fig. 10, a resonance in the input match appears around 10.4 GHz. While the resonance is not strong unless at a higher scan angle such as 50 degrees and would not be destructive to a front-end module, it is nonetheless an undesirable behavior. Therefore, setting 10.3 GHz as the upper limit of the match and shifting the center frequency to 10.25 GHz, the -10dB match bandwidth of the array is 3% at 0 degrees scan angle, 4.9% at 10 and 30 degrees, and 7.4% at 50 degrees.

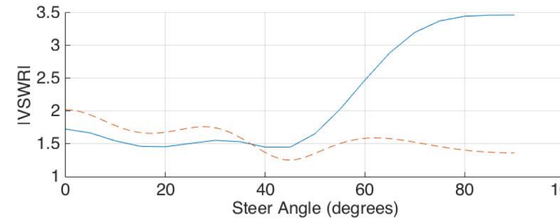


Fig. 8. The VSWR of the 15mm-spaced (half-wavelength) array without cell wall modifications is plotted in solid blue, whereas the VSWR of the 17-mm spaced modified array is plotted in dashed red.

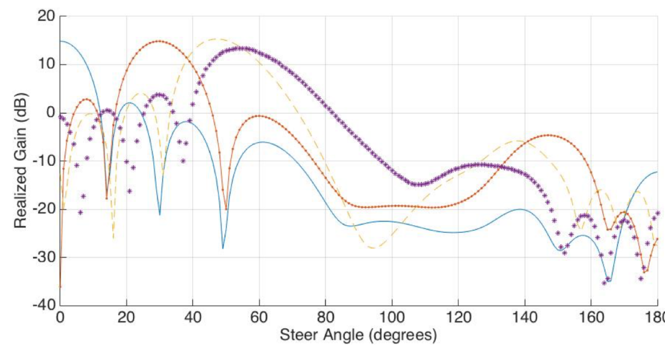


Fig. 9. The gain pattern of the array at 0, 10, 30, and 50 degrees. After 50 degrees, the antenna does not scan as strongly; instead it begins to compress and does not scan much farther than 60 degrees, while gain begins to drop off.

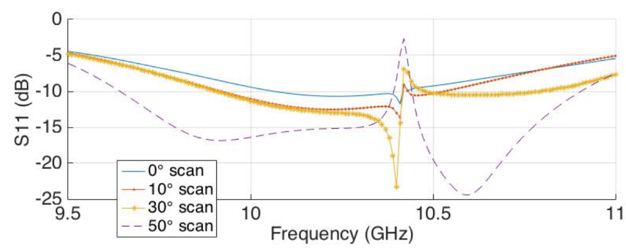


Fig. 10. Active S_{11} parameter for various scan angles.

VI. Conclusion

By implementing two fins on either side of the unit cell and conducting a parametric study of the dimensions of the fin and adjusting the spacing of the array, a 7-element finite patch array was successfully scanned from 0 to 50 degrees while maintaining a VSWR below 2. Future work can be done in investigating non-uniform amplitude excitation and how different weighting distributions can be used to reduce negative effects on input VSWR at various scan angles of an array. The parametric study can also be expanded across frequency to smooth out the resonance within the design presented here.

References

[1] R. J. Mailloux, *Phased Array Antenna Handbook*. Artech House, 2005.

[2] D. Popovic, "Constrained lens arrays for communication systems with polarization and angle diversity," Ph.D. dissertation, University of Colorado at Boulder, 2002.

[3] D. F. Kelley and W. L. Stutzman, "Array antenna pattern modeling methods that include mutual coupling effects," *IEEE Trans. on Antennas and Propagation*, vol. 41, no. 12, pp. 1625–1632, Dec 1993.