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A Review of Planar Ultrawideband Modular Antenna (PUMA) Arrays

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***Abstract*—Planar Ultrawideband Modular Antenna (PUMA) arrays are low-cost, wide-scan, and low-cross polarization dual-polarized UWB arrays that combine excellent electrical performance with convenient and practical feeding/fabrication processes. Each member of the PUMA array family consists of tightly coupled horizontal dipoles over a ground plane with novel feeding schemes that enable simple PCB fabrication. This feeding eliminates the need for baluns, "cable organizers," and other external support mechanisms to produce stand-alone, high-efficiency radiators. Additionally, all PUMA arrays consist of dual-offset dual-polarized lattice arrangements for modular, tile-based assembly. This paper will review the basic operation principles of the PUMA arrays followed by the technological evolution of the PUMA array family. Fabricated PUMA arrays and full-wave simulations of structures that can be manufacutured with standard fabrication technologies will be shown along with results.**

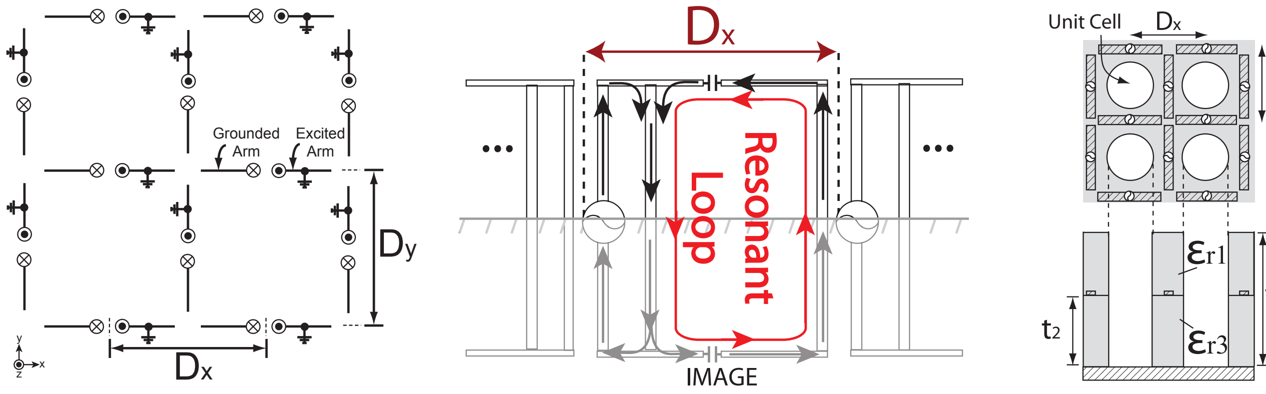
I. INTRODUCTION

Ultrawideband antenna arrays persist to be popular for multifunctional RF systems, where multiple antennas serving different purposes can be consolidated into a single aperture [1]. The plethora of functionalities utilized by such systems (e.g. radar, communications, electronic warfare, etc.) operate over several frequency bands, typically beginning at the upper end of the ultra-high frequency (UHF) band up into extremely-high frequency (EHF) bands. Consequently, it would be desirable to have a single array with enough bandwidth to accomodate this entire frequency range. Electrical properties such as wide-scan capability and polarization diversity would also be necessary to satisfy exclusive application requirements. However, due to physical limitations, it is difficult to design such an array, especially in a low-cost fashion. Ultrawideband arrays are commonly non-modular and troublesome to fabricate above X-band due to complex geometries, leading to high expenditures.

Due to their geometrical simplicity, low-profile, and good wide-scan performance, planar array technologies have become an appealing area of research in ultrawideband arrays. Several notable arrays were developed to elucidate the demand for maximal bandwidth with a planar architecture. The current sheet antenna (CSA) array [2] is one such array that employs the concept of Wheelers' current sheet [3] to counteract capacitance produced from tightly-coupled horizontal dipoles with an inductive ground plane over a wide 9:1 bandwidth. Other planar arrays such as the fragmented aperture array (FAA) [4], [5] and long slot array [6] also achieve wide bandwidths with the addition of loading lossy materials [7], [8] to suppress resonances from the introduction of a ground plane. Also, although the array layers are fully printable and planar, each of these arrays require external three-dimensional support mechanisms to maintain their wideband performance. Such devices include wideband exteran baluns and "cable organizers" that shield the vertical field lines to prevent scan-induced resonances [9]. All of these factors lead to a truly non-planar architecture that ultimately impair low-cost manufacturing, radiation efficiency, and fabrication at frequencies above X-band, let alone EHF.

The Planar Ultrawideband Modular Antenna (PUMA) array [10] was designed to circumvent the performance-limiting feeding methods that plague ultrawideband array technologies while also retaining a simple, modular design for convenient assembly and simple fabrication. Unlike other dual-polarized ultrawideband arrays, PUMA arrays are fabricated solely with low-cost multilayer PCB fabrication due to their simple architecture - planar etched circuits and plated vias with no external support. The feeding scheme allows for direct connection to standard RF interfaces with unbalanced feed-lines with the introduction of a novel common-mode mitigation tactic. As will be revisited later, the initial PUMA array was able to achieve a wide bandwidth when fed directly with a 50Ω unbalanced interface [11]. This array was used as a foundation for proceeding PUMA arrays, where several other designs came about to improve the performance. Such research directions, which will be followed later, include methods to enhance the bandwidth and frequency scalability, while always retaining the convenient feeding, fabrication, and modularity characteristics inherent to the PUMA family.

This paper will review the design fundamentals and evolution of the PUMA array family. The following section will



(a) (b) (c)

Fig. 1. Several key design traits of PUMA arrays. (a) A top view of the basic dual-polarized arrangement of a PUMA array utilizing shorting vias to reduce the common-mode resonant dimensions. (b) Cross-sectional view along a fed plane of the PUMA array displaying the resonant loop formed at the low band-edge. (c) Perforations are drilled through the PTFE substrate/superstrate of PUMA arrays to mitigate the onset of surface waves within the desired scan volume.

highlight the theory behind the PUMA array operation. Section III will present various PUMA arrays and the design routes taken to approach a low-cost, ultrawideband, EHF-scalable array from a top-level physical viewpoint while concluding with Section V.

II. PUMA FUNDAMENTALS

Like other planar arrays, PUMA arrays employ capacitively-coupled dipoles as seen within Fig. 1 to counteract an inductive ground plane over a wide impedance. However, PUMA arrays are unique such that they retain efficient wideband electrical performance without the assistance of complex baluns or organizers and connect directly to 50Ω RF interfaces. Several key design parameters that enable this functionality will be reviewed in this section, and the interested reader is encouraged to read [12] and the cited PUMA papers.

A. *Feeding, Shorting Vias, and Implications*

Ideally, the currents on the dipole feed lines would be equal in magnitude and balanced opposite in phase over an extremely wide bandwidth to ensure no vertically polarized currents on the feed lines produce catastrophic resonances, or common-modes, within the frequency band. This is typically achieved through inserting an external balun to force a 180° phase difference between both lines. In addition to this, the feed lines must also be shielded to prevent unbalanced currents when scanning along the E-plane due to mutual coupling. This feeding approach not only introduces added expenditures and lossy devices, but also includes fabrication complexities when scaling to higher frequencies.

Unlike other arrays, PUMA arrays are fed with unbalanced RF connections and produce resulting unequal magnitude currents occur between the two dipole feed lines. The asymmetry in the vertical currents manifests itself as a common-mode resonance between the mid and high end of the band. To suppress this common-mode, PUMA arrays utilize shorting vias to push it above the grating lobe onset frequency. As previously examined for dual-polarized configurations, the common-mode resonance occurs when the path length between shorted lines in the E/H-planes is equal to half a wavelength. When a shorting via is electrically connected to a dipole arm, this distance is reduced as displayed in Fig. 1(a) to effectively push the common-mode resonance higher in frequency.

Although alleviating the in-band common-mode resonances, the advent of shorting vias alters the low-frequency behavior of the array. Shown in Fig. 1(b), two circulating current loops are formed, where their size is dependent upon the positioning of the shorting vias themselves. It was shown that the circumference of the larger loop dictates the low-frequency band edge. Thus, more bandwidth desires the shorting via(s) closer to the feed lines for a larger low-end loop resonance.

B. *Surface Wave Mitigation*

PUMA arrays utilize thick ($\lambda_h/4$) PTFE dielectric substrates for mechanical support of the feed lines and shorting vias, and also for the simplicity of the dipole arms in multilayer PCB fabrication processes. Surface waves are supported within the dielectric materials at certain scan angles and design tactics are employed to ensure the scan volume remains free of scan blindnesses. The most critical factor in controlling the scan blindness angles is the effective permittivity. To assist in this, PUMA arrays cleverly perforate the dielectric layers between the dipoles to effectively reduce the permittivity by introducing air-filled holes like presented in Fig. 1(c). However, these dielectric layers also play a major role in impedance matching over a wide bandwidth. Thus, optimizing the size of these perforations and the relative permittivity of the dielectric layers becomes a key design trade-off in ensuring wide-scan capability and acceptable impedance performance.

III. PUMA ARRAY EVOLUTION

This section will briefly describe some PUMA array designs to highlight some design decisions and maturity of the PUMA technology over the years.

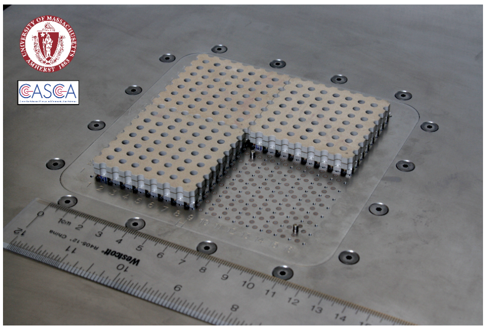


Fig. 2. Three fabricated 8x8 PUMA modules. Simple modular construction is made possible due to the convenient architecture of PUMA arrays.

A. *PUMAv1*

The initial PUMA array was developed based entirely upon the previously discussed design principles. This array was constructed modularly with a low-profile of about $\lambda_{high}/3$. The 16×16 prototype was fed directly from a 50Ω unbalanced interface. Low VSWR and good scan performance was demonstrated with low cross-polarization in the D-plane out to $\theta = 45°$ over a 3:1 bandwidth up to 21 GHz [11]. An image of the prototype is shown below in Fig. 2, demonstrating its simple, modular assembly. Fig. 4[b] contains the measured broadside VSWR.

B. *PUMAv2*

Once the theory and full-wave simulations were validated with the measured results, future research was spurred to increase the bandwidth. Using full-wave infinite cell analysis, a 5:1 bandwidth with very similar performance to the preceding array was achieved by printing a planar matching network on the opposite side of the ground plane [13]. A top view of the array's unit cell, referred to as the PUMAv2, can be seen within Fig. 3. In this design the array was purposely mismatched in such a way that a simple matching section, consisting of just a series capacitor and a quarter-wave transformation section, could provide a wideband impedance compensation.

Although this method proved to increase the bandwidth of the preceding PUMA array through simulation while retaining direct 50Ω feeding and modularity, the frequency scalability was severely limited. This version of the PUMA array required increased capacitance to further compensate for a highly inductive low-frequency band generated from the introduction of shorting vias. One method to accomplish this was to print the orthogonal h-v dipoles on different layers to synthesize a maximized capacitance. However, the separation thickness between these two layers soon became extremely thin and consequently met manufacturing limitations at 5 GHz - directly limiting any type of frequency scalability. In addition to this, the matching network lateral dimensions did not easily fit within a unit cell.

C. *PUMAv3*

The third installment of the PUMA array family (appropriately referred to as the PUMAv3) focused upon maintaining even wider bandwidth with similar concepts from the preceding array, but now also enabling mm-wave frequency scalability and ensuring the entire array and matching components fit within one unit cell. To accomplish this, several new topological changes were made that will be detailed exclusively in an upcoming paper. The PUMAv3 adds a capacitive plate to further compensate for the low-end inductance while also repositioning the shorting vias to achieve optimal bandwidth and common-mode suppression. A high-pass filter is also synthesized to further optimize the low-band edge. The new changes to this array allow for fabrication tolerances to be met comfortably with existing designs yielding an improved 6:1 bandwidth and operaton up to 45 GHz. The PUMAv3 unit cell is compared with the preceding design in Fig. 3. VSWR charts comparing the PUMAv3, preceding PUMA arrays, and other efficient wideband technologies are shown in Fig. 4

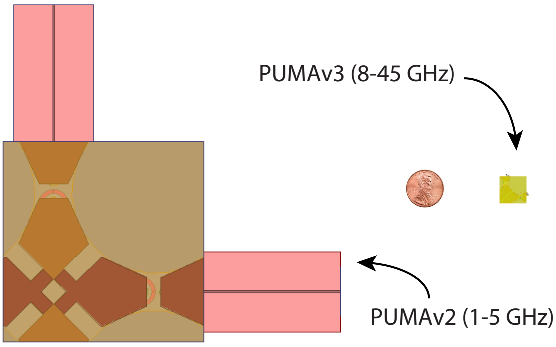


Fig. 3. Dual-polarized full-wave models of the PUMAv2 (left) and the PUMAv3 (right) compared to a standard U.S. penny. Each model is designed to meet fabrication requirements at their highest possible operating frequencies.

IV. CONCLUSION

The PUMA array has evolved over the years to strive to become a low-cost, efficient EHF-scalable ultrawideband array. This review briefly encompassed the fundamental design traits of PUMA arrays and summarized the physical and electrical characteristics of three PUMA arrays. Comparisons highlighting the architectural and electrical differences between three installments of the PUMA array family were revisited.

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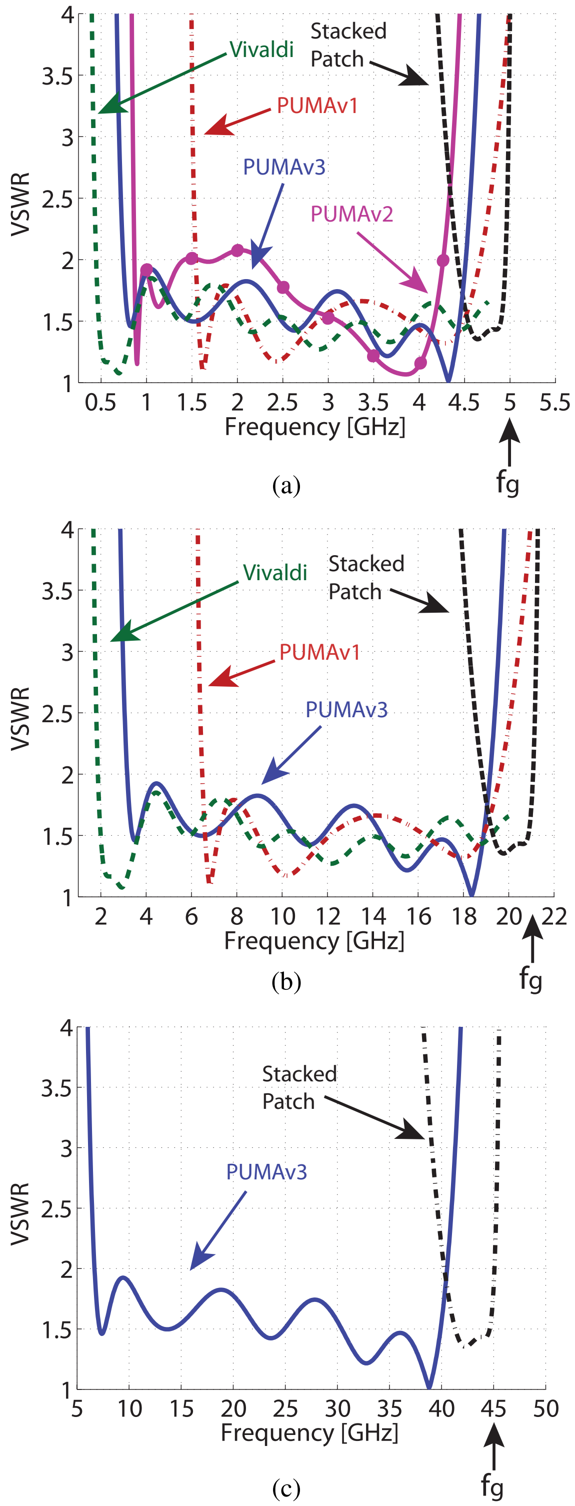

(a)

(b)

(c)

Fig. 4. Broadside VSWR charts over different operating frequency ranges of several dual-polarized PUMA arrays and some state-of-the-art vertically integrated and planar UWB arrays. As the technology matures, PUMA arrays approach the bandwidth of the Vivaldi while maintaining the geometrical simplicity and frequency scalability of the stacked patch array. (a) UWB arrays operating up to 5 GHz. (b) UWB arrays operating up to 21 GHz. (c) UWB arrays operating up to 45 GHz.

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