

A 7-21GHz Planar Ultrawideband Modular Array

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Introduction

Wideband, low-cost, and low-profile modular phased arrays are in high demand for future multifunctional systems. Currently, low-profile ultrawideband arrays such as the current sheet array (CSA) [1] or the fragmented aperture array (FSA) [2] use printed layers, but rely on 3D machined feed organizers and external wideband baluns that contribute to cost and limit modularity and scaling to higher frequencies. This paper presents the Planar Ultrawideband Modular Array (PUMA), a fully planar implementation of Wheeler's current sheet [3] requiring no feed organizers or external baluns, that can be fabricated entirely using standard planar microwave circuit processes. This allows for low-cost aperture fabrication, high volume production and frequency scalability. The unique feed arrangement of PUMA allows for a modular egg-crate construction, with direct connection to standard 50Ω interfaces, and low profile ($\approx \lambda/3$ at its highest frequency). Predicted dual-polarized infinite array performance has demonstrated a 3:1 bandwidth (7-21GHz) and scanning with $VSWR < 2.2$ out to $\theta = 45^\circ$ in all planes. Measurements of a $16 \times 16 \times 2$ array are currently in progress.

PUMA Topology

The PUMA, shown in Fig. 1(a), is an egg-crate dual-polarized dipole array that uses a unique feeding mechanism through unbalanced feeding and a pair of shorting posts at each dipole arm. This simple design, apart from its all-planar fabrication allows modular assembly by splitting the array between the feed lines as shown in Fig. 1(a).

Theory and Design

This section outlines the PUMA operation principles using simple theoretical models. This will provide unique insights that lead to explicit design guidelines. For completeness, an overview of the dipole current-sheet operation is first provided. Next the critical common-mode resonance problem in unbalanced-fed non-connected arrays is presented, and a simple, elegant solution is proposed, leading to the PUMA. The low frequency behavior of PUMA is dictated by a loop-mode resonance, thus its control strategy is presented. Finally, due to the thick PUMA dielectric substrates, a method of controlling surface waves is given.

Current sheet concept: The ultimate broadband radiator is a continuous current sheet. In [4], an ingenious realization was devised using the interplay of capacitive coupled dipoles with the ground plane. Since this is not the novel aspect of this array, the interested reader is referred to [3] and [5] for the complete theory and design guidelines. The dipoles are inductive at high frequency and capacitive at low frequency, and "see" the ground plane as a short-circuited transmission line, with $Z_{in} = jZ_0 \tan(\beta d)$ (where β is the propagation constant in the dielectric, and d is the distance to the ground). By choosing $d = \lambda_{mid}/4$, the ground reactance counteracts

the reactance of the dipoles over a wide frequency range. Further bandwidth and scan stability is achieved by adding superstrates.

Controlling the common-mode resonance with shorting posts: The PUMA has unbalanced feed lines exciting balanced dipole arms, which is known to excite a catastrophic common-mode resonance near midband, as shown by the solid curve in Fig. 2(c). This resonance occurs whenever currents on the exposed vertical feed lines are not perfectly balanced, producing a net current flow that couples into a vertical resonant electric field distribution that resonates along the diagonal dimension of a unit cell, shown in Fig. 2, i.e. $\lambda_{cm}/2 = \sqrt{D_x^2 + D_y^2}$, where D_x and D_y are the E- and H-plane spacings, respectively. In the PUMA this catastrophic resonance is shifted out of band by placing a shorting post on each dipole arm effectively forcing the vertical electric field to zero at strategic locations to shorten the resonant length, as shown in Fig. 2(b). This is a novel ingredient in PUMA, permitting all-planar fabrication using standard PCB vias, by eliminating the need for 3D organizers and external baluns. The new resonant length L of the common mode is

$$L = \sqrt{(D_x - 2s)^2 - D_y^2} \Rightarrow f_{cm} \approx \frac{c_0}{2\sqrt{\epsilon_r 3} \sqrt{(D_x - 2s)^2 - D_y^2}} \quad (1)$$

where $2s$ is the shorting post separation. From (1), one can shift f_{cm} out of band by increasing the short separation s .

Controlling the low frequency loop resonance: The shorts present an open ($\lambda/4$ shorted high impedance transmission line) to the dipoles at midband, and affect minimally the impedance at high-frequencies. However, at low frequencies they form a half-wave resonant loop, which dictates the low-frequency performance. Circulating currents between neighbors as shown in Fig. 3(a), form a resonant loop that is driven by a small loop, and using image theory can be modeled as a loop antenna as shown in Fig. 3(b). The circumference of this loop approximately predicts the resonant frequency as

$$f_{loop} \approx \frac{c_0}{2\sqrt{\epsilon_r 3}(4d + 2D_x - 3s)} - |f(C)|, \quad (2)$$

where $|f(C)|$ represents the effect of capacitive loading due to inter-element capacitance C . From (2), reducing f_{loop} (wider bandwidth) requires minimal short spacing s , and maximal capacitive coupling, leading to an interesting compromise with (1).

Surface wave mitigation: Because the PUMA is printed on thick, low permittivity PTFE substrates rather than air [4], it can excite surface waves, leading to scan blindness at certain high frequencies and wide angle scans [5]. The location of such scan blindnesses can be analytically predicted by considering the surface wave circles $\left(\frac{\beta_{sw}}{k_0}\right)^2 = \left(\frac{m}{D_x/\lambda} + u\right)^2 + \left(\frac{n}{D_y/\lambda} + v\right)^2$ in u, v space, where β_{sw} is the surface wave propagation constant, k_0 is the free space wavenumber, and m and n are the TM/TE surface wave mode indexes. To shift surface wave excitation out of scan volume, β_{sw} must be minimized; since the dielectric thicknesses at the highest frequency are fixed to $\lambda/4$, the only option is to reduce ϵ_r . This is achieved by perforating the dielectric layers with holes, where controlling the hole diameter reduces the effective permittivity according to $\epsilon_{reff} = \frac{\pi}{2} \left(\frac{D}{W}\right)^2 + \epsilon_r \left(1 - \frac{\pi}{2} \left(\frac{D}{W}\right)^2\right)$, [6], where D and W are the diameter and separation of the holes.

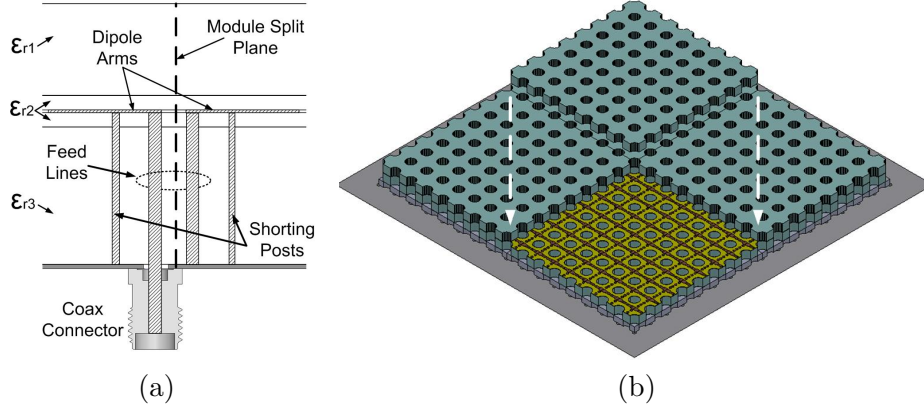


Figure 1: The PUMA array. (a) cross section view; (b) prototype of the $16 \times 16 \times 2$ 4 module array currently under measurement.

Results for PUMA for 7-21GHz SatCom Application

This design uses two 2.94mm thick layers ($\approx \lambda/4$ at midband) of Rogers 5880LZ ($\epsilon_r = 1.96$) for the bottom and top dielectric layers, since it's a low permittivity PTFE with low z-expansion coefficient. The Rogers 5880 middle dielectric layer hosts the two dipole polarizations etched onto each side. Element spacing is $D_x = D_y = 6.6\text{mm}$, which allows grating lobes to enter visible space above $\lambda_g/2 = 6.6\text{mm} \Rightarrow f_g = 23.5\text{GHz}$, which requires reasonably more T/R modules than the minimum. The infinite array active VSWR (referenced to 50Ω) scan performance was evaluated using Ansys/Ansoft HFSS, and is shown in Fig. 4 in three principle planes of the array. The black bars indicate the operating band of interest, and the Right Hand Circular Polarization (RHCP) active VSWR shows a good match (< 2.2) in all three planes out to $\theta = 45^\circ$.

Conclusion

The PUMA is a novel, low-profile, truly planar ultrawideband phased array that is directly fed by standard 50Ω connectors and can be fabricated in modules using low-cost fabrication. The theory of operation and main design guidelines were presented. Simulation results demonstrated $\text{VSWR} < 2.2$ out to scan angles of $\theta = 45^\circ$ over a 3:1 bandwidth. Measurements are under way, and will be presented in the conference.

References

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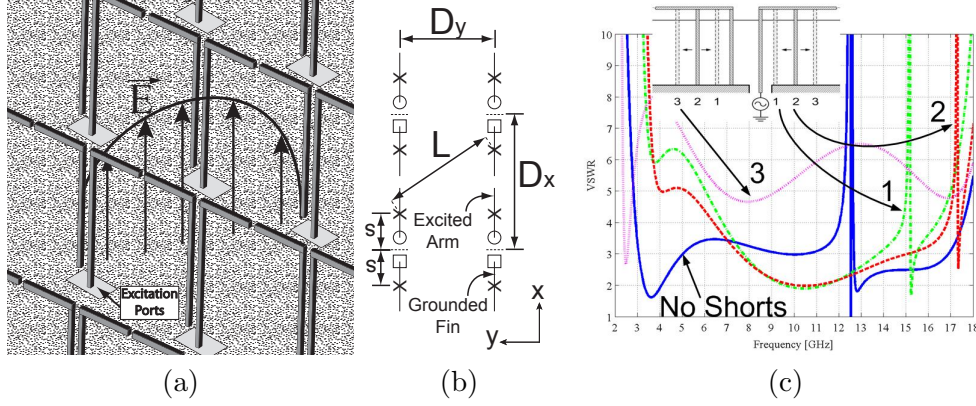


Figure 2: The common-mode resonance problem and its remedy. (a) Resonance in unbalanced non-connected dipole arrays; (b) top view of array, showing the shorting posts (x) and resonant length L ; (c) common-mode VSWR anomalies for various short locations

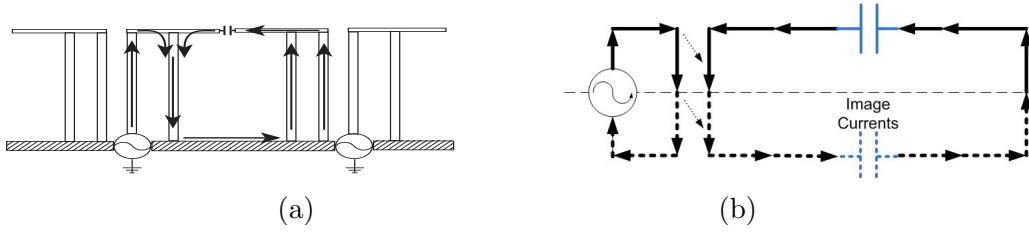


Figure 3: Low frequency loop-mode resonance in the PUMA. (a) Current distribution on structure at resonance; and (b) circuit model of loops using image theory.

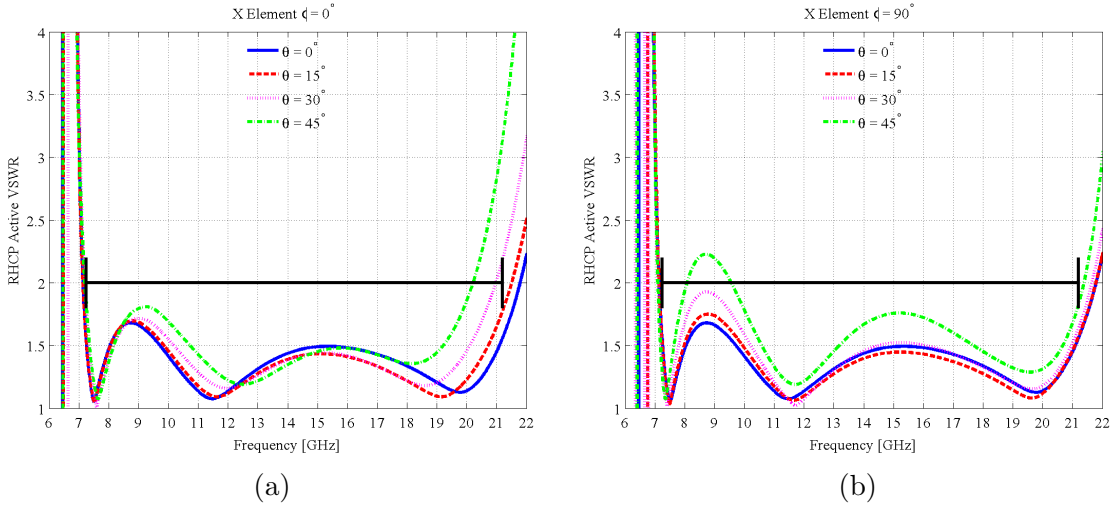


Figure 4: Infinite array active VSWR of a 7-21GHz (3:1) PUMA array. RHCP active VSWR in the (a) $\phi = 0^\circ$ and (b) $\phi = 90^\circ$ planes.