Wideband, Wide Scanning Conformal Arrays with Practical Integrated Feeds

Jonathan P. Doane, Willam F. Moulder, Kubilay Sertel, and John L. Volakis

***Abstract*—A key challenge in designing wideband dipole arrays is developing a wideband balun that is sufficiently compact to fit within a single unit cell. A new technique has recently been developed which uses the the reactance of a compact balun as an impedance matching network to improve the bandwidth of a Tightly Coupled Dipole Array (TCDA). In this paper, we apply this technique to two TCDA designs, with and without resistive loading. The first design uses a compact balun and low-loss materials to achieve 7.2:1 bandwidth, with VSWR<2.6:1 while scanning to $\pm 45°$in all planes. The second design uses a similar balun design along with a resistive sheet placed below the dipoles, achieving a bandwidth of 14.2:1 with VSWR<2.4:1 at broadside, and $> 70\%$ efficiency across most of the band.**

I. Introduction

Tightly Coupled Dipole Arrays (TCDAs) are of interest due to their low profile, wide bandwidth, good scan performance, and low cross polarization [1]–[3]. However, in practice, the array feed must include baluns or 180° hybrids that can sustain similar wide bandwidths. Ideally, a small balun could be integrated within each unit cell. However, the available volume is quite limited, particularly for arrays operating above 500MHz. For example, a TCDA operating from 600-4500MHz may have only 30mm separation ($\sim\lambda$/17 at 600MHz) between the dipoles and ground plane and the same distance between elements. Practical implementation of baluns that fit within this available volume is quite difficult, and previous attempts yielded only modest bandwidths (less than 2:1) [4]–[6]. Active balun circuits may be used, but they are unidirectional, introduce electronic noise, and have low power handling capacity making them unsuitable for many applications. An alternative technique foregoes baluns altogether and uses vias to mitigate common mode resonances, resulting in 5:1 bandwidth with external impedance matching [7]. However, for maximum bandwidth and performance, TCDAs use bulky external baluns or 180° hybrids located below the ground plane [8], significantly increasing the total size, weight, and cost of the array.

A major challenge in developing a low loss, passive balun is that they typically require significant size if they are to be broadband. For example, a Marchand balun [9] must incorporate very high- and very low-impedance transmission lines to provide a wideband impedance match. However, with limited space, these features are not trivial to implement, and the balun's reactance is increased, corresponding to reduced bandwidth. The bandwidth is further limited by the high impedance of the array (commonly $\sim$200Ω), which must be matched to a 50Ω feed within a small volume.

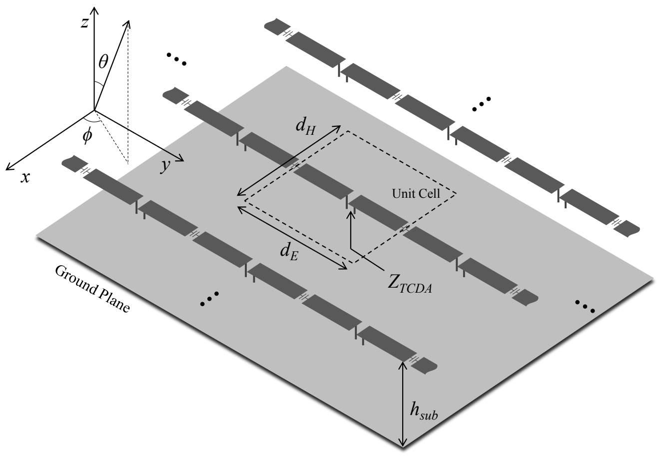
Recently, a novel approach was suggested to overcome these limitations by including the balun itself as part of the impedance matching network for the TCDA [10], [11]. By tuning the reactance slope of an electrically-small balun, the array bandwidth can be increased, rather than decreased. This paper presents an overview of several new designs which make use of this impedance matching approach to achieve extremely wide bandwidth and wide scanning, while simultaneously providing a practical low-cost feed matched to a standard 50Ω transmission line.

The first design is presented in Section II and makes use of reactive baluns to achieve a bandwidth of 7.2:1, with VSWR<2.6:1 while scanning to ±45° in all planes. The second design, presented in Section III, makes use of a similar feed design, but also includes a resistive sheet between the dipoles and the ground plane to suppress a resonance within the substrate at higher frequencies [12]. Although this reduces the efficiency of the array somewhat, the power absorbed in the resistive sheet is minimized by properly designing the superstrate layer. In this way, a resistively-loaded TCDA with an integrated balun is designed which delivers 14.2:1 bandwidth, with VSWR<2.4:1 at broadside, while its radiation efficiency is kept above 70% for most of the band.

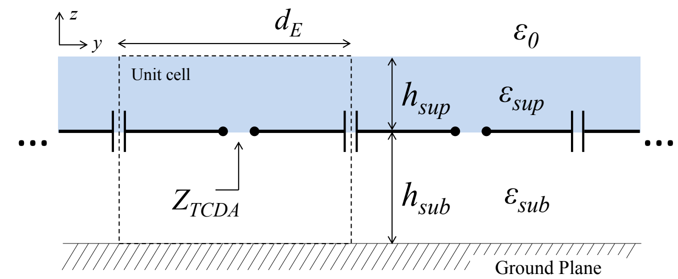
II. The Tightly Coupled Dipole Array with Integrated Balun (TCDA-IB)

A Tightly Coupled Dipole Array (TCDA) uses horizontal dipoles placed above a conducting ground plane, as shown in Fig. 1. By capacitively coupling adjacent dipoles, the array supports currents at wavelengths which greatly exceed the dimension of a single element. Moreover, the dipole inductance and inter-element capacitance serve to cancel the reactance of the nearby ground plane over a wide bandwidth. An approximate equivalent circuit for the unit cell of a TCDA was given in [1], and is shown in Fig. 2 for an array located at a height h_{sub} above a ground plane with a dielectric superstrate of thickness h_{sup}. In this circuit, the dipole inductance is represented by L_{dipole}, and the inter-element capacitance is denoted as $C_{coupling}$. The substrate, superstrate, and free space layers are each represented by transmission line sections, with properties determined by the propagating Floquet mode within each corresponding layer. The impedance of this transmission line network is denoted as Z_L, and is independent of the radiating aperture design. This impedance can be thought of as a fixed load to the system. We note that the bandwidth of the array is therefore fundamentally limited by the Fano limit of Z_L, given in [13], [14].

The input impedance of the array, denoted as Z_{TCDA}, is typically $\sim$200Ω, and the feed circuit must therefore also



(a)



(b)

Fig. 1. A Tightly Coupled Dipole Array (TCDA) consisting of capacitively coupled dipole elements, placed above a conducting ground plane. (a) Isometric view showing dipoles aligned with the y-axis and the ground plane normal to the z-axis. Substrate and superstrate materials are not shown. (b) Cross-sectional view in $y-z$ plane showing substrate and superstrate layers.

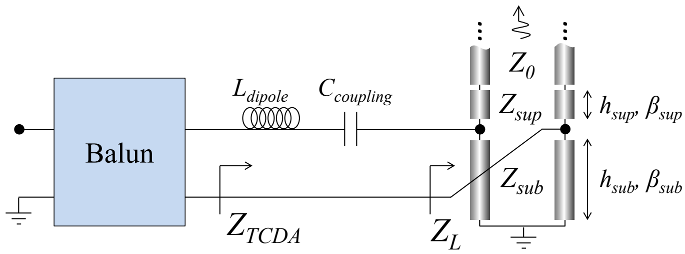
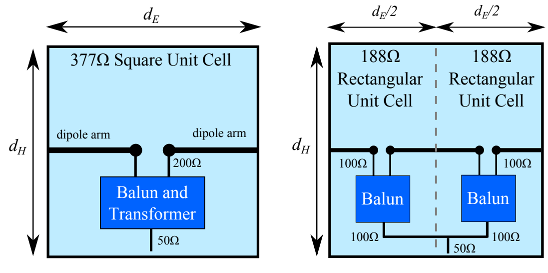


Fig. 2. Equivalent circuit of the TCDA's unit cell. A balun connects each TCDA element to a standard unbalanced transmission line.

include a 50Ω to 200Ω transformer, which requires significant volume. In our design we eliminate this transformer altogether by reducing the E-plane unit cell width by a factor of 2. As such, Z_{TCDA} is halved. The feed and balun can then operate at 100Ω, with two sets of dipoles and baluns per original (square) unit cell (see Fig. 3). The output of the 100Ω baluns are then combined via a power divider to form a single 50Ω feed, with no impedance transformation required. Reducing the E-plane dimension also serves to eliminate common modes resonances that can deteriorate scanning performance [5].

The above approach doubles the number of baluns in the array, and thus the balun size and cost become especially critical. Unfortunately, wideband passive baluns are in general bulky, heavy, and expensive. For a Marchand balun constructed



(a) Standard square unit cell (b) "Double" unit cell

Fig. 3. Top down representation of the unit cell. The impedance of the unit cell is proportional to the aspect ratio d_E/d_H. By splitting the cell into two halves, the impedance of each is correspondingly reduced by a factor of two. Recombining these halves in parallel again reduces the impedance at the common port by another factor of two.

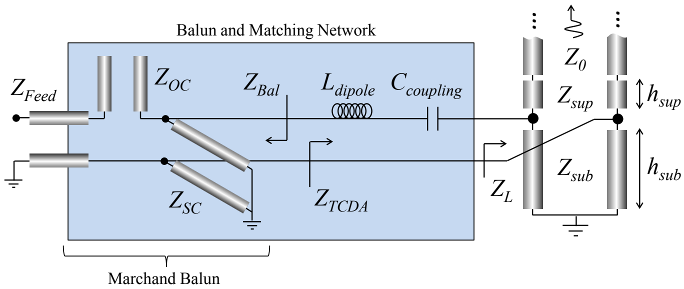


Fig. 4. TCDA-IB equivalent circuit with a Marchand balun feed. The addition of the balun's two transmission line stubs increases the overall order of the matching network, leading to increased impedance bandwidth.

from coupled quarter wave transmission line stubs (see Fig. 4), extreme impedance ratios are required between Z_{OC}, Z_{Bal}, and Z_{SC} in order to obtain wideband performance [9]. Compact Marchand baluns cannot implement such large impedance ratios in neighboring transmission lines, and are therefore inherently reactive and band limited.

However, we can exploit this reactance as a matching network for the array. Together, the stubs Z_{OC} and Z_{SC} along with L_{dipole} and $C_{coupling}$ form a three stage matching network to Z_L, as shown in Fig. 4. By optimizing the circuit model, a maximum impedance bandwidth for the TCDA and balun was found to be 8.9:1 with VSWR<2:1 at broadside. When scanning to 45° with VSWR<2.5:1, the optimized bandwidth is reduced to 7.5:1. This represents a ∼40% increase over the maximum bandwidth obtained when optimizing the simple TCDA circuit in Fig. 2. Thus, by incorporating the balun within the matching network, the bandwidth of the overall array is significantly increased. Concurrently, the total size, weight and cost of the array is reduced by eliminating the need for external baluns. We refer to this design approach as the Tightly Coupled Dipole Array with Integrated Balun (TCDA-IB).

The implementation of this design is depicted in Fig. 5. The entire array and feed circuit can be fabricated on a single PCB, resulting in a low cost lightweight array. Simulation of the infinite array was performed using Ansoft HFSS. After tuning the design, the array achieved 7.2:1 bandwidth (0.69-4.95GHz) with VSWR<2:1 at boresight. When scanning to

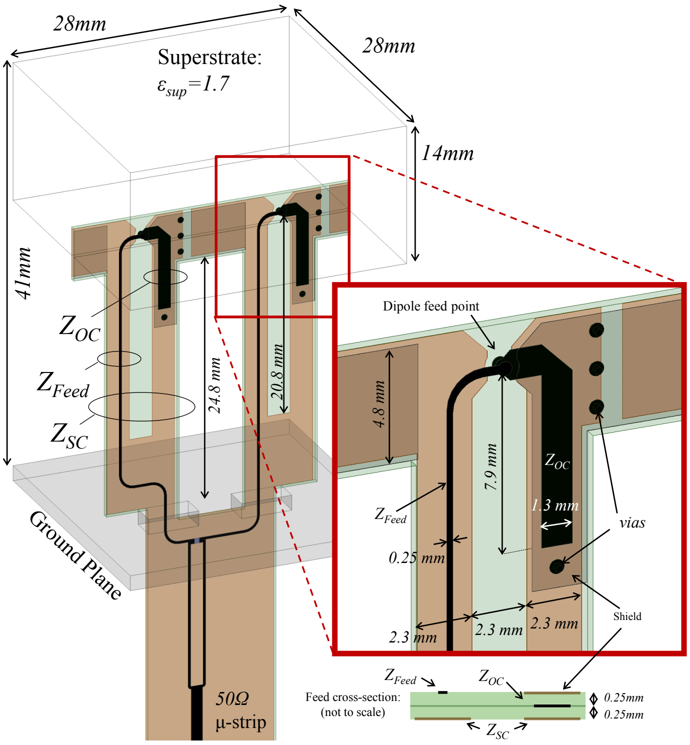


Fig. 5. Implementation of a unit cell of the TCDA-IB. Each unit cell contains two 100Ω baluns, fed by a single 50Ω microstrip trace.

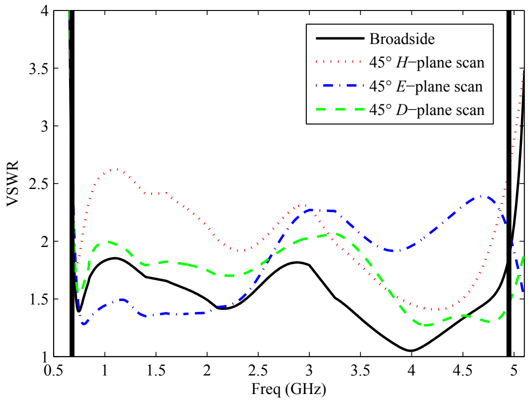


Fig. 6. Simulated VSWR of TCDA-IB unit cell, matched from 0.69-4.95GHz (7.2:1 BW).

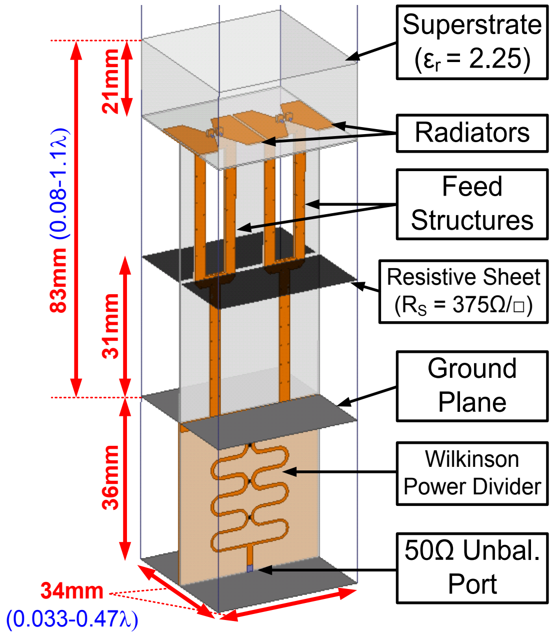
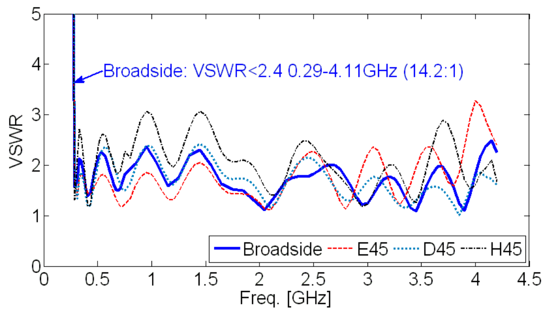
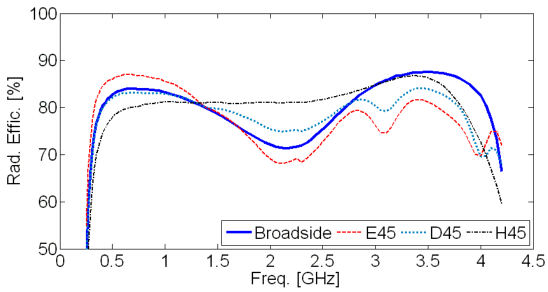


Fig. 7. Resistively-loaded TCDA-IB.



(a) VSWR



(b) Radiation Efficiency

Fig. 8. Simulated performance of resistively-loaded TCDA-IB unit cell (a) VSWR (b) Radiation Efficiency.

45° in all planes, the VSWR remains under 2.6:1 over the same bandwidth (see Fig. 6). If desired, T/R modules or phase shifters can be integrated directly on the circuit board, which is not possible with a standard TCDA because of the need for external baluns located between the array and electronics.

III. Resistively-Loaded Tightly Coupled Dipole Array with Integrated Balun

The bandwidth of the TCDA-IB can be further improved by including a resistive sheet between the dipoles and the ground plane, as shown in Fig. 7. All lossless planar arrays above a ground plane suffer from a catastrophic resonance that occurs when the spacing between array and ground plane reaches $\lambda/2$ [13]. However, this resonance can be suppressed by including a resistive sheet between the dipoles and ground plane, allowing the array to operate at higher frequencies [12]. Although this does result in reduced radiation efficiency, these losses can be minimized by including a dielectric superstrate. In essence, the dielectric loading reduces the radiation resistance, causing more power to be radiated away from the substrate and minimizing the losses in the resistive sheet.

Fig. 8a shows the simulated VSWR of the infinite array unit cell, depicted in Fig. 7. As seen, for broadside radiation, the array is matched (VSWR<2.4) over a 14.2 bandwidth (0.29-4.11GHz). Scanned array results are also given, namely for cases where beam is pointed 45° from the broadside axis in the E-, H-, and D-planes. Importantly, the array remains fairly well matched across the band while scanning, with the VSWR criteria relaxed to <3:1. Fig. 8b shows the radiation efficiency for broadside and scanned cases. As seen, at broadside scan case the radiation efficiency is greater than 70% over the majority of the band. The efficiency decays slightly when scanning, but does not drop below 66%. The "dips" in radiation efficiency at higher frequencies seen in the E- and D-scanned curves are due to the isolation resistors in the power divider.

IV. Conclusions

A new technique for feeding a Tightly Coupled Dipole Array with Integrated Baluns (TCDA-IB) was developed which eliminates the need for external or active baluns and improves the bandwidth of the array. By introducing a simple circuit that functions both as a balun and impedance matching network, the optimized bandwidth reached 7.2:1 while scanning to ±45° in all directions, without the use of any lossy materials. We note that since no external feed circuitry is required, T/R modules or phase shifters can be integrated directly onto the PCB substrate, enabling an extremely low-profile wideband electronically scanned array (ESA).

The bandwidth of the TCDA-IB can be further increased by including a resistive card within the substrate. By doing so, an array was developed which delivers 14.2:1 bandwidth and scans to ±45° in all planes. Despite the use of resistive materials, high radiation efficiency was maintained by using a dielectric superstrate to direct energy away from the lossy card.

Both the lossless and the lossy TCDA-IB designs demonstrate the importance of co-designing the array and balun together as a single network, rather than individually. The resulting designs are simple, practical, low cost array systems with extremely wide bandwidth and excellent scanning capabilities. Importantly, each element is matched to a standard 50Ω transmission line and does not require bulky and expensive external baluns. They are therefore attractive for a variety of wideband communication and sensing applications, and for small and low-cost platforms.

References

[1] B. A. Munk, "Broadband Wire Arrays," in *Finite Antenna Arrays and FSS*, 1st ed. Wiley-IEEE Press, Jul. 2003, ch. 6, pp. 181–213.

[2] B. Munk *et al.*, "A low-profile broadband phased array antenna," in *Antennas and Propagation Society International Symposium, 2003. IEEE*, vol. 2. IEEE, Jun. 2003, pp. 448–451 vol.2.

[3] J. L. Volakis and K. Sertel, "Narrowband and Wideband Metamaterial Antennas Based on Degenerate Band Edge and Magnetic Photonic Crystals," *Proceedings of the IEEE*, vol. 99, no. 10, pp. 1732–1745, Oct. 2011.

[4] J. A. Kasemodel, C.-C. Chen, and J. L. Volakis, "Broadband planar wide-scan array employing tightly coupled elements and integrated balun," in *Phased Array Systems and Technology (ARRAY), 2010 IEEE International Symposium on*. IEEE, Oct. 2010, pp. 467–472.

[5] D. Cavallo, A. Neto, and G. Gerini, "PCB Slot Based Transformers to Avoid Common-Mode Resonances in Connected Arrays of Dipoles," *Antennas and Propagation, IEEE Transactions on*, vol. 58, no. 8, pp. 2767–2771, Aug. 2010.

[6] ——, "A wideband (3 to 5 GHz) wide-scan connected array of dipoles with low cross polarization," in *Antennas and Propagation (EUCAP), 2012 6th European Conference on*. IEEE, Mar. 2012, pp. 3239–3242.

[7] S. S. Holland and M. N. Vouvakis, "The Planar Ultrawideband Modular Antenna (PUMA) Array," *Antennas and Propagation, IEEE Transactions on*, vol. 60, no. 1, pp. 130–140, Jan. 2012.

[8] C. A. Balanis, Ed., *Modern Antenna Handbook*, 1st ed. Wiley-Interscience, Sep. 2008.

[9] D. M. L. Bartholomew, "Optimim design for a broadband microstrip balun," *Electronics Letters*, vol. 13, no. 17, pp. 510–511, Aug. 1977.

[10] J. P. Doane, K. Sertel, and J. L. Volakis, "A 6.3:1 Bandwidth Scanning Tightly Coupled Dipole Array with Co-Designed Compact Balun," in *Antennas and Propagation Society International Symposium (APSURSI)*, Jul. 2012.

[11] ——, "A Wideband Scanning Conformal Array with a Compact Compensating Balun," in *Antenna Applications Symposium*, Sep. 2012.

[12] W. F. Moulder, K. Sertel, and J. L. Volakis, "Superstrate-Enhanced Ultrawideband Tightly Coupled Array With Resistive FSS," *Antennas and Propagation, IEEE Transactions on*, vol. 60, no. 9, pp. 4166–4172, 2012.

[13] J. P. Doane, K. Sertel, and J. L. Volakis, "Bandwidth limits for lossless planar arrays over ground plane," *Electronics Letters*, vol. 48, no. 10, pp. 540+, 2012.

[14] ——, "Matching Bandwidth Limits for Arrays Backed by a Conducting Ground Plane," *Antennas and Propagation, IEEE Transactions on*, vol. Accepted.