A Wideband and Wide Scanning Tightly Coupled Dipole Array with Meta-Surface Wide-Angle Impedance Matching

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Abstract **─** A low profile ultra-wideband tightly coupled dipole array is studied. The antenna elements are fed by Marchand baluns of small size and low cost. A meta-surface based wide-angle impedance matching (MS-WAIM) layer is introduced to replace the traditional dielectric WAIM, improving the beam scan performance and reducing the antenna profile. The simulation shows that the proposed antenna array can operate over 2.4-12.4 GHz, approximately 5:1 bandwidth with maximum scanning angle of 50^o for both E plane and 45^o for H plane. The antenna profile above the ground is only $0.578\lambda_H$ at the highest operating frequency. This antenna array can find its application in the forthcoming massive MIMO beamforming systems for 5G.

Index Terms **─** Meta-surface, phased array, tightly coupled dipole array, ultra-wide band, wide angle scanning.

I. INTRODUCTION

Wide-band antenna array has received extensive research over decades due to their important roles in military use, including remote, radar and electronic warfare [1],[2]. With scan ability, they make it possible to real time track object quickly; By producing multi-beams, multi-object task could be carried out simultaneously. For another side, to attain high data rates and large capacity, the next generation system (5G) plans to exploit frequency band below 6GHz (so called sub 6GHz band), which can provide spectrum covering 2.5 to 2.7 GHz, 3.3 to 3.8 GHz and additional frequencies between 4.4 to 5GHz [3]. The 5G also intent to use phase array technology to overcome interference problem, improving the signal transmission direction. However, the application of conventional phase array, such as slots array and microstrips array is confined by some shortcomings, including narrow bandwidth, limited scanning angle etc. [4].

Vivaldi antenna has been regarded as good candidate for ultra-wideband (UWB) antenna. Numerous studies were made during the past three decades, leading to Vivaldi array that achieve bandwidths over 10:1 at wide scans [5]. With excellent performance, Vivaldi antennas array has already been put into practice. However, this taper slot array suffers from some drawbacks such as high profile and high cross-polarization, which limit its further application requiring compact structure and low cross-polarization [6].

Mutual coupling is always a major concern in the design of traditional array antenna since it can degrade the efficiency as well as radiation patterns of the antennas, therefore many efforts have been made to reduce the undesirable coupling between array elements [7],[8]. On the other hand, tightly coupled dipole array (TCDA) has drawn more and more attention since Munk *et* al published the first prototype in 2003 [9]. In contrast to the traditional antenna array, the elements of TCDA are placed so closely, that the resulting strong capacity can compensate the inductance introduced by ground at the low frequency band [10]. TCDA is proved to be feature with low profile and low cross-polarization level comparing with Vivaldi antenna array [11]-[13], hence they are believed to have promising application of the future UWB antenna. One major challenge for the realization of TCDA is the design of an equally wideband feed network, which not only provide impedance transformation but also transition from unbalance to balance feeding [14]-[18][15]. Another challenge faces the designers is that the bulky dielectric WAIM, which is usually $\lambda_H/4$ [10][13], rising both the profile and the cost of the antenna array.

In this paper, a low profile ultra-wideband tightly coupled dipole array is studied. The antenna elements are fed by Marchand baluns of small size and low cost. A

Submitted On: February 7, 2021
Accepted On: March 21, 2021

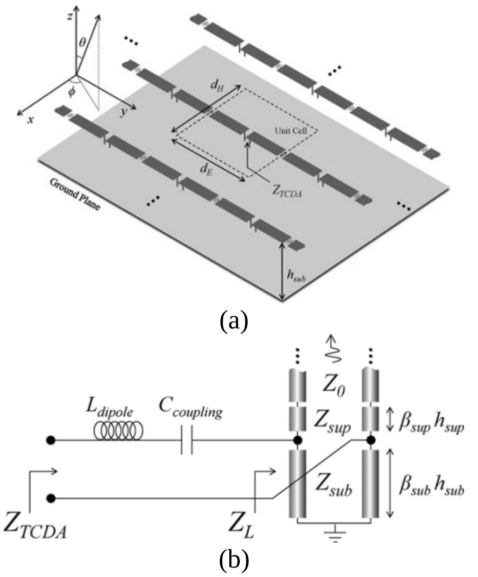
https://doi.org/10.47037/2021.ACES.J.360708

meta-surface based wide-angle impedance matching (MS-WAIM) layer is introduced to replace the traditional dielectric WAIM, improving the beam scan performance and reducing the antenna profile. The simulation shows that the proposed antenna array can operate over 2.4-12.4 GHz, approximately 5:1 bandwidth with maximum scanning angle of 50° for both E plane and 45° for H plane. The antenna profile above the ground is only $0.578\lambda_{\mathbf{H}}$ at the highest operating frequency. This antenna array can find its application in the forthcoming massive MIMO beamforming systems for 5G.

II. EQUIVALENT CIRCUIT ANALYSIS

The concept of TCDA could be traced backed to current sheet array (CSA). As shown in Fig. 1 (a). horizontal dipoles are placed periodically in array, where the distance between the adjacent elements is very small [14]. With the resulting strong capacitance, the array supports currents at wavelengths which significantly exceed the scale of individual element. To achieve uni-directional radiation, ground is introduced beneath the array. In the view of circuit, inter-element capacitance in associate with dipole inductance can counteract the reactance brought by the ground, thus broaden the bandwidth.

Figure 1 (b) presents the equivalent circuit for TCDA. In this schematic diagram, we denote dipole inductance by L_{dipole}, the inter-element capacitance by $C_{coupling}$. The substrate, superstrate, and free space layers are indicated by transmission line sections. Generally, the input impedance of TCDA is 100-200Ω, which brings a great challenge to the design of impedance matching network (conventional source is 50Ω).



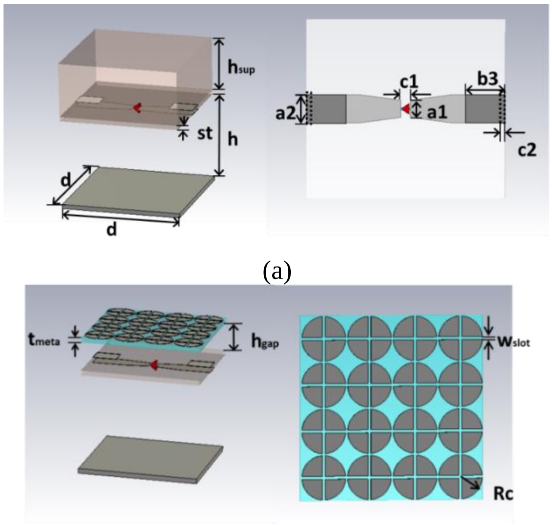
(a)

(b)

Fig. 1. (a) TCDA consisting of capacitively coupled dipole elements, placed above a conducting ground plane, and (b) equivalent circuit for the TCDA.

III. STRUCTURE DESIGN

A unit cell of the TCDA fed by a 150 Ω lumped gap source is placed at distance of h above the ground, as shown in Fig. 2 (a), where the dipole is printed on the bottom of Rogers RT5880 dielectric slab (ε_r=2.2) thickness of 0.5mm. There is small gap between the ends of the dipole arms (presented by dash line in the caption), bringing in strong coupling of adjacent elements, while the patch on the top of the dielectric slab is used to reinforce the capacitance. An electronically thick ($t=\lambda_{\mathbf{H}}/4$) layer with low permittivity is placed above the antenna for wide band tuning, though at the expense of increasing the weight and cost of the antenna array.



(a)

(b)

Fig. 2. (a) TCDA with dielectric MAIM, and (b) TCDA with Meta_surface MAIM.

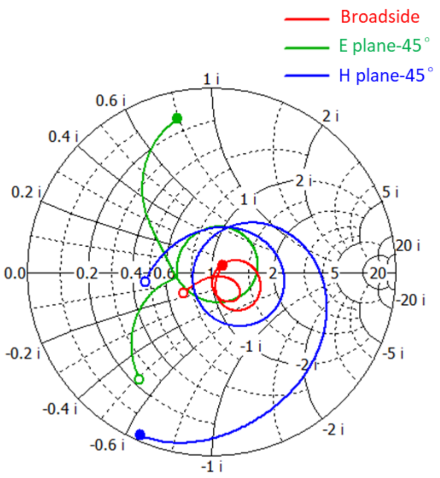
An adaptation is introduced to improve the situation, the bulky superstrate is substituted by a thin dielectric slab (Rogers RO3033, ε_r=3) with meta surface, as show in Fig. 2 (b). The meta-surface is comprised of small circular patches with cross slots in the center. It is worth noting that the lattice spacing of meta-surface is considerably smaller than that of the dipole array [16]. Thereby the meta-surface can be regarded as homogenized, in other words, a single relative permittivity in the case of a dielectric WAIM slab [19]. Similar to FSS, meta-surface could be treated on a Floquet mode by mode basis during analysis with multimode equivalent network, and when the array is fed, a sequence of Floquet modes will be excited. Accordingly, the Z_{sup} in the equivalent circuit of Fig. 1 (b) should be replaced by meta-surface impedance Z_W, comprising a series Floquet impedances,

$$Z_W = \sum_m \sum_n Z_{W_{mn}}.$$

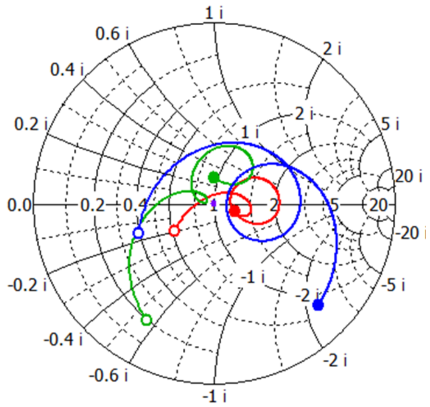
All impedances are function of polarization, scan angle (θ,φ). To prevent surface wave, there is an air layer between the superstrate and the dipole slab. In practice, foam plate is usually used to realize such suspension structure.

The proposed meta-surface WAIM is simulated in associated with TCDA, as shown in Fig. 2 (b). To focus on meta-surface WAIM and give a concise analysis, feeding system is not included in the model in the primary design. For comparison of the performance, the same TCDA is also simulated with conventional dielectric superstrate. Full-wave simulations are carried out with commercial software CST, and to ensure accuracy of the simulation, we adopt frequency domain solver as tetrahedral mesh can provide better fitting for realistic model. The boundaries are set as periodic for x and y direction, open space for z direction, the dimension of the unit cell, the ground plane height and the dipole scale are set the same and kept constant for both arrays. It's noted that the TCDA with the proposed meta_surfance WAIM could provide better frequency/ angular response.

Figure 3 presents the simulated input impedance for both TCDAs, including broadside, 45° scan in E and H plane. It manifests that the impedance curves of array with meta-surface are more confined to the center of the smith chart, comparing with that of array with dielectric-loaded array, indicating better matching and wider bandwidth during scanning. Specially impedance matching is more difficult for beam scanning in the H plane than in other planes, because increasing Floquet modes are excited, leading to detune of the array [20]. It's observed that the introduction of meta_suface WAIM alleviates this detuning (see blue line in the chart). Nevertheless, it should be noted that vertically oriented feed-lines, which will be introduced in the following section, also have different response to Floquet modes, therefore they can provide additional degrees of freedom to the design of the TCDA, and improve the performance.

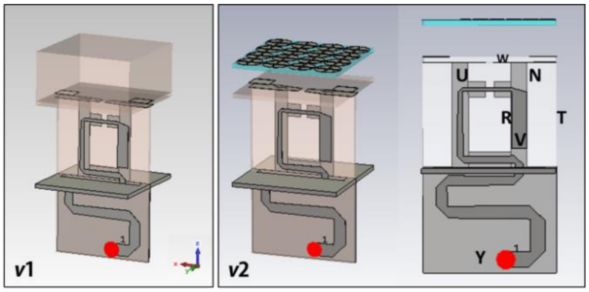


(a)



(b)

Fig. 3. S_{11} of the TCDAs with: (a) conventional dielectric superstrate, and (b) meta-surface WAIM, for broadside, E plane 45° and H plane 45° scan.



(a) (b)

Fig. 4. Illustration of the TCDA with: (a) conventional dielectric MAIW and Marchand balun, and (b) meta-surface MAIW and Marchand balun

Feed and matching network for TCDA should carry out two jobs: impedance transformer and unbalanced to balanced feeding. As mentioned before, the input impedance of the TCDA is 150Ω, which is much larger than conventional 50Ω excitation. For another side, dipoles must be fed differentially, whereas practical feed networks, such as 50Ω coaxial line, fall into unbalanced transmission line category. Marchand Balun with taper feeding line is suggested to serve as feeding system for the TCDA, as shown in Fig. 4. The Marchand balun is composed of coupled quarter-wave transmission lines printed on one side of the dielectric slab (Rogers RT5880, ε_r=2.2, thickness=0.5mm), while the taper feeding line together with a short circuit line printed on the other side of the slab [21]. To realize more compact structure, the straight feeding line is adapted to meandered line and by doing so the profile of the TCDA will be reduced.

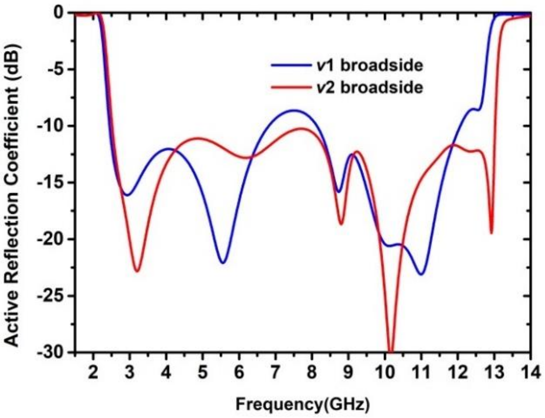
Similarly, two models are studied: *v*1 is the combination of conventional dielectric loaded TCDA and the feeding balun mentioned above, as shown in Fig. 4 (a). *v*2 is similar with *v*1, only that the dielectric superstrate is replaced by meta_surface MAIW, as shown in Figs. 4 (b) and (c).

All the scheme parameters mentioned above are given in Table 1.

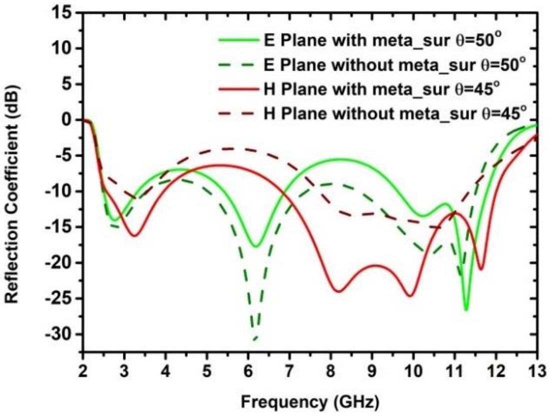
Table1: Parameters of the antenna (mm)

Parameter	Value	Parameter	Value	Parameter	Value
h_{sup}	6.3	c_1	0.8	N	1.8
st	0.5	t_{meta}	0.5	R	4
h	10	h_{gap}	3	V	1.4
d	12.5	w_{slot}	0.2	T	5.6
a1	0.6	Rc	1.5	Y	1.55
a2	1	U	1.5	c_2	0.01
b	2.5	W	0.4		

The simulated active reflection coefficients of the two models are presented in Fig. 5 (a), indicating that at broadside model *v*2 achieves approximately 5.42:1 impedance bandwidth (2.4–13 GHz) for active $S_{11}<10$, which is better than that of *v*1 (2.3-12GHz), meaning meta-surface WAIM with lighter and thinner substrate, is totally competent to counteract the reactance of TCDA, broadening band width effectively. What's more, comparing with *v*1, *v*2 enjoys more compact structure ($0.578\lambda_H$ above the ground), reducing the profile of the TCDA.



(a)



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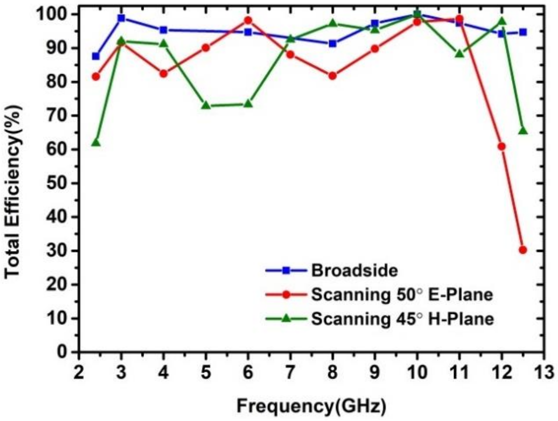


(c)

Fig. 5. Simulated active S_{11} of *v*1 and *v*2: (a) for broadside, (b) different scan angles for E/H plane, and (c) total efficiency for *v*2 while scanning into the E, H plane.

Modern phase array theory suggests that, the array suffers from impedance mismatch as the beam scans off the broadside direction. Specially, the element resistance alters with $\cos\theta$ and $1/\cos\theta$ in the E plane (TM polarization) and H plane (TE polarization), leading to the degradation of transmitted power [22]. As Fig. 4 (b) shows, when the beam goes in the E plane and scans up to 50º, there is very limit difference between the two models, though the impedance width for *v*2 is a little wider than that of *v*1, being 2.4-12.4GHz with active $S_{11}<-6$. However, when it comes to scanning in the H plane, meta-surface MAIW manifests itself in improving impedance match. It can be observed that as the scan proceeds in H plane, and reaches θ=45º, active S_{11} for *v*1 surges dramatically, exceeding -6dB over the majority of the operating frequency band. In contrast, active S_{11} for *v*2 is significantly lower and less than -6dB within the whole operating frequency band, this is because the meta-surface WAIM provides capacitive reactance, which compensates inductive reactance introduced by dipole array backed by a ground plane, hence broaden the TCDA impedance width efficiently. The efficiency of model v2 for both broadside and scanning cases are presented in Fig. 5 (c) The efficiency was showed to be no less than 60% while taking into account mismatch losses.

An 8×8 array of proposed unit cell *v*2 is also simulated. Figure 6 presents theoretical aperture limit ($4\pi D/\lambda^2$) calculation as well as the full-wave simulation with CST. It can be observed that the theoretical aperture limits($4\pi D/\lambda^2$) calculated of the array of theoretical gain limit is almost in consistent with the gain of the array from CST prediction. 3D radiation pattern of the array for 3GHz, 6GHz and 8GHz are showed in Fig. 7. It can be seen, as the length of the dipoles at high frequencies is approaching to half wavelength, the side lobes level at these frequencies is high.

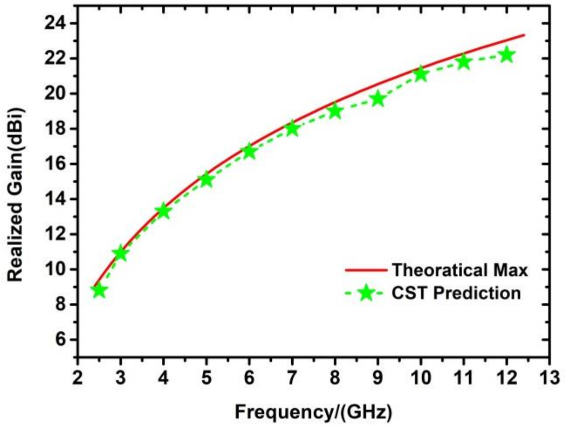
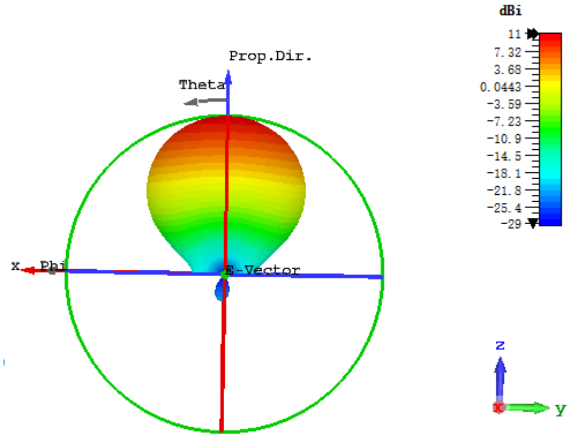
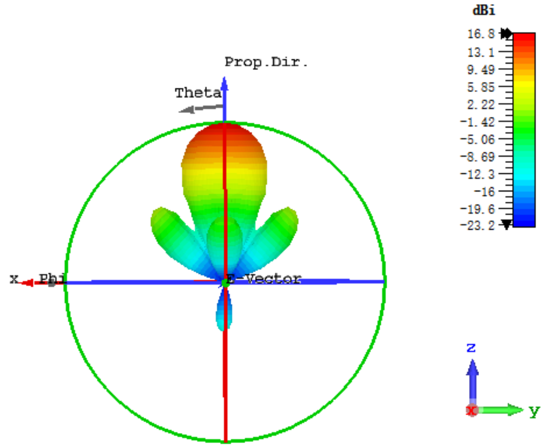


Fig. 6. Theoretical aperture limits calculation and CST prediction of the array for 8×8 of *v*2.



(a)



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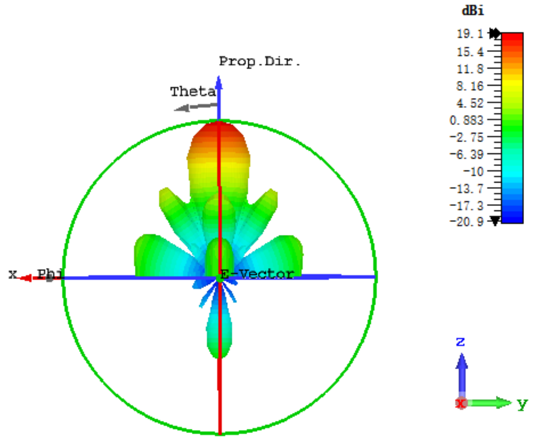

(c)

Fig. 7. Radiation pattern of the 8×8 array of proposed unit cell *v*2 working at: (a) 3 GHz; (b) 6 GHz; (c) 8GHz.

IV. CONCLUSION

A low profile ultra-wideband tightly coupled dipole array is studied. The antenna elements are fed by Marchand baluns of small size and low cost. A meta-surface based wide-angle impedance matching (MS-WAIM) layer is introduced to replace the traditional dielectric WAIM, improving the beam scan performance and reducing the antenna profile. The simulation shows that the proposed antenna array can operate over 2.4-12.4 GHz, approximately 5:1 bandwidth with maximum scanning angle of 50° for both E plane and 45° for H plane. The antenna profile above the ground is only 0.578λH at the highest operating frequency. This antenna array can find its application in the forthcoming massive MIMO beamforming systems for 5G.

ACKNOWLEDGMENT

This work was supported by the Equipment Pre-Research Area Foundation of China (Grant No. 61402090118).

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