Phase Compensation for Decoupling of Large-Scale Staggered Dual-Polarized Dipole Array Antennas

Changning Wei, Zhen-Yuan Zhang, and Ke-Li Wu, *Fellow, IEEE*

***Abstract*— Staggered array antenna is a common array configuration for large-scale array antennas due to its favorable radiation characteristics and relatively large element spacing. In developing a compact staggered dipole array, the most challenging issue is how to simultaneously reduce the four mutual couplings taking place between adjacent co-polarized antenna elements with diversified phase laggings. A large difference in the phase of different mutual couplings makes simultaneous reduction of all the mutual couplings by applying the recently developed array-antenna decoupling surface (ADS) technique difficult. In this article, a phase compensation method by using a staple-shaped probe for alleviating the largest phase offset is proposed conceptually and verified experimentally. With the proposed phase compensation method, the ADS technique can be effectively applied to a compact staggered dipole array with a wideband simultaneous decoupling. The design guideline for the phase compensation probe is presented by EM simulation and a parametric study. Two practical design examples of dual polarized staggered dipole arrays are given to demonstrate the effectiveness of the proposed phase compensation method in conjunction with ADS, showing a promising potential for wideband simultaneous decoupling of a large-scale dual polarized staggered dipole array-antenna.**

***Index Terms*— Array-antenna decoupling surface (ADS), decoupling, large-scale array antenna, massive multiple input and multiple output (M-MIMO), mutual coupling, staggered array.**

I. Introduction

WITH the spectrum being at a premium, especially in the sub-6 GHz bands, and the demands for high data throughput, the massive multiple input and multiple output (M-MIMO) technology has been recognized as the most compelling spatial multiplexing technology and will be adopted in the 5G and future wireless communication systems [1]. It has been shown that the M-MIMO technology can provide unprecedented spatial multiplexing gain, excellent spectral efficiency, and superior energy efficiency [1]–[4]. Theoretically, the larger the number of antenna elements on base-station array antennas, the higher the spectral efficiency of an M-MIMO system. A great deal of effort has been paid to the research of various challenging problems facing to M-MIMO systems. One of the critical issues is how to reduce the mutual couplings among all the adjacent antenna elements in a 2-D dual polarized array antenna [4], [5]. This issue appears to be intolerable for a compact M-MIMO array antenna, in which the center-to-center spacing is equal to or less than half a wavelength.

Mutual coupling in a large-scale array antenna has received tremendous attention in the domains of phased array radars, wireless communications, and array signal processing since array antennas were put into use after World War II [6]. In practice, mutual coupling arouses the following major concerns:

1) narrowed scan angle due to substantial active impedance changes in a phased array [7], [8];
2) reduced mean channel capacity due to the degraded signal-to-interference-noise ratio (SINR) [9];
3) deteriorated radiation efficiency [10];
4) degraded efficiency and linearity of power amplifiers in an M-MIMO system due to an unpredictable loading condition determined by the channel dependent precoding in the presence of the mutual coupling [11]; and
5) distorted radiation patterns of antenna elements.

It will be shown in this article that the element radiation patterns in an M-MIMO array antenna will be severely suffered from distortion and gain drop in the principal directions due to mutual coupling, which leads to a degraded beamforming performance.

Although a lot of research has been done to reduce the mutual coupling in an array antenna, the majority of the works fall in the realm of antenna arrays with few antenna elements. In dealing with decoupling of two antenna elements, the mainstream method is to cancel the mutual admittance by an additional shunt connected circuit, for instance, [12]–[15]. A conceptual breakthrough called self-curing decoupling technique for two inverted-F antennas is reported very recently [16], by which neither interconnected circuit nor destructive structure on the ground between two antennas is needed. Reduction of mutual coupling among multiple antennas is more challenging and should take different decoupling philosophy. Among very few available approaches for decoupling of multiple antennas, the dummy element method with and without reactive loads sounds to be an effective approach for low gain antennas [17], [18]. An attempt of using metamaterial to enhance the isolation of a 2 by 2 interorthogonal linearly polarized slot array antenna is reported recently [19].

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All of the aforementioned decoupling techniques are not suitable for a dual polarized broad side array antenna, which is the mainstream array configuration for M-MIMO systems. The main difficulties for the techniques to be adopted for practical M-MIMO array antennas lie in the fact that none of them is scalable to a large scale 2-D dual polarized array in a wide frequency band without sacrificing the matching bandwidth.

Scaling up an M-MIMO system in a constrained space in conjunction with an appropriate precoding is an effective way to improve spectral efficiency toward the Shannon limit [20]. The space constrain of an M-MIMO array antenna for a base station is stipulated by the construction code of cellular base stations, the windage, the weight, the size and the cost. However, packaging a large number of antenna elements in a small footage or a compact M-MIMO array, if the spatial correlation is acceptable, is full of challenges. The most eminent challenge is how to reduce mutual coupling and to minimize the distortion of element radiation patterns.

Very recently, a new technique called array-antenna decoupling surface (ADS) is proposed for reducing mutual coupling in a 2-D dual polarized array in a wideband by Wu *et al.* [21]. For the convenience of the readers, the basic concept of ADS is briefly reviewed here.

ADS is a thin substrate consisting of a plurality of electrically small metal patches. As depicted in Fig. 1, a reflected wave of the transmitted wave by ADS goes to the coupled antenna. The function of ADS is to cancel the coupled wave with the reflected wave without altering the matching noticeably. As the reflected wave received by the port of the transmitting antenna, say port 1, is usually weak, it can be assumed that the antenna matching for the array with ADS is as good as that without ADS. Therefore, the reflected wave received by the coupled antenna, say port 2, which is denoted as S_{21}^{Refl}, can be found by

$$S_{21}^{\text{Refl}} = S_{21}^{\text{ADS}} - S_{21}^{\text{Array}} \tag{1}$$

where S_{21}^{ADS} is the S_{21} parameter between ports 1 and 2 for the array with ADS, and S_{21}^{Array} is the S_{21} parameter of the original array without ADS. Therefore, the decoupling of ports 1 and 2 means that $S_{21}^{\text{ADS}} = 0$, which leads to

$$\text{Magnitude balance condition: } \left|S_{21}^{\text{Refl}}\right| - \left|S_{21}^{\text{Array}}\right| = 0 \tag{2a}$$

$$\text{Phase balance condition: } \angle\left(S_{21}^{\text{Array}}\right) - \angle\left(S_{21}^{\text{Refl}}\right) - \pi = 0. \tag{2b}$$

The magnitude balance condition is mainly satisfied by adjusting the size of the metal patches whileas the phase balance condition is achieved by choosing an appropriate height H. Obviously, the frequency bandwidth for simultaneous decoupling of all the adjacent c-pol elements highly depends on simultaneous satisfaction of the phase balance condition for all the c-pol mutual couplings in the band of interest with the same H.

There are various types of antenna elements for M-MIMO array antennas, including patch antennas, slot antennas, dielectric antennas, and dipole antennas. Among them, the dipole antenna is a very popular choice for the arrays for base stations due to its simplicity in dual polarization structure, lightweight, compact size, high gain, and a wide bandwidth [22], [23].

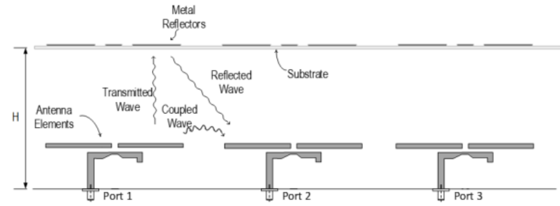


Fig. 1. Schematic of an array antenna and an ADS.

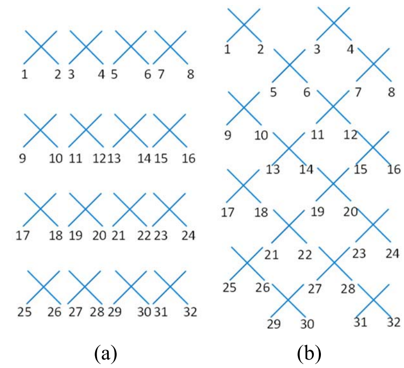


Fig. 2. Layout and numbering scheme of two array configurations for M-MIMO dual polarized (in 45° and −45°) arrays. (a) 4 × 4 uniform array. (b) 4-4-4-4 staggered array.

There are two types of commonly used array layout configurations for M-MIMO array antennas: the uniform array configuration and the staggered array configuration, as shown in Fig. 2(a) and (b), respectively. The staggered array configuration is arranged by shifting each column alternatively by one vertical spacing. The staggered configuration provides a relatively larger spacing between two c-pol elements by slightly increasing the array dimension in the vertical direction. It has been found that a staggered array has a better performance in the grating lobes [24]–[26]. It is also found that element patterns in the horizontal and vertical planes of a staggered array present less distortion than those of a uniform array due to reduced scattering effect and mutual coupling.

In developing a compact staggered dipole array, the most challenging issue is how to simultaneously reduce the four mutual couplings between adjacent c-pol elements with diversified phase laggings. A large difference in phase laggings of the mutual couplings makes simultaneous reduction of the mutual couplings by applying ADS difficult. In this article, a phase compensation method for alleviating the largest phase offset is proposed conceptually and verified experimentally. The method uses a staple-shaped probe to compensate the phase lagging of mutual coupling between two diagonal E-plane c-pol elements so that good simultaneous satisfaction of phase balance conditions of all the adjacent c-pol mutual couplings can be achieved in a wideband sense in applying ADS without sacrificing the matching bandwidth.

In this article, a practical design guideline is concluded by a parametric study of a typical 2-1-2 staggered array by HFSS EM simulation. Two practical design examples, including a 4-4-4-4 staggered dipole array with column spacing of 0.5λ at the center frequency and a compact 2-1-2 staggered array

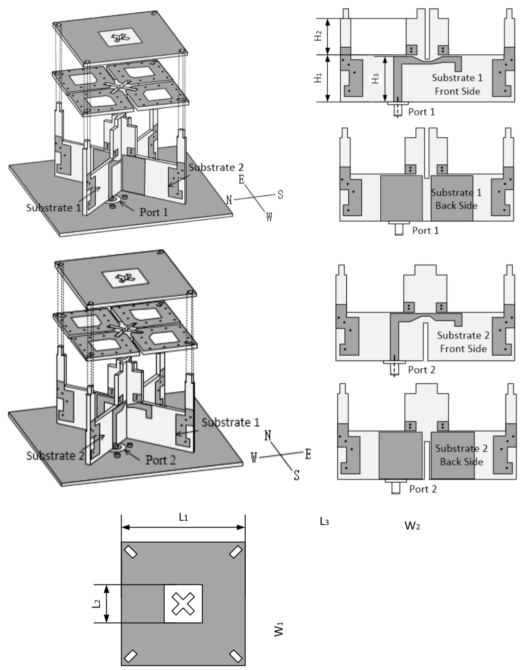


Fig. 3. Isometric view, printed circuit board by parts and dimensions of a dual polarized dipole antenna.

TABLE I
DIMENSIONS OF THE DIPOLE ANTENNA ELEMENT (mm)

L_1	L_2	L_3	W_1	W_2	H_1	H_2	H_3
24	8	11.85	3.2	0.8	9	6.9	8.8

with column spacing of 0.4λ are designed and measured. The mutual couplings among all the adjacent antenna elements in the arrays are reduced to below -25 dB in the major sub-6 GHz frequency band of 5G wireless communications, showing a very promising potential for 5G systems, in which high performance M-MIMO array antennas must be used.

II. Issues in Applying ADS to Staggered Dipole Array

In this article, the dipole antenna element that consists of two pairs of orthogonally placed diamond-shaped half-wavelength radiators and a quarter wavelength balun is used [23]. The metal parts of the dipole are printed on a RO3003 substrate with thickness of 0.8 mm, dielectric constant $\varepsilon_r = 3$ and loss tangent of 0.001. A director patch is placed in front of the dipole radiators for broadening the bandwidth. The details of the dipole antenna element are shown in Fig. 3 with the dimensions listed in Table I. The EM simulation in this article is conducted using HFSS.

There are four distinct c-pol mutual couplings between adjacent antenna elements in horizontal, vertical and diagonal directions in a staggered array. Referring to the illustrative 2-1-2 array layout shown in Fig. 4, the four c-pol mutual couplings are the H-plane couplings $S_{1,7}$, $S_{1,3}$, and $S_{1,5}$, and the E-plane coupling $S_{2,6}$ in the diagonal direction. In this article, the nominal spacing between columns and rows are, respectively, 43 and 30 mm. The spacing scaling factor p is introduced as a design parameter.

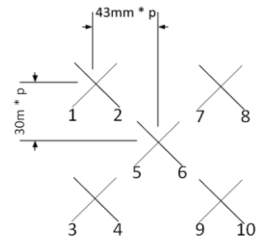


Fig. 4. Element number assignment of a 2-1-2 staggered array and definition of spacing scaling factor p.

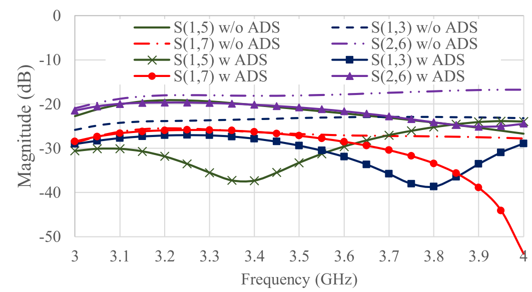


Fig. 5. Simulated magnitude of typical mutual couplings in the 2-1-2 array ($p = 1$) with and without ADS.

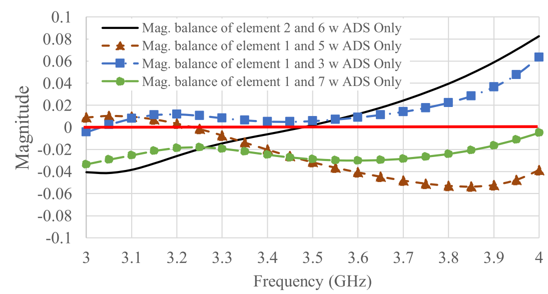


Fig. 6. Magnitude balance of four c-pol mutual couplings of a staggered dipole array with $p = 1$ and ADS.

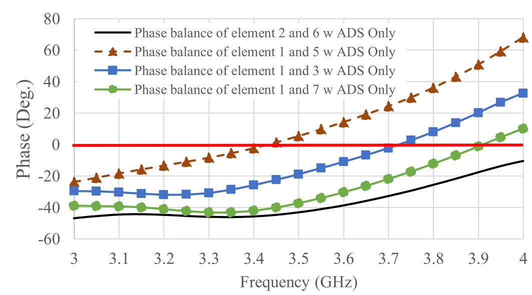


Fig. 7. Phase balance of four c-pol mutual couplings of a staggered dipole array with $p = 1$ and ADS.

Having applied the ADS design guideline given in [21] to the 2-1-2 staggered dipole array, the mutual couplings among the c-pol elements with and without ADS can be EM simulated, as given in Fig. 5. It is seen that while the H-plane c-pol mutual couplings are effectively reduced to below -25 dB across the frequency band of 3.3 – 3.8 GHz the mutual coupling for the E-plane c-pol elements is reduced insignificantly.

To understand the problem, the magnitude balance and the phase balance of the four c-pol mutual couplings in the staggered dipole array with $p = 1$ are presented in Figs. 6 and 7, respectively. According to the design guideline of ADS, both the magnitude and phase balance conditions should approach

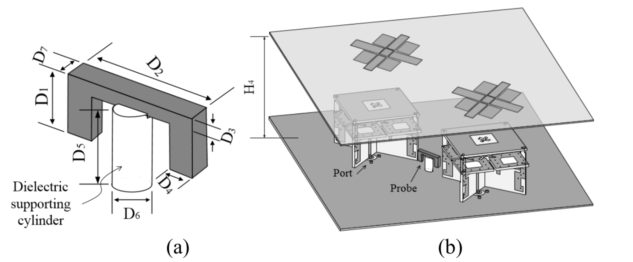


Fig. 8. Isometric view of the staple-shaped phase compensation probe. (a) Dimensions of the probe. (b) Probe placed at the middle of and in-line with two diagonally coupled dipole antennas in a compact staggered array.

zero in order to achieve good mutual coupling cancellation. Three interesting points can be observed from Figs. 6 and 7: 1) the magnitude balance for decoupling of the four c-pol mutual couplings can be well satisfied in the band of interest; 2) the larger the spacing between two H-plane c-pol elements, the higher the phase balance frequency; and 3) the phase balance frequency of the two E-plane c-pol elements, i.e., $S_{2,6}$, is the highest and is far beyond the frequency band. The large difference in the phase balance condition of the E-plane c-pol coupling with others makes the simultaneous wideband decoupling using ADS difficult.

III. Phase Compensation and Method

To cope with the diversified phase balance conditions of the c-pol mutual couplings in a compact staggered array, a phase compensation method that extends the phase lagging of the mutual coupling between two E-plane c-pol elements, such as elements 2 and 6 in Fig. 4, is proposed. The method places a staple-shaped probe in the middle of and in-line with the two diagonal E-plane dipole antennas. An isometric view of the proposed probe and its placement between two diagonally placed dipoles in the presence of ADS are shown in Fig. 8. The staple-shaped probe is made of a bended metal bar supported by a dielectric cylinder with a low dielectric constant. The length of leg D_1, the length of crown D_2, and the height of the probe are the three main design parameters. The total length of the probe should not be close to a resonance length to avoid any parasitic resonance. By placing the probe in-line with the polarization of the two diagonal E-plane coupled elements, the impact of the probe to the x-pol coupling is minimized.

In applying phase compensation probes, the ADS needs to be designed first to optimally cancel the three H-plane c-pol mutual couplings within the frequency band of interest with less priority on the E-plane c-pol mutual coupling. It has been discussed in [21] that designing the ADS requires very good understanding of the field distribution in the vicinity of the coupled antennas for choosing a legitimate pattern of the metal patches on ADS. In this article, a cross-shaped broken patch with four auxiliary square patches is chosen as the basic unit. The size of the metal patches and the height of the ADS are designed by optimally satisfying the magnitude and phase balance conditions [21]. The phase compensation probe is used to enable the phase balance of the E-plane mutual coupling in the frequency band of interest. The design guideline of the staple-shaped probe for phase compensation is illustrated through a parametric study of the 2-1-2 staggered dipole

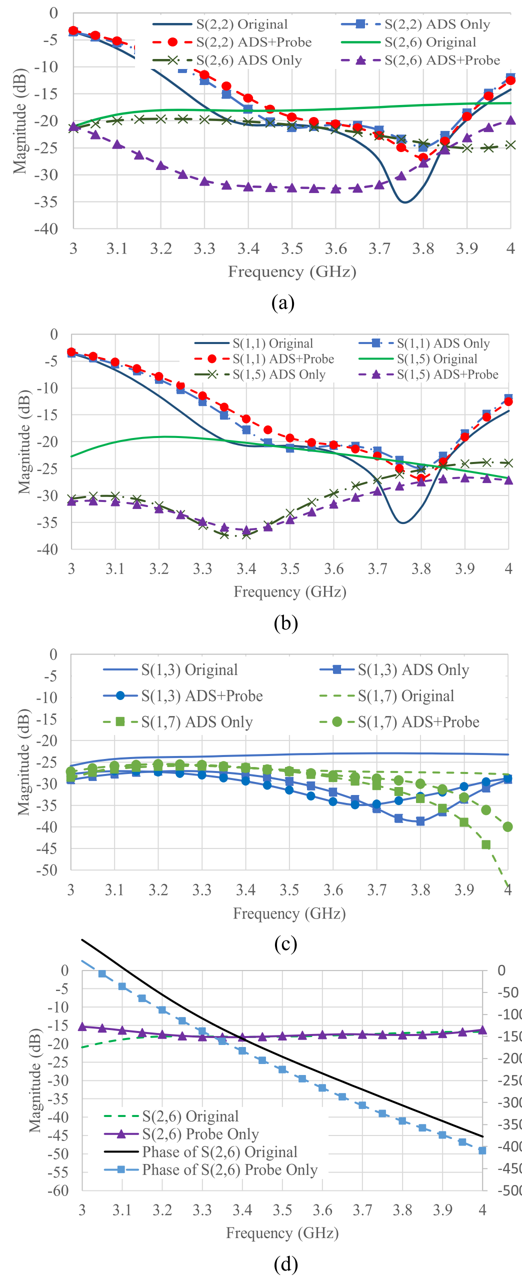


Fig. 9. Simulated (a) reflection coefficient at port 2 and mutual coupling $S_{2,6}$ with different decoupling options. (b) Reflection coefficient at port 1 and mutual coupling $S_{1,5}$ with different decoupling options. (c) Mutual couplings $S_{1,3}$ and $S_{1,7}$ with different decoupling options. (d) Magnitude and phase of mutual coupling $S_{2,6}$ with and without the probe.

array with the layout shown in Fig. 4 and the scaling factor $p = 1$ using EM simulation. The four concerned c-pol mutual couplings are $S_{1,3}$, $S_{1,7}$, $S_{1,5}$, and $S_{2,6}$, among which $S_{2,6}$ is the E-plane c-pol coupling. The magnitude of reflection coefficient at port 2 and mutual coupling $S_{2,6}$ for the decoupling options of no any decoupling, only ADS decoupling and the ADS plus the probe decoupling are shown in Fig. 9(a). It can be seen that $S_{2,6}$ will be greatly reduced over a wideband to below -25 dB while the reflection coefficient remaining nearly the same as that when only ADS is applied. Fig. 9(b) says that the c-pol mutual coupling $S_{1,5}$ is reduced by about 15 dB with the ADS from its original value and that the matching conditions at antenna port 1 for the options with only the

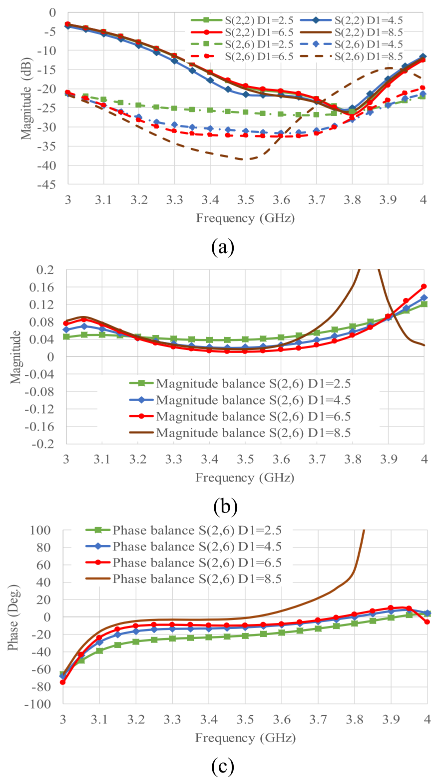


Fig. 10. Simulated E-plane mutual coupling versus leg length D_1. (a) Reflection coefficient at port 2 and magnitude of $S_{2,6}$. (b) Magnitude balance. (c) Phase balance, where crown length $D_2 = 18$ mm and probe height $D_5 = 11$ mm.

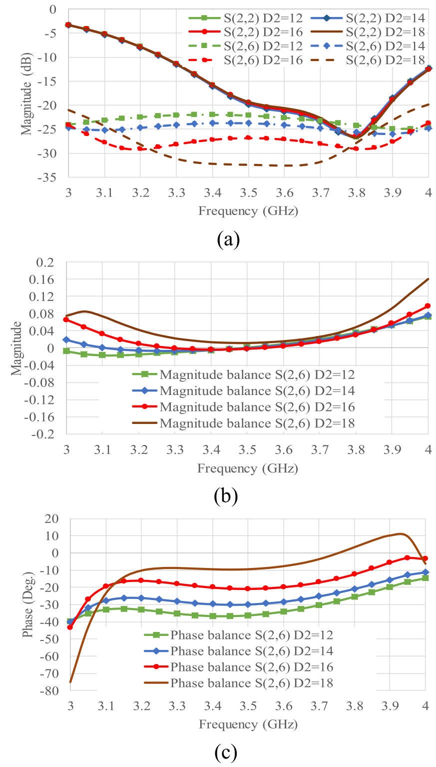


Fig. 11. Simulated E-plane mutual coupling versus crown length D_2. (a) Reflection coefficient at port 2 and magnitude of $S_{2,6}$. (b) Magnitude balance of $S_{2,6}$. (c) Phase balance of $S_{2,6}$, where leg length $D_1 = 6.5$ mm and probe height $D_5 = 11$ mm.

ADS and with the ADS plus the probe remain nearly the same. The H-plane c-pol mutual couplings $S_{1,3}$ and $S_{1,7}$ with different decoupling options are shown in Fig. 9(c), exhibiting a reduction to a level lower than −25 dB after applying only the ADS. The good news is that the probe does not affect the H-plane c-pol mutual couplings noticeably. To further illustrate the phase compensation effect using the staple-shaped probe, the magnitude and phase of $S_{2,6}$ of the array with and without the probe are superimposed in Fig. 9(d). It can be observed that the probe does not affect the magnitude but the phase offset is decreased by about 30°, or the phase balance is improved by 30°. The results in Fig. 9 justify that a staple-shaped probe independently compensates the phase of the diagonal E-plane mutual coupling without noticeably affecting other H-plane c-pol mutual couplings.

To investigate the range of the compensation method, EM simulation on the 2-1-2 staggered dipole array with ADS is conducted with variation of the design dimensions of the probe. Special attention is paid to the S-parameter, magnitude balance and phase balance of mutual coupling $S_{2,6}$, and the results are presented in Figs. 10–12. In the EM simulation, the thickness of the probe is set to 2 mm. The other physical dimensions of the array and the ADS are given in Table III. The important observations from this parametric study are: 1) the dimensions of the staple-shaped probe do not affect the matching condition of the concerned antenna elements; 2) the dimensions of the staple-shaped probe do not affect the magnitude balance significantly but improve the phase balance condition greatly; 3) an over-length leg may cause parasitic resonance; 4) the length of crown plays the dominant role in phase compensation; and 5) there is an optimal value for each of design dimensions.

With an appropriate design of ADS with attentions paid to the three H-plane c-pol mutual couplings and an optimal choice of the design dimensions of the probe, EM simulation shows that the decoupling bandwidth for all the c-pol mutual couplings below −25 dB in the band of 3.3 – 3.8 GHz, or 14% fractional bandwidth can be achieved.

IV. Design Examples

To demonstrate the effectiveness of the phase compensation method in conjunction with ADS for simultaneous decoupling of a practical staggered dipole array antenna, two array prototypes working in the frequency band of 3.3 – 3.8 GHz will be discussed in this section. The first example is a 4-4-4-4 staggered dipole array with nominal column spacing of 0.5λ at the center frequency. The second example is a 2-1-2 compact staggered dipole array with nominal column spacing of 0.4λ.

A. A 4-4-4-4 Staggered Dual Polarized Dipole Array Antenna

The prototyped 4-4-4-4 staggered dual polarized dipole array antenna with ADS plus phase compensation probes is shown in Fig. 13. A photograph of the fabricated ADS for the array is shown in Fig. 13(a) and that for the array antenna with staple-shaped probes is shown in Fig. 13(b). The

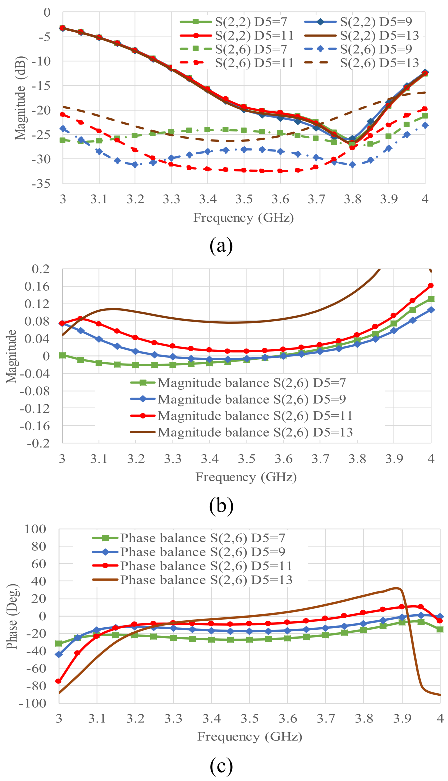


Fig. 12. Simulated E-plane mutual coupling versus height of probe D_5. (a) Reflection coefficient at port 2 and magnitude of $S_{2,6}$. (b) Magnitude balance of $S_{2,6}$. (c) Phase balance of $S_{2,6}$, where crown length $D_2 = 18$ mm and leg length $D_1 = 6.5$ mm.

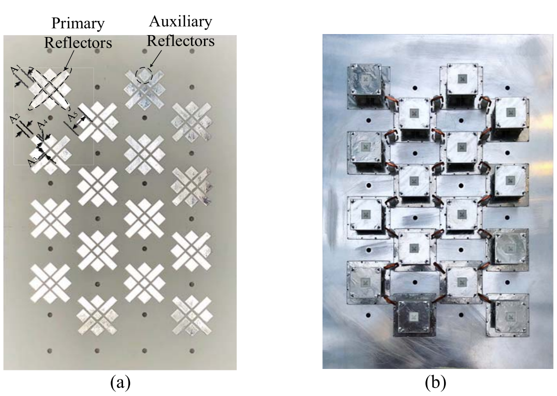


Fig. 13. Photograph of the prototyped 4-4-4-4 staggered dipole array. (a) ADS with reflective patches. (b) Array antenna with staple-shaped probes between diagonal E-plane c-pol elements (with the ADS removed).

TABLE II

DIMENSIONS OF ADS AND STAPLE-SHAPED PROBE FOR THE 4-4-4-4 STAGGERED ARRAY IN mm

H_4	A_1	A_2	A_3	A_4	A_5	D_1	D_2	D_5	D_3	D_4	D_6	D_7
34	8.9	6	1.6	1.6	17	7.4	17	9.8	1.9	1.9	6	2

detailed dimensions are listed in Table II. The height of the ADS is 34 mm above the ground plane. The substrate used for the ADS is Roger's Ro4730JXR substrate with dielectric constant of $\varepsilon_r = 2.98$, loss tangent of 0.0023, and the thickness of 0.78 mm. The center-to-center column spacing of the array is 43 mm or 0.5λ at the center frequency.

The basic idea underlying wideband simultaneous decoupling of the array is to use ADS to deal with the mutual couplings with a small spread of phase balance, which are the H-plane mutual couplings in the array, and then to find the optimal dimensions of staple-shaped probe that is placed in the middle of and in-line with every pair of diagonal E-plane c-pol dipole elements. The ADS consists of two primary reflectors and four square auxiliary patches for each dual polarized dipole unit. Each primary reflector is composed of three broken metal strips and is placed symmetrically with respect to the center of a dual polarized dipole unit to minimize the cross coupling of two orthogonally placed dipoles. It is stressed that the primary reflectors are mainly designed to decouple the c-pol antenna elements. The auxiliary patches can help to compensate the decoupling of the mutual couplings in the H-plane with different separation distances, such as $S_{1,3}$ and $S_{1,9}$. It is found that the layout of the auxiliary patches performs better than that used in [21] in terms of less influence on impedance matching and cross polarization.

The dimensions of the staple-shaped probe in this design are the same as those listed in Table II. Each probe is mechanically supported by a 3-D printed dielectric post whose dielectric constant is near 1. The phase compensation probe is mainly used for decoupling the E-plane c-pol antenna elements. The dimensions of the probe are optimally chosen to achieve the best phase balance of the concerned mutual coupling in the band of interest.

Due to the symmetry of the 4-4-4-4 array, only the measured reflection coefficient of and the mutual couplings between typical elements are presented in Fig. 14. The element number assignment is given in Fig. 2(b). As shown in Fig. 14(a), the measured reflection coefficient is about or better than -15 dB in the frequency band of 3.3 – 3.8 GHz. It should be mentioned that the dimensions of a dipole antenna element are optimized in the presence of ADS. The measured mutual couplings among typical antenna elements in the array with and without ADS plus probe decoupling are superimposed in Fig. 14(b)–14(g). It can be observed that: 1) the mutual coupling between the E-plane c-pol elements, say $S_{2,6}$, is greatly improved from -17 to -33 dB at the center frequency and below -25 dB within the frequency band of 3.3 – 3.8 GHz; 2) the E-plane mutual couplings are reduced by at least 12 dB and are lower than -25 dB within the band; 3) the mutual couplings between the H-plane c-pol elements, say $S_{1,3}$, $S_{1,5}$, $S_{1,9}$, $S_{2,4}$, $S_{2,10}$, and $S_{1,11}$ are also reduced significantly to below -25 dB in the band; 4) strong c-pol mutual couplings in the H-plane, say $S_{1,5}$ and $S_{1,9}$, are reduced to lower than -25 and -29 dB, respectively; 5) the cross coupling between two dual polarized elements in the same unit, say $S_{1,2}$, remains below -30 dB in the presence of ADS and staple-shaped probes; 6) the mutual couplings between x-pol elements in different antenna units, say $S_{1,4}$, $S_{1,6}$, $S_{1,10}$, and $S_{2,5}$, are originally low and are retained below -30 dB; 7) the mutual coupling level and decoupling performance for the edge element and those in the middle of the large 4-4-4-4 array is very similar, say $S_{2,4}$ and $S_{6,8}$, $S_{2,10}$, and $S_{6,14}$, which are separated with the same space; and 8) the reflection coefficient of all the elements is better than -15 dB within the

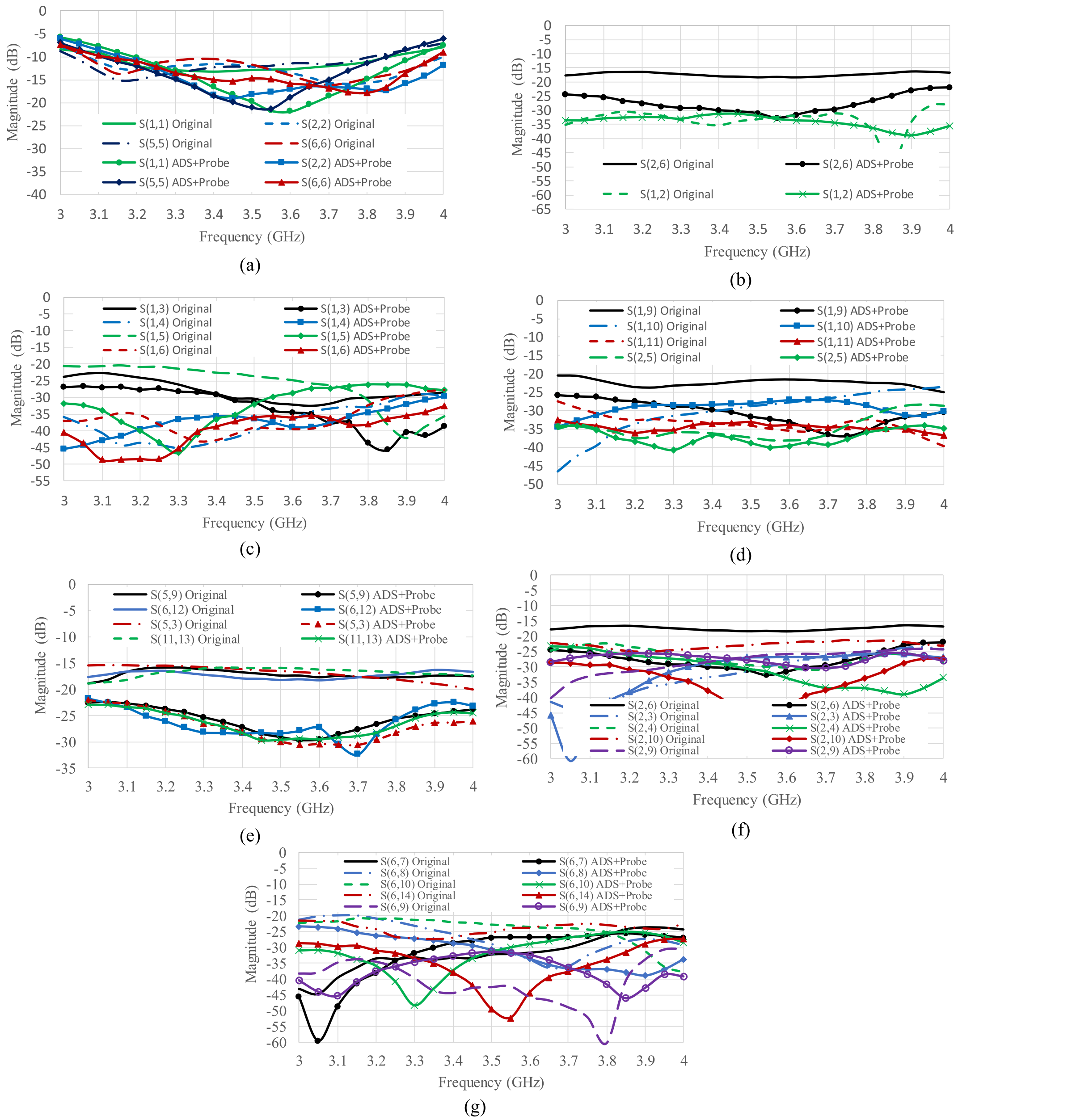


Fig. 14. Measured S-parameters of typical antenna elements of the 4-4-4-4 array with and without ADS plus probe decoupling. (a) Reflection coefficient. (b)–(g) Mutual couplings.

TABLE III

DIMENSIONS OF ADS AND STAPLE-SHAPED PROBE FOR THE 2-1-2 COMPACT STAGGERED ARRAY IN mm

H_4	A_1	A_2	A_3	A_4	A_5	D_1	D_2	D_5	D_3	D_4	D_6	D_7
33	8	5	1.2	1.2	16	6.5	18	11	1.9	1.9	6	2

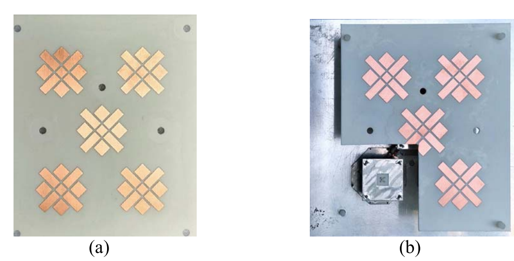


Fig. 15. Photograph of the prototyped 2-1-2 compact dipole array. (a) ADS with reflective patches. (b) Array antenna with staple-shaped probes and ADS (with a corner cutoff to show dipole antenna elements).

band. The reflection coefficient without using the decoupling method is worse than that with the decoupling method because the matching condition is optimized to its best performance in the presence of ADS plus decoupling probes.

B. A 2-1-2 Compact Staggered Dual Polarized Dipole Array

The second example is a 2-1-2 compact staggered dipole antenna array, of which the center-to-center column spacing equals to 0.4λ at the center frequency. The antenna element is designed to achieve a good matching condition in the presence of ADS and phase compensation probes. The detailed dimensions of the antenna element are listed in Table III and element number assignment is given in Fig. 4. A photograph of the array antenna with the fabricated ADS and phase

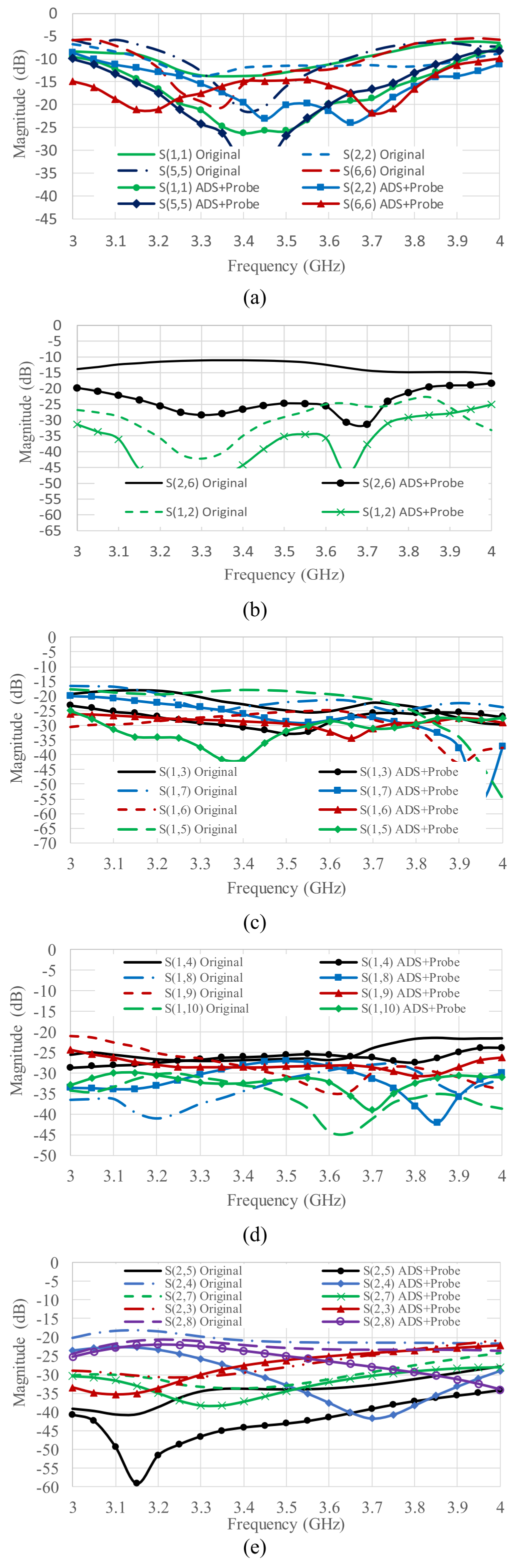


Fig. 16. Measured S-parameters of the 2-1-2 array with and without ADS plus probe decoupling. (a) Reflection coefficient of typical antenna elements. (b)–(e) Mutual couplings between typical antenna elements, including H-plane c-pol, E-plane c-pol of different elements and the x-pol in the same antenna unit and between different antenna units.

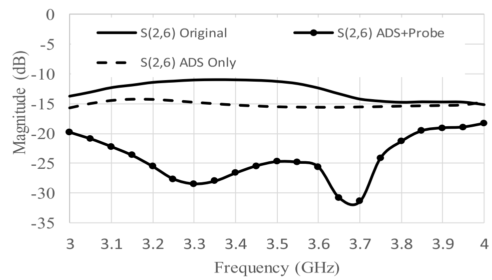


Fig. 17. Measured $S_{2,6}$ in different decoupling conditions: original without any decoupling; with ADS only; and with ADS + probes decoupling.

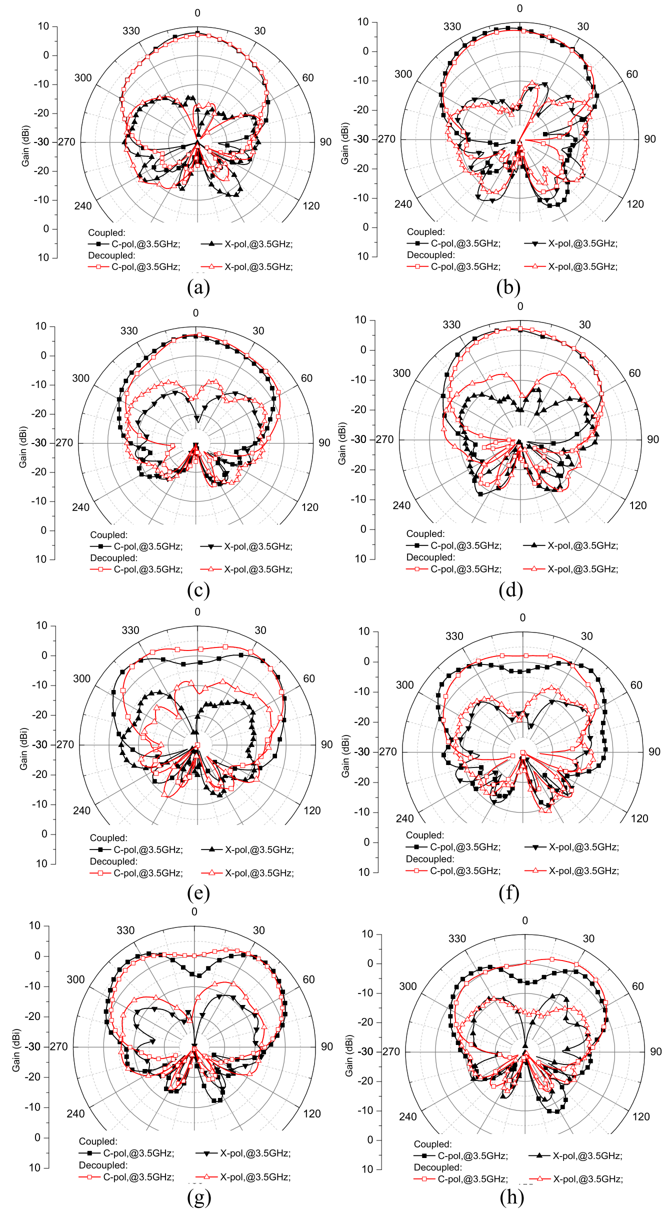
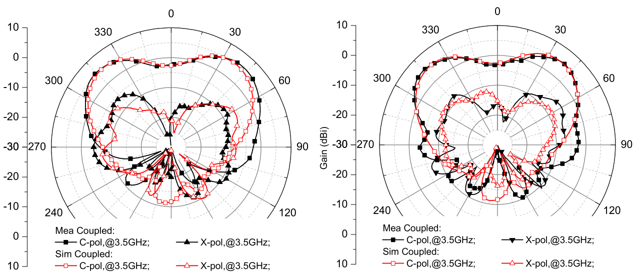


Fig. 18. Measured radiation patterns of the 2-1-2 dual polarized compact dipole array with and without decoupling at the center frequency. (a) Vertical plane of element 1. (b) Horizontal plane of element 1. (c) Vertical plane of element 2. (d) Horizontal plane of element 2. (e) Vertical plane of element 5. (f) Horizontal plane of element 5. (g) Vertical plane of element 6. (h) Horizontal plane of element 6.

compensation probes is shown in Fig. 15. The array is called a compact array as its column spacing is less than half a wavelength.

The measured S-parameters of typical antenna elements are presented in Fig. 16. As shown in Fig. 16(a), the reflection coefficient of all the elements is better than −15 dB within



(a) (b)

Fig. 19. Comparison of the measured and simulated radiation patterns of element 5 without decoupling. (a) Vertical plane. (b) Horizontal plane.

the frequency band from 3.3 to 3.75 GHz. The mutual coupling with and without using the decoupling method is superimposed in Fig. 16(b)–16(d). It can be observed that the original mutual coupling between the E-plane c-pol elements is strongest and is at the level of -11 dB. After applying the proposed decoupling method, the E-plane c-pol coupling is reduced to below -25 dB within frequency band from 3.3 to 3.75 GHz. In order to justify the superiority of the proposed decoupling method, the measured mutual coupling $S_{2,6}$ in the arrays without any decoupling, with only ADS decoupling, and with ADS plus probes decoupling are superposed in Fig. 17, showing that about 5 dB additional reduction in most of the frequency band can be achieved with the proposed method. The mutual couplings of the H-plane c-pol antenna elements, say $S_{1,7}$, $S_{1,5}$, $S_{2,4}$, and $S_{1,9}$, are all below -24 dB after applying the proposed decoupling method. The mutual coupling between two x-pol elements in the same antenna unit, say $S_{1,2}$, is also reduced. The mutual coupling between x-pol elements of different units, say $S_{1,4}$, $S_{1,6}$, $S_{2,7}$, $S_{2,5}$, and $S_{1,10}$, is originally low before applying ADS, and is not deteriorated after the decoupling. In conclusion, with the proposed decoupling method all the mutual couplings in the compact array are reduced to below -24 dB in most of the frequency band.

In developing an M-MIMO array antenna, radiation pattern of an array element is also a major concern. The typical distortion in the radiation pattern of an array element is a significant gain reduction in the broadside directions. The drop of the gain is mainly caused by the mutual couplings among adjacent antenna elements and leads to a poor performance of beamforming in an M-MIMO system. In this 2-1-2 dual polarized array, elements 1 and 2 are representative ones for the edge elements whereas elements 5 and 6 are the center elements. The measured radiation patterns of these elements in the horizontal and vertical planes are presented in Fig. 18. It is obvious that the radiation patterns of the center elements are seriously distorted due to strong mutual coupling with the adjacent antenna elements, causing a deep gain drop in principal radiation directions. As convinced by the measured radiation patterns, the pernicious distortion can be effectively repaired by the proposed decoupling method using ADS plus phase compensation probes. To validate the measured radiation patterns, the measured and EM simulated patterns of element 5, which is in the original 2-1-2 array without any decoupling means, in both the horizontal and vertical planes are compared in Fig. 19, showing very good agreement.

V. Conclusion

A new concept of phase compensation to the ADS technique for wideband simultaneous decoupling of a compact dual polarized staggered dipole array antenna is proposed in this article. As an important supplement method to ADS, the phase compensation for the mutual coupling between E-plane c-pol elements is made by placing a staple-shaped probe in-line with and at the middle of the two elements. The phase compensation probe can effectively improve the phase balance of the E-plane coupling to the same level as those of the H-plane c-pol mutual couplings in the frequency band of interest, making the ADS technique more versatile for practical applications. By combining ADS with phase compensation probes, the mutual couplings, of all the c-pol and x-pol, in a compact large-scale staggered dipole array can be reduced significantly in a wide frequency band. A dimensional parametric study illustrates the design guideline of the proposed phase compensation method.

Two practical design examples of dual polarized staggered dipole array antennas are given, demonstrating the superiority of the proposed ADS plus probes decoupling method not only in the reduction of mutual coupling in a wideband sense but also the repairing capability of the distortion in element radiation patterns. The proposed method overcomes a major limitation in applying the ADS technique to a compact staggered dual polarized dipole array antenna and suggests a feasible way to build a high performance but compact M-MIMO array antenna.

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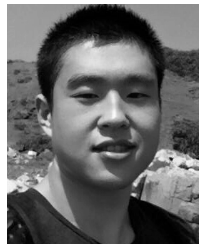

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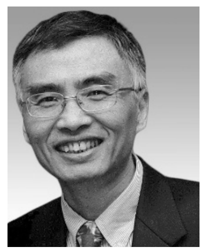

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