Two-Element Huygens Dipole Array with High Isolation and Improved Directivity

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***Abstract* - A compact broadside radiating two-element Huygens dipole array with high isolation and improved directivity is presented. The overall height of the developed array is λ_0/20.3 and the center-to-center distance between elements is only 0.301λ_0. The array's outstanding performance is facilitated by a specially designed scatterer, which consists of a pair of meander-line resonators connected by a metallic strip and printed on an additional layer. The simulated values demonstrate that the proposed decoupling structure not only reduces the mutual coupling level from -14.4 dB to -50.4 dB, i.e., a 36 dB reduction; but it also improves the peak directivity and front-to-back ratio (FTBR) values by 0.66 dB and 12.7 dB, respectively.**

I. INTRODUCTION

Huygens dipole antennas (HDAs) have drawn considerable attention owing to their unique advantageous radiation performance characteristics including high directivities, high front-to-back ratios (FTBRs), wide beamwidths, and independences of large ground [1-4]. In recent years, a variety of electrically small HDAs with different characteristics have been investigated to cater to many specific space-limited wireless communication systems such as single-polarization [1], dual-polarization [2], polarization reconfigurability [3], and pattern reconfigurability [4]. As fifth generation (5G) and beyond wireless systems evolve, there is intense interest in compact, high directivity arrays with attractive performance characteristics to meet the demands of their stakeholders. However, one must deal with strong mutual coupling effects when the distance between the adjacent elements is small. In particular, they can significantly deteriorate the radiation performance, e.g., distort the radiation patterns. Therefore, it is highly desirable to develop an effective decoupling technology to significantly reduce the expected mutual couplings in high-density HDA arrays in order to boost their potential for applications in space-limited wireless platforms.

Many decoupling techniques have been utilized in antenna arrays to reduce mutual coupling, such as composite meta-structures [5], mushroom electromagnetic band gap structures (EBG) [6], and defected ground structures [7]. As an alternative, array-antenna decoupling surfaces (ADSs) have also been utilized [8]. Unfortunately, these decoupling technologies cannot be applied to high-density HDA arrays because large ground planes are required to achieve the arrays' broadside radiation patterns and high gain values. While neutralization lines have been considered to reduce the mutual coupling in high-density monopole antenna arrays, those systems have very limited application in low-profile, compact practical engineering situations.

In this paper, a specially-engineered decoupling structure is reported that is placed atop a two-element HDA array whose center-to-center element distance is only 9.75 mm at 1.51 GHz (0.301 λ_0). The simulated S-parameter values demonstrate that it increases the isolation level from -14.4 to as high as –50.4 dB. Moreover, the Huygens source-based radiation performance characteristics for each HDA are maintained. The peak directivity and FTBR values witness 0.66 dB and 12.7 dB improvements, respectively.

II. TWO-ELEMENT HDA ARRAY WITH THE DECOUPLING STRUCTURE DESIGN

The configuration of the two-element HDA with its decoupling structure is shown in Fig. 1. As shown in Figs. 1(a) and (b), the array consists of four substrate layers that are labeled as Layer_1, Layer_2, Layer_3, and Layer_4, respectively. All of the substrate layers are Taconic TLY-5 with relative dielectric constant ε_r = 2.2, loss tangent tan δ = 0.0009, and copper cladding thickness 0.017 mm. All these substrates have the same radius (60 mm), but different thicknesses (h_1 = h_2 = h_3 = 0.51 mm, h_4 = 1.58 mm).

As shown in Figs. 1(a) and 1(b), the magnetic elements are two capacitively loaded loops (CLLs) that are oriented in parallel with each other. The horizontal portions of these CLLs are printed on the upper surfaces of Layer_2 and Layer_4. As shown in Fig. 1(d), the centerlines of the upper faces of the two CLLs are placed symmetrically on the both sides away from the Layer_2 center. They have the same size (L4 × W6). As shown in Fig. 1(e), the bottom segments of the CLLs have the same total lengths (2×L5+g2) and widths (W6) as do their counterparts on the top of layer_2. They are centered below those counterparts; the distance between their centers is g1. These segments are separated by gaps having the length g2 along the x-axis. The segments on Layer_2 and Layer_4 of each CLL are connected by two cylindrical copper columns whose heights and radii are, respectively, h5 and R1. These four columns pass completely through layer_3, as shown in Fig. 1(b).

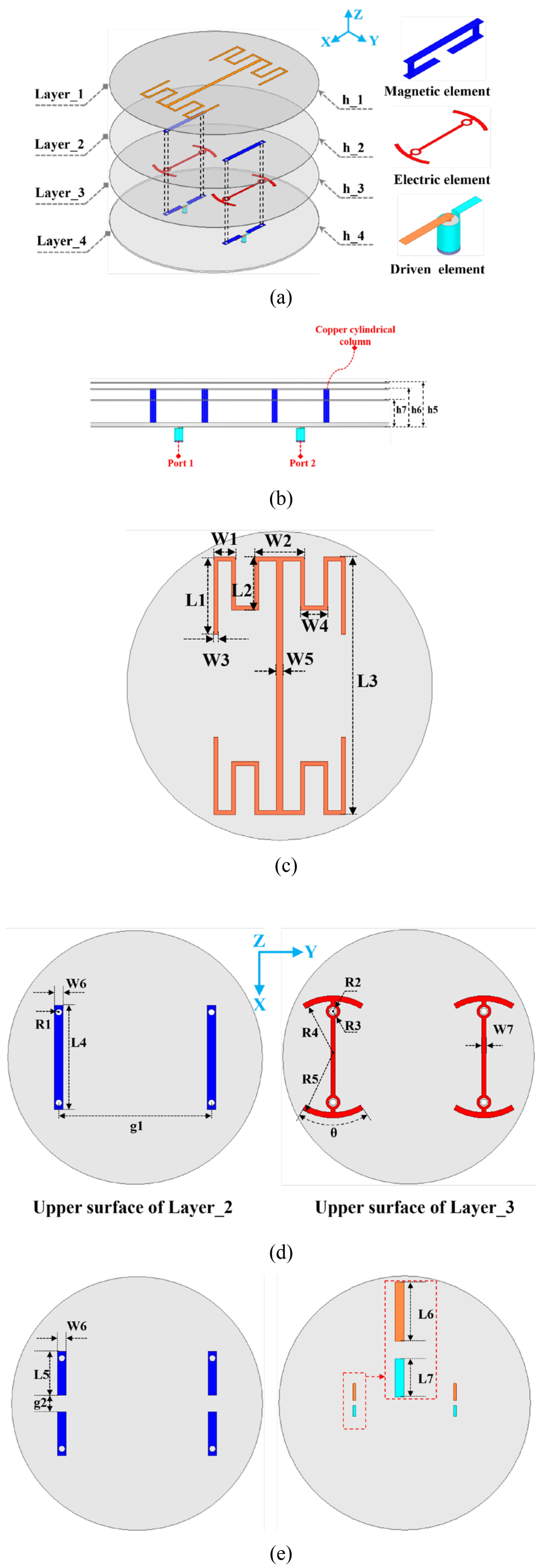


Fig. 1 Configuration of the two-element Huygens dipole array with the decoupling structure. (a) 3-D view. (b) Side view. (c) Upper surface of Layer_1. (d) Upper surface of Layer_2 and Layer_3. (e) Upper and lower surface of Layer_4.

The two electric elements, i.e., two Egyptian axe dipoles (EADs), are printed on the upper surface of Layer_3, as shown in Fig. 1(d). They have the same size (R5 × W7). Four copper rings with the same inner radius (R2 < R3) are introduced on these EAD elements to avoid any direct connection with the four copper columns of the CLL elements.

In order to reduce the mutual coupling between the two elements of the HDA array, a pair of face-to-face arranged meander-line resonators connected by a metallic strip is placed on the upper surface of Layer_1 of the HDA array as shown in Figs. 1(a) and 1(c). Currents are induced on the decoupling structure by the fields radiated by the HDAs. The consequent scattered fields they produce mitigate the effects of the mutual coupling, thus efficiently improving the port isolation.

TABLE I.
OPTIMIZED DESIGN PARAMETERS OF THE TWO-ELEMENT HUYGENS DIPOLE ARRAY WITH THE DECOUPLING STRUCTURE (IN MILLIMETERS)

h_1=0.51	*h_2=0.51*	*h_3=0.5*	*h_4=1.58*	*h5=9.76*
h6=8.45	*h7=6.24*	*L1=31*	*L2=20.6*	*L3=102*
L4=41	*L5=17.1*	*L6=10*	*L7=6.5*	*W1=8.6*
W2=17.6	*W3=.6*	*W4=10.6*	*W5=2.4*	*W6=3.5*
W7=1.6	*R1=1.25*	*R2=1.8*	*R3=2.8*	*R4=21.95*
R5=24.05	*g1=60*	*g2=6.8*	*θ=60 °*	*Null*

III. SIMULATED RESULTS OF THE TWO-ELEMENT HUYGENS DIPOLE ARRAY

The simulated performance characteristics of the HDA are presented in Figs. 2 and 3. As shown in Fig. 2, the simulated –10-dB overlapping impedance bandwidth (i.e., $|S_{11}| \leq -10$ dB) for both ports was 10 MHz, covering 1.506 to 1.516 GHz. The simulated isolation level between the two ports was greater than 50 dB. Correspondingly, the simulated center-to-center electric distance between the two elements at the center of the operational frequency range f_0 = 1.511 GHz is $d = 0.301\ \lambda_0$.

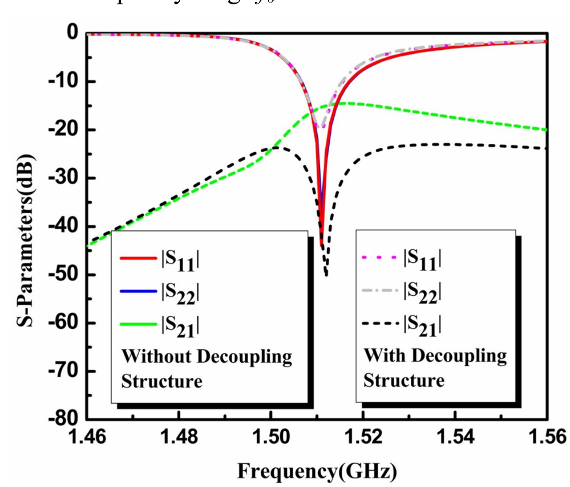
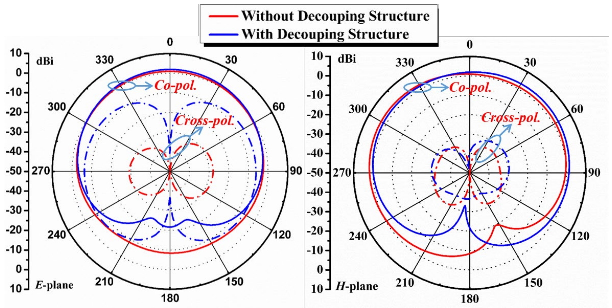
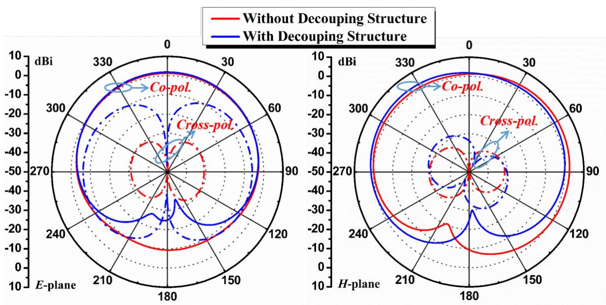


Fig. 2 Simulated S-parameters of the Huygens dipole array without and with the decoupling structure as functions of the source frequency.



(a)



(b)

Fig. 3 Simulated directivity patterns of the Huygens dipole array without and with the decoupling structure at the resonance frequency f_0 = 1.511 GHz. (a) Only port 1 is excited. (b) Only port 2 is excited.

The simulated directivity patterns in the *E*- and *H*- planes are given in Fig. 3, respectively. When port 1 is excited, the simulated peak directivity value is 2.88 dBi at the resonance frequency center 1.511 GHz with the FTBR = 23 dB and the radiation efficiency (RE) = 80.1%. The simulated half-power beamwidths are 179°, from -89° to 90° in the z0x-plane, and 223°, from -119° to 104° in the z0y-plane, respectively. Note that the half-power beamwidth in the H-plane is much larger than that in the E-plane which is quite close to the theoretical half-power beamwidth of a standard electrically small Huygens dipole (140°) [1].

As is shown in Fig. 2, the simulated $|S_{11}|$ values indicate that the resonance frequency of the HDA array loaded with the decoupling structure is basically unchanged. In contrast, because the decoupling structure acts as an effective radiator [9, 10], the coupling energy is well cancelled, which significantly reduces the effects of the mutual coupling. As a consequence and as illustrated with the directivity pattern comparisons shown in Fig. 3, there is an improvement in both the peak directivity and FTBR values when the decoupling structure is present in the two-element HDA array.

IV. Conclusion

A decoupling element has been developed and was then integrated into a broadside radiating two-element HDA system. This decoupling element, a pair of face-to-face meander-line resonators connected by a rectangular strip, was introduced on a layer placed atop the two-element Huygens dipole array. The composite system is compact and low-profile. The simulated values demonstrated that the decoupling element not only increases the isolation between the ports of the two HDAs to approximately a 50.4 dB level for the very small distance of separation, $0.3\lambda_0$, between them, but also improves the peak directivity and FTBR values in comparison to the array without the decoupling element. The very attractive performance characteristics of this innovative compact array may prove to be beneficial for many narrowband LoRA wireless communication systems. The efficacy of the decoupling structure and the resulting two-element HDA array loaded with it has been verified experimentally with the measurements of its optimized prototype [11].

References

[1] R. W. Ziolkowski, "Low profile, broadside radiating, electrically small Huygens source antennas," IEEE Access, vol. 3, pp. 2644–2651, 2015.

[2] M.-C. Tang, Z. Wu, T. Shi, H, Zeng, W. Lin and R. W. Ziolkwski, "Dual-Linearly Polarized, Electrically Small, Low-Profile, Broadside Radiating, Huygens Dipole Antenna," IEEE Trans. Antennas Propag., vol. 66, no. 8, pp. 3877-3885, Aug. 2018.

[3] M.-C. Tang, Z. Wu, T. Shi, and R. W. Ziolkowski, "Electrically small, low-profile, planar, Huygens dipole antenna with quad-polarization diversity," IEEE Trans. Antennas Propag., vol. 66, no. 12, pp. 6772-6780, Dec. 2018.

[4] Z. Wu, M.-C. Tang, and R. W. Ziolkowski, "Ultralow-profile, electrically small, pattern-reconfigurable metamaterial-inspired Huygens dipole antenna," IEEE Trans. Antennas Propag., vol. 68, no. 3, pp. 1238-1248, Mar. 2020.

[5] M.-C. Tang, S.Q. Xiao, J. Guan, Y. Y. Bai, S. S. Gao, and B. Z. Wang, "Composite metamaterial enabled excellent performance of microstrip antenna array," Chin. Phys. B, vol. 19, no. 7, pp. 074214(1-5), 2010.

[6] M. Coulombe, S. F. Koodiani, and C. Caloz, "Compact elongated mushroom (EM) –EBG structure for enhancement of patch antenna array performances," IEEE Trans. Antennas Propag., vol. 58, no. 4, pp. 1076-1086, Apr. 2010.

[7] S. Xiao, M.-C. Tang, Y.-Y. Bai, S. Gao, and B.-Z. Wang, "Mutual coupling suppression in microstrip array using defected ground structure," IET Microw. Antennas Propag., vol. 5, pp. 1488–1494, May. 2011.

[8] K. L. Wu, C. Wei, X. M, and Z.-Y. Zhang, "Array-antenna decoupling surface," IEEE Trans. Antennas Propag., vol. 65, no. 12, pp. 6728–6738, Dec. 2017.

[9] M.-C. Tang, B. Zhou, and R. W. Ziolkowski, "Flexible uniplanar electrically small directive antenna empowered by a modified CPW-feed," IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 914-917, 2016.

[10] M.-C. Tang, B Zhou, Y Duan, X Chen, and R. W. Ziolkowski, "Pattern-reconfigurable, flexible, wideband, directive, electrically small near-field resonant parasitic antenna," IEEE Trans. Antennas Propag., vol. 66, no. 5, pp. 2271-2280, 2018.

[11] M.-C. Tang, X. Chen. T. Shi, H. Tu, Z. Wu and R. W. Ziolkowski, "A compact, low-profile, broadside radiating two-element Huygens dipole array facilitated by a custom-designed decoupling element," early access, IEEE Trans. Antennas Propag., Jan. 10 2021, DOI: 10.1109/TAP.2020.3048579.