Decoupling of high-density, dual-polarized, cross-dipole arrays using broadband low-profile composite isolator

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Abstract
A low-profile composite isolator (CI) for the decoupling of broadband, high-density, dual-polarized cross-dipole arrays is introduced and investigated. The CI is composed of periodically resonant strips and a metallic wall, which are etched on both sides of a thin dielectric-slab and vertically placed above the ground plane. The collaboration between the strips and the wall empowers the CI’s broadband operation performance characteristics with low profile (0.16 λ0) and ultra-thin thickness (0.0045 λ0). A two-element cross-dipole array loaded with CI is fabricated and tested to verify its decoupling effect. The two ±45°dual-polarized cross-dipole elements with impedance bandwidth of 45% (ranging from 1.7 to 2.7 GHz) are built with centre-to-centre distance of 0.45 λ0 (corresponds to free space wavelength at 1.7 GHz). The measured results, in good agreement with the simulation values, indicated that, after loading CI, the array witnessed 10 dB co-polarized and 5 dB cross-polarized isolation improvements while maintaining stable radiation patterns over the entire operational band, without increasing the overall array height.

1 INTRODUCTION

With the vigorous development of wireless communication technology and explosive growing number of mobile communication users, it is necessary for the base stations to provide greater message capacity and better quality of service to meet the demand of ever-growing data transmission [1]. However, the space resources available for base stations are becoming increasingly scarce. To cope with the above cumbersome situation, development of the compact and high-performance base station antennas and high-density arrays with low mutual coupling is an effective solution [2]. In details, it requires the base station antennas to possess not only the dual-polarization characteristics, which could effectively combat multipath fading to improve channel capacity, data transmission speed and communication reliability [3], but also the broad impedance bandwidth, which could cover the multiple frequency ranges of communication standards (such as 2G, 3G, and 4G) to avoid the repetitive construction of base stations [4]. Concomitantly, the decoupling of broadband, high-density, dual-polarized arrays is a strong challenge, because it requires the isolators effective in reducing the mutual coupling in two directions orthogonal to each other in a wide frequency range even with low transverse sizes.

Recently, several effective decoupling approaches for dual-polarized antenna array have been reported, which can be in general classified into following two categories: One is the construction of decoupling structures to suppress the coupling waves from adjacent elements. For example, by using a metamaterial cavity, which contains a couple of frequency selective surface (FSS) and a couple of negative-index material (NIM), the free space coupling waves from the dual-polarized patch arrays can be decreased [5]. By arranging the metal cavities and artificial periodic structures (APS) around the dual-polarized magnetically coupled patch antennas, the mutual coupling between adjacent elements can be reduced [6]. By placing the metastructures consisted of grounded capacitive loaded loops (GCLLs) and π-shaped elements orthogonal to each other halfway between the dual-polarized-multilayered patch antennas, the near-field surface-wave coupling levels can be lowered [7]. By using specific topology optimized structures in both the radiation patches layer and the ground plane layer, the
isolation levels between two dual-polarized patch antennas can be improved [8]. The other focuses on the usage of decoupling structures to generate new fields cancelling out the mutual coupling fields between adjacent radiators. For instance, by placing a planar decoupling surface, which is composed of many electrically small metal patches, above a dual-polarized cross-dipole array, the partially reflected waves from patches can be controlled to cancel out the mutual coupling waves [9]. By integrating an H-shaped structure and a couple of meander lines into a two-element dual-polarized patch array, the coupling waves from both E-plane and H-plane can be cancelled out, respectively [10]. Although effective, these techniques may witness certain unavoidable drawbacks due to their inherent decoupling operation mechanism. The integration of metastructures, decoupling surfaces or H-shaped structure, and meander lines would inescapably increase the total height of the array, because decoupling structures should be placed above the radiators [7,9,10]. The usage of metamaterial cavities, APSs, or the specific topology optimized structures may not be suitable for high-density broadband array application due to their quite large transverse sizes [5,6] and relatively narrow operational bandwidths [8].

In [11], we numerically reported a composite isolator (CI) structure for the decoupling of high-density arrays. Due to its planar printed form, the developed CI could be easily integrated into closely spaced arrays for broadband dual-polarization base station antenna array systems without occupying additional concerning transverse space or increasing the overall thickness. The design methodology and working mechanism of the CI are thoroughly investigated. Moreover, the decoupling capability of the developed CI for varying interelement spacing, for example, as close as 0.35 \( \lambda_0 \) (\( \lambda_0 \) corresponds to the free space wavelength at the lower bound of the operational band), is analyzed and
dramatic isolation enhancements are obtained. First of all, in Section 2, the design methodology and isolation performance characteristics of developed CI are presented. Next in Section 3, the wideband (up to 45%) decoupling performance of a two-element cross-dipole array with the centre-to-centre spacing of 0.45 \( \lambda_0 \) is accomplished by integrating the proposed CI into it. The decoupling results from the two-element array with different array spacings are presented as well. Besides, the current distributions on the CI structure are provided to illustrate its decoupling mechanism. Finally, some conclusions are summarized in Section 4.

2 CONFIGURATION OF THE COMPOSITE ISOLATOR

In this section, the wide band stop characteristics of our proposed CI are investigated, as shown in Figure 1. Here, we use plane waves to excite the isolators in different cases as shown in Figure 1a. The plane waves propagating along the y-axis with its electric \( (E_z) \) field being parallel to the z-axis and its magnetic \( (H_y) \) field being parallel to the x-axis are set to illuminate the isolators. The parallel-plate waveguide simulation model is utilized to realize the plane wave incidence scenario. The boundary conditions of perfect electric conducting and perfect magnetic conducting are set in the z-axis and x-axis directions, respectively. And two excitation wave guide ports were assigned in the y-direction [12,13]. This simulation method has been widely used for the antenna and array designs [7,14–16]. The corresponding transmission coefficients \( |S_{21}| \) are provided in Figure 1b.

In step (I), only a single straight metallic strip with a height of 30 mm (around one-quarter wavelength) is placed vertically to the ground. The simulated \( |S_{21}| \) indicates that there is a strong resonance dip \( \odot \) at 2.27 GHz to prevent the plane wave propagating, with the isolation level of 35.59 dB and 10 dB bandwidth of 8.5%. The current distribution indicates that the grounded strip operates in the monopole fundamental mode [17]. Next, in step (II), in order to increase the decoupling frequency bandwidth, multiple same size strips are parallely located to form a parasitic array. As shown in Figure 1b, a three-element array shows a larger bandwidth of 13.5% and meanwhile, since the strips are very close to each other, the strong mutual coupling between neighbouring elements red-shifts the resonance \( \odot \) to 2.21 GHz with a higher isolation level of 41.49 dB [18]. As anticipated, when more strips are added to form a five-element array, the resonance \( \odot \) witnesses further red-shift (at 2.17 GHz) with isolation bandwidth of 17.1%. Note that, two additional weaker resonant ripples appear at 2.43 and 2.49 GHz, respectively, which are ascribed to the capacitive coupling effect arising from the presence of multiple monopole resonators [7]. Finally, in step (III), an additional grounded metallic wall with a height lower than the strips' is added by the periodic strip array to form a CI unit. The vertically polarized currents on the strips could induce the wall to generate semicircular current and thereby producing a second resonance \( \odot \). By adjusting the height of the wall, the isolation bandwidth could be enhanced up to 36%, as shown in Figure 1b.

3 DECOUPLING OF BROADBAND DUAL-POLARIZED CROSS-DIPOLE ARRAY

In this section, the proposed CI is used in a broadband two-element cross-dipole array to demonstrate its wideband mutual coupling suppression performance characteristics. The array

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**Figure 2** Geometry of a cross-dipole element: (a) 3-D view, (b) front view, (c) side view for the feeding structure for port 1, and (d) side view for the feeding structure for port 2.
with CI was simulated, and the prototype was fabricated and tested.

### 3.1 Cross-dipole antenna element

The antenna element consisting of two main radiators and two microstrip feeding structures (the feeding structures for ports 1 and 2), which are perpendicular to each other [19–23], is shown in Figure 2. As shown in Figure 2b, the main radiators include two orthogonal dipoles printed on a 0.8-mm-thick F4B substrate with relative permittivity: \( \varepsilon_r = 4.4 \), and loss tangent: \( \tan \delta = 0.0025 \) to achieve dual-polarized operation. Four sockets are designed to make room for the two substrates with feeding structures. As shown in Figure 2c,d, the \( \Gamma \)-shaped feeding structures are printed on one side of a 0.8-mm-thick F4B substrate to connect two 50Ω SMA connectors. On the other side, the rectangle patches are printed to connect the dipoles and ground plane. Moreover, the gaps in the centre of both substrates are designed to guarantee the orthogonal placement between each other.

### 3.2 Cross-dipole array with CI

Here, a 0.787-mm-thick Rogers 5880 dielectric slab (\( \varepsilon_r = 2.2 \), \( \tan \delta = 0.0009 \)) with periodic strips and a metallic wall on both sides is proposed to construct a new CI unit as shown in

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**TABLE 1** Optimized design parameters of the cross-dipole array with CI (all dimensions are in millimetres)

| d   | h   | l-w | h-w |
|-----|-----|-----|-----|
| 80  | 36  | 78.4| 13  |
| \( d_1 \) = 2 | \( d_2 \) = 1 | \( d_1 \) = 7 | \( h_{\text{sub}} \) = 58 | \( l_{\text{rad}} \) = 22 |
| \( \text{gap} \) = 2 | \( h_{\text{sub}} \) = 33 | \( l_{\text{sub}} \) = 50 | \( a \) = 15 | \( l_1 \) = 31 |
| \( l_2 \) = 15 | \( l_3 \) = 8 | \( l_4 \) = 31 | \( l_5 \) = 5 | \( l_6 \) = 4.5 |
| \( l_7 \) = 16 | \( l_{\text{ring}} \) = 16 | \( h_{\text{sub}} \) = 26 | \( w_1 \) = 2 | \( w_2 \) = 2 |

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**FIGURE 3** A two-element cross-dipole array loading with the CI: (a) side view of the composite isolator, (b) front view of the array, (c) side view of the array, and (d) the fabrication photograph.
Figure 4. S-parameters of the array with CI: (a) |S_{11}|, |S_{22}|, |S_{33}|, and |S_{44}|; (b) |S_{12}|; (c) |S_{13}|; and (d) |S_{14}|

Table 2. Decoupling performance of the arrays with different element spacings

| Centre-to-centre spacing (*\lambda_0) | Edge-to-edge distance (*\lambda_0) | Operational bandwidth (GHz) | Radiation efficiency (%) | Isolation level (dB) |
|-------------------------------------|----------------------------------|-----------------------------|------------------------|---------------------|
| 0.45                                | 0.12                             | 1.7–2.7                     | 98                     | 22.2 | 27 | 14.7 | 22 | 14.9 | 20 |
| 0.4                                 | 0.068                            | 1.7–2.65                    | 97.2                   | 95.7 | 18.5 | 22 | 12.4 | 18.9 | 12.1 | 18.6 |
| 0.35                                | 0.017                            | 1.7–2.7                     | 96                     | 92.8 | 14.8 | 20.8 | 9.4 | 17 | 9.6 | 16.5 |

Figure 3a. There are 20 strips, and the length of each strip is around one-quarter dielectric wavelength corresponding to the centre frequency 2.2 GHz. Three plugs on the substrate and the slots in the ground plane are designed to ensure the good connection between the substrate and ground. To verify the decoupling efficacy of the CI, a two-element cross-dipole array with centre-to-centre distance D = 80 mm (0.45 \lambda_0 at lower operational bound 1.7 GHz) is designed. Four CI units consist of a fence structure surrounding each cross-dipole element. The dimensions of the array with the CI are given in Table 1.

The S-parameters are measured by an agilent E5071C network analyzer. As shown in Figure 4a, the reflection coefficients (|S_{11}|) of ports 1 and 2 are both lower than -10 dB over the frequency band from 1.7 to 2.7 GHz of our interest. Note that, compared with the isolated cross-dipole element, the mutual coupling between the cross-polarized ports (|S_{12}|) for one element itself in the array without CI deteriorates from -32.21 to -22.18 dB. After loading the CI, the measured (simulated) |S_{12}| is reduced to below -32 dB (-27 dB) as shown in Figure 4b. Meanwhile, the measured (simulated) coupling between copolarized ports and cross-polarized ports between two adjacent elements, |S_{13}| and |S_{14}| are, respectively, reduced to below -24.3 dB (-22 dB) and -21.8 dB (-20 dB) over the entire operational band as shown in Figure 4c,d. Clearly, due to the presence of the CI, the isolation between copolarized ports witnesses an average ~7 dB improvement in the range of 3.5–10 dB within the operational bandwidth. On the whole, the simulation and measurement are well consistent with each other. The acceptable deviation between the measured and simulated results could be ascribed to the fabrication, assembly, and measurement errors. Furthermore, the decoupling performances of proposed CI when the cross-dipole elements are with different centre-to-centre spacings (i.e. 0.45 \lambda_0, 0.4 \lambda_0 and 0.35 \lambda_0) are summarized in Table 2. Note that, a smaller centre-to-centre spacing of the array witnesses a lower isolation level, as anticipated in [7–10]. It is demonstrated that our proposed CI maintains sustainable decoupling performance characteristics despite of the decrease of the element spacing, manifesting its superior decoupling capability for high-density array applications. In addition, it is noted that the radiation efficiency witnessed a little (less than 5%) decrease for the arrays with above element spacings due to the presence of the isolator.

Figure 5 presents the peak realized gain values and the radiation efficiency of the arrays with and without CI. The
array with CI exhibits stable peak realized gain values ranging from 5.7 to 7.6 dBi and maintains high radiation efficiency above 97.5% in the whole operational band. The far-field patterns of the arrays with and without CI are provided in Figure 6. When only port 1 is excited, the measured (simulated) half-power beamwidths in the E-plane and H-plane are 88° (137°) and 67° (72°), and 87° (95°) and 72° (107°) at two frequencies of 1.85 and 2.45 GHz, respectively, for arrays with CI. The above deviations between measured and simulated results are ascribed to the unavoidable errors in the fabrication, assembly, and measurement processes. Notice that, the presence of CI expanded the half-power beamwidths in the E-plane, while the beamwidths in H-plane maintain unchanged on the whole operational band, leading to a little decrease of the peak realized gain values shown in Figure 5.

It is worth mentioning that, a two-element probe-fed patch antenna array with and without CI has been numerically studied. According to our simulation results, about an average 7 dB isolation improvement within the entire operational fractional bandwidth of 25% is obtained. It indicated that our proposed CI is effective for other types of antenna arrays.

3.3 | Decoupling mechanism

According to our above simulation and experimental study, the design principles of our proposed CI can be summarized as follows: First, the length of the parasitic strips should be set around one-quarter dielectric wavelength corresponding to the objective frequency, making them effective resonators. Second, the number of the resonant strips should be kept no less than 10 to form a stable broadband parasitic array. Third, the height of the wall should be set half of the length of the periodic strips. Since it is simple, symmetric, high efficiency, and can entirely surround each radiator element, our proposed CI is suitable for large array applications. Here, in order to investigate the decoupling mechanism of the CI, its surface current

**FIGURE 5** Peak realized gain and radiation efficiency of the arrays with and without CI.

**FIGURE 6** Normalized radiation patterns of the arrays with and without CI when only port 1 is excited: (a) at 1.85 GHz and (b) at 2.45 GHz.
distributions when port 1 is excited are demonstrated in Figure 7. Figure 7a shows that the periodic resonant strips are in uniform operating in monopole fundamental mode at the lower frequency of 1.85 GHz. By contrast, periodic semi-circular surface current distributions on the metallic wall are observed at the higher frequency of 2.65 GHz as shown in Figure 7b. This phenomenon is in good agreement with that in Figure 1, exhibiting that the two strong resonances could be well excited to reduce the mutual coupling between two cross-dipole elements in a wide frequency range. In addition, we note that since the vertically polarized current on the isolator surface is induced to contribute the end-fire radiation of the array, its presence could increase the half-power beamwidth in the $E$-plane to a certain extent, which has been demonstrated in Figure 6.

Furthermore, Table 3 provides a comprehensive performance comparison between the proposed CI and other recently reported decoupling approaches for dual-polarized arrays. Clearly, it can be observed that, besides stable decoupling effect in a much wider operational bandwidth, the proposed CI allows a closer separation between adjacent dual-polarized antenna elements, because of its very low transverse size. Moreover, the integration of the proposed isolator does not require any increase in the total height of the array. In comparison with the reported miniaturized dual-band single-polarized [24] or dual-polarized [25] base station array, which works on the decoupling between two different neighbouring bands by resorting to band-notch antenna elements, the developed CI structure allows for the wideband decoupling of closely spaced high-density base station arrays operating in the same operation bandwidth.

### Table 3 Comparisons between our proposed CI and recently reported approaches in dual-polarized arrays

| Reference | Array type     | Centre-to-centre spacing ($\lambda_0$) | Operational bandwidth (%) | Average additional decoupling (dB) | Decoupling mechanism                  | Increasing the array total height |
|-----------|----------------|----------------------------------------|---------------------------|-----------------------------------|---------------------------------------|----------------------------------|
| [5]       | Patch array    | 1.55                                   | 7.7                       | ~7                                | Suppressing coupling waves             | Yes                              |
| [6]       | Patch array    | 1.3                                    | 7.7                       | ~6                                | Suppressing coupling waves             | Yes                              |
| [7]       | Patch array    | 0.6                                    | 8.7                       | ~7                                | Suppressing coupling waves             | Yes                              |
| [8]       | Patch array    | 0.35                                   | 2.5                       | ~8                                | Suppressing coupling waves             | No                               |
| [9]       | Cross-dipole array | 0.495                           | 14.1                      | ~14                               | Cancelling out coupling waves          | Yes                              |
| [10]      | Patch array    | 0.5                                    | 11.8                      | ~9                                | Cancelling out coupling waves          | Yes                              |
| This work | Cross-dipole array | 0.45                            | 45                        | ~7                                | Suppressing coupling waves             | No                               |

4 | CONCLUSION

A broadband CI for reducing the mutual coupling between high-density dual-polarized arrays is proposed. The CI consists of periodic strips and a metallic wall on the opposite sides of a substrate, which can collaborate with each other for wideband isolation improvement of antenna arrays. By introducing the CI into a two-element cross-dipole array with the distance only 0.45 $\lambda_0$, the mutual coupling $|S_{12}|$, $|S_{13}|$, and $|S_{14}|$, could be reduced to lower than -27 dB, -22 dB, and -20 dB, respectively, over a 45% fractional bandwidth, without increasing the overall array profile. The proposed CI can be used as an effective tool in the design of compact, broadband, dual-polarized, and decoupling array platforms such as base station systems and high-density phased array systems.
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