Composite metamaterial enabled excellent performance of microstrip antenna array*

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This paper reports that the split ring resonators and complementary split ring resonators are compounded to construct a novel compact composite metamaterial. The composite metamaterial exhibits a unique property of blocking electromagnetic wave propagating in two directions near the resonant frequency. An example of two-element microstrip antenna array demonstrates that the developed metamaterial enables array performance that is an improvement in comparison with the traditional one, including mutual coupling suppression of 9.07 dB, remarkable side lobe suppression and gain improvement of 2.14 dB. The mechanism of performance enhancement is analysed based on the electric field and Poynting vector distributions in array. The present work not only is a meaningful exploration of new type composite metamaterial design, but also opens up possibilities for extensive metamaterial applications to antenna engineer.

Keywords: compact composite metamaterial, mutual coupling reduction in microstrip array, gain improvement

PACC: 4270Y, 9430P, 7430G, 7785

1. Introduction

Microstrip antenna array on high dielectric constant substrate is of special interest due to its compact size. However, the utilisation of high dielectric constant substrate can result in some drawbacks. One of the severest problems is the inevitable excitation of surface waves, which can incur strong mutual coupling among elements. According to Refs. [1] and [2], the mutual coupling is one of the major sources of degradation in array performance. Therefore, achieving a high degree of isolation between elements is an important approach for improving the array performance. In order to decrease the mutual coupling in the array, a lot of methods are introduced up to the present, for example, loading electromagnetic bandgap (EBG) structures[3] and defected ground structures (DGSs).[4] However, EBG structures take up too much space because at least several periodic units are needed to ensure good performance; DGSs need to be etched on the ground plate, this leads to inevitable strong backward radiation.

Recently metamaterials have been studied extensively due to their unique properties, such as inversion of the Snell law, inversion of the Doppler effect, and backward Cherenkov radiation.[5−15] In this paper, we propose a novel compact composite metamaterial compounded by split ring resonators (SRRs) and complementary split ring resonators (CSRRs) and analyse its particular electromagnetic properties. The developed metamaterial is integrated into a microstrip array to enhance array performance. An example of two-element microstrip array demonstrates that mutual coupling reduction of 9.07 dB, remarkable side lobe suppression and gain improvement of 2.14 dB are obtained via the use of composite metamaterial.

2. Novel compact composite metmaterial design

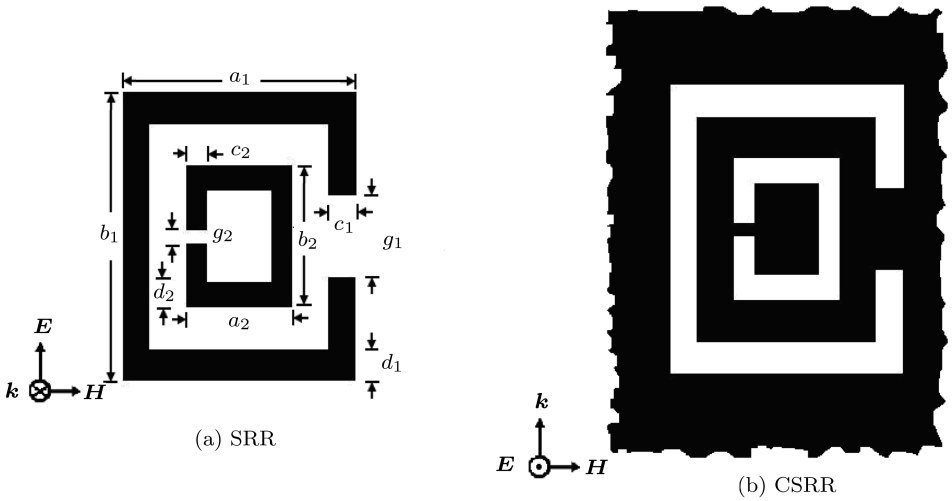
Figure 1(a) shows a rectangle SRR structure. The electromagnetic wave propagates perpendicularly to the SRR plane with the electric field $\boldsymbol{E}$ polarised in the direction parallel to the SRR plane and perpendicular to the SRR splitting gap. The electric excitation is induced by external electric field $\boldsymbol{E}$, because $\boldsymbol{E}$ is polarised perpendicularly to the SRR splitting gap.[16−19] Accordingly, the SRR can block elec-

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tromagnetic wave propagating near its resonant frequency based on Refs. [17] and [19]. However, there is no external magnetic excitation in this structure,[20,21] due to the fact that the magnetic field $\boldsymbol{H}$ is polarised in the direction parallel to the SRR plane.



(a) SRR (b) CSRR

Fig. 1. Geometries of SRR and CSRR units (black zones represent the metallisation).

Figure 1(b) shows a rectangled CSRR structure, which is the dual counterpart of the SRR shown in Fig. 1(a). In the sense of Babinet's principle,[22] the electric excitation is provided, when electromagnetic wave propagates in the direction parallel to CSRR plane, with the external electric field $\boldsymbol{E}$ polarised in the direction perpendicular to the CSRR plane.[18,22] According to Refs. [18] and [23], the CSRR can block electromagnetic wave propagating near its resonant frequency. Similarly, there is no external magnetic excitation, since the external magnetic field $\boldsymbol{H}$ is parallel to the complementary splitting gap of CSRR.

In this paper, we propose etching SRRs and CSRRs oppositely on the two sides of substrate to construct a novel compact composite metamaterial. According to the above analysis, the composite metamaterial can block electromagnetic wave propagating in two directions near its resonant frequency. One is the direction perpendicular to the substrate [in Fig. 1(a) case], and the other is the direction parallel to substrate [in Fig. 1(b) case].

The unique property of the composite metamaterial is utilised to suppress the mutual coupling between elements in microstrip array and improve the array performance. In microstrip array, the mutual coupling between E-plane-coupled elements is stronger than that between H-plane-coupled elements.[1,2,4] Therefore, the mutual coupling suppression in E-plane-coupled array is only discussed in this paper. As an example, a two-element array is studied to perform the property of the composite metamaterial.

3. Experimental results

The two-element array with the composite metamaterial is designed by using Ansoft HFSS 9.0, manufactured and measured, with the element spacing being about $0.5\lambda_0$ (λ_0 is the corresponding wavelength in free space). Its photograph is shown in Fig. 2, and the detailed configuration parameters of the array are listed in the caption. The measured scattering parameters and patterns are shown in Fig. 3. For the purpose of comparison, the measured results of the traditional array (without metamaterial) are also shown in Fig. 3. From Fig. 3(a), it can be found that the resonance frequency of the traditional array is around 5.76 GHz and the corresponding mutual coupling reaches –16.11 dB. The result implies that a strong mutual coupling occurs in this design.[24]

Due to the slow-wave effect of notched apertures,[4] when the composite metamaterial is integrated into the array, the resonance frequency shifts a little to 5.82 GHz, and a feeble mutual coupling of –25.18 dB is attained. The mutual coupling is sharply suppressed (9.07 dB reduction) in comparison with the traditional array. Figures 3(b) and 3(c)

show the comparisons of the measured radiation patterns in E-and H-planes, respectively. As a general conclusion, it can be said that the array with the composite metamaterial has remarkable directivity improvement and side lobe suppressed with slightly increased backward radiation. However, the strong backward radiation occurs in the DGS-loaded array due to the DGS aperture etched on the ground.[4] The measured results indicate that a gain improvement of 2.14 dB is achieved by loading the composite metamaterial.

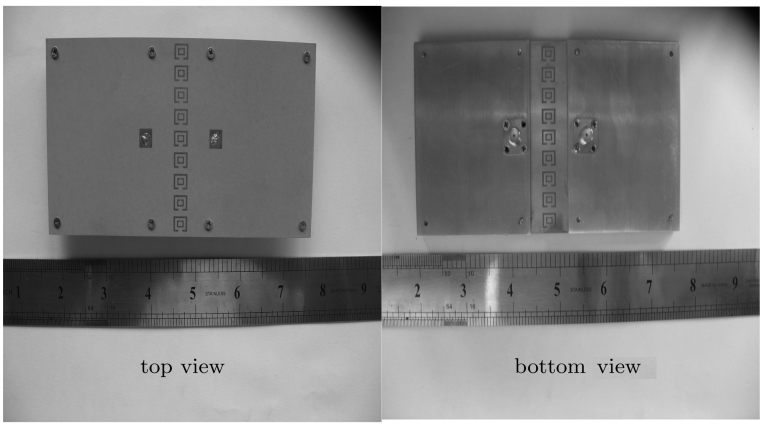


Fig. 2. Top and bottom view of composite metamaterial loaded array. Grounded substrate 140 mm×70 mm×2.0 mm, radiation patch 6.7 mm×6.6 mm; element spacing 29.4 mm; and substrate permittivity $\varepsilon_r = 10.2$, $a_1 = 5.5$ mm, $b_1 = 7.11$ mm, $c_1 = 0.65$ mm, $d_1 = 0.78$ mm, $g_1 = 2$ mm, $a_2 = 2.5$ mm, $b_2 = 3.5$ mm, $c_2 = 0.5$ mm, $d_2 = 0.65$ mm, $g_2 = 0.26$ mm.

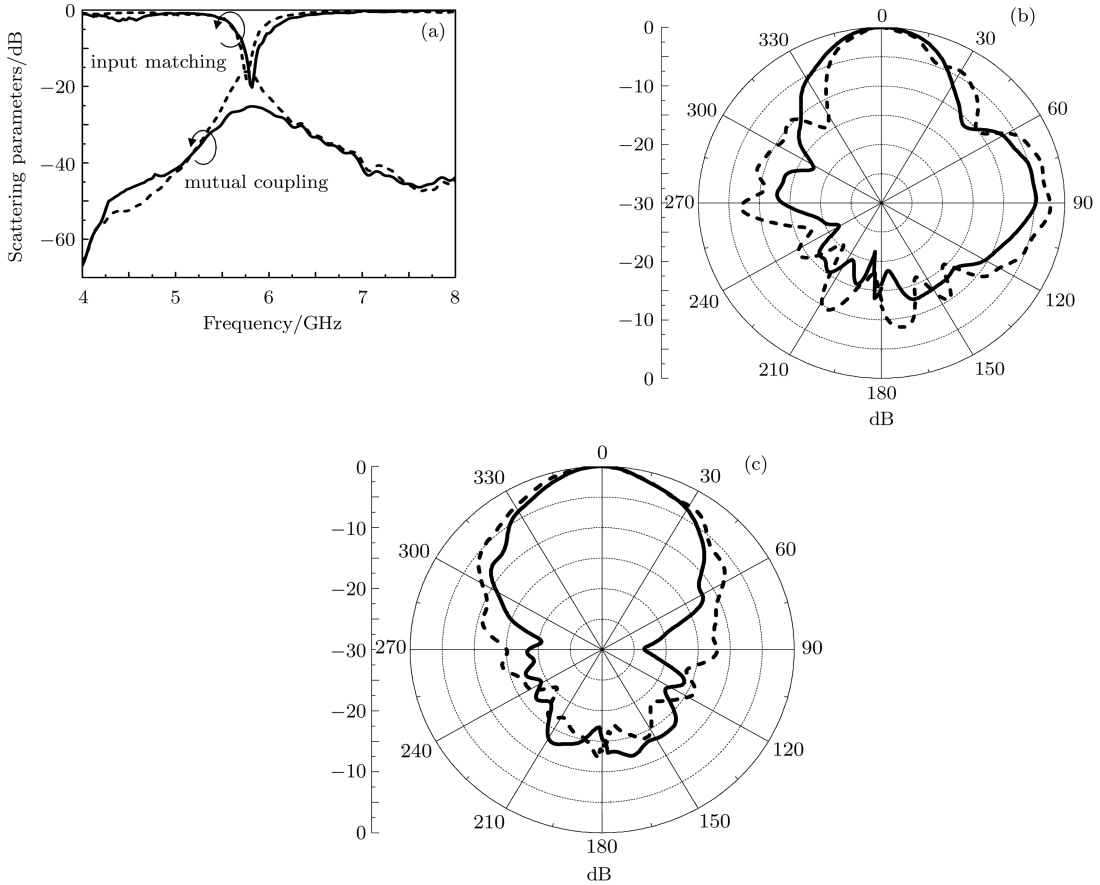


Fig. 3. Experimental results of composite metamaterial loaded array (solid line) and traditional array (dashed line): (a) scattering parameters; (b) normalised radiation pattern in E-plane; (c) normalised radiation pattern in H-plane.

4. Discussion

The improvement of the array performance can be analysed based on the characteristics of the composite metamaterial. It is well known that in microstrip array TM mode wave plays a dominant role in the excited surface waves,[1,3,25,26] and its electric field is perpendicular to the ground at the interface of substrate and ground. Considering the CSRRs response in specific electromagnetic environment shown in Fig. 1(b), we present its electric response on the condition that the actual electromagnetic environment coincides with the environment in Fig. 1(b). Therefore, by etching periodical CSRRs on the ground at the centre of the array[18,22] and adjusting their dimensions to accommodate the array operating frequency, a strong mutual coupling suppression is achieved.

The etched periodical CSRRs-apertures are placed so close to the elements in E-plane that a certain electromagnetic energy in the upward space could leak through the apertures, which degrade the array radiation performance. Figures 4(a) and 4(b) show the tangent component of Poynting vector distributions in E-plane of the traditional array and the CSRRs-loaded one, respectively. It is observed that, the etched periodical CSRRs-apertures incur a strong energy leaking into the backward space.

In Fig. 4(b), it can be found that there is a certain energy propagating perpendicularly to the substrate around the etched CSRRs-apertures, especially at the interface of air and substrate above CSRRs. Figure 4(c) demonstrates the tangent E-field distribution at the interface of air and substrate. This figure indicates that the dominant E-field is polarised in the direction parallel to z-direction in the air-substrate interface. Considering the SRRs response in specific electromagnetic environment shown in Fig. 1(a), we suppress a strong energy leaking by placing periodical SRRs on the air-substrate interface at the centre of the array.[16−21] Figure 4(d) shows the tangent component of Poynting vector distribution in E-plane of the SRRs- and CSRRs-loaded array. By comparing Fig. 4(d) with Fig. 4(b), the energy radiating into backward space through the etched CSRRs-apertures is weakened distinctly and the corresponding forward radiation is improved due to the periodical SRRs loading.

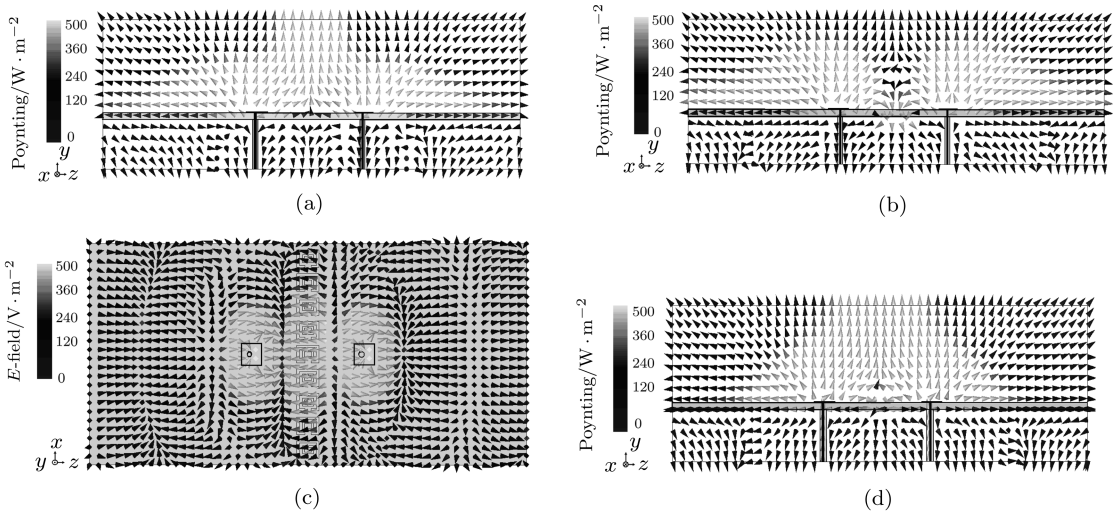


Fig. 4. Poynting vector and E-field distributions simulated by Ansoft HFSS 9.0: (a) tangent component of Poynting vector of traditional array in symmetrical plane which passes through centres of two patches; (b) tangent component of Poynting vector of CSRRs-loaded array in symmetrical plane; (c) tangent component of E-field of CSRRs-loaded array on air-substrate interface; (d) tangent component of Poynting vector of composite metamaterial loaded array in symmetrical plane.

The above studies demonstrate that the composite metamaterial compounded by SRRs and CSRRs can not only effectively suppress the propagation of the electromagnetic wave in two orthogonal directions, but also has a compact size. Therefore, it enables excellent performance of microstrip antenna array with almost consummate manner. Such a good example demonstrates its potential applications to antenna engineering, such as multiple-input multiple-output (MIMO) system and superdirective array. The

MIMO system is an integration of multiple antennas restricted in limited space, which requires low mutual coupling to ensure balanced and steady performance. Etching proposed metamaterial instead of DGS between antennas can be preferred to suppress mutual coupling and improve each antenna gain, due to its inherent characteristics of blocking electromagnetic wave propagation in two vertical directions, as mentioned in Section 3. Buell *et al.*[2] have fabricated an excellent superdirective array by using embedded circuit (EC) metamaterial isolators. However, the EC metamaterial placed halfway between elements, on the condition that the intact grounded substrate is divided into pieces, increases the complexity of manufacturing process and degrades the mechanical stability of the whole array. The proposed metamaterial, which is etched at the array to ensure superdirectivity, could overcome the EC metamaterial defects in manufacturing process and the array mechanical stability. The above examples imply that the developed composite metamaterial has actually potential application to antenna engineering.

5. Conclusion

A novel compact composite metamaterial compounded by SRRs and CSRRs is proposed based on the electric excitation condition. To perform its unique characteristics, we use it to suppress the mutual coupling between elements and improve the performance of the microstrip array. Due to integrating the composite metamaterial, the two-element microstrip array exhibits a mutual coupling suppression of 9.07 dB, remarkable side lobe suppression and gain improvement of 2.14 dB with slightly increased backward radiation. The example displays a good potential application of the developed composite metamaterial, such as MIMO systems and superdirective arrays.

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