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Mutual Coupling Reduction of Dual-Frequency Patch Antenna Arrays

Yantao Yu, Lijun Yi, Xiaoya Liu, and Zhaokai Gu

College of Communication Engineering
Chongqing University, Chongqing, 400044, China
yantaoyu@cqu.edu.cn, yiljcqu@163.com

Abstract ─ In this paper, a compact patch antenna array with dual resonant frequencies is presented. The mutual coupling between array elements can be reduced simultaneously at two frequencies by inserting a simple C-shaped resonator between the radiating patches and etching an inverted C-shaped slot defected ground structure (DGS) on the ground plane. The characteristics of the DGS and the resonator are investigated, respectively. The measured results show that the isolation between the antenna ports has been enhanced about 10 dB and 18 dB at the two operation frequencies with the presence of the proposed DGS and resonator structure.

Index Terms ─ Defected ground structure (DGS), dual frequency, mutual coupling, patch array, resonator.

I. INTRODUCTION

In order to accommodate higher data rates and provide increased capacity, the multi-port antenna arrays are widely used in new generation of wireless communication systems. However, it is very difficult to realize multiple antennas in a small size wireless device while keeping a high level of isolation between antenna elements [1], especially for dual-frequency arrays. In such a case, surface waves and near fields can lead to coupling between the antenna elements. As the separation between array elements becomes smaller, the effect of mutual coupling becomes more severe, which may result in severe degradation to the antenna's radiation properties, e.g., increment of the magnitude of S_{12} and distortion of radiation pattern.

Mutual coupling has attracted a lot of research in past years [2]. Different methods have been proposed in the literature to deal with the mutual coupling while keeping the array with compact design [3,4]. The orientations and feed configurations of antenna elements can be changed to minimize the inter-element mutual coupling [5-7]. Various decoupling networks using reactive components [8] or hybrid couplers [9] have been proposed to increase the isolation between antenna ports. However, the designed networks may be very complicated. There are some other methods for printed antennas, e.g., using parasitic elements [10], defected ground structures (DGS) [11-13] and microstrip sections [14]. Most of the designs in the literature are for arrays with single operating frequency band. However, dual-frequency operation is preferred for many popular communication standards. Mutual coupling reduction for dual-frequency arrays has also attracted many studies. The paper [15] describes a procedure to achieve simultaneous decoupling and matching at two frequencies using decoupling network with series and parallel combination of inductors and capacitors. A reconfigurable dual-band monopole array with high isolation is given in [16], which exploits the neutralization techniques and uses a switch to control the operating frequency band.

In this paper, a compact design utilizing a simple microstrip resonator and a defected ground structure to reduce the mutual coupling between a dual-frequency patch antenna array is proposed. In Section II, the design of compact dual-frequency patch antenna array is presented. In Section III, the characteristics of the DGS and the resonator are analyzed and the mutual coupling reduction of the array is studied both numerically and experimentally. Furthermore, the technique is extended to arrays with four elements. Finally, Section IV concludes the paper.

II. THE DUAL-FREQUENCY ARRAY

The geometrical structure of the proposed dual-frequency patch antenna array is shown in Fig. 1. This antenna array is designed on an FR4 substrate with a relative permittivity of 4.4, a thickness of 1.6 mm and a loss tangent of 0.02. The overall dimension ($W \times L$) of the antenna is 75 mm × 60 mm. The element spacing D is 7 mm. Without the C-shaped resonator, as in Fig. 1 (a), and the inverted C-shaped slot, as in Fig. 1 (b), the original patch array resonates at two frequencies. The antenna array is simulated using the EM software Ansoft HFSS and the S-parameters of the optimized patch array are shown in Fig. 2. Since the array structure is symmetrical, S_{11} equals to S_{22} and only S_{11} is shown in the figure. The optimum dimensions of the patch antenna are W_2 = 18 mm, L_2 = 22 mm, W_3 = 9 mm, L_3 = 14.55 mm, L_4 = 2 mm, H = 1 mm and L_8 = 7 mm. It can be seen from

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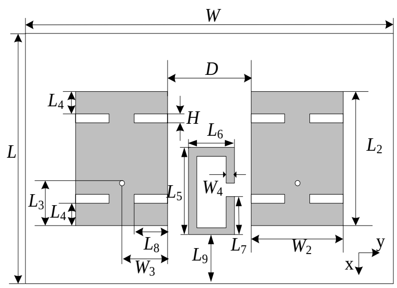
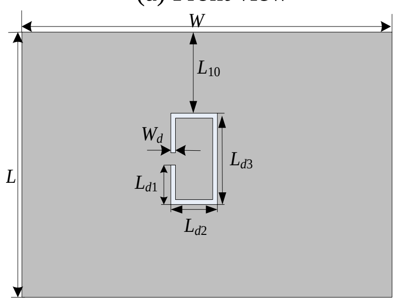
Fig. 2 that the array resonates at 2.78 GHz and 4.12 GHz, respectively. It is also noticed that the magnitudes of the transmission coefficients S_{12} are about -11 dB and -22 dB at the two operating frequencies, respectively.



(a) Front view



(b) Back view

Fig. 1. The structure of the proposed patch array.

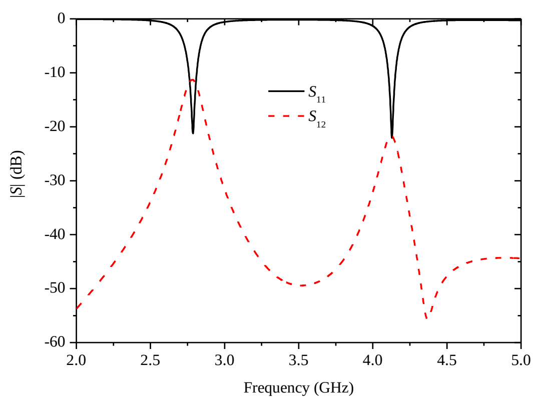


Fig. 2. The *S*-parameters of the proposed dual-frequency patch antenna array.

III. MUTUAL COUPLING REDUCTION

To reduce the mutual coupling of the dual-frequency patch antenna array, a C-shaped resonator is inserted between the radiating patches and an inverted C-shaped DGS is etched on the ground plane. The effects of the presence of the DGS and the resonator are studied as follows.

A. Inverted C-shaped DGS

The inverted C-shaped DGS, as shown in Fig. 1 (b), is etched from the ground plane of the patch array. The inverted C-shaped slot resonates and creates a stop band. To study the frequency characteristics of the DGS structure, a microstrip filter model as shown in Fig. 3 was built. The performance of the filter is analyzed in the EM simulator Ansoft HFSS by changing the dimensions of the slot. Figure 4 shows the transmission coefficients of the filter with various values of L_{d1}. It can be seen that the stop band frequency decreases as the increase of L_{d1}. Figure 5 shows the transmission coefficients of the filter with various values of L_{d2}. The parameter L_{d2} has a similar effect on the performance of the filter as L_{d1} does because they determine the total size of the slot. In addition, the transmission coefficients of the filter for different slot widths are plotted in Fig. 6. It is noted that the stop band frequency increases as the increase of W_d. The moderate value of W_d = 1 mm is chosen in our design.

By properly choosing the dimensions of the DGS structure, the desired band rejection characteristic can be achieved. Figure 7 shows the simulated and measured *S*-parameters of the designed filter with the optimized dimensions of W_d = 1 mm, L_{d1} = 4.9 mm, L_{d2} = 9 mm and L_{d3} = 12 mm. The measured results agree well with the simulated ones. It can be seen that the filter has a stop band at 2.78 GHz, which is the lower operating frequency of the patch array. By employing the proposed DGS in the array, the surface wave excited in the substrate can be suppressed and the mutual coupling can be reduced.

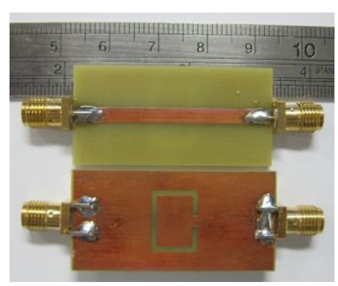


Fig. 3. The fabricated prototype of the DGS section.

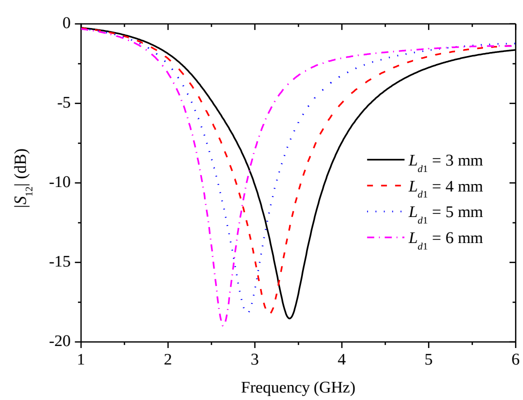


Fig. 4. The transmission coefficients of the filter with various L_{d1}.

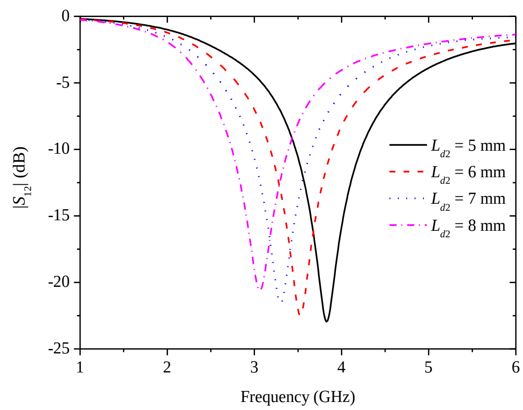


Fig. 5. The transmission coefficients of the filter with various Ld_2.

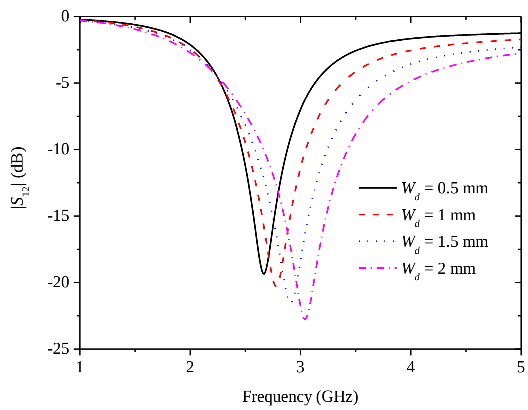


Fig. 6. The transmission coefficients of the filter with various W_d.

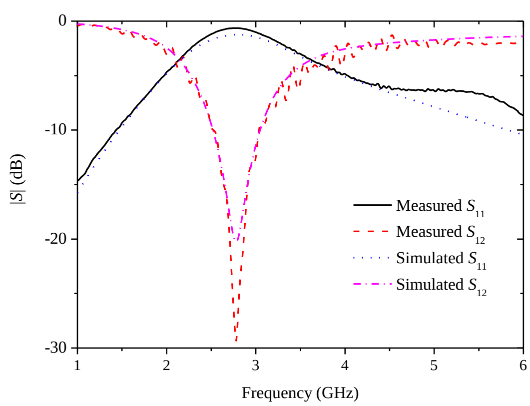


Fig. 7. The *S*-parameters of the optimized filter.

B. C-shaped resonator

The C-shaped resonator placed between the two radiating patches, as shown in Fig. 1 (a), is strongly involved in the coupling at the upper operation frequency of the array and is a half-wavelength resonator. A similar parametric study as for the DGS can be done here and then the dimensions of the resonator can be optimized to obtain the best result. Figure 8 depicts the fabricated resonator with coupled microstrip lines. The dimensions of the resonator are $W_4 = 1$ mm, $L_5 = 15$ mm, $L_6 = 5.5$ mm and $L_7 = 5.8$ mm. The simulated and measured *S*-parameters of the structure are shown in Fig. 9. It can be seen that this structure has a bandpass function at about 4.1 GHz. Therefore, with the C-shaped resonator added, an extra indirect coupling path is introduced, which can cancel out the direct mutual coupling between the two elements.

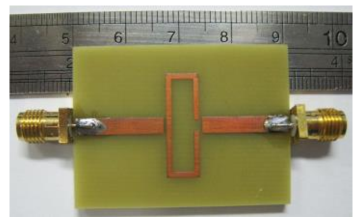


Fig. 8. The fabricated prototype of the resonator.

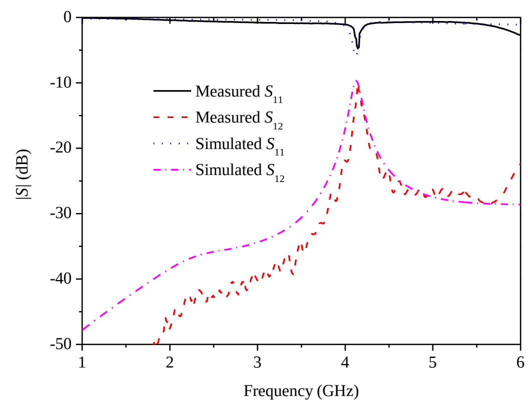


Fig. 9. The *S*-parameters of the resonator.

C. Mutual coupling reduction of the array

According to the above studies on the proposed DGS and resonator structures, both of them can be involved in the coupling at two different resonant frequencies of the patch array. The DGS reduces the mutual coupling at 2.78 GHz and the resonator does it at 4.12 GHz.

In order to investigate their effects on mutual coupling reduction of the array, different combinations of the DGS and resonator structures are studied. Firstly, the combination of the inverted C-shaped DGS and the C-shaped resonator is investigated. In this case, the openings of the two structures are in the opposite directions, as shown in Fig. 1. L_9 is the distance from the bottom of the resonator to the lower edge of the substrate, while L_{10} is the distance from the top of the DGS to the upper edge of the substrate. The relative positions of the DGS, the resonator and the array change as the values of L_9 and L_{10} vary. Figure 10 and Fig. 11 show the transmission coefficients of the array for different values of L_9 and L_{10}, respectively. It can be seen from the two figures that the relative position of the DGS and the resonator does affect the mutual coupling of the array. When L_9 = 17 mm and L_{10} = 30 mm, the achieved enhancement in port isolation are more than 10 dB and 20 dB at the lower frequency and the higher frequency, respectively.

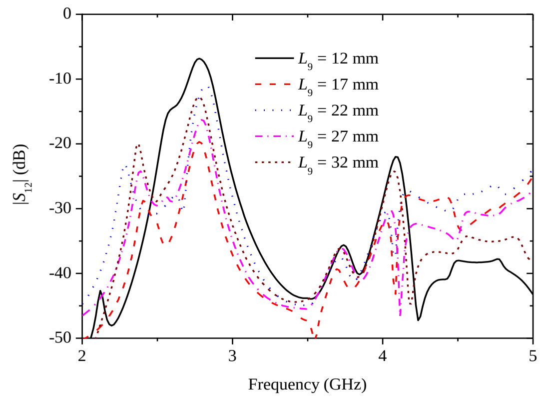


Fig. 10. The transmission coefficients of the array with various L_9.

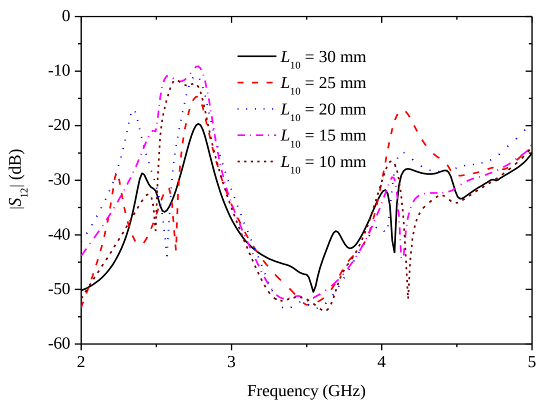


Fig. 11. The transmission coefficients of the array with various L_{10}.

Furthermore, the combination of the C-shaped DGS and the C-shaped resonator is studied. In this case, the openings of the two structures are in the same direction. Figure 12 shows the S-parameters of the array after optimization. It can be seen that the port isolation is increased by 6 dB at the lower frequency and about 20 dB at the higher frequency, which is worse than that of the first one. Therefore, the results of the first design are used in the rest of the paper.

Figure 13 shows the fabricated prototype of the optimized design of the proposed patch array. Figure 14 shows the simulated and the measured reflection coefficients of the patch array with and without the DGS and resonator structures, respectively. With the addition of the DGS and resonator, the array structure is no longer symmetrical, so S_{22} is also shown in Fig. 14. Figure 15 shows the simulated and measured transmission coefficients of the array with and without the DGS and resonator. It can be seen that the simulation results agree well with the measurement results, although with a slight frequency shift. It is also clearly shown in the figures that the measured transmission coefficients have been reduced about 10 dB at 2.78 GHz and 18 dB at 4.12 GHz and the ports of the array are well matched.

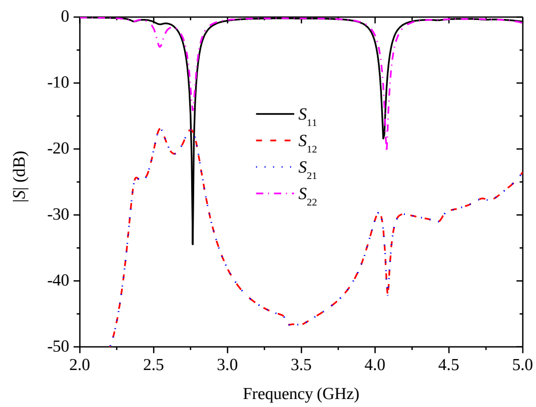
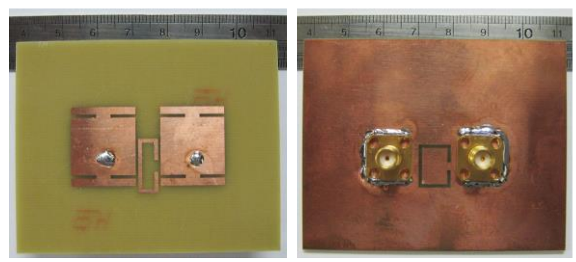


Fig. 12. The S-parameters of the array with the openings of the DGS and resonator in the same direction.



(a) (b)

Fig. 13. The fabricated prototype of the proposed patch array: (a) top view and (b) bottom view.

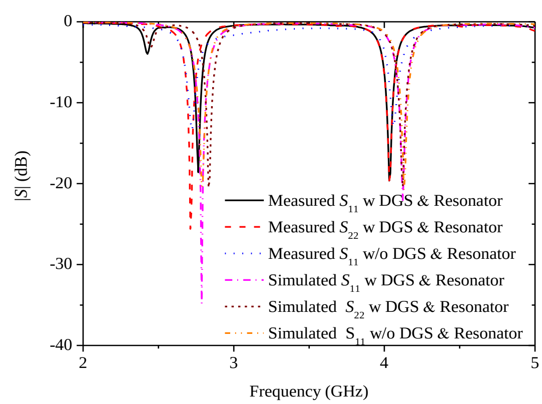


Fig. 14. The simulated and measured reflection coefficients of the array with and without the DGS and resonator.

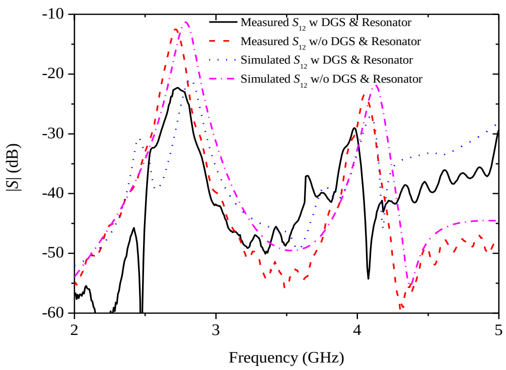


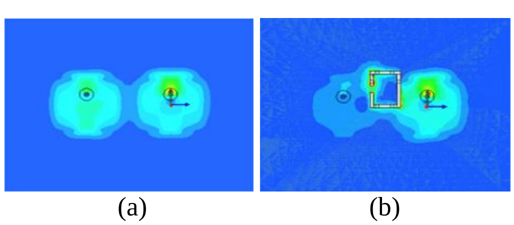
Fig. 15. The simulated and measured transmission coefficients of the array with and without the DGS and resonator.

Figure 16 shows the simulated current distributions at two frequencies 2.78 GHz and 4.12 GHz when the right antenna element is excited while the left one is terminated with a matched load of 50 Ω. It is observed from the figure that without the presence of the DGS and the resonator, a strong mutual coupling exists between the two patches at each resonant frequency. The mutual coupling has been significantly reduced with the implementation of the DGS and the resonator. The calculated radiation efficiency of the proposed array is about 60%. The simulated radiation patterns of the patch array at 2.78 GHz and 4.12 GHz are depicted in Fig. 17. It is obvious that the radiation patterns of the patch array remain their general shapes before and after implementing the DGS and resonator structure.

Correlation coefficient is an important parameter in MIMO applications to evaluate their diversity performance. It is required to minimize the correlation between antenna elements because that the lower the correlation, the higher will be the diversity gain. By assuming uniform external signal source distribution, the envelope correlation coefficient (ECC) can be calculated from the S-parameters using [17]:

$$\rho_e(1,2) = \frac{\left|S_{11}^* S_{21} + S_{12}^* S_{22}\right|^2}{(1-\left|S_{11}\right|^2 - \left|S_{21}\right|^2)(1-\left|S_{22}\right|^2 - \left|S_{12}\right|^2)}. \quad (1)$$

Figure 18 shows the envelope correlation of the patch array with and without DGS using the above equation. It can be seen that the envelope correlation in the frequency band of interest is very low, which means that the antenna array has good spatial diversity and is suitable for MIMO applications.



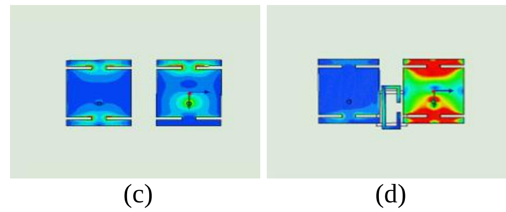


Fig. 16. Simulated current distributions: within the ground plane at 2.78 GHz: (a) without the DGS and (b) with the DGS. Within the radiating patches at 4.12 GHz: (c) without the resonator and (d) with the resonator.

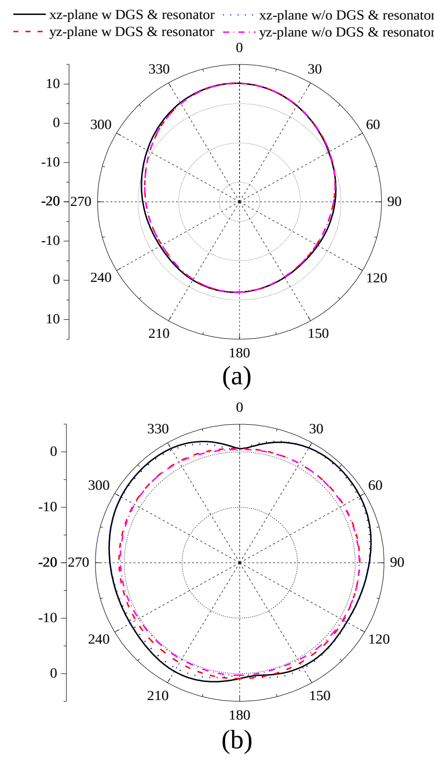


Fig. 17. Radiation patterns of the array with and without DGS and resonator: (a) 2.78 GHz and (b) 4.12 GHz.

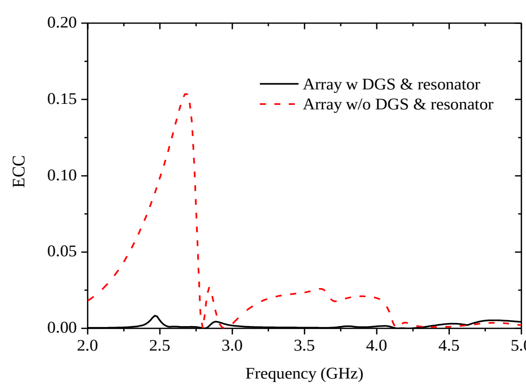


Fig. 18. The calculated envelope correlation coefficient of the patch array with and without DGS and resonator.

The results of the comparison between the proposed array and the other designs in literature are presented in Table 1. It is observed from Table 1 that the proposed DGS and resonator structures help in better isolation enhancement with less edge-to-edge spacing and lower structural complexity.

Table 1: Various comparison between the proposed array and other designs

Paper	Approach	Frequency (f_0) in GHz	Edge to Edge Spacing	Improvement in S_{12} (dB)	Structural Complexity	Size of the Array (mm^2)
[18]	Slotted meander-line resonator	4.8	0.11 λ_0 (7 mm)	6 to 16	Moderate	54×45
[19]	Slotted complementary split-ring resonators	5	0.25 λ_0 (15 mm)	10	High	78×60
[20]	Capacitively loaded loops	0.84 & 2.85	0.067 λ_0 (14 mm)	7 and 9	Very high	50×100
[21]	Meandering slotted high impedance surface	6 & 9.15	3 λ_0 (50 mm)	8 and 13	Very high	100×42
This paper	DGS & resonator	2.78 & 4.12	0.06 λ_0 (7 mm)	10 and 18	Low	75×60

D. Extension to larger array

In this section, we extend the proposed technique to a linear array with four elements. In the new array, the dimensions of the element antenna and the DGS and resonator remain the same as in Section C. The element spacing is still 7 mm. Figure 19 shows the S-parameters of the array without the proposed DGS and resonator. It is noticed that the mutual coupling between adjacent elements is highest. The magnitudes of S_{12} at the two operating frequencies are -12 dB and -21 dB, respectively, while $|S_{13}|$ and $|S_{14}|$ are both below -20 dB across the frequency bands. With the addition of the DGS and resonator, the isolation between array elements has been obviously increased. It can be seen from Fig. 20 that $|S_{12}|$ has been reduced to -23 dB at the lower frequency and -30 dB at the higher frequency, while $|S_{13}|$ and $|S_{14}|$ have an averaged reduction of 6-8 dB at the operating frequencies.

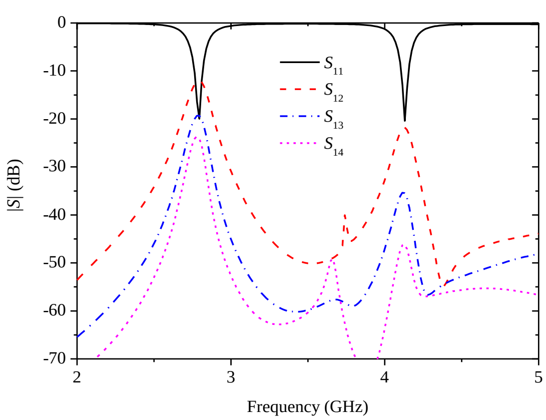


Fig. 19. The S-parameters of the four-element array without the proposed DGS and resonator.

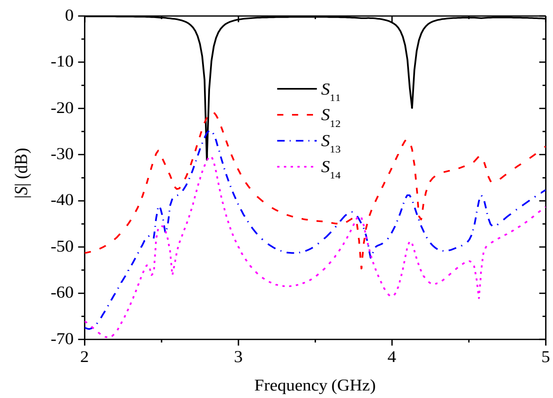


Fig. 20. The S-parameters of the four-element array with the proposed DGS and resonator.

IV. CONCLUSION

The mutual coupling reduction of a novel compact patch antenna array with dual resonant frequencies has been presented. Simulations and measurements show that the C-shaped resonator and the inverted C-shaped slot defected ground structure could effectively suppress the mutual coupling of an array at two frequencies simultaneously. The proposed structures are simple and can be easily fabricated together with the printed patches.

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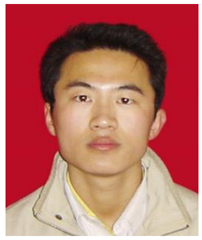
Yantao Yu received the B.Eng. degree (1st class honors) and the Ph.D. degree both from the National University of Singapore, in 2004 and 2009, respectively. From 2008 to 2009, he worked at Motorola Electronics Pte Ltd., Singapore, as an RF Engineer. From 2009 to 2010, he was a Research Fellow with the National University

of Singapore. He is currently an Associate Professor in the College of Communication Engineering, Chongqing University, China. His research interests include analysis and design of antennas and compact antenna arrays.

Lijun Yi received the B.Eng. degree from the Chongqing Univesity, China in 2013. He is working toward the Master degree in the same university from 2013. His research interests include mutual coupling of array and wideband antennas.

Xiaoya Liu received the B.Eng. degree from the Northwest Polytechnical University, China in 2014. She is working toward the Master degree in the Chongqing University from 2014. Her research interests include antenna design, decoupling network and microwave circuits.



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