Compact Antenna Array with Newly Designed Decoupling Network

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Abstract **─** The design of a compact two-element antenna array with highly isolated ports is presented in this paper. The high port isolation is achieved by inserting a decoupling network between the ports of the antenna elements. The decoupling network is designed based on the method of eigen-mode analysis and is realized by the simple microstrip lines. The systematic design procedure of the decoupling network is presented. The achieved microstrip decoupling network is simple and easy to fabricate. The measured results show that the isolation between the antenna ports has been increased by more than 13 dB for a two-element monopole array with the element spacing of 0.1λ.

Index Terms **─** Compact array, decoupling network, eigen-mode analysis, microstrip line.

I. INTRODUCTION

The multiple-input multiple-output (MIMO) technology, which is considered as one of the key technologies of the next generation communication system, has been proven to be effective in improving the channel capacity and throughput. The study of MIMO antenna arrays has received tremendous attention from the researchers all over the world. When multiple antennas are implemented in a platform with limited size, the array has to be kept compact. However, the small separation between the array elements in MIMO systems causes strong mutual coupling effect, which results in severe degradation of the radiation performance [1] and diminishes the benefits of a multiple antenna system [2].

The problem of mutual coupling has attracted a lot of research interest and many contributions have been made to remove or reduce the mutual coupling effect in recent years [3-6]. Electromagnetic band-gap (EBG) structures and defected ground structures (DGS), both with the bandstop features, were proposed to suppress the mutual coupling [7-10]. However, the EBG technology requires enough periodic unit structures to be placed between the antenna elements, which may occupy much space and is not suitable for the arrays with closely spaced elements. While for the defected patterns etched on the ground plane, it may lead to strong backward radiation [11]. Another promising technique using the neutralization lines (NL) was reported to reduce the mutual coupling between two antennas [12, 13]. Although the NLs are simple and require little space, they are usually designed intuitively and must be redesigned for different antennas.

Design of a decoupling network (DN) connecting to the antenna array is another effective and systematic method to increase the isolation between the antenna ports. Decoupling networks have been achieved by connecting the simple reactive elements or a section of transmission line between the input ports and antenna ports, but with the constraint that the mutual impedances of the array must be made to be reactive [14, 15]. After that, various DNs composed of the lumped elements [16-18] were proposed to obtain high port isolation without the abovementioned constraint. However, there is a practical problem with those DNs that there may be no such commercial lumped components with the theoretically calculated values when realizing the networks.

In this paper, a decoupling network using only the microstrip lines for a compact two-element array is proposed. In Section II, the design theory of the decoupling network is explained. In Section III, the design example of a two-element monopole array is presented with the discussion of the simulated and measured results. Finally, Section IV concludes the paper.

II. DESIGN THEORY OF THE DN

The configuration structure of the proposed microstrip decoupling network for a two-element antenna array is shown in Fig. 1. A section of microstrip transmission line with the characteristic impedances of Z_1 and the electrical length of θ_1 is

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connected in serial to each port of the array. Another section of microstrip line with the characteristic impedances of Z_2 and the electrical length of θ_2 is connected in parallel between the two ports. With the addition of the three sections of microstrip lines, the two-element array can be decoupled. The values of the parameters Z_1, Z_2, θ_1 and θ_2 can be calculated by the method of eigen-mode analysis [15].

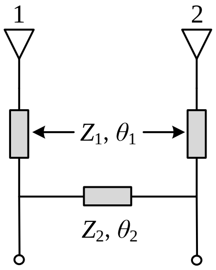


Fig. 1. Configuration structure of the decoupling network for a two-element antenna array.

The impedance matrix Z^a of an antenna array with two identical elements is given by:

$$Z^a = \begin{bmatrix} Z_{11}^a & Z_{12}^a \\ Z_{12}^a & Z_{11}^a \end{bmatrix}. \tag{1}$$

The eigenvalues of the impedance matrix are given by $Z_a = Z_{11}^a + Z_{12}^a$ and $Z_b = Z_{11}^a - Z_{12}^a$, while the corresponding orthogonal eigenvectors are $\mathbf{e}_a = [1\ ,\ 1]^T$ and $\mathbf{e}_b = [1, -1]^T$, respectively. According to the theory of eigen mode, the equivalent circuits of the DN can be analyzed as in Fig. 2.

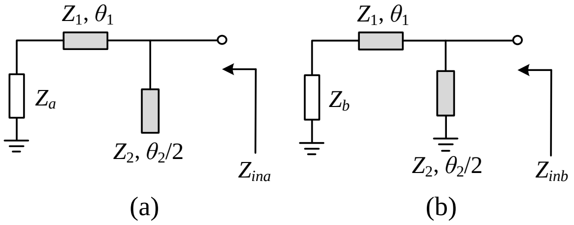


Fig. 2. Equivalent circuits of the DN for different modes: (a) odd mode; (b) even mode.

The input admittances of each mode are given by:

$$Y_{ina} = \frac{(Z_1 + jZ_a \tan\theta_1)}{Z_1(Z_a + jZ_1 \tan\theta_1)} + j\frac{\tan(\theta_2/2)}{Z_2}, \tag{2}$$

$$Y_{inb} = \frac{(Z_1 + jZ_b \tan\theta_1)}{Z_1(Z_b + jZ_1 \tan\theta_1)} - j\frac{1}{Z_2 \tan(\theta_2/2)}. \tag{3}$$

Then, the real and imaginary parts of (2) and (3) are as follows, respectively:

$$G_{ina} = \frac{\left(Z_1 - X_a \tan\theta_1\right) Z_1 R_a + R_a \tan\theta_1 \left(Z_1 X_a + Z_1^2 \tan\theta_1\right)}{\left(Z_1 R_a\right)^2 + \left(Z_1 X_a + Z_1^2 \tan\theta_1\right)^2}, \tag{4}$$

$$B_{ina} = \frac{Z_1 R_a^2 \tan\theta_1 - \left(Z_1 - X_a \tan\theta_1\right)\left(Z_1 X_a + Z_1^2 \tan\theta_1\right)}{\left(Z_1 R_a\right)^2 + \left(Z_1 X_a + Z_1^2 \tan\theta_1\right)^2} + \frac{\tan\left(\theta_2/2\right)}{Z_2}, \tag{5}$$

$$G_{inb} = \frac{\left(Z_0 - X_b \tan\theta_1\right) Z_0 R_b + R_b \tan\theta_1 \left(Z_0 X_b + Z_0^2 \tan\theta_1\right)}{\left(Z_0 R_b\right)^2 + \left(Z_0 X_b + Z_0^2 \tan\theta_1\right)^2}, \tag{6}$$

$$B_{inb} = \frac{Z_1 R_b^2 \tan\theta_1 - \left(Z_1 - X_b \tan\theta_1\right)\left(Z_1 X_b + Z_1^2 \tan\theta_1\right)}{\left(Z_1 R_b\right)^2 + \left(Z_1 X_b + Z_1^2 \tan\theta_1\right)^2} - \frac{1}{Z_2 \tan\left(\theta_2/2\right)}. \tag{7}$$

The array can be decoupled when the modal impedances/admittances are equal. Set

$$Y_{ina} = Y_{inb}, \tag{8}$$

and evaluate the real and imaginary parts, respectively, which results in two equations with four variables, that is:

$$f_1 = G_{ina} - G_{inb} = 0, \tag{9}$$

$$f_2 = B_{ina} - B_{inb} = 0. \tag{10}$$

If the characteristic impedances Z_1 and Z_2 are chosen, the functions are a group of binary nonlinear equations which can be solved by the ‘gamultiobj’ function in MATLAB. Then, the values of the electrical lengths θ_1 and θ_2 can be obtained. Finally, the decoupled ports can be matched by using the conventional L-section impedance matching networks with the system impedance of $Z_0 = 50\ \Omega$.

Theoretically speaking, the proposed decoupling procedure can be extended to the antenna arrays with more than two antenna elements. The above procedure can be used to decouple two different eigen modes at each time. Then, repeat the same procedure until all the modes are decoupled. However, if the number of array elements is large, then the resulted decoupling network will be complicated, which makes it difficult to be implemented. Therefore, the proposed decoupling network is typically applied to the arrays with four or less elements.

III. DESIGN EXAMPLE AND RESULTS

The monopole antenna is used as the array elements due to its simplicity. The DN for the two-element monopole antenna array operating at 2.4 GHz is designed to verify the proposed method.

A. Two-element monopole antenna array

As shown in Fig. 3, the length of the array element is h = 30.5 mm and the element spacing is d = 12 mm, which is about 0.1λ. It is noted that the proposed DN is applicable to the antenna arrays with different element separations. The monopole elements are mounted on a FR4 substrate, which has a thickness of t = 1.6 mm and the dielectric constant of 4.4. The top surface of the FR4 substrate is copper, which acts as the ground plane of the monopole array. The size of the substrate is $W \times L$ = 70 mm × 70 mm. The monopole elements are fed by microstrip lines with a length of l = 36.5 mm and a width of w = 3 mm. To keep the constancy and avoid the spurious radiation, both the microstrip feed lines and the subsequently designed DN are printed on the lower surface of the substrate.

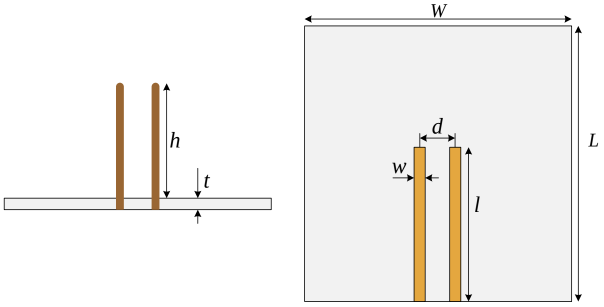


Fig. 3. The geometry of two-element monopole antenna array: (a) side view; (b) bottom view.

The designed monopole array was simulated in HFSS and Fig. 4 shows the simulated S-parameters. It can be seen that the S_{12} is as high as -8 dB at 2.4 GHz. The strong mutual coupling makes the antenna array unmatched, where the S_{11} is only -7 dB at the operating frequency. Therefore, a decoupling network is required to reduce the mutual coupling between the array elements.

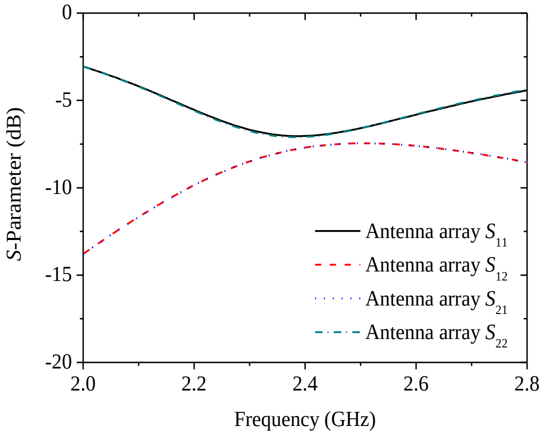


Fig. 4. The simulated S-parameters of the two-element monopole array.

B. Design of the decoupling network

The impedance parameters of the antenna array at the operating frequency can be obtained directly from HFSS or from the transformation of the **S** matrix of the array. The conventional 50 Ω microstrip line is used for all the microstrip sections of the design. The values of the electrical lengths θ_1 and θ_2 of the decoupling network are calculated by adopting a simple genetic algorithm, i.e., gamultiobj, in MATLAB. The L-section impedance matching networks are then designed to match the decoupled ports, with θ_3 being the electrical length of the series branch and θ_4 being that of the open stub.

The designed microstrip decoupling and matching network is then connected to the two-element monopole array and simulated in HFSS. After a fine tuning, the obtained values of the parameters are shown in Table 1. Figure 5 shows the simulated results of the S-parameters of the array with the decoupling and matching network. It is obvious that both of the S_{11} and S_{12} have been reduced to around -30 dB at the operating frequency of 2.4 GHz. The isolation between the antenna ports has been significantly improved by about 20 dB.

Table 1: Values of the design parameters of the microstrip decoupling and matching network

Parameter	Value
θ_1	133.3°
θ_2	148.6°
θ_3	63.2°
θ_4	72.7°

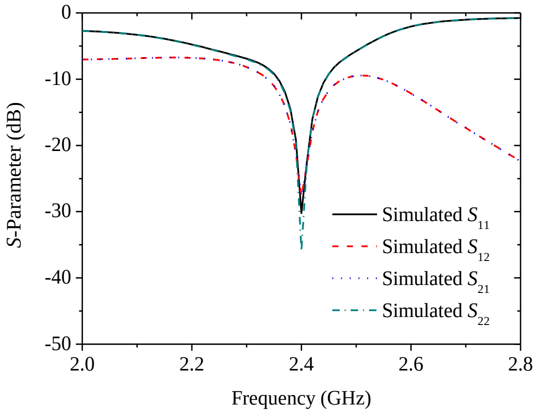


Fig. 5. The simulated S-parameter of the array with the decoupling and matching network.

The prototype of the designed monopole array with microstrip decoupling and matching network was fabricated, as shown in Fig. 6. It was measured by using a Keysight E5063A Vector Network Analyzer and the achieved results are plotted in Fig. 7. From the figure, it can be seen that the S_{12} is -21 dB and the S_{11} is around -20 dB at the center frequency, which validates the effectiveness of the decoupling method. Good agreement between the simulated and measured results was obtained.

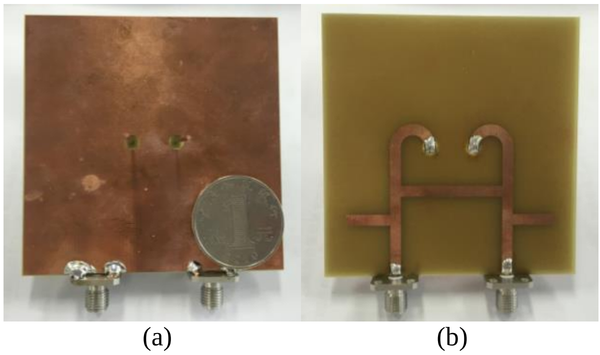

(a) (b)

Fig. 6. The fabricated monopole array with the decoupling and matching network: (a) top view; (b) bottom view.

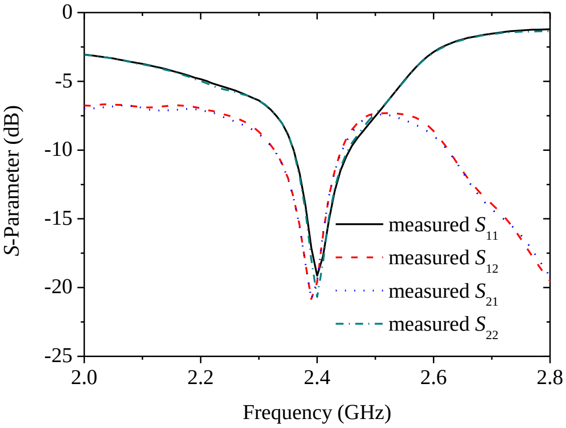
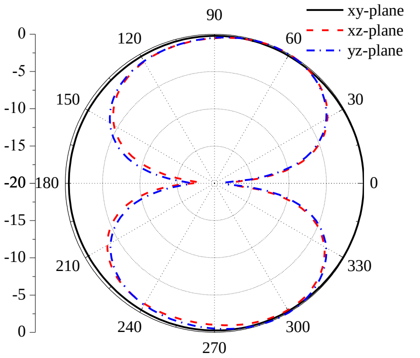


Fig. 7. The measured *S*-parameter of the array with the decoupling and matching network.

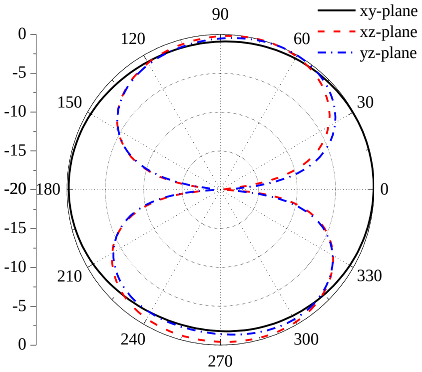
The normalized radiation patterns of both the original and decoupled arrays at the operating frequency of 2.4 GHz are illustrated in Fig. 8, respectively. With both of the elements excited, the radiation patterns remain consistent in a certain level.

IV. CONCLUSION

The systematic design procedure of the decoupling network for a two-element antenna array has been presented. The DN contains only simple microstrip lines and is easy to implement. By adopting the method of eigen-mode analysis, the design parameters of the network can be obtained. The measured results of the design example show that the port isolation of a two-element monopole array has been enhanced by more than 13 dB, which illustrates the effectiveness of the proposed decoupling network.



(a)



(b)

Fig. 8. The radiation patterns of antenna arrays at operating frequency of 2.4 GHz: (a) original array; (b) decoupled array.

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