Parasitic Elements Based Decoupling Technique for Monopole Four Square Array Antenna

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***Abstract*— An alternative approach to port decoupling for the monopole four square array antenna is proposed. In contrast to the decoupling of the monopole four square array antenna based on eigenmodes theory, port decoupling over wider frequency band is obtained by a proper choice of parasitic elements dimensions and positions for a given array elements spacing without extending the overall area. The decoupled ports of the array may then be matched by using conventional matching circuits.**

Keywords—decoupling network; eigenmodes; array elements; parasitic elements; matching circuit.

I. INTRODUCTION

Mutual coupling is a common problem in the applications of antenna arrays. It is well known that the beamforming function of a compact antenna array affected by the existence of strong mutual coupling between array elements. To compensate for strong mutual coupling, element spacing of more than half-wavelength is required. In applications where a space of less than half-wavelength is available, strong mutual coupling will distort the beam patterns [1]. Many attempts have been made to reduce or to compensate for this effect. In [2-4], decoupling networks have been suggested based on the theory of eigenmodes of the antenna array matrix. The concept of eigenmodes based decupling networks has been applied to decouple the monopole four square array ports [5]. However, these methods are only applicable to the decoupling of arrays over a small bandwidth at a single frequency. The bandwidth of decoupled narrowband antennas could be enhanced by generating multiple resonances, where each reactive element in the decoupling network is replaced with either a series or a parallel combination of an inductor and a capacitor in order to achieve decoupling at dual frequencies or wider bandwidth [6].

In [7], perfect decoupling between two arbitrary spaced antennas has been proposed using a reactively loaded parasitic antenna in between the array two active antennas. Tuning the reactive load of the parasitic element in addition to the dimensions of active and parasitic elements has provided perfect port isolation over a narrow frequency band. In this paper, the concept of parasitic decoupling elements is applied to the monopole four square array antenna to obtain good port isolation over a wider frequency band. Instead of reactively loaded parasitic element, short circuited parasitic elements are proposed. By proper choice of parasitic elements positions and dimensions in addition to the active elements dimensions, port isolation over a wider frequency range is obtained for a given array elements spacing without extending the overall area. The decoupled ports of the array could then be matched using conventional matching networks [8].

II. THEORITICAL ANALYSIS

Consider an array of two active elements and one short circuited parasitic element in between as in Fig.1. The terminal currents and voltages are related through the impedance matrix as

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z_{11} & Z_{12} & Z_{13} \\ Z_{21} & Z_{22} & Z_{23} \\ Z_{31} & Z_{32} & Z_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix} \tag{1}$$

The short circuit condition for the parasitic element implies that $V_2 = 0$, and due to reciprocity, $Z_{ij} = Z_{ji}$, where $i \neq j$, $\{i, j = 1,2,3\}$. Substituting into (1) and rearrangement, the voltages and currents of array active elements are related as

$$\begin{bmatrix} V_1 \\ V_3 \end{bmatrix} = \begin{bmatrix} Z'_{11} & Z'_{13} \\ Z'_{13} & Z'_{33} \end{bmatrix} \begin{bmatrix} I_1 \\ I_3 \end{bmatrix} \tag{2}$$

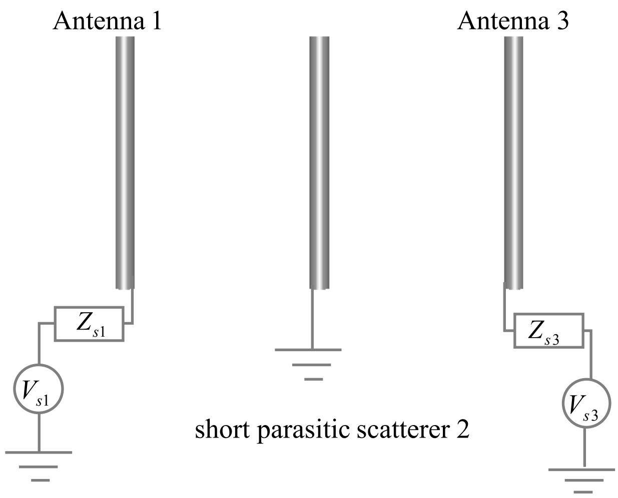


Fig. 1. Two active elements array with one short parasitic element as a shorted decoupling element.

where for identical array elements

$$Z'_{11} = Z_{11} - \frac{Z_{12}^2}{Z_{22}} = Z'_{33}$$
$$Z'_{13} = Z_{13} - \frac{Z_{12}^2}{Z_{22}} \tag{3}$$

For decoupled ports the condition $Z'_{13} = 0$ should be satisfied which implies that Z_{13} should equal to Z_{12}^2 / Z_{22}. The array active and parasitic elements in Fig.1 are quarter wavelength monopoles, so tuning the parasitic element length and diameters will compensate for the mutual coupling between array active elements. The input impedance of array decoupled ports is now mismatched to the source impedance ($50\,\Omega$) by the same factor Z_{12}^2 / Z_{22}. The decoupled ports of the array could then be matched by using conventional matching circuits.

III. Decoupling of the Monopole Four Square Array Antenna

For the Monopole Four Square Array Antenna (MFSAA) in [5], four parasitic elements are required to decouple adjacent array active elements and one parasitic element in the center to decouple non adjacent array active elements as Fig.2 shows. For nonadjacent array active elements, the length and diameter of the parasitic element in the center of the array are optimized to compensate for mutual coupling between non adjacent array active elements, while for adjacent array active elements the length, diameter, and position of parasitic elements at distance d from the center are optimized to get isolated ports. The position of the four parasitic elements is optimized by adjusting the distance d from the center which is the radius of the circle where the four parasitic elements are placed. Due to the symmetry of the MFSAA, the four parasitic elements placed between adjacent array elements at distance d from the center should have the same length.

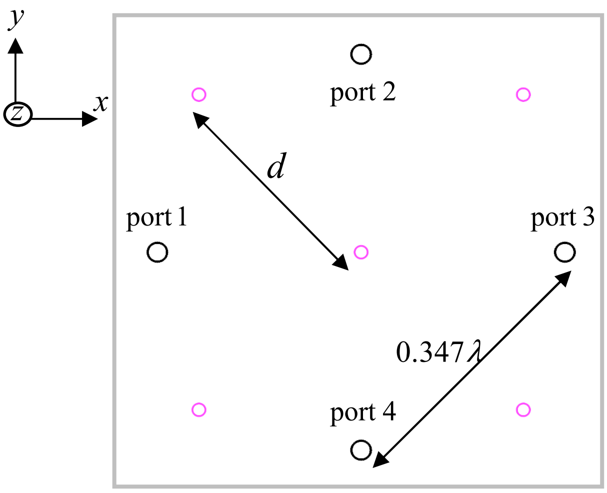


Fig. 2. Monopole four square array with five short parasitic elements (pink) to decouple array active elements (black). The monopoles are quarter wavelength at $2.45\,\text{GHz}$.

The length and position of parasitic elements placed between adjacent array active elements, the length of the parasitic element at the center for nonadjacent array active elements, the diameter of the array parasitic elements in addition to the array active elements length for given separation distance of 0.347λ between adjacent array active elements for the purpose of beam steering with high front to back ratio for WLAN applications are all optimized with Empire XCcel for good port isolation. The optimization goal is defined such that isolation of more than 20 dB between array ports at 2.45 GHz is obtained. Port isolation of more than $30\,\text{dB}$ as shown in Fig.3 is obtained for array active elements length of 0.2λ, parasitic elements lengths of 0.253λ and 0.286λ between adjacent and nonadjacent array active elements respectively, and $d = 0.22\lambda$. The diameters of array active and parasitic elements are chosen to be 0.025λ and 0.016λ respectively. The decoupled ports are mismatched to the $50\,\Omega$ as seen in Fig. 3. A matching network of an open circuit stub is designed; the stub length and position from the feed point are optimized for good return loss at $2.45\,\text{GHz}$. For comparison, Fig.4 and Fig.5 show the MFSAA scattering parameters with and without parasitic decoupling elements and matching circuit. The scattering parameters (S_{12} and S_{13}) represent the coupling between adjacent and nonadjacent array active elements respectively. Azimuth and elevation patterns for the MFSAA with and without parasitic decoupling elements are shown in Fig.6.

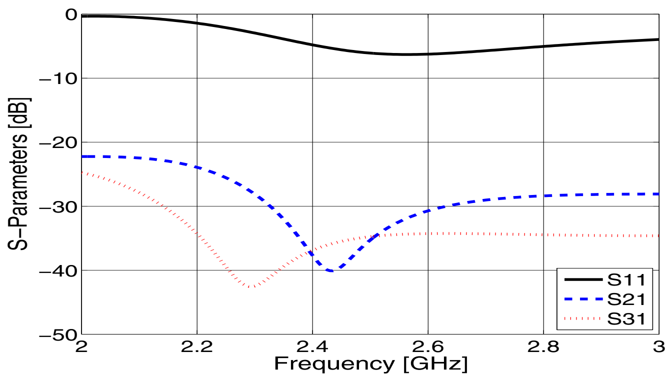


Fig. 3. Simulated S-parameters of the MFSAA with parasitic decoupling elements.

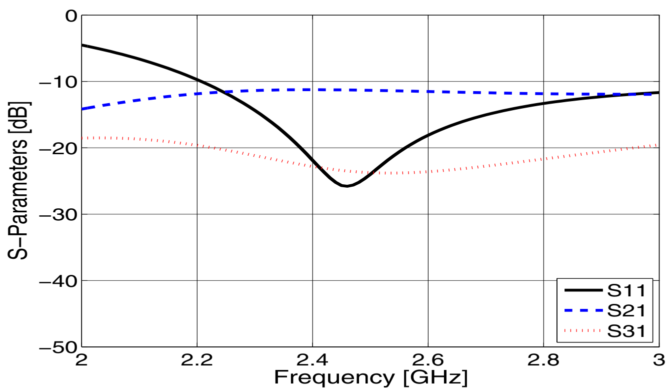


Fig. 4. Simulated S-Parameters of the MFSAA without parasitic decoupling elements and matching circuit.

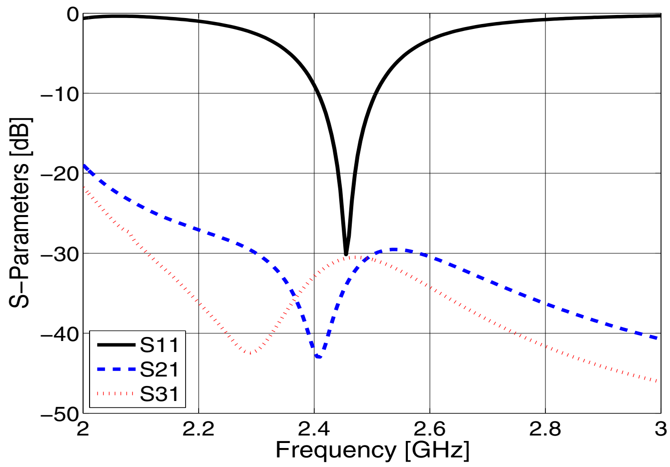
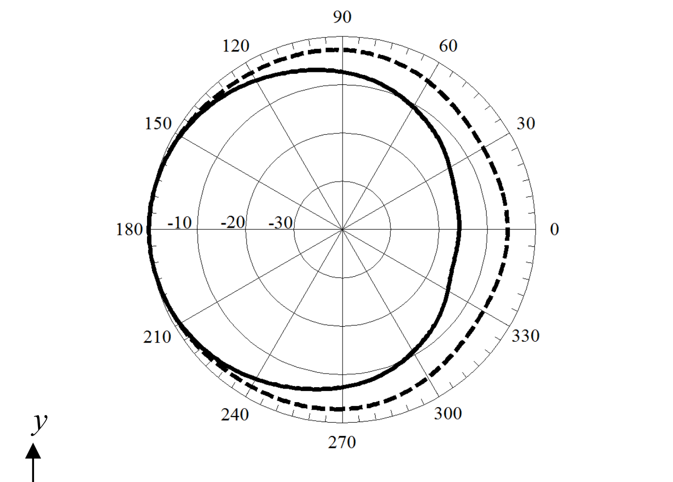
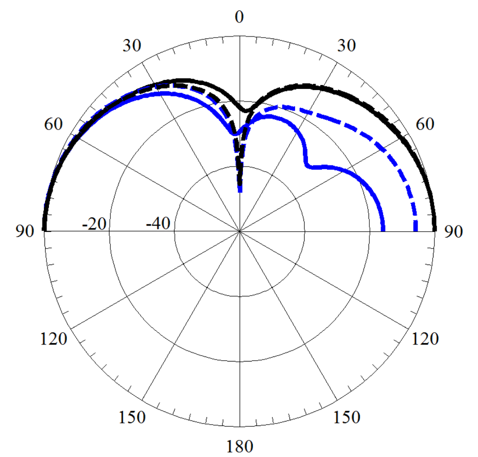


Fig. 5. Simulated S-Parameters of the MFSAA with Parasitic decoupling elements and matching circuit.



(a)



(b)

Fig. 6. MFSAA radiation pattern with (solid) and without (dashed) parasitic decoupling elements and matching circuit. (a) Azimuth pattern and (b) elevation pattern at phi $= 0^\circ$ (blue) and at phi $= 90^\circ$ (black).

When port1 is fed with all other ports matched terminated, the "active" element pattern shows distinct directive radiation in the azimuth plane due to the superposition of radiation from the active element and mainly the parasitic elements (the terminated elements do not radiate, if perfectly decoupled). This pattern distortion is seen to be 10 dB stronger than in the case of the MFSAA without decoupling of ports which is due to the close coupling and consequent high radiating currents of the parasitic elements. If port 2, 3, or 4 is excited, the radiation pattern is rotated in step of 90°. In the elevation plane, the null at $\theta = 0^\circ$ is seen to be partially filled due to the spurious radiation from the microstrip line matching circuit, while radiation contributions of the parasitic elements combine with the active element radiation to create a dip at $\theta = 45^\circ$ for phi $= 0^\circ$ plane.

IV. EXPEREMENTAL RESULTS

The parasitic decoupling elements and matching circuit for the MFSAA are fabricated on a ground plane surface of $90\,\text{mm} \times 90\,\text{mm}$ ($0.735\lambda \times 0.735\lambda$), and it is made from RO4003 substrate of thickness $0.813\,\text{mm}$, dielectric constant $\varepsilon_r = 3.38$, and loss tangent 0.0027. The array active elements are made from copper wires of 0.025λ in diameter, while the array parasitic elements are made from copper wires of 0.016λ in diameter. The decoupled ports are matched to $50\,\Omega$ with an open circuit stub of length 0.23λ and width 0.01λ. The stub is placed at distance 0.1λ from the feeding point. The fabricated whole structure of the MFSAA with parasitic decoupling elements and matching circuit is shown in Fig.7. The whole structure is placed on a large ground plane to provide an infinite ground. Measured scattering parameters in Fig.8 give an isolation of more than $20\,\text{dB}$ for a wide frequency range between $2\,\text{GHz}$ and $3\,\text{GHz}$, good agreement between measured and simulated scattering parameters is achieved. The scattering parameters (S_{12} and S_{13}) represent coupling between adjacent and nonadjacent array active elements respectively.

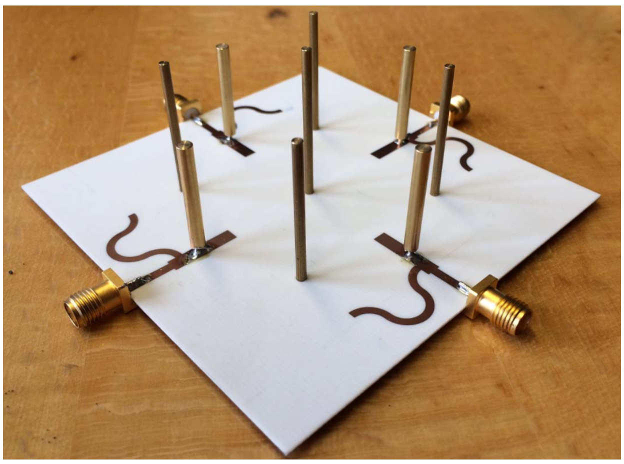


Fig. 7. Monopole four square array with parasitic decoupling elements and matching circuit.

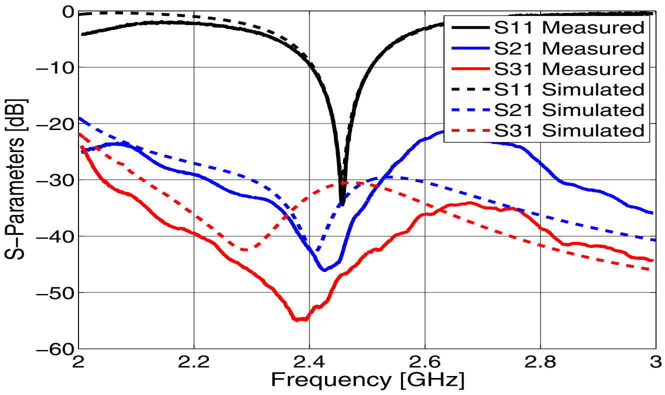


Fig. 8. Measured and simulated S-Parameters of the MFSAA with parasitic decoupling elements and matcing circuit.

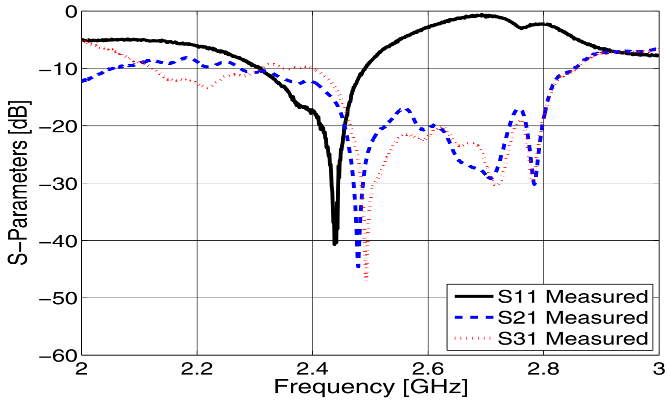


Fig. 9. Measured S-Parameters of the MFSAA with eigenmodes-based decoupling network and matcing circuit.

The calculated radiation efficiency is 93% for the MFSAA with parasitic decoupling elements and matching circuit compared to 84% for the MFSAA without parasitic decoupling elements and matching circuit.

For comparison, in [5] a decoupling matching network based on eigenmodes analysis was derived and fabricated to decouple the MFSAA. The measured scattering parameters in Fig.9 for eigenmodes based decoupling network show port isolation of more than $30\ \mathrm{dB}$ at single frequency of $2.48\ \mathrm{GHz}$. In eigenmodes based decoupling networks; the eigenmodes admittances of the array admittance matrix are matched to the same input impedance using shunt and series lumped elements. In addition, in practice, there may be no such commercial components with the calculated values when implementing the network. Usually the reactive elements have to be realized to microsrtip lines. Although the lines can be meandered the overall size of the decoupling and matching network is large. Microstrip line realization of the decoupling networks limits the freedom of optimizing for wider frequency band; therefore narrow frequency band is obtained for decoupling the MFSAA with eigenmodes based decoupling network compared to the parasitic decoupling elements.

V. CONCLUSION

In this paper, a parasitic elements based decoupling network is designed and fabricated to decouple the MFSAA. Measured scattering parameters are in good agreement with the simulated ones. A comparison with eigenmodes based decoupling network shows a narrow frequency band compared to that obtained from the parasitic based decoupling network. The narrow band of the eigenmodes based decoupling network could be enhanced by generating multiple resonances, where each reactive element in the decoupling network is replaced with either a series or parallel combination of an inductor and a capacitor in order to achieve decoupling at wider bandwidth, but on the other hand, the overall size of the array area will be increased.

One important application of decoupling matching techniques in addition to the maximum power transfer from the antennas to the loads, is for multiple input multiple output systems (MIMO); where suppression of mutual coupling between array elements of MFSAA using parasitic elements realizes an independent channel of operation for MIMO with isolation of more than $30\ \mathrm{dB}$ between array ports of 0.347λ separation. An enhancement of more than $10\ \mathrm{dB}$ is achieved compared to the conventional MIMO systems which shows an isolation of about $20\ \mathrm{dB}$ for half wavelength separation between array elements [9].

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