Port Decoupling for Small Arrays by Means of an Eigenmode Feed Network

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***Abstract*—An alternative approach to port decoupling and matching of arrays with tightly coupled elements is proposed. The method is based on the inherent decoupling effect obtained by feeding the orthogonal eigenmodes of the array. For this purpose, a modal feed network is connected to the array. The decoupled external ports of the feed network may then be matched independently by using conventional matching circuits. Such a system may be used in digital beam forming applications with good signal-to-noise performance. The theory is applicable to arrays with an arbitrary number of elements, but implementation is only practical for smaller arrays. The principle is illustrated by means of two examples.**

***Index Terms*—antenna arrays, antenna array feeds, adaptive arrays, mutual coupling**

I. Introduction

DIGITAL beam forming can be used to adaptively shape the radiation pattern of an array to maximize the gain in a pre-specified direction of incidence (beam forming) or to spatially reject interference (adaptive nulling). Mutual coupling between the antenna elements leads to system performance degradation. It causes a reduction in the signal-to-noise ratio (SNR) [1, 2] and a decrease in the eigenvalues of the covariance matrix of the signal, which controls the response time of an adaptive array [1]. The effects of mutual coupling become more severe when the inter-element spacing is reduced beyond half a wavelength. In many applications, the available volume restricts the physical size of the antennas. For maximum versatility, the number of elements in an adaptive array needs to be as large as possible. On the other hand, the increased mutual coupling associated with a decrease in element spacing limits the frequency bandwidth and increases the sensitivity to dissipative losses. The required bandwidth and radiation efficiency dictates the maximum number of array elements for a given platform size. It nevertheless remains vital that mutual coupling be taken into consideration during the design of arrays, especially in cases of reduced inter-element spacing.

In shaped beam antennas, modification of the excitation vector can compensate for mutual coupling [3]. Signal processing techniques may be applied to the received signal vectors from adaptive arrays in digital beam forming and direction finding applications to counter the effects of mutual coupling [4 – 7]. The SNR of receiver or transmitter channels can only be optimized through proper matching of the port impedances of the array for arbitrary element excitations. Due to mutual coupling, port impedances vary for different element excitations. SNR degradation resulting from impedance mismatches cannot be compensated for through signal processing, but can be overcome via the implementation of a RF decoupling network (DN) [8, 9]. Decoupling networks have been implemented by connecting simple reactive elements between the input ports and antenna ports, but this is only applicable in special cases where the off-diagonal elements of the admittance matrix are all purely imaginary [8]-[10]. The design of decoupling networks for 3-element [11] and 4-element [12] arrays with arbitrary complex mutual admittances was described. The DNs described in [11, 12] are symmetrical networks. Network elements were obtained by either applying an eigenmode analysis or a complete network analysis of the DN/array combination.

In this paper, we propose an alternative approach to achieve port decoupling. It involves a modal feed network which makes use of the orthogonality of the eigenmodes of the array to achieve decoupling. The input ports to the feed network and array combination can then be matched independently. In digital beam forming applications, the required element weights are obtained as a linear combination of the orthogonal eigenmode vectors.

II. Theory and Design of Modal Feed Network

A. S-parameters of feed network and array combination

Consider an (M+N)-port passive feed network connected to an N-element array, as shown in Fig. 1. We denote the first M ports as the external ports and the remaining N ports as the internal ports, which are connected to the array. Assume that the array can be modeled as an N-port network with scattering parameter matrix $\mathbf{S^a}$. The S-parameters of the combination of the feed network and the array can then be obtained by following using the multiport connection method [13]. The scattering parameter relation $\mathbf{b} = \mathbf{Sa}$ for the feed network can be separated into two groups; the first corresponding to the M

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external ports (denoted by **e**) and the second corresponding to the N internally connected ports (denoted by **i**):

$$\begin{bmatrix}\mathbf{b_e}\\ \mathbf{b_i}\end{bmatrix} = \begin{bmatrix}\mathbf{S_{ee}} & \mathbf{S_{ei}}\\ \mathbf{S_{ie}} & \mathbf{S_{ii}}\end{bmatrix}\begin{bmatrix}\mathbf{a_e}\\ \mathbf{a_i}\end{bmatrix}. \quad (1)$$

$\mathbf{S_{ee}}$, $\mathbf{S_{ei}} = \mathbf{S_{ie}}^T$ and $\mathbf{S_{ii}}$ are $M \times M$, $M \times N$ and $N \times N$ sub-matrices, while $\mathbf{a_e}, \mathbf{b_e}$ and $\mathbf{a_i}, \mathbf{b_i}$ are column vectors of dimension M and N respectively. Since the internal ports are connected directly to the array, we have that

$$\mathbf{a_i} = \mathbf{S^a}\,\mathbf{b_i}\,. \quad (2)$$

Combining (2) and the second relation of (1) yields

$$(\mathbf{S^a})^{-1}\mathbf{a_i} = \mathbf{S_{ie}}\mathbf{a_e} + \mathbf{S_{ii}}\mathbf{a_i}\,, \quad (3)$$

so that

$$\mathbf{a_i} = [(\mathbf{S^a})^{-1} - \mathbf{S_{ii}}]^{-1}\mathbf{S_{ie}}\mathbf{a_e}\,. \quad (4)$$

Substituting (4) into the first relation of (1) gives

$$\mathbf{b_e} = \left\{\mathbf{S_{ee}} + \mathbf{S_{ei}}[(\mathbf{S^a})^{-1} - \mathbf{S_{ii}}]^{-1}\mathbf{S_{ie}}\right\}\mathbf{a_e} = \mathbf{S^c}\,\mathbf{a_e}\,, \quad (5)$$

where $\mathbf{S^c}$ is the $M \times M$ scattering parameter matrix of the feed network and array combination.

B. Ideal modal feed network

Now consider a so-called modal feed network with $2N$ ports. The modal feed network has N external ports and the remaining N internal ports are connected to an N-port array of uniformly spaced, identical elements. The feed network produces the nth eigenvector of $\mathbf{S^a}$ at the internal ports in response to an input signal at external port n.

An ideal modal feed network will have the following characteristics:

$$\mathbf{S_{ee}} = \mathbf{S_{ii}} = \mathbf{0}\,, \quad (6)$$

$$\mathbf{S_{ie}} = [\mathbf{e}_1 \ \ \mathbf{e}_2 \ \ \ldots \ \ \mathbf{e}_N]\,, \quad (7)$$

$$\mathbf{S_{ei}} = \mathbf{S_{ie}}^T = \mathbf{S_{ie}}^{-1}\,, \quad (8)$$

where column vector $\mathbf{e}_m$ is the mth orthonormal eigenvector of the array scattering parameter matrix $\mathbf{S^a}$. Note that $\mathbf{S_{ie}}$ is the orthogonal matrix which diagonalizes $\mathbf{S^a}$.

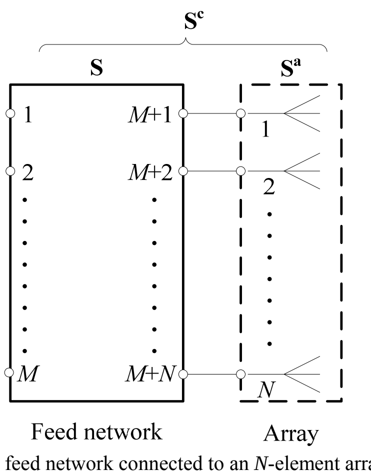

Fig. 1. (M+N)-port feed network connected to an N-element array.

The S-parameters of combined feed network and array are obtained by substituting (6), (7) and (8) into (5) to obtain

$$\begin{aligned}\mathbf{S^c} &= \mathbf{0} + \mathbf{S_{ei}}[(\mathbf{S^a})^{-1} - \mathbf{0}]^{-1}\mathbf{S_{ie}}\\ &= \mathbf{S_{ie}}^{-1}\,\mathbf{S^a}\,\mathbf{S_{ie}}\\ &= \mathrm{diag}[\lambda_1, \lambda_2, \ldots \lambda_N]\,,\end{aligned} \quad (9)$$

where λ_m is the mth eigenvalue of $\mathbf{S^a}$. The input ports of the combined network are therefore decoupled ($\mathbf{S}_{ij}^{\mathbf{c}} = 0$, $i \neq j$) but mismatched ($\mathbf{S}_{ii}^{\mathbf{c}} \neq 0$). They can be matched individually by introducing appropriate matching networks.

For a desired element excitation $\mathbf{y} = [y_1, y_2, \ldots y_N]^T$, the signals required at the external ports of the modal feed network, $\mathbf{x} = [x_1, x_2, \ldots x_N]^T$, are obtained from

$$\mathbf{x} = \mathbf{S_{ie}}^{-1}\,\mathbf{y} = \mathbf{S_{ei}}\,\mathbf{y}\,. \quad (10)$$

C. Practical modal feed network

It is often more practical to implement a modal feed network which produces orthogonal output vectors, but with an additional phase shift ϕ_m associated with mode m. We still assume that $\mathbf{S_{ee}} \approx \mathbf{0}$ and $\mathbf{S_{ii}} \approx \mathbf{0}$, but here we have

$$\mathbf{S_{ie}} = \mathbf{P}\boldsymbol{\Phi}\,, \quad (11)$$

$$\mathbf{S_{ei}} = \mathbf{S_{ie}}^T = \boldsymbol{\Phi}\,\mathbf{P}^{-1}, \quad (12)$$

where

$$\boldsymbol{\Phi} = \mathrm{diag}[e^{j\phi_1}, e^{j\phi_2}, \ldots e^{j\phi_N}]\,, \quad (13)$$

and

$$\mathbf{P} = [\mathbf{e}_1 \ \ \mathbf{e}_2 \ \ \ldots \ \ \mathbf{e}_N]\,. \quad (14)$$

The S-parameters of the N-port network resulting from connecting the modal feed network to the array are then given by

$$\begin{aligned}\mathbf{S^c} &= \mathbf{S_{ei}}\,\mathbf{S^a}\,\mathbf{S_{ie}}\\ &= \boldsymbol{\Phi}\,\mathbf{P}^{-1}\,\mathbf{S^a}\,\mathbf{P}\,\boldsymbol{\Phi}\\ &= \mathrm{diag}[\lambda_1 e^{j2\phi_1}, \lambda_2 e^{j2\phi_2}, \ldots \lambda_N e^{j2\phi_N}]\,.\end{aligned} \quad (15)$$

The signals required at the external ports of the modal feed network are related to the desired element excitations via

$$\mathbf{x} = \mathbf{S_{ie}}^{-1}\,\mathbf{y} = \boldsymbol{\Phi}^*\,\mathbf{P}^T\,\mathbf{y}\,, \quad (16)$$

with $\boldsymbol{\Phi}^*$ being the conjugate of matrix $\boldsymbol{\Phi}$.

III. Results and Discussion

To illustrate the principle, two practical examples are examined: a 2-element linear array and a 2×2 planar array. In both cases, the array elements are monopoles consisting of brass rods mounted on a 62 mil FR4 (ε_r = 4.4) substrate. The upper metallization of the substrate acts as the ground plane, as shown in Fig. 2. The elements are excited via microstrip lines etched on the bottom surface of the substrate.

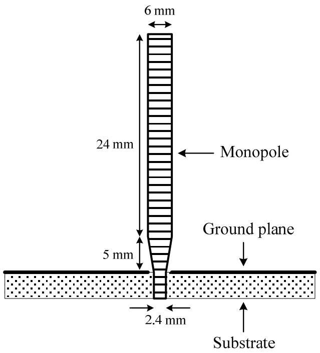

Fig. 2. Monopole array element used in the construction of prototype arrays.

A. 2-element dipole array

The S-parameters of an array with two identical elements are given by

$$\mathbf{S^a} = \begin{bmatrix} S_{11}^a & S_{12}^a \\ S_{12}^a & S_{11}^a \end{bmatrix}. \quad (17)$$

The eigenvalues of $\mathbf{S^a}$ are $\lambda_1 = S_{11}^a + S_{12}^a$ and $\lambda_2 = S_{11}^a - S_{12}^a$, while the orthonormal eigenvectors are given by

$$\mathbf{e}_1 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ 1 \end{bmatrix} \quad , \quad \mathbf{e}_2 = \frac{1}{\sqrt{2}}\begin{bmatrix} 1 \\ -1 \end{bmatrix}. \quad (18)$$

The modal feed network for such an array may be implemented as a rat-race 180º hybrid. With port numbering as defined in Fig. 3, the S-parameters of the hybrid are given by

$$\mathbf{S} = \frac{-j}{\sqrt{2}}\begin{bmatrix} 0 & 0 & 1 & 1 \\ 0 & 0 & 1 & -1 \\ 1 & 1 & 0 & 0 \\ 1 & -1 & 0 & 0 \end{bmatrix}. \quad (19)$$

In this case, we find that $\phi_1 = \phi_2 = -90°$. The S-parameters of the 2-port network resulting from connecting the hybrid to the array are obtained from (15) as

$$\mathbf{S^d} = \begin{bmatrix} -S_{11}^a - S_{12}^a & 0 \\ 0 & S_{12}^a - S_{11}^a \end{bmatrix}. \quad (20)$$

The combined network may then be matched by providing suitable matching circuits at ports 1 and 2.

A prototype monopole array with an element spacing of 0.1λ was fabricated, as shown in Fig. 4. The monopole length was chosen to provide an impedance match ($S_{11}^a \approx 0$) at a frequency of 2.6 GHz.

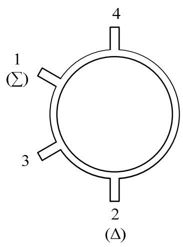

Fig. 3. Port numbering for a rat-race 180º hybrid coupler which acts as modal feed network for the 2-element array.

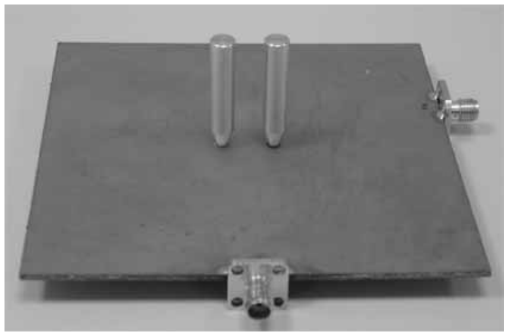

Fig. 4. 2-element monopole array mounted on a substrate. The upper metallization of the substrate acts as the ground plane.

The scattering parameters of the array were measured using an Agilent Technologies 8510C Network Analyzer. The measured scattering parameters of the array are shown in Fig. 5. The reflection coefficient is small, but a high level of mutual coupling of approximately −5 dB at 2.6 GHz is observed.

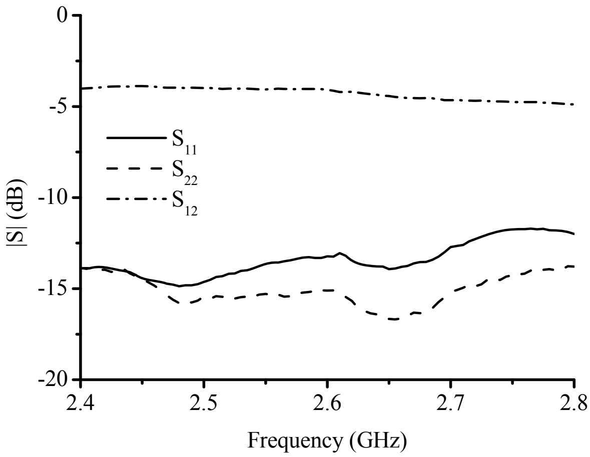

Fig. 5. Measured scattering parameters of the 2-element monopole array. The elements are reasonably well matched, but due to the small spacing, the mutual coupling is high.

The modal feed network shown in Fig. 6 (but without the matching stubs) was realized on the lower surface of the substrate and connected to the array. The S-parameters were again measured and the results are shown in Fig. 7. The two ports are no longer matched, but according to (20), this is to be expected. However, the two ports are isolated, with the mutual coupling being less than –20 dB across the frequency band.

Finally, the external ports were matched by introducing stubs at ports 1 and 2, as depicted in Fig. 6. Theoretically, this should be a straightforward task of calculating stub lengths and positions to match the impedances corresponding to the port reflection coefficients in (20). It should however be noted that the currents induced on the array elements for a specific mode are strictly not a direct superposition of the currents for single element excitation. This causes some impedance variations, and therefore some tuning was required to obtain the measured results shown in Fig. 8. Decoupling and matching are achieved simultaneously, albeit over a narrow frequency band.

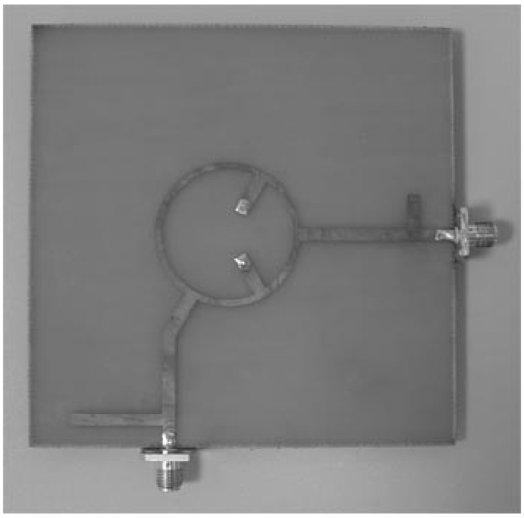

Fig. 6. Modal feed network, implemented as a rat-race hybrid on the lower surface of the substrate.

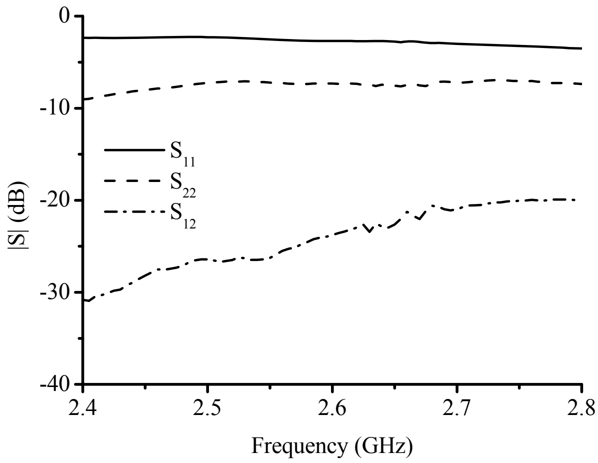

Fig. 7. Measured scattering parameters of the hybrid coupler connected to the 2-element monopole array. The external ports of the modal feed network are decoupled but not matched.

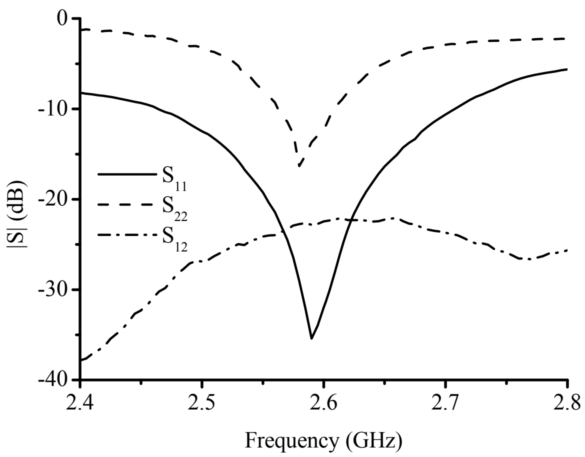

Fig. 8. Measured scattering parameters of the 2-element monopole array with matching networks at the external ports of the modal feed network. The ports are both decoupled and matched.

Measured and simulated modal radiation patterns of this array are shown in Fig. 9 and Fig. 10. The patterns were measured in an anechoic chamber. The antenna was fed at one of the two input ports of the modal feed network, while the remaining input port was terminated in a matched load. The simulations were performed using the commercial software package IE3D [14]. The simulation model included the effect of the feed network, but an infinite groundplane was assumed for pattern calculations.

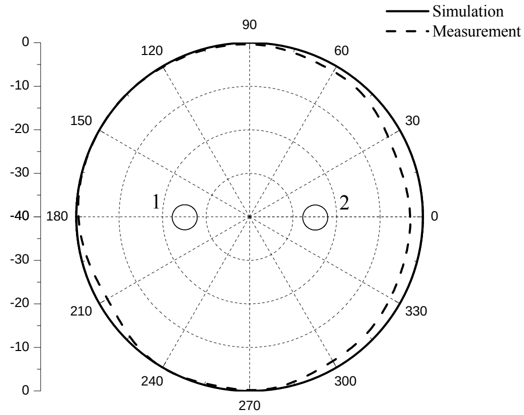

Fig. 9. Simulated and measured radiation patterns for mode 1 of the 2-element monopole array.

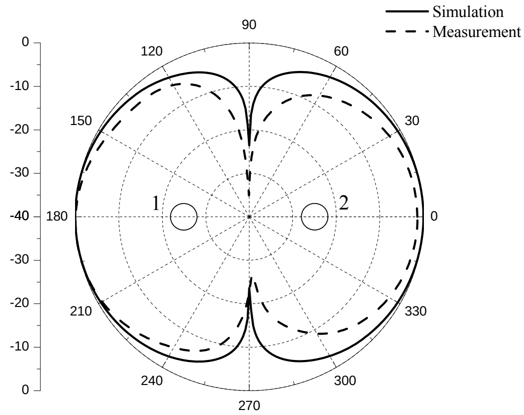

Fig. 10. Simulated and measured radiation patterns for mode 2 of the 2-element monopole array.

B. 2×2 element dipole array

A symmetrical 2×2 array has the following S-parameters:

$$\mathbf{S^a} = \begin{bmatrix} S_{11}^a & S_{12}^a & S_{13}^a & S_{14}^a \\ S_{12}^a & S_{11}^a & S_{14}^a & S_{13}^a \\ S_{13}^a & S_{14}^a & S_{11}^a & S_{12}^a \\ S_{14}^a & S_{13}^a & S_{12}^a & S_{11}^a \end{bmatrix}. \qquad (21)$$

The eigenvalues of $\mathbf{S^a}$ are given by $\lambda_1 = S_{11}^a + S_{12}^a + S_{13}^a + S_{14}^a$, $\lambda_2 = S_{11}^a + S_{12}^a - S_{13}^a - S_{14}^a$, $\lambda_3 = S_{11}^a - S_{12}^a - S_{13}^a + S_{14}^a$ and

$\lambda_4 = S_{11}^a - S_{12}^a + S_{13}^a - S_{14}^a$, while the orthonormal eigenvectors are

$$\mathbf{e}_1 = \tfrac{1}{2}\begin{bmatrix}1\\1\\1\\1\end{bmatrix},\ \mathbf{e}_2 = \tfrac{1}{2}\begin{bmatrix}1\\1\\-1\\-1\end{bmatrix},\ \mathbf{e}_3 = \tfrac{1}{2}\begin{bmatrix}1\\-1\\-1\\1\end{bmatrix},\ \mathbf{e}_4 = \tfrac{1}{2}\begin{bmatrix}1\\-1\\1\\-1\end{bmatrix}. \quad (22)$$

An 8-port modal feed network can be implemented by using 90º hybrid couplers, as shown in Fig. 11. The scattering parameters of this network are defined by $\mathbf{S_{ee}} = \mathbf{S_{ii}} = \mathbf{0}$ and

$$\mathbf{S_{ie}} = \mathbf{S_{ei}}^T = \tfrac{1}{2}\begin{bmatrix} e^{-j\theta} & e^{j(\pi/2-\theta)} & e^{j(\pi-\theta)} & e^{j(\pi/2-\theta)} \\ e^{-j\theta} & e^{j(\pi/2-\theta)} & e^{-j\theta} & e^{j(-\pi/2-\theta)} \\ e^{-j\theta} & e^{j(-\pi/2-\theta)} & e^{-j\theta} & e^{j(\pi/2-\theta)} \\ e^{-j\theta} & e^{j(-\pi/2-\theta)} & e^{j(\pi-\theta)} & e^{j(-\pi/2-\theta)} \end{bmatrix}. \quad (23)$$

The phase terms in (13) are therefore $\phi_1 = -\theta$, $\phi_2 = \phi_4 = \pi/2 - \theta$ and $\phi_3 = \pi - \theta$. The S-parameters of a combination of this feed network and the 2×2 array are obtained from (15) as

$$\begin{aligned}\mathbf{S^d} = \mathrm{diag}\Big[& (S_{11}^a + S_{12}^a + S_{13}^a + S_{14}^a)e^{-j2\theta}, \\ & (-S_{11}^a - S_{12}^a + S_{13}^a + S_{14}^a)e^{-j2\theta}, \\ & (S_{11}^a - S_{12}^a - S_{13}^a + S_{14}^a)e^{-j2\theta}, \\ & (-S_{11}^a + S_{12}^a - S_{13}^a + S_{14}^a)e^{-j2\theta} \Big] .\end{aligned} \quad (24)$$

The external ports of the feed network can again be matched with the addition of conventional matching circuits.

The 2×2 monopole array shown in Fig. 12 was fabricated. The inter-element spacing was arbitrarily chosen as 20 mm (approximately 0.17λ). The measured S-parameters of the array are shown in Fig. 13. Strong mutual coupling is observed.

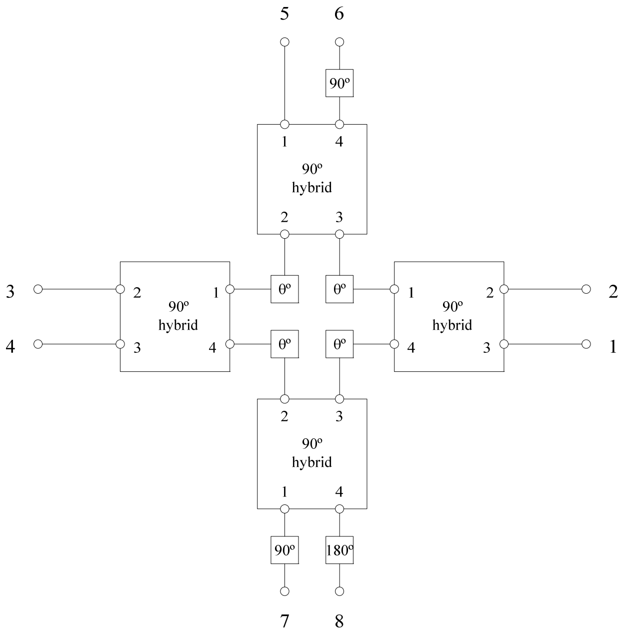

Fig. 11. 8-port modal feed network for the 2×2 element array.

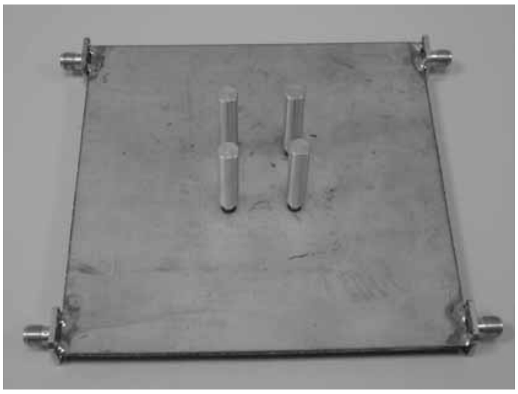

Fig. 12. 2×2 element monopole array with inter-element spacing of 20 mm.

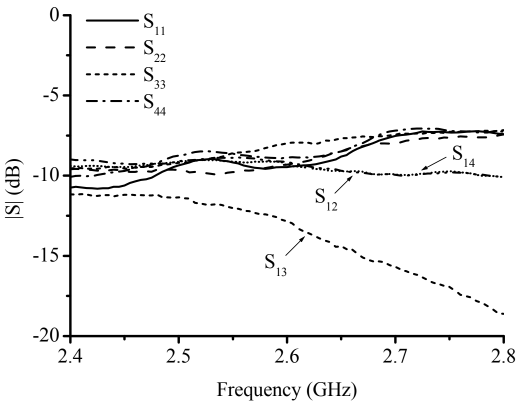

Fig. 13. Measured scattering parameters of the 2×2 array. The array ports are neither decoupled nor matched.

The modal feed network shown in Fig. 14 (without the matching stubs) was realized using −3dB 90º branchline couplers. It was implemented on the lower surface of the substrate and connected to the array. The measured S-parameters are shown in Fig. 15. The ports are not matched, but the introduction of the modal feed network has the effect of decoupling the ports.

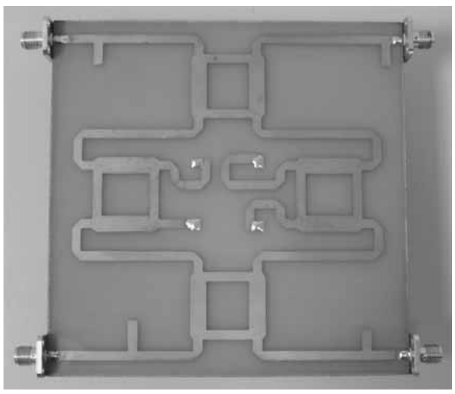

Fig. 14. 8-port modal feed network consisting of four −3 dB 90º branchline couplers.

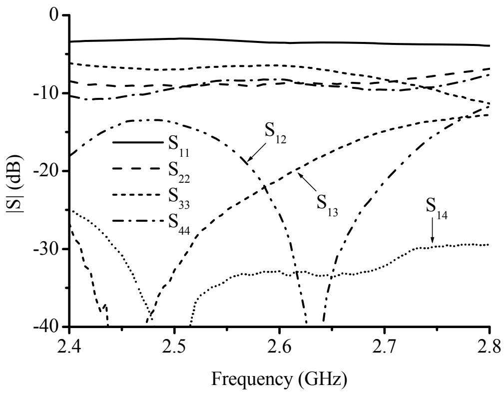

Fig. 15. Measured scattering parameters of the modal feed network connected to the 2×2 array. The external ports of the combined network are decoupled.

With the addition of stub matching networks at ports 1 to 4, decoupling and matching are achieved simultaneously. The measured S-parameters are shown in Fig. 16. Some tuning was again required in order to achieve resonance at a fixed frequency for each of the four eigenmodes.

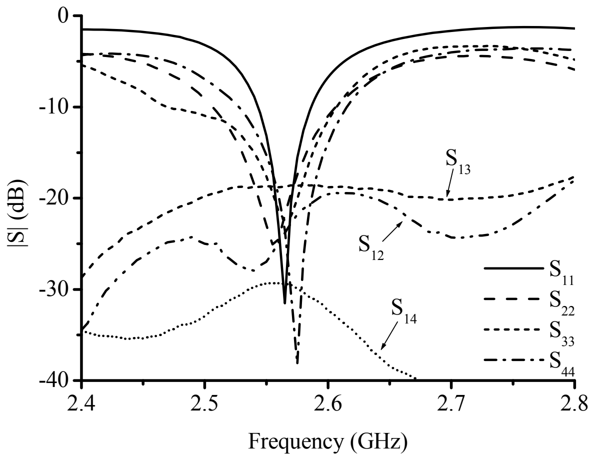

Fig. 16. Measured scattering parameters of the 2×2 array with matched external ports of the modal feed network.

The radiation patterns of the four modes were computed using IE3D [14], and the results are shown in Figs. 17 and 18. The modal feed network in Fig. 14 was included in the simulation model for the calculation of the currents on the antenna elements and the respective radiation patterns. The eigenpatterns are mutually orthogonal according to the definition provided in [9]. An arbitrary pattern within the 4-dimensional space of radiation patterns available from the original array can be obtained from a weighted linear combination of the modal patterns [9].

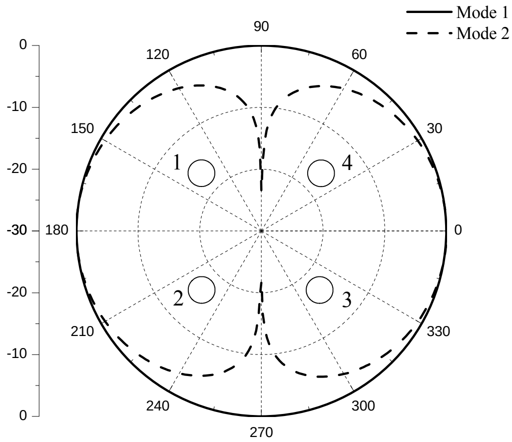

Fig. 17. Simulated radiation patterns (normalized) of the 2×2 array for eigenmodes 1 and 2.

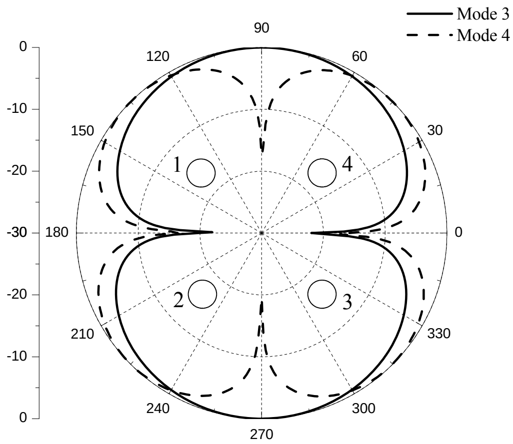

Fig. 18. Simulated radiation patterns (normalized) of the 2×2 array for eigenmodes 3 and 4.

IV. CONCLUSION

The introduction of a modal feed network ensures isolation between the input ports of the system, which can then be matched independently. The frequency bandwidth of such a system is limited by the level of mutual coupling in the original array [8], but also depends on the extent of the impedance mismatch observed at the external ports of the modal feed network. In order to minimize the mismatch, it is desirable to start off with an array with matched elements, i.e. $\left|S_{11}^{a}\right|$ should be as small as possible.

Theoretically, the alternative approach to port decoupling and matching presented in this paper is applicable to arrays with an arbitrary number of uniformly-spaced, identical elements. However, the complexity involved in the implementation of the modal feed network may limit application of this method to smaller arrays.

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