A MATCHING ALGORITHM FOR 4-ELEMENT CIRCULAR ANTENNA ARRAYS BASED ON THE EVEN-AND-ODD MODE (EOM) ANALYSIS SCHEME

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ABSTRACT

An efficient and a practical way for optimally matching of 4-element circular antenna arrays is presented. The Even-and-Odd mode (EOM) analysis scheme is applied to interpret the physics beyond the coupling mechanisms of the antenna elements and also to reduce the size of the geometry to a quarter of the original geometry. A matching algorithm based on EOM analysis scheme is presented. A numerical example that validates the accuracy of the matching method is demonstrated.

INTRODUCTION

Matching of antenna arrays has always been a difficult task due to unavoidable electromagnetic coupling between the antenna elements. When a matching network is applied to the array, the radiation impedances of the elements also change due to undesired coupling; thus, the applied matching network does not work. It is a common practice to employ an iterative design-and-build (or design-and-simulate) type of matching algorithm to circumvent this problem. However, this type of method may take days to complete the design, since it requires lots of prototypes to be built or lots of computer simulations to be run. In this work, we propose a fast algorithm based on the well-known Even and Odd Mode (EOM) analysis technique to match 4-element circular antenna arrays [1].

THE EOM REPRESENTATION OF THE PROBLEM

It is possible to make use of the symmetries in the geometry by employing the EOM analysis to end up with four 1-element sub-geometries. Using Perfect Magnetic Conductor (PMC) or Perfect Electric Conductor (PEC) boundary walls, one can obtain the even-even (EE), even-odd (EO), odd-even (OE), and odd-odd (OO) mode 1-element equivalent geometries which are only a quarter of the original geometry. With this construct, we can easily express the S-matrix of the array in terms of the S-parameters of the EOM equivalents as follows:

$$S=\frac{1}{4}\begin{bmatrix} S_{ee}+2S_{eo}+S_{oo} & S_{ee}-S_{oo} & S_{ee}-2S_{eo}+S_{oo} & S_{ee}-S_{oo} \\ S_{ee}-S_{oo} & S_{ee}+2S_{eo}+S_{oo} & S_{ee}-S_{oo} & S_{ee}-2S_{eo}+S_{oo} \\ S_{ee}-2S_{eo}+S_{oo} & S_{ee}-S_{oo} & S_{ee}+2S_{eo}+S_{oo} & S_{ee}-S_{oo} \\ S_{ee}-S_{oo} & S_{ee}-2S_{eo}+S_{oo} & S_{ee}-S_{oo} & S_{ee}+2S_{eo}+S_{oo} \end{bmatrix} \tag{1}$$

where S_{ee}, S_{eo} (S_{oe}), and S_{oo} are the S-parameters for the EE, EO (OE), and OO mode cases, respectively. This representation is similar to Butler Matrix (BM) model which is a common tool when analyzing circular antenna arrays [2]. The relationship between the BM modes and EOMs are listed below:

$$\boldsymbol{a}_{EE}=\boldsymbol{a}_{BM\ 0} \qquad \boldsymbol{a}_{EO}=\frac{(1+j)}{2}\boldsymbol{a}_{BM+1}+\frac{(1-j)}{2}\boldsymbol{a}_{BM-1}$$

$$\boldsymbol{a}_{OE}=\frac{(1-j)}{2}\boldsymbol{a}_{BM+1}+\frac{(1+j)}{2}\boldsymbol{a}_{BM-1} \qquad \boldsymbol{a}_{OO}=\boldsymbol{a}_{BM\pm 2} \tag{2}$$

where a's are the 4x1 excitation vectors for the associated radiation modes. EOM representation is so powerful that the EE, EO, OE and OO modes become orthogonal vectors for the vector space of radiation pattern modes. This model enables us to analyze and match these modes separately. Furthermore, any other radiation pattern mode can be written as a linear combination of these basic EOMs [3]. First, let's assume that the normalized returned power coefficients are given by $\boldsymbol{b}=\boldsymbol{S}\cdot\boldsymbol{a}$ as follows;

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} & S_{13} & S_{12} \\ S_{12} & S_{11} & S_{12} & S_{13} \\ S_{13} & S_{12} & S_{11} & S_{12} \\ S_{12} & S_{13} & S_{12} & S_{11} \end{bmatrix} \cdot \begin{bmatrix} 0.5 \\ 0.5e^{j\vartheta_2} \\ 0.5e^{j\vartheta_3} \\ 0.5e^{j\vartheta_4} \end{bmatrix} \tag{3}$$

For simplicity, the first port is taken as the phase reference port. Then, the power reflected at the ports P_{ref} can be written as a linear combination of the reflected powers from the basic EOMs as given below

$$P_{ref} = c_{ee} \cdot |S_{ee}|^2 + c_{eo} \cdot |S_{eo}|^2 + c_{oo} \cdot |S_{oo}|^2 \tag{4}$$

where c_{ee}, c_{eo} and c_{oo} are the associated mode coefficients given by;

$$\begin{aligned} c_{ee} &= \left|1 + e^{j\vartheta_2} + e^{j\vartheta_3} + e^{j\vartheta_4}\right|^2 / 16 \\ c_{eo} &= \left(\left|1 - e^{j\vartheta_3}\right|^2 + \left|e^{j\vartheta_2} - e^{j\vartheta_4}\right|^2\right) / 8 \\ c_{oo} &= \left|1 - e^{j\vartheta_2} + e^{j\vartheta_3} - e^{j\vartheta_4}\right|^2 / 16 \end{aligned} \tag{5}$$

Eqn (4) tells that instead of solving the 4-element full geometry of the original problem, it is sufficient to solve three of 1-element sub-geometries corresponding to EE, EO and OO modes to find the total returned (or radiated) power from the array system.

THE MATCHING SCHEME

We demonstrate that basic EOMs are independent and orthogonal. So, they can be matched perfectly with any matching scheme. This statement is numerically validated with an example which is constructed and simulated in HFSS [4] with monopole antennas that form a 4-element circular array as illustrated in Fig.1. Any other radiation mode, constructed by different weightings of the basic EOMs, can not be matched perfectly but can only be optimized with a proper matching strategy. This is due to the fact that all basic vectors contribute to this particular mode. So, all of them have to be matched simultaneously which is not possible since they have different boundary walls (i.e., different radiation impedances). We devise a scheme to find the optimum match for a particular radiation mode based on our EOM model. The steps of our fast scheme which requires only one-simulation of EOM models can be summarized as follows: (i) Simulate the EOM equivalents of the geometry as shown in Fig.2 and record the radiation impedances, (ii) Obtain a relationship between the matching network variables and the radiation impedance values (iii) Find the total reflected power in terms of basic modes' S-parameters (or Z-parameters) (iv) Minimize the total reflected power while finding an optimum point for the matching network parameters with a computer program. Therefore, optimization can be done separately in the computer without resorting to lengthy design-and-simulate cycle. In the next section, this matching method is validated with a numerical example in HFSS by demonstrating a good agreement between the calculated and the simulated reflection coefficients.

THE NUMERICAL RESULTS

First, to check the accuracy of EOM representation; the array geometry shown in Fig.1 is simulated by HFSS and the S-parameters are plotted in Fig.3 as solid lines. Then, the EOM equivalents of the geometry as shown in Fig.2 are simulated and the reconstructed S-parameters are plotted in Fig.3 as dashed lines. As easily seen from this figure, a very good agreement is obtained between the original and the reconstructed S-parameters. In addition, the original 4-element simulation was completed in 656 minutes; whereas, the each of three EOM simulations took only 39 minutes which in turn represents a computation time saving of around 82%. To optimally match the array for a random excitation vector, we apply our matching scheme that we described in the previous section. To do that, we selected $\boldsymbol{a} = \frac{1}{2} \cdot [e^{j90^\circ}\ 1\ e^{j270^\circ}\ 1]^T$ as the selected power coefficients for a particular directional mode of operation. The unmatched array responds to this excitation as in Fig.4 which obviously shows no resonance behavior around the frequencies of our interest. HFSS reported that only 11.6% of the total power is being radiated at 3 GHz. By applying our scheme EOM coefficients are calculated as c_{ee}=0.3430, c_{eo}=0.4849 *and* c_{oo}=0.1720 for this particular mode. To match this mode, we selected short-circuited single-stub tuning as our matching topology. Next, we wrote a *Matlab* code to maximize the total radiated power at 3 GHz while numerically changing the stub parameters. Our code found the maximum radiation efficiency that we can get with the given geometry and the existent matching technique is 68.77% at 3GHz. Corresponding stub parameters are calculated *d*= 0.2024λ and *l*= 0.9754λ (see Fig.5). We have plotted the total reflected power versus frequency in Fig. 6 for this calculated result. In the last step, we actually constructed this array in HFSS as shown in Fig.4 with the calculated stub parameters as we found in the fourth step and simulated the structure. The calculated and simulated total reflected power figures are compared in Fig.6. As observed from figure, a well optimum resonance is achieved around 3GHz and this result is validated by the HFSS simulation.

DISCUSSIONS

In this work, we presented a matching technique for 4-element circular antenna arrays of identical elements with a scheme based on the EOM analysis method. By exploiting the even and odd symmetries of the geometry, it is possible to decompose the original 4-element problem into four 1-element equivalents. Such a representation is so useful that we can reduce the computation time to simulate a full geometry to about 18.75% of the original simulation. Furthermore, we have proposed a matching algorithm that is based on the EOM approach. This algorithm requires only one-simulation of the EE, EO and the OO modes for the unmatched array. Then, the search for finding the optimum point to get the maximum efficiency is accomplished by a computer program without resorting to iterative design-and-simulate type search methods.

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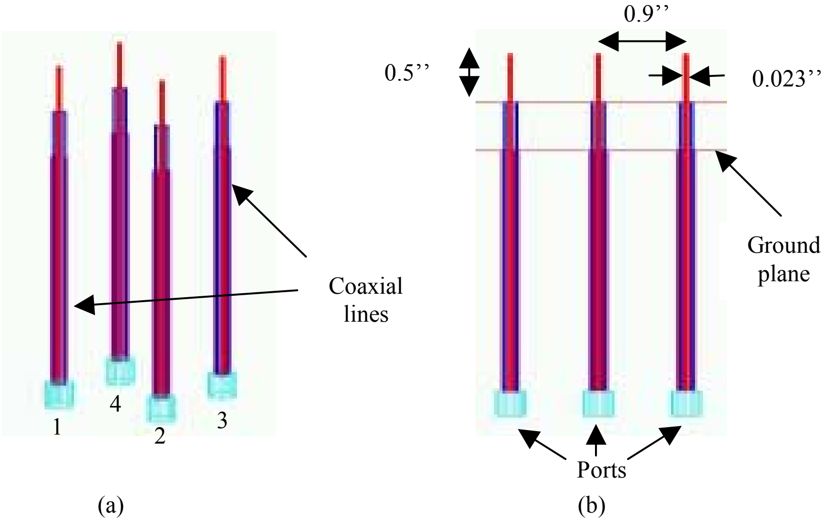

Fig. 1. (a) Inclined view of 4-element antenna array sytem designed in HFSS. (b) Side view.

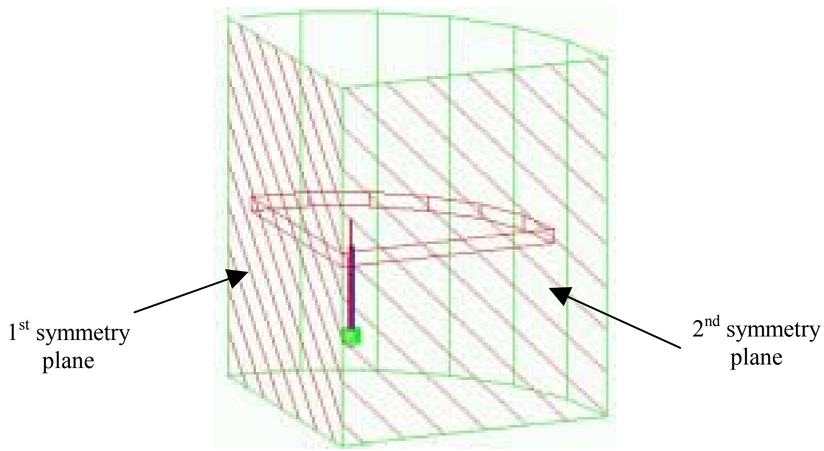

Fig.2. 1-element EOM equivalent of the 4-element full geometry of the geometry in Fig. 2.

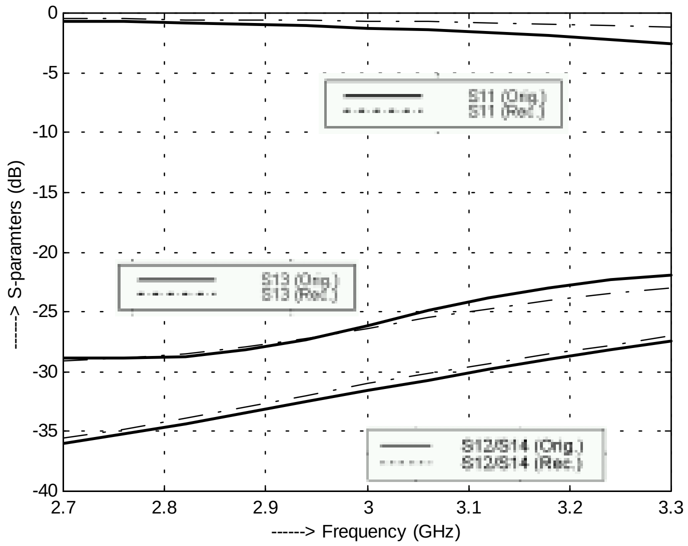

Fig. 3 Comparison of the original (solid) and the reconstructed S-parameters (dashed) using the EOM technique.

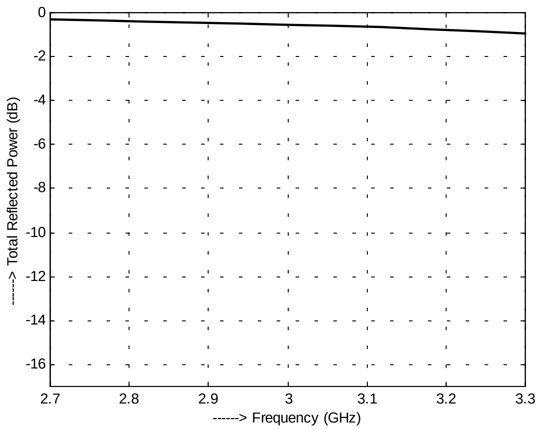

Fig. 4 Total reflected power versus frequency for the directional mode without any matching network.

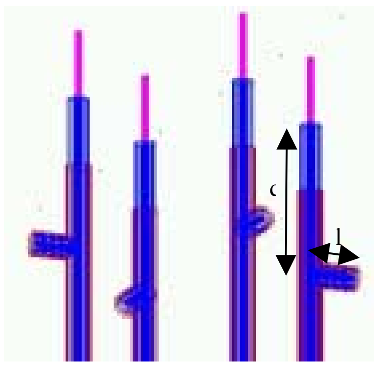

Fig. 5 4-element circular array geometry with single-stub matching network.

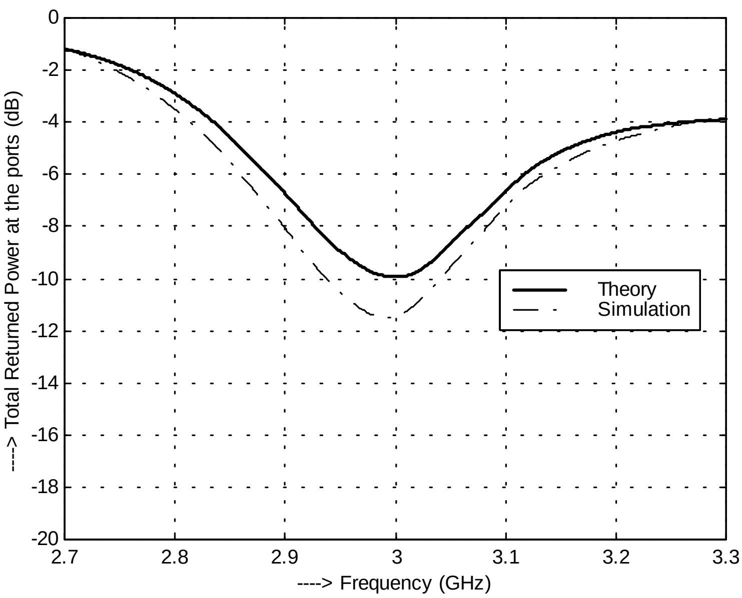

Fig. 6 Total returned power after applying the optimum match for our 4-element circular array. Theoretical (Solid) and simulated (Dashed) result.