Sensors & Transducers, Vol. 21, Special Issue, May 2013, pp. 193-198

Sensors & Transducers

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The Analysis and Measurement for Three-port Scatter Parameters of Substructure in Multimode Feed Network

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Received: 30 March 2013 /Accepted: 14 May 2013 /Published: 30 May 2013

Abstract: In opinion of substructure cascade, multimode feed network is composed of impedance transforming substructure and isolating substructure. Starting from the characteristic of the substructure in multimode feed network, a method of measurement for its three-port scatter parameters of substructure is presented, based on the applying of the available two-port vector network analyzer (VNA), considering the port impedance matching, the three-port scatter parameters of substructure in multimode feed network are researched, the mixed-mode S-parameters of three-port networks are used to verify the actual measured data. All those provide a favorable base for the optimizing design of the entire multimode multi-feed antenna system. *Copyright © 2013 IFSA.*

Keywords: Multimode feed network, Substructure, Three-port, Scatter parameters.

1. Introduction

The multimode feed network of multi-mode multi-feed shortwave antenna is composed of impedance convertor and isolator [1], the equivalent circuits are shown in Fig. 1, both the two substructures are based on the transmission-line transformer. It is the key to the short-wave multi-mode multi-feed antenna and complicated in structure. The function of impedance convertor in multi-mode feed network is for impedance match. The function of isolator in multi-mode feed network is to divide (or synthesize) power and isolate the signal. In opinion of substructure cascade, the characteristic of feed network can gain through the characteristic of impedance transforming substructure and isolating substructure. To give an effective and convenient analysis for substructures will provide the foundation for the design and optimization of multi-mode feed network and be of great applied value for the design, analysis of transmission-line transformer, isolator on short-wave and microwave.

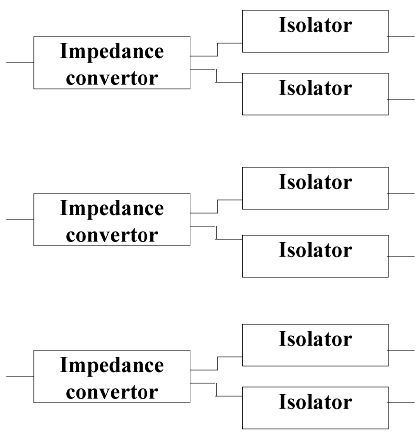

Fig. 1. The Feed Network Configuration.

For the convenient cascade of the multimode feed network, the two-port network is not only inadequate for the characteristic of substructure, but also not precise enough. Analyzing by three-port network is aptitude. So, the three-port network parameters are derived.

In this paper, from the passive network characteristic of substructure in the multimode feed network, considering the port impedance matching, the three-port scatter parameters(S-parameters) of substructure in multimode feed network are researched, the mixed-mode S-parameters of three-port networks are used to verify the actual measured data. Those not only are used to examine the results, but also can help to the optimize goal. These theoretical results provide the effective foundation for the device, modeling and optimize of the multimode feed network.

2. Overview of the Substructure Analyzing Method of Interconnect-net

With the progress of software and hardware of computer, the combination of numerical method using high-speed computer technology and Electromagnetism resolution method has solved a great deal of questions of the application domain, especially in the analyzing and designing of electromagnetic components. Several years ago, we brought forward the substructure analyzing method of interconnect-net [2], based on great capacity database, to settle the question that we encountered while researching, for example the difficulty in analyzing and optimizing the complex electromagnetic structure, the certain blindness in designing and machining.

Microwave net analyzing method has been developing rapidly. Recently, as a result of the progress of information and electronics, especially using of computer widely, microwave network is advancing more quickly than ever and appearing many new concept, theory and method. The substructure analyzing method of interconnect-net is on the base of our microwave engineering experience, technology of software and hardware of computer and microwave auto highly precise measure, it analyzes net using substructure idea, the outline of this method as follow:

1. Treat the complex net as the cascading of a set of substructures;
2. With the substructure database model, use multiple methods to character the net property of substructures. Database is a basic method here;
3. Using the net cascading method to get the overall net parameters;
4. With the direct use of the database data and the use of some technologies such as data lookup, data interpolation, database self-completeness, data pre-compute and data visualization, the net analyzing will be performed effectively;
5. Based on the analysis, optimization design can be achieved with the use of complex optimization method and the tact-select method, process trace technology.

The basic goal of the substructure analyzing method of interconnect-net is to resolve the question of analyzing and microwave net, and it also can settle the question of analyzing and optimizing design of analogy physical net, for example:

1. The analyzing and optimizing design of net which has some complex substructure.
2. Improving the calculate speed of substructure cascade of some certain model.

Substructure can be basic net unit or a set of net unit due to different objects. The aim is to make analyze more quickly and calculate more precise, for the convenience of debug, design and the optimization of system performance. The mainly point is which of definite electronic-magnetism characteristic or net parameter. For the multimode feed network usually, we use the S-parameters to describe the port characteristic of a certain substructure [3], for it has some merits as follow:

1. Easy to measure and use.
2. S-parameters can calculate circuit with Smith chart.
3. When preference plane moving, the change of S-parameters is reflected on phase only.
4. It is easy to deduce the S-parameters of multiple ports network.

3. Substructure in Multimode Feed Network

The substructure network S-parameters can be measured easily by Vector Network Analyzer (VNA).

Impedance convertor and isolator can be abstracted as three-port networks having the function of impedance transforming, see Fig. 2. BALUNS usually is used when these three ports networks are measured with two ports VNA. Balanced port 2 and 3 can be converted to unbalanced ports and impedance transforming is finished to match reference impedances of VNA.S-parameters of balanced ports and unbalanced ports can be gained with BALUNS. But substructure cascade need all 9 S-parameters of three ports networks [4]. So it is unsuited to measure S-parameters of substructure with BALUNS.

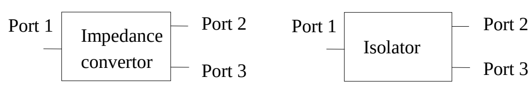

Fig. 2. The feed network substructure.

By the notion of substructure cascade, impedance convertor and isolator are looked on as substructures of multimode feed network. Impedance convertor and isolator are composed of windings, which is coiled with high permeability cores.

When signals are input from port 2 and port 3 which are same amplitude and phase, magnetic-flux which has inverse direction in cores is quit each other. Two signals are added.

When signals are input from port 2 and port 3 which are same amplitude and out-of-phase, 180 degrees, magnetic-flux which has same direction in cores is added each other. Inductive reactance which is produced by winding will reject signals to pass.

When arbitrary signals are input from port 2 and port 3, these two signals can be decomposed to common mode signal and differential mode signal. According to the same methods as above, the characteristic of substructure can be analyzed. So the transmission parameters of substructure networks when arbitrary signals pass networks can be got from the transmission parameters of networks when common mode signals pass networks whichever stare networks work in.

Otherwise, in the model of substructure at Fig. 2, the connecting way of port 2 and port 3 can influence the transmission parameters measured. So in each state, only a part of S-parameters of substructure networks can be gained when the S-parameters of networks are measured and transformed in this state.

When signals are input from port 1, the methods of analyzing are same to above.

In terms of the definition of S-parameters of multi-ports,

$$S_{ij} = \left.\frac{b_i}{a_j}\right|_{a_j=0,\quad when \quad i\neq j} \tag{1}$$

S-parameters can be gained through all ports are matched except for port j. But usually the reference impedances of two ports VNA are 50 ohms or 75 ohms and the reference impedances at two ports are uniform. For example, Agilent 4395A VNA has two kinds of reference impedances to select [5], 50 ohms and 75 ohms. So it is also difficult to measure this kind of three ports network which having the function of impedance transforming by definition through impedance match.

Applying knowledge about arbitrary impedance transformations, indefinite admittance matrix and mixed-mode S-parameters of three ports networks [6], this paper presents a method of measuring and analyzing [S] of substructure in multimode feed network at low frequency. As an example, isolating substructure is measured and its [S] is gained by this method. To verify test results, the measuring result of [S] is transformed to mixed-mode [S]. The curves of mixed mode [S] are in good agreement with theoretic results.

4. Measuring of Substructure in Multimode Feed Network

Through above analyze to substructure in multimode feed network, the following measurement method can be applied at low frequency.

Port 3 at Fig. 2 of substructure is grounded, see Fig. 3. Then three-port networks are transformed to two-port networks.

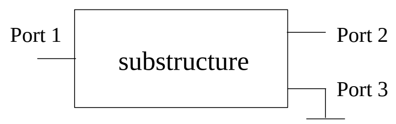

Fig. 3. The two-port substructure.

4.1. Transforming of S-parameters at Different Reference Impedance

It is assumed that ports reference impedance of two ports VNA is Z0 and the calibration can be done in a Z0 ohms environment. The networks will be measured with this VNA.S-parameters matrix will be gained and it is signed as

$$\left[S^{Z_0-Z_0}\right] = \begin{bmatrix} S_{11}^m & S_{12}^m \\ S_{21}^m & S_{22}^m \end{bmatrix} \tag{2}$$

$\left[S^{Z_0-Z_0}\right]$ can be transformed to $\left[R^{Z_0-Z_0}\right]$ according to the relationships of S-parameters matrix and R-parameters matrix of two ports networks. $\left[R^{Z_0-Z_0}\right]$ can be signed as:

$$\left[R^{Z_0-Z_0}\right] = \begin{bmatrix} R_{11}^m & R_{12}^m \\ R_{21}^m & R_{22}^m \end{bmatrix} = \frac{1}{S_{21}^m}\begin{bmatrix} S_{12}^m S_{21}^m - S_{11}^m S_{22}^m & S_{11}^m \\ -S_{22}^m & 1 \end{bmatrix} \tag{3}$$

It is assumed that the matching impedance at port 1 is Z_1 and it is Z_2 at port 2 in the two ports networks[7].The R-parameters matrix of this network can be got from $\left[R^{Z_0-Z_0}\right]$ according to the transforming rules of R-parameters matrix in different reference impedance environment. It is signed as

$$\left[R^{Z_1-Z_2}\right] = \begin{bmatrix} R_{11}^{Z_1-Z_2} & R_{12}^{Z_1-Z_2} \\ R_{21}^{Z_1-Z_2} & R_{22}^{Z_1-Z_2} \end{bmatrix} = Q^{Z_1-Z_0} R^{Z_0-Z_0} Q^{Z_0-Z_2} \tag{4}$$

where

$$Q^{Z_1-Z_0} = \frac{1}{2\left|N_{Z_1-Z_0}\right|^2}\sqrt{\frac{R_e(Z_1)}{R_e(Z_0)}}\begin{bmatrix} 1+N_{Z_1-Z_0}^2 & 1-N_{Z_1-Z_0}^2 \\ 1-N_{Z_1-Z_0}^2 & 1+N_{Z_1-Z_0}^2 \end{bmatrix} \tag{5}$$

$$N_{Z_1-Z_0} = \sqrt{\frac{Z_1}{Z_0}} \tag{6}$$

$$Q^{Z_0-Z2} = \frac{1}{2\left|N_{Z_0-Z_2}\right|^2}\sqrt{\frac{R_e(Z_0)}{R_e(Z_2)}}\begin{bmatrix} 1+N_{Z_0-Z_2}^2 & 1-N_{Z_0-Z_2}^2 \\ 1-N_{Z_0-Z_2}^2 & 1+N_{Z_0-Z_2}^2 \end{bmatrix} \tag{7}$$

$$N_{Z_0-Z2} = \sqrt{\frac{Z_0}{Z_2}} \tag{8}$$

$\left[R^{Z_1-Z_2}\right]$ is transformed to $\left[S^{Z_1-Z_2}\right]$ according to the relationships between R-parameters matrix and S-parameters matrix of two ports networks.

$$\left[S^{Z_1-Z_2}\right] = \begin{bmatrix} S_{11}^{Z_1-Z_2} & S_{12}^{Z_1-Z_2} \\ S_{21}^{Z_1-Z_2} & S_{22}^{Z_1-Z_2} \end{bmatrix} = \frac{1}{R_{22}^{Z_1-Z_2}}\begin{bmatrix} R_{12}^{Z_1-Z_2} & R_{11}^{Z_1-Z_2}R_{22}^{Z_1-Z_2} - R_{12}^{Z_1-Z_2}R_{21}^{Z_1-Z_2} \\ 1 & -R_{21}^{Z_1-Z_2} \end{bmatrix} \tag{9}$$

$\left[S^{Z_1-Z_2}\right]$ is the S-parameters matrix of the two ports network when it has the function of impedance transforming from Z_1 to Z_2.

4.2. S-parameters Matrix Transformation From Two-port to Three-port

$\left[S^{Z_1-Z_2}\right]$ at (9) is transformed to Y-parameters matrix according to the relationships between S-parameters matrix and Y-parameters matrix of two ports networks.

$$[Y] = \begin{bmatrix} Y_{11} & Y_{12} \\ Y_{21} & Y_{22} \end{bmatrix} = \left([I] - \left[S^{Z_1-Z_2}\right]\right)\left([I] + \left[S^{Z_1-Z_2}\right]\right)^{-1} \tag{10}$$

where [I] is the identity matrix.

The Y-parameters matrix of three ports network can be gained according to knowledge about indefinite admittance matrix when network is in the state of that port 3 is grounded.

$$\left[Y^{3g}\right] = \begin{bmatrix} Y_{11}^{3g} & Y_{12}^{3g} & Y_{13}^{3g} \\ Y_{21}^{3g} & Y_{22}^{3g} & Y_{23}^{3g} \\ Y_{31}^{3g} & Y_{32}^{3g} & Y_{33}^{3g} \end{bmatrix} = \begin{bmatrix} Y_{11} & Y_{12} & -Y_{11}-Y_{12} \\ Y_{21} & Y_{22} & -Y_{21}-Y_{22} \\ -Y_{11}-Y_{21} & -Y_{12}-Y_{22} & Y_{11}+Y_{21}+Y_{12}+Y_{22} \end{bmatrix} \tag{11}$$

Y-parameters matrix can be got according to the relationships between Y-parameters and S-parameters of three ports networks.

$$\left[S^{3g}\right] = \begin{bmatrix} S_{11}^{3g} & S_{12}^{3g} & S_{13}^{3g} \\ S_{21}^{3g} & S_{22}^{3g} & S_{23}^{3g} \\ S_{31}^{3g} & S_{32}^{3g} & S_{33}^{3g} \end{bmatrix} = \left([I] - \left[Y^{3g}\right]\right)\left([I] + \left[Y^{3g}\right]\right)^{-1} \tag{12}$$

where [I] is the identity matrix.

4.3. Transformation from [S^{3g}] to Common and Differential Mode Transmission Parameters

Mixed-mode S-parameters matrix of three ports network can be gained from [S^{3g}] according to the relationships between mixed-mode S-parameters and single-ended S-parameters matrix. It is

$$S^{M3} = \begin{bmatrix} S_{11}^3 & S_{1C}^3 & S_{1D}^3 \\ S_{C1}^3 & S_{CC}^3 & S_{CD}^3 \\ S_{D1}^3 & S_{DC}^3 & S_{DD}^3 \end{bmatrix} = MS^{3g}M^{-1} \tag{13}$$

where $M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix}$

4.4 S-parameters of Substructure

It is assumed that S-parameters matrix of substructure is [S].That is

$$S = \begin{bmatrix} S_{11} & S_{12} & S_{13} \\ S_{21} & S_{22} & S_{23} \\ S_{31} & S_{32} & S_{33} \end{bmatrix}$$

According to power relationships, a part of S-parameters can be gained from (13).They are

$$S_{12} = \sqrt{2}S_{1C}^3 \quad S_{21} = \sqrt{2}S_{C1}^3$$
$$S_{22} = S_{CC}^3 \quad S_{32} = S_{DC}^3 \tag{14}$$

Mixed-mode S-parameters matrix of two ports network can be gained according to the same method when port 2 is grounded [8]. It is

$$S^{M2} = \begin{bmatrix} S_{11}^2 & S_{1C}^2 & S_{1D}^2 \\ S_{C1}^2 & S_{CC}^2 & S_{CD}^2 \\ S_{D1}^2 & S_{DC}^2 & S_{DD}^2 \end{bmatrix}$$

A part of S-parameters of substructure can be got by the same method. They are

$$S_{13} = \sqrt{2}S_{1C}^2 \quad S_{31} = \sqrt{2}S_{C1}^2$$
$$S_{33} = S_{CC}^2 \quad S_{23} = S_{DC}^2 \tag{15}$$

To S_{11}, it is can be got from

$$S_{11} = \frac{S_{11}^3 + S_{11}^2}{2} \tag{16}$$

Then S-parameters matrix of substructure is gained.

5. Application, Analysis and Example

Because of the different function, the two substructures have the different ends connected together [9], the different input port and the different output port. In this paper, an isolator is taken as example.

Example: Isolator to be exampled consists of six tunes of coaxial-line (characteristic impedance is 50 ohm) wound on a ferrite core, with outer and inner dimensions of $0.061m$ and $0.025m$ respectively. The core thickness is $0.015m$.

Where: ε_{eff} = the effective dielectric constant of the media inside the coil [10] (ε_{eff} of coaxial-line to be used in this example is 2.1).

S-parameter can be measured with Agilent 4395A, measuring frequency from 0MHz to 80MHz, Ports impedance of isolator are $Z_1 = 200\Omega$, $Z_2 = Z_3 = 400\Omega$. The $\left[Q^{Z_0-Z_1}\right]$ can be gained from (5) and (7).Then

$$Q^{200-50} = \begin{bmatrix} 5/4 & -3/4 \\ -3/4 & 5/4 \end{bmatrix} \; Q^{50-400} = \sqrt{2}\begin{bmatrix} 9/8 & 7/8 \\ 7/8 & 9/8 \end{bmatrix}$$

S-parameters matrix can be got by programming. To verify data, isolator is analyzed with mixed-mode S-parameters [11]. It is

$$S^M = \begin{bmatrix} \overline{S_{11}} & \overline{S_{1C}} & \overline{S_{1D}} \\ \overline{S_{C1}} & \overline{S_{CC}} & \overline{S_{CD}} \\ \overline{S_{D1}} & \overline{S_{DC}} & \overline{S_{DD}} \end{bmatrix}$$

In ideal instances, a part of mixed-mode S-parameters of isolator can be got by analyzing and calculating. That is

$$\begin{aligned} &\left|\overline{S_{1D}}\right| = 0 \;\; \left|\overline{S_{1C}}\right| = 1 \;\; \left|\overline{S_{CD}}\right| = 0 \\ &\left|\overline{S_{D1}}\right| = 0 \;\; \left|\overline{S_{C1}}\right| = 1 \;\; \left|\overline{S_{DC}}\right| = 0 \end{aligned} \tag{17}$$

S-parameters matrix of isolator measured is transformed to mixed-mode S-parameters according to the following formula: $S^M = MSM^{-1}$

where $M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1/\sqrt{2} & 1/\sqrt{2} \\ 0 & 1/\sqrt{2} & -1/\sqrt{2} \end{bmatrix}$.

The corresponding mixed-mode S-parameters are compared with those in (17). The following is the comparative curves.

They are in good agreement at Fig. 4. So this method can be used to measure three-port Scatter Parameters of Substructure in multimode feed network at low frequency.

6. Conclusions

In opinion of substructure cascade, multimode feed network is composed of impedance transforming substructure and isolating substructure. Impedance transformer and isolator can be abstracted as three-port networks having the function of impedance transforming.

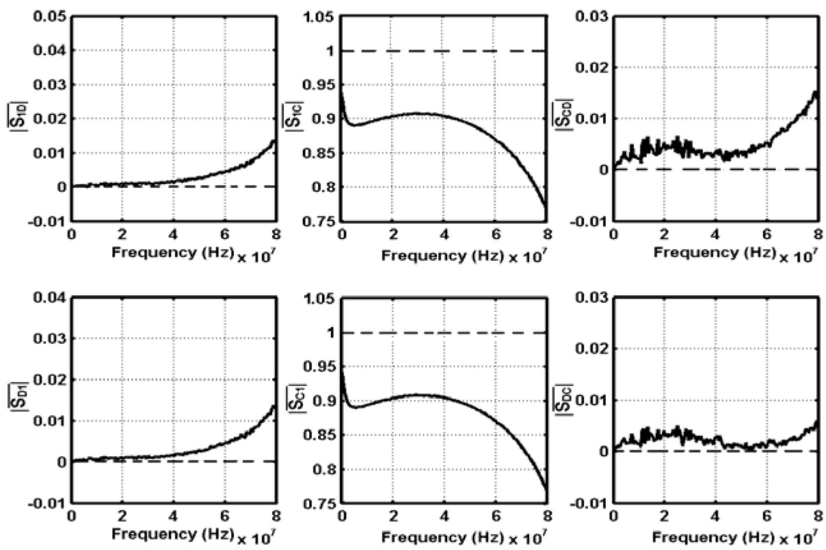

Fig. 4. The comparison of metrical and theoretic result.

This paper presents a method of measuring and analyzing [S] of this kind of three-port networks at low frequency with two ports VNA which has arbitrary reference impedances. the three-port scatter parameters of substructure in multimode feed network are researched, the mixed-mode S-parameters of three-port networks are used to verify the actual measured data. The proposed method also can provide a favorable base for the optimizing design of the entire multimode multi-feed antenna system.

Acknowledgements

This work is supported by National Natural Science Foundation of China (61077037), Key Scientific and Technological Project of Henan Province (102102210033), Science and Technology Research Project of The Education Department of Henan Province (12B510014), National Training Programs of Innovation and Entrepreneurship for Undergraduates, Henan Normal University (201210476075).

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