The Mutual Coupling Effects in Large Microstrip Leaky-Mode Array

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Abstract

A twenty-element microstrip array that emits twenty coupled leaky modes is analyzed and validated by a novel, generic technique combing the full-wave integral equation method and coupled mode theory. The new method enables fast, accurate assessment of coupled leaky modes and gives physical insight on how the large array may excite the leaky modes considering the mode-coupling effects.

I. Introduction

Microstrip had been known for supporting the leaky modes in a variety of ways [1]-[4]. The microstrip leakage usually takes place in the form of space wave or surface wave. Imagine that an additional microstrip is introduced in parallel to the existing one, the modal spectra, including the leaky modes, will be altered by the newly added line because these two microstrips couple to each other. If the process of adding new lines continues, eventually a large coupled linear array that radiates as many leaky modes simultaneously is established. The quest for obtaining the complex dispersion characteristics of these leaky modes is essential for gaining physical insight on how the array performs.

The difficulty for attaining all the complex leaky modes, however, arises significantly with the increasing number of microstrips in the array as shown in Fig. 1. In the modal spectra, these leaky modes are closely distributed with their real-part or imaginary-part values so close that great care must be exercised to obtain correct solutions. This paper tackles the large microstrip leaky-mode array problem by combining the full-wave integral equation method [5] for solving the dispersion characteristics of the coupled leaky-mode and the mode-coupling formation for the large array [6,7]. The benefits of the proposed approach are at least two-fold. First, fast and accurate assessment of leaky-mode dispersion characteristics can be achieved with the least numerical efforts. Second, the condition for exciting the specific leaky mode is readily available from the eigenvectors of the coupled-mode solutions, rendering better understanding and use of the N-coupled leaky modes in the large microstrip linear array of N elements.

II. Two-Element Leaky-Mode Array

II.a The Full-Wave Analysis

The novel approach for tackling the large microstrip leaky-mode array problem begins with the breakdown of the large array into a two-element array, from which we characterize the leaky properties by invoking the well-known full-wave integral equation method [5]. The dyadic Green's function can be derived as:

$$\begin{bmatrix} Z_{zz}(\gamma) & Z_{zx}(\gamma) \\ Z_{xz}(\gamma) & Z_{xx}(\gamma) \end{bmatrix} \cdot \begin{bmatrix} J_z \\ J_x \end{bmatrix} = \begin{bmatrix} E_z \\ E_x \end{bmatrix} \tag{1}$$

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where γ is the propagation constant. The unknowns in the full-wave analysis are current distributions on the metal strips and are represented by the recently developed basis functions [8]. After applying the Galerkin procedure a nonstandard eigenvalue problem can be formulated to obtain the complex propagation constant γ. Fig. 2 shows the first higher-order leaky modes, namely EH1 even-mode (γe) and EH1 odd-mode (γo), representing the full-wave solutions for the leaky modes of the two-element array. Fig.2 also shows that EH1 odd-mode (even-mode) can be obtained by inserting an electric (magnetic) wall at the symmetry plane, Another view derived from the symmetric walls is that the coupled symmetric strips supporting the EH1 odd-mode (even-mode) are out-of-phase (in-phase). Thus the in-phase and out-of-phase transverse modal currents reflect two states of the two-element microstrip array.

II.b. The Coupled-Mode Formation

The above-mentioned in-phase and out-of-phase states of the two leaky modes can be linked to the coupled-mode formation of the complex waves [6,7]. In other words, the dispersion characteristics of Fig. 2 can be viewed as the coupled solutions of two identical leaky modes, which posses the same leaky dispersion characteristics with those of a single microstrip. By invoking the coupled-mode theory (eqs. (7) and (8) of [6]), the single-line leaky-mode, standing for the condition before any mode-coupling occurs, and the coupling coefficient can be deduced to

$$\gamma = (\lambda_e + \lambda_o) / 2 \qquad (2)$$

$$C = (\lambda_e - \lambda_o) / 2 \qquad (3)$$

The validity of (2) for computing the leaky mode of a single, undisturbed microstrip is illustrated in Fig. 3, which compares the dispersion characteristics of 1) a single microstrip using the full-wave analysis directly, and 2) the leaky modes deduced from (2) using the coupled-mode data of Fig. 2. Excellent agreement has been achieved between the two sets of data, implying the mode-coupling formation of the multiple leaky modes is an alternative, accurate model.

III. N-Element Leaky-Mode Array

The coupled-mode formation can be extended to a large microstrip array as shown in Fig. 1. By extending the results obtained in section II, the N coupled leaky modes propagating along the N-element microstrip array can be described by a system of differential matrix equation expressed as follows:

$$\frac{d}{dz}\begin{bmatrix} E_1(z) \\ \cdot \\ E_i(z) \\ \cdot \\ E_N(z) \end{bmatrix} = \begin{bmatrix} -\gamma & C_{12} & \cdot & C_{ij} & \cdot & C_{1N} \\ C_{21} & -\gamma & \cdot & C_{2j} & \cdot & C_{2N} \\ \cdot & \cdot & & \cdot & & \cdot \\ \cdot & \cdot & & \cdot & & \cdot \\ C_{N1} & C_{N2} & \cdot & C_{Nj} & & -\gamma \end{bmatrix} \bullet \begin{bmatrix} E_1(z) \\ \cdot \\ E_i(z) \\ \cdot \\ E_N(z) \end{bmatrix} = [A] \bullet \begin{bmatrix} E_1(z) \\ \cdot \\ E_i(z) \\ \cdot \\ E_N(z) \end{bmatrix} \qquad (4)$$

where E*i* is the wave amplitude on the *i'th* element and γ is the leaky-mode of single microstrip. The mutual coupling coefficient, C_{ij}, is defined as coupling coefficient on the *i'th* element caused by the wave propagating on the *j'th* element. C_{ij} is equal to C_{ji} when the coupling mechanism is isotropic or reciprocal. In practice, the amount of coupling coefficient is negligible except for the adjacent element. Thus the characteristic matrix [A] can be reduced to a banded matrix with $C_{ij} \neq 0$ for $|i-j|=1$. The values of γ and C_{ij} are obtained by computing (2) and (3), respectively. Therefore we may proceed solving the eigenvalues of [A], which correspond to the complex propagation constants of the coupled leaky modes.

The validity of applicability of (4) is confirmed by comparing the coupled modes' solutions with those obtained by the rigorous full-wave analysis for a three-element array, where excellent agreement between the two approaches can be seen in Fig. 4. The companion solutions are the eigenvectors, denoted as [$1/\sqrt{2}$,1,$1/\sqrt{2}$], [-1,0,1], and [$-1/\sqrt{2}$,1,-$1/\sqrt{2}$], which respectively correspond to the leaky modes that are microstrip-like, coupled-slot-like, and CPW-like. Finally, a large twenty-element microstrip array with equal strip's width and spacing is investigated. The twenty coupled EH1 modes are obtained by solving the eigenvalues of [A] of dimension 20 by 20. Fig.5 plots the twenty leaky modes, which are tightly distributed in the mode chart that would be very difficulty to obtain if the full-wave analysis is directly invoked. Furthermore Fig. 6 plots the eigenvectors (or states) of the 20-element array. Only four out of the twenty eigenvectors are shown. The states No. 1 and No. 14 have the same cosine-like amplitude distribution along the 20 elements. They, however, have different phases; state 1 alternates phase between the adjacent elements. State 14 has in-phase distribution at approximately 100°. Notice that the CPU times required to compute the data in Fig. 4 (a 3-element array) and Fig. 5 (a 20-element array) are not much different using the typical personal computer.

IV. Conclusion

To a certain specific type of leaky mode incorporated into a large microstrip array of N elements, the mutual coupling effects in this array can be described by N coupled leaky modes. Case studies for 2-, 3-, and 20-element microstrip arrays are presented. Solving the tightly distributed leaky modes for the large array is shown to be linked to the standard eigenvalue problem derived from the coupled mode formation of complex waves. This novel approach allows fast and accurate computation of all these leaky modes while at the same time provides useful physical insight about how the individual leaky mode contributes to the array's performance.

V. Acknowledgment

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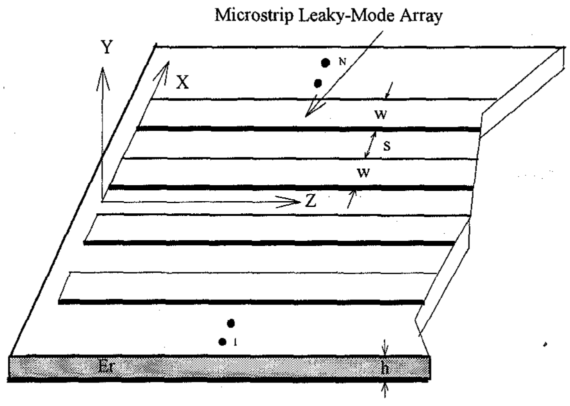

Fig. 1 A generic, large microstrip leaky-mode array of N elements

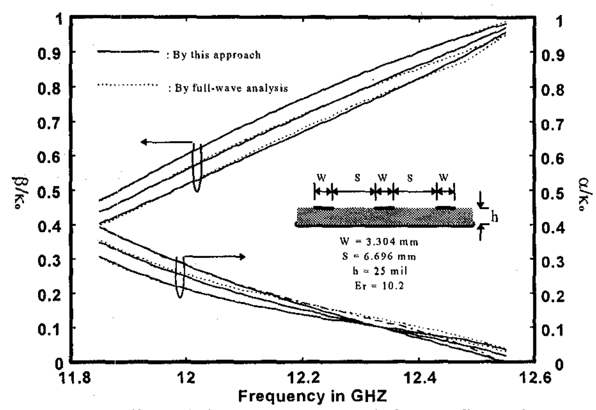

Fig.4 Validity of the new approach is confirmed by studying the three-element array, showing very good agreement for data obtained by the full-wave analysis a the new approach.

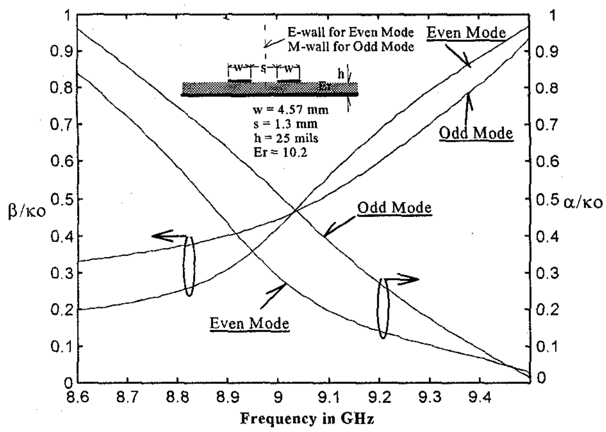

Fig. 2 Dispersion characteristics of the two-element microstrip leaky-mode array, showing two states (in-phase and out-of-phase) associated with the leaky modes

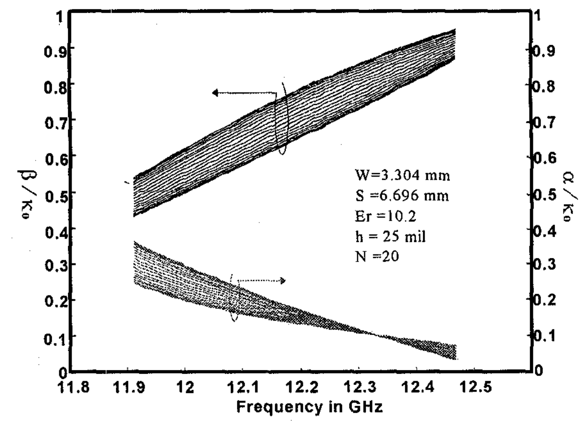

Fig. 5 First higher-order leaky modes of a twenty-element microstrip array obtained by using the new approach, showing twenty pairs of complex propagation constants.

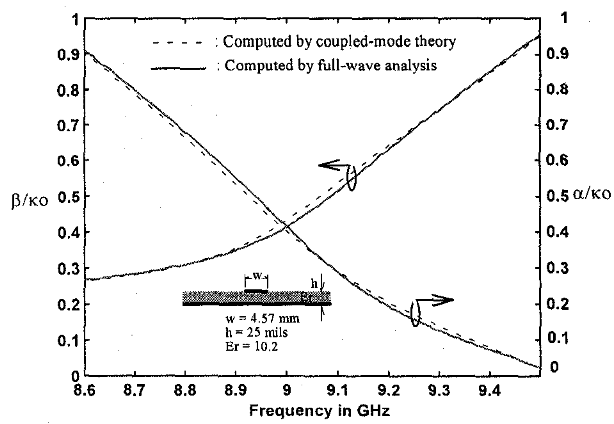

Fig.3 Comparison of the dispersion characteristics of a single microstrip line computed by the full-wave analysis and the coupled-mode approach [eq. (2)].

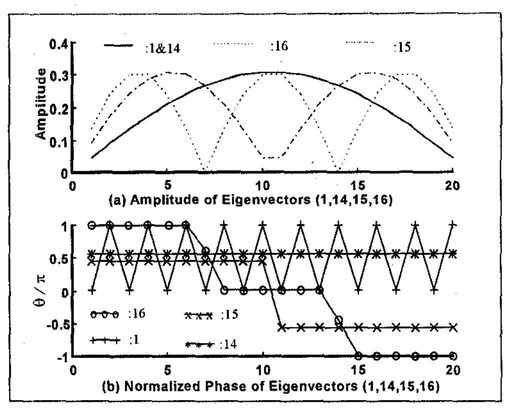

Fig.6 Four out of twenty eigenvectors (states) associated with solutions of Fig.5 are plotted to illustrate the internal amplitude and phase distribution of certain state in the array