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SENSITIVITY ANALYSIS OF ITERATIVE ADJOINT TECHNIQUE FOR MICROSTRIP CIRCUITS OPTIMIZATION

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ABSTRACT: *This paper presents an accurate and efficient full-wave method, combined with iterative adjoint technique, for analyzing sensitivities of planar microwave circuits with respect to design parameters. Method of moments (MoM) in spatial domain is utilized, and generalized conjugate residual iterative scheme is applied to solve the linear matrix equations with fast convergence. Green's functions for multilayer planar structures in DCIM form are employed to simplify the spatial domain manipulation. In the present method, a conventional integration model and the corresponding adjoint model are solved by MoM respectively. The adjoint technique, with the aid of iterative schemes, could significantly reduce the computational requirements, especially for the large electrical size device with many perturbing design parameters. Numerical results of S-parameter sensitivities of a low-pass microstrip filter by the present method are presented. Accuracy and efficiency are validated.* © 2007 Wiley Periodicals, Inc. Microwave Opt Technol Lett 49: 607–609, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/mop.22204

Key words: *iterative scheme; method of moments; adjoint techniques; sensitivity; DCIM; optimization; microstrip circuits*

1. INTRODUCTION

Sensitivity analysis is used to evaluate the sensitivity of system performance with respect to design parameters for optimized design. The sensitivity is usually denoted by the gradient of a response function, and then an efficient optimization method makes use of the derivative information of the response to obtain suitable design parameters. This article studies the efficiency of full-wave sensitivity analysis by the method of moments (MoM).

Sensitivities of charges and current densities for planar structures were first investigated by MoM in Refs. 1 and 2. In Ref. 1, shape sensitivities of electrostatic problems for planar structures were studied. By applying the flux-transport theorem, a new integral equation (IE) for the total derivative of the charge with respect to a geometrical parameter was derived from the original IE for the charge distribution. The two IEs were solved by the MoM using the same set of basis and testing functions. A similar approach with mixed potential integral equation (MPIE) was applied to analyze the sensitivities of current density distributions and S-parameters with respect to geometrical parameters in Ref. 2. Although this technique could obtain accurate sensitivity results, it needs complicated manipulations to analytically simplify the impedance matrix elements and its implementation into the optimization environment would require large amount of reprogramming of the current MoM simulation tools. To make the programming implementation easier, a feasible adjoint technique [3] combined with MoM was proposed in Ref. 4 to realize the full-wave sensitivity analysis. Above techniques employ LU decomposition [5] to solve the two matrix equations, requiring $O(N^3)$ computation loads.

This article presents a full-wave technique to analyze sensitivities of multilayer planar structures. With the aid of iterative adjoint technique and the spatial Green's functions in DCIM form [6, 7], the present technique has the following advantages: (1) the adjoint technique is employed to make the sensitivity analysis very easy to implement into the current MoM-based simulation tools; (2) the iterative scheme (generalized conjugate residual, GCR) is introduced to solve the matrix equation, requiring $O(N^2)$ computation for each step. It would greatly save computation time if the iteration converges fast; (3) the spatial Green's kernel in DCIM form makes it possible to investigate the performance sensitivity with respect to the geometrical parameters, which the Green's function is dependent on. This case cannot be solved in Ref. 2. In the present study, sensitivities of S-parameters of a low-pass filter with respect to the design parameters are analyzed to validate the accuracy and efficiency of the present technique.

2. FORMULATION

MoM subject to the MPIE has been proved as an accurate and efficient technique to analyze properties of multilayer planar structures. Current density distribution on metal patch is first solved via linear matrix equation as

$$\boldsymbol{Z}(\boldsymbol{x})\boldsymbol{I} = \boldsymbol{V} \tag{1}$$

where $\boldsymbol{x}$ is a vector of design parameters, which need to be adjusted to optimize circuit performance. Elements in the impedance matrix $\boldsymbol{Z}$ are obtained as

$$\boldsymbol{Z}_{ij} = j\omega\varepsilon\int_{S_i}\int_{S_j}\overline{\boldsymbol{G}}_A(\boldsymbol{r},\boldsymbol{r}')\cdot\boldsymbol{f}_j(\boldsymbol{r}')\cdot\boldsymbol{f}_i(\boldsymbol{r})ds'ds + \frac{1}{j\omega}\int_{S_i}\int_{S_j}G_q(\boldsymbol{r},\boldsymbol{r}')\nabla\cdot\boldsymbol{f}_i(\boldsymbol{r})\nabla'\cdot\boldsymbol{f}_j(\boldsymbol{r}')ds'ds \tag{2}$$

where $\boldsymbol{f}_i(\boldsymbol{r})$ and $\boldsymbol{f}_j(\boldsymbol{r}')$ are the RWG testing and basis functions, and S_i and S_j are their supports, respectively. $\overline{\boldsymbol{G}}_A$ and G_q are the spatial Green's functions in DCIM form for vector and scalar potentials respectively. Here, we use GCR iterative schemes to solve the matrix equation, which needs $O(N^2)$ computation cost for each iterative step. The scattered field can be expressed as

$$\boldsymbol{E}_{\mathrm{sc}} = -j\omega\boldsymbol{A} - \nabla\Phi \tag{3}$$

where the vector and scalar potentials can be obtained by using

$$\boldsymbol{A}(\boldsymbol{r}) = \int\int_S \overline{\boldsymbol{G}}_A(\boldsymbol{r},\boldsymbol{r}')\cdot\boldsymbol{I}(\boldsymbol{r}')dS' \tag{4}$$

$$\Phi = \int\int_S G_q(\boldsymbol{r},\boldsymbol{r}')\nabla\cdot\boldsymbol{I}(\boldsymbol{r}')dS' \tag{5}$$

With the aid of the spatial Green's functions, planar-multilayered microstrip geometries can be considered efficiently.

After obtaining the current density $\boldsymbol{I}$, we are interested in the sensitivity of the response function ψ, which is dependent on the design parameters explicitly and inexplicitly through the current density, as

$$\nabla_x \psi = \nabla_x^e \psi + \nabla_{\boldsymbol{I}} \psi \cdot \nabla_x \boldsymbol{I} \tag{6}$$

Here, the adjoint technique is used to efficiently and clearly calculate the sensitivity of response function. Taking the gradient of Eq. (1), we obtain

$$\nabla_x \boldsymbol{I} = \boldsymbol{Z}^{-1}(\nabla_x \boldsymbol{V} - \nabla_x \boldsymbol{Z}\bar{\boldsymbol{I}}) \tag{7}$$

where $\bar{\boldsymbol{I}}$ means $\boldsymbol{I}$ holds constant during the differentiation. Then, substituting Eq. (7) into Eq. (6), we have

$$\nabla_x \psi = \nabla_x^e \psi + \nabla_{\boldsymbol{I}} \psi \boldsymbol{Z}^{-1}(\nabla_x \boldsymbol{V} - \nabla_x \boldsymbol{Z}\bar{\boldsymbol{I}}) \tag{8}$$

An adjoint vector $\hat{\boldsymbol{I}}$ is defined as

$$\hat{\boldsymbol{I}}^T = \nabla_{\boldsymbol{I}} \psi \boldsymbol{Z}^{-1} \tag{9}$$

Then, we have another linear matrix equation from Eq. (9)

$$\boldsymbol{Z}^T \hat{\boldsymbol{I}} = [\nabla_{\boldsymbol{I}} \psi]^T \tag{10}$$

This is referred to as an adjoint linear model, parallel with the original one in Eq. (1). In the adjoint matrix Eq. (10), the impedance matrix is just the transposition of the $\boldsymbol{Z}$ in Eq. (1), eliminating the need to fill the matrix again. The exciting source vector is the explicit derivative of response function with respect to the current density distribution.

It is noted that the $\boldsymbol{Z}$ matrix elements are usually complex, and the transposition of a complex matrix involves conjugation. To make it clear to manipulate, the complex matrix equation is replaced by the real systems as follows

$$\begin{bmatrix} \boldsymbol{Z}_{\mathrm{R}} & -\boldsymbol{Z}_{\mathrm{I}} \\ \boldsymbol{Z}_{\mathrm{I}} & \boldsymbol{Z}_{\mathrm{R}} \end{bmatrix}^T \begin{bmatrix} \hat{\boldsymbol{I}}_{\mathrm{R}} \\ \hat{\boldsymbol{I}}_{\mathrm{I}} \end{bmatrix} = \begin{bmatrix} \nabla_{\boldsymbol{I}_{\mathrm{R}}} \psi \\ \nabla_{\boldsymbol{I}_{\mathrm{I}}} \psi \end{bmatrix} \tag{11}$$

where $\boldsymbol{Z}_R = \mathrm{Re}\{\boldsymbol{Z}\}$, $\boldsymbol{Z}_I = \mathrm{Im}\{\boldsymbol{Z}\}$, $\hat{\boldsymbol{I}}_{\mathrm{R}} = \mathrm{Re}\{\hat{\boldsymbol{I}}\}$, $\hat{\boldsymbol{I}}_{\mathrm{I}} = \mathrm{Im}\{\hat{\boldsymbol{I}}\}$, $\nabla_{\boldsymbol{I}_{\mathrm{R}}} \psi = \partial\psi/\partial \boldsymbol{I}_{\mathrm{R}}$, and $\nabla_{\boldsymbol{I}_{\mathrm{I}}} \psi = \partial\psi/\partial \boldsymbol{I}_{\mathrm{I}}$. The adjoint vector $\hat{\boldsymbol{I}}$ is then solved again by the iterative scheme.

After obtaining both the current density vector $\boldsymbol{I}$ and the adjoint vector $\hat{\boldsymbol{I}}$ through Eqs. (1) and (10), the sensitivity of response function with respect to the design parameter x could be calculated from Eq. (8) as

$$\nabla_x \psi = \nabla_x^e \psi + \hat{\boldsymbol{I}}^T(\nabla_x \boldsymbol{V} - \nabla_x \boldsymbol{Z}\bar{\boldsymbol{I}}) \tag{12}$$

From the earlier procedure, we finally obtain the performance sensitivity with respect to design parameters after solving two linear models. Iterative scheme is employed to solve each matrix equation, requiring $O(N^2)$ computation cost for each iterative step. For the fast convergence iterative method, the cost of twice iteration is still far smaller than the direct matrix inverse cost $O(N^3)$ (LU decomposition), especially when N is large.

In addition, the adjoint technique is used to guarantee the efficiency regardless of the number of perturbing design parameters. The time-consuming linear matrix Eqs. (1) and (10) are only required to solve once to obtain the current density vector and adjoint vector. For the different design parameter, differences are only involved in Eq. (12). Thus, computation load is mainly associated with the derivatives of Z matrix elements $\nabla_x \boldsymbol{Z}$ in Eq. (12). For the planar structures, this situation would be worse when the perturbing parameters are regarding the material properties of substrate layer (ε, μ) or the thickness of each lay, which would require the derivatives of Green's kernels. The computation cost is expensive to obtain the derivatives of the planar Green's functions in spectral domain, and sometimes it is very difficult to realize. In this article, the use of planar Green's functions in DCIM form makes it possible to calculate the derivatives in spatial domain efficiently. In this way, the derivatives could be replaced by finite-difference, for which the accuracy would be subject to the order of the finite-difference. An example of the S-parameter sensitivity of a low-pass filter with respect to the substrate permittivity is followed to validate the accuracy and efficiency of the proposed technique.

3. NUMERICAL RESULTS

A low-pass microstrip filter is shown in Figure 1. The dimension of the filter is $W_1 = 2.413$ mm, $W_2 = 2.54$ mm, $W_3 = 5.65$ mm, $a = 12.257$ mm, and $h = 0.794$ mm. The sensitivity of S-parameters with respect to the substrate permitivity is investigated. The response functions we are interested in are the analytical expressions of S_{11} and S_{21}. The matched load simulation (MLS) [8] is employed for the extraction of S-parameters from the current distribution. In MLS, traveling waves are forced in the output port so that the S-parameter could be calculated directly on the input line because of the matched load. The magnitude of S-parameters for the filter are given by

$$|S_{11}| = \frac{|I_1| - |I_2|}{|I_1| + |I_2|} \quad |S_{21}| = \frac{2|I_p|}{|I_1| + |I_2|} \tag{13}$$

where $I_1 = I_{\max}$ and $I_2 = I_{\min}$ are the current maximum and minimum of the standing wave pattern on the input line respectively, and I_{p} is the current magnitude at the output reference plane (traveling wave).

After the current distribution $\boldsymbol{I}$ is solved through Eq. (1), the adjoint matrix Eq. (10) should be constructed and solved for $\hat{\boldsymbol{I}}$. Take the $|S_{11}|$ for example, it is only explicitly determined by $I_{\max}$ and $I_{\min}$ through Eq. (13) so that the adjoint excitation only has two non-zero elements for the real and image part respectively as

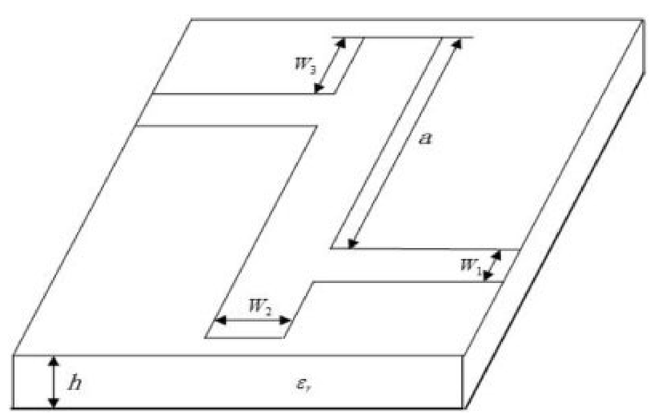
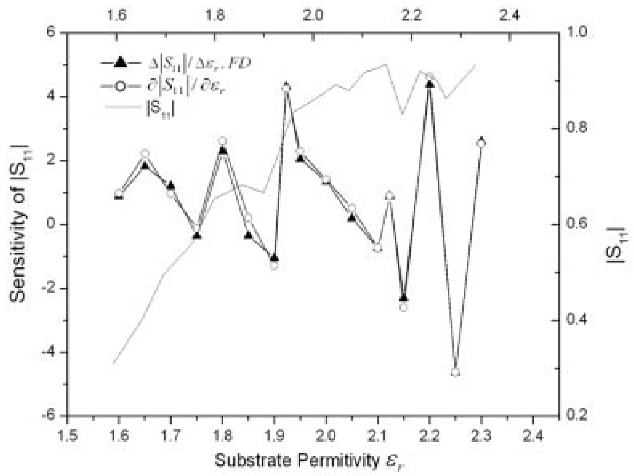
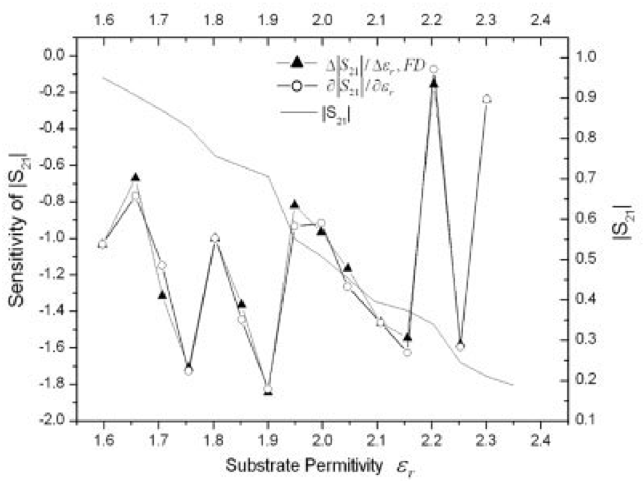


Figure 1 Configuration of a low-pass microstrip filter



(a) Sensitivity of $|S_{11}|$



(b) Sensitivity of $|S_{21}|$

Figure 2 *S*-parameter sensitivities versus substrate permittivity at 6 GHz

$$\nabla_{I_{Rm}} f = \begin{cases} \dfrac{2I_{1R}|I_2|}{|I_1|(|I_1| + |I_2|)^2}, & \text{when } I_m = I_{max} \\ \dfrac{-2I_{2R}|I_1|}{|I_2|(|I_1| + |I_2|)^2}, & \text{when } I_m = I_{min} \\ 0, & \text{else} \end{cases} \tag{14a}$$

$$\nabla_{I_{Im}} f = \begin{cases} \dfrac{2I_{1I}|I_2|}{|I_1|(|I_1| + |I_2|)^2}, & \text{when } I_m = I_{max} \\ \dfrac{-2I_{2I}|I_1|}{|I_2|(|I_1| + |I_2|)^2}, & \text{when } I_m = I_{min} \\ 0, & \text{else} \end{cases} \tag{14b}$$

where $I_{1R} = \mathrm{Re}\{I_1\}$, $I_{1I} = \mathrm{Im}\{I_1\}$, $I_{2R} = \mathrm{Re}\{I_2\}$, and $I_{1I} = \mathrm{Im}\{I_1\}$. After $\boldsymbol{I}$ and $\hat{\boldsymbol{I}}$ have been obtained, the sensitivity could be calculated via Eq. (12). Since the *S*-parameters and the exciting source $\boldsymbol{V}$ are not explicitly determined by the perturbing parameters, the first two terms in the right hand of Eq. (12) are zeros and only the third term remains, in which the derivative of Z matrix is approximated by finite difference (FD). It is a similar way to solve the sensitivity of $|S_{21}|$.

Figure 2 shows the magnitude of *S*-parameters of the low-pass filter at 6 GHz and their sensitivities respectively, with respect to the substrate permittivity. Sensitivities calculated by the present method show very good consistency with those obtained by FD directly from the *S*-parameter curves.

4. CONCLUSIONS AND DISCUSSION

In this article, the iterative adjoint technique is successfully applied to the analysis of sensitivity of microstrip circuits. The adjoint technique makes it easy to implement the full-wave sensitivity analysis for design optimization into the current MoM-based simulation tools. The use of the iterative schemes reduces the computational time in the conventional MoM procedure. The spatial Green's functions in DCIM form simplify the derivatives of the impedance matrix elements and realize the sensitivity analysis with respect to the design parameters, which the Green's functions depend on. Numerical methods validate the accuracy of the present technique.

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HIGH POWER 60 GHz PUSH–PUSH OSCILLATOR USING InALAs/InGaAs METAMORPHIC HEMT TECHNOLOGY

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ABSTRACT: *This paper reports a high power 60 GHz push–push oscillator fabricated using 0.12 μm GaAs metamorphic high electron-mobility transistors. By combining high-power metamorphic high electron mobility transistor (MHEMT) optimized for millimeter-wave operation and push–push technique, the oscillator achieved 7.4 dBm of output power at 59 GHz with 37 dBc fundamental frequency suppression. To*