INTEGRATED HARMONIC BALANCE AND ELECTROMAGNETIC OPTIMIZATION WITH GEOMETRY CAPTURE

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ABSTRACT

This paper presents an integrated approach to nonlinear circuit optimization. Electromagnetic simulations are seamlessly integrated into harmonic balance simulation and optimization. For the first time, complicated planar structures can be made fully optimizable through the parameterization process of our breakthrough Geometry Capture technique. They are then treated as individual elements in electromagnetic simulations and are embedded into the overall nonlinear circuit to be optimized. A comprehensive class B frequency doubler design demonstrates our approach.

INTRODUCTION

In this paper we present a novel approach to nonlinear circuit design by directly integrating electromagnetic (EM) simulations into harmonic balance (HB) optimization. The parameterized microstrip subcircuit is simulated by the EM simulator. The results are returned to the HB simulator for complete circuit simulation and optimization. We parameterize a complicated planar structure as a whole using the breakthrough "Geometry Capture" technique. This technique was created to make arbitrary microstrip structures fully optimizable.

Large-signal circuit optimization with the HB technique has been significantly advanced during the last decade (e.g., [1-5]). The computational time is greatly reduced due to the efficiency of the HB simulation and the elegant sensitivity calculation [3]. HB optimization using the FAST sensitivity technique has been applied to performance- and yield-driven designs [4, 5].

Conventionally, the microstrip elements are modeled by equivalent circuits, approximate physical models or look-up tables. The entire circuit is simulated at the circuit level. EM

simulators are used for generating equivalent circuits or look-up tables outside the optimization loop. In our recent pioneering work direct utilization of EM simulators in the optimization process has been limited to predefined substructures such as microstrip lines, steps and T-junctions, which are then connected in circuit-theoretic fashion (e.g., [6, 7]). The primary disadvantage of that approach is that many effects, such as the couplings between different elements, are not dealt with since the microstrip substructures are simulated individually.

With the availability of powerful workstations, massively parallel systems and fast, robust, commercial EM simulators, circuit designers are increasingly interested in interfacing EM simulations with circuit theory-based simulations (e.g., [8]). However, the EM simulators, whether stand-alone or incorporated into CAD frameworks, may not realize their full potential to the designer unless they are driven by optimization routines to automatically adjust the designable parameters [9].

Our novel approach to EM/HB optimization is demonstrated by a comprehensive class B frequency doubler design. OSA90/hope [10] and em [11] connected through Empipe [10] are used to carry out all the computations.

INTEGRATION OF EM AND HB SIMULATION

In general, a nonlinear circuit can be partitioned into a nonlinear subcircuit, a linear subcircuit and an excitation subcircuit as shown in Fig. 1. The linear subcircuit can be further divided into a lumped element subcircuit and a microstrip element subcircuit also shown in Fig. 1. Let the circuit parameters be

$$\phi = \left[\begin{array}{ccc} \phi_N^T & \phi_{LL}^T & \phi_{LM}^T \end{array} \right]^T \qquad (1)$$

where ϕ_N are the parameters of the nonlinear subcircuit, ϕ_{LL} and ϕ_{LM} are the parameters of the lumped element subcircuit and the microstrip element subcircuit, respectively. The HB equation of the circuit can be written as

$$F(\phi, V(\phi)) = I(\phi, V(\phi)) + j\Omega Q(\phi, V(\phi)) + Y(\phi)V(\phi) + I_s = 0 \qquad (2)$$

where V is the vector of nonlinear port voltages to be solved for, I and Q the vectors of currents and charges entering the nonlinear ports, respectively, Ω the angular frequency matrix, I_s the vector of equivalent excitation currents, and Y the equivalent admittance matrix of the linear subcircuit corresponding to the connection ports. Y is a function of frequency f and parameters of the linear subcircuit ϕ_{LL} and ϕ_{LM}, which can be expressed as

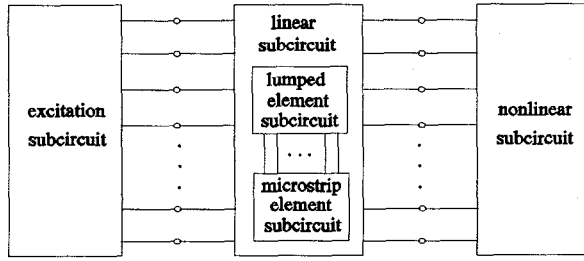$$Y(\phi) = Y(f, \phi_{LL}, R_{EM}(f, \phi_{LM})) \qquad (3)$$

Fig. 1. Partition of a nonlinear microwave circuit for combined HB/EM simulation.

where $R_{EM}(f, \phi_{LM})$ represents the EM responses.

Once $R_{EM}(f, \phi_{LM})$ is returned from the EM simulator $Y(\phi)$ is obtained from (3) and then the HB equation (2) is solved. The Newton update for solving (2) can be written as

$$V_{new}(\phi) = V_{old}(\phi) - [J(\phi, V_{old}(\phi))]^{-1}F(\phi, V_{old}(\phi)) \qquad (4)$$

where $J(\phi, V(\phi))$ is the Jacobian matrix.

GEOMETRY CAPTURE

"Geometry Capture" [10] is a user-friendly tool for parameterizing arbitrary structures. It facilitates automatic translation of the values of user-defined designable parameters to the layout description in terms of absolute coordinates. The latter is the required input to EM simulators. During optimization, this translation is performed for each new set of parameter values before the EM simulator is invoked.

Using a graphical layout editing tool (such as *xgeom* for *em* from Sonnet Software [11]), the user generates a set of geometries marking the evolution of the structure under consideration as the designable parameters change. For example, consider parameterization of a step structure shown in Fig. 2. Two parameters, the width W and length L, are selected as designable. The evolution of the structure is described by the nominal structure, the structure reflecting a change in W and the structure reflecting a change in L. The Geometry Capture form editor with the corresponding data entries is shown in Fig. 3. The first three entries are names of the files containing the nominal geometry, the control parameters and the optional DC S-parameter data, respectively. The following two entries refer to the geometries generated with perturbed values of W and L.

The resulting information is then processed by Empipe to establish the mapping between the designable parameter values and the geometrical coordinates.
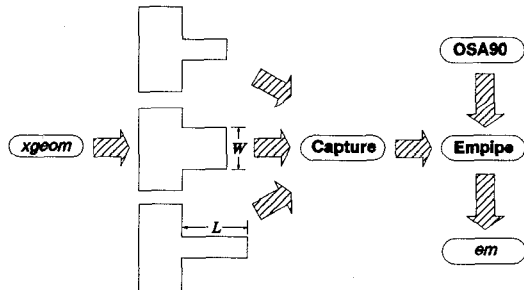

Fig. 2. Illustration of Geometry Capture for parameterizing the step structure w.r.t. L and W.

Fig. 3. Geometry Capture form editor for parameterization of the step structure.

GRADIENT-BASED DIRECT HB AND EM OPTIMIZATION

Consider a vector of circuit responses

$$R_{CT}(\phi) = R(\phi, V(\phi, R_{EM}(\phi))) \qquad (5)$$

which may include output voltages, currents, powers, power gains, etc. Let S be a set of design specifications. The objective function for a design problem can be written as

$$U(\phi) = U(R_{CT}(\phi), S) \qquad (6)$$

The corresponding design optimization problem is

$$\underset{\phi}{\text{minimize}} \quad U(\phi) \qquad (7)$$

The derivatives of U w.r.t. each design variable ϕ_i in ϕ are required to solve (7) using a gradient-based optimizer. From (6) we have

$$\frac{\partial U}{\partial \phi_i} = \left[\frac{\partial U}{\partial R_{CT}}\right]^T \frac{\partial R_{CT}}{\partial \phi_i} \qquad (8)$$

$\partial U/\partial R_{CT}$ depends on the form of the objective function defined by (6). $\partial R_{CT}/\partial \phi_i$ can be derived from (5) as

$$\frac{\partial R_{CT}}{\partial \phi_i} = \frac{\partial R}{\partial \phi_i} + \left[\frac{\partial R^T}{\partial V}\right]^T \left\{\frac{\partial V}{\partial \phi_i} + \left[\frac{\partial V^T}{\partial R_{EM}}\right]^T \frac{\partial R_{EM}}{\partial \phi_i}\right\} \qquad (9)$$

which can be evaluated using an elegant gradient estimation technique [7].

SIMULATION AND OPTIMIZATION OF A CLASS B FREQUENCY DOUBLER

A class B frequency doubler is used as an example to demonstrate our new approach of integrated HB/EM simulation and optimization. The circuit structure, shown in Fig. 4, follows [12]. It consists of a single FET (NE71000) and a number of distributed microstrip elements including two radial stubs and two large bias pads.

Significant couplings between the distributed microstrip elements exist in this circuit, e.g., the couplings between the radial stubs and the bias pads. The conventional approach using
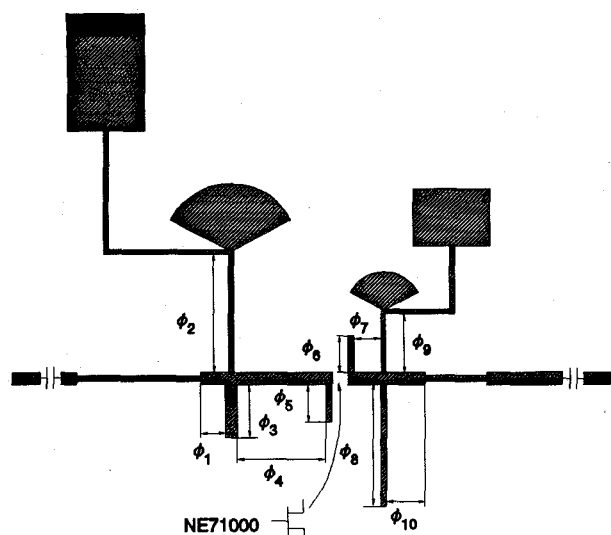
Fig. 4. Circuit structure of the class B frequency doubler.

empirical or physical models for individual microstrip elements neglects these couplings and therefore may result in large response errors. In order to take into account these couplings the entire microstrip structure should be considered as a single element to be simulated and optimized.

The design specifications are

conversion gain $\geq$ 3 dB

spectral purity $\geq$ 20 dB

at 7 GHz and 10 dBm input power.

We use the Curtice and Ettenberg FET model [13] to model the FET NE71000. The model parameters are extracted from the typical DC and S parameters [14] using HarPE [10].

The entire microstrip structure between the two capacitors (see Fig. 4) is parameterized using our Geometry Capture and considered as one element to be simulated by em [11]. The results are directly returned to OSA90/hope through Empipe for HB simulation and optimization. Ten parameters denoted as ϕ_1, ϕ_2, ..., ϕ_{10} are selected as design variables. The minimax optimizer of OSA90/hope is used to carry out the performance-driven design.

The values of design variables before and after optimization are listed in Table I. The conversion gain versus input power before and after optimization is shown in Fig. 5. The source and output voltage waveforms before and after optimization are plotted in Fig. 6. The 3D view of conversion gain versus frequency and input power before and after optimization are shown in Fig. 7. Significant improvement of the circuit performance is obtained and all specifications are satisfied after optimization.

ACKNOWLEDGEMENT

TABLE I
DESIGN VARIABLE VALUES
BEFORE AND AFTER OPTIMIZATION

Variable	Before Optimization	After Optimization
ϕ_1	1.5	1.494
ϕ_2	8.1	7.820
ϕ_3	3.3	3.347
ϕ_4	5.7	5.992
ϕ_5	2.4	2.550
ϕ_6	2.4	2.305
ϕ_7	1.8	1.750
ϕ_8	7.9	7.827
ϕ_9	4.2	4.242
ϕ_{10}	2.7	2.622

All dimensions are in mm.
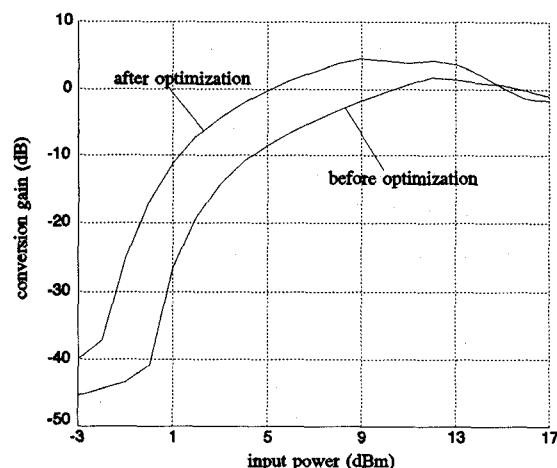

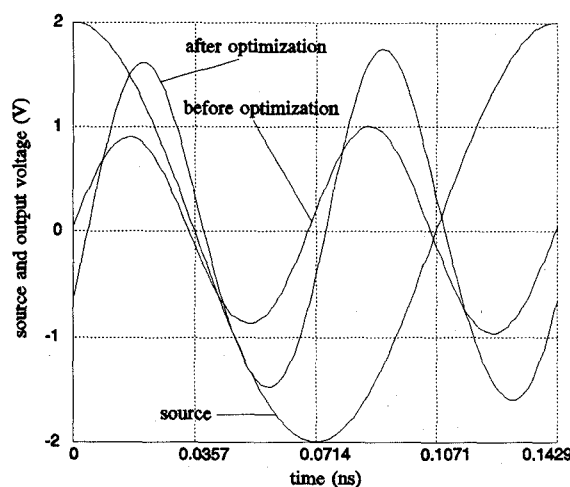Fig. 5. Conversion gain versus input power before and after optimization.

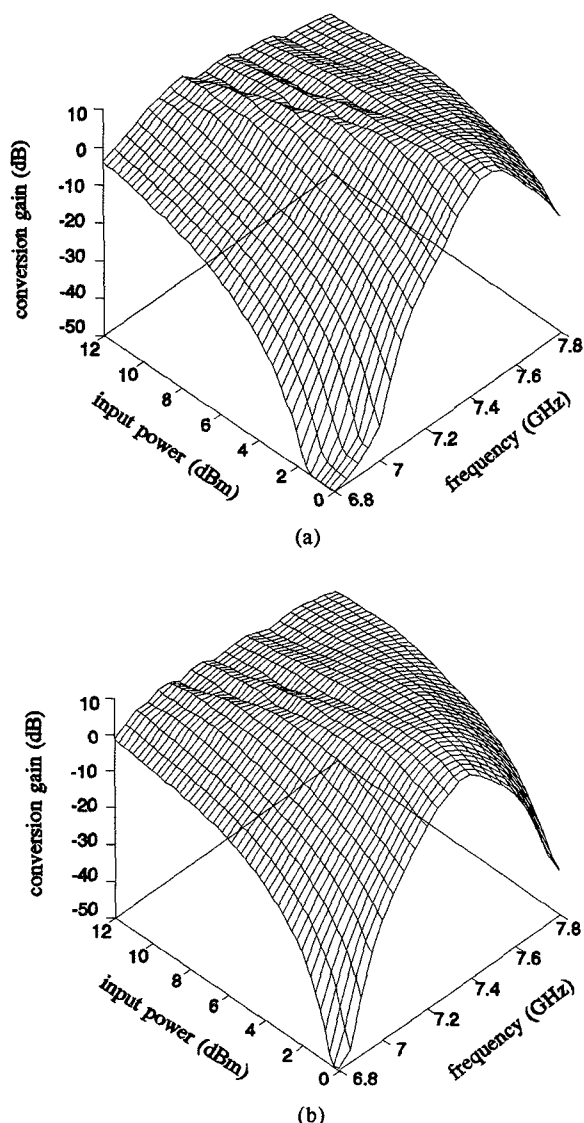Fig. 6. Source and output voltage waveforms before and after optimization.

(a)

(b)

Fig. 7. 3D view of conversion gain versus input power and frequency, (a) before and (b) after optimization.

CONCLUSIONS

We have presented an integrated approach to nonlinear circuit design. The importance of using EM simulators directly in nonlinear HB simulation and optimization has been emphasized. The features of our new approach have been demonstrated by optimization of a class B frequency doubler exploiting our user-friendly Geometry Capture technique for arbitrary structure parameterization. Geometry Capture provides a powerful tool for microwave engineers to accurately design circuits consisting of complicated structures and investigate new microstrip components.

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