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ELECTROMAGNETIC OPTIMIZATION
WITH GEOMETRY CAPTURE**

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Full Length

Prioritized List of Areas:

- 1. EM Analytical and Numerical Techniques**
- 2. CAD Procedures, Techniques and Modeling**
- 3. Nonlinear Modeling and Analysis**

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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.

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SUMMARY

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 an individual element 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., [1-6]). The computational time is greatly reduced due to the efficiency of the HB simulation and the elegant sensitivity calculation [3, 4]. HB optimization using the FAST sensitivity technique has been applied to performance- and yield-driven designs [5, 6].

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., [7, 8]). 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 with circuit simulation (e.g., [9-11]). 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 [12].

Our novel approach to EM/HB optimization is demonstrated by a comprehensive class B frequency doubler design. OSA90/hope [13] and *em* [14] connected through Empipe [15] 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

$$\phi = \begin{bmatrix} \phi_N^T & \phi_{LL}^T & \phi_{LM}^T \end{bmatrix}^T \quad (1)$$

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

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

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 linear subcircuit ϕ_{LL} and ϕ_{LM} , which can be expressed as

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

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

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

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

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

Geometry Capture

Automated EM optimization raises a number of challenges. We have refined interpolation and modeling techniques [7, 8, 10, 15-17] in order to reconcile the discrete nature of numerical EM solvers and the requirement of continuous variables and gradients by the optimizers. We have also introduced an intelligent data base to eliminate duplicate EM simulations.

There is also the problem of geometrical parameterization. Conventional circuit theory based simulators assume a library of built-in elements with predefined parameters. Circuits to be simulated must be modeled as a set of such interconnected elements. The characteristics of each element can be modified parametrically by, for instance, changing a numerical entry in the netlist. EM simulators, on the other hand, deal directly with the layout representation of a circuit. The numerical values contained in their "netlist" are typically geometrical coordinates which cannot be related in an obvious way to designable parameters.

An Empipe element library [15] was created in our earlier work. The library contains geometrical primitives (lines, bends, junctions, gaps, stubs, etc.) from which a subcircuit structure can be built. This approach gained immediate acceptance by CAD users by virtue of its familiarity and ease of use. Also, it minimizes the complexity of EM analysis since each time only one elementary geometry is analyzed. However, this approach inherently omits possible proximity couplings between the elements since they are connected by the circuit-level simulator. Furthermore, it does not accommodate structures which cannot be decomposed into library elements.

To provide a tool for parameterizing arbitrary structures, we created the user-friendly "Geometry Capture" [15]. Using a graphical layout editing tool (such as *xgeom* for *em* from Sonnet Software [14]), the user generates a set of geometries marking the evolution of the structure under consideration as the designable parameters change (Fig. 2). The resulting geometries are then processed by Empipe to extract the information from which a mapping between the geometrical coordinates and the designable parameter values is established. Fig. 3 depicts an EM optimization

framework in which Geometry Capture for arbitrary structures complements the Empipe library of typical primitives.

Gradient-Based Direct HB and EM Optimization

Consider a vector of circuit responses

$$\mathbf{R}_{CT}(\boldsymbol{\phi}) = \mathbf{R}(\boldsymbol{\phi}, \mathbf{V}(\boldsymbol{\phi}, \mathbf{R}_{EM}(\boldsymbol{\phi}))) \quad (5)$$

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

$$U(\boldsymbol{\phi}) = U(\mathbf{R}_{CT}(\boldsymbol{\phi}), \mathcal{S}) \quad (6)$$

The corresponding design optimization problem is

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

The derivatives of U w.r.t. each design variable ϕ_i in $\boldsymbol{\phi}$ are required to solve (7) using gradient-based optimizers. From (6) we have

$$\frac{\partial U}{\partial \phi_i} = \left[\frac{\partial U}{\partial \mathbf{R}_{CT}} \right]^T \frac{\partial \mathbf{R}_{CT}}{\partial \phi_i} \quad (8)$$

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

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

which can be evaluated by perturbation with an elegant gradient estimation technique [8].

The complete design optimization can be illustrated by the flowchart shown in Fig. 4.

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, as shown in Fig. 5, follows

[18]. 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 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

$$\begin{aligned} \text{conversion gain} &\geq 3 \text{ dB} \\ \text{spectral purity} &\geq 20 \text{ dB} \end{aligned}$$

at 7 GHz and 10 dBm input power.

We use the Curtice and Ettenberg FET model [19] to model the FET NE71000. The model parameters are extracted from the typical DC and S parameters [20] using HarPE [21].

The entire microstrip structure between the two capacitors is considered as one element to be simulated by *em* [14]. The results are directly returned to OSA90/hope through Empipe for HB simulation and optimization. Ten parameters including ϕ_{ML1} , ϕ_{ML2} , ..., ϕ_{ML10} 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. 6. The source and output voltage waveforms before and after optimization are plotted in Fig. 7. The 3D view of conversion gain versus frequency and input power before and after optimization are shown in Fig. 8. Significant improvement of the circuit performance is obtained and all specifications are satisfied 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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References

- [1] V. Rizzoli, A. Lipparini and E. Marazzi, "A general-purpose program for nonlinear microwave circuit design," *IEEE Trans. Microwave Theory Tech.*, vol. 31, 1983, pp. 762-770.
- [2] K.S. Kundert and A. Sangiovanni-Vincentelli, "Simulation of nonlinear circuits in the frequency domain," *IEEE Trans. Computer-Aided Design*, vol. CAD-5, 1986, pp. 521-535.
- [3] J.W. Bandler, Q.J. Zhang and R.M. Biernacki, "A unified theory for frequency domain simulation and sensitivity analysis of linear and nonlinear circuits," *IEEE Trans. Microwave Theory Tech.*, vol. 36, 1988, pp. 1661-1669.
- [4] J.W. Bandler, Q.J. Zhang and R.M. Biernacki, "Practical, high-speed gradient computation for harmonic balance simulators," *IEEE Int. Microwave Symp. Dig.* (Long Beach, CA), 1989, pp. 363-366.
- [5] J.W. Bandler, Q.J. Zhang, J. Song and R.M. Biernacki, "FAST gradient based yield optimization of nonlinear circuits", *IEEE Trans. Microwave Theory Tech.*, vol. 38, 1990, pp. 1701-1710.
- [6] J.W. Bandler, R.M. Biernacki, Q. Cai, S.H. Chen, S. Ye and Q.J. Zhang, "Integrated physics-oriented statistical modeling, simulation and optimization," *IEEE Trans. Microwave Theory Tech.*, vol. 40, 1992, pp. 1374-1400.
- [7] J.W. Bandler, R.M. Biernacki, S.H. Chen, P.A. Grobelny and S. Ye, "Yield-driven electromagnetic optimization via multilevel multidimensional models," *IEEE Trans. Microwave Theory Tech.*, vol. 41, 1993, pp. 2269-2278.

- [8] J.W. Bandler, R.M. Biernacki, S.H. Chen, D.G. Swanson, Jr., and S. Ye, "Microstrip filter design using direct EM field simulation," *IEEE Trans. Microwave Theory Tech.*, vol. 42, 1994, pp. 1353-1359.
- [9] P.P.M. So, W.J.R. Hoefer, J.W. Bandler, R.M. Biernacki and S.H. Chen, "Hybrid frequency/time domain field theory based CAD of microwave circuit," *Proc. 23rd European Microwave Conf.* (Madrid, Spain), 1993, pp. 218-219.
- [10] J.W. Bandler, R.M. Biernacki, S.H. Chen and P.A. Grobelny, "A CAD environment for performance and yield driven circuit design employing electromagnetic field simulators," *Proc. Int. Symp. Circuits and Systems* (London, England), vol. 1, 1994, pp. 145-148.
- [11] M.I. Sobhy, E.A. Hosny, M.H. El-Azeem, P. Russer and B. Isle, "Interfacing electromagnetic structures and lumped nonlinear circuits," *Third Int. Workshop on Integrated Nonlinear Microwave and Millimeterwave Circuits INMMC'94 Dig.* (Duisburg, Germany), 1994, pp. 223-230.
- [12] J.W. Bandler, "Circuit design with direct optimization-driven electromagnetic simulators," *IEEE Int. Microwave Symposium, Panel Session on Circuit Design with Direct Optimization-Driven Electromagnetic Simulators* (San Diego, CA), 1994.
- [13] *OSA90/hope™*, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1994.
- [14] *em™* and *xgeom™*, Sonnet Software, Inc., Suite 203, 135 Old Cove Road, Liverpool, NY 13090-3774, 1994.
- [15] *Empipe™*, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1994.
- [16] R.M. Biernacki and M.A. Styblinski, "Efficient performance function interpolation scheme and its application to statistical circuit design," *IEEE Int. J. Circuit Theory and Appl.*, vol. 19, 1991, pp. 403-422.
- [17] R.M. Biernacki, J.W. Bandler, J. Song and Q.J. Zhang, "Efficient quadratic approximation for statistical design," *IEEE Trans. Circuits and Systems*, vol. 36, 1989, pp. 1449-1454.
- [18] "Non-linear CAD benchmark," *Microwave Engineering Europe*, November 1993, pp. 11-15.
- [19] W.R. Curtice and M. Ettenberg, "A nonlinear GaAs FET model for use in the design of output circuits for power amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-33, 1985, pp. 1383-1394.
- [20] "RF and Microwave Semiconductors," *NEC Data Book*, NEC California Eastern Laboratories, 1994.
- [21] *HarPE™*, Optimization Systems Associates Inc., P.O. Box 8083, Dundas, Ontario, Canada L9H 5E7, 1994.

TABLE I
DESIGN VARIABLE VALUES
BEFORE AND AFTER OPTIMIZATION

Variable	Before Optimization	After Optimization
ϕ_{ML1}	1.5	1.494
ϕ_{ML2}	8.1	7.820
ϕ_{ML3}	3.3	3.347
ϕ_{ML4}	5.7	5.992
ϕ_{ML5}	2.4	2.550
ϕ_{ML6}	2.4	2.305
ϕ_{ML7}	1.8	1.750
ϕ_{ML8}	7.9	7.827
ϕ_{ML9}	4.2	4.242
ϕ_{ML10}	2.7	2.622
All dimensions are in mm.		

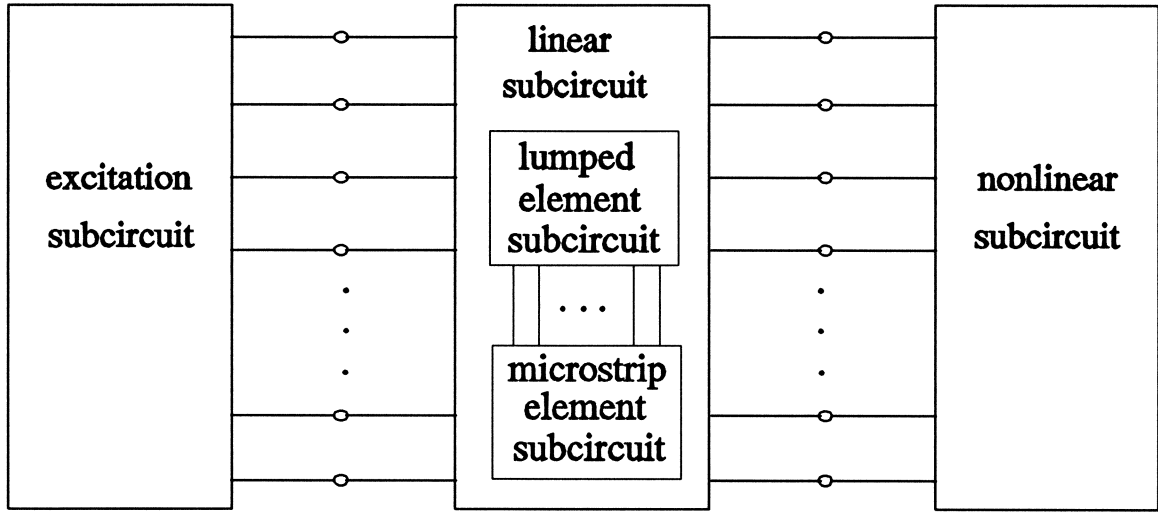


Fig. 1. Partition of a nonlinear microwave circuit for combined HB/EM simulation.

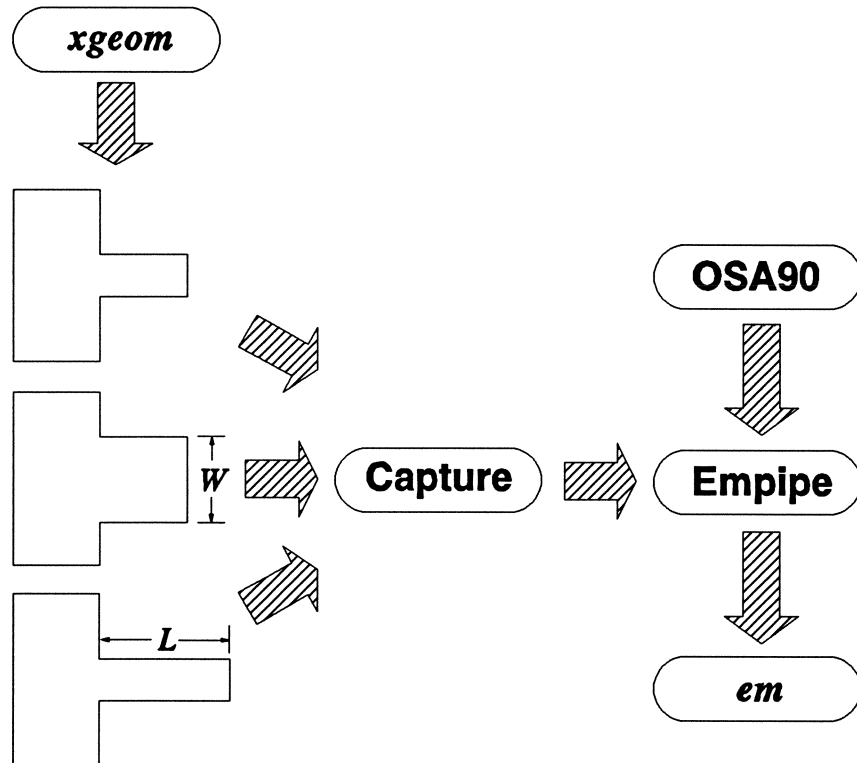


Fig. 2. An illustration of Geometry Capture for parameterizing L and W .

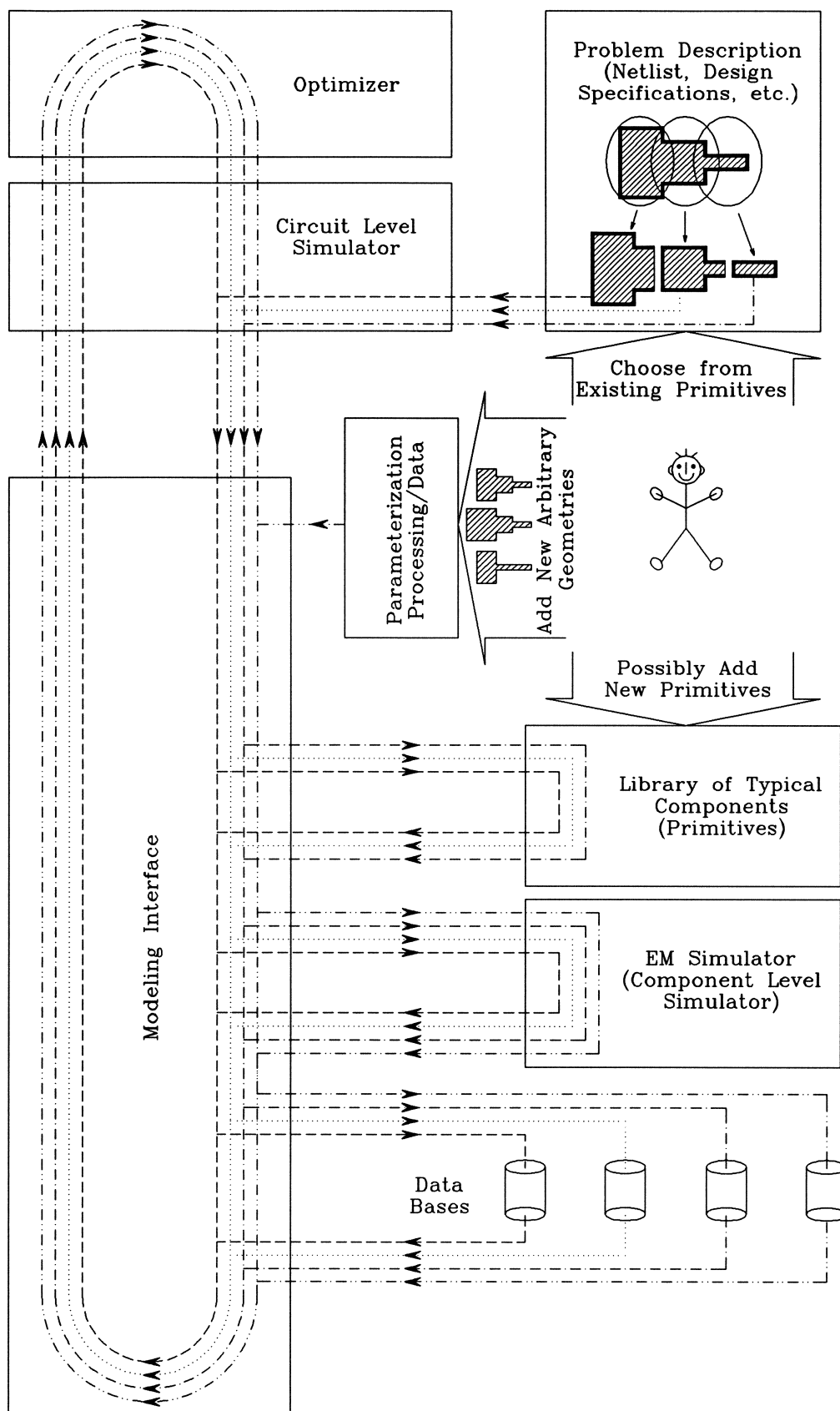


Fig. 3. EM optimization environment combining Geometry Capture for arbitrary structures and the Empipe library of typical microstrip primitives.

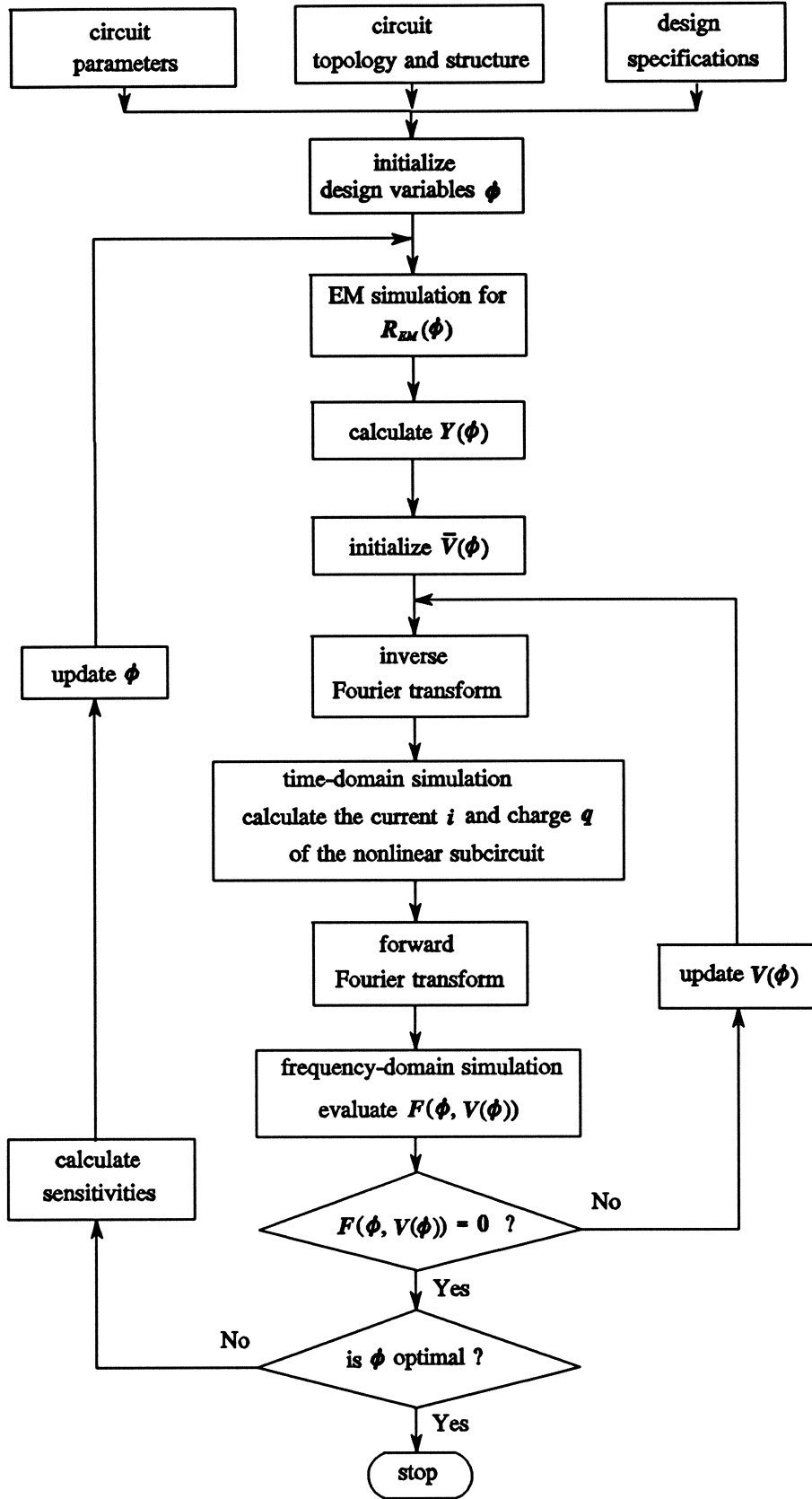


Fig. 4. Flowchart of integrated EM/HB circuit design optimization.

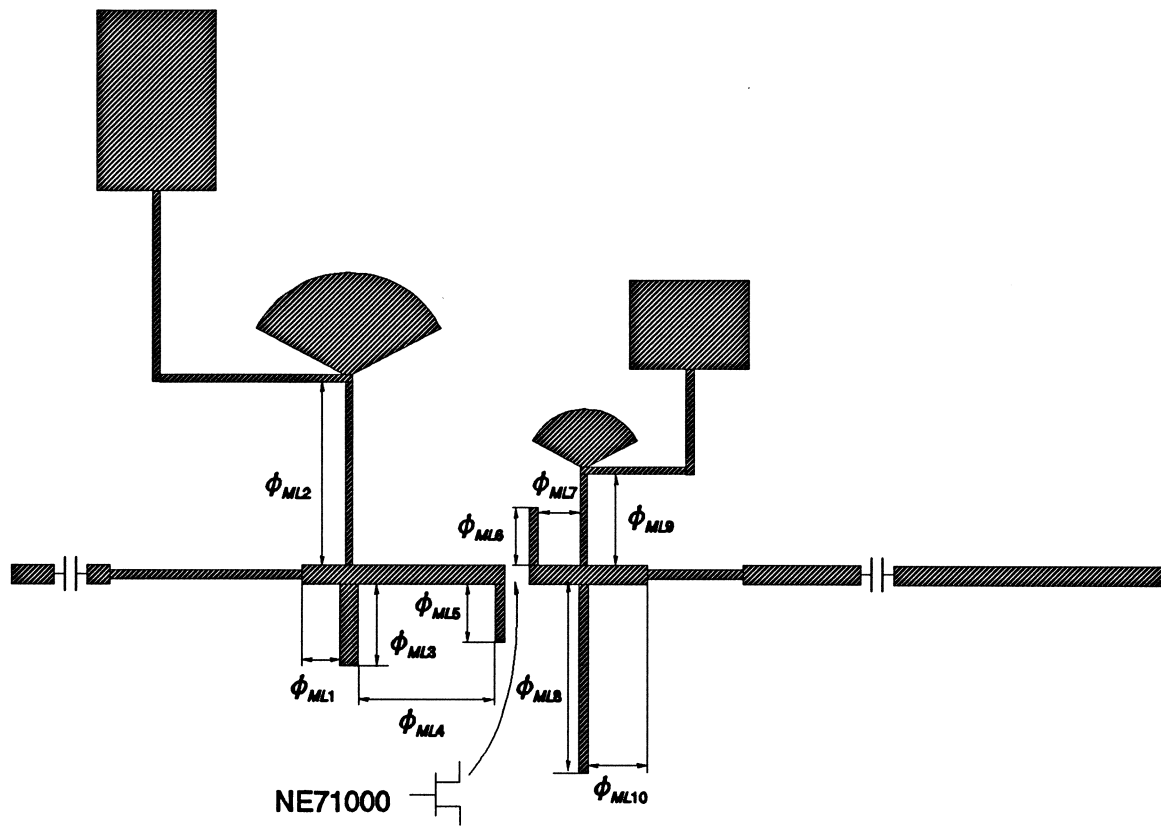


Fig. 5. Circuit structure of the class B frequency doubler.

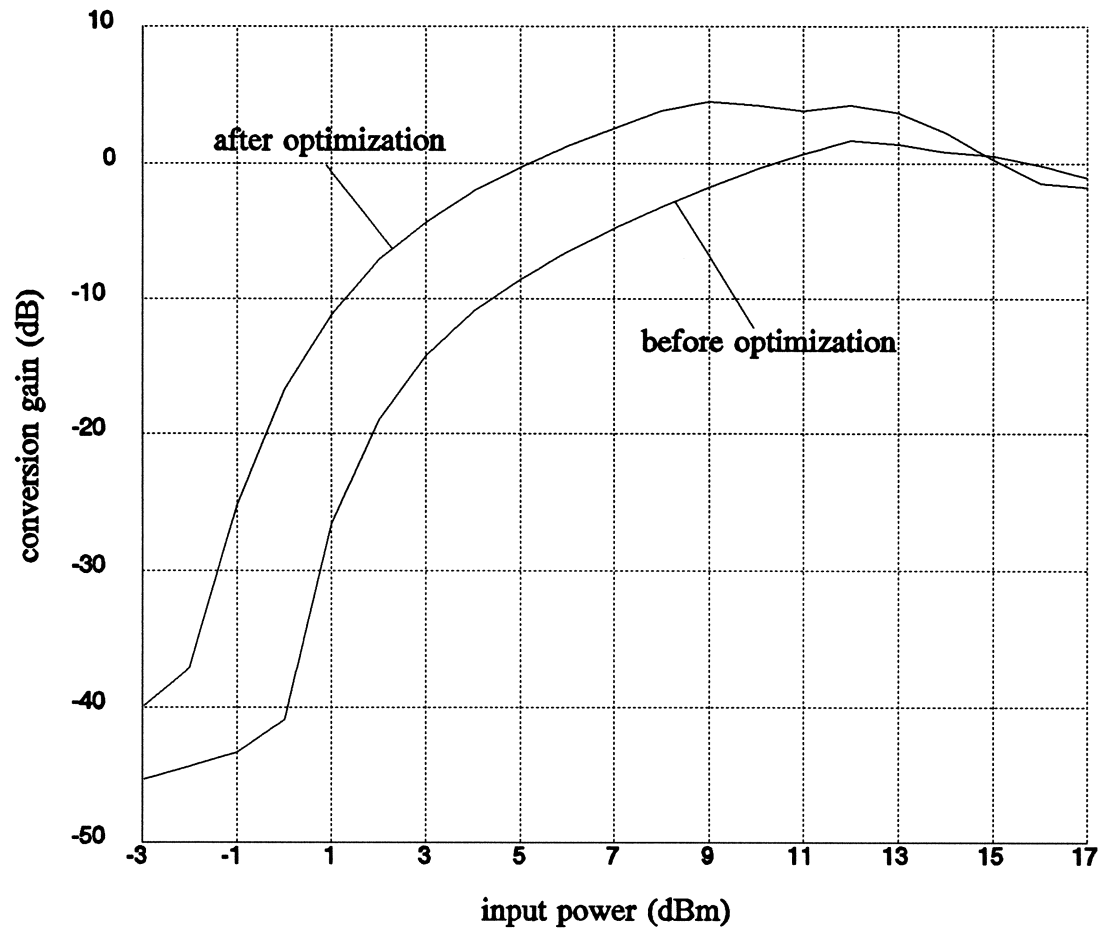


Fig. 6. Conversion gain versus input power before and after optimization.

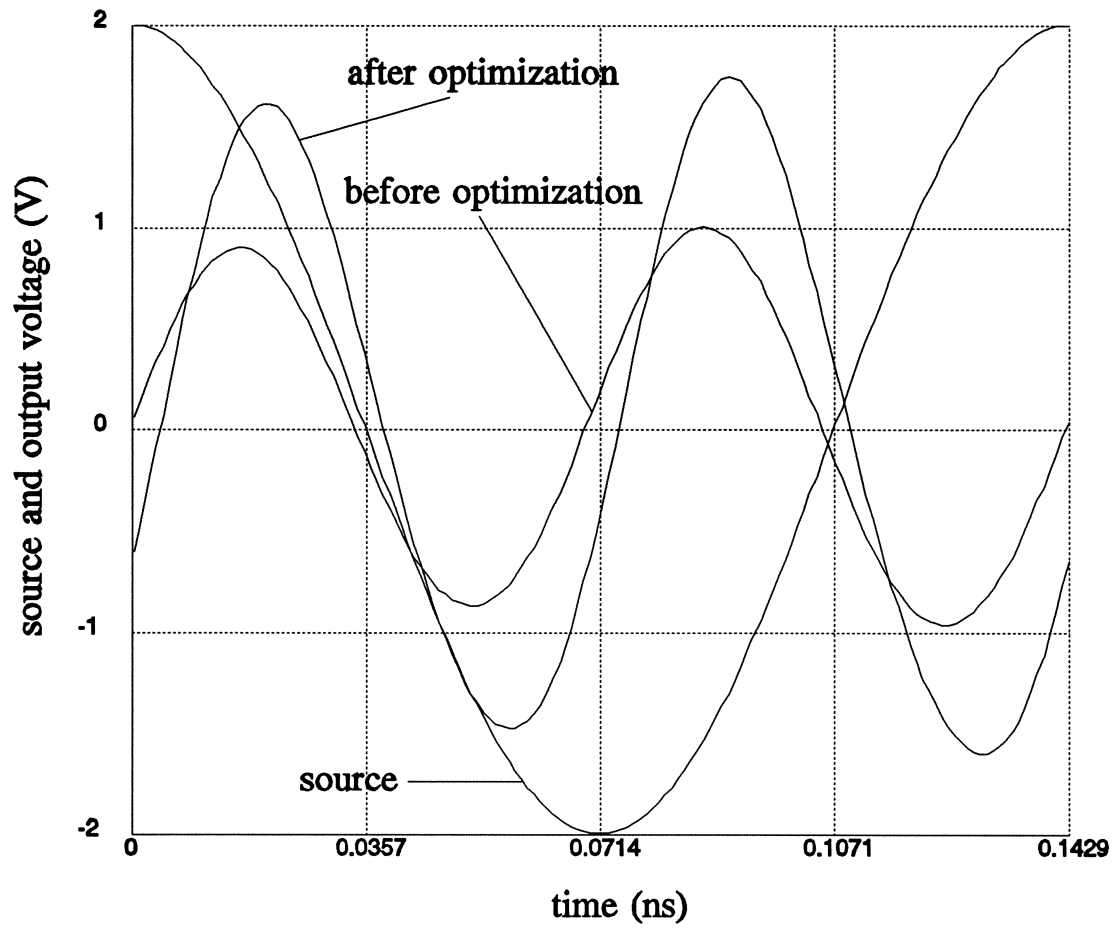


Fig. 7. Source and output voltage waveforms before and after optimization.

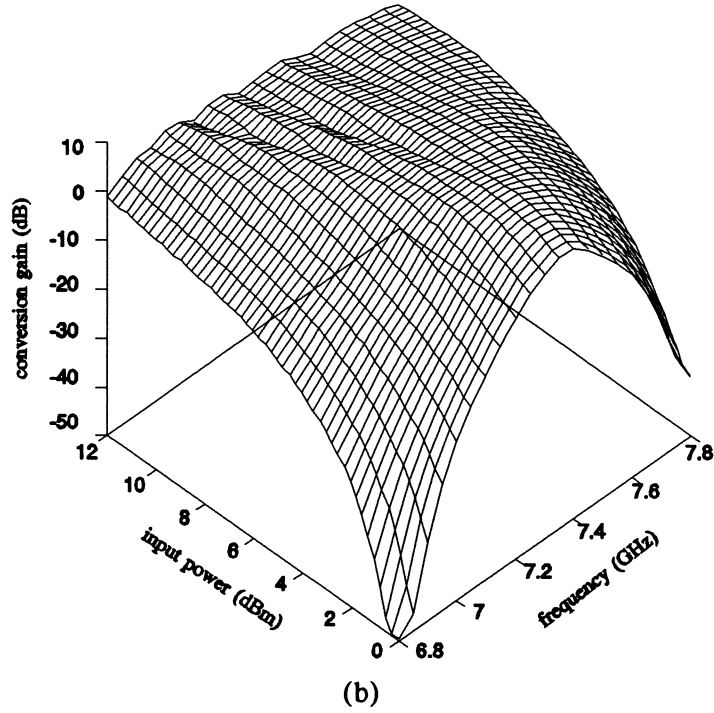
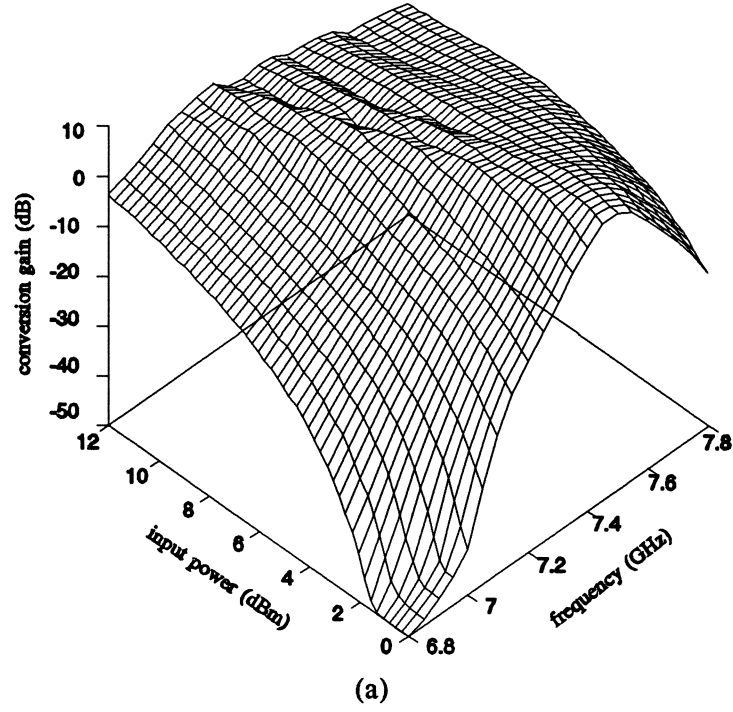


Fig. 8. 3D view of conversion gain versus input power and frequency, (a) before and (b) after optimization.