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 OSA's 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

large-signal circuit optimization with the harmonic balance (HB) technique has been significantly advanced with increasing efficiency in HB simulation and sensitivity calculation

fast and robust commercial electromagnetic (EM) simulators have proven to be a valuable tool in microwave CAD

EM simulators, whether stand-alone or incorporated into CAD frameworks, cannot realize their full potential unless they are driven by optimization routines

increasing demands from engineers to integrate EM simulations with circuit theory-based simulations within an optimization loop

first-pass success in circuit design requires accurate simulations for optimization

optimization of complicated structures and development of new components requires handling of arbitrary geometries

Advances in EM Optimization

conventional approaches

microstrip elements are modeled by equivalent circuits, approximate physical models or look-up tables

EM simulators are used for generating equivalent circuits or look-up tables outside the optimization loop

our pioneering work (*OSA's Empipe, 1992*)

direct utilization of EM simulators in the optimization process

predefined library of typical structures such as microstrip lines, steps, *T*-junctions, which can be connected in a circuit-theoretic fashion

our new approach

integrated EM and HB simulation and optimization

arbitrary planar structures fully optimizable through the parameterization process of OSA's breakthrough Geometry Capture technique

Integration of EM and HB Simulation

nonlinear subcircuit is simulated in the time domain

linear lumped element subcircuit is simulated in the frequency domain at the circuit level

linear microstrip element subcircuit is simulated by EM simulators at the field level

the results are integrated into the HB equation

$$\boldsymbol{F}(\boldsymbol{\phi}, \boldsymbol{V}(\boldsymbol{\phi})) = \boldsymbol{I}(\boldsymbol{\phi}, \boldsymbol{V}(\boldsymbol{\phi})) + j\Omega\, \boldsymbol{Q}(\boldsymbol{\phi}, \boldsymbol{V}(\boldsymbol{\phi})) + \boldsymbol{Y}(\boldsymbol{\phi})\boldsymbol{V}(\boldsymbol{\phi}) + \boldsymbol{I}_s = \boldsymbol{0}$$

$\boldsymbol{\phi} = \begin{bmatrix} \boldsymbol{\phi}_N^T & \boldsymbol{\phi}_{LL}^T & \boldsymbol{\phi}_{LM}^T \end{bmatrix}^T$ circuit parameters

$\boldsymbol{Y}(\boldsymbol{\phi}) = \boldsymbol{Y}(f, \boldsymbol{\phi}_{LL}, \boldsymbol{R}_{EM}(f, \boldsymbol{\phi}_{LM}))$ equivalent admittance matrix of the entire linear subcircuit

$\boldsymbol{R}_{EM}(f, \boldsymbol{\phi}_{LM})$ EM responses returned from EM simulators

the Newton update for solving the HB equation

$$\boldsymbol{V}_{new}(\boldsymbol{\phi}) = \boldsymbol{V}_{old}(\boldsymbol{\phi}) - [\boldsymbol{J}(\boldsymbol{\phi}, \boldsymbol{V}_{old}(\boldsymbol{\phi}))]^{-1}\boldsymbol{F}(\boldsymbol{\phi}, \boldsymbol{V}_{old}(\boldsymbol{\phi}))$$

$\boldsymbol{J}(\boldsymbol{\phi}, \boldsymbol{V}(\boldsymbol{\phi}))$ the Jacobian matrix

Geometry Capture
(*OSA, 1994*)

a technical breakthrough for parameterization of arbitrary structures for EM optimization

a user-friendly tool to establish the mapping between the designable parameter values and the geometrical coordinates

translation of the values of user-defined designable parameters to the layout description in terms of absolute coordinates for EM simulators

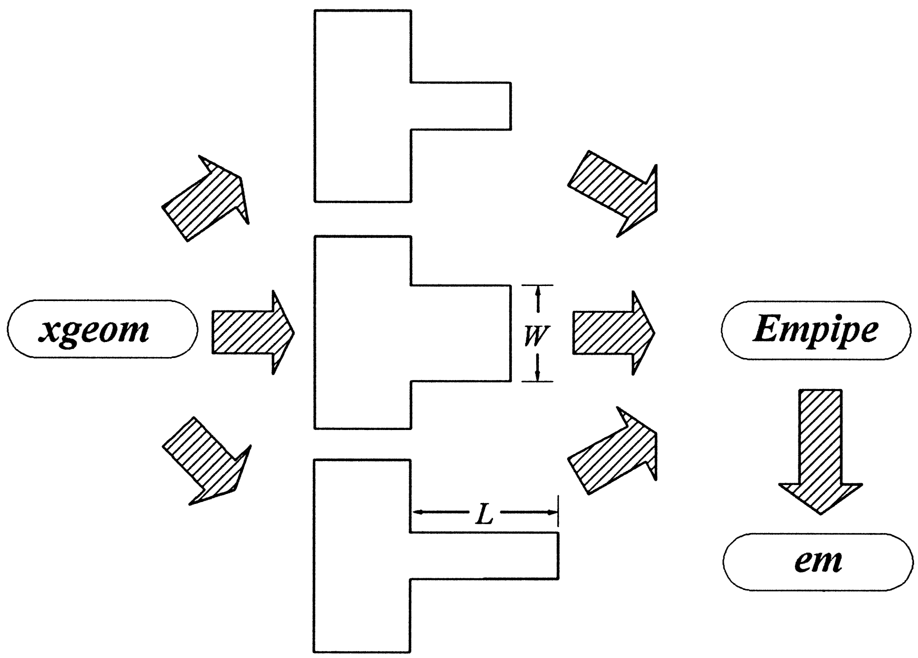
translation is automatically involved

utilization of the graphical layout editing tool provided by the EM simulators (such as ***xgeom*** for ***em*** from Sonnet Software)

parameterizable

geometrical dimensions
dielectrical layer
metallization

Illustration of Geometry Capture

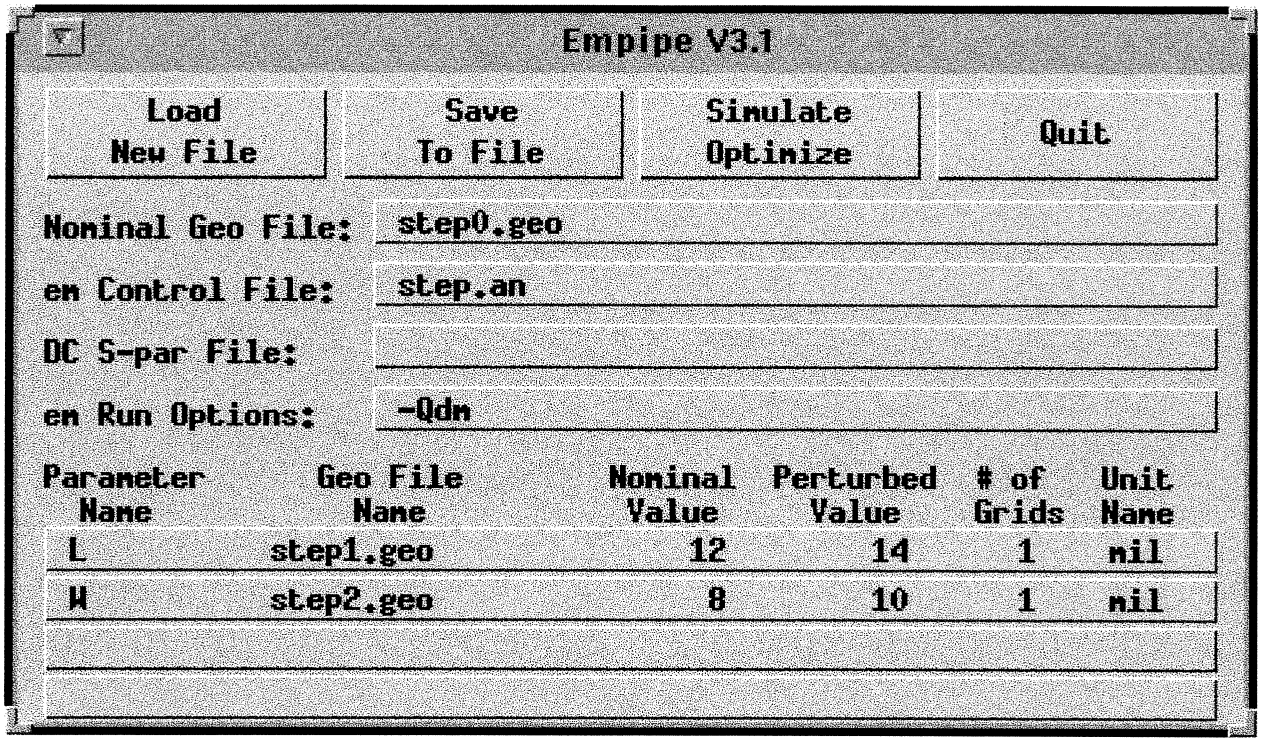


two parameters, the width W and length L, are selected as designable

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

Geometry Capture Form Editor



step0.geo	"geo" file for the nominal geometry
step1.geo	"geo" file for the geometry with perturbed *L*
step2.geo	"geo" file for the geometry with perturbed *W*
step.an	the file containing the control parameters for ***em***

Empipe processes the input information and automatically generates the "ckt" file and drives ***em*** for EM simulation and optimization

Gradient-Based Direct HB and EM Optimization

consider a vector of circuit responses

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

which may include output voltages, currents, powers, power gains, S parameters, etc.

an appropriate objective function $U(\boldsymbol{\phi})$ (e.g., minimax, ℓ_1, ℓ_2 or Huber function) is formulated from $\boldsymbol{R}_{CT}$ and the specifications imposed on $\boldsymbol{R}_{CT}$

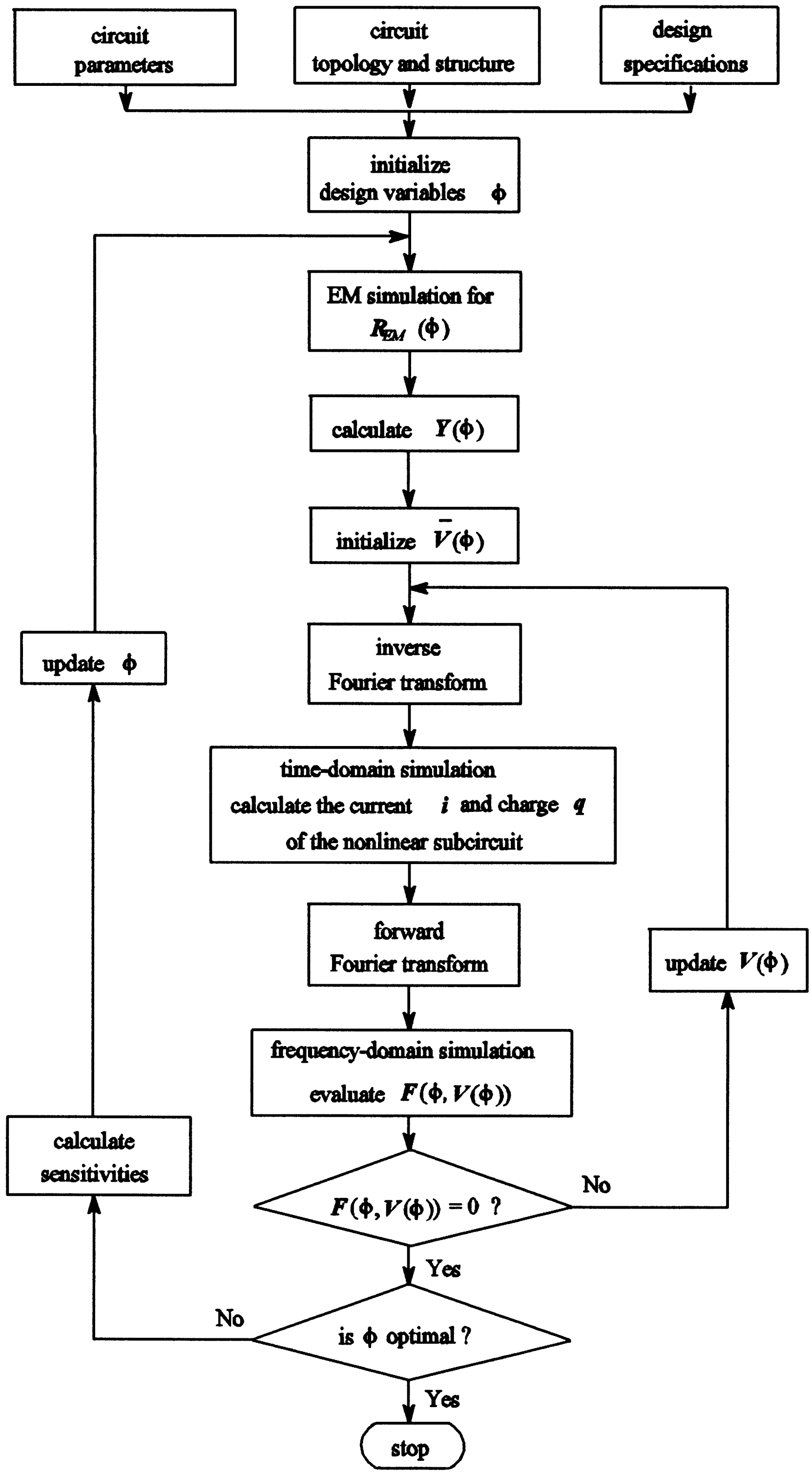
optimization

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

derivatives of $\boldsymbol{R}_{CT}$ w.r.t. each design variable ϕ_i in $\boldsymbol{\phi}$ are required for gradient-based optimization

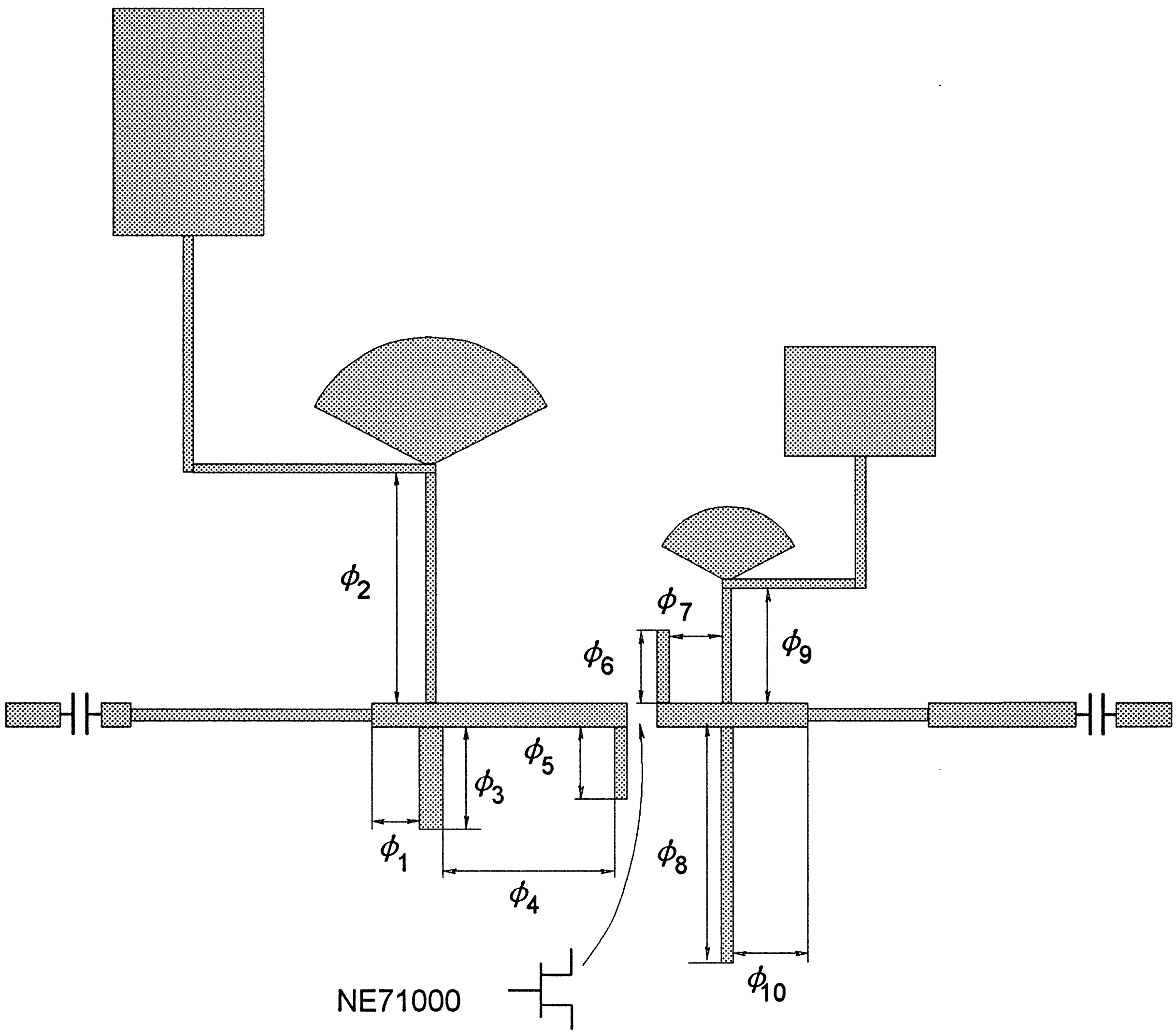
$$\frac{\partial \boldsymbol{R}_{CT}}{\partial \phi_i} = \frac{\partial \boldsymbol{R}}{\partial \phi_i} + \left[\frac{\partial \boldsymbol{R}^T}{\partial \boldsymbol{V}}\right]^T \left(\frac{\partial \boldsymbol{V}}{\partial \phi_i} + \left[\frac{\partial \boldsymbol{V}^T}{\partial \boldsymbol{R}_{EM}}\right]^T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

Flowchart of EM/HB Optimization



EM Optimization of a Class B Frequency Doubler

(*Microwave Engineering Europe, 1994*)



Circuit Characteristics and Design Specifications

the circuit 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, e.g., the couplings between the radial stubs and the bias pads

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 these couplings into account the entire microstrip structure should be considered as a single element to be simulated and optimized

the specifications are given at 7 GHz and 10 dBm input power

conversion gain ≥ 3 dB
spectral purity ≥ 20 dB

Simulation and Optimization

the NE71000 is modelled by the Curtice and Ettenberg FET model with parameters extracted from typical DC and *S* parameters using HarPE

the entire microstrip structure between the two capacitors is parameterized using Geometry Capture and considered as one element to be simulated by Sonnet's ***em***

the EM simulation 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

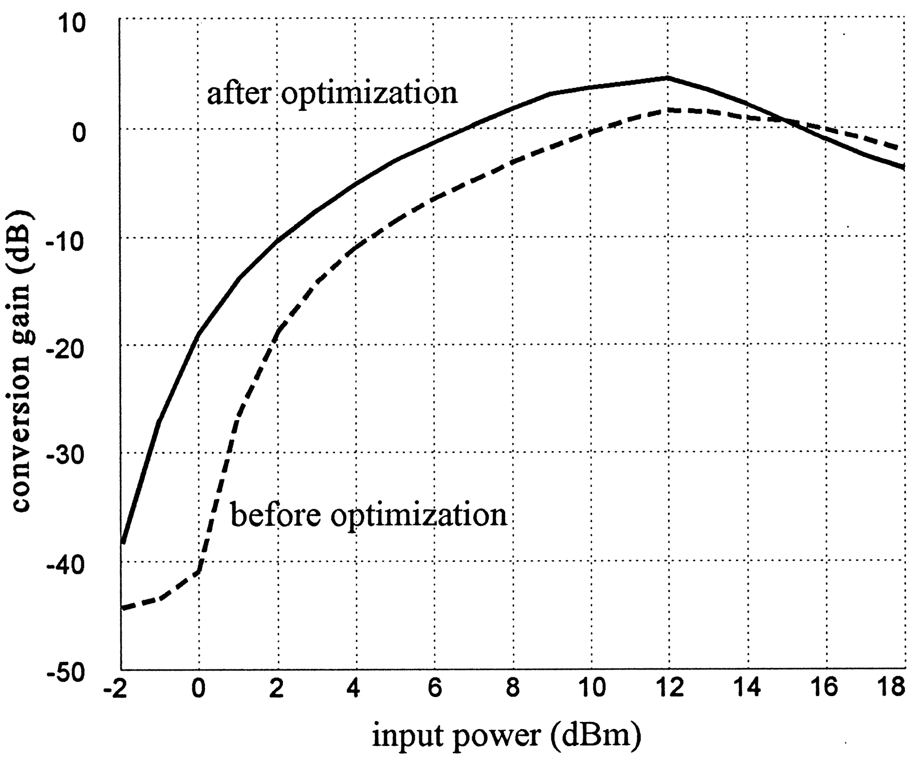
the minimax optimizer of OSA90/hope is used to carry out the performance-driven design

DESIGN VARIABLE VALUES BEFORE AND AFTER OPTIMIZATION

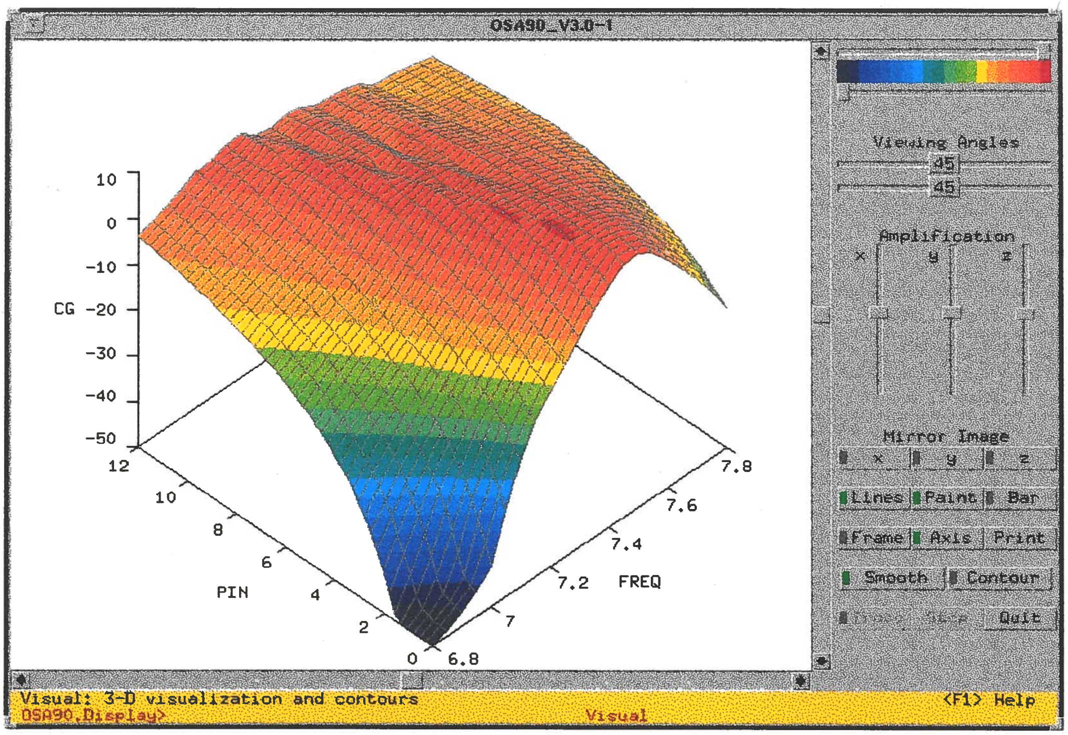
Variable	Before Optimization	After Optimization
ϕ_1	1.5	1.494
ϕ_2	8.1	7.820
ϕ_3	3.3	3.347
ϕ_4	5.7	5.992
ϕ_5	2.4	2.550
ϕ_6	2.4	2.305
ϕ_7	1.8	1.750
ϕ_8	7.9	7.827
ϕ_9	4.2	4.242
ϕ_{10}	2.7	2.622

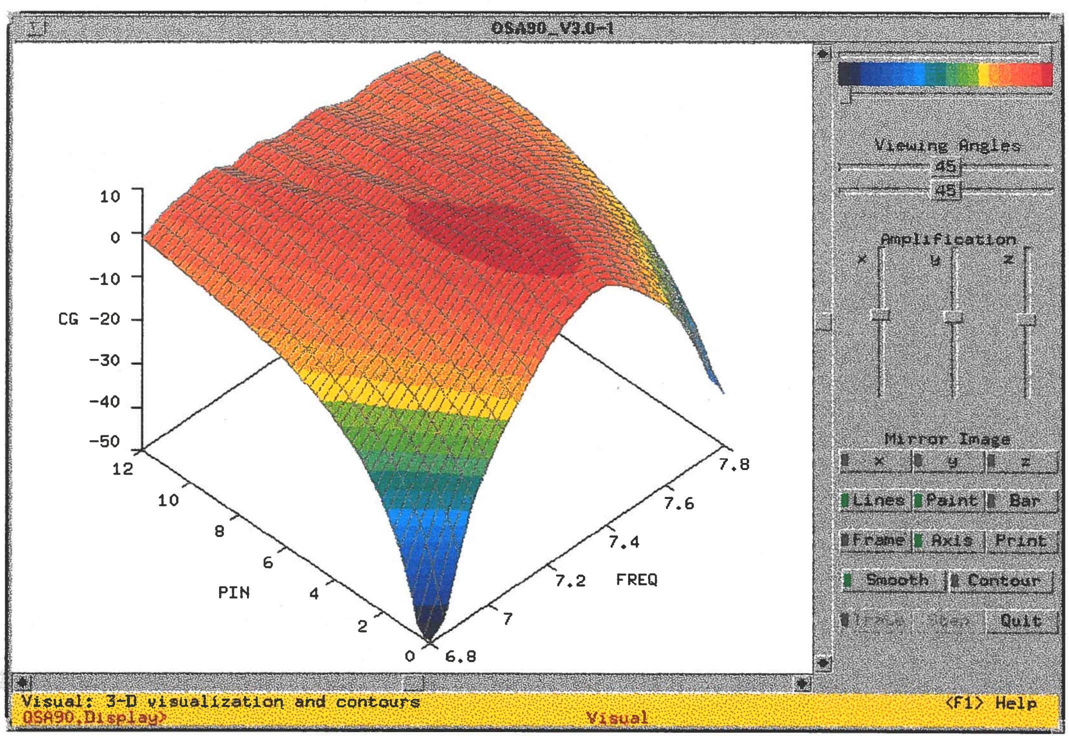
All dimensions are in mm.

Conversion Gain Before and After Optimization



3D View of Conversion Gain Before and After Optimization





Conclusions

a ground-breaking approach to integrating previously disjoint simulation technologies for automated EM optimization of linear and nonlinear microwave circuits

an exciting breakthrough: OSA's Geometry Capture technique makes EM optimization of arbitrary planar structures a reality

a powerful tool for microwave engineers to accurately design circuits consisting of complicated structures and investigate new microstrip components

seamless integration of EM analyses with HB optimization taking advantage of the accurate EM models for passive components

integration of physical simulation for active devices and EM simulation for passive elements will be the key to the success of nonlinear circuit design

a formula for future microwave CAD

EM simulation
+ physical simulation
+ Space Mapping
+ model optimization
⇒ first-pass success