AN ARCHITECTURE FOR NEXT GENERATION MICROWAVE CAD SOFTWARE SYSTEMS

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J.W. Bandler*, Q.J. Zhang**, S.H. Chen* and R.M. Biernacki*

Abstract This paper presents an inter-program pipe communication technique facilitating high speed numerical interaction between independent programs. Features scattered in separate programs such as device libraries, simulators and optimizers can be combined for new applications without physically linking them together. This provides a new architecture for large-scale CAD software systems.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada under Grants STR0040923, OGP0007239 and OGP0042444 and in part by Optimization Systems Associates Inc.

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I. INTRODUCTION

In a recent review of MIMIC progress, Cohen [1] emphasized the mandate for open software architecture. Such an architecture is essential for an advanced CAD approach to modeling, sensitivity analysis, optimization, statistical design, process-oriented circuit design, steady state and transient simulations, circuit as well as layout analysis within the same software framework. Systems of such scale have proven to be extremely expensive to develop, debug, maintain and upgrade. Consequently, software modularity and adaptability as stressed by Corbex et al. [2] and McMacken and Chamberlain [3], must be facilitated. A necessary step is to connect several previously separate programs, as has been done in Academy [4] and Microwave Design Workstation [5].

The constant evolution of new technology, algorithms and requirements challenges even the most advanced microwave CAD system available today. A software system, regardless of how comprehensively conceived, may quickly become outdated unless it is frequently upgraded. Due to the large size of today's simulators, it is very expensive to write new versions every time technology or knowledge undergoes changes. Software modules from different organizations often need to be integrated. In this case, adding new modules should require minimal knowledge of, and minimal or no change to, the existing system. These requirements are beyond the presently used approach for syntactic connection of a predetermined set of programs, for preprocessing and postprocessing. The ability to efficiently iterate between separate programs for highly repetitive procedures such as optimization and statistical design is vital but not yet available in existing CAD systems.

In this paper we present an advanced technique for open software architecture called IPPC (inter-program pipe communication). The technique offers a twofold significant impact on the state-of-art of microwave CAD software. Firstly, it allows highly repetitive data communication between totally independent programs. Secondly, an unlimited number of non-predetermined and new software modules can be added to existing software systems with no modification, no re-compilation and no re-linking of the existing systems. Therefore, a software user can add new modules to an existing IPPC-based system, allowing the existing system's optimizers, statistical drivers, etc., to interact iteratively with his own module. The user's modules are separate executables not linked with the existing software. Thus, independent development, testing and execution of new code are facilitated. The confidentiality of the user's program is totally secured. Experiments have been conducted on McCAE, our research CAD system based on OSA90 [6].

The basic form of communication is between two programs, a parent program and a child program. Communication between one parent and several children and grandchildren is also possible. The overhead CPU cost of IPPC in practical situations is found to be negligible. The technique has been tested on various UNIX workstations.

II. THE IPPC LIBRARY

IPPC is a library for inter-program pipe communication. It allows a user to combine two application programs, as illustrated in the schematic diagram of Fig. 1. It requires minimal modification to the child program and no modification to the IPPC-based parent program. A small IPPC server is the vehicle for communication between the parent and the child programs. The IPPC server we developed includes several C functions, e.g.,

```
ippc_open(child_program)
ippc_read(a, n, size, pid)
ippc_write(a, n, size, pid)
ippc_close(pid)
ippc_iterations(pid)
```

where "child_program" is the name of the child program, "a" is an array containing the data to be transferred, "n" is the number of data items, "size" is the size per data item, and "pid" is the process identifier of the child program.

The user attaches the IPPC server to his or her program to generate a pipe-ready version (an executable program). The user starts the parent and specifies in the circuit file the name of the child, the input parameters, and the output. In our system, the input parameters can be defined as constants, optimizable variables and expressions. The parameters can include frequency, bias voltages, large-signal input power, etc.

During simulation or optimization involving the child, the parent executes the child as a separate process. In forking the child process, two inter-process pipes are created. The two-way communication is established by using each pipe to transfer data one-way.

III. EFFICIENCY OF IPPC

Conventional software links all modules into a single executable. In our architecture the overall system consists of several independent executables. According to our benchmark test [7], the speed of IPPC is 1.7 Megabytes per second on a Sun SPARCStation 1. The CPU overhead cost of using IPPC typically adds only about 1% to the conventional approach of subroutine calls.

IV. SIMULATION AND OPTIMIZATION OF MULTIPLEXERS

Here, we employ McCAE as the IPPC-based parent and SIMUX as the child. Both parent and child programs were originally developed without ever envisaging any connection between them. SIMUX simulates contiguous or noncontiguous band multiplexers consisting of multicavity filters distributed along a waveguide manifold.

We optimized a 5-channel multiplexer using our IPPC technology. The center frequency of the multiplexer is 12.1GHz. We impose a 20dB lower specification on the common port return loss of the circuit at 98 frequency points in the range 12GHz to 12.2GHz. There are 60 design variables including the spacings between adjacent channels, input and output transformer ratios, diagonal and off diagonal coupling parameters of all the filters.

The foregoing specifications and resulting error functions for optimization are formulated and evaluated in parent McCAE. The frequency sweep driver is in McCAE. The circuit response is computed in child SIMUX. Parent McCAE's minimax optimizer is used. In each of the 38 optimization iterations, McCAE updates all 60 variables and feeds the updated values to SIMUX. Also in each iteration McCAE arranges a 98 point frequency sweep. The computed return loss and individual channel insertion loss responses are fed back from SIMUX to McCAE at each frequency. After optimization, all the specifications are met. Figs. 2 and 3 show the multiplexer responses before and after optimization, respectively.

In making the child SIMUX accessible to McCAE, only an IPPC server for data read and write needs to be added to SIMUX. The rest of SIMUX undergoes absolutely no modification.

The total number of iterations of data communication between the two separate executables SIMUX and McCAE is 3,724 (38 optimization iterations x 98 frequencies).

V. STATISTICAL ANALYSIS OF TIME-DOMAIN RESPONSES

Here, McCAE's statistical design capabilities are applied to an external time-domain simulator. The circuit we consider is a feedback network with tapered RC line [8] shown in Fig. 4. The line is exponentially tapered having unit length and parameters $r(x) = e^x$, $c(x) = e^x$. We assume a normal distribution with 10% standard deviation on the K factor of the network. The step response of the network with 200 outcomes was calculated. The sweep response is shown in Fig. 5.

The Monte-Carlo driver and the random number generator are in McCAE. The time sweep range is formulated by McCAE. An independent time-domain simulator based on numerical Laplace inversion [8] computes the transient response at a given time point. The are 200 outcomes. For each outcome the circuit is simulated at 100 time points. Data communication between McCAE and the transient simulator was repeated for 20,000 iterations!

VI. CONCLUSIONS

We have presented an inter-program pipe communication technique. Strict isolation of complicated data structures and program modules are featured. This will allow creation, testing and evaluation of new algorithms done in a simple and timely manner. The technique allows not only syntactic connection of different programs such as for preprocessing and postprocessing, but also numerical iterations between separate programs for intensive numerical procedures such as optimization and statistical design. The technology could revolutionize the development of the next generation large-scale microwave CAD software systems.

At this time, McCAE has no "built-in" facilities for either multiplexer analysis or time-domain simulation. Implementing such facilities using conventional programming would require expensive modifications to McCAE. Using IPPC, McCAE can solve totally unexpected problems and employ new methods without any modification, not even relinking.

The addition of new modules does not expand the physical size of the existing software system. Therefore, we can add a virtually unlimited number of new modules, which are all independent executables.

REFERENCES

[1] E.D. Cohen, "MIMIC from the department of defense perspective," *IEEE Trans. Microwave Theory Tech.*, vol. 38, 1990, pp. 1171-1174.

[2] C.H. Corbex, A.F. Gerodolle, S.P. Martin and A.R. Poncet, "Data structuring for process and device simulations," *IEEE Trans. Computer-Aided Design*, vol. 7, 1988, pp. 489-500.

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[4] *Academy*, EEsof Inc., Westlake Village, CA 91362.

[5] *Microwave Design Workstation*, Compact Software Inc., Paterson, NJ 07504.

[6] *OSA90*, Optimization Systems Associates Inc., Dundas, Ontario, Canada L9H 5E7, 1990.

[7] J.W. Bandler, Q.J. Zhang, G. Simpson and S.H. Chen, "IPPC: a library for inter-program pipe communication", Simulation Optimization Systems Research Laboratory and Department of Electrical and Computer Engineering, McMaster University, Hamilton, Canada L8S 4L7, Report SOS-90-10-U, 1990.

[8] J. Vlach and K. Singhal, *Computer Methods for Circuit Analysis and Design*, New York, NY: Van Nostrand Reinhold, 1983, Chapter 10.

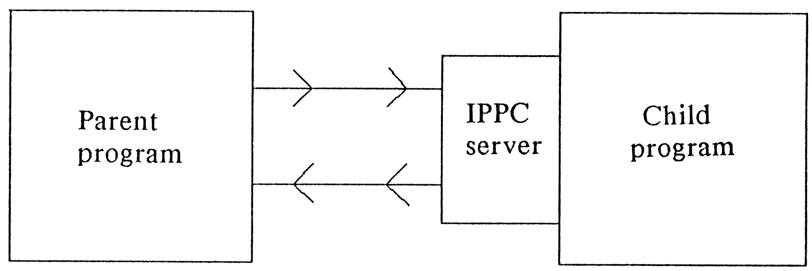

Fig. 1. Schematic diagram of IPPC between two independent programs.

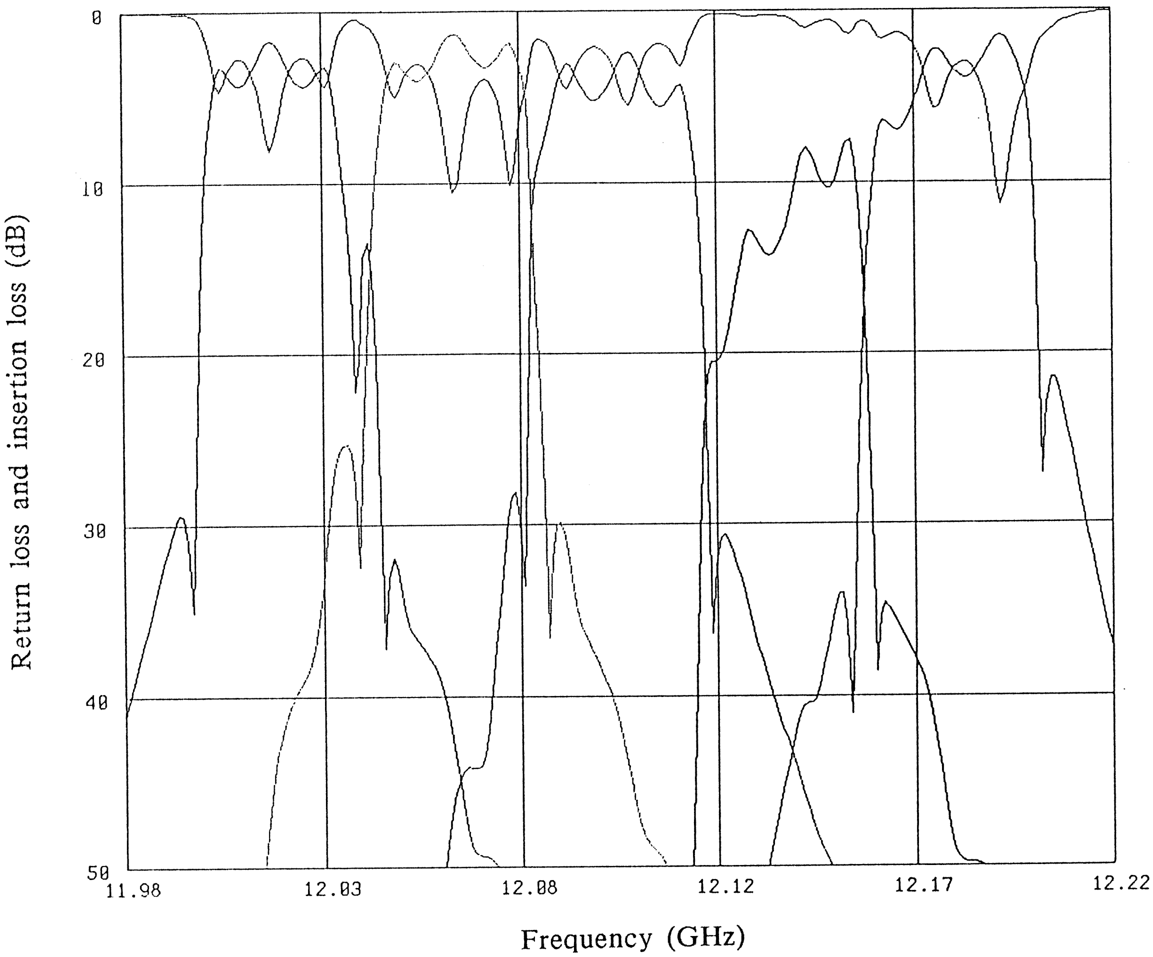

Fig. 2. Common port return loss and individual channel insertion loss responses of the 5-channel microwave multiplex before optimization.

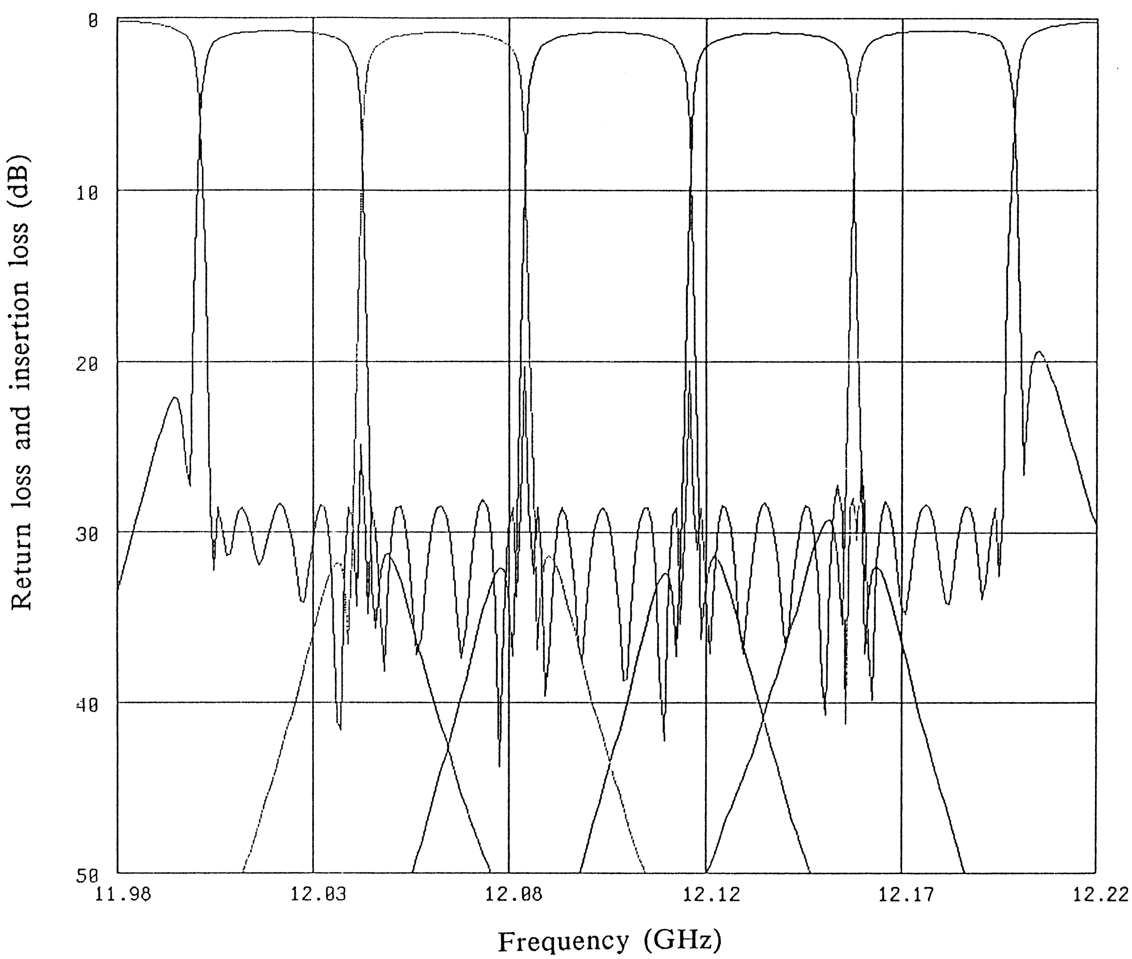

Fig. 3. Common port return loss and individual channel insertion loss responses of the 5-channel microwave multiplexer after optimization. Numerical optimization including formulation of error functions and updating of variables is done in McCAE. Circuit responses are computed in SIMUX. The two separate programs interacted for 3724 iterations.

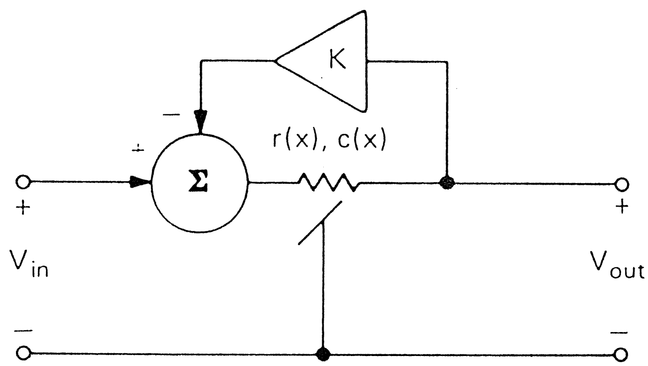

Fig. 4. A feedback network with exponentially tapered RC lines [8].

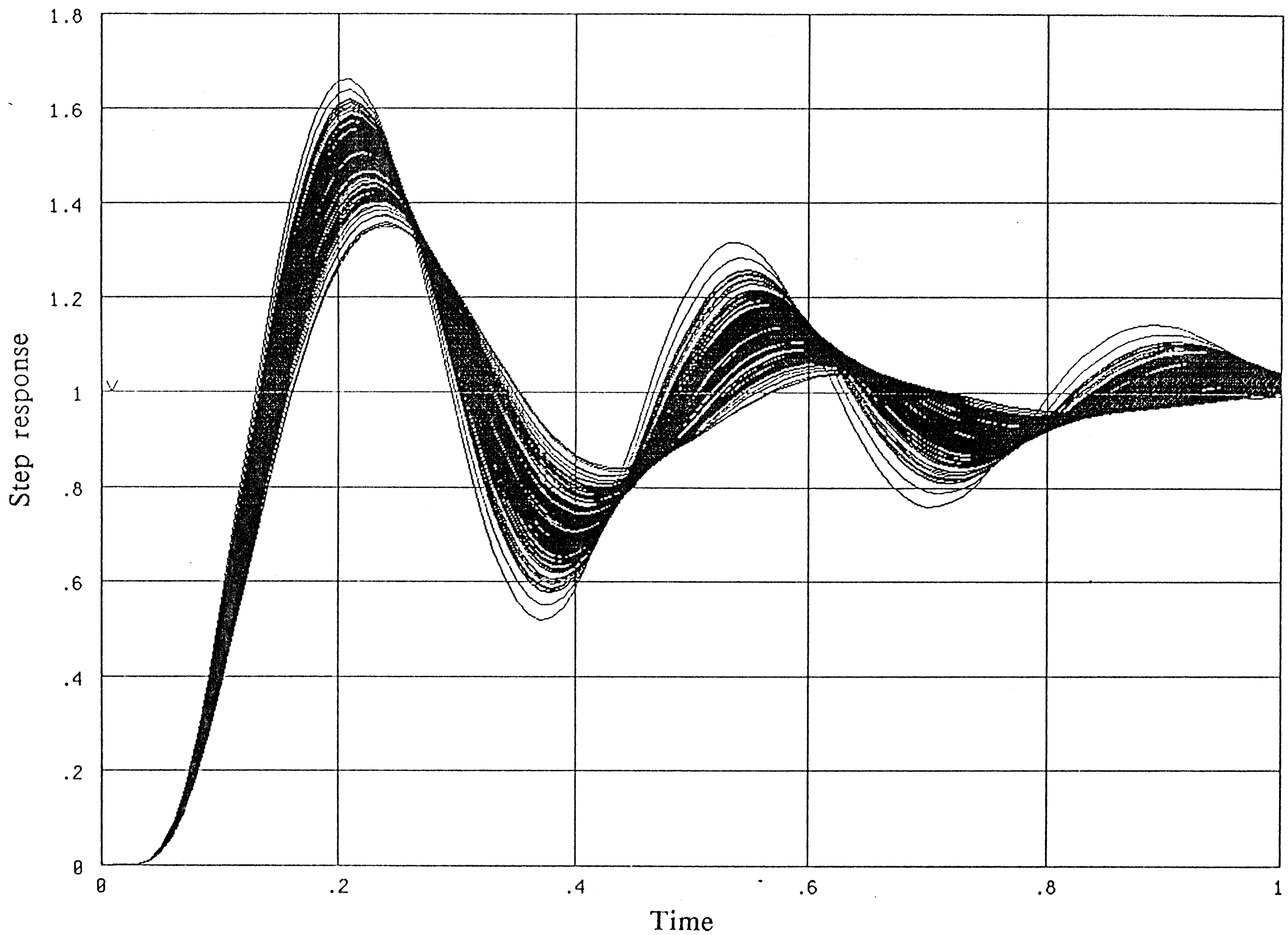

Fig. 5. Statistical transient response of the feedback network to a unit step excitation. There are 200 statistical circuit outcomes. Statistical analysis including random number generation is done in McCAE. Circuit responses are computed in the child program, i.e., an independent time-domain simulator. The two separate programs communicated for 20,000 iterations.

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SUMMARY

Introduction

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The IPPC Library

IPPC is a library for inter-program pipe communication. The communication, in its basic form, allows the user to combine two application programs: the parent and the child. It requires minimal modification to the child program and no modification to the IPPC-based parent program. A small IPPC server is the vehicle for communication between the two programs. The IPPC server we developed includes several C functions, e.g.,

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The Monte-Carlo driver and the random number generator are in McCAE. The time sweep range is formulated by McCAE. An independent time-domain simulator based on numerical Laplace inversion [6] computes the transient response at a given time point. The are 200 outcomes. For each outcome the circuit is simulated at 100 time points. Data communication between McCAE and the transient simulator was repeated for 20,000 iterations!

Conclusions

We have presented an inter-program pipe communication technique. Strict isolation of complicated data structures and program modules are featured. This allows creation, testing and evaluation of new algorithms in a simple and timely manner. The technique permits not only syntactic connection of different programs such as for preprocessing and postprocessing, but also numerical iterations between separate programs for intensive numerical procedures such as optimization and statistical design. The addition of new modules does not expand the physical size of the existing software system. Therefore, we can add a virtually unlimited number of new modules, which are all independent executables.

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References

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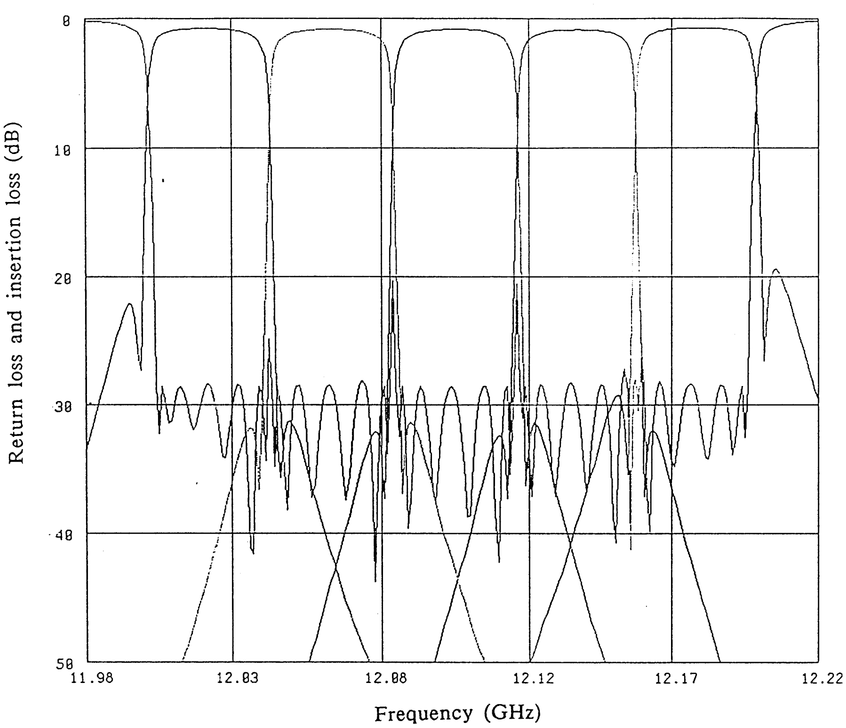

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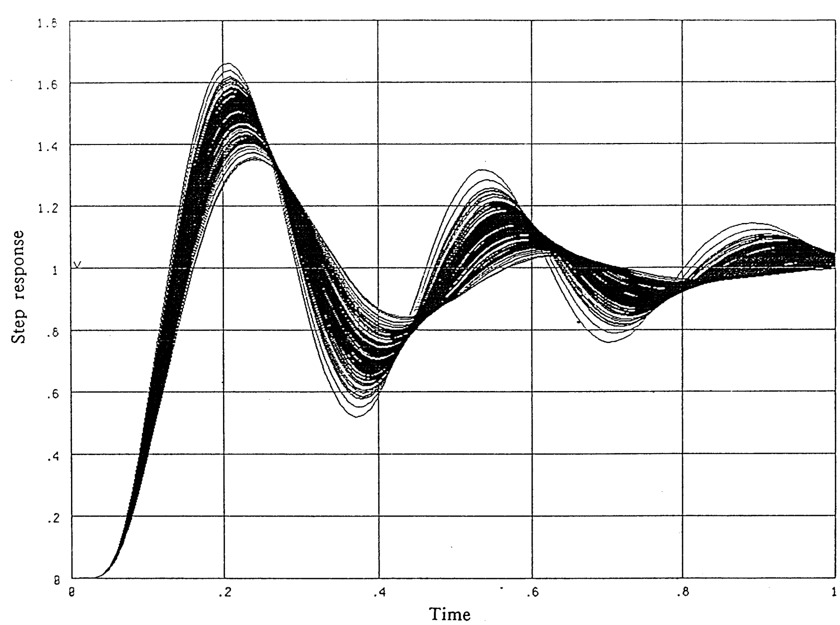

Fig. 2. Statistical transient response of the feedback network to a unit step excitation. There are 200 statistical circuit outcomes. Statistical analysis including random number generation is done in McCAE. Circuit responses are computed in the child program, i.e., an independent time-domain simulator. The two separate programs communicated for 20,000 iterations.

PHYSICS-BASED DESIGN AND YIELD OPTIMIZATION

OF MMICs

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PHYSICS-BASED DESIGN AND YIELD OPTIMIZATION OF MMICs

J.W. Bandler*, Q. Cai*, R.M. Biernacki*, S.H. Chen* and Q.J. Zhang**

Abstract This paper addresses physics-based design and yield optimization of MMICs. Multi-dimensional statistical models are considered for the physical, geometrical and process-related parameters of active and passive devices. An efficient gradient-based yield optimization technique is employed. The yield of an X-band amplifier is improved from 45% to 73.5%.

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada under Grants STR0040923, OGP0007239 and OGP0042444 and in part by Optimization Systems Associates Inc.

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** Q.J. Zhang is now with the Department of Electronics, Carleton University, Ottawa, Canada K1S 5B6.

I. INTRODUCTION

With the rapid progress of GaAs fabrication technology, MMICs are becoming more and more practical [1]. Because the active and passive components are fabricated on a common semi-insulating substrate, post-production tuning of MMICs is restricted, and device replacement is not possible. Therefore, yield analysis and optimization is accepted as an indispensable part of the MMIC design methodology.

Some approaches to yield optimization have been developed during the past two decades [2-10], including a recent gradient-based technique for nonlinear circuits by Bandler *et al* [11]. However, most of the algorithms assume statistical variables in equivalent circuit models. There are serious doubts as to whether such models are capable of reflecting the actual statistical properties of the geometrical and process parameters.

In this paper, we present an approach which integrates the concept of yield optimization with physics-based device models. We directly consider as design variables the physical, geometrical and process-related parameters, both for active and passive devices. These may include, for example, FET gate length, gate width, doping density, the number of turns of spiral inductors, geometry dimensions of metal-insulator-metal (MIM) capacitors, etc. The statistics of the physics-based model parameters are modelled by a multidimensional normal distribution. Statistical correlations between parameters are also considered, which is very important for MMICs. The efficient sensitivity technique FAST (Feasible Adjoint Sensitivity Technique) [11] is employed to permit high speed gradient-based yield optimization.

A three stage X-band amplifier demonstrates our approach. The FETs as well as the spiral inductors and MIM capacitors are described by physics-based models. We first achieve a minimax nominal design, which is then used as the starting point for yield optimization. The yield, as estimated by Monte Carlo analysis with 200 outcomes, is 45% for the nominal design. It is improved to 73.5% after yield optimization.

II. PHYSICS-BASED MODELS FOR ACTIVE AND PASSIVE DEVICES

The main advantage of physics-based models is that the model parameters relate directly and clearly to physical reality. For MMICs, such models are defined through device geometry, material parameters and process parameters. For example, a physics-based FET model has been developed by Khatibzadeh and Trew [12]. A modified version [13] is used to model the FETs in our amplifier example. The model equations include [12-14]

$$I_g = I_{gc}(\phi_a, t) + \frac{\partial Q_g(\phi_a, t)}{\partial t} \tag{1}$$

$$I_d = I_{dc}(\phi_a, t) + \frac{\partial Q_d(\phi_a, t)}{\partial t} \tag{2}$$

$$I_s = I_{sc}(\phi_a, t) + \frac{\partial Q_s(\phi_a, t)}{\partial t} \tag{3}$$

$$I_g + I_d + I_s = 0 \tag{4}$$

where ϕ_a is the vector of model parameters including gate length, gate width, channel thickness, doping density, etc. I_{gc}, I_{dc}, I_{sc}, Q_g, Q_d and Q_s are the gate, drain and source conduction currents and accumulation charges, respectively, which are nonlinear functions of ϕ_a. The schematic diagram of the model is shown in Fig. 1.

Passive devices can be represented in general by their n-port Y matrices. For example, we represent spiral inductors, MIM capacitors and planar resistors by their two-port Y matrices $Y(\phi_p)$, where ϕ_p is a vector of parameters. For MIM capacitors, ϕ_p includes the geometrical dimensions of the metal plate, the dielectric constant and the thickness of the dielectric film. For spiral inductors, ϕ_p includes the substrate height, the conductor width and spacing, and the number of turns. The configuration and schematics of spiral inductors, MIM capacitors and planar resistors are shown in Fig. 2.

III. STATISTICAL MODELS

Existing methods of statistical analysis and yield optimization usually assume statistical variables in equivalent circuit models. There are serious limitations in such approaches. It is difficult to relate the statistical distributions of equivalent circuit model parameters to those of the geometrical and process parameters. We have to assume, for instance, that statistical variations in a single physical parameter will affect many equivalent circuit model parameters, and at the same time each equivalent circuit model parameter is affected by many physical parameters. Consequently, the equivalent circuit model parameters are correlated and such correlations are difficult to estimate. In many cases, independent uniform and/or normal distributions are assumed without much justification. Sophisticated statistical modeling techniques using large samples of measurements have been proposed in an attempt to alleviate some of these problems [15].

Physics-based models have the advantage that the model parameters can be related directly and clearly to the geometrical and process parameters. From experience, we can usually identify those parameters that are subject to significant statistical variations. Also, since we are directly dealing with statistical perturbations at the lowest level, the assumption of a normal distribution is justified. Due to the nature of the MMIC technology, correlations between statistical variables can be significant and should be included in the model (for example, the geometrical dimensions of the different devices produced on the same wafer are likely to be correlated). Again, with physics-based models it is much easier to identify the correlated statistical variables than in the case of equivalent circuit models.

IV. YIELD-DRIVEN DESIGN OPTIMIZATION

Yield-driven design can be formulated as the one-sided ℓ_1 optimization problem [10,11]

$$\underset{\phi^0}{minimize}\ U(\phi^0) \tag{5}$$

$$U(\phi^0) = \sum_{i \in I} \sum_{j \in J} \alpha_i e_j(\phi^i) \tag{6}$$

where the α_i is a set of suitable weights as defined in [11]. The error function e is defined as

$$e_j(\phi^i) = K[R_j(\phi^i) - S_j] \tag{7}$$

where ϕ^i is the parameter vector of the ith statistical outcome, R_j represents the circuit response of interest and S_j the design specification on R_j. $K = 1$ when S_j is an upper specification, and $K = -1$ when S_j is a lower specification. The index sets I and J in (6) identify those error functions that violate the specifications.

The vector ϕ contains the parameters of the physics-based models for the active and passive devices. It includes optimizable (designable) parameters and statistical parameters. Some parameters can be both optimizable and statistical. Physics-based models enable us to make a meaningful selection of optimizable parameters. With an equivalent circuit model, some of the parameters defined as optimizable do not correspond directly to physically designable parameters. Therefore, the optimized solution has to be translated into a physical design. Because it is difficult to incorporate physical constraints into an equivalent circuit model, in some cases the optimized solution may not be physically realizable. Using physics-based models, we can optimize variables that are tangible and within realistic constraints.

V. A THREE STAGE X-BAND AMPLIFIER

A three stage small-signal X-band cascadable amplifier is considered. The design is based on the circuit topology and the fabrication layout described in [16], but with different parameter values. The amplifier contains three MESFETs which are built using an interdigitated structure based on two gate fingers of dimensions 200μm$\times$1.0μm. The matching circuits are composed of inductors and capacitors arranged in bandpass topology. All passive components are realized using lumped MMIC elements: spiral inductors, MIM capacitors and bulk resistors. The second and third MESFET are biased through a 1500Ω GaAs bulk resistor. The drains and the first gate bias are bypassed by a high value MIM capacitor. The input-output matching circuit includes a series capacitor to make the amplifier cascadable without additional components. The circuit diagram of the amplifier is shown in Fig. 3.

The amplifier is to meet the following specifications. In the passband (8GHz - 12GHz), gain = 14±2dB and VSWR < 2. In the stopband (below 6GHz or above 15GHz), gain < 2dB.

First, a nominal design is performed. We use a physics-based model for the MESFETs but equivalent circuit models for all passive elements. As in a traditional design, only the matching circuits are optimized. The parameters of the active devices (MESFETs) have fixed values. There are 14 design variables, namely, C_1, C_2, C_3, C_4, L_1, L_2, ..., L_{10}. The nominal solution is achieved by minimax optimization after 35 iterations (about 3 minutes on a Sun SPARCstation 1). The gain and VSWR before and after optimization are shown in Fig. 4. The values of the design variables before and after optimization are listed in Table I.

The minimax nominal design is used as the starting point for yield optimization. We use physics-based models for both the MESFETs and the passive elements. Since all devices are made from the same material and on the same wafer, they share many common parameters. All three MESFETs have the same values for the critical electric field, saturation velocity, relative dielectric constant, built-in potential, low-field mobility and high-field diffusion coefficient. All the MIM capacitors have the same dielectric film, and all bulk resistors have the same sheet resistance. The geometrical parameters can have different values for different devices, including the gate length, gate width, and channel thickness of the MESFETs, the metal plate area of the MIM capacitors, and the number of turns of the spiral inductors. The doping densities of the MESFETs are also considered as independent parameters.

A total of 37 parameters are considered as statistical variables. They include the gate length, gate width, channel thickness and doping density of the MESFETs, as well as the geometrical parameters of the passive elements. The mean values and standard deviations of the statistical variables are listed in Table II. Correlations are also included in our statistical model. Most significant are the correlations between the same parameters from different devices. For instance, the gate lengths of the three MESFETs are significantly correlated. The correlation matrix used in our model is given in Table III.

The number of turns of the 10 spiral inductors, the metal plate area of the 4 MIM capacitors, and the channel thickness and doping density of the MESFETs are chosen as the variables for yield optimization. At the starting point (i.e., the minimax nominal design), the yield is 45% as estimated by Monte Carlo analysis with 200 statistical outcomes. The yield is improved to 73.5% at the solution of the yield optimization (about 3 hour CPU time on a Sun SPARCstation 1). The solution is given in Table IV. The Monte Carlo sweep of gain and VSWR before and after yield optimization are shown in Fig. 5 and Fig. 6, respectively.

VI. CONCLUSIONS

The ability to predict and enhance production yield is critical for the continued success of MMIC technology. We have presented the principle of physics-based design and yield optimization of MMICs. The advantages of physics-based models over equivalent circuit models in statistical analysis and optimization have been emphasized. Physics-based models deal directly with the lowest level of fabrication/technological parameters, and are essential for the next generation of microwave CAD.

REFERENCES

[1] A.R. Jha, R. Goyal and B. Manz, "Introduction," in *Monolithic Microwave Integrated Circuits: Technology & Design*, R. Goyal Ed. Boston: Artech House, 1989, Chapter 1.

[2] R.M. Biernacki, J.W. Bandler, J. Song and Q.J. Zhang, "Efficient quadratic approximation for statistical Design," *IEEE Trans. Circuits Syst.*, vol. 36, 1989, pp. 1449-1454.

[3] J.W. Bandler and H.L. Abdel-Malek, "Optimal centering tolerancing, and yield determination via updated approximations and cuts," *IEEE Trans. Circuits Syst.*, vol. CAS-25, 1978, pp. 853-871.

[4] H.L. Abdel-Malek and J.W. Bandler, "Yield optimization for arbitrary statistical distributions: Part I-theory," *IEEE Trans. Circuits Syst.*, vol. CAS-27, 1980, pp. 245-253.

[5] S.W. Director and G.D. Hachtel, "The simplicial approximation approach to design centering," *IEEE trans. Circuits Syst.*, vol. CAS-24, 1977, pp. 363-372.

[6] R.S. Soin and R. Spence, "Statistical exploration approach to design centering," *Proc. Inst. Elec. Eng.*, vol. 127, Pt. G., 1980, pp. 260-269.

[7] M.A. Styblinski and A. Ruszczynski, "Stochastic approximation approach to statistical circuit design," *Electron. Lett.*, vol. 19, 1980, pp. 300-302.

[8] E. Polak and A.L. Sangiovanni-Vinventelli, "Theoretical and computational aspects of the optimal design centering, tolerancing, and tuning problem," *IEEE Trans. Circuits Syst.*, vol. CAS-26, 1979, pp. 795-813.

[9] K. Singhal and J.F. Pinel, "Statistical design centering and tolerancing using parametric sampling," *IEEE Trans. Circuits Syst.*, vol. CAS-28, 1981, pp. 692-701.

[10] J.W. Bandler and S.H. Chen, "Circuit optimization: the state of the art", *IEEE Trans. Microwave Theory Tech.*, vol. 36, 1988, pp. 424-443.

[11] 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.

[12] M.A. Khatibzadeh and R.J. Trew, "A large-signal, analytic model for the GaAs MESFET," *IEEE Trans. Microwave Theory Tech.*, vol. 36, 1988, pp. 231-238.

[13] J.W. Bandler, Q.J. Zhang and Q. Cai, "Nonlinear circuit optimization with dynamically integrated physical device models," *IEEE Int. Microwave Symp. Digest* (Dallas, TX), 1990, pp. 303-306.

[14] A. Madjar and F.J. Rosenbaum, "A large-signal model for the GaAs MESFET," *IEEE Trans. Microwave Theory Tech.*, vol. MTT-29, 1981, pp. 781-788.

[15] J.W. Bandler, R.M. Biernacki, S.H. Chen, J.F. Loman, M.L. Renault and Q.J. Zhang, "Combined discrete/normal statistic modeling of microwave devices,", *Proc. 19th European Microwave Conf.* (London, England), 1989, pp. 204-210.

[16] C. Kermarrec and C. Rumelhard, "Microwave monolithic integrated circuits," in *GaAs MESFET Circuit Design*, R. Soares Ed. Boston: Artech House, 1988, Chapter 9.

[17] I.J. Bahl, "Transmission Lines", in *Microwave Solid State Circuit Design*, I.J. Bahl and P. Bhartia Ed. New York: Wiley, 1988, Chapter 2.

TABLE I

DESIGN VARIABLE VALUES FOR NOMINAL DESIGN

Design Variable	Before Optimization	After Optimization
C_1(pF)	0.62	0.335
C_2(pF)	0.55	1.446
C_3(pF)	0.45	0.367
C_4(pF)	0.62	0.308
L_1(nH)	1.59	1.001
L_2(nH)	2.36	2.073
L_3(nH)	0.31	0.460
L_4(nH)	0.31	0.432
L_5(nH)	0.59	0.460
L_6(nH)	0.31	0.263
L_7(nH)	0.13	0.154
L_8(nH)	1.00	0.664
L_9(nH)	0.59	0.552
L_{10}(nH)	2.36	1.652

TABLE II

ASSUMED DISTRIBUTIONS FOR STATISTICAL VARIABLES

Variable	Mean Value	Standard Deviation (%)
N_d(cm^{-3})	2.0×10^{17}	7.0
GL(μm)	1.0	3.5
GA(μm)	0.24	3.5
GW(μm)	400	2.0
W_L(μm)	20	3.0
S_L(μm)	10	3.0
d(μm)	0.1	4.0
C_1_S(μm^2)	541.9	3.5
C_2_S(μm^2)	2335.5	3.5
C_3_S(μm^2)	593.6	3.5
C_4_S(μm^2)	498.2	3.5

The doping density N_d, gate length GL, channel thickness GA and gate width GW of the three MESFETs have the same distribution. The conductor width W_L and spacing S_L of the 10 spiral inductors L_1, L_2, ..., L_{10} have the same distribution. d is the thickness of the dielectric film for all MIM capacitors. C_i_S is the area of the metal plate of MIM capacitor C_i.

TABLE III

ASSUMED PARAMETER CORRELATIONS FOR THE THREE MESFETS

	GA_1	GL_1	GW_1	N_{d1}	GA_2	GL_2	GW_2	N_{d2}	GA_3	GL_3	GW_3	N_{d3}
GA_1	1.00	0.00	0.00	-0.25	0.80	0.00	0.00	-0.20	0.78	0.00	0.00	-0.10
GL_1	0.00	1.00	0.00	-0.10	0.00	0.80	0.00	-0.05	0.00	0.78	0.00	-0.05
GW_1	0.00	0.00	1.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.78	0.00
N_{d1}	-0.25	-0.10	0.00	1.00	-0.20	-0.05	0.00	0.80	-0.15	-0.05	0.00	0.78
GA_2	0.80	0.00	0.00	-0.20	1.00	0.00	0.00	-0.25	0.80	0.00	0.00	-0.20
GL_2	0.00	0.80	0.00	-0.05	0.00	1.00	0.00	-0.10	0.00	0.80	0.00	-0.10
GW_2	0.00	0.00	0.80	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.80	0.00
N_{d2}	-0.20	-0.05	0.00	0.80	-0.25	-0.10	0.00	1.00	-0.20	-0.05	0.00	0.80
GA_3	0.78	0.00	0.00	-0.15	0.80	0.00	0.00	-0.20	1.00	0.00	0.00	-0.25
GL_3	0.00	0.78	0.00	-0.05	0.00	0.80	0.00	-0.05	0.00	1.00	0.00	-0.10
GW_3	0.00	0.00	0.78	0.00	0.00	0.00	0.80	0.00	0.00	0.00	1.00	0.00
N_{d3}	-0.10	-0.05	0.00	0.78	-0.20	-0.10	0.00	0.80	-0.25	-0.10	0.00	1.00

TABLE IV

DESIGN VARIABLE VALUES FOR YIELD OPTIMIZATION

Design Variable	Before Optimization	After Optimization
GA(μm)	0.24	0.22
N_d(cm^{-3})	2.0×10^{17}	2.25×10^{17}
C_1_S(μm^2)	541.9	507.9
C_2_S(μm^2)	2335.5	1950.9
C_3_S(μm^2)	593.6	517.4
C_4_S(μm^2)	498.2	485.5
L_1_N	3.0	2.93
L_2_N	3.8	3.81
L_3_N	2.3	2.03
L_4_N	2.3	2.39
L_5_N	2.3	2.49
L_6_N	1.9	1.88
L_7_N	1.6	1.63
L_8_N	2.6	2.69
L_9_N	2.5	2.51
L_{10}_N	3.6	3.69

L_i_N is the number of turns of the spiral inductor L_i.

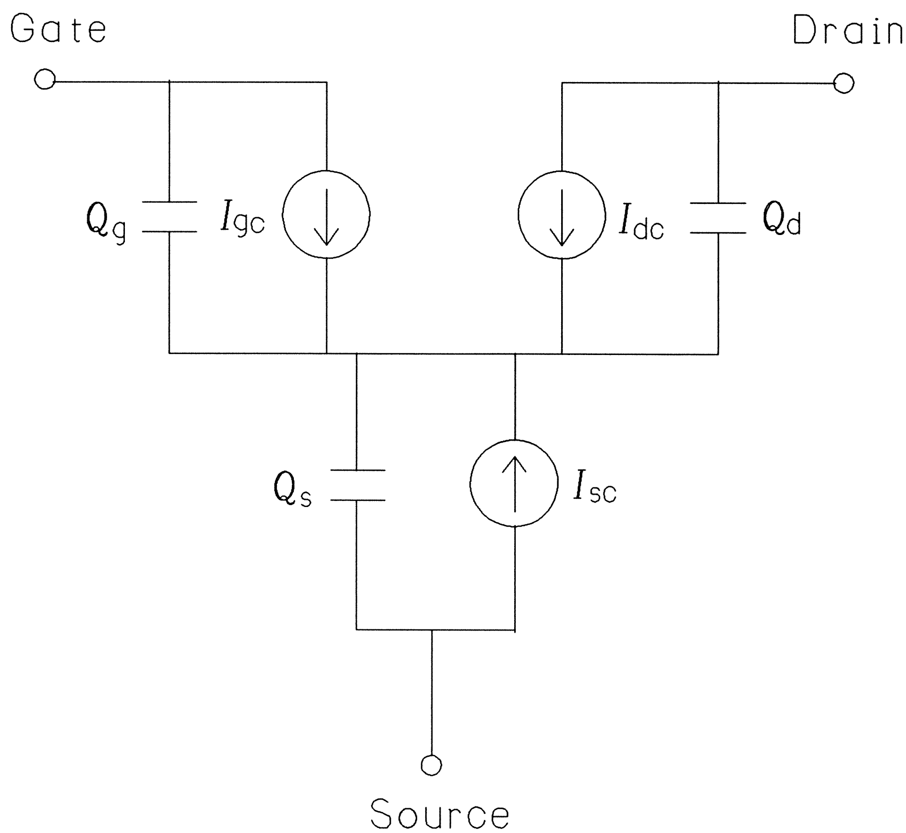


Fig. 1. Schematic diagram for the physics-based MESFET model.

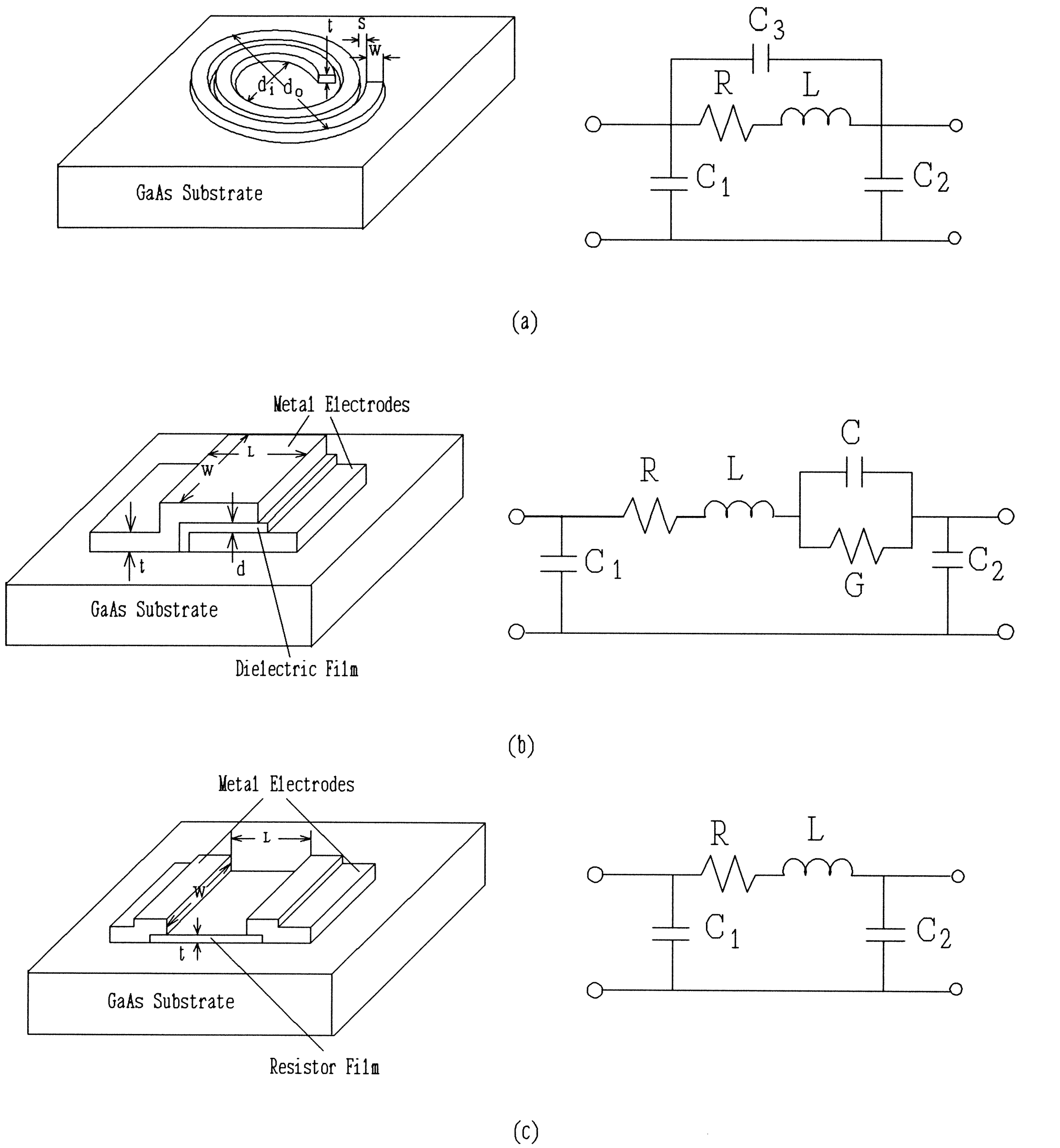


Fig. 2. **Configuration of passive devices and their corresponding two port equivalent circuits [17]: (a) spiral inductor, (b) MIM capacitor and (c) planar resistor.**

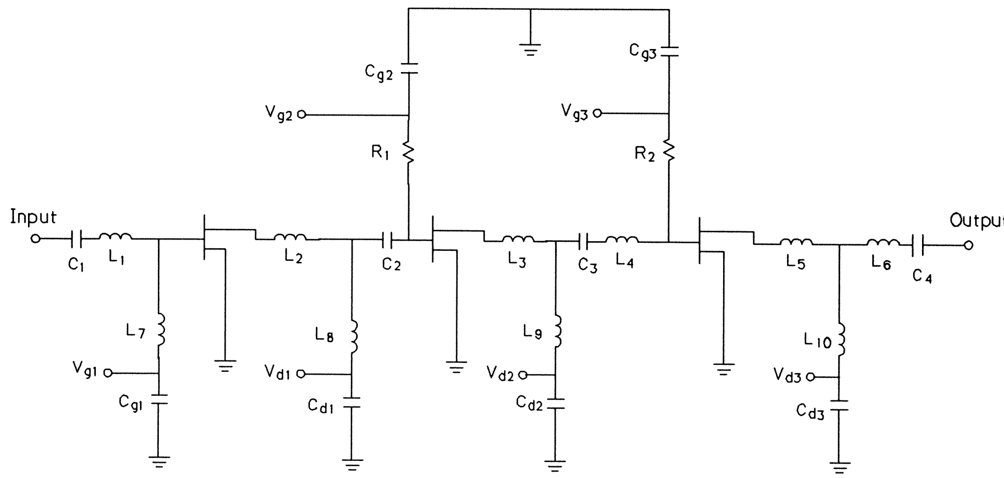
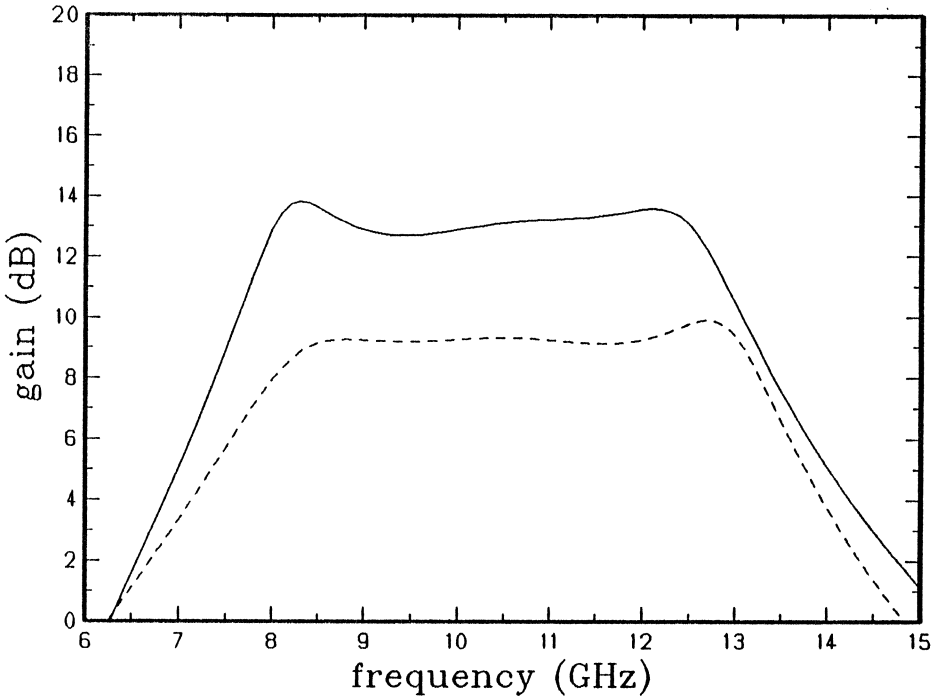
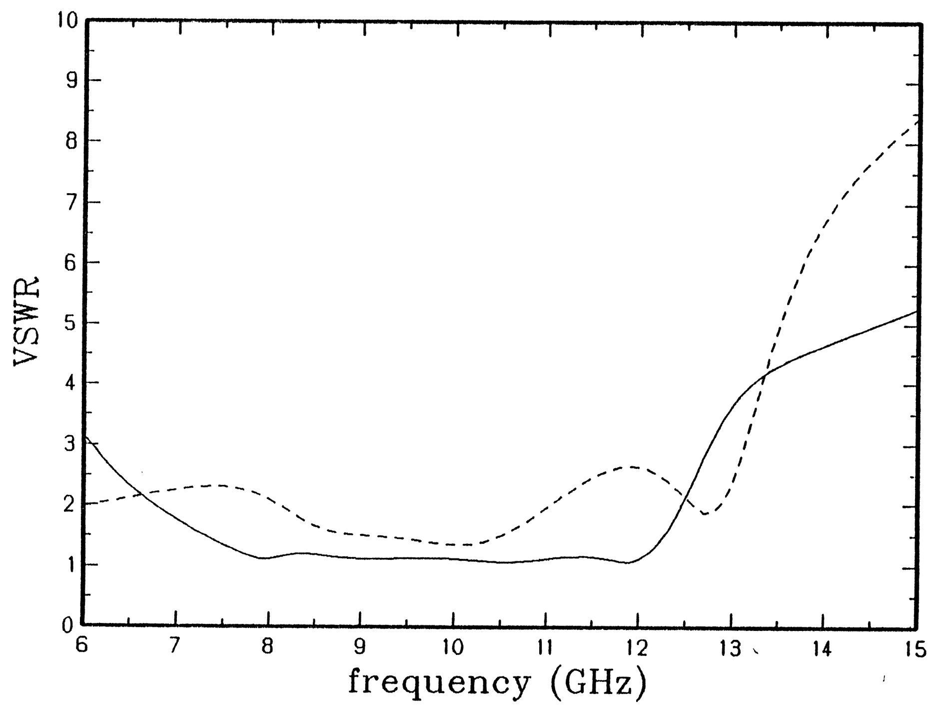


Fig. 3. Circuit diagram of X-band amplifier [16].

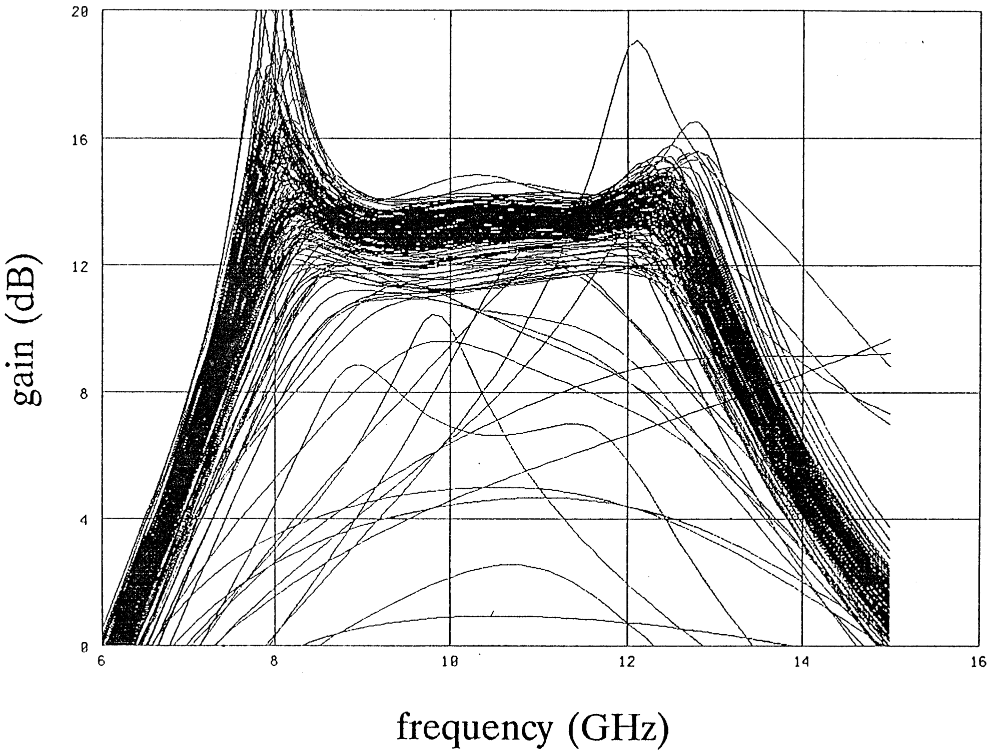


(a)

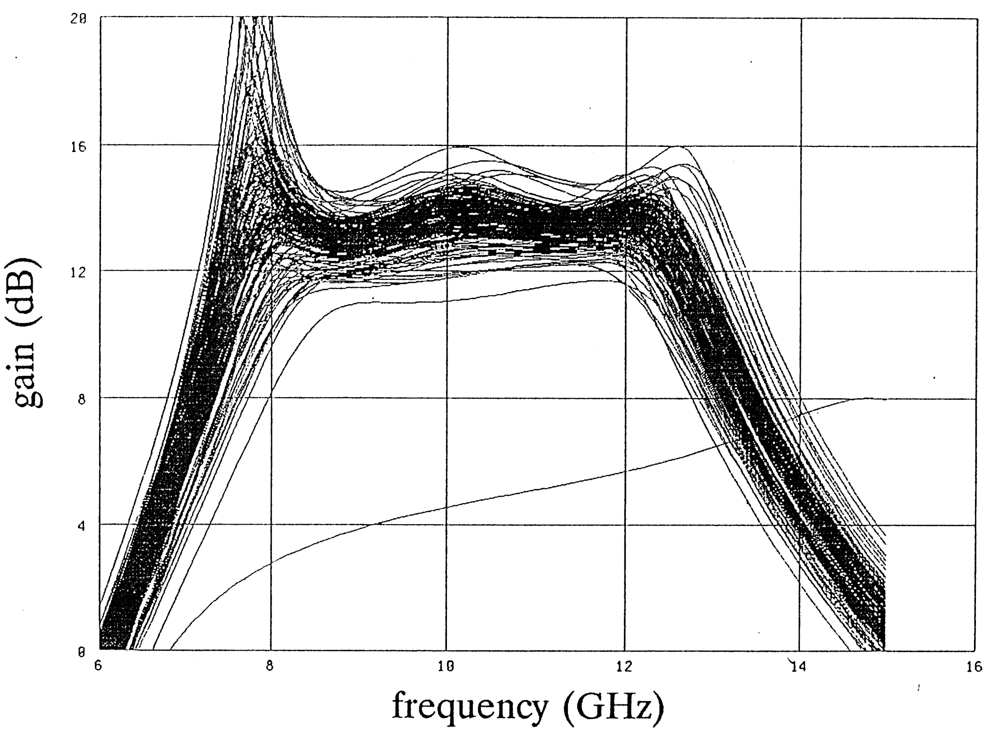


(b)

Fig. 4. (a) Gain and (b) VSWR versus frequency before (---) and after (——) nominal design optimization.

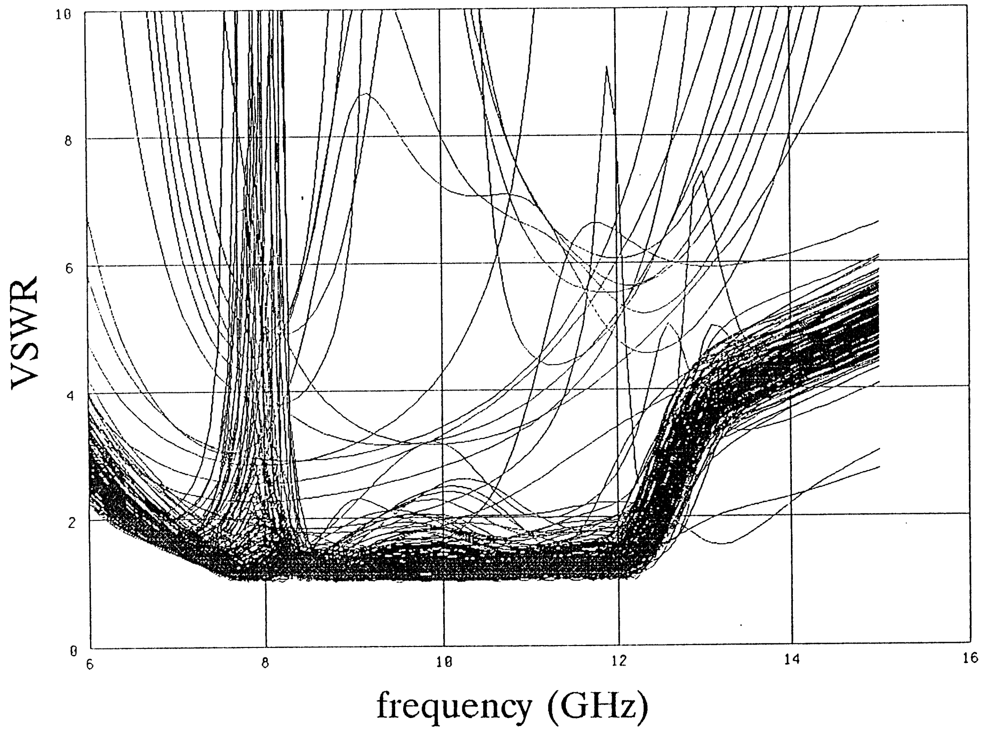


(a)

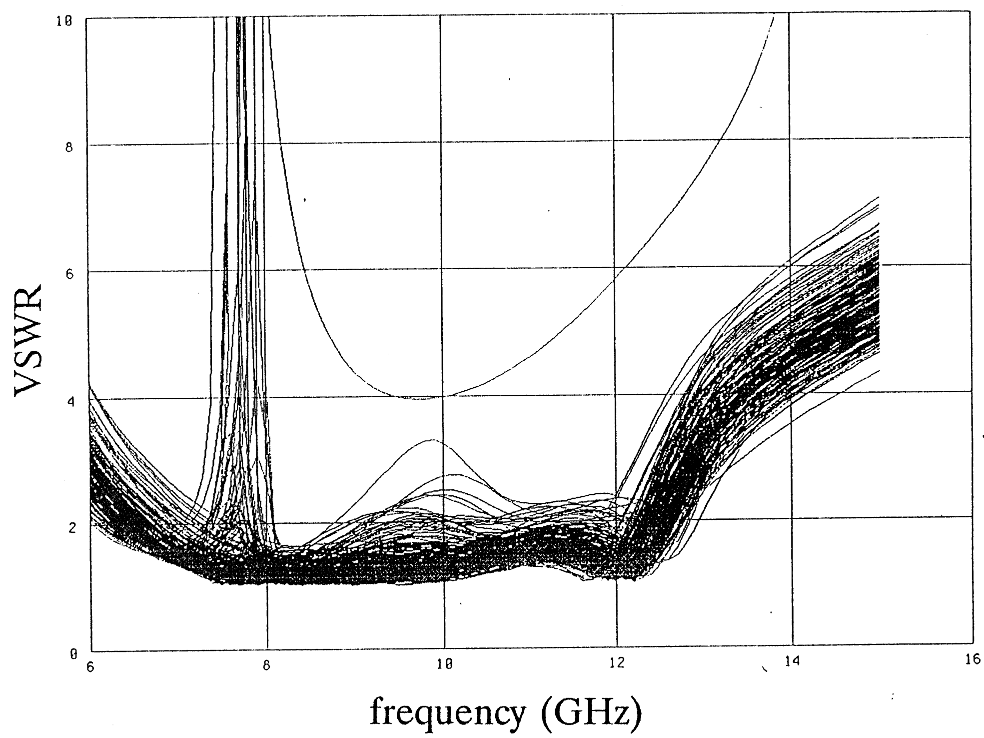


(b)

Fig. 5. Monte Carlo sweep of gain versus frequency (a) before and (b) after yield optimization.



(a)



(b)

Fig. 6. Monte Carlo sweep of VSWR versus frequency (a) before and (b) after yield optimization.