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MIXED-DOMAIN MULTI-SIMULATOR STATISTICAL PARAMETER EXTRACTION AND YIELD-DRIVEN DESIGN

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Abstract

We present a mixed-domain, multi-simulator statistical parameter extraction and yield-driven optimization system. An intelligent interface combines and enhances the features of otherwise disjoint simulators. Time-domain, frequency-domain and electromagnetic simulations are, for the first time, integrated for efficient statistical modeling and design with mixed-domain specifications. Our approach is demonstrated by statistical modeling of GaAs MESFETs and yield optimization using, simultaneously, SPICE device models, Sonnet's electromagnetic simulator ***em*** and OSA's design optimization system OSA90/hope.

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SUMMARY

Introduction

Statistical modeling and design which take into account the manufacturing tolerances and model uncertainties are indispensable for today's microwave CAD, especially for MMIC design (e.g., [1-5]).

Available general purpose CAD systems do not address all aspects of contemporary circuit design adequately. On the other hand, there are specialized systems representing the state of the art methodology in focused areas. This frequently forces the designer to use different systems to address different aspects of design. However, incompatible user interfaces and data formats make such a design process tedious and time-consuming. To efficiently utilize the potential of available systems an intelligent optimization interface is required.

In this paper we present a flexible approach to mixed-domain multi-simulator statistical modeling and design. A smart open architecture interface is used to connect various CAD systems in a uniform and user-friendly manner. For the first time, time-domain, frequency-domain and electromagnetic (EM) simulations are integrated into a powerful mixed-domain optimization environment. We demonstrate statistical modeling and design using SPICE [6], ***em*** [7] and OSA90/hope [8] interfaced through Spicepipe [9] and Empipe [10].

The parameter extraction/postprocessing (PEP) approach [3] is used for statistical modeling. Statistical parameter extraction of a MESFET is performed based on the SPICE model. The devices are simulated by SPICE. Optimization is carried out by OSA90/hope. The extracted models are postprocessed by HarPE [11] to obtain the parameter statistics.

Mixed-domain statistical design (yield optimization) is demonstrated by three examples. A low-pass filter design including specifications defined in both time- and frequency-domain and a small-signal amplifier design utilize our interface between SPICE and OSA90/hope. Combined time-, frequency- and field-level yield optimization is exemplified by the design of a broadband small-signal amplifier with microstrip components. The MESFET is simulated by SPICE.

Microstrip components are accurately simulated by ***em***. The circuit-level simulations and optimization are performed by OSA90/hope.

Datapipe Technique for Optimization Interface

Our intelligent optimization interface is based on the Datapipe technique [8, 12]. It utilizes UNIX's interprocess pipe communication facility to establish high speed data connections between different processes. A schematic of the Datapipe interface between a parent process and a number of child processes is shown in Fig. 1.

The parent communicates with each child through a Datapipe protocol at the parent side and a Datapipe server at the child side. The Datapipe protocol consisting of a set of communication standards defines the sequence and meaning of the data fields to be exchanged between the parent and the child. The Datapipe server is a set of functions to be included in the child for reading data from and writing data to the parent. The parent and the child can be totally independent. This is especially suitable for sensitive software since the source code does not need to be revealed.

In general, there is no limit to the number of children that can be interconnected with a single parent through Datapipes. Furthermore, the parent and the children can run on different computers connected in a network. This facilitates parallel processing which can significantly speed up CPU intensive optimization [13].

As an example, the Datapipe interface between OSA90/hope and a number of external simulators including ***em***, SPICE, TLM [14] and AWE [15] is shown in Fig. 2.

Statistical Parameter Extraction with SPICE and OSA90/hope

Suppose there are n_d sets of data measured from n_d devices and n_i measured responses in the ith data set

$$\boldsymbol{S}^i = [S_1^i \; S_2^i \; \dots \; S_{n_i}^i]^T, \qquad i = 1, 2, \dots, n_d \tag{1}$$

Corresponding to $\boldsymbol{S}^i$ we have the SPICE responses

$$R_{SP}(\phi^i) = [R_{SP_1}(\phi^i)\ R_{SP_2}(\phi^i)\ \dots\ R_{SP_{n_i}}(\phi^i)]^T, \quad i = 1, 2, \dots, n_d \tag{2}$$

$\phi^i = [\phi_1^i\ \phi_2^i\ \dots\ \phi_{n_\phi}^i]^T$ is the ith set of model parameters to be extracted with n_ϕ being the number of model parameters.

The error and objective functions are constructed in OSA90/hope. Let the error vector be

$$e_{OS}(\phi^i) = [e_{OS_1}(\phi^i)\ e_{OS_2}(\phi^i)\ \dots\ e_{OS_{n_i}}(\phi^i)]^T \tag{3}$$

where

$$e_{OS_j}(\phi^i) = R_{SP_j}(\phi^i) - S_j^i \tag{4}$$

then the parameter extraction problem can be defined as

$$\underset{\phi^i}{minimize}\ \ U_{OS}(\phi^i) \triangleq H[e_{OS}(\phi^i)] \tag{5}$$

where U_{OS} is the objective function created in OSA90/hope and H represents a norm of the error vector such as the ℓ_1, ℓ_2 or the Huber norm. The parameter extraction is repeated for all data sets. The model statistics such as the mean values, standard deviations and correlations between different parameters are obtained using HarPE by postprocessing the resulting sample of individually extracted models.

Statistical Modeling of GaAs MESFETs

As an example we consider statistical modeling from a sample of GaAs MESFET measurement data which was obtained by aligning the wafer measurements to consistent bias conditions [5]. There are 35 data sets (devices) containing the small-signal S parameters measured at frequencies from 1 to 21 GHz with a 2 GHz step under two bias conditions (gate bias: -0.7 V and -0.5 V, drain bias: 5 V).

The equivalent circuit shown in Fig. 3 is used to model the GaAs MESFETs. There are 18 model parameters. The parameter statistics obtained by PEP include the mean values, standard deviations, discrete density functions (DDF) and correlation matrix. The parameter mean values and standard deviations are listed in Table I.

To verify the statistical model we compare the statistics of the model responses estimated by Monte Carlo simulation with those of the data. Table II lists the mean values and standard deviations of S parameters and drain currents from the model and data at two bias points. We can see a very good mean value agreement between data and the model responses. The standard deviation discrepancies are likely due to the already noticed inadequate statistical modeling capabilities of equivalent circuit models [3].

Mixed-Domain Multi-Simulator Yield Optimization

We consider a parent system and m child systems interfaced through Datapipes as shown in Fig. 1. The parent integrates the simulation results returned from each child and performs the circuit-level simulation and optimization.

Assuming that n_o outcomes are used in yield optimization, responses of the ith outcome $\boldsymbol{\phi}^i$ can be written as

$$\boldsymbol{R}_P(\boldsymbol{\phi}^i) = \boldsymbol{R}_P(\boldsymbol{\phi}^i, \boldsymbol{R}_{C_1}(\boldsymbol{\phi}^i), \boldsymbol{R}_{C_2}(\boldsymbol{\phi}^i), \ldots, \boldsymbol{R}_{C_m}(\boldsymbol{\phi}^i)) \qquad i = 1, 2, \ldots, n_d \tag{6}$$

where $\boldsymbol{R}_P$ represents the circuit-level responses simulated by the parent and $\boldsymbol{R}_{C_k}$, $k = 1, 2, \ldots, m$, represents the responses of the subcircuits simulated by the kth child. Although each child is usually designated to one particular type of simulation, $\boldsymbol{R}_{C_k}$ can be generally expressed as

$$\boldsymbol{R}_{C_k}(\boldsymbol{\phi}^i) = \boldsymbol{R}_{C_k}(\boldsymbol{R}^t_{C_k}(\boldsymbol{\phi}^i), \boldsymbol{R}^f_{C_k}(\boldsymbol{\phi}^i), \boldsymbol{R}^e_{C_k}(\boldsymbol{\phi}^i)) \tag{7}$$

where $\boldsymbol{R}^t_{C_k}$, $\boldsymbol{R}^f_{C_k}$ and $\boldsymbol{R}^e_{C_k}$ represent time-domain, frequency-domain and EM responses, respectively.

For the ith outcome and the jth specification S_j, $j = 1, 2, \ldots, n_s$, the error function is defined as

$$e_j(\boldsymbol{\phi}^i) = R_{P_j}(\boldsymbol{\phi}^i) - S_j \tag{8}$$

if S_j is an upper specification, or as

$$e_j(\boldsymbol{\phi}^i) = S_j - R_{P_j}(\boldsymbol{\phi}^i) \tag{9}$$

if S_j is a lower specification. If all $e_j(\boldsymbol{\phi}^i)$, $j = 1, 2, ..., n_s$, are nonpositive the outcome $\boldsymbol{\phi}^i$ is acceptable. The design yield is defined as the ratio of the number of acceptable outcomes to the total number of outcomes considered.

The yield optimization problem can be formulated as

$$\underset{\boldsymbol{\phi}^0}{\mathit{minimize}} \quad U(\boldsymbol{\phi}^0) = \sum_{i=1}^{n_o} H[\alpha_i v(\boldsymbol{\phi}^i)] \tag{10}$$

where α_i are positive multipliers and $v(\boldsymbol{\phi}^i)$ is the generalized ℓ_p function as defined in [16]. H can be the one-sided ℓ_1 function [16] or the one-sided Huber function [17].

Examples of Yield Optimization

To explore the flexibility of mixed-domain multi-simulator yield optimization we consider three circuits: a low-pass filter, a small-signal amplifier and a broadband small-signal amplifier with microstrip components. The design procedure for each circuit consists of nominal design followed by yield optimization.

The low-pass filter shown in Fig. 4 is designed to meet the specifications defined in both frequency- and time-domain. The specifications are

$$\begin{array}{ll} \mathrm{INSL} \leq 1.5 \text{ dB} & \text{for } 0 < \omega < 1 \\ \mathrm{INSL} \geq 25 \text{ dB} & \text{for } \omega > 2.5 \end{array}$$

in the frequency domain, and

$$0.45 \text{ V} \leq V_{out} \leq 0.55 \text{ V} \quad \text{for } 3.5 \text{ s} < t < 20 \text{ s}$$

in the time domain, where INSL is the insertion loss, ω the angular frequency in rad/s, t the time and V_{out} the output voltage.

The time-domain simulation is performed by SPICE. The frequency-domain simulation and the mixed-domain optimization are performed by OSA90/hope. L_1, L_2 and C_1 with uniform distribution of 10% tolerance are selected as design variables. The yield is increased from 29% at the nominal design to 67% after optimization. Monte Carlo sweeps of the time- and frequency-domain responses are plotted in Fig. 5.

The circuit schematic of the small-signal amplifier [2] is shown in Fig. 6. The MESFET is simulated in SPICE with the foregoing statistical model. The SPICE results are returned to OSA90/hope through Spicepipe for circuit-level simulation and optimization. The design specifications are

$$7.25 \text{ dB} < |S_{21}| < 8.75 \text{ dB}$$
$$|S_{11}| < 0.5$$
$$|S_{22}| < 0.5$$

for frequencies from 8 to 12 GHz.

The matching circuit elements, namely, L_1, L_2, L_3, L_4, L_5, L_6, C_1, C_2, C_3, C_4 and R_1, are chosen as design variables with uniform distribution of 5% tolerance. A total of 28 statistical parameters is considered. After optimization, the yield is increased from 16% at the nominal design to 52%. The histograms of $|S_{21}|$ at 12 GHz before and after optimization are depicted in Fig. 7.

To illustrate mixed-domain yield optimization including EM simulation we consider a broadband small-signal amplifier with microstrip components [18] as shown in Fig. 8. The specification is

$$7.5 \text{ dB} < |S_{21}| < 8.5 \text{ dB} \quad \text{for 6 GHz - 18 GHz}$$

The microstrip components are accurately simulated by ***em*** [7]. The MESFET is simulated by SPICE using the model shown in Fig. 3. In this case parameter statistics are obtained by PEP from the synthetic data generated by Monte Carlo simulation using the model given in [18]. The frequency-domain simulation and yield optimization are carried out by OSA90/hope.

Each of the microstrip T-structures is defined by six geometrical parameters and the feedback microstrip line is defined by two geometrical parameters [18]. Uniform distribution with 0.5 mil tolerance is assumed for all geometrical parameters. Following [18], we consider 8 geometrical parameters as design variables. The small-signal gain before and after optimization in nominal design are plotted in Fig. 9. The results for yield optimization will be included in the final submission of the paper.

Conclusions

We have described the Datapipe open architecture technique for interfacing disjoint simulators. Using this technique we have integrated a number of simulators into a powerful optimization environment facilitating mixed-domain nominal and statistical device modeling and circuit design. Our approach has been exemplified by statistical modeling of GaAs MESFETs and yield optimization of three circuits. For the first time, accurate EM field-level simulations have been combined with SPICE device modeling and powerful circuit-level optimization. The Datapipe technique provides a cost effective means for microwave engineers to efficiently utilize available simulators.

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TABLE I

PARAMETER MEAN VALUES AND
STANDARD DEVIATIONS OF
THE STATISTICAL SPICE MESFET MODEL

Parameter	Mean	Standard Deviation (%)
C_{gs} (pF)	0.4651	2.87
C_{gd} (pF)	0.0293	2.52
λ (1/V)	4.046×10^{-3}	9.75
V_{to} (V)	-2.4863	5.32
β (A/V^2)	0.0135	5.64
B (1/V)	2.3032×10^{-3}	9.44
α (1/V)	1.9413	7.61
R_d (Ω)	0.0111	8.35
R_s (Ω)	6.5941	5.15
PB (V)	0.6279	7.80
R_g (Ω)	3.7129	6.62
G_{ds} (1/Ω)	3.5593×10^{-3}	2.28
C_{ds} (pF)	0.0485	2.50
L_g (nH)	0.0306	7.97
L_d (nH)	0.0783	9.11
L_s (nH)	0.0344	3.40
C_{ge} (pF)	0.0379	9.96
C_x (pF)	20.0	-

Parameters C_{gs} through PB are the intrinsic SPICE MESFET parameters [6]. Parameters R_g through C_x are the extrinsic parameters with C_x (pF) assumed fixed (non-statistical), see Fig. 3.

TABLE II

MEAN VALUES AND STANDARD DEVIATIONS OF DATA AND SPICE MODEL RESPONSES*

	Bias 1				Bias 2			
	Data		SPICE MODEL		Data		SPICE MODEL	
	Mean	Dev. (%)	Mean	Dev. (%)	Mean	Dev. (%)	Mean	Dev. (%)
$Re\{S_{11}\}$	-0.197	9.18	-0.192	12.5	-0.153	12.1	-0.170	13.7
$Im\{S_{11}\}$	-0.756	1.1	-0.747	1.07	-0.764	1.0	-0.760	1.01
$Re\{S_{12}\}$	0.0733	2.7	0.0770	3.1	0.0770	2.71	0.0784	2.93
$Im\{S_{12}\}$	0.0519	2.36	0.0527	4.89	0.0559	2.46	-0.054	4.68
$Re\{S_{21}\}$	-0.212	8.35	-0.432	15.2	-0.230	6.99	-0.433	15.3
$Im\{S_{21}\}$	1.78	1.22	1.736	8.71	1.687	1.67	1.650	9.22
$Re\{S_{22}\}$	0.440	1.43	0.434	3.33	0.439	1.44	0.442	3.27
$Im\{S_{22}\}$	-0.364	0.89	-0.364	0.96	-0.367	0.89	-0.366	0.97
I_d (A)	0.0401	8.16	0.0407	14.7	0.0332	9.51	0.0338	16.1

Bias 1: $V_G = -0.5$ V, $V_D = 5$ V.
Bias 2: $V_G = -0.7$ V, $V_D = 5$ V.

* S parameters at 11 GHz.

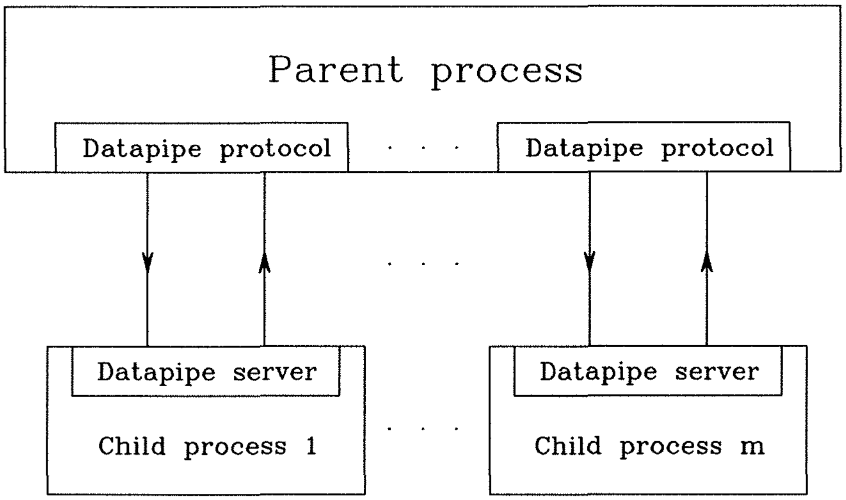


Fig. 1. Datapipe schematic.

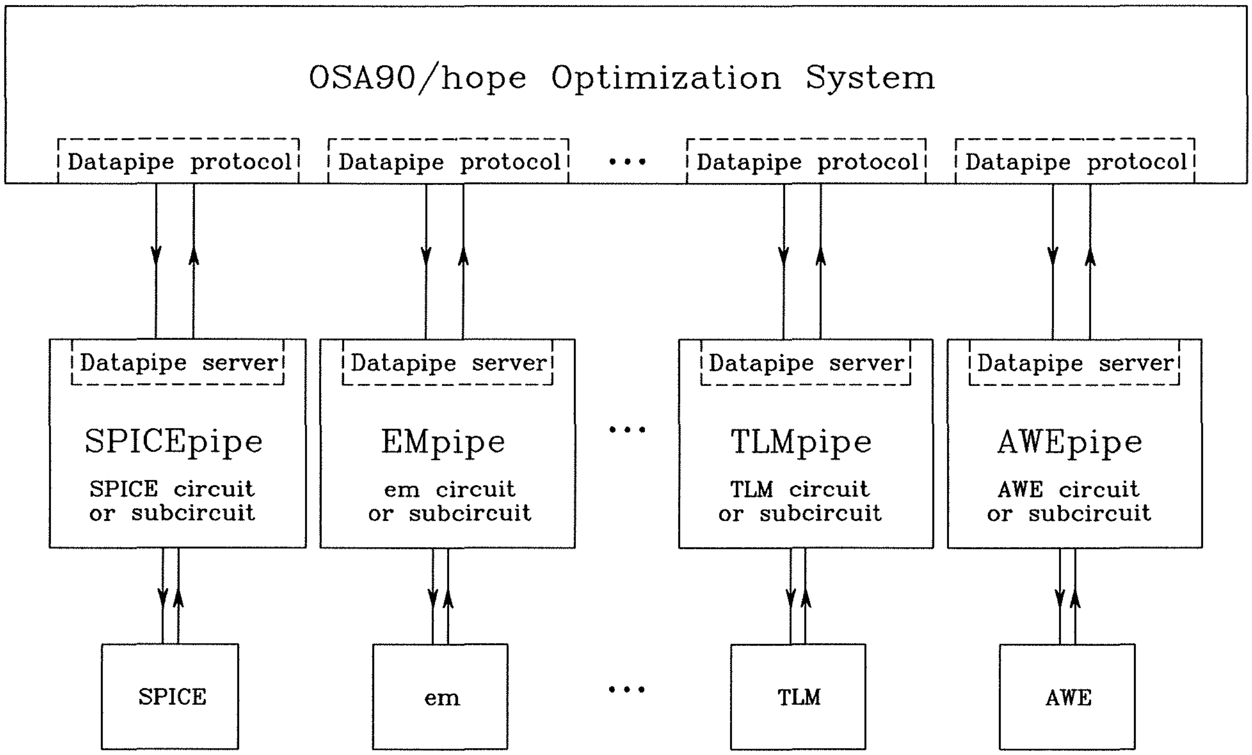


Fig. 2. Datapipe interface between OSA90/hope and several external simulators.

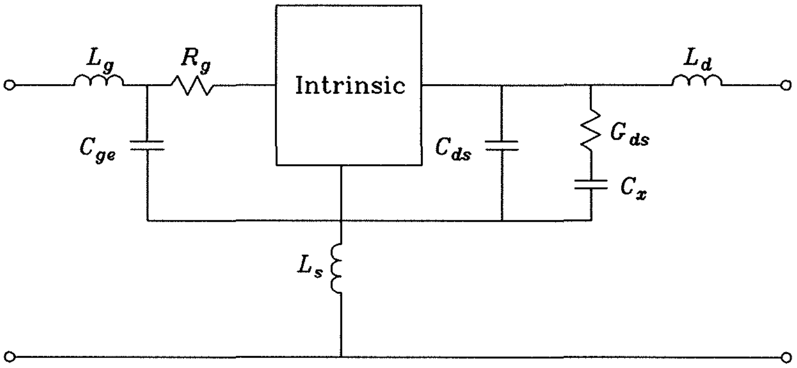


Fig. 3. Equivalent circuit for the SPICE MESFET model.

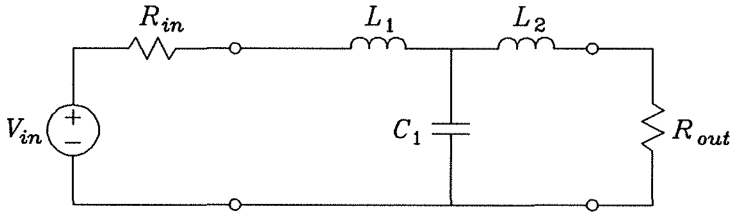
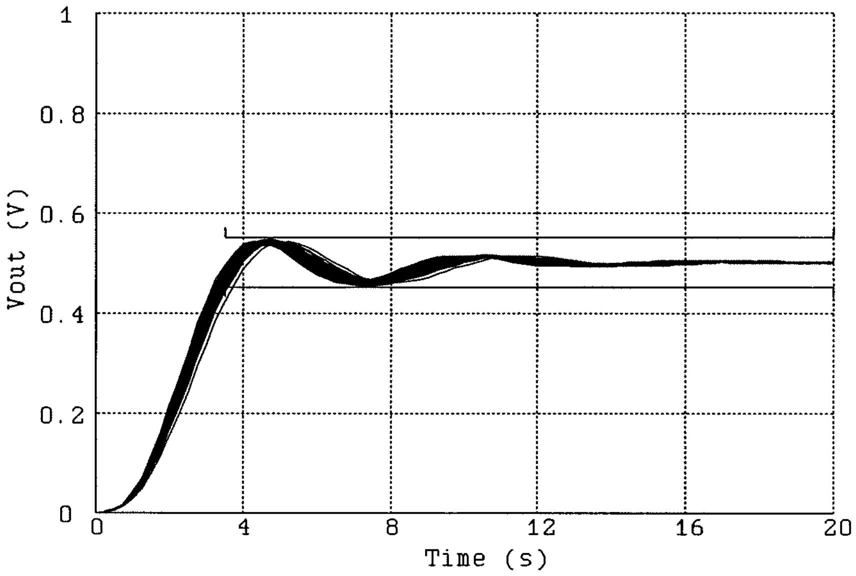
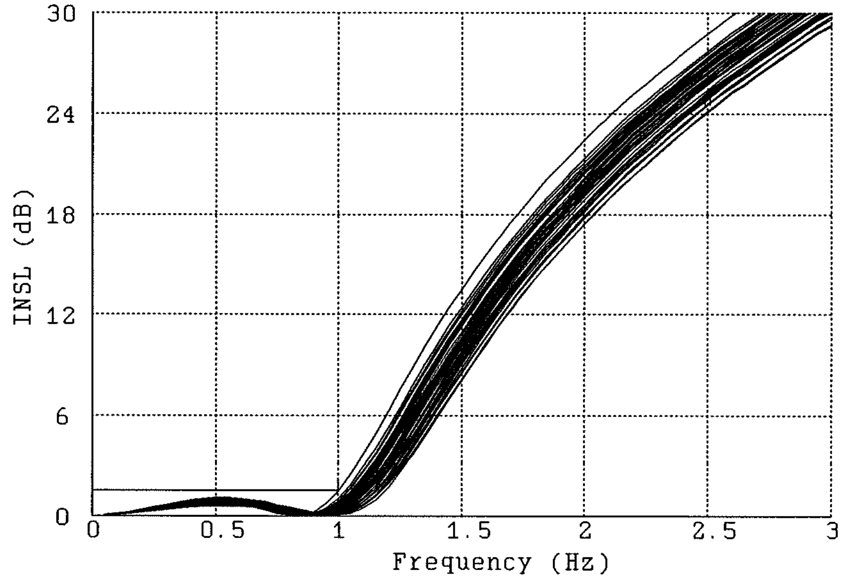


Fig. 4. The low-pass LC filter.



(a)



(b)

Fig. 5. Monte Carlo sweeps of the low-pass filter responses in (a) the time-domain and (b) the frequency-domain.

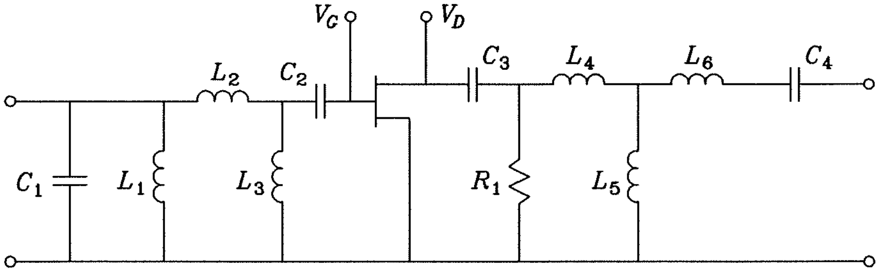
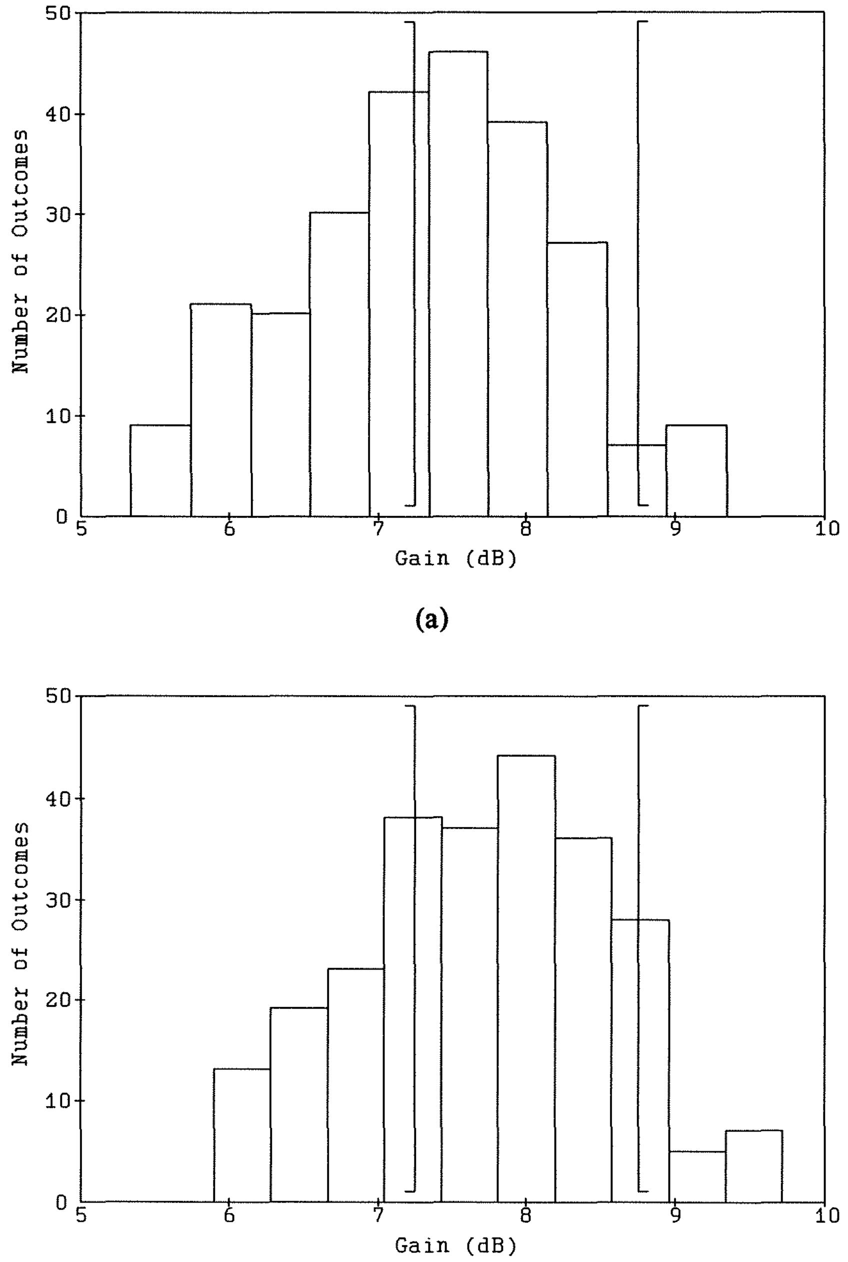


Fig. 6. The small-signal amplifier [2].



(a)

(b)

Fig. 7. Histograms for the gain of the small-signal amplifier at 12 GHz (a) before and (b) after yield optimization.

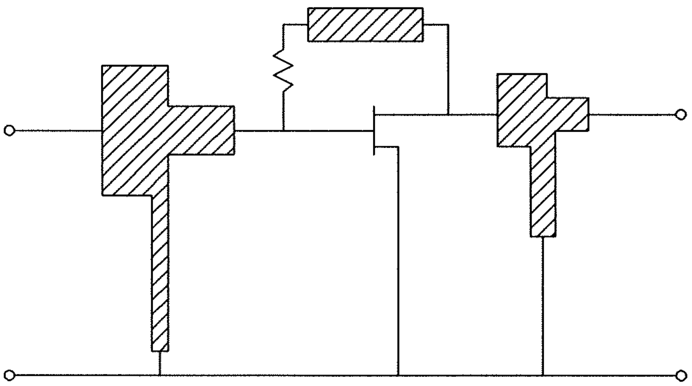


Fig. 8. The broadband small-signal amplifier with microstrip components [18].

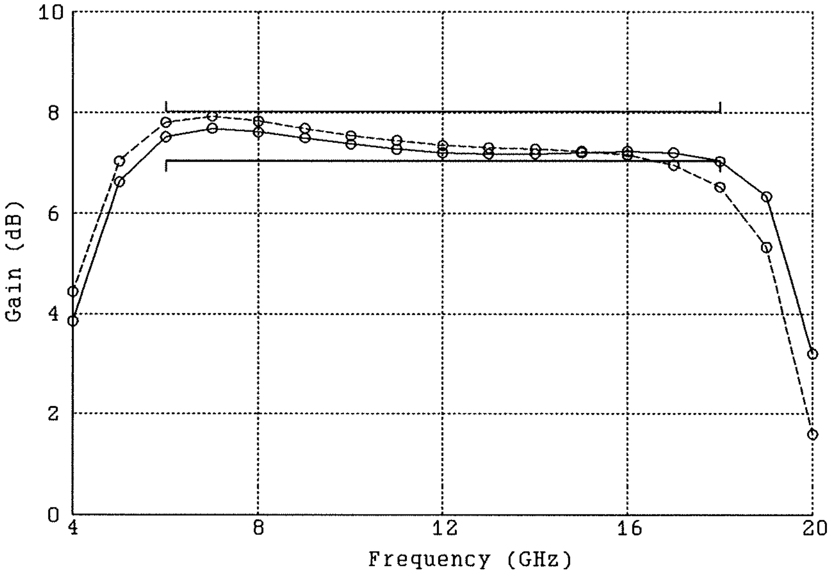


Fig. 9. Gain of the broadband small-signal amplifier before (---) and after (——) nominal design.