OSA

STATISTICAL PHYSICS-BASED MODELING AND YIELD-DRIVEN DESIGN OF MICROWAVE CIRCUITS

OSA-92-OS-4-V

April 28, 1992

Optimization Systems Associates Inc.

Dundas, Ontario, Canada

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Quadratic Modeling

to reduce the number of actual time-consuming circuit simulations

suitable for any application where a large number of expensive simulations is required

multidimensional quadratics

maximally flat interpolation technique: applying the least-squares constraint to the second order term coefficients provides unique solution

fixed pattern of base points leads to extremely efficient modeling

Gradient Quadratic Modeling

to take advantage of available gradient information - in OSA90/hope and in HarPE available through the *FAST* technique

quadratic modeling applied to responses and their gradients simultaneously

especially suitable for gradient-based yield-driven design

a low-pass filter and an MMIC amplifier design illustrate the merits

Implementation of Gradient Quadratic Modeling

types of variables

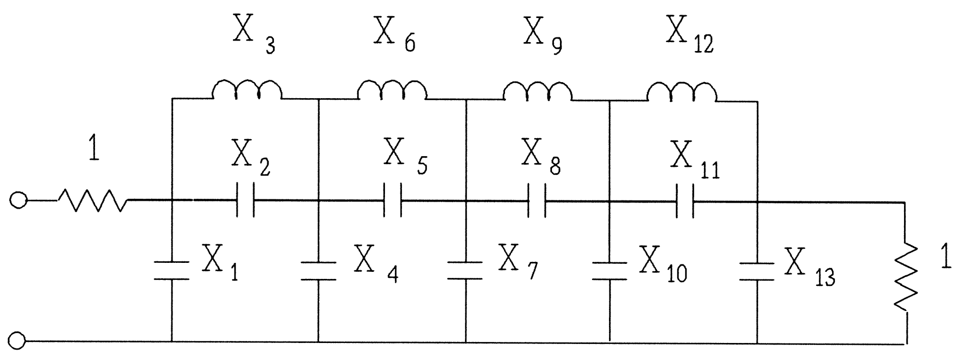
n_{DS} designable variables with statistics
n_D designable variables without statistics
n_S non-designable variables with statistics

use the same set of $2(n_{DS} + n_S) + 1$ base points for both responses and gradients

build quadratic models for all responses and gradients at each iteration

evaluate the models for all statistical outcomes

13-Element Low-Pass Filter



Specifications

insertion loss less than 0.4dB at 21 angular frequencies from 0.25 to 1 and greater than 49dB at 7 frequencies from 1.05 to 1.115

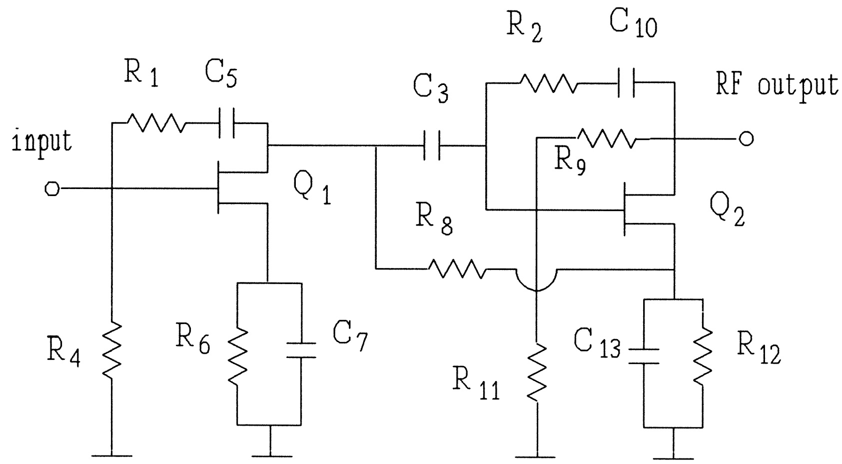
Design Parameters

13 elements, normal distribution with 0.5% standard deviation

Yield

33.4% at the initial minimax solution is increased to 76%

Two-Stage GaAs MMIC Feedback Amplifier



FET Model

small-signal physics-based Ladbrooke model

Specifications

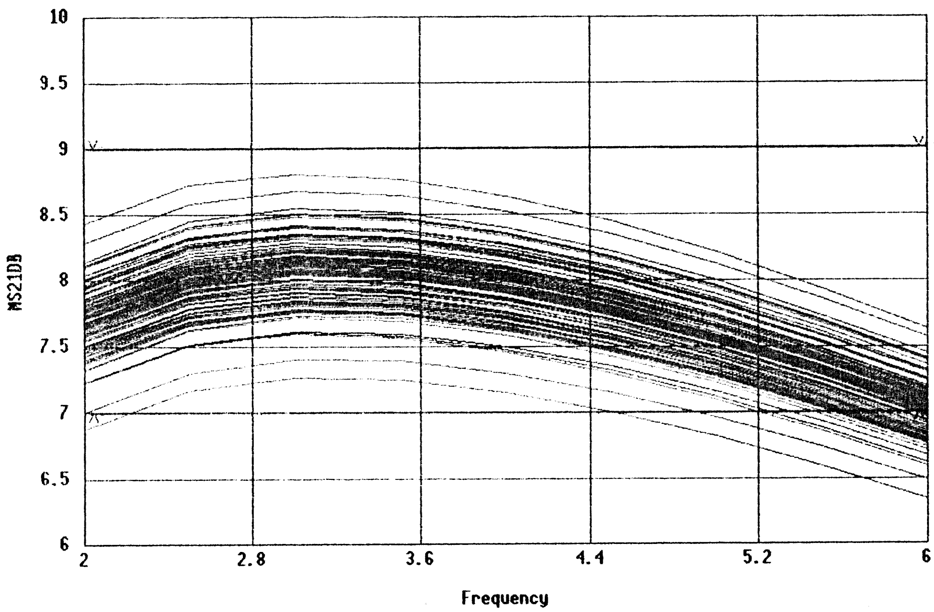
small-signal gain: between 7dB and 9dB
VSWR at the input port: less than 2
VSWR at the output port: less than 2.2

Design Parameters

R_1, R_2, and C_3

Responses of Two-Stage GaAs MMIC Feedback Amplifier

at the starting point (minimax solution) yield is 32.1%



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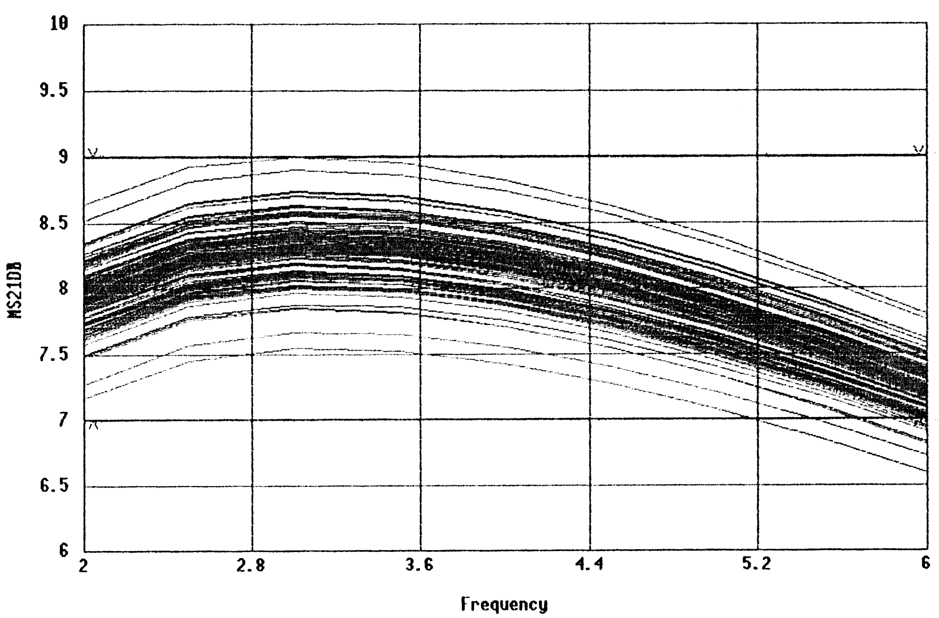


Physics-Based Design and Yield Optimization of MMICs

the ability to predict and enhance production yield is critical for the continued success of MMIC technology

physics-based models (PBMs) for active and passive devices dealing directly with the lowest level of fabrication/technological parameters are essential for the next generation of microwave CAD

PBMs allow to include physical parameters as design variables

the advantages of PBMs over traditional equivalent circuit models (ECMs) are particularly clear in statistical modeling

yield optimization of a three stage X-band amplifier illustrates the merits

Equivalent Circuit Models (ECMs)

equivalent circuit models representing active devices

statistical properties assigned to the parameters of ECMs

difficult to represent actual statistical properties of the devices

high computational efficiency

Physics-Based Models (PBMs)

using PBMs for both active devices and passive components

statistical properties assigned to physical parameters

reflecting actual statistical properties of the devices

more computationally intensive than ECMs

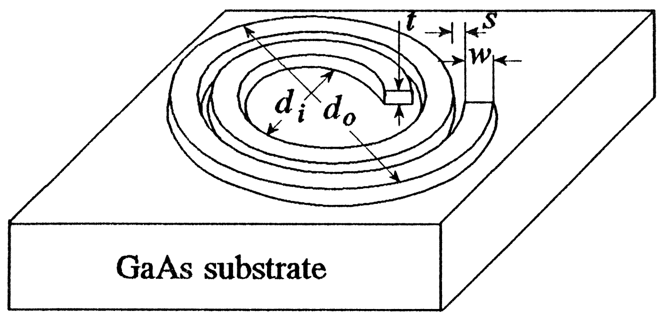
PBMs for Passive Devices

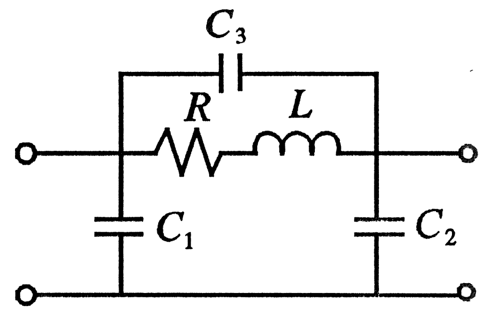
passive devices represented by their n-port **Y** matrices

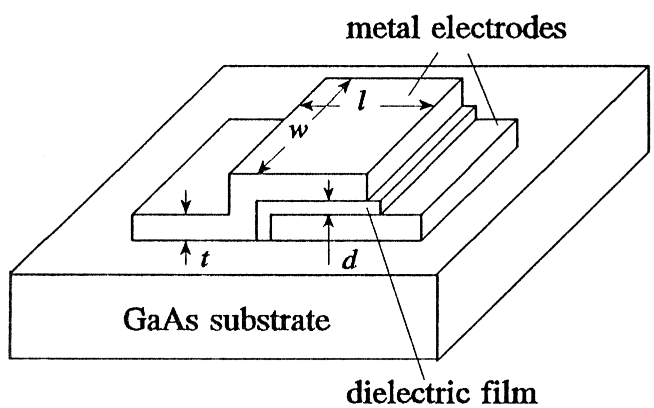
the entries of **Y** are calculated from equivalent circuit components

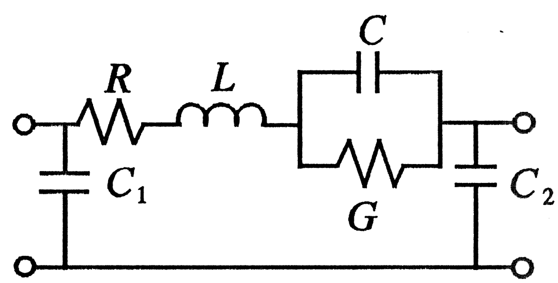
the expressions of the equivalent circuit components are derived from (simplified) device physics

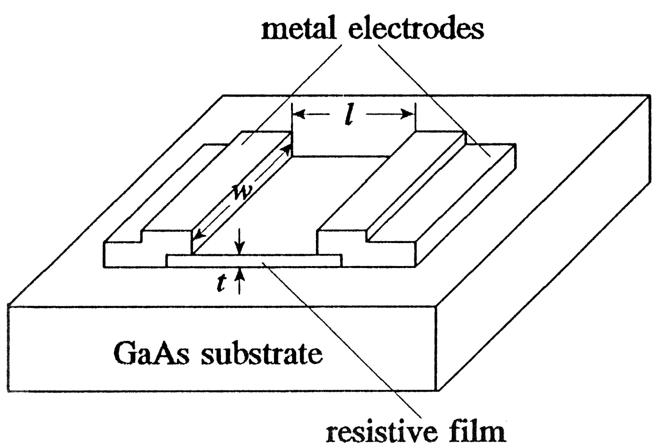
Examples of PBMs for Passive Devices

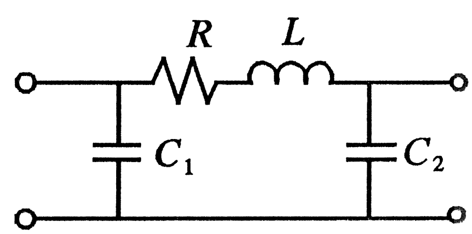




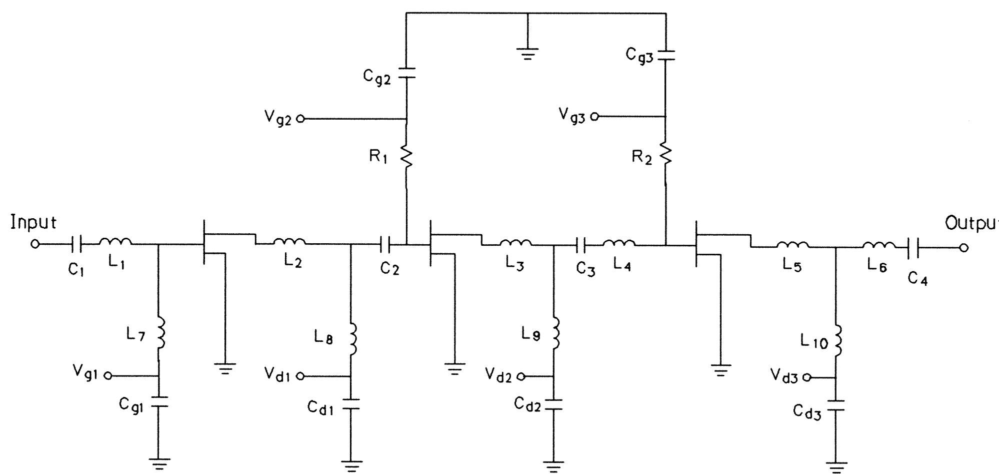








Yield Optimization of a Three Stage X-band Amplifier using OSA90/hope



Specifications

8GHz - 12GHz: gain between 12dB and 16dB, VSWR < 2
in the stopband: gain < 2dB

Variables

37 statistical variables with correlations
16 design variables

Assumed Distributions for Statistical Variables for the Three Stage X-band Amplifier

Variable	Mean Value	Std Dev	Variable	Mean Value	Std Dev
$N_d(cm^{-3})$	$2.0\ 10^{17}$	7.0	d(m)	0.1	4.0
L_G(m)	1.0	3.5	S_{C1}(m^2)	532.7	3.5
A_G(m)	0.24	3.5	S_{C2}(m^2)	2278.9	3.5
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The doping density N_d, gate length L_G, channel thickness A_G and gate width W_G 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. S_{Ci} is the area of the metal plate of MIM capacitor C_i.

Predicted and Verified Yield for Different Specifications

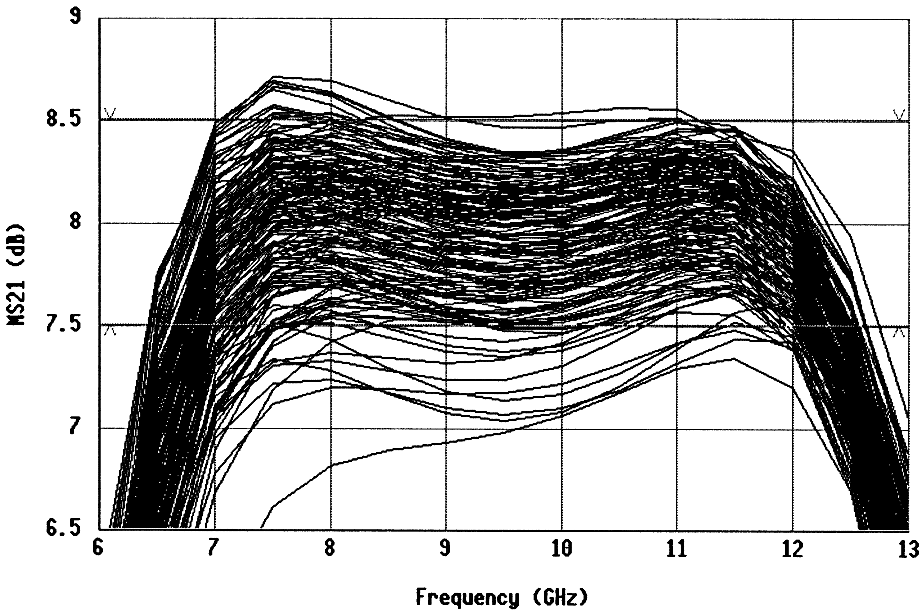
Specification	Before Yield Optimization		After Yield Optimization	
	Predicted Yield (%)	Verified Yield (%)	Predicted Yield (%)	Verified Yield (%)
Spec. 1	17.5	15.7	67	57.9
Spec. 2	21	20	83	75.7
Spec. 3	44	37.1	98	93.6

Spec. 1: $7.5\text{dB} < |S_{21}| < 8.5\text{dB}$, $|S_{11}| < 0.5$, $|S_{22}| < 0.5$
Spec. 2: $6.5\text{dB} < |S_{21}| < 7.5\text{dB}$, $|S_{11}| < 0.5$, $|S_{22}| < 0.5$
Spec. 3: $6.0\text{dB} < |S_{21}| < 8.0\text{dB}$, $|S_{11}| < 0.5$, $|S_{22}| < 0.5$

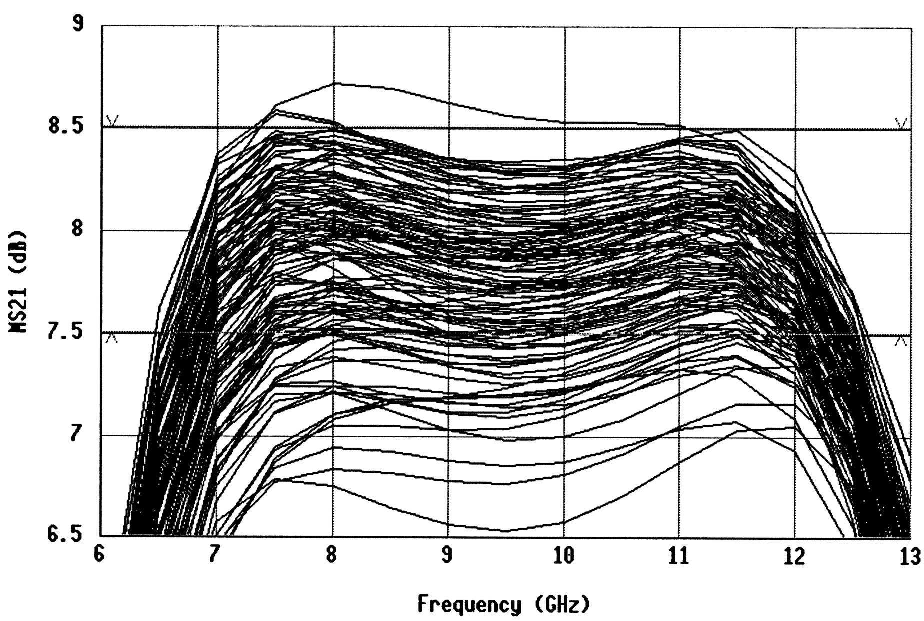
200 Monte Carlo outcomes are used for predicted yield, 140 for verified yield.

Yield Comparison

Monte Carlo simulation using the new MESFET model



Monte Carlo simulation using device data



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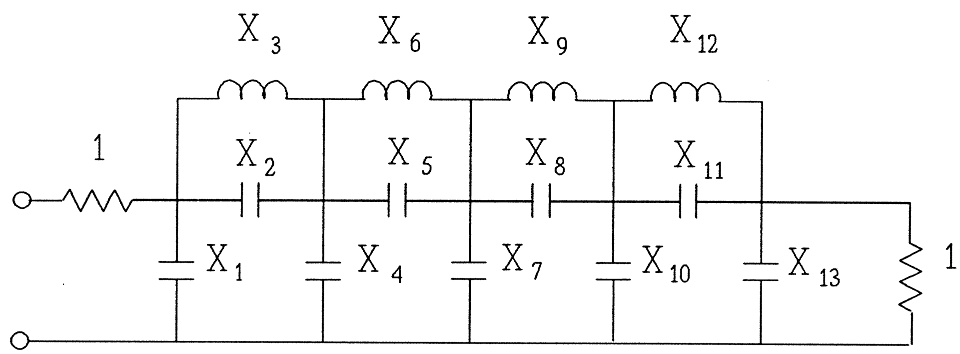

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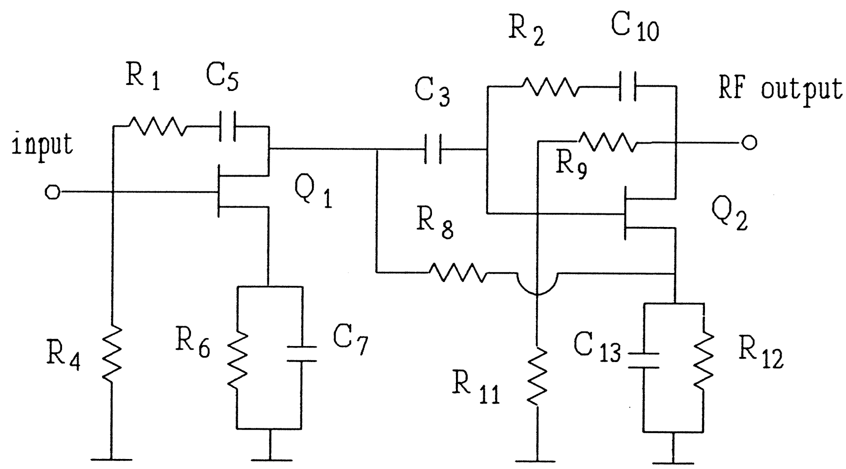

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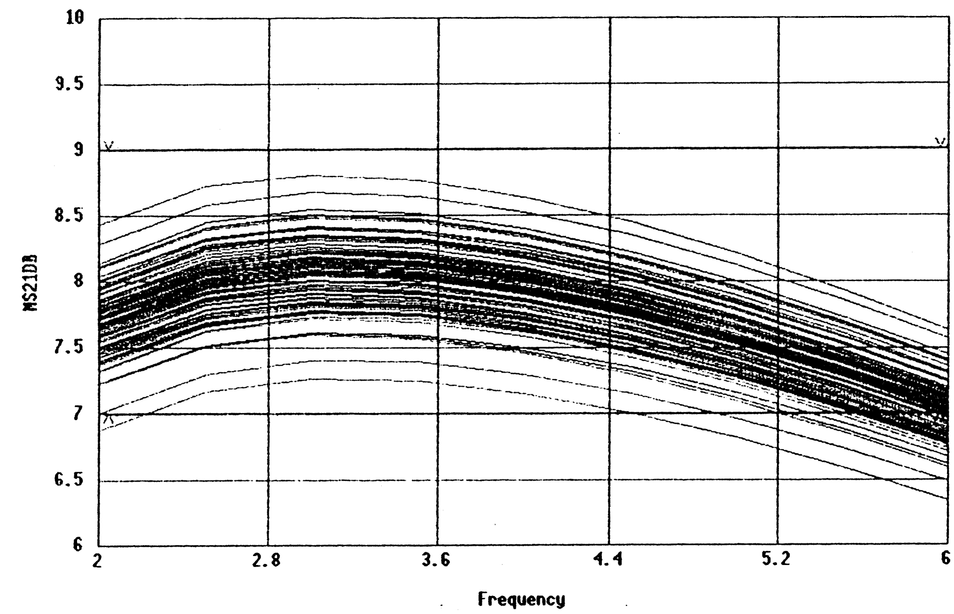

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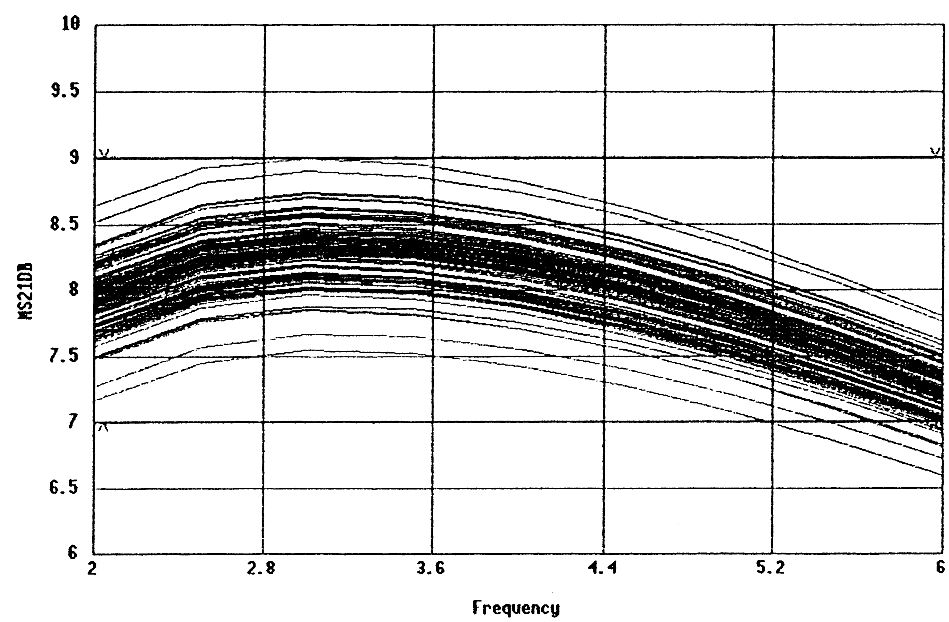

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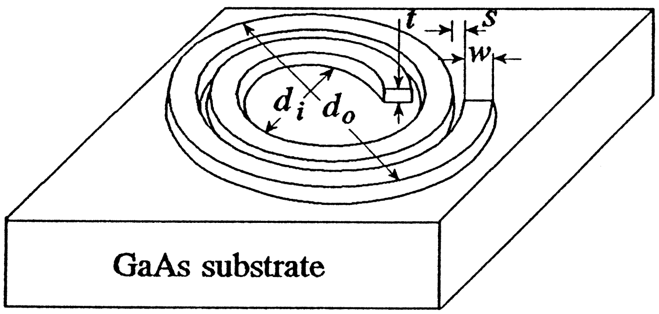

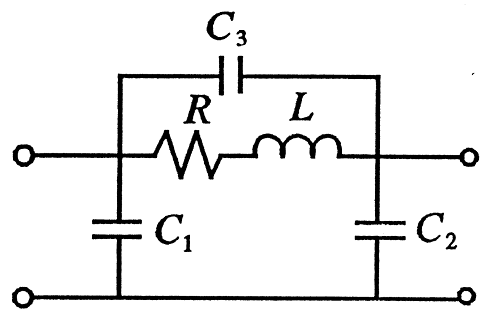

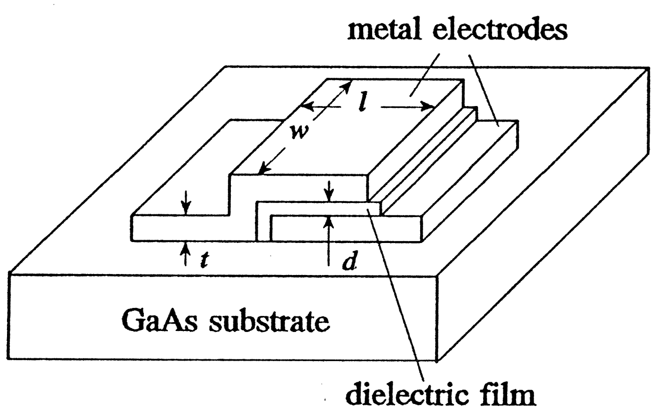

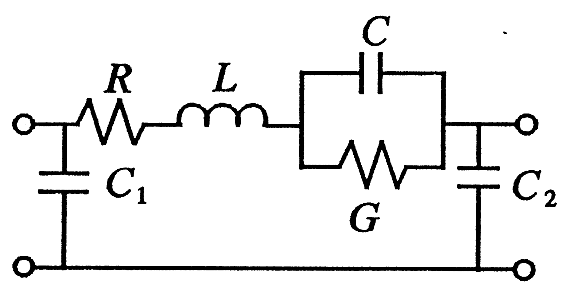

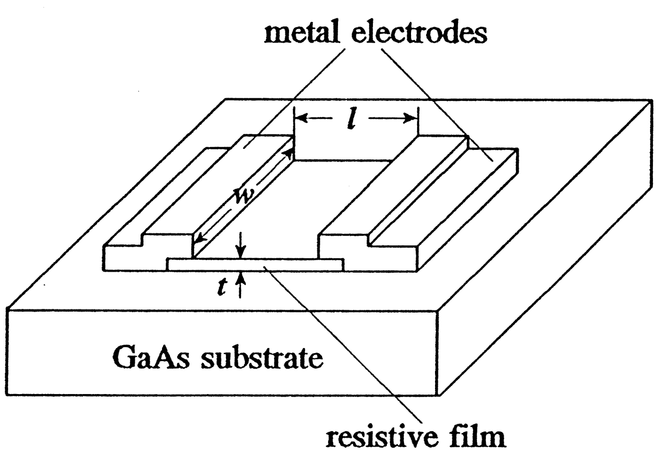

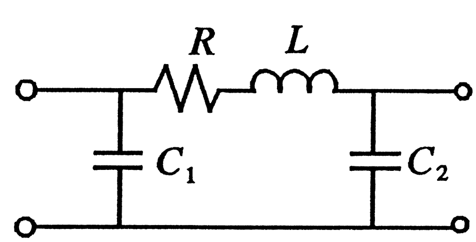

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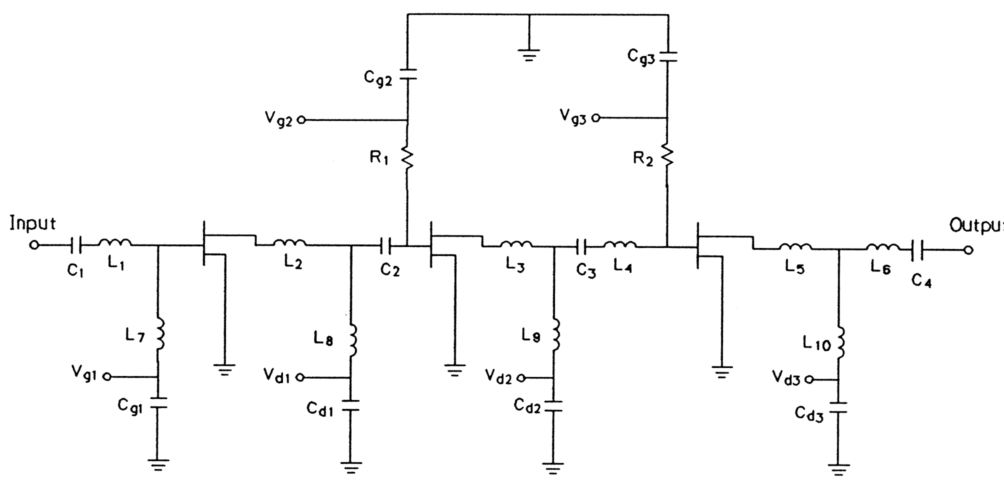

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ASSUMED PARAMETER CORRELATIONS FOR THE THREE MESFETS

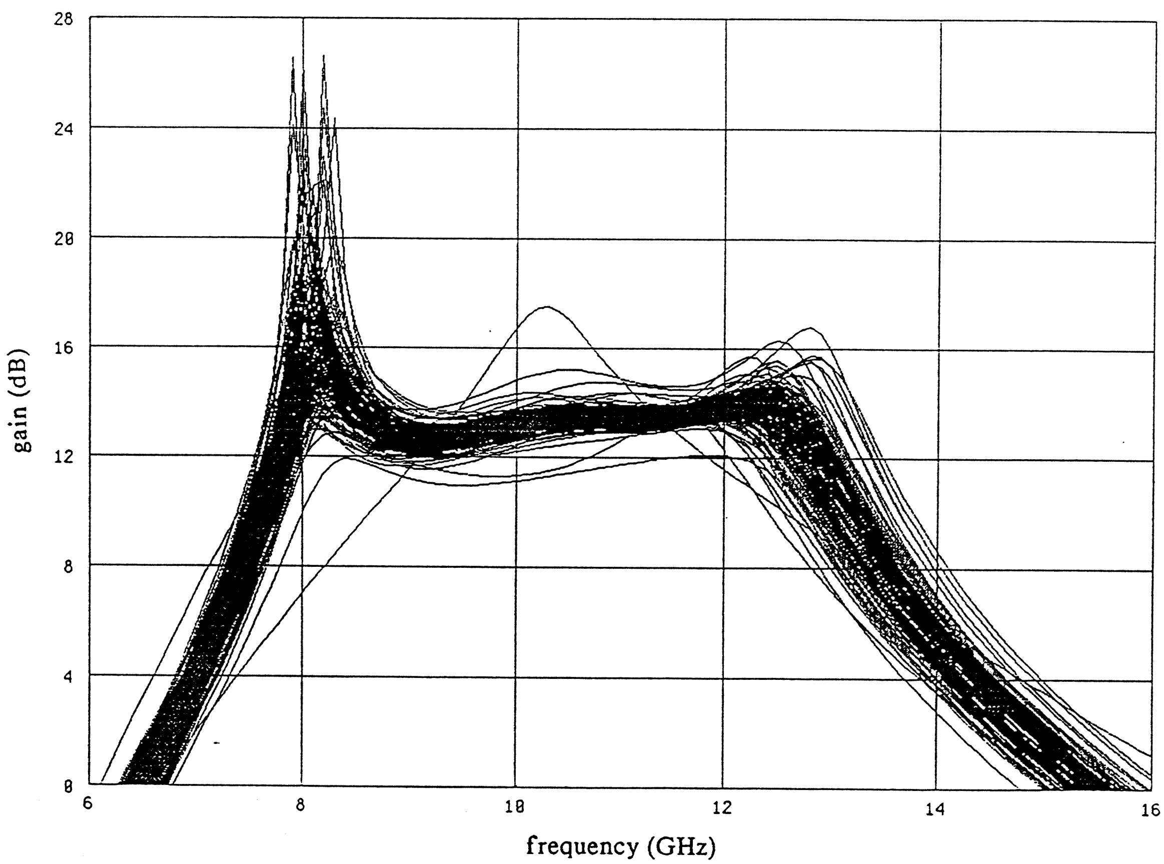
	A_{G1}	L_{G1}	W_{G1}	N_{d1}	A_{G2}	L_{G2}	W_{G2}	N_{d2}	A_{G3}	L_{G3}	W_{G3}	N_{d3}
A_{G1}	1.00	0.00	0.00	-0.25	0.80	0.00	0.00	-0.20	0.78	0.00	0.00	-0.10
L_{G1}	0.00	1.00	0.00	-0.10	0.00	0.80	0.00	-0.05	0.00	0.78	0.00	-0.05
W_{G1}	0.00	0.00	1.00	0.00	0.00	0.00	0.80	0.00	0.00	0.00	0.78	0.00
N_{d1}	-0.25	-0.10	0.00	1.00	-0.20	-0.05	0.00	0.80	-0.15	-0.05	0.00	0.78
A_{G2}	0.80	0.00	0.00	-0.20	1.00	0.00	0.00	-0.25	0.80	0.00	0.00	-0.20
L_{G2}	0.00	0.80	0.00	-0.05	0.00	1.00	0.00	-0.10	0.00	0.80	0.00	-0.10
W_{G2}	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
A_{G3}	0.78	0.00	0.00	-0.15	0.80	0.00	0.00	-0.20	1.00	0.00	0.00	-0.25
L_{G3}	0.00	0.78	0.00	-0.05	0.00	0.80	0.00	-0.05	0.00	1.00	0.00	-0.10
W_{G3}	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

Design Variables for Yield Optimization of the Three Stage X-band Amplifier

Design Variable	Before Opt.	After Opt.	Design Variable	Before Opt.	After Opt.
A_G(m)	0.24	0.243	n_{L3}	2.33	2.04
N_d(cm^{-3})	2.0 10^{17}	2.03 10^{17}	n_{L4}	2.29	2.34
S_{C1}(m^2)	532.7	552.2	n_{L5}	2.32	2.39
S_{C2}(m^2)	2278.9	1910.2	n_{L6}	1.84	2.08
S_{C3}(m^2)	583.1	554.2	n_{L7}	1.49	1.50
S_{C4}(m^2)	468.7	477.2	n_{L8}	2.65	2.82
n_{L1}	2.88	2.79	n_{L9}	2.43	2.48
n_{L2}	3.98	4.11	n_{L10}	3.27	3.35

n_{Li} is the number of turns of the spiral inductor L_i.

Gain of the Three Stage X-band Amplifier Before Yield Optimization



200 outcomes

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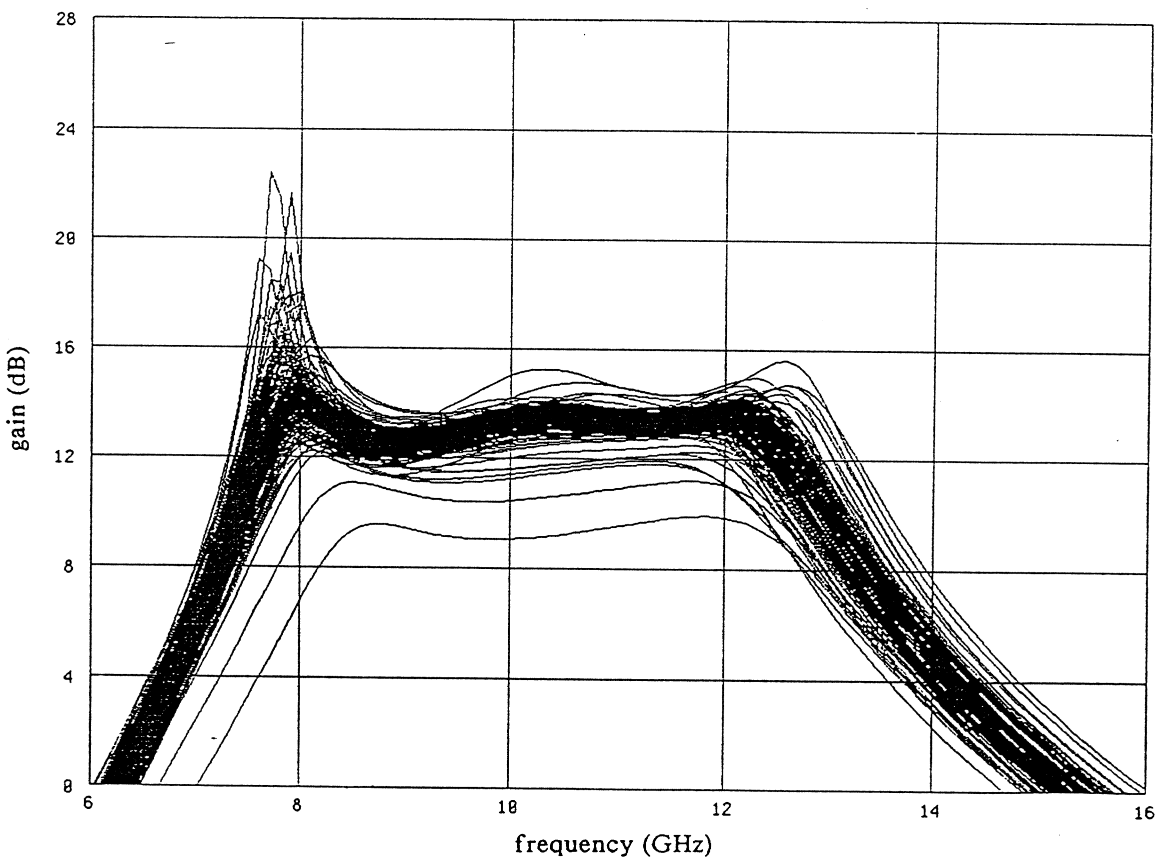

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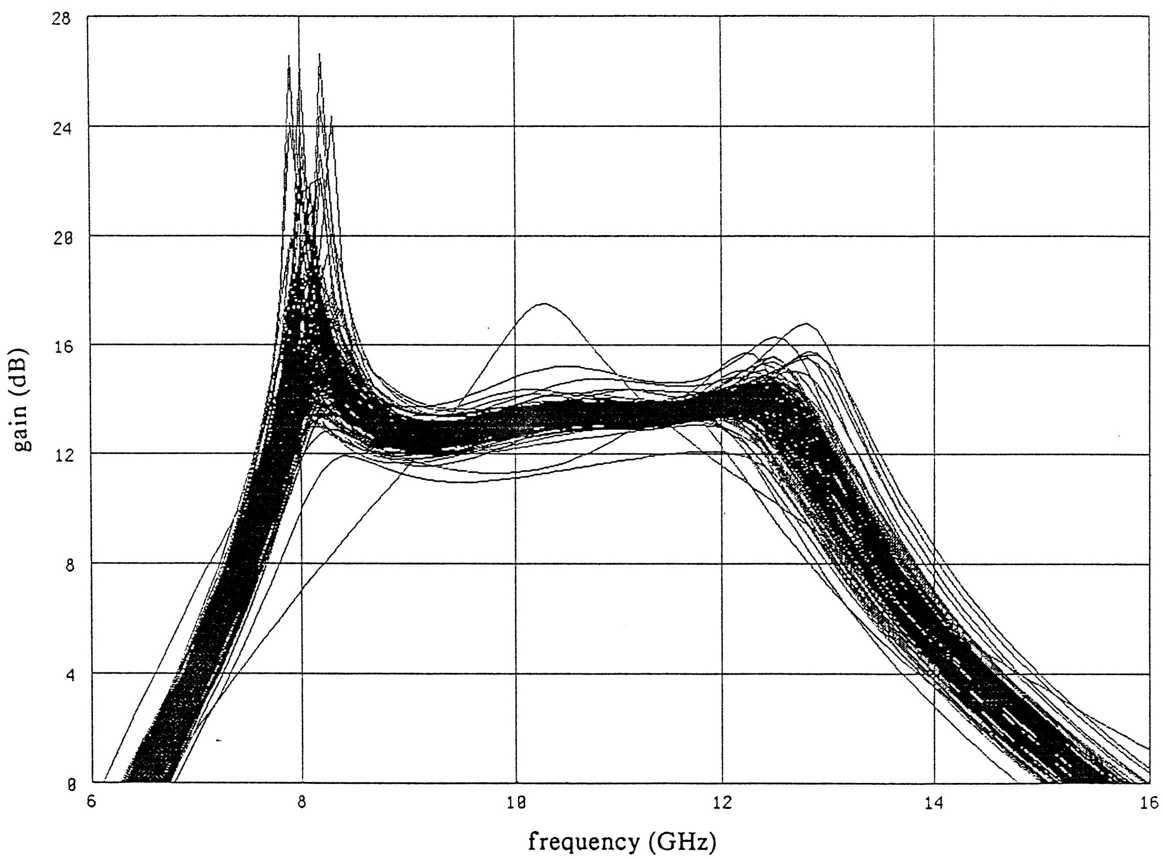

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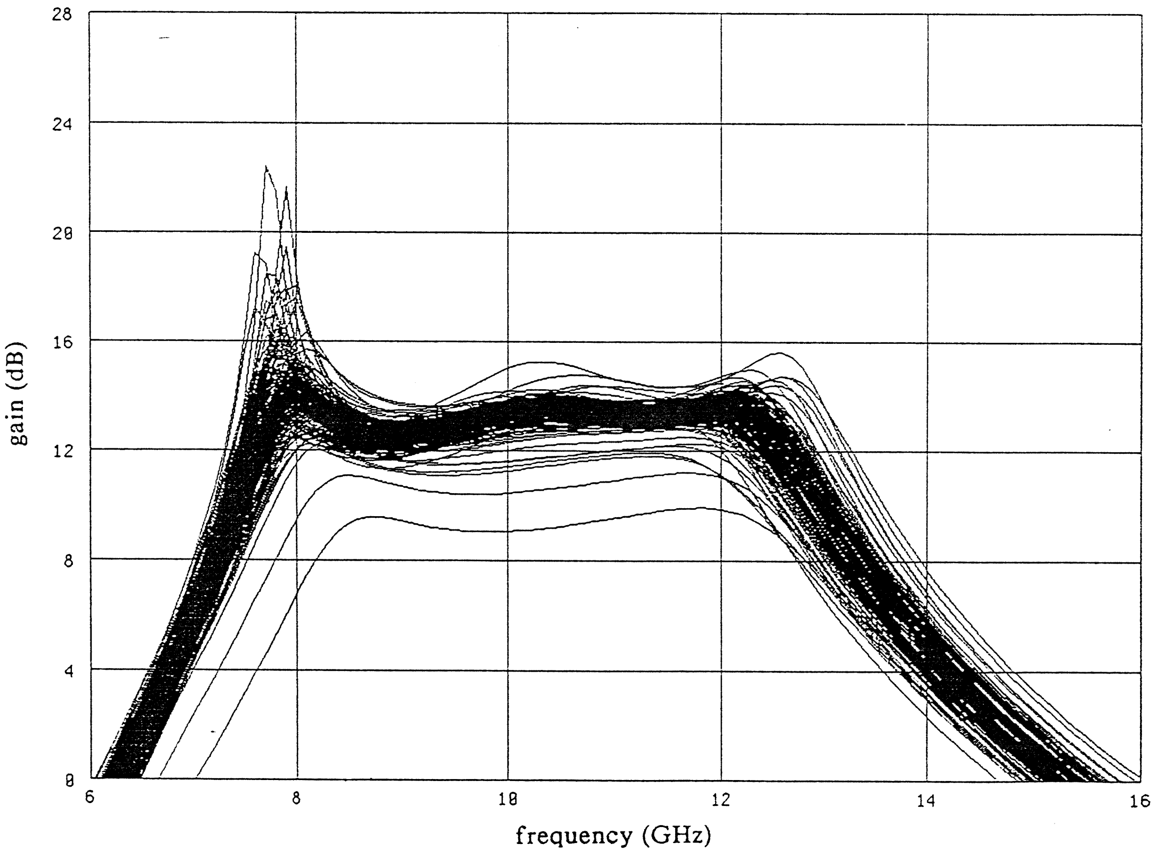

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Statistical Modeling of GaAs MESFETs

statistical modeling is a prerequisite for yield-driven and cost-driven circuit design

statistical modeling may be approached at

equivalent circuit parameter level

measurement level

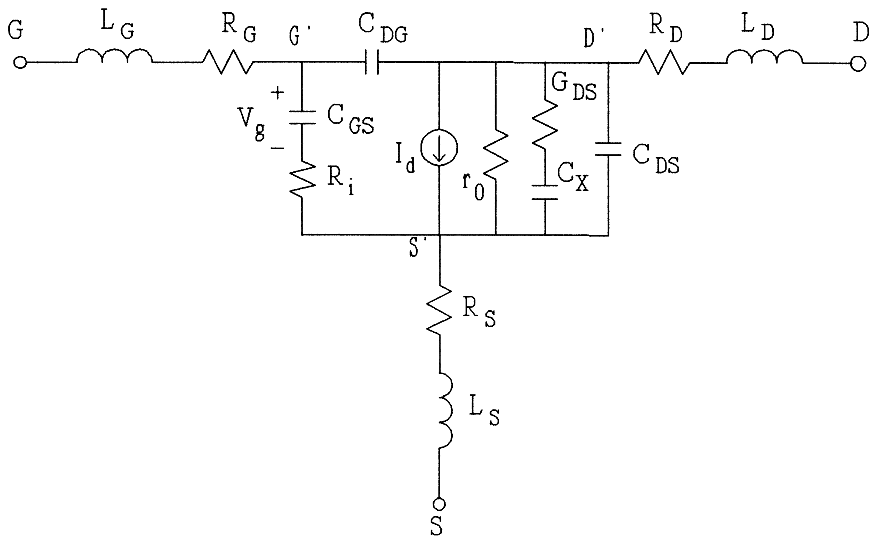
physical and material parameter level

the equivalent circuit model can accurately fit the data from which the model parameters are extracted, because it has fewer constraints and more variables than the physical model

the model based on physical parameters can preserve the statistical characteristics of the actual device

for yield-driven and cost-driven circuit design, physics-based statistical models are more accurate

FET Model Equivalent Circuit



the Materka and Kacprzak nonlinear FET model

nonlinear intrinsic FET parameters

$\{I_{DSS}, V_{p0}, \gamma, E, K_E, \tau, S_S, R_{10}, K_R, C_{10}, C_{1S}, K_1, C_{F0}, K_F\}$

linear extrinsic parameters

$\{L_G, R_G, R_D, L_D, R_S, L_S, G_{DS}, C_{DS}\}$

The Ladbrooke Physics-Based MESFET Model

the model is in equivalent circuit form

the elements of the equivalent circuit are expressed in terms of physical and geometrical parameters

g_m, τ, r_0, C_{GS}, C_{DG}, R_i, R_D, R_S, and L_G are functions of the physical parameters and bias conditions

R_G, L_D, L_S, G_{DS} and C_{DS} are assumed to be linear components

the model parameters of the Ladbrooke MESFET model to be extracted are

$$\{L_{g0}, W, N, v_{sat}, V_{B0}, a_0, r_{01}, r_{02}, r_{03}, L_{G0}, R_G, L_D, L_S, G_{DS}, C_{DS}\}$$

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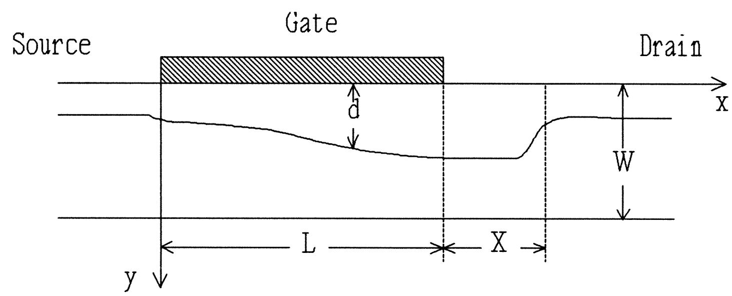

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for example

$$g_m = \epsilon v_{sat} Z_G / d$$

$$C_{DG} = 2\epsilon Z_G / (1 + 2X/L_{g0})$$

$$L_G = \mu_0 \, d Z_G / (m^2 L_{g0}) + L_{G0}$$

the equivalent depletion depth d, the voltage dependent space-charge layer extension X and the channel current are obtained as

$$d = [2\epsilon(-V_{G'S'} + V_{B0})/(qN)]^{0.5}$$

$$X = a_0\{2\epsilon/[qN(-V_{G'S'} + V_{B0})]\}^{0.5} (V_{D'G'} + V_{B0})$$

$$I_{CH} = qNv_{sat}(W-d)Z_G$$

Statistical Modeling Procedure

measurement data

four-finger 0.5 μm GaAs MESFET measurement data from Plessey Research Caswell

69 individual devices from two wafers

each device is measured under 3 bias conditions and at frequencies from 1GHz to 21GHz with 0.4GHz step

modeling procedure

extract model parameters for each individual device

postprocess to obtain the statistics of the model

the form of the statistical model

nominal values (mean values)

tolerances (standard deviations)

discrete distribution functions (DDFs)

correlation matrix

Verifications of Statistical FET Device Modeling

statistical models must be able to predict the statistical behaviour of actual devices

the model responses and the actual device responses must be statistically consistent

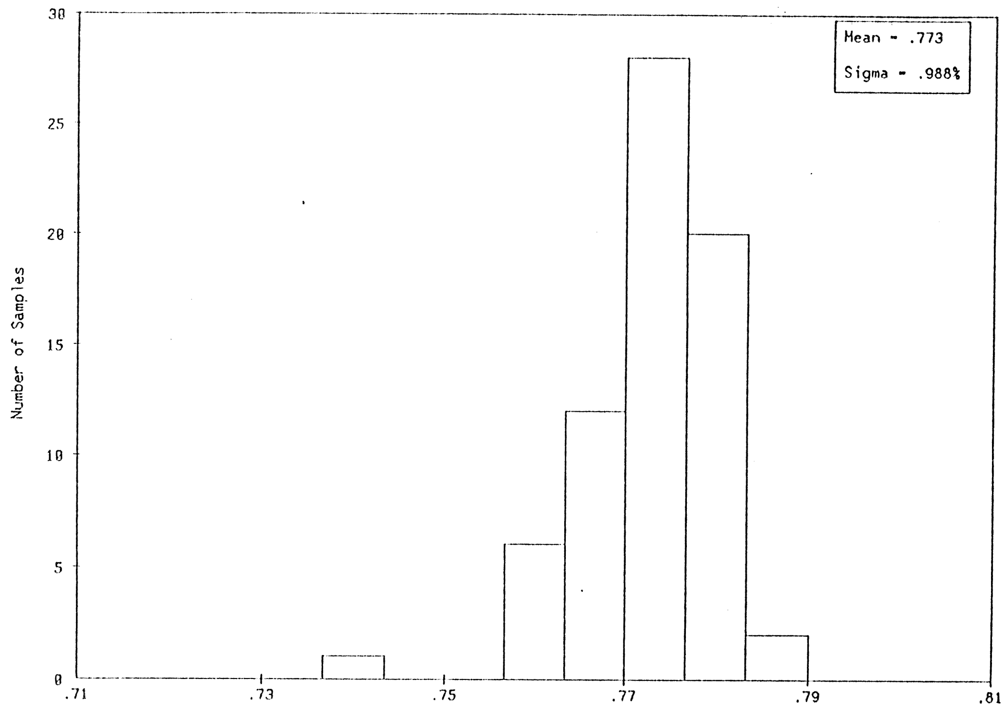
we calculate S parameters of the Ladbrooke and the Materka and Kacprzak models through Monte Carlo simulations at one bias point and one frequency point

the statistics of the simulation results are compared with the statistics of the measurements

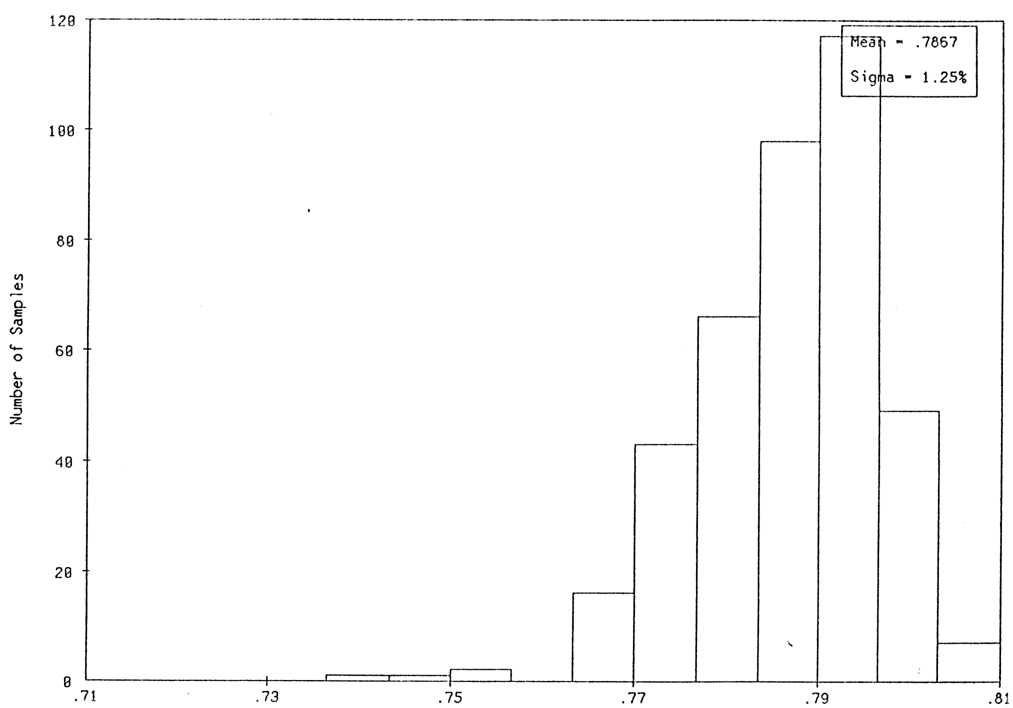
MEAN VALUES AND STANDARD DEVIATIONS OF MEASURED AND SIMULATED S PARAMETERS AT 11GHZ

	Measured		Simulated			
			Ladbrooke		Materka	
	Mean	Dev.(%)	Mean	Dev.(%)	Mean	Dev.(%)
$\|S_{11}\|$	.7730	.988	.7856	.764	.7725	1.74
$\angle S_{11}$	-114.3	1.36	-119.3	1.10	-114.9	1.63
$\|S_{21}\|$	1.919	.802	1.679	1.34	1.933	15.2
$\angle S_{21}$	93.35	.856	94.06	.835	93.43	.860
$\|S_{12}\|$	.0765	3.77	.07542	3.68	.07564	5.07
$\angle S_{12}$	34.00	2.51	31.98	2.33	33.72	2.14
$\|S_{22}\|$	0.5957	1.48	.5838	1.54	.5935	4.19
$\angle S_{22}$	-38.69	2.10	-36.86	1.42	-37.85	3.31

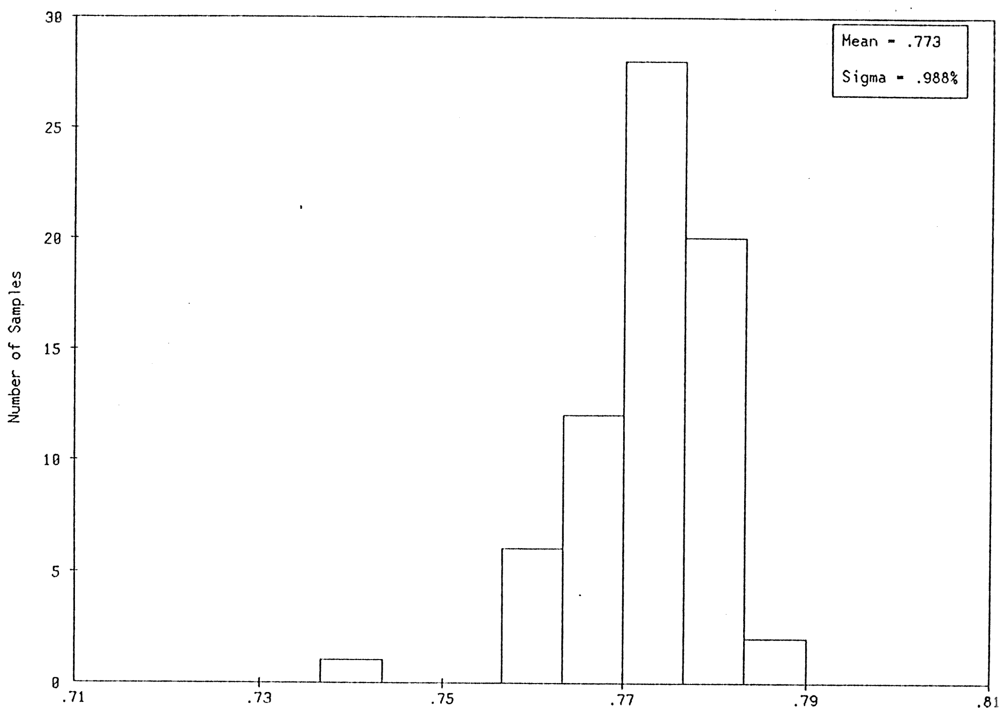
Histogram of $|S_{11}|$ at 11GHz from Measurement



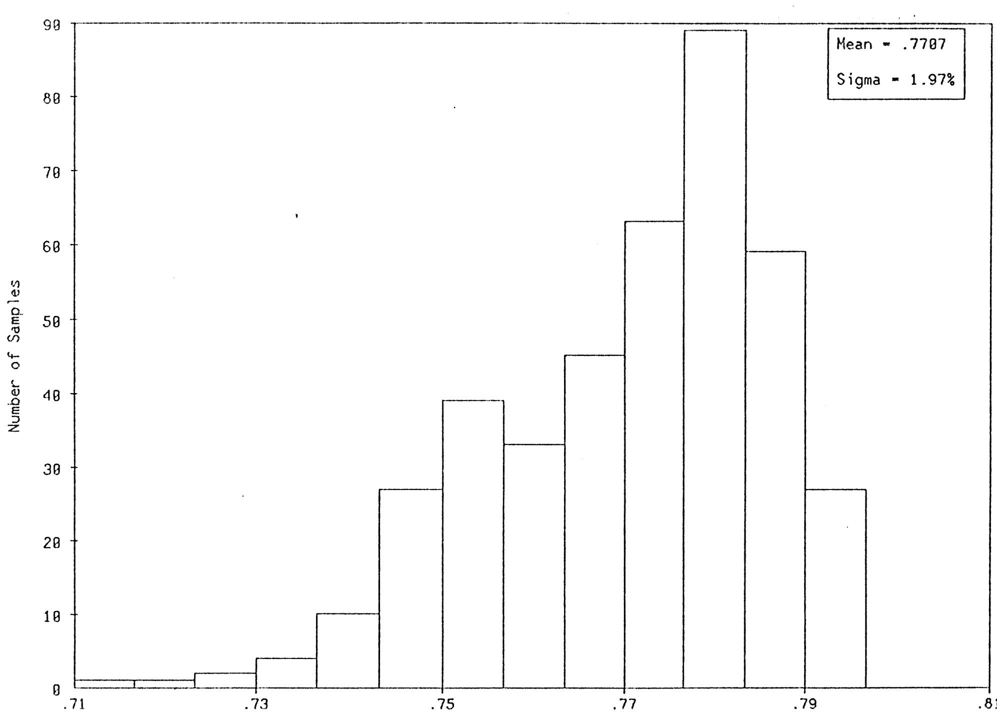
Histogram of $|S_{11}|$ at 11GHz from the Ladbrooke Model



Histogram of $|S_{11}|$ at 11GHz from Measurement



Histogram of $|S_{11}|$ at 11GHz from the Materka Model



Physics-Based Small-Signal Statistical FET Model

the small-signal Ladbrooke model provides more reliable estimates of device statistics than normal equivalent circuit models

the Ladbrooke model does not have DC simulation capability

the physics-based Khatibzadeh and Trew model provides good DC simulation but is inaccurate for small-signal simulation

we combine the DC Khatibzadeh and Trew characterization and the small-signal Ladbrooke formulas to form a new physics-based small-signal FET model

the new model is being tested within the statistical environment of HarPE and OSA90/hope

the new model is particularly suitable for bias-dependent small-signal FET statistical modeling

Predictable Yield-Driven Circuit Optimization

combined Khatibzadeh and Trew/Ladbrooke model

the model is characterized from device measurements of 0.5 μm GaAs MESFET provided by Plessey Research Caswell

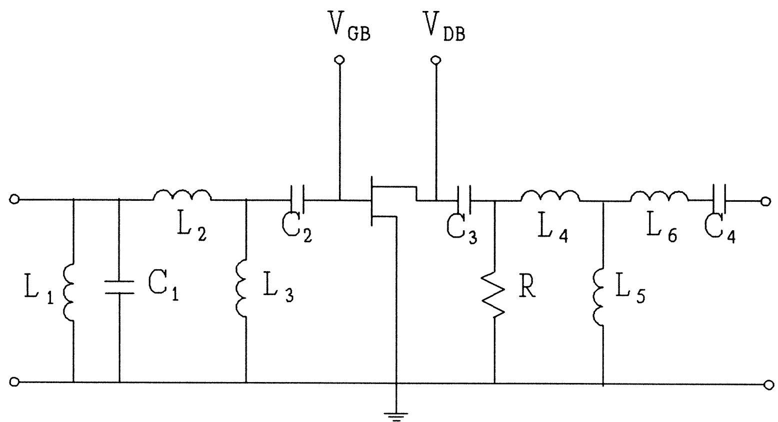
design of a small-signal broadband amplifier is investigated using OSA90/hope

(1) nominal design

(2) yield optimization (using 100 outcomes)

yield estimates by Monte Carlo analyses before and after yield optimization are 17.5% and 67%

Small-Signal Broadband Amplifier



specifications

$|S_{21}| = 8\text{dB} \pm 0.5\text{dB}$

$|S_{11}| \leq 0.5$

$|S_{22}| \leq 0.5$

design variables are the matching network elements

$L_1, L_2, L_3, L_4, L_5, L_6, C_1, C_2, C_3, C_4, R$

ASSUMED PARAMETER CORRELATIONS FOR THE THREE MESFETS

	A_{G1}	L_{G1}	W_{G1}	N_{d1}	A_{G2}	L_{G2}	W_{G2}	N_{d2}	A_{G3}	L_{G3}	W_{G3}	N_{d3}
A_{G1}	1.00	0.00	0.00	-0.25	0.80	0.00	0.00	-0.20	0.78	0.00	0.00	-0.10
L_{G1}	0.00	1.00	0.00	-0.10	0.00	0.80	0.00	-0.05	0.00	0.78	0.00	-0.05
W_{G1}	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
A_{G2}	0.80	0.00	0.00	-0.20	1.00	0.00	0.00	-0.25	0.80	0.00	0.00	-0.20
L_{G2}	0.00	0.80	0.00	-0.05	0.00	1.00	0.00	-0.10	0.00	0.80	0.00	-0.10
W_{G2}	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
A_{G3}	0.78	0.00	0.00	-0.15	0.80	0.00	0.00	-0.20	1.00	0.00	0.00	-0.25
L_{G3}	0.00	0.78	0.00	-0.05	0.00	0.80	0.00	-0.05	0.00	1.00	0.00	-0.10
W_{G3}	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