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Abstract

This paper addresses physics-based design and yield optimization of MMICs. Multidimensional 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%.

SUMMARY

Introduction

With the rapid progress of GaAs fabrication technology, MMICs are becoming more and more practical [1]. 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. The existing approaches to yield optimization, e.g., [2-4], assume as statistical variables the parameters of equivalent circuit models. There are serious doubts, however, 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 models of both active devices and passive components. Statistics are directly applied to physical and geometrical parameters and through model simulation are reflected in the circuit responses. Correlations between parameters are also considered, which is very important for MMICs.

Design of a three stage amplifier illustrates our approach. The conventional performance-driven design produced a yield of 45%. Our yield optimization improves it to 73.5%.

Physics-Based Models for Active and Passive Components

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. We follow the physics-based FET model developed by Khatibzadeh and Trew [5]. More precisely, a modified version [6] is used to model the FETs in our amplifier design. The model parameter vector ϕ_a includes gate length, gate width, channel thickness, doping density, etc. Model simulation is performed in the time domain and iteratively solves nonlinear physics-based equations to determine the gate, drain and source conduction currents I_{gc}, I_{dc}, I_{sc} and the and accumulation charges Q_g, Q_d and Q_s for given parameter values ϕ_a and the intrinsic device voltages.

Passive components such as spiral inductors, MIM capacitors and planar resistors are represented in the frequency domain by their two-port Y matrices $Y(\phi_p)$, where ϕ_p is the 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.

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. Statistical variations in a single physical parameter 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 [7].

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.

Yield-Driven Design Optimization

Yield-driven design is formulated as a one-sided ℓ_1 optimization problem [3,4] with the error functions defined by the response values relative to the window specifications, and evaluated for a number of statistically generated circuit outcomes. The vector ϕ combines the parameters of the physics-based models for the active devices ϕ_a and the parameters of passive components ϕ_p. It includes optimizable (designable) parameters and statistical parameters. Some parameters can be simultaneously optimizable and statistical. Physics-based models enable us to make a meaningful selection of optimizable parameters. Using physics-based models, we can optimize variables that are tangible and within realistic constraints.

A Three Stage X-band Amplifier

Yield optimization of a three stage small-signal X-band cascadable amplifier shown in Fig. 1 was carried out. The circuit topology and the fabrication layout follow [8]. The amplifier contains three MESFETs which are built using an interdigitated structure based on two gate fingers of dimensions 200μmx1.0μm. 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 the third MESFETs are biased through a 1500Ω GaAs bulk resistor. The drains and the first gate bias are bypassed by a large MIM capacitor. The amplifier was designed 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 was performed. As in a traditional design, only the matching circuits were optimized with the parameters of the active devices (MESFETs) being fixed. The resulting minimax nominal design was used as the starting point for yield optimization.

Since all devices are made from the same material and on the same wafer, they share some 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.

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, and the geometrical parameters of the passive elements. The mean values, standard deviations and correlations for the statistical variables will be reported in the full paper. Most significant are the correlations between the same parameters for different devices. For instance, the gate lengths of the three MESFETs are significantly correlated.

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 were chosen as design variables for yield optimization. At the starting point (i.e., the minimax nominal design), the yield was 45% as estimated by Monte Carlo analysis with 200 statistical outcomes. The yield was improved to 73.5% at the solution of the yield optimization (about 3 hours CPU time on a Sun SPARCstation 1). The Monte Carlo sweep of gain before and after yield optimization is shown in Fig. 2.

Conclusions

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

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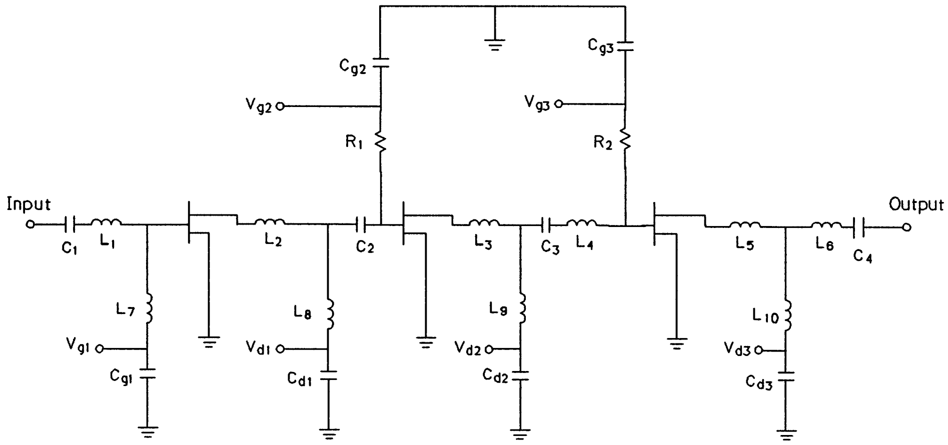
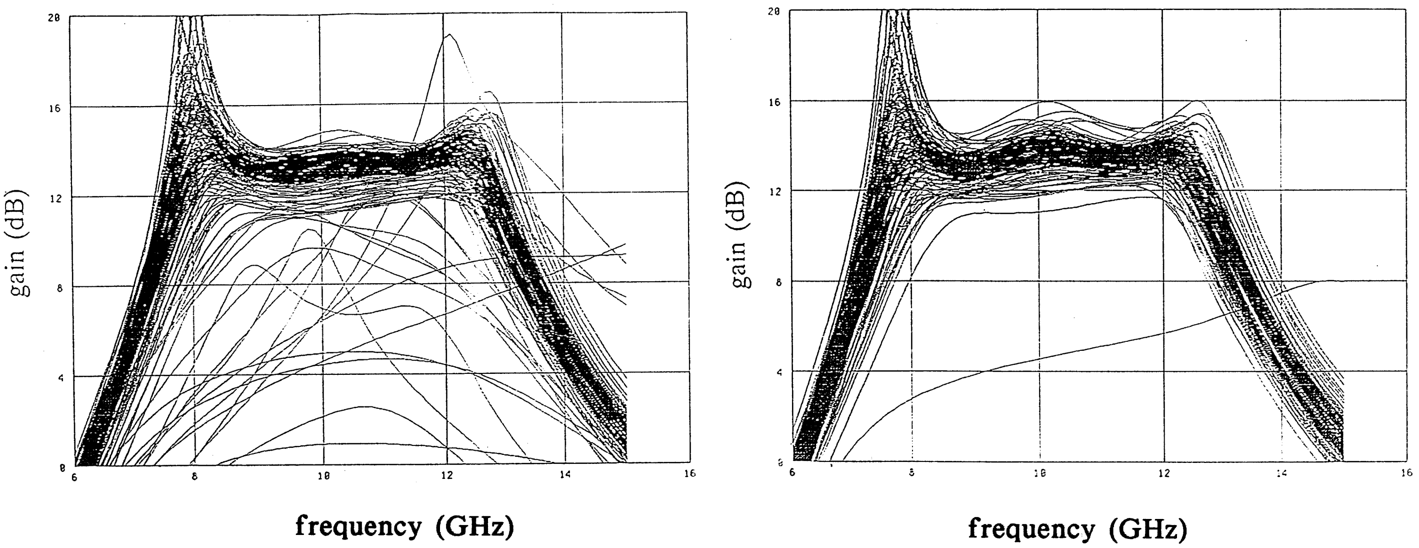


Fig. 1. Circuit diagram of X-band amplifier [8].



(a)

(b)

Fig. 2. Monte Carlo sweep of gain versus frequency (a) before and (b) after yield optimization.