Computer-Aided Design of Monolithic MESFET Distributed Amplifiers

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Abstract **—A computerized optimization method called simulated annealing is applied to the design of monolithic distributed amplifiers. The element values in the small-signal equivalent circuit model of the MESFET's, the characteristics of the gate and drain transmission lines, and the number of stages are generated to match a specified frequency response by this computer-aided design (CAD) process. The success of this process lies in the fact that it is fully automatic and the only input needed is the desired flat band gain and the 3 dB point. The method itself is sufficiently general that it can be applied to a variety of design problems. Excellent agreement is shown when the distributed amplifier designed is simulated using Touchstone, a popular microwave simulation program.**

I. Introduction

A DISTRIBUTED amplifier using a MESFET was first demonstrated by Jutzi [1]. Techniques for determining the device parameters were described by Fukui [2]. Subsequently, the concept of distributed amplification was applied successfully to GaAs MESFET amplifiers at microwave frequencies [3]–[5].

Following this development, design and analysis methods were applied to optimize the performance of distributed amplifiers [6]–[8]. The design of a distributed amplifier involves a careful choice of many variables, such as the characteristics of the MESFET's, the number of stages, and the characteristics of the gate and drain lines, to match with the desired frequency response. An analysis of a distributed amplifier based on an equation developed for the normalized gain was described [6]. Analytical/graphical techniques were proposed to provide a close approximation to the optimum design of a distributed amplifier [6]–[8]. These methods involve heavy expertise in determining a set of good initial parameters. Several iterations are necessary to achieve an acceptable design. Since these methods utilize graphical charts, they are prone to error.

This paper describes the investigation and development of a computer-aided design (CAD) procedure that has hitherto not been used for the design of distributed amplifiers. A design-by-simulation methodology based on an optimization algorithm is applied in this new CAD procedure to a monolithic distributed amplifier under design. This procedure is completely automatic and does not require the user to have any expertise in the analysis of distributed amplifiers. It will be shown that the only necessary input is the desired gain and the 3 dB roll-off point and that the procedure automatically designs a monolithic distributed amplifier that matches the requirements.

This paper is organized as follows. Section II describes the design-by-simulation methodology which is used along with an optimization algorithm called simulated annealing, described in Section III. The details of implementing the design-by-simulation methodology with simulated annealing are given in Section IV. The design procedure will then be demonstrated by an example in Section V. The simulation of the distributed amplifier using Touchstone is also presented for comparison. We will also compare this method with previously published experimental results.

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II. Design-By-Simulation Methodology

Given a set of circuit parameters, computer simulation can be used to predict the performance of a circuit before it is physically built. The objective of a design is to determine the parameters of a circuit so that the circuit will provide the performance specified by the designer. The new CAD process described in this paper uses a set of analytical equations to simulate the distributed amplifier under design. An optimization process is then applied to determine the circuit parameters so that the simulation results match with the requirements. This *design-by-simulation* methodology is an alternative to the more commonly used *design-by-analysis* methodology.

The optimization problem in a design-by-simulation procedure is defined as the problem of finding the minimum of a given objective function depending on many interrelated parameters. Let the circuit parameters of a distributed amplifier under design be represented by V_i, where $i=1$ to n, and n is the total number of parameters in the circuit. In addition, assume the desired and simulated characteristics (e.g., the frequency response) of a distributed amplifier are represented by M_j and M_j', respectively, where $j=1$ to m, and m is the number of desired characteristics. The objective function used in this design-by-simulation method can then be written as the normalized total least-squares difference between the de-

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sired and simulated characteristics, which is defined as

$$F(V_i) = \sum_{j=1}^{m} \left(\frac{(M_j - M_j')}{M_j} \right)^2 . \quad (1)$$

In this manner, the design problem of a distributed amplifier is translated into an optimization problem which tries to determine a set of V_i which minimize the objective function, $F(V_i)$.

III. Simulated Annealing Optimization

The success of a design-by-simulation method depends on the capability of the optimization method which is used to fit the simulated circuit characteristics to desired requirements. Gradient methods have been successfully applied to optimization problems for some time [9]–[11]. The direct application of such methods can be computationally intensive and the issue of convergence must be addressed. Variations and improvements of these methods have been proposed. However, the problem of local minima has not been directly tackled, the usual recipe being "trying a number of initial solutions."

Theoretically, the best solution of an optimization problem exists under a certain well-defined objective function and can be guaranteed only by generating and evaluating all possible solutions. However, the size of the solution space (i.e., all the possible solutions) is extremely large and it grows exponentially with the number of variables in the problem. It is generally impossible to perform an exhaustive search to locate the best solution in a reasonable time.

A typical optimization process utilizes an iterative improvement strategy. First, an initial set of estimated parameters is generated as the starting point of a search process; small variations are then made to these parameters at each step to generate a new set of parameters, which is evaluated according to the objective function to be minimized. In order to guarantee the convergence of an optimization process, traditional algorithms are greedy and accept only those changes that can improve the cost of the objective function.

One inherent drawback of this type of search is that it can be easily trapped into the local minima of an objective function if good initial values are not available. An approach called *simulated annealing* (SA) has been proposed and applied as a method to find a near-optimal solution for combinatorial optimization problems [12], [13]. SA associates the statistical mechanics, which deals with the behavior of systems with many degrees of freedom in thermal equilibrium at a finite temperature, with the combinatorial optimization problem, which finds the minimum of a given function depending on many parameters.

The perturbations of parameters to minimize an objective function in an optimization process are analogous to the displacements of atom locations to minimize the energy in an annealing process. The excellent analogy between the two processes suggested the application of an annealing process to an optimization problem, thus the name simulated annealing. In order to apply the concept and mechanism of annealing to the optimization problem, a control parameter, pseudotemperature, has to be artificially introduced in a simulated annealing process to simulate the temperature which governs the Boltzmann distribution.

An SA optimization process proceeds in a way similar to the traditional iterative improvement methods except that a pseudotemperature control parameter is set to be a large number at the beginning of the process and is artificially decreased very slowly during the process. Different intermediate solutions are generated and an intermediate solution is accepted if the objective function is improved. The success of the SA process lies in the fact that it conditionally accepts some error-increasing intermediate solutions to allow the exploration of the solution space in directions which temporarily worsen the objective function, in the hope of eventually escaping from local minima and finding a global minimum. In an SA process the acceptance of an error-increasing intermediate solution is governed by a Boltzmann-like probability distribution

$$P(\Delta F, T) = e^{-k\Delta F/T} \quad (2)$$

where ΔF is the difference in the objective function values between the present and previous intermediate solutions, k is a weighting factor, and T is the pseudotemperature. At each pseudotemperature, an appropriate number of intermediate solutions are generated and evaluated to simulate the slow cooling procedure. The SA process stops when the objective function's value has virtually remained unchanged for several consecutive temperature steps.

It has been proved, both theoretically and experimentally, that the simulated annealing approach is insensitive to initial values and asymptotically produces the global optimal solution with probability 1 [14]. This method has been successfully applied to determine the model of a device [15].

IV. CAD of Distributed Amplifiers

Broad-band amplifier design is concerned with the gain–bandwidth requirements. The distributed amplifier allows the addition of device transconductance without adding device parasitic capacitance. As a result, there will be an excellent gain–bandwidth product with flat gain and low *VSWR*. It is, therefore, appropriate to use the desired frequency response of a distributed amplifier as the basis for the design procedure. Even though only the frequency response of a distributed amplifier is used in this paper, it will be obvious, after the following description, that other features such as noise figures can also be considered in the objective function (1) as well.

This design-by-simulation process uses the analysis of a distributed amplifier which is described in [6]. A schematic diagram of the MESFET distributed amplifier is shown in Fig. 1. A simple equivalent circuit of this distributed amplifier is provided in Fig. 2. The drain-to-gate feedback capacitance C_{dg} is neglected since it is low enough in GaAs MESFET's not to cause gain variations with frequency in the distributed amplifier [16]. The CAD process will yield

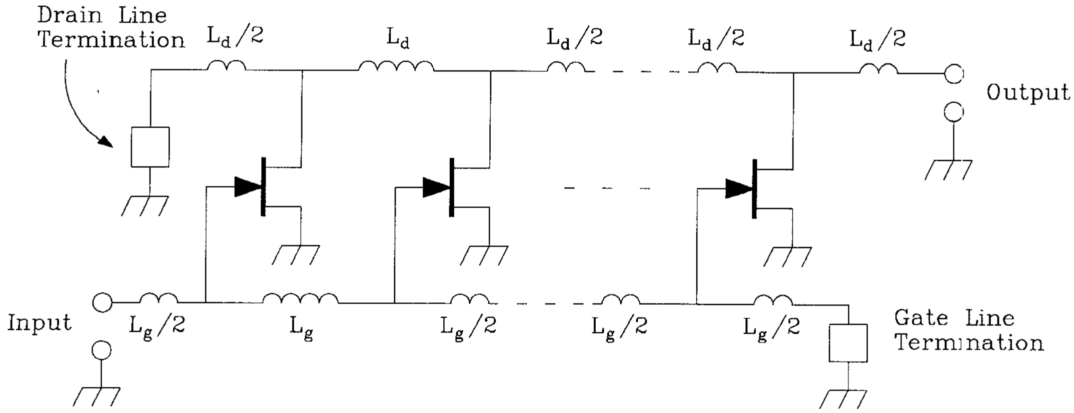

Fig. 1. Schematic diagram of a FET distributed amplifier.

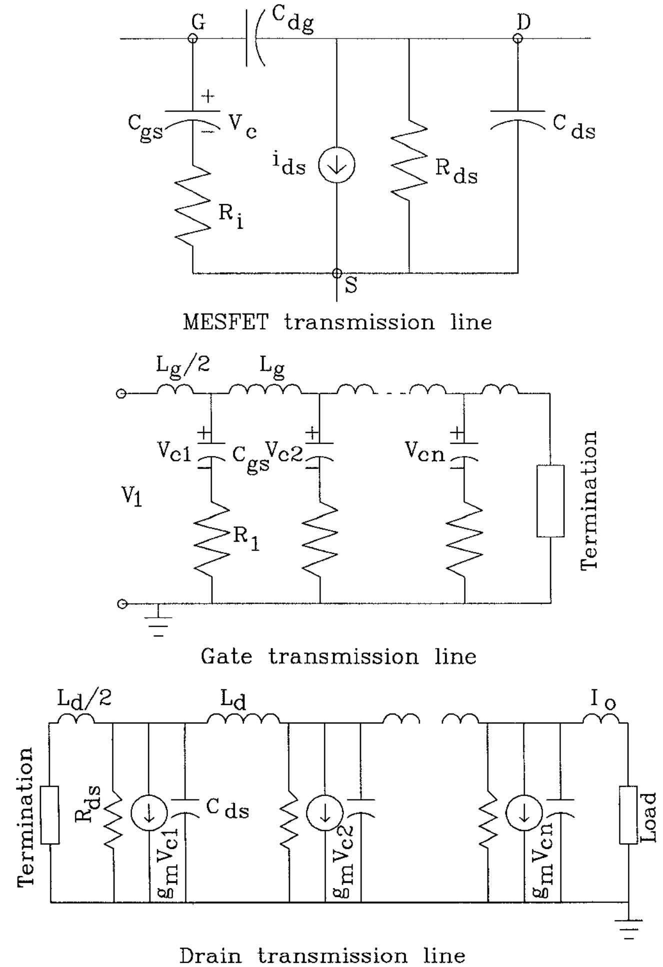

Fig. 2. Simplified equivalent circuit model of a MESFET distributed amplifier.

values for R_i, the effective input resistance between the gate and the source terminals; C_{gs}, the gate-to-channel capacitance; R_{ds} and C_{ds}, the drain-to-source resistance and capacitance respectively; g_m, the dc transconductance of the MESFET's; n, the number of stages; and L_d and L_g, the characteristic inductances of the drain and gate transmission lines respectively. In other words, the design of a monolithic MESFET distributed amplifier is completely specified in the result of this CAD procedure.

The normalized gain of the MESFET distributed amplifier shown in Fig. 1 as given in [6, eqs. (14) and (15)] is used in this CAD procedure.

In the notation of [6], the CAD process starts by assigning typical values to the parameters in this model, which includes R_i, R_{ds}, g_m, ω_c, and n. R_{01} and R_{02} are chosen as 50 Ω for matching purposes. Therefore, we have $C_{gs} = C_{ds} + C_p = C'_{ds}$, since the cutoff frequencies of the lines are also constrained to be equal. C_p is an external capacitance added to the device output capacitance C_{ds}.

The frequency response of such a distributed amplifier based on the values of these parameters is simulated according to the gain equations. A normalized least-squares error between this frequency response (i.e, M'_j, where j is the number of frequencies specified) and the desired frequency response (M_j) is calculated according to (1) and used as the objective function in the SA optimization process. Keeping the pseudotemperature fixed, random perturbation is introduced into the parameter values to generate modified amplifier designs. The perturbation induced in a parameter is controlled so that it will not bring the parameter out of its reasonable range. For each design generated, its frequency response is simulated and its least-squares error is evaluated with respect to the desired response. If the least-squares error is reduced by an intermediate design, it is accepted and used for further parameter perturbation. The acceptance of an error-increasing design is governed by the Boltzmann-like probability distribution in (2). This modification step is performed a number of times with T fixed. Then T is reduced according to

$$T_2 = \beta * T_1 \tag{3}$$

where T_1 and T_2 are the present and next temperatures, respectively, and β is a constant between 0.8 and 0.95. In this manner, T is gradually reduced towards 0 until a stopping condition is reached. The selection of a starting temperature and a temperature reduction factor is critical in an SA process. They are generally determined experimentally and guidelines for selecting them can be found in [17]. The stopping condition is satisfied either when the least-squares error is very small or when the least-squares

TABLE I
RANGES OF PARAMETER PERTURBATION

PARAMETERS	LOWER BOUND	UPPER BOUND
R_s (Ω)	2	6
C_{gs} (pF)	0.2	0.7
R_{ds} (Ω)	100	500
C_{ds} (pF)	0.05	0.09
f_c (GHz)	20	32
g_m (S)	0.02	0.07
n	1	10

TABLE II
DESIGN EXAMPLE PARAMETERS

PARAMETERS	INITIAL SOLUTION	FINAL SOLUTION
R_s (Ω)	3	5.17
C_{gs}^* (pF)	0.303	0.306
R_{ds} (Ω)	250	256.43
$C_{ds}'^*$ (pF)	0.303	0.306
f_c (GHz)	21	20.8
g_m (S)	0.03	0.0684
n	5	4
L_d^* (nH)	0.7579	0.7652
L_g^* (nH)	0.7579	0.7652

error does not change for a number of T's. The latter case indicates that the desired frequency response is not possible using the predetermined ranges of parameters. The designer may then decide to relax the ranges of parameters or modify the desired characteristics.

V. DESIGN EXAMPLE

This design-by-simulation procedure has been used to design a MESFET distributed amplifier with a 15 dB flat band gain and a 20 GHz cutoff frequency. Referring to the Boltzmann-like distribution described in (2), the SA process starts at $T = 2000$ with $k = 30000$. At each temperature step, the number of iterations performed is 40. The temperature T is decreased according to (3) with $\beta = 0.9$. The ranges of parameter perturbation used in the design process are shown in Table I. In order to guarantee the ability of fabrication for this distributed amplifier, these ranges are selected around typical MESFET's with $W \approx 300$ μm and $L \approx 1$ μm. The result of this design is provided in Table II, which gives the initial and final parameters for a distributed amplifier. Some of the parameters in the design are derived from others and marked with (*) in Table II. At the end of the process, the value of the objective function has been reduced from an initial value of 0.21406 to 0.000022, virtually a perfect match. The calculated frequency response of the final design is shown in Fig. 3 along with the inputs to the CAD process.

In order to verify the design generated by this CAD process, the outcome distributed amplifier specified in Table II is simulated using Touchstone. The frequency

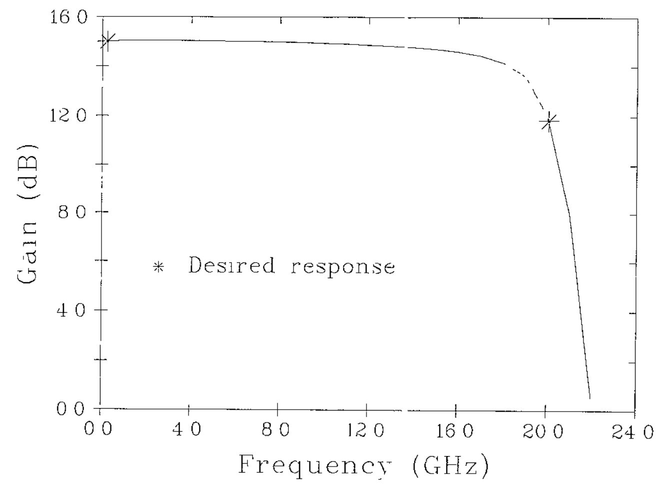

Fig. 3. Frequency response of the design example calculated with equations (14) and (15) of [6].

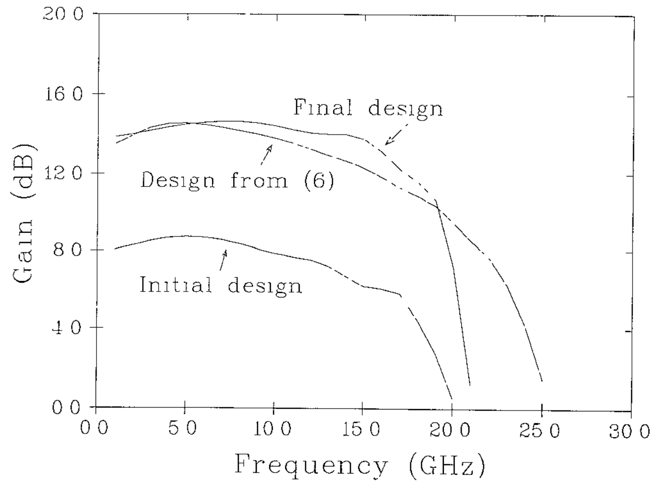

Fig. 4. Frequency response of the design example simulated with Touchstone.

response of the final design along with that of a distributed amplifier specified by the initial parameters is shown in Fig. 4. The same frequency response requirement was used in [7] to generate a design using a graphical method. For purposes of comparison, the Touchstone simulation result of the design provided in [7] is also shown in Fig. 4. It can be seen from this figure that the distributed amplifier designed by this CAD process produces the required frequency response. Only four stages are needed, which can be deemed as a significant improvement over the design demonstrated in [7], which requires eight stages.

This CAD process has been implemented on a 10 MHz PC-AT class machine. Despite the slow speed of this machine, the entire process takes less than 20 s to finish.

VI. CONCLUSION

In this paper, we have shown a CAD method of design-by-simulation that is used to design a monolithic distributed amplifier of specified frequency response. This method is based on an optimization process called simulated annealing. The procedure automatically designs the active and passive elements of an amplifier, with the flat band gain and 3 dB bandwidth being the only inputs. As an example, a distributed amplifier has been designed to match a required frequency response. The Touchstone simulation result of this design has shown that its frequency response agrees with the requirement.

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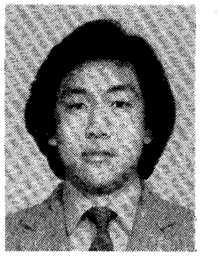

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