COMPUTER-AIDED DESIGN OF MESFET DISTRIBUTED AMPLIFIER

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ABSTRACT

An automatic CAD procedure for the design of a MESFET distributed amplifier is described. This procedure is based on a novel design method called design-by-simulation. A combinatorial optimization process called simulated annealing is applied in this design procedure to provide information about the number of stages, the MESFET model parameters, and the characteristics of microstrips used for matching networks in an amplifier which matches the desired frequency response. This procedure is fully automatic and the only input needed is the desired gain and the 1-dB point.

I. Introduction

The principle of distributed amplification dated back to an invention which was patented in 1937 [1]. Other researchers have analyzed the distributed amplifier and extensive references are available in the literature [2-4]. A distributed amplifier using a MESFET was first demonstrated in [5]. The concept of distributed amplification was then applied successfully to GaAs MESFET amplifiers at microwave frequencies [6-8].

The design of a distributed amplifier involves a careful choice of the variables, such as the characteristics of the MESFET's, the number of stages, and the characteristics of the 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 [9]. An analytical/graphical procedure was proposed to provide a close approximation to the optimum design of a distributed amplifier [10]. This work is based on the analysis of [9] and claims that the optimum number of stages, the FET dimensions, and the values of lumped inductors used in the amplifier can be determined given specific gain and 1-dB bandwidth requirements. As explained in [10], this method is a manual (i.e., non-computer) method which involves heavy expertise in determining a set of good initial parameters. Several repetitions are necessary to achieve an acceptable result. Since this method is based on the interpretation of graphical charts, it is also error prone.

We will describe the investigation and development of a CAD procedure for the design of a distributed amplifier. A design-by-simulation methodology based on a combinatorial optimization algorithm is applied in this new CAD procedure to a distributed amplifier under design. This procedure is completely automatic and does not require the user to have any expertise in the analysis of a distributed amplifier. The only necessary input is the desired gain and the 1-dB roll off point and the procedure automatically designs a distributed amplifier to match with the requirement of the user.

II. Design-By-Simulation

The goal of design is to determine the parameters of a circuit so that the circuit will provide the service specified by the designer. In this new CAD process, a combinatorial optimization process is applied to the simulation results of a distributed amplifier under design which is represented by a set of analytical equations, and thus the name *design-by-simulation*. A combinatorial optimization problem is defined as the problem of finding the minimum of a given objective function depending on many interrelated parameters. Let the circuit parameters of an 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 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. Then the design problem of a distributed amplifier can be translated into a combinatorial optimization problem which tries to determine a set of V_i's which minimize an objective function. A typical objective function in this design-by-simulation method would be the normalized total least square difference between the desired and simulated characteristics, which is defined as

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

III. Combinatorial Optimization

A typical heuristic optimization process utilizes an iterative improvement strategy which is comprised of two phases. An initial set of estimated parameters is generated as the starting point of the heuristic 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. Traditional heuristic algorithms are greedy and accept only those changes that can improve the cost of the objective function.

One inherent drawback of this type of heuristic search is that it can be easily trapped into the local minima of an objective function. An approach called simulated annealing (SA) has been proposed and applied as a method to find a near optimal solution for combinatorial optimzation problems [11]. 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. It has been proved that, under certain assumptions, the simulated annealing approach asymptotically produces the global optimal solution with probability one [12]. This approach has already been extensively used in a VLSI (Very Large Scale Integration) design process such as the placement and routing problem [13]. Furthermore, this SA method has been successfully applied to the modeling of a device [14, 15].

In order to apply the concept of SA to the design-by-simulation problem, a control parameter called pseudo-temperature is introduced into the design process. The optimization process proceeds in a way similar to the traditional iterative improvement methods except that the pseudo-temperature decreases very slowly from an initial large value. The selection of a new parameter set is based on the following considerations. A random integer i between 1 and the total number of parameters, say m, is generated. A parameter V_i is selected according to this random number. The current value of this parameter is modified by introducing a small random perturbation to it. The sign of this perturbation is also determined randomly. The modified set of variables is then used to calculate the objective function defined in (1).

A parameter set is accepted if this normalized least square difference is reduced as in conventional methods. The acceptance of an error-increasing model is governed by a Boltzman-like probability distribution

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

where ΔF is the difference in the objective function between the present and previous parameter sets, k is the weighting factor, and T is the pseudo-temperature. At each temperature, an appropriate number of changes are applied to the configuration to simulate the slow cooling procedure. The stopping criterion is satisfied when the objective function's value has virtually remained unchanged for several consecutive temperature steps.

As shown in the Boltzman-like distribution, the probability of accepting an error increasing design depends on the control parameter, T. For the same amount of error increment, a design has a higher probability of being accepted at high T. This provides a hill-climbing capability to escape from local minima so that a good initial solution is not necessary for a global optimization. Since T is decreased gradually in the optimization process, the solutions accepted at low T will gradually concentrate into near optima and the process eventually approaches itself into a normal iterative improvement process when T is so low that virtually all error increasing solutions are rejected.

IV. Implementation

Broadband 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 gain as the basis for the optimization procedure. This design-by-simulation process uses the model of a distributed amplifier which is illustrated in [9]. The normalized gain of the MESFET distributed amplifier as given in eqs. (14) and (15) of [9] is used in this implementation with the simple equivalent circuit of the MESFET distributed amplifier as shown in Figure 1. The drain-to-gate capacitance C_{dg} is neglected since the device is assumed to be unilateral. The design-by-simulation process starts by assigning typical values to the parameters in this model, which includes R_i, R_{ds}, g_m, C_{ds}, C_{gs}, f_c, n, R_{01}, and R_{02}, where

R_i, R_{ds}, g_m, C_{ds}, C_{gs} are the intrinsic model parameters of the FET's to be designed;

f_c is the cutoff frequency of the lines;

n is the number of stages; and

R_{01} and R_{02} are the square roots of L_g/C_g and L_d/C_d and represent the characteristic resistances of the gate and drain transmission lines, respectively.

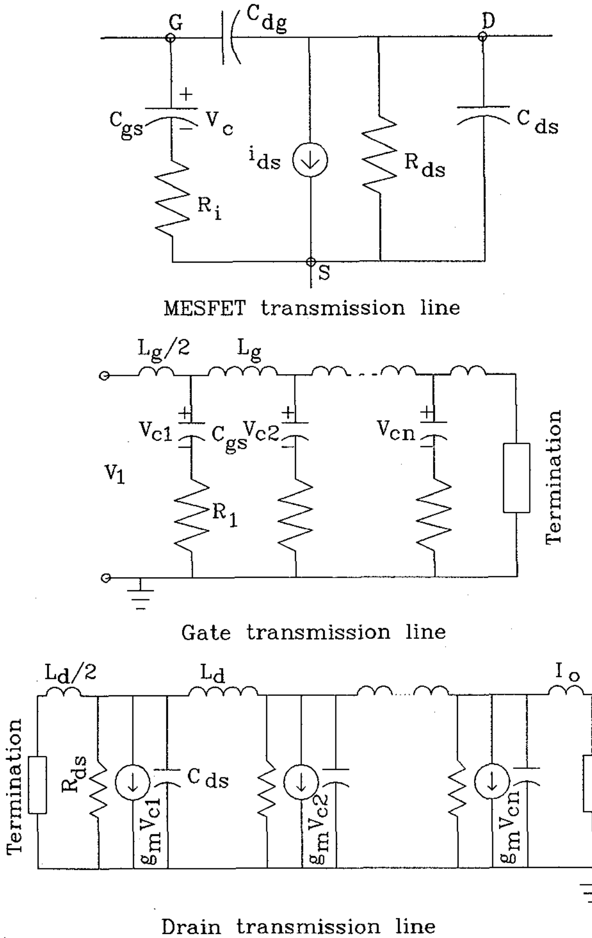

Figure 1 The equivalent circuit.

The current frequency response of such a distributed amplifier based on these parameters is simulated according to the gain equation given in [9]. A normalized least square error between this frequency response and the desired frequency response is calculated and used as the objective function in the SA optimization process. Keeping the pseudo temperature 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 square error is evaluated with respect to the desired response. If the least square error is reduced by a new design, it is accepted and used for further parameter perturbation. The acceptance of an error increasing design is governed by the Boltzman-like probability distribution in (1). This modification step is performed for a number of times with T unchanged. 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 stopping condition is satisfied either when the least square error is very small or the least square error didn't 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. Testing and Evaluation

This design-by-simulation procedure has been used to design an MESFET distributed amplifier to match with the desired frequency response given in Table 1. Referring to the Boltzman-like distribution described in (2), the SA process starts at $T = 2{,}000$ with $k = 30{,}000$. At each temperature step, the number of iterations performed is 40. The temperature T is decreased according to (3) with $\beta = 0.9$. The range of parameter perturbation is shown in Table 2. The result of a design is provided in Table 3 which gives the initial and optimal parameters for a distributed amplifier to match with the frequency response requirement given in Table 1. The frequency response of the final design is shown in Figure 2 along with the flat band gain and 1 dB roll off point indicated by circles.

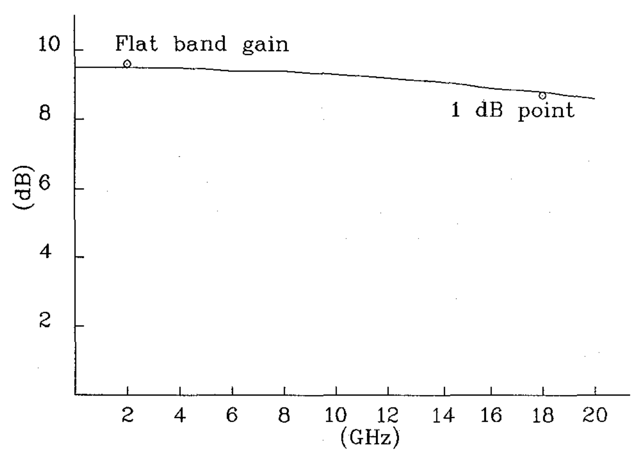

Figure 2 The frequency response of the design.

Table 1 The desired frequency response.

Frequency	Voltage Gain	Description
2 GHz	9.7 dB	Flat bad gain
18 GHz	8.7 dB	1 dB point

Table 2 The range of perturbation.

Parameters	Lower Bound	Upper Bound
R_i (Ω)	1	5
C_{gs} (pF)	0.1	0.5
R_{ds} (Ω)	100	500
C_{ds} (pF)	0.01	0.1
f_c (GHz)	20	200
g_m (S)	0.01	0.07
R_{01} (Ω)	25	75
R_{02} (Ω)	25	75
n	1	10

Table 3 The design example parameters.

Parameters	Initial Solution	Final Solution
R_i (Ω)	3	5
C_{gs} (pF)	0.2	0.5
R_{ds} (Ω)	250	247.7
C_{ds} (pF)	0.05	0.056
f_c (GHz)	100	154.1
g_m (S)	0.03	0.054
R_{01} (Ω)	50	26.6
R_{02} (Ω)	50	26.6
n	3	5

VI. Conclusion

The method of design-by-simulation has been used to design a distributed amplifier of specified frequency response. This method is based on a combinatorial optimization process called simulated annealing. The procedure automatically designs the amplifier with the flat band gain and 1 dB bandwidth being the only inputs. Ongoing research includes the extension of this method to large signal non-linear circuits and also to noise analysis.

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