Appendix

Computer-Aided Design (CAD) and Optimization

A computer-aided design (CAD) software package for microwave circuit analysis and optimization can be a very useful tool for RF/microwave engineers. Several microwave CAD programs are commercially available, such as SUPERCOMPACT and HP (Agilent)-Advanced Design System (ADS), with the capability of analyzing microwave circuits consisting of transmission lines, lumped elements, active devices, coupled lines, waveguides, and other components. Such computer programs are fast, powerful, and accurate. Nevertheless, they still require an experienced engineer with a good understanding of microwave design methodologies.

A typical design process will usually begin with specifications or design goals for the circuit. Based on previous designs and his own experience, an engineer can develop an initial design, including specific components and a circuit layout. CAD programs can then be used to model and analyze the design, using initial data given by the engineer for each of the components. They may include effects such as loss and discontinuities. Some of the CAD programs can be used to optimize the design by adjusting some of the circuit parameters to achieve the best performance. The CAD analysis can also be used to study the effects of component tolerances and errors, and to improve circuit reliability and robustness. When the design meets the specifications, an engineering prototype can be built and tested. If the measured results satisfy the specifications, the design process is completed. Otherwise the design will need to be revised, and the procedure repeated.

Without CAD tools, a design process would require construction and measurement of a laboratory prototype at each iteration, which would be expensive and time consuming. CAD can greatly decrease the time and cost of a design, while enhancing its quality. The simulation and optimization process is especially important for monolithic microwave integration circuits (MMIC) because these circuits can not easily be tuned or trimmed after fabrication.

CAD techniques are not without limitations. Of primary importance is that fact that a computer model is only an approximation to a ‘‘real-world’’ circuit, and can not completely account for the inevitable effects of component and fabrication tolerances, surface roughness, spurious coupling, higher-order modes, and junction discontinuities. These limitations appear more prominent at high frequencies, typically above 10 GHz.

In the following sections, some of the CAD capabilities will be described with the emphasis on CAD optimization.

A-1 CAD Analysis

We approach most design problems in stages, progressing from the simplest circuit model to the most complex. A complete circuit is constructed by connecting all the elements put together by an engineer. Then, by applying various circuit and network analysis techniques, various specifications of the circuit can be calculated. The calculations are usually straightforward but sometimes very tedious. A good CAD program provides a good computing tool in this situation as it is fast, powerful and accurate.

Like most computer programs, a user needs to tell a CAD program what to do. That is, in most CAD programs, a user is required to give initial input to the programs on the circuit parameters, layout, source, load and output parameters in an input file. Once these are appropriately set up, most of CAD packages will give results much faster than done manually. A design efficiency is much improved.

In our case, HP-ADS will be applied. The details on how to use it for linear and nonlinear circuit analysis can be found in the HP-ADS manuals provided.

A-2 CAD Optimization

One of great advantages in using computer models is optimization. The CAD simulators replace the test equipment and change element values in a circuit in order to achieve the prescribed goal(s) or objective(s). In other words, it is not necessary to actually build and test hardware. CAD provides a means of easily adjusting elements that are difficult, if not possible, to change once the circuit has been fabricated (For example, the mask set for a monolithic microwave integrated circuit (MMIC) can cost in excess of $50,000 and often requires weeks and months between design and test). With the easy adjustment of the circuit parameters in CAD, an optimization process can then be performed where the set of element values that provides a circuit response as close as possible to the specified target response can be found.

Error Function and Optimization Specifications

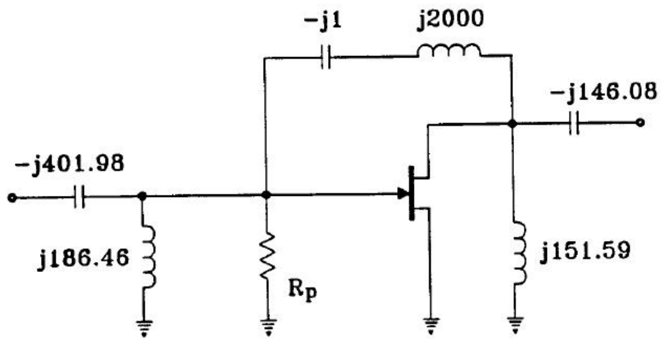
Mathematically, the optimization process is essentially the problem of maximizing or minimizing of a given function in respect to the element values

$$E = f(x_1, x_2, ...x_N) \tag{1}$$

subject to certain constraints. The function E is known as the *objective* function, *performance measurement*, *cost function* or *error function* (which is to be maximized or minimized). We usually create an error function that describes the difference between the actual and desired response of a circuit. Hence, we are concerned with minimizing E or reducing the error between the calculated and target responses.

For example, in the circuit shown below, we want to construct a 25-dB gain amplifier by adjusting the value of the gate stabilization resistor, R_p. The problem in this case is to determine the value of R_p which results in G_p =25 dB. The constraint for R_p is that is should be less than 18.35 k due to the stability of the amplifier. The error function can then be defined as

$$E(R_p) = [G(R_p) - 25dB]^2 \tag{2}$$



The intermediate results from an optimization process is as follows:

Iteration	$R_p(\Omega)$	$G_p(dB)$	E
1	19350.	31.196	38.4
2	9175.0	27.657	7.02
3	4587.5	25.346	0.119
4	2293.7	22.893	4.44
5	3440.625	24.352	0.420
6	4041.0625	24.889	0.012
7	4300.78125	25.126	0.016
8	4157.42188	25.010	0.0001
....			
14	4146.22193	25.001	0.000001
15	4145.10194	25.000	0.000000

In other words, the CAD optimizer uses the error function as a criterion and computes along a computational path that leads to a smaller and smaller value of the error function.

The errors function used for a frequency range by most CAD optimizers is

$$E = \frac{1}{n} \sum_{f=f_L}^{f=f_U} \{W_1[P_1(f) - G_1(f)]^2 + W_2[P_2(f) - G_2(f)]^2 + ...\} \tag{3}$$

where

f_L is the lowest frequency limit.

f_U is the upper frequency limit.
n is the number of frequencies in the range.
$P_i(f)$ is the parameter to be optimized.
$G_i(f)$ is the corresponding goal for $P_i(f)$ at each frequency.
W_i is the weight that indicates the importance of the parameters to be optimized.

Before an optimization process begins, we need to "inform" a CAD program of all the above parameters. We need to give the weight W_is which allow the control of relative importance of each design goal $P_i(f) - G_i(f)$. The higher the value of W_i, the more important the goal $G_i(f)$.

The frequency factors are introduced to account for the frequency dependence of a circuit. For example, for an amplifier, we may want to have a flat gain of G_p in a passband from f_L to f_U. In optimization, usually, a set of uniformly sampling frequency points is selected within [f_L, f_U]. The optimization is then carried out at all these sampling frequency points to have the desired characteristics. If the number of the points is large enough, we can expect that we can achieve the desired goal over the whole bandwidth. Therefore, we need to tell the program values of f_L and f_U as well as the number of sampling points *n*. More often, however, we specify the frequency step Δf (the difference between two neighboring sampling frequency points) instead of *n*. The CAD programs will then compute $n = (f_U - f_L)/\Delta f + 1$ if necessary.

Zero value of the error function is not often obtained in a practical optimization. Therefore, in order to terminate an optimization process, most CAD optimizers allow us to specify some other conditions that include inequalities, as well as equalities, for the optimization goal. For example, we may want an amplifier to have a gain G_p = 20 dB with the input reflection coefficient $|\Gamma| = 0.1$. In addition to the parameters for the error function, we may also give two inequalities for terminating the optimization process if it does not converge fast enough: $G_p \geq 20$ dB and $|\Gamma| \leq 0.1$. Consequently, as the optimization process goes, the value of error function becomes smaller and smaller. When the $G_p \geq 20$ dB and $|\Gamma| \leq 0.1$ are both satisfied, the optimization process will terminate. In other words, we should give two optimization objectives to an optimizer:

(1) parameters for the following error function:

$$E = \frac{1}{n} \sum_{f=f_L}^{f=f_U} \{W_1[G_1(f) - 20dB]^2 + W_2[|\Gamma| - 0.1]^2\} \tag{4}$$

(2) inequalities for termination of the optimization process:

$$G_p \geq 20 \text{ dB and } |\Gamma| \leq 0.1 \tag{5}$$

Optimization Methods

Numerous optimization strategy or techniques are available. They can be generally classified as either direct or indirect method, depending on how the error function(s) is/are used to locate the minimum. Direct methods compute directly the error function as a function of element values to minimize the function, and indirect methods use the differential properties of the error function. Some techniques employ both approaches.

One of the simplest direct methods is the grid search technique. We simply define a minimum and maximum search limit for all the elements, divide each element interval into a number of segments, and then evaluate the error function for all possible combinations of discrete element values. The minimum is located by simple comparison of the values of the error functions at all the discrete element values. The method is, however, very inefficient, as values of the error function at all the discrete points have to be evaluated. It may take quite amount of CPU time. For example, two elements divided into 100 segments each require 100×100=10,000 function evaluations, and five elements requires 10,000 million evaluations! Many approaches have been developed to improve the efficiency. Due to its nature of mathematic complexity, we will not discuss them here. They can, however, be found in many literatures.

Among the most powerful indirect methods are those based on the negative gradient:

$$-\nabla E = -[\frac{\partial f}{\partial x_1}, \frac{\partial f}{\partial x_2}, ..., \frac{\partial f}{\partial x_N}]^T \qquad [6]$$

which is a direction vector in the *N*-dimensional space pointing in the direction of maximum function-value decrease. As a result, we can simply move in the direction where the error function decreases at the fastest rate. Intuitively, it seems that the gradient-based approach is more efficient than the direct search. However, it suffers two disadvantages: one being the possibility of settling in a local minimum rather than a global minimum and the other being the slow convergence when the element values are close to a minimum. In addition, computing the gradient numerically can be a significant source of error, often resulting in convergence problems. Again, various techniques have been proposed to overcome the above shortcomings for the gradient-based approach. They can be found in the literature.

Optimization Strategy

The most effective optimization strategy is to begin with a sound idealized design, formulate a realistic error function based on the specifications, and then gradually increase the complexity. The approach ensures that the optimizer is never far from the minimum and will rapidly converge. However, we must consider the physical aspects of the design, which requires that we place certain constraints on the element values. For example, microstrip and stripline constructions limits the characteristic impedance of transmission lines to a relatively narrow range. Similarly, lumped element values are limited by physical constraints or parasitics. Most optimizers require the input of the constraints of the element values. Nevertheless, imposing constraints may force an optimizer to start some distance from the optimum, and therefore complicates the optimization process.

As to which optimization technique to choose, there are no definite guidelines for a general problem. Most optimizers are equipped with different optimization methods. Therefore, if one method is not working or converges very slowly, the user should terminate the process and then continue with the other methods until the results are satisfactory.

A-3 Final Comments

The use of computer analysis and optimization programs is of great importance in the design of today's RF/microwave circuits. It significantly increases efficiency and reduces cost of a design. Quite often, it becomes a must in designing a circuit of certain complexity. However, we should note that computer analysis and optimization programs are just tools to assist a design. Like any other tools, to use them appropriately, one needs to have good knowledge both in CAD and in design theory and practicality.