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The Use of Parametric Modeling in Microwave Circuit Design

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Abstract

The increasing level of complexity of MIC and MMIC circuits has increased reliance on computer aided design tools. Economical concerns and demand for faster design cycles has translated into the need for more accurate and sophisticated component models for these CAD systems. In this paper we describe the use of parametric, frequency dependent models for more accurate and realistic active and passive component model development. Two examples are presented to demonstrate the power of this method for the design of analog circuits.

Introduction

The increasing demand for high performance circuits with wider bandwidths, higher frequencies has revealed the deficiencies of existing methods and computer tools used so far in constructing electrical models for widely used components such as MESFETs, inductors and capacitors. Many times one finds that simple, fixed value, lumped element representation does not simulate the true response of the component with satisfactory accuracy. The electrical behavior is usually more complex, and requiring more sophisticated and detailed description. Some of the discrepancies are attributed to well understood, however difficult to model physical phenomena. The mutual inductance and capacitive coupling between the turns of a planar thin-film inductor might be an example of this. Some elements are just too difficult to describe analytically, like bends and other discontinuities in microstrip lines. Some discrepancies on the other hand do not have good physical explanation, let alone an analytical description. Frequency dependency of various components of a typical MESFET model, which is sometimes attributed to material or distributed effects, is a good example of this last category.

Another limitation of the widely used linear analysis and simulation programs is their inability to account for various complex relationships that may exist between circuit and model elements. For example, conductance of a p-n junction diode is related to the equivalent junction capacitance through a well defined relationship. Most simulators do not allow the use of expressions to interrelate values, allowing only independent variables in a circuit description.

Need for Parametric Models

There is a need for a CAD system and a simulator which handles such parametric relations between various circuit components even if they are mathematically very complex. Such a capability would allow development of more accurate and realistic component models for microwave circuit design. In most cases even if the exact analytical solution is difficult to obtain, present automated measurement methods have enabled us to determine the electrical behavior of components for very wide range of measurement parameters. Parametric modeling allows creation of new component models using algebraic expressions, rather than insisting upon approximations made with built-in fixed models. This does not have to mean generating an arbitrary collection of elements and variables to represent the measured data [1]. In most cases the deviation from ideal behavior is in an expected direction and good qualitative explanations exist. In the case of a MESFET, for example, such theories have been verified by computer programs that solve the full time-dependent drift-diffusion equations or Monte Carlo analysis. The problem with these approaches is that these programs run on "mainframes" and may take hours to calculate a point. Interfacing such a program with a linear analysis program is very impractical. Parameterizing and optimization of the circuit components in terms of bias voltages and currents is also expected to open new frontiers in linear analog circuit design. Designers will have a powerful tool to exploit the various parametric relations between circuit components and external inputs.

The ability to generate user-defined, parametric models is already a serious necessity. The number of components, different sizes,

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shapes, materials, and processes that are available for microwave circuit design is overwhelming. It is not feasible to generate a new different model for each single component and recompile it into the simulator. Component variety is increasing at such a rate that the idea of a fixed, built-in cell library is not practical anymore.

Examples

We have developed such a CAD system that allows a hierarchical, parametric circuit definition. A description of the program can be found elsewhere [2-3], so we will not dwell upon its details. We will use two examples to demonstrate the parametric modeling concept described above. First we will look at a spiral inductor model, a component frequently used in MMIC circuit designs. The departure of the thin-film planar spiral inductor from ideal lumped element behavior is well known and many attempts have been made to derive closed form expressions for the actual characteristics. Again, most of the analytical approaches developed so far are difficult to implement in a circuit simulator or they require long computation times. The fixed lumped element model is usually very inaccurate over large bandwidths. Such a model is shown in Fig. 1a together with actual data on a 3-turn inductor. The approximation is good only in a narrow frequency band. The error e, defined as the sum of the squares of the differences, is normalized to unity for comparison later. The S_{11} data displayed includes other small fixed circuit parasitics that have not been shown in the model. The model was optimized for minimum e. Figure 1b shows the Fig. 1a. model, of the same topology, but with frequency dependent components. The inductance value tends to decrease with frequency due to the mutual inductance between the turns, similarly the varying phase shift of the odd and even mode voltages around the spiral tends to increase the effective capacitances [4]. These effects are approximated by simple linear relations except for the series resistance which increases as f^2. Optimization was used to determine the coefficients of the f and f^2 terms that gave the best fit to the measurement. The final agreement was very good and the error term e was reduced to 4% of the one in Fig. 1a.

The second example involves a voltage controlled wide-band attenuator. The circuit is shown in Fig. 2a. Three MESFETs are connected in a "pi" configuration. The series and parallel elements are controlled by separate biases and there is a combination of gate biases V_1 and V_2 which produces a desired attenuation with minimum input/output VSWR. The size of the FETs used determine the bandwidth, isolation and insertion loss. Thus, a design was generated with FET gate peripheries and gate biases as the parameters. A knowledge of the scaling rules for the FET model and bias dependencies are needed. These are relatively easy to obtain through mea-

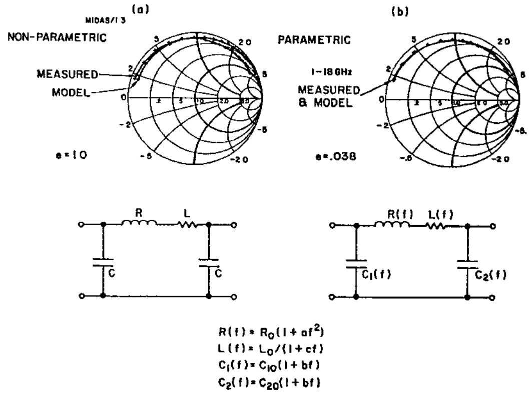

Figure 1. Fixed lumped-element model of a 3-turn spiral inductor is compared with a parameterized model that has the same topology. Parametric model duplicates the measured S_{11} data over 1-18 GHz with much less error.

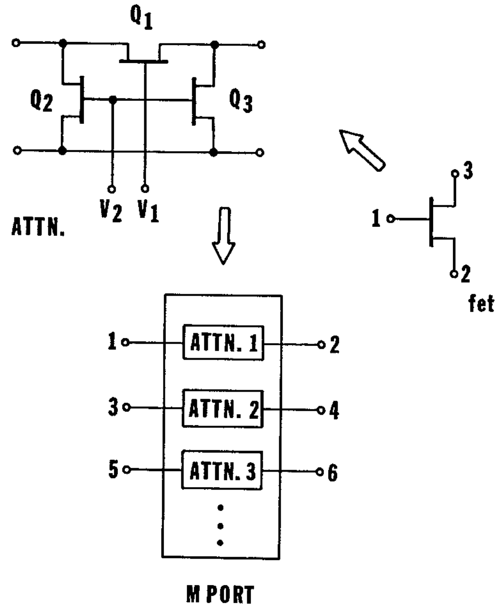

Figure 2a. Three MESFETs, connected in pi-configuration to form a wide-band matched attenuator.

surements, and analytical models which account for various bias dependencies also exist.

A subcircuit is created which contains the parameterized FET models in pi configuration. Then for each attenuation setting of interest, this subcircuit is invoked with unique parameters and a large multiport network is formed (Fig. 2b). The attenuation goals for the subcircuits are chosen such that they cover a desired attenuation range. Increasing the number of ports and subcircuits one can increase the resolution of the V_1 and V_2 curves versus attenuation. The 2n bias values (two bias settings for each subcircuit) and two device sizes (Q_1 and Q_2) are optimized for the

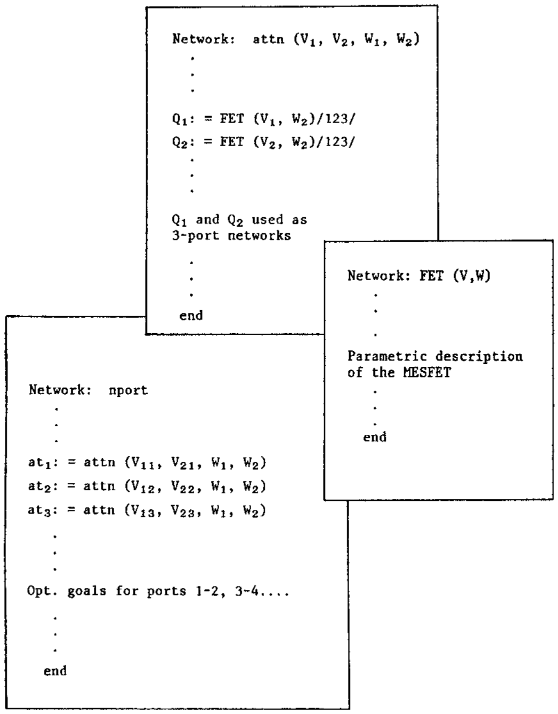

Figure 2b. Construction of a multiport network from subcircuits to find the optimum FET sizes and bias settings for the desired attenuation states.

desired values of attenuation across the frequency range of interest with good VSWR at all ports. Using a typical MESFET passive device model [5], a 0-10 dB matched attenuator is designed with the goals mentioned above. Only four subcircuits were used for simplicity. The results are shown in Fig. 3. In addition to rf performance simulation, the two optimum device sizes and the shape of V_1 and V_2 versus attenuation is also obtained.

Conclusion

In conclusion, we have described a parametric modeling concept for advanced microwave circuit design and for model extraction. In addition to the examples we have shown, the parametric modeling technique can be used to solve a wide variety of circuit problems.

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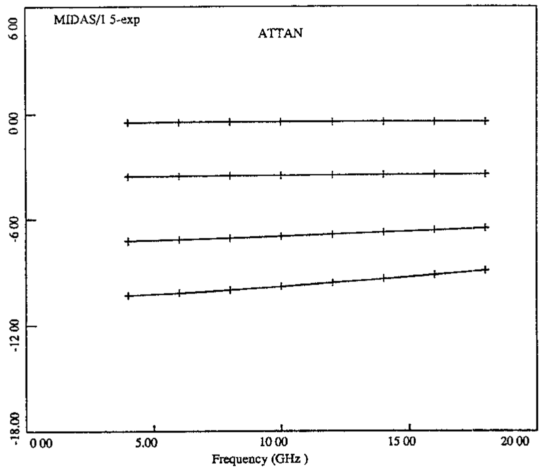

Figure 3a. Optimized circuit performance simulation. The four attenuation settings are: 0 dB, 3.5 dB, 7 dB and 10 dB.

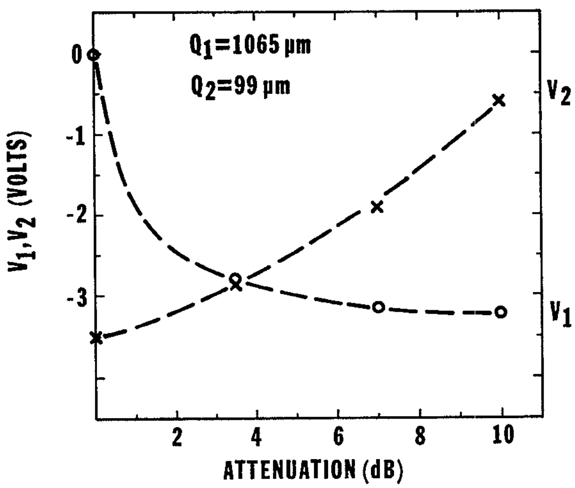

Figure 3b. The gate bias voltages required for any attenuation setting between 0-10 dB is shown here. The optimum device sizes for this range and bandwidth are also indicated.