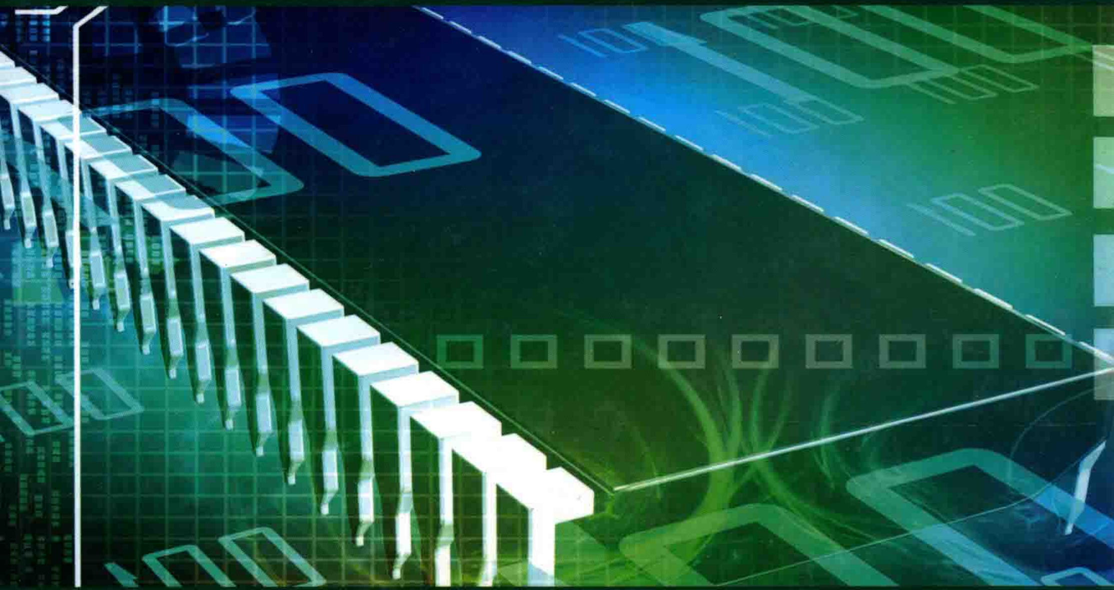

Passive RF Integrated Circuits

modeling, characterization and measurement

Edited by

Pierre Saguet

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Passive RF Integrated Circuits

Introduction

This work is intended in its broadest sense, for designers of integrated circuits, high frequency hybrid technology or even microwaves. Circuit design is carried out from elaborate models in research and development, models which try to include a maximum number of functional elements or interference affecting the circuit. When frequency increases, models become more complicated as it is no longer possible to ignore propagation effects in circuits, which implies that a model using Maxwell equations must be used in most cases.

Naturally, it is unthinkable for designers to analyze or synthesize circuits by manipulating these equations directly. It is thus important to develop equivalent electrical circuits that take into account all these effects where possible.

As shown, modeling is essential. Supplied models must be reliable within a given validity range. Their preparation stems from numerical analysis including, if necessary, electromagnetic phenomena. Then it is imperative they are validated by measurements either in the frequency or time domain.

Six authors, each an expert in the field addressed within this book, describe all these analysis aspects: modeling, characterization and measurement.

Chapter 1 is dedicated to the most widely used numerical analysis methods in the field: the method of moments, finite element method and finite difference method. The first two operate in the frequency domain while the third works in the time domain.

A fourth method, the TLM (transmission line matrix) method, which also works in the time domain, is described in detail in the Chapter 2 and is applied to coplanar filters.

Chapter 3 deals with multi-scale circuits. It is difficult to use traditional methods when we must analyze circuits whose dimensions are on the one hand in microns or submicrons, but on the other hand in millimeters or even centimeters when they are implanted on a printed circuit. An original and effective solution using the method of auxiliary sources is described in this chapter. Its use in planar circuits is presented.

It is well known that when frequency becomes high, one of the major problems is the placement of chips into their package. Chapter 4 deals with this problem and clarifies the models of distributed and localized packages. Examples of modeling and the extraction of (resistance, inductance, capacitance, and conductance) parameters within the meaning of Maxwell or electric cells under Kirchoff are presented as well as experimental validation results. The comparison of the performance of some plastic packages brings this chapter to a close.

As mentioned above, the characterization of circuits and the experimental validation of models are both essential.

Chapter 5 deals in a very thorough manner with the characterization in the frequency domain at high frequency. The measurement of scattering parameters using a network analyzer is detailed by highlighting the different types of errors that we can encounter and their corrections. In particular, the characterization of passive elements is studied.

The final chapter addresses measurement in the time domain. Complementary to measurements in frequency domain, time domain reflectometry is a powerful tool for modeling impedance and for the localization and characterization of defects in integrated circuits by a simple observation of the response time at the input of the test circuit. On the other hand, measurement in the time domain is essential for the study of digital circuits and in particular, the study of crosstalk in interconnections. The determination of scattering parameters using a time domain method enables the results obtained in Chapter 5 in the time domain to be completed.

Thus, a large number of concepts essential to the study of circuits in the field of high frequency are described within this book and we hope that the overview presented will be of valuable assistance to designers.

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Chapter 1

Numerical Analysis Methods for Passive Circuits

1.1. Introduction

The large number of numerical techniques used to analyze the behavior of the electromagnetic field can be classified into two groups: differential methods and integral methods. All the methods discretize the domain of the problem and transform the field equations into a system of linear equations. Differential methods such as finite element or finite difference in the time domain (FDTD) discretize all of the space, while integral methods require only the discretization of the surfaces of conductors. Another popular method, the TLM (Transmission Line Matrix) method, can be considered a differential method. All of these methods use Maxwell equations, in the time domain or in harmonic form.

The harmonic form of Maxwel equations is obtained using the Fourier transform and, mutually, an inverse Fourier transform enables the time response from the frequency response to be obtained.

Chapter written by Pierre SAGUET.

Maxwell equations in the frequency domain are not adapted for the nonlinear environment because the harmonics are created for each frequency in the steady state. Moreover, they are not applicable during transients. The method of moments (MoM) and the finite element method working in the frequency domain are generally restricted to linear problems. The finite difference in the time domain and the transmission line matrix provide the electric and magnetic fields at all times. Thus, dielectric or non-linear elements can be incorporated into both methods.

In this first chapter we will describe the MoM, finite element method and FDTD in more detail. The TLM method is described and applied to coplanar filters and antennas in Chapter 2.

1.2. Method of moments

The principle consists of discretizing integro-differential equations and transforming them into matrix equations which we can then solve using standard methods.

1.2.1. *General method*

We search for a numerical solution for the equation:

$$\boldsymbol{L} f = g \qquad [1.1]$$

L is a differential or integro-differential linear operator, f is an unknown function (vector), g is a known function (vector). The set of functions (f), for which ***Lf*** exists, constitutes the space source of ***L***.The set of functions {g}, the result of the operation ***Lf***, constitutes the space image of ***L***.

The first step is to represent ***f*** in an approximated way, using a linear combination of basis known functions f_n, which belong to the source of ***L***:

$$f \simeq f_{app} = \sum_{n=1}^{N} \alpha_n f_n \qquad [1.2]$$

α_n are constant coefficients to be determined. N will have to be selected in order for the approximation to be acceptable.

Inserting [1.2] into [1.1] gives:

$$\sum_{n=1}^{N} \alpha_n (\boldsymbol{L} f_n) \simeq g \qquad [1.3]$$

In the second step, a set of test functions W_m m = 1, 2, 3, …M, located in the space image of $\boldsymbol{L}$ is selected. Equation [1.3] is projected on each of the test functions, which are translated using M equations. The projection is defined by the scalar product:

$$< f,h >= \int_{dom} f * h dx$$

Thus:

$$\sum_{n=1}^{N} \alpha_n < W_m, \boldsymbol{L} f_n >=< W_m, g > \qquad m = 1,2, ...M \qquad [1.4]$$

or, in matrix form: $[L_{mn}]\,[\alpha_n] = [g_m]$.

$L_{mn} = < W_m, \boldsymbol{L} f_n >$: boundary element matrix.

α_n: coefficients column vector.

$g_m = < W_m, g >$: excitations column vector.

Unknown coefficients α_n are obtained by the inversion of L_{mn}:

$$\left[\alpha_n\right] = \left[\boldsymbol{L}_{mn}\right]^{-1} \left[g_m\right]$$

Matrix L_{mn} should not have singularities so that it can be inversed.

1.2.2. *Choice of basis and test functions*

The effectiveness of the MoM depends largely on the choice of basis and test functions. Theoretically, the basis and test functions must be linearly independent and, in order to obtain an exact solution, the number of basis functions should be infinite. In fact, experience shows that generally, a few basis functions are sufficient to obtain a good approximation of ***f***, especially if all these functions satisfy the boundary conditions imposed in the problem. However, this is not obligatory and in order to simplify the calculation of scalar products, it will sometimes be more effective to select functions that can be easily integrated, even if it means using a few more functions.

The test functions can be chosen to be identical to the basis functions. This method is known as the Galerkin method. It generally gives very good results and this is why it is commonly used.

Listed below are some factors which enable the basis and test functions to be selected:

- accuracy of desired solution,
- ease of evaluation of elements of matrix L,
- size of matrix to be inversed,
- conditioning of matrix L.

The most commonly used basis and test functions are the following:

– Dirac functions (collocation method). We stipulate that the equation to be solved is verified in some points in the domain. This means using Dirac functions as test functions;

– rectangular functions. Simple function approximations. The basis functions are defined on a studied sub-interval, which enables a sparse matrix to be obtained; for example, if we take N points uniformly spaced along the domain [0, 1], the rectangular functions are defined by:

$$P(x) = \begin{cases} 1 & \text{if } |x| < \dfrac{1}{2(N+1)} \\ 0 & \text{if } |x| > \dfrac{1}{2(N+1)} \end{cases}$$

that is to say the rectangular function is centered at 0 with $\frac{1}{N+1}$ as width.

A linear combination of functions $f_n = P(x - x_n)$ gives an approximation by a simple function for f.

In the same way, the piecewise approximation can be made using basis functions such as the "triangle" type, defined by:

$$T(x) = \begin{cases} 1 - |x|(N+1) & \text{if } |x| < \dfrac{1}{2(N+1)} \\ 0 & \text{if } |x| > \dfrac{1}{2(N+1)} \end{cases}$$

A linear combination of "triangle" functions under the form:

$$f(x) = \sum_{n=1}^{N} \alpha_n T(x - x_n)$$

gives a piecewise linear approximation of f.

The use of sinusoidal-type, sin ($n\pi x/a$), basis and test functions, which are very easy to use, is the basis of the spectral method.

1.2.3. *Application example*

To illustrate the method, we solve the following equation:

$$-\frac{d^2 f}{dx^2} = 1 + 4x^2 \qquad [1.5]$$

We propose to find f (x) in the interval [0, 1] verifying the boundary conditions f(0) = f (1) = 0. The differential operator is $L = -\frac{d^2}{dx^2}$.

We choose the basis functions of the form:

$$f_n = x - x^{n+1} \qquad [1.6]$$

We note that all the basis functions verify the boundary conditions well:

$$f_n(0) = f_n(1) = 0$$

Let us now use the collocation method on equally spaced points x_m:

$$x_m = \frac{m}{N+1} \qquad m = 1,2,\ldots,N \qquad [1.7]$$

Equation [1.3] is written as:

$$\sum_{n=1}^{N} \alpha_n \left[-\frac{d^2}{dx^2}\left(x - x^n\right) \right] = 1 + 4x^2 \qquad [1.8]$$

If we stipulate that equation [1.8] is verified for all the x_m points, we obtain the matrix elements: