Chapter 1

Introduction

In designing high-speed digital integrated circuits (IC), it is getting more important to account for the parasitic effects of packaging and interconnects on the signal integrity. The rapid progress in VLSI technology has led to integrated circuits with finer features, increased input/output (I/O) pins, faster speed and higher power consumption. High operating speed and tightening design dimensions necessitate attentive design of signal paths from driver to receiver considering signal purity, crosstalk, interconnect delay, and simultaneous switching noise. And careful control of package and interconnect parasitics leads to improving the performance of the circuits. Therefore, for the performance evaluation of the circuit it becomes an inevitable step to accurately characterize the electrical parameters of various interconnections such as interconnects within VLSI chips, high pin-count packages connecting an IC to outer circuits, multichip modules (MCM) or printed circuit board (PCB) routing between individual IC's, and transmission lines for upper levels of interconnections.

In computer systems as well as in digital communication systems, the interconnects linking chips on printed circuit board and modules start to behave like transmission lines when the operating speed is faster and the "wavelength" of the signal of interest becomes comparable to the length of the interconnect. To reduce the length-related transmission line effects such as interconnect delay and to accommodate several hundred I/O pins of a large chip a novel, efficient packaging approach, such as multichip modules (MCMs), for digital and mixed signals is getting more important than single chip packaging. Shorter length in MCMs reduces the interconnect delay, but the smaller cross-section and the high wiring density of the interconnects result in high resistance as well as skin and proximity effects, and cause significant losses and couplings. Hence, for high-speed designs, interconnect and signal integrity analysis becomes more important. SPICE-like or other convolution based circuit simulations are incorporated with the models of drivers and receivers and the electromagnetic field solver characterizing interconnects and packages. But, even with advanced numerical electromagnetic field solvers, analyzing the entire packages and interconnects requires a tremendous amount of time and memory. Hence, packages and interconnects are divided into several different sub-problems, the equivalent circuits of each problem are extracted, and the performance of the entire circuit is evaluated.

The geometry of the signal paths includes two dimensional regular transmission lines, three dimensional arrangements, shape changes, vias, bends, connectors, and complex reference planes. For regular transmission lines two dimensional field solvers are sufficient. But more elaborate three or two and a half dimensional electromagnetic field solvers are necessary for the more complex geometries of bends, meshed reference planes, connectors, vias, and other interconnect discontinuities, and the integrated inductor in high frequency communication systems. And the complexity of the geometries, the efficiency, and the accuracy needed should be considered in selecting a proper electromagnetic solver among various two or three dimensional field solvers. When the cross-sectional dimension of interconnects is small compared to the wavelength of interest, the quasi-static assumption is valid and a quasi-static field solvers can save considerable computational time compared to full-wave field solvers. Also when the displacement current is negligible compared to the conduction current inside of the conductor for the frequency when $\sigma >> \omega\varepsilon$ (where σ is the conductivity of the metal, ω the angular frequency, and ε the permittivity), the charge is confined only on the surface of the conductor and the static capacitance are still relevant for quasi-static analysis [1, 2]. Therefore, capacitance calculation is decoupled from resistance and inductance calculations. And for two-dimensional geometries fields behave as quasi-TEM mode.

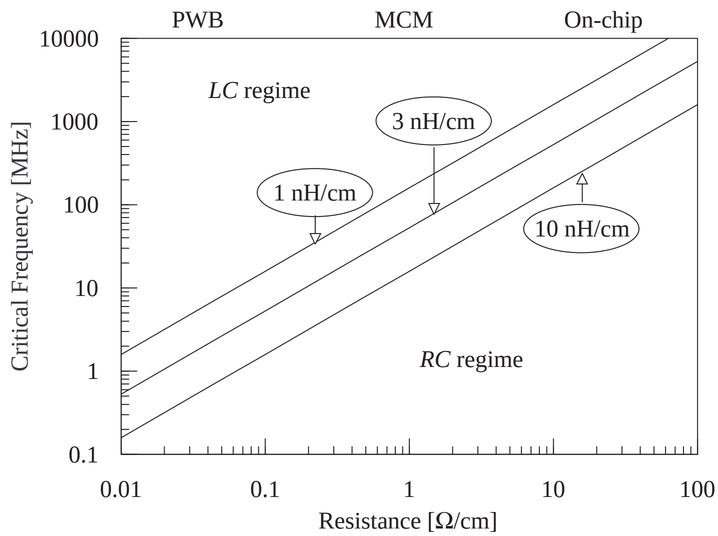

Figure 1.1: Critical frequency ($\omega = R / L$) vs. resistance of interconnects with varying inductance of 1, 3, and 10 nH/cm.

Usually the inductance of interconnects and packages does not vary much from geometry to geometry and is on the order of nH/cm. Figure 1.1 shows the critical frequency when the resistance becomes equal to the reactance in cases of 1, 3, and 10 nH/cm [3]. The interconnects behave as lossless transmission lines (i.e., line resistance can be ignored) for frequencies much higher than the critical frequency and as *RC* lines (i.e., line inductance can be ignored) for frequencies much lower than the critical frequency. Digital signal contains broad-band frequency spectrum from DC to frequencies about the inverse of rise time of the signal. For broad-band frequency spectrum both resistance and inductance should be considered especially for multi-chip module (MCM) level of interconnects. Therefore, lossy transmission line analysis is required. The skin and proximity effects start to appear around the critical frequency, and resistance and inductance become frequency dependent.

In this dissertation an efficient and accurate quasi-static technique is presented for evaluating frequency dependent resistance and inductance of high-speed digital interconnects and modern monolithic microwave integrated circuits (MMIC) for a broad-band of frequencies spanning from DC to high frequency, including skin and proximity effects. In modern monolithic microwave integrated circuits (MMIC) as well as in high-speed digital integrated circuit (IC) interconnects, the transverse geometries of transmission lines have been miniaturized and, therefore, the conductor loss is increasing. Hence, the problems of finite thickness and finite conductivity of conductors have received increased attention.

Despite continuous developments in numerically analyzing electromagnetic field problems, many of them still need a considerable amount of computational time to be accurately solved, especially when two or more media are involved. If the internal characteristics of a medium could be represented by only the external fields imposed at the surface of a medium via boundary conditions and, therefore, a two or more media, multi-region problem could be substituted by an one medium, exterior problem, then the task would be greatly simplified. These conditions relate the tangential components of the electric and magnetic fields at the surface of a medium as an impedance factor, and are called the impedance boundary conditions (IBC) or the approximate boundary conditions (ABC). This IBC is a function only of the geometries of the structures and the electromagnetic properties of the material concerned. The problems are then solved by applying an appropriate electromagnetic field solver, such as the finite element method (FEM), the boundary element method (BEM), the electric/magnetic field integral equation method (MFIE/EFIE), the finite difference time domain method (FDTD), etc. But the existing standard impedance boundary condition (SIBC) or Leontovich's boundary condition requires *a priori* known surface impedance or approximates the surface impedance. In Chapter Two, the effective internal impedance (EII) models are derived at the surface of the conductor, which approximate the surface impedance of an isolated conductor and are used to represent resistance and internal inductance of lossy rectangular conductors from low frequency where the skin depth is larger than the cross-sectional dimensions of the problem to high frequency where the skin depth is far smaller than the cross-sectional dimensions of the problem. It is shown that BEM combined with EII as SIBC (i.e., multi-region problem is replaced by an exterior problem and EII approximates the surface impedance) fails to accurately capture the low frequency resistance and inductance of multiconductor lines, while BEM combined with EII but considering the conductor interior (i.e., the conductor interior is replaced by the exterior medium and the impedance shell is defined at the conductor surface) becomes identical to the surface ribbon method (SRM) of Chapter Four. Also, the effective internal impedance (EII) and the SIBC are compared, and the pertinence of the effective internal impedance (EII) models and limits of SIBC are explained.

Various field solvers can be utilized with the impedance boundary conditions (IBC). The conformal transformation has been a valuable tool all along for design and analysis of transmission lines and waveguides such as coaxial lines, microstrip lines, coplanar waveguides, etc. Usually it has been based on the assumption of quasi-TEM propagation and lossless thin conductors. Recently, the effective internal impedance (EII) has been combined with the conformal mapping technique for conductor loss modeling, and it has been applied to a coplanar waveguide (CPW) and symmetric twin conductors [21]. This technique is fairly accurate for mirror symmetric structures. In Chapter Three, this technique is applied to examples of a microstrip line and a V-shaped conductor backed coplanar waveguide (VGCPW), and the calculated results are compared to more rigorous quasi-static solution and previous work on conductor loss calculation using the conformal mapping technique, which is only valid at high frequency. It is explained that the effective internal impedance (EII) approximates to the standard impedance boundary condition (SIBC) when it is incorporated with the conformal mapping technique.

In Chapter Four, EII has been combined with the surface current integral equation and is applied to calculating the conductor loss for various planar transmission lines. Because it requires the discretization only on the conductor surface instead of across the interior of the conductor in the volume filament methods (VFM), and EII is used to represent resistance and internal inductance of the conductor, it is called the surface ribbon method (SRM). By comparing SRM to the surface equivalent theorem, it is shown that EII is different from SIBC and the surface equivalent theorem at low frequency and EII satisfies SIBC and the surface equivalent theorem at high frequency. Also, SRM is compared with previous studies of the integral equation method (IEM) or succeeding spectral domain method (SDM), exploiting the impedance boundary conditions (IBC). Through several planar transmission lines, the accuracy and the speed of SRM are examined. The minimal discretization on the conductor surface and computational efficiency under these conditions are examined by comparing to the volume filament method (VFM) based on the volume current integral equation. Also, the impacts of the skin and proximity effects on signal degradation and crosstalk of coupled lossy transmission lines are shown for an example of a simple circuit.

In two dimensional problems, the surface current integral equation has been successfully combined with the effective internal impedance (EII) and it significantly reduces computational load. In Chapter Five, this approach is extended into three dimensional geometries under the quasi-static assumption. The surface current integral equations are set for two tangential directions on the conductor surfaces, EII is defined for all segmented ribbons on the conductor surfaces corresponding to two tangential current flows, and Kirchhoff's voltage law (KVL) is applied using mesh analysis to ensure current continuity condition. This three dimensional surface ribbon method (3DSRM) can be utilized to calculate frequency dependent resistance and inductance of three dimensional geometries such as discontinuities, bends, simple vias, complex reference planes, integrated spiral inductors, etc. Through the examples of right-angled bends, meander lines, and a microstrip line with a meshed ground plane, the efficiency and accuracy of the technique is examined. For comparison the rigorous quasi-static technique of the partial element equivalent circuit method (PEEC) is utilized, which exploits the volume current integral equations, discretization inside the conductor, and mesh analysis.