A Microwave and Computational Electromagnetics Curriculum with Motivating Signal Integrity Applications

Vikram Jandhyala and Yasuo Kuga

Dept of Electrical Engineering, University of Washington, Seattle WA 98195
Email: {jandhyala,ykuga}@ee.washington.edu, Ph: 206-543-2186, Fax: 206-543-3842

A senior and graduate level curriculum in microwaves and computational electromagnetics is described. In a manner analogous to the use of robotics for undergraduate course foci, a signal integrity focus is proposed, and course projects are tailored to that area. The advantage is a coherent and continuous understanding of the application of electromagnetic principles across topics, and sustained student interest, in different courses.

1. Introduction

Electromagnetics, historically, has not been the subject of choice of seniors and graduate level students. While this trend is probably changing with the advent of modern motivating applications of electromagnetics in circuits, communications, nanotechnology, and biology amongst others, there is certainly a need for more application-oriented motivational approaches while not sacrificing on the rigor of the material. This paper presents a successful approach to merging applications, simulation, and rigorous theory as practiced in senior and graduate level courses in electrical engineering department at the University of Washington.

While the senior and graduate curriculum itself consists of more than 12 quarter courses in different sub-fields, we will concentrate here on a subset of courses, 480 (Microwave engineering), 571 (electromagnetics for high-speed circuits), 573 (computational electromagnetics), and 574 (advanced computational electromagnetics). In this subset, the focal applications are tuned to the signal integrity area as applied to microwave, RF, and on-chip structures. This is an ongoing process but is presented as a means to show the success of tailoring courses in microwaves and computational electromagnetics around motivating applications. The applications themselves may change over time, from circuits-oriented to biology or nano-technology, but the key feature is to not lose the rigor in the courses while teaching it in a motivating and interesting manner. The courses are part of a recently-designed combined circuits-electromagnetics curriculum.

1. Signal Integrity-Centered Projects in EE480

Originally, EE480, an EM senior course, was designed to teach transmission line (TL) and electromagnetic (EM) theories. Within the context of an ongoing EM-circuit curriculum NSF CRCD grant, we have developed several signal integrity (SI) projects in EE480. In order to effectively teach SI, we have combined analysis, numerical simulations, and experiments. The course starts with TL theory and we apply the TL model to extract the dielectric constant of common substrate material. After going through the basic training of a microwave network analyzer, students are asked to conduct dielectric constant measurements experiments. This process will enable them to relate the TL theory to the practical problem of measuring permittivity and permeability. This is also an inverse problem. The simple analytical solution known as Nicolson-Ross Method, becomes unstable at some frequencies and the students will be able to understand the problems associated with the inversion process. The next several weeks are dedicated for the time-domain methods. Time domain reflectometry (TDR) is used

0-7803-8883-6/05/$20.00 ©2005 IEEE

for extracting small parasitic inductance of a coil. To extract the inductance value, the time constant and integration over voltage response methods is used. The importance of parasitic inductance on digital circuits is discussed here. Students also measure the forward and backward coupling noise of different coupled lines. By using the lumped element model, they extract the coupling coefficients and values of mutual capacitance and inductance. Ansoft HFSS, the finite-element 3-D EM simulation tool, is widely used in industry and we use this as an integral part of EE480. A partially filled rectangular waveguide analysis is used to train students on HFSS. Students are asked to compare analytical results with the numerical simulations.

After completing these lab projects, students become familiar with both frequency- and time-domain tools. In the final project, they are asked to use all knowledge learned in EE480 and create a simulation tool; in particular a time-domain simulation tool for non-uniform microstrip TLs. The non-uniform TL cannot simply be expressed as cascaded ideal TLs. The parasitic admittance associated with a discontinuity becomes important for high-speed circuits and must be included in the simulation model such as in PSPICE. Because we do not at present have a good time-domain simulation tool for teaching, the approach we are taking is the combination of the frequency-domain simulation tool (HFSS) and time-domain model (PSPICE). First, students use the frequency domain EM simulation tool to obtain the detailed characteristics of a non-uniform TL. Then we assume the discontinuity can be modeled using a simple T-network and employ the parameter extraction method to obtain the lumped element model. This process requires converting S-parameters to either ABCD. Using the optimization process, students can find the approximate values of parasitic L and C. Once the T-network is obtained, this can be included into the PSPICE model. The final step is to conduct the time-domain PSPICE simulations. The simulation results must be compared with the experimental results obtain by TDR. The test microstrip PCB (Duroid 5870) is shown in Fig.1. The HFSS Simulation is run from 1 to 10 GHz to obtain the predicted S-parameters for the model as shown in Fig.1.

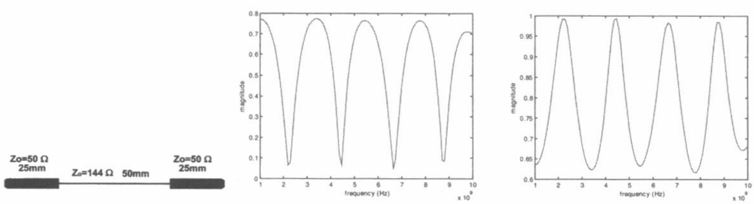

Fig. 1: Left: Test microstrip PCB. Right: S11 and S21 data for the non-uniform TL

Once S-parameters a obtained for non-uniform TL using HFSS, a Matlab program is written for finding the optimum values of C and L of a T-network which represents the discontinuities occurring where the TL thickness changes. The PSPICE circuit model is constructed and the simulation is conducted, comparison with TDR is shown in Fig. 3.

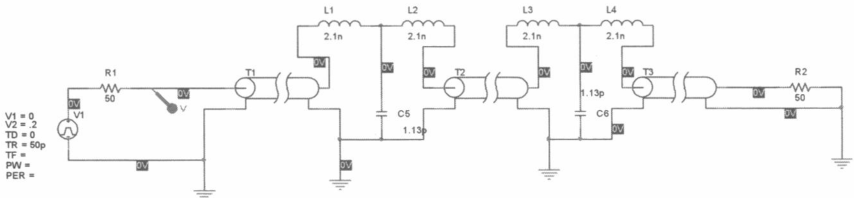

Fig. 2: PSPICE Lumped Element Model. Extracted values are C=1.332 pf and L=2.111 nH.

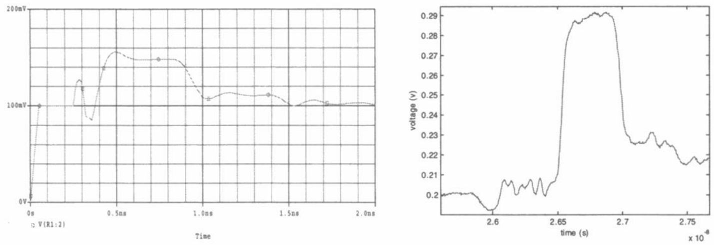

Fig. 3: Left PSPICE simulation. Right: TDR step response of the test PCB.

2. Analyzing high-speed circuit effects in EE 571

This is an intermediate/advanced level course for graduate students. Students are taught multi-conductor transmission line equations. The first computing project in Matlab involves creating an RLGC matrix simulator for transmission lines. Layered media methods are taught and developed for multi-layered boards and substrates. Reduced-order model techniques, particularly asymptotic waveform evaluation, are discussed. Finally, a programming course project involving a complete multi-conductor transmission line simulator, including parasitic extraction in layered media, model order reduction, and transient simulation is developed. Shown in Fig. 4 are results of model order reduction on transmission lines (left), and transient simulation (right) through a co-planar waveguide with and without a decoupling capacitor, and with and without a split ground plane. The overall course structure enables students to understand what technique to use in which aspect of high-speed circuit modeling.

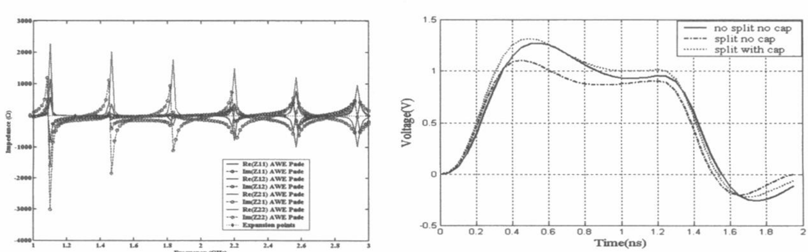

Fig. 4: AWE-based transmission line models (left), propagation through a co-planar waveguide (right).

3. Computational Electromagnetics and Signal Integrity in EE 573 and EE 574

This is a pair of courses that discusses computational electromagnetics algorithms, and recent advances. In EE 573, students start with understanding the finite difference time domain method (FDTD). The FDTD is then applied to signal integtrity cross-talk and scattering problems. The main part of the course deals with integral equation methods. Surface equivalence principles, quadrature methods, integral equation formulations, code development, mesh inputs, and visualization are discussed in detail. The students create from scratch a 3D capacitance extraction code. In the final project, a full-wave 3D code is developed with modules provided by the instructor.

EE 574 is a rarity; an entire course on fast methods and advances. Again, the motivating examples are large-scale parasitic extraction. The instructor provides large meshes and material parameters. In the context of parasitic extraction, three multilevel techniques are implemented; fast multipole methods, FFT-based methods, and multilevel QR-based methods. Full-wave fast methods particularly based on the fast multipole method and recent variations are analyzed in detail, and small Matlab modules are created. The final project is an accelerated version of the 3D capacitance code developed in EE 573.

The aim behind this course sequence is to familiarize both electromagnetics and non-electromagnetics students with modern techniques used for 3D signal integrity simulation while at the same time teaching more general computational EM principles.

4. Conclusions

Using signal integrity as the motivating application throughout the EM curriculum enables sustained student interest while maintaining theoretical and computational rigor of the courses, and also prepares those students who are interested to enter the chip-related industry.

Acknowledgements
We would like to acknowledge support from the NSF Combined Research and Curriculum Development program, software donations from Ansoft corporation, and discussions and suggestions from Intel corporation.