AC 2010-1463: MAKING THE ABSTRACT COME ALIVE IN AN INTRODUCTORY ELECTRODYNAMICS COURSE

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Making the Abstract Come Alive in an Introductory Electrodynamics Course

Abstract

It has long been recognized in the engineering education community that practical laboratory exercises improve student understanding of abstract engineering concepts. The Department of Electrical and Computer Engineering at the United States Naval Academy (USNA), a four year undergraduate institution, meets this challenge by making laboratories an integral part of almost every course offered. Most courses include a weekly three hour lecture and a two hour laboratory. Recently a laboratory component was successfully added to the department's introductory electrodynamics course. The purpose of this paper is to illustrate how students used the design of microwave microstrip circuits to improve their grasp of theoretical electrodynamics concepts. In addition, students were exposed to the practical aspect of design including limitations inherent in the simulation, design, fabrication and testing of high frequency circuits.

This paper will explain the details of laboratory exercises developed for the course and the supporting software, fabrication facility and test equipment. Additional laboratory exercises beyond the initial course offering that focus on optical propagation and antenna design will be described. Student and instructor assessment of the efficacy of the laboratory exercises will be discussed. The added laboratory's influence on formal course evaluations and exam results will be presented.

Introduction

Several approaches to assist student comprehension of abstract electrodynamics concepts have been proposed. These methods range from simulations using numerical packages, spread sheets and mathematical computational packages to hardware based experiments to facilitate student learning [1-4]. This paper proposes a new addition to practical laboratory experiences that take students from their initial design, simulation, and fabrication to the final test of their project [5-6].

The electrodynamics course at the United States Naval Academy begins with transmission line theory, considered to be a useful pedagogical link between circuit analysis and the vector calculus required for describing free space propagation of electromagnetic waves. This approach has successfully helped students understand wave propagation concepts even before the course included a laboratory. The added laboratory provides an immediate illustration of transmission line topics using SONNET™, a 3D Planar Electromagnetic software package for the design and simulation of microstrip components.(SONNET Lite™ is free online but a University Program makes the software available at a discount for colleges and universities.) After an introduction to clean room procedures and a photolithography process, students fabricate their designs and test them using a network analyzer. The final design task is a 5 GHz matching circuit. The exercises allow students the opportunity to follow their design from original concept to final test. The fabrication of student designs occurs during the vector calculus review that follows transmission line theory. Hence the laboratory exercises prevent a gap in course concepts and create a natural link between transmission line wave propagation concepts and planar wave propagation in free space. After the fundamentals of planar wave propagation are presented optical exercises on topics such a polarization states are planned. The course topics include antenna theory, an application of electrodynamics easily supported by SONNET ™ software that allows students to create patch antennas.

The first part of this paper is an overview of the initial course offering with sample laboratory exercises. The second part of the paper describes the expanded laboratory exercises planned for future course offerings. The discussion and conclusion present student and instructor assessment of the efficacy of the laboratory exercises and the added laboratory's influence on formal course evaluations and exam results.

Course Overview

The electrodynamics course is a junior level second semester course. The prerequisites are multivariable calculus and an introductory electromagnetics physics course. This four credit course has three lecture hours and a two hour laboratory. The initial course topic is the mathematics of one dimensional traveling waves followed by an introduction to transmission line theory. An explanation of wave propagation on a lossless transmission line using the lumped element model provides a sufficient foundation to use SONNET ™, a 3D Planar Electromagnetic software package for the design and simulation of microstrip components, to illustrate these course concepts. The first laboratory exercise is simply Chapter 3 and 4 from the Getting Started SONNET ™ manual

The topic of input impedance is followed by the second laboratory exercise. After completing Chapter 5 of the Getting Started manual, students are asked to design and simulate an open circuited 10 GHz 50 Ω microstrip transmission line capacitor. Students simulate their design for a 25 mil thick alumina substrate with a lossless metal and find the reflection coefficient and input impedance. Historically students experience a steep learning curve as they shift their perspective from the instantaneous signal propagation approximation of introductory electrical circuits to grasping the effect of signal propagation time at higher frequencies. This relatively easy high frequency circuit design shown in Figures 1 and 2 clearly illustrates the effect of changing transmission line lengths on circuit performance. Students also begin to experience some of the limitations of ideal designs when real materials are simulated such as the difference between actual and effective dielectric constant.

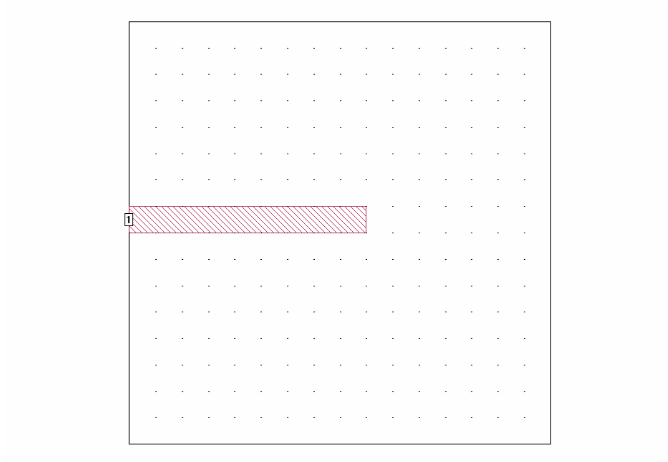

Figure 1: 2D View of a Microstrip Transmission Line Capacitor

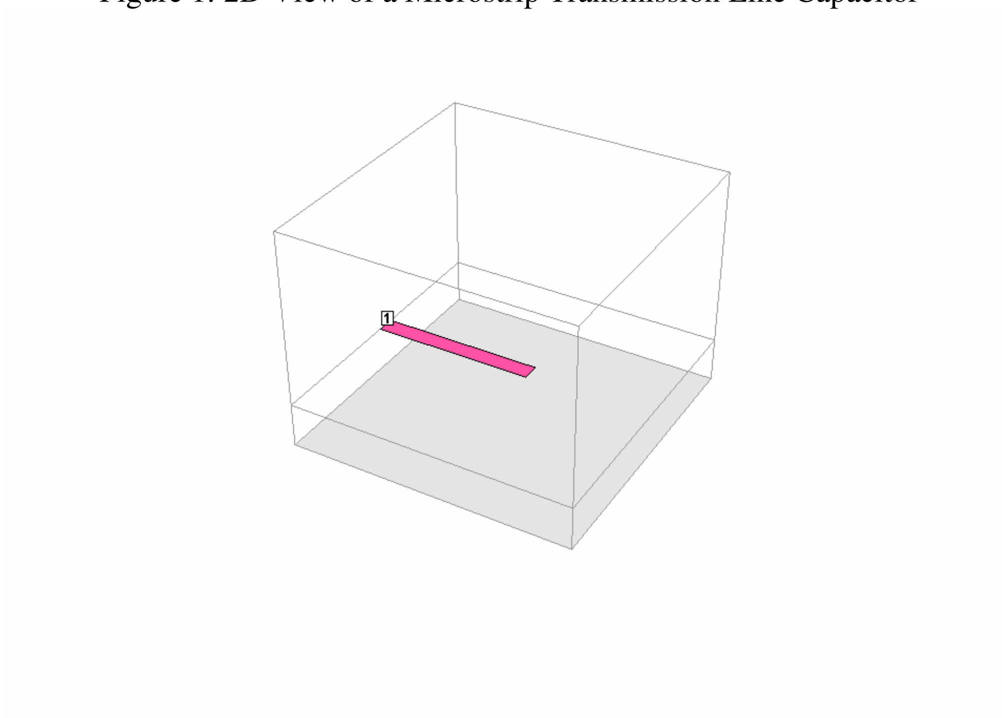

Figure 2: 3D View of a Microstrip Transmission Line Capacitor

Smith charts are presented then students design a stub capacitor that cancels out the imaginary impedance of an inductive circuit. This lab links the stub capacitor from the second laboratory exercise to a more complex circuit and acts as an introduction to matching circuits. Students discover the utility of parameter sweeps to optimize their design instead of guessing different values and the utility of their ideal design as a starting point for their finished design. Students were able to use chapters 10 and 11 from the SONNET™ User's Manual to learn about parameterization. The concept of de-embedding a circuit from connectors and feed lines was introduced. Students read chapters 7 and 8 of the User's Manual and use SONNET™'s de-embedding capability during the laboratory exercise. In addition students discover the efficacy of using a Smith Chart rather than a linear graph to display their simulation results.

The initial laboratory exercises are a sufficient foundation for student design, simulation, fabrication and test of a 5 GHz circuit matching a 50 ohm load to an input impedance, $Z_{in} = 100 - j100\Omega$. The matching circuit is designed for copper coated Duroid® a high frequency microwave laminate. This material is provided by Rogers Corporation via the Rogers University Program free of charge to colleges and universities. Students are asked to fit their design on a 1" x 2" rectangular substrate. The final design is turned into a mask inexpensively fabricated offsite

The project made use of the USNA Microfabrication Lab shown in Figure 3. This is a small class 10,000 cleanroom used for both courses and student and faculty research. Major equipment in the facility includes a mask aligner, a metal evaporation system, a probe station equipped with a microscope and micromanipulators and a ventilated chemical hood

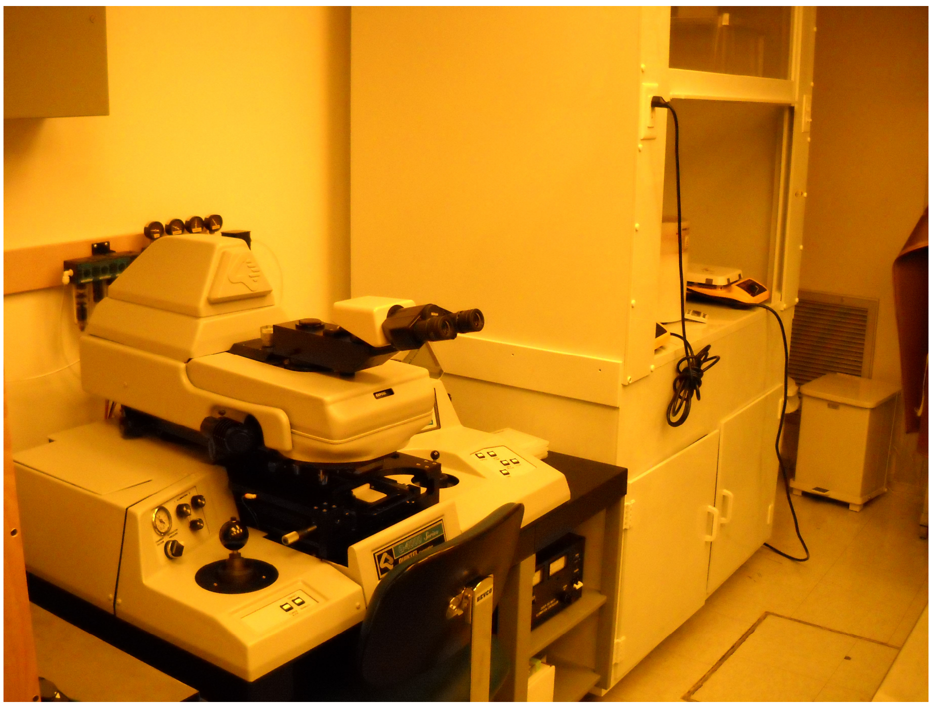

Figure 3: USNA Class 10,000 Cleanroom with View of the Mask Aligner

The lab primarily supports classes in the Electrical and Computer Engineering department, but is also used by students from other departments.

After an overview of circuit fabrication techniques, students in the electrodynamics class fabricated their designs using low cost transparency masks. The students used photolithography and then etching in ferric chloride to transfer their patterns onto the factory pre-coated Duroid®. While the course made use of the already existing laboratory facility, it should be noted that this process could be reproduced with an ultraviolet lamp, beakers and a fume hood. The final product was tested on an Agilent Technologies E5071A 300KHz to 8.5 GHz network analyzer using the Anritsu 3680-20 Universal Test Fixture shown in Figure 4. Students were required to discuss any deviations between their original theoretical calculations and their finished design.

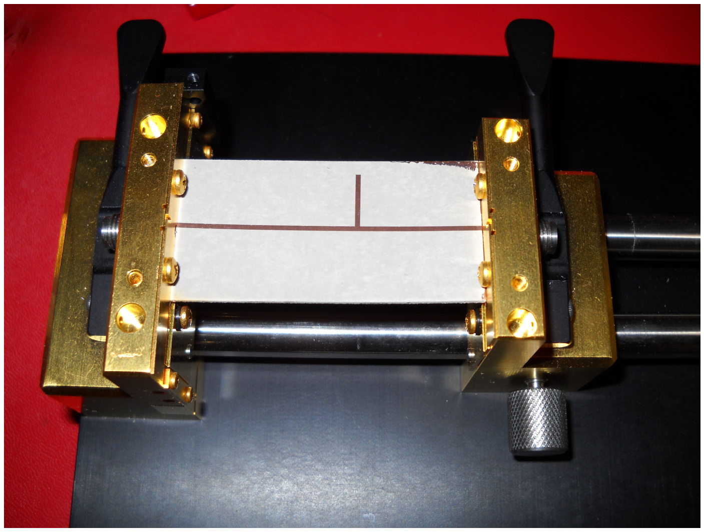

Figure 4: 5GHz Matching Circuit Mounted in an Anritsu 3680 Universal Test Fixture

An Expanded Laboratory

The laboratory component was so well received by students, that additional laboratory exercises will be included in the next course offering. The 5GHz matching circuit described in the previous section is fabricated during the vector calculus review that follows transmission line theory and precedes free space wave propagation. The current laboratory exercises illustrated transmission line wave propagation concepts. Free space optical laboratories will be used to illustrate planar wave propagation. The laboratories use HeNe lasers and photodiodes with linear polarizers and half and quarter waveplates to demonstrate applications of polarization and to introduce the concept of optical modulation.

The final laboratory planned is the design, fabrication and test of a microwave (patch) antenna. Students will use SONNET™ to design a 2.5 GHz patch antenna on Duroid® and match it to a 50 Ω SMA connector. The same fabrication method, materials and skills are required as for the 5 GHz matching circuit. Final test of their design will use the USNA anechoic chamber. This laboratory is a simplified version of a recent successfully completed senior design project shown in Figure 5.

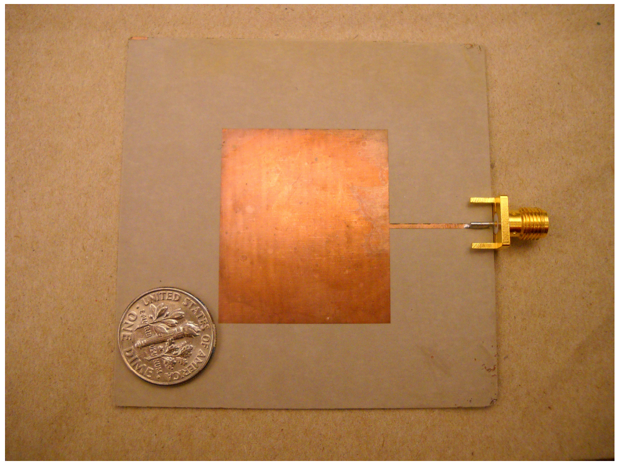

Figure 5: Microstrip Antenna Fabricated on Duroid ®

Discussion

The Department of Electrical and Computer Engineering at the United States Naval Academy offers laboratories as an integral part of almost every course offered. Most courses include a weekly three hour lecture and a two hour laboratory. The introductory electrodynamics course was one of the few without a laboratory. Given a student population familiar with the efficacy of hands on learning in almost all of their courses, student course evaluations frequently requested an added laboratory for electrodynamics. After the initial course offering with the added lab, course evaluations frequently sited the lab as one of the strongest features of the course. In the words of one student "building the stub capacitor was a really good way to see what we theorized about". Students frequently commented during lab that the theory was making sense to them as they worked through the lab. At least anecdotally, the laboratory improved student motivation and course mastery.

The final exam for the course covered topics that ranged from transmission line theory to antenna concepts. It is interesting to note that although the teacher, homework assignments, book and final exam questions were unchanged, the grades for the transmission line question improved from an average of 60% for the two previous course offerings without the transmission line labs to a 71% for the same exam question after the lab was added as shown on Figure 6. Exam questions for free space propagation and antennas exhibit little change. The addition of free space propagation and antenna design labs, as described in the previous section, should improve student performance based on the transmission line results. It is difficult to draw statistically significant results from the limited data available at this point, but the results are encouraging.

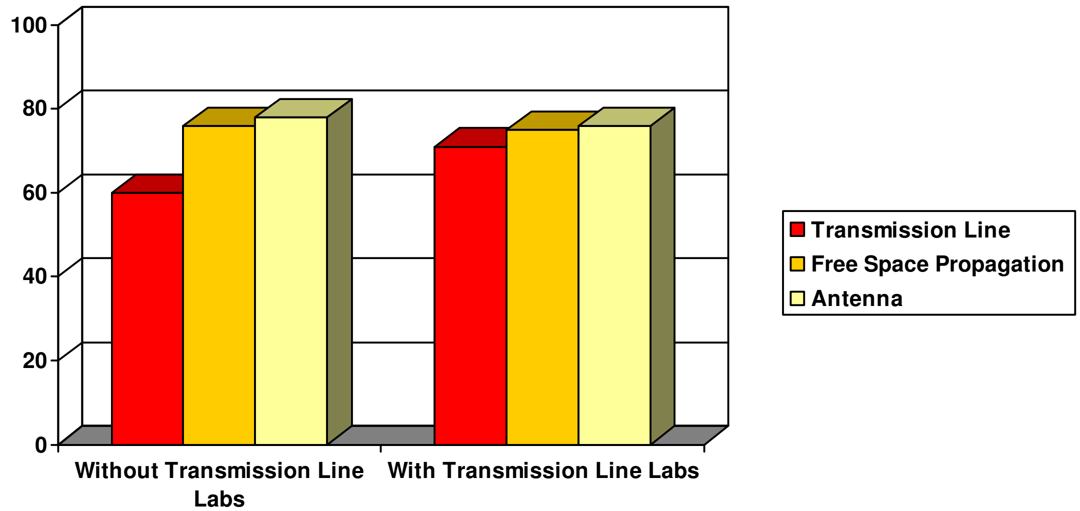

Figure 6: Final Exam Student Performance

Conclusion

The Department of Electrical and Computer Engineering at the United States Naval Academy successfully added a laboratory component to the department's introductory electrodynamics course. Students simulated simple microstrip components and designed, fabricated and tested a 5GHz matching circuit. The project exposed students to electromagnetic simulation software, clean room photolithography techniques and a network analyzer for the first time.

Exam data indicates that the transmission line labs improved subject mastery related specifically to transmission line theory. Planned additional laboratory exercises beyond the initial course offering on free wave propagation and antenna design were described. Improved subject mastery of these topics is expected given initial exam results for transmission line theory.

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