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Teaching Applied Electromagnetics to Engineering Technology Students

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Abstract

In a world where computer bus speeds have increased beyond 1 GHz and wireless communications/connectivity are common place, electronics and telecommunication engineering technology (ET) graduates require an understanding of basic applied electromagnetic concepts. To address this issue, many ET programs now offer courses in radio frequency electronics, transmission lines, and other high frequency concepts. This paper discusses a new engineering technology course recently implemented at Texas A&M University that stresses fundamental principles and real world applications of applied electromagnetics. The course includes a weekly lab for reinforcing the classroom concepts. The course begins by expanding on concepts that students have learned in their basic circuits courses. By discussing the concept of "real" components and parasitic capacitances and inductances, students learn to look at even the most basic circuits in a new way, recognizing new sources of coupling, crosstalk, and loss. Transmission line concepts are then introduced followed by Maxwell's equations. Students learn the concepts of the plane wave, wave reflection and transmission, boundary conditions, and penetration depth. These principles are then applied to waveguides, antennas, and free space wave propagation. The final subject of the course is an introduction to RF communication links. Basic communication system architectures are presented and the concepts of noise, signal-to-noise ratio, and link budgets are introduced. This paper will discuss the course curriculum and the laboratory in detail.

Introduction

In today's industry where many electronic systems operate at increasing frequencies, an understanding of fundamental electromagnetics is becoming not only a desired trait but also a requirement for the entry-level engineering technology (ET) graduate. Whereas twenty years ago, an understanding of high frequency effects was only required by a very specialized group of people, it is now a necessity in most ET positions. It is anticipated that in the near future, most system engineer positions will require a working knowledge of analog, digital and radio frequency (RF) concepts.[1] For example, with the speed of modern computer networks, the successful telecommunications engineering technology graduate must understand transmission lines and impedance matching. If the network involves a wireless link, then he or she must also have an understanding of antennas and electromagnetic propagation.[2] Similarly, the electronics engineering technology graduate that designs and lays out printed circuit boards, especially those with high clock speed microcontrollers and processors on board, must deal with real component effects, transmission line effects, and electromagnetic coupling effects. In fact, even technologists that do not deal directly with electromagnetic effects often have to deal with the consequences of electromagnetic interference and its mitigation.[3]

While electromagnetics (EM) is considered a core course among electrical engineering programs, many engineering technology curriculums tend to shy away from the fundamental concepts, choosing instead to deal with specific applications such as antennas and/or transmission lines using canned formulas and simple approximations. While these are some of the most common applications of EM concepts seen by engineering technologists, true competence in these areas require a deeper understanding of basic EM principles. For instance, to have an intuitive feel for coupling between wires and transmission lines requires that one be able to visualize the distribution of electric and magnetic fields. Another example is signal propagation between antennas. To have an understanding of signal attenuation, polarization, and transmission, one needs to understand the concepts of conductivity, permittivity, permeability, and their effect on wave propagation. For these reasons, the Electronics (EET) and Telecommunications (TET) programs at Texas A&M have decided to consolidate most of the RF and EM applications typically taught in various courses into a single course.

This new engineering technology course has recently been implemented at Texas A&M University and stresses fundamental principles and real world applications of applied electromagnetics. The course includes a weekly lab for reinforcing the classroom concepts. The course begins by expanding on concepts that students have learned in their basic circuits courses. By discussing the concept of "real" components and parasitic capacitances and inductances, students learn to look at even the most basic circuits in a new way, recognizing new sources of coupling, crosstalk, and loss. Transmission line concepts are then introduced and hands-on experiments are used to help students grasp the fundamentals. The next topic is Maxwell's equations. Students learn the concepts of the plane wave, wave reflection and transmission, boundary conditions, and penetration depth. These principles are then applied to antennas and free space wave propagation. The final subject of the course is an introduction to RF communication links. Basic communication system architectures are presented and the concepts of noise, signal-to-noise ratio, and link budgets are introduced. This paper will discuss the course curriculum and the laboratory in detail and lessons learned will also be presented.

Electromagnetics in Engineering Technology

Most traditional electrical engineering programs still require students to take a minimum of one course on electromagnetics. This course typically covers EM using a very theoretical approach and does not usually include a lab. Students can then elect to take advanced courses that apply the fundamentals to a variety of subjects including antenna theory, microwave circuit design, communication systems, etc. Also, the fundamentals course is typically supported by math courses in calculus, vector calculus and differential equations; and at least one physics course in electro- and magneto- statics. Even with this knowledge, most electrical engineers are still not proficient in real-world electromagnetic problems without additional graduate or industrial experience.

In contrast, engineering technology programs generally do not require courses in vector calculus and differential equations. The only prior exposure to the background material required for an EM course are courses in basic calculus and an introductory physics course in basic electric and magnetic fields concepts. Thus, the difficulty of offering a truly meaningful experience in electromagnetics to engineering technology students should be no surprise. In fact, a web-based survey of several engineering technology programs indicated that few offer a course specifically in electromagnetic concepts. Instead, most programs tend to offer courses in specific application areas of EM such as transmission lines, antennas, and/or RF electronics.[4,5]

While these types of courses do expose ET students to many of the most common applications of EM, a true understanding of electromagnetic effects requires that a student have an intuitive feel for basic EM. Also, while ET students may eventually be exposed to most EM concepts over the course of a four-year curriculum, it is this author's opinion that they should see these principles in a single course motivated with many real-world examples. In this way, they begin to see relationships between theory and application.

Another example that indicates there is inadequate attention being paid to electromagnetics in engineering technology is the lack of available EM textbooks written specifically for ET students. In fact, a search by the author found only one good text for engineering technology students.[6] However, the good news is that there are many tools and web-based simulations available that illustrate many EM fundamentals through intuitive graphical examples. Using the available text and these examples, a relevant course can be developed.

Course Curriculum

Approximately three years ago, interest of the EET/TET programs at Texas A&M began to grow in the area of electromagnetics and RF electronics. At the time, more and more funded student projects involved some level of wireless communications hardware, and it became obvious that the students had a fundamental lack of knowledge in that area. While some specific EM and high frequency applications such as basic transmission lines and antennas were being addressed in various courses, overall the students lacked an appreciation for the concepts needed to successfully understand and design high frequency systems. Thus, it was decided that all basic EM related concepts would be addressed in a single course. The new applied electromagnetics course was first offered in the fall of 2002. At that time, it was decided that the course would be a lecture-only course because of the lack of availability of good RF lab equipment. Since then, the course has been offered two more times with a lab being added to the course in the fall of 2003. The lab will be discussed in more detail in the next section.

One of the first hurdles to creating the new course was finding an appropriate textbook. While many texts in electromagnetics exist, they are targeted at engineering and physics programs where the students have been exposed to vector calculus and differential equations.

Also, most of these texts are written from a theoretical perspective and do not use many real-world examples. After a search of existing texts, one was finally found that was targeted specifically at engineering technology. "Lines and Fields in Electronic Technology" by Stanley and Harrington[6] met most of the needs of the class. One minor drawback of the text is that it avoids most of the traditional mathematics used in EM, even aspects that engineering technology majors should be prepared to understand. This was addressed by augmenting the lecture and lecture notes with additional material. In addition to the textbook, the author has found many interactive graphical examples such as Java applets on the web that help give the students an intuitive understanding of fundamental concepts. The course website[7] catalogs these examples and they are used in class throughout the semester as teaching tools. The students respond well to these examples and the author has found that they use them extensively outside of class, often returning the next lecture period with additional questions.

The course begins with a review of basic circuit concepts and a general overview of electromagnetics. The students are shown that the circuit principles they have been learning are really approximations of a more general theory where it is assumed that the electromagnetic fields being produced by the components in a circuit are localized. With this in mind, lumped elements are discussed and students begin to develop an appreciation of parasitics and their effect on frequency response. They see how typically neglected effects such as mutual capacitance, self-inductance, resistive loss, and inductive coupling can be modeled by adding parasitic components to the schematic of a circuit. They also learn how to determine when parasitics are negligible and when they are not.

Once students have an appreciation for real circuits and how non-negligible parasitics can make a simple circuit very complex, transmissions lines are introduced. The textbook being used is very good about slowly introducing new concepts and the students first use bounce diagrams to discuss DC and pulsed waveform effects on transmission lines. Next the effects of transmission lines on sinusoidal signals are explored and the math is motivated through a distributed element model. The students learn about characteristic impedance, velocity factor, attenuation, reflection and transmission, effect of load and source impedance, standing wave ratio (SWR), etc. They also learn how to work with and design practical transmission lines such as parallel wire, coaxial, and microstrip lines. Finally, the use of the Smith Chart and the design of impedance matching networks are discussed.

Next Maxwell's equations are introduced as a means to understand electromagnetic problems that are not physically constrained. While engineering technology students do not have the math background to work extensively with Maxwell's equations, some basic mathematical analysis is performed in class to remove some of the mystery usually attributed to electromagnetics, and the wave equation is derived. The students then learn about plane waves, material properties, wave reflection and transmission, wave propagation in dielectrics, lossy materials, and conductors, and about skin depth. These concepts are applied to real-world applications including waveguides, fiber optics, and antennas. The students also explore wave propagation in free space and over a ground plane and the Friis transmission equation is studied.

The final topic of the course is communication systems architecture. The students learn about basic transmitter and receiver architectures. Noise, noise temperature, noise figure and signal-to-noise ratio are also discussed. Because of time constraints, this area is not covered in depth; however the author is currently working on a follow-on course to introduce RF electronics and communication systems in more detail.

The Laboratory Experience

After teaching the applied electromagnetics course twice as lecture-only, it became apparent that the students would benefit greatly from an associated lab experience as detailed in Table 1.

Table 1 – Laboratory Assignments

Lab	Description	Software and Hardware Tools Used
Lab 1	Real Components – Study of the frequency response of resistors, inductors, and capacitors, determination of parasitic values.	Agilent 8712ET Network Analyzer
Lab 2	Parasitic Effects – Study of stray capacitance, inductance, and resistance in circuits, predicting capacitive and inductive coupling, modeling parasitic effects.	Orcad PSpice
Lab 3	DC and Pulsed Waveforms on Transmission Lines – Verification of bounce diagrams, signal propagation, and study of reflections on transmission lines.	Orcad Pspice Transmission Line Simulation Applets
Lab 4	Sinusoidal Waveforms on Transmission Lines – Study of reflections on transmission lines, phase shifts due to propagation effects, and attenuation.	Orcad Pspice Transmission Line Simulation Applets Agilent 8712ET Network Analyzer
Lab 5	Smith Chart and Impedance Matching – Study of impedance matching techniques such as quarter wave transformers, lumped element matching networks and single stub matching networks; use of the Smith Chart.	Smith Chart Smith Chart Software
Lab 6	Microstrip Design – Study of microstrip transmission lines and microstrip coupling effects, design and fabrication of a simple microstrip circuit with matching networks.	Microstrip Design Applets Agilent 8712ET Network Analyzer
Lab 7	Electromagnetic Plane Wave Propagation and Waveguides – Study of plane wave propagation using simulation tools and investigation of waveguides using Java applet analysis tools.	EM Propagation Simulation Applets Waveguide Analysis Applets
Lab 8	Antenna Design and Testing – Study of antenna design principles, modeling of antennas, measurement of antenna properties such as impedance, VSWR, and antenna pattern; fabrication and testing of an antenna.	NEC Antenna Modeling Software Agiilent 8592L Spectrum Analyzer Agilent 8712ET Network Analyzer
Lab 9	Receiver Architectures – Study of typical receiver architectures, design of a simple AM homodyne receiver.	Agiilent 8592L Spectrum Analyzer MiniCircuit Discrete RF Components

One of biggest obstacles to a creating a meaningful laboratory experience was the lack of available RF equipment. Fortunately, the department did have a network analyzer and a spectrum analyzer (two of the more expensive tools needed in an RF lab). However, the lab also needed multiple benches with RF generators and high frequency scopes. To solve this problem most of the experiments were designed to work at 10MHz so that standard Agilent student bench equipment could be used. In addition discrete amplifier, filters, mixers, and directional couplers were purchased so that basic network analysis experiments could be performed on the bench. With this equipment, a set of nine experiments was designed.

The first two labs were designed to teach the students about parasitic resistance, capacitance and inductance. In the first lab, the students plotted the frequency response of different types of capacitors and inductors using a network analyzer and bench equipment and then developed a simple model to account for loss and self resonance. In the second lab, the students built a simple circuit with two long leads and a load and then modeled the circuit in Pspice. Exciting the circuit with a pulsed waveform, they noticed that their simple Pspice model did not accurately predict the ringing that they saw in the actual measurements. They then calculated the parasitic inductance and capacitance in their circuit and added it to their model creating a more accurate representation of what they saw. It is interesting to note that many of the groups challenged themselves to find as accurate a model as possible, adding lead resistance, source resistance and load parasitics.

The next three labs involved transmission lines. Using standard bench equipment, directional couplers, RG-58 coaxial cable, and assorted loads (open, short, 50 ohms), students experimented with the effects of transmission lines on switched DC, pulsed waveforms and sinusoidal waveforms. Experiments included studying time domain reflectometry; predicting and measuring reflected signals, time delay and phase shifts; predicting and measuring attenuation; and creating matching networks using the Smith Chart. The students also built a simple network analyzer using directional couplers to measure forward and reverse waves on transmission lines.

When the students were comfortable with transmission line concepts, they were tasked with a two week lab to design, build, and test a simple microstrip board with matching networks. Using knowledge learned in class, the students designed a printed circuit board with 50 ohm traces, a quarter wave matching network, and a stub matching network. They then layed out the circuit and had it fabricated (see Figure 1) through Express PCB[8].

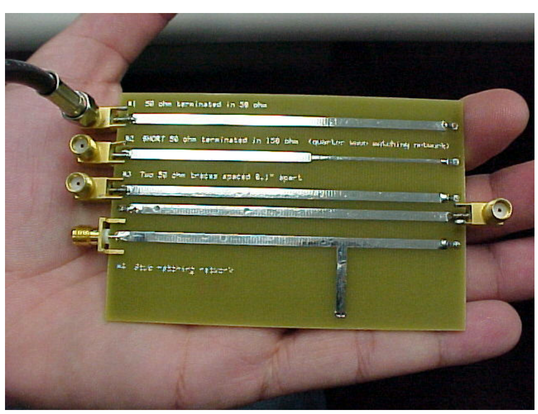

Figure 1 – Construction of a simple microstrip printed circuit.

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Once the board was finished, the students soldered on RF connectors and surface mount components. Finally, they used a network analyzer to test the board for matching and for coupling between independent traces. This lab was done in groups of four to defray cost and because of resource constraints. The project not only helped reinforce EM concepts but also exposed the students to the process of laying out and fabricating a printed circuit board, a skill that will be used in several follow-on courses including their senior design project.

Lab 7 covered the basics of electromagnetic wave propagation and waveguides. This lab was an interactive lecture/lab where the instructor used various web resources to help the students visualize the mathematics of plane wave propagation and to teach students about waveguides. As part of the lab, the students are given a physical piece of waveguide and are asked to calculate the cutoff frequency, guide impedance, and guide wavelength for different modes. They then determine the dominant mode, predict the usable frequency range of the guide, and compare this to the specification for the guide they are given.

The eighth lab is another two week project and the students again work in teams of four. The objective is for the groups to "design", build and test a simple antenna (see Figure 2).

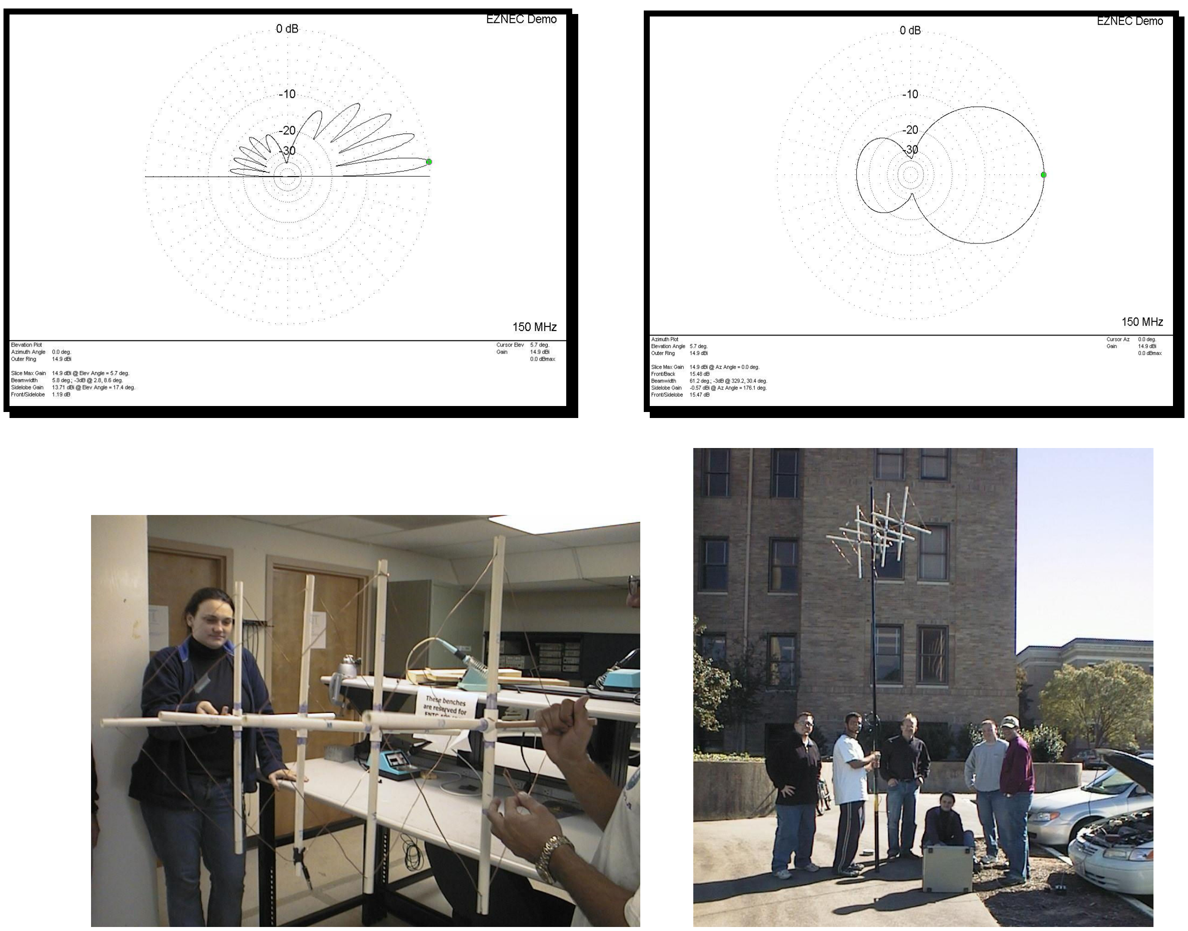

Figure 2 –Simulation, construction, and testing of an antenna.

The only constraints placed on the students are that the antenna has to operate between 50MHz and 1000MHz, it has to have an azimuthally directional pattern, and it cannot be a simple dipole. The students are allowed to use web and library resources to find ideas for their antennae. Once their antenna is selected, they model it using NEC antenna modeling software and then construct it. Last semester, they were tasked to find an NEC software package on the web; however most of these are evaluation versions and are extremely limited. In future offerings of the course, a full version will be purchased and installed for use by the students. Once the antenna is built, they work with the course instructor to test it. Using a network analyzer and a spectrum analyzer, the input impedance, VSWR, front/back ratio, and azimuthal antenna pattern plot are measured. The students then compare these to the expected and modeled results.

In the final lab, the students learn about basic receiver architectures and build a simple homodyne AM radio receiver. First, using a spectrum analyzer, they find the frequencies of two radio stations they want to receive. Then, using a front-end low pass filter, a mixer, a function generator as an oscillator, audio low pass filters and an active speaker, they build an AM receiver capable of picking up these local broadcast stations. As expected, this is one of the labs that interested them the most. For future offering of the class, the author hopes to have students build a simple audio amplifier as part of their electronics course. This amplifier could then be used in this lab.

These labs were developed during the summer of 2003 and were offered for the first time in the fall of 2003. Most of the experiments were designed to be performed in groups of two; however, the microstrip and antenna projects were done in groups of four as mentioned above. While some refinements were made to the labs, in general the experiments were successfully in engaging the students' interest. Procedures for these labs can be found on the course website.[7]

Lessons Learned

The applied electromagnetics course has been offered now for three semesters. Student feedback to the course has been very positive as assessed through increasing enrollment, student evaluations, and anecdotal information. In addition, the creation of this course to cover EM fundamentals has released time in other courses. This has allowed other professors to introduce new topics and/or cover existing topics in more detail. The course has increased student interest in RF electronics and electromagnetics as evidenced by an increase in senior projects involving EM and RF principles. The course has also been discussed with industry members and feedback about the new curriculum has been positive. Those industry members involved in data networking and semiconductor test have been particularly supportive of this initiative.

Of the lessons learned while teaching the class, the most important was the need for a relevant lab experience. Because electromagnetic concepts are often hard to grasp, hands-on experience with the fundamentals has been invaluable to the students. It is also been a great motivator to students to work on a highly visible project such as antenna testing and have people come up to them to ask questions, making them the experts.

Finally, from the level of interest that the students have shown, it has become apparent that this course needs to be followed up with a course targeted at the application of EM principles. Many schools use an RF electronics course or a communications course to introduce high frequency concepts. With the new knowledge that students now have in applied electromagnetics, such a course could be used to reinforce the concepts and to give them practical experience in applying these principles to the real-world.

Conclusions

As electronic circuits operate at higher and higher frequencies, the successful engineering technology graduate needs to have a good understanding of fundamental electromagnetic concepts. To this end, the EET and TET programs at Texas A&M University have consolidated the teaching of high frequency applications into a single course on applied electromagnetics. This course begins with lumped element approximations to high frequency effects, then discusses transmission lines, and finally introduces Maxwell's equations. To complement the classroom lectures, a lab has been developed to help students visualize the basic concepts. To augment their hands-on experience, the lab includes design projects such as the design and construction of microstrip circuits the construction and testing of antennas.

This new course has now been taught for three semesters with the lab having been taught twice. The average class size is 30 students, however the most current offering has an enrollment of 48 students. While the students were engaged in the lecture-only class, the lab has really helped spark their curiosity, interest, and understanding. The students are especially enthusiastic about the antenna design project and the AM receiver experiment. Because of the interactive nature of the labs, it has been determined that more than sixteen students per lab section detracts from the lab experience.

Equally as important, the new applied electromagnetics course has had an impact on the rest of the curriculum, especially in telecommunications. Students are now obviously more prepared for material presented in upper level courses and professors have been able to cover advanced material more deeply. Future work includes the development of a follow-on class in RF electronics where students will design and build a radio transceiver.

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