THE GRADUATE COURSE IN ELECTROMAGNETICS: INTEGRATING THE PAST, PRESENT, AND FUTURE

D. A. ROGERS AND B. D. BRAATEN
Department of Electrical and Computer Engineering
North Dakota State University
Fargo, ND

Abstract

In electrical engineering graduate programs, the first course in electromagnetic theory and applications has been a staple for over 40 years. It has passed through the hands of multiple professors at many different institutions while using only a few standard textbooks in various editions. While a compelling goal has been to introduce students to the main areas of electromagnetic theory in common research use, it often has had a laboratory component. The challenge in the first graduate course is to review and build enough of a foundation to launch the student into product design and research and to wet his or her appetite for advanced study.

Introduction

A half century ago the first course at the graduate level in electromagnetic theory commonly was based on a textbook such as Plonsey and Collin.[1] The course strongly emphasized Maxwell's equations and their analytical solution with applications to open- and closed-structures. In many respects the course outline followed that of its undergraduate cousin, but at the graduate level virtually every topic was approached with increased mathematical rigor. This theoretical emphasis was especially strong in the United States in the wake of Sputnik and the scientific accomplishments of the Soviet Union. For example, the Coulomb's Law review introduced some students to an entirely vector description of electromagnetics problems, many of which required integral calculus for solution. Gauss's flux and divergence theorems quickly led to Poisson's equation, which would be expressed in the three common coordinate systems. The divergence theorem led to Green's first and second identities, proved in detail, with the Dirichlet and Neumann conditions used to derive the Uniqueness Theorem. It should be noted that in a modern course the tendency is to pass over most of the details of the proofs of these theorems due to the compression of a multitude of subjects into one course.

A few years later we find as the principal textbook author Robert E. Collin.[2] He authored several books at different levels that have endured even to the present. The course now involved studies of waveguides using vector potential methods, magneto-ionic media, propagation in the neutral atmosphere, antennas as sources of electromagnetic fields, analytical methods in various coordinate systems, electromagnetics resonators, and so forth. By the 1980's and 1990's, as undergraduate education in electromagnetics was declining at some institutions, electromagnetics educators at the graduate level had to refocus on the basics. This made the work of David M. Pozar[3] and Constantine A. Balanis[4] very useful as these authors brought their readers from the level of undergraduate electrical physics to research levels in electrical engineering. Hardware design studies became more important with some supplementing their courses with textbooks by authors like K. C. Gupta.[5] Along the way Akira Ishimaru[6] authored a book that could be used in the first and subsequent courses.

A 21st century course is now likely to include a review of plane-wave and transmission-line theories since they underlie much of modern high-frequency device analysis and design. Magneto-ionic theory is still useful as a means of introducing effective dielectric constants that are less than unity. Microwave network theory and microline design techniques appeal to students and form a basis for creative laboratory projects. Noise and systems studies introduce the student to some of the realities they will encounter. Students still need explanations of electromagnetics, so they welcome mathematical and theoretical insights that are clear and comprehensively presented. Even some optics can be included, especially as a consequence of a vector potential understanding of guided-wave theory. Since electromagnetics theory is a well-established discipline, almost all of the "old stuff" is still relevant in the 21st century. However, there is a tendency to teach new mathematical and theoretical concepts using a "just-in-time" approach.

What Will Our Students Need?

An important consideration in this course is to develop an approach that reaches the audience of the next few decades. We have worked in a small graduate program that already has had a good record of producing M.S. graduates for about 50 years and Ph.D.'s since the 1980's. We expect only moderate increases in these numbers over the next few years. The electromagnetics course needs to serve those specializing in some area of electromagnetics, but it also would be beneficial to attract good students who are not specialists. The course should be designed for electrical and computer engineers and those from related fields who can benefit from it. Considering that more and more research is focusing on very high-speed or very small devices, the course should serve the traditional electrical and computer engineering (ECE) specialties and those working in material science, nanoscale science and engineering, and areas of applied physics such as the space sciences. An undergraduate background in electromagnetics is assumed, but we can't assume that background is strong. Correspondingly, an undergraduate background in electric circuits, including the use of phasor or time harmonic methods is necessary. This points again to our 16-week course where the first three weeks or so is devoted to a review from a graduate perspective of circuits and fields concepts. Good starting points are transmission line theory, plane wave propagation in a vacuum, and rectangular metallic waveguides. These are foundational to the area and can serve to review and reinforce the major concepts of electromagnetics and circuits. Beyond this, of course, we need to consider where the students will go following this course.

The Contemporary Graduate Electromagnetics Course

Today's graduate electromagnetics course deals with various engineering applications of electromagnetic theory. Topics to be considered include transmission lines, waveguides, microwave networks, passive microstrip devices, antennas, optical waveguides, wave propagation in open and closed structures, and wave propagation in neutral and ionized media.

The current version of the course attempts to introduce and review those concepts the student will need in subsequent courses and in research. As we will explain, we also attempt to present material that has applications to other specialties and career fields. The order of material presented here we feel is quite convenient to the learning process; of course, other arrangements are certainly possible.

The course begins with a review of uniform plane-wave propagation in a vacuum and in isotropic lossy media. This model of propagation adequately describes radio propagation after a wave has left a transmitting antenna and before it reaches the receiving antenna. It also is a close cousin of propagation along a transmission line. A detailed understanding of these simple cases is very valuable to the future practicing engineer or researcher. The process of study includes Maxwell's equations in the time and phasor domains (which includes a review of partial and ordinary differential equations), boundary conditions, and power flow.

It's interesting to review transmission line theory from an electric circuits perspective in both the time and phasor domains and discover the relationships that exist between the transmission line model and the plane-wave model. For transmission lines, it is useful to discuss the various types of impedance transformers along with the general concept of impedance matching. This reviews and reinforces for the student this basic electric circuits concept from their past studies.

After introducing the design and analysis of microstrip transmission lines (printed-circuit lines), various passive devices along with their design and detailed analysis are presented. Typically the student learns about microstrip power dividers and couplers, impedance transformers, and filters. Students are introduced to both low-frequency and high-frequency realizations of these devices and then are guided in designing devices to operate in the lower microwave region (a few gigahertz). This is a great opportunity for the student's general electrical engineering education. They learn how to layout their designs using Agilent's ADS system.[7] They export a gerber file to the department milling machine, and then compare the performance of the device to the theoretical predictions of ADS.

Students then choose a project in which they will apply this process to a more advanced device that they have chosen for study. With the background that now exists, students can move ahead, for the most part, in developing their own projects outside of class. This milestone in the class experience can be a good opportunity to take some class time to talk about ethical issues in the discipline, often taken from current news events. Two possible examples are the health concerns in cell phone usage and the health effects of high-voltage transmission lines. It's likely that the class won't come to any final conclusions on such issues, but at least they will be aware that the engineering profession is aware and concerned about such issues.

We are now ready to tackle something more substantial. First, we solve the classical rectangular waveguide problem using a product solution of the partial differential equations. This problem shows clearly why there can be so many different modes or solutions to this problem. This problem serves as a benchmark for comparison with the results of more advanced methods. It also helps the student to understand what a mode is later when we introduce the optical fiber as a communication channel. But, continuing with the rectangular waveguide, this is an opportunity to introduce the Hertz potential method to solve a variety of waveguide and multilayer microsrip devices or antennas.

The Hertz potential unites the vector and scalar potential commonly encountered in electromagnetics. It is a convenient tool for the study of the rectangular waveguide, the cylindrical waveguide, the coaxial waveguide, and even optical fibers. These structures can also be the occasions for the study of solutions to Maxwell's equations in various coordinate systems.

Antennas are treated in a subsequent course, but system aspects of the antenna are appropriate in the first graduate course in electromagnetics. Here we introduce the concept of the electric field due to a transmitting antenna and the resulting electrical output of a receiving antenna. This is followed by developing the relationships that exist among antenna size, path length, and electrical noise.

A terrestrial radio link involving a transmitting and receiving antenna provides the opportunity for study of such problems over a hypothetical flat earth or a spherical earth. One can also add atmospheric effects such as refraction (the four-thirds earth radius concept) and scattering, and, for longer paths and lower frequencies, we can include anisotropic wave propagation in the ionosphere. Although this is a rather old problem, as was mentioned above, it does give the opportunity to introduce a naturally occurring propagation situation in which the index of refraction can be less than unity. This can prepare the student for the metamaterial problems to be encountered in contemporary research.

We can come back to earth by considering microwave devices from the perspective of matrix methods and physical realizability. Microwave circuits are often considered by using the scattering parameters. A review of matrix methods that should be useful to those in other specialties leads directly to demonstrating the relationship of these parameters to those encountered in other courses: impedance parameters, admittance parameters, and the ABCD parameters. Measurement instruments often give results directly as scattering parameters, and, after a little experience, the engineer starts to think and design directly in the scattering parameter domain. However, at the analysis level, she/he most move back to the circuits level. The relationships involved are shown nicely through well-known matrix properties.

Finally, we have a brief introduction to optical signal transmission to include the calculation of optical fiber numerical aperture through a review of Snell's law at the core-cladding interface followed by a brief introduction to optical fiber mode theory. This latter study is facilitated by our earlier study of waveguides.

Course Project

As was mentioned above, early on students begin work on a course project. Usually there are enough students in class to break up into five or six groups of two each. The two share the workload for the project. This includes designing the devices, implementing and simulating them using ADS, obtaining the resulting circuit boards from the milling machine, and measuring the device performance. These measurements are compared to the ADS simulations or to simulations produced by other software such as Matlab (the standard mathematical package used in the department). Finally, the project teams must present their results to the class at times scheduled at the end of the semester. The oral presentation is given using PowerPoint. Each student presents a portion of the technical presentation, usually limited to about 20 minutes total. The presentation is made to the entire class, and the targeted audience is their classmates. Attendance is required for all students for all presentations. An unexcused absence results in points deducted from the absent student's presentation score. The presentation score is based on several factors:

- the quality of the visual presentation materials
- organization and preparation
- English grammar and speech
- the ability to communicate the topic to the class
- presentation at a level appropriate to the class
- being on time and speaking within time limits.

The project presentation is a good first step in preparation for the eventual graduate degree defense that every student is required to face.

Where Do We Go From Here?

Hopefully students from specialties outside of electromagnetics are helped by the range of studies and activities in this course. But how are students wishing to do research in electromagnetics or in closely related areas like optics served through this course and the offerings in a small graduate program like ours?

The course covers basic concepts and topics in electromagnetics that are essential to the electromagnetics specialist. And the project gives practical design and measurement experience that serves well students doing research in our department. The course is a good fit for what we do, but more is needed. Beyond the mentoring the student receives from a core group of research faculty, the student needs additional course work.

Several additional graduate courses exist to develop the student's research abilities. In electrical engineering, students can choose courses in electronics, signal processing, communications, and control systems that will improve their knowledge of applied physics and mathematics. In electromagnetics we offer courses in antennas, electromagnetic compatibility, and signal integrity. Physics and electrical engineering cooperate in offering courses in optics, optical signal transmission, lasers, and photonics. Physics offers courses in electromagnetics and computational physics that can be useful to some students. Finally, mathematics offers a wide range of courses useful to electromagnetics research; complex variable theory, applied differential equations, and partial differential equations are good examples. Carefully planned courses of study can lead our graduate students to have backgrounds that will facilitate their progress and growth in research.

Undergraduate and graduate education is very important and is a strong emphasis of the ECE Department as a whole. Efforts are underway in ECE to promote research activity. An integration of research and course work is one method of developing a new type of research program.

At this time there are approximately 400 undergraduate and 30 graduate students in the NDSU ECE Department. Contained in this group of students are very talented and bright individuals capable of thinking independently, taking initiative, and leading groups of people. One method of challenging these capable students is to integrate active research programs directly into the courses currently being taught in the ECE curriculum. Over the past few semesters, the authors have been working to bring research activities into the courses in electromagnetics that were mentioned earlier. In particular, research topics associated with flexible antennas, microwave circuitry, and printed antennas have been introduced as projects in these courses. During the semester several milestones have been defined. Some of these milestones involve a literature search, reproduction of published results, new designs or new research, synthesis, and testing. To meet these milestones the daily or weekly homework loads have been reduced, and, in place of this effort, the students are required to write bi-weekly reports and present them to the class. At the end of the course, the students are required to prepare a conference paper summarizing their new results, and part of the final grade depends on this submission. Student feedback on these courses has been outstanding. On a scale of 0 to 5.0 (5.0 = a very good course), the overall course rating has been 4.6, and two journal and four conference papers have been published as a direct result of these courses. Furthermore, several of the most talented students continued their stay at NDSU and enrolled in the graduate program. A future aspect of this integrated research and coursework plan is to extend this concept to include other courses outside of the area of electromagnetics and work with other faculty within and outside of the ECE Department. Results from this broader research integration will be presented in a future paper.

What Goals Should Our Course Have?

Some outcomes that we expect are that: (i) students will be able to analyze and design the devices studied in the course, (ii) they will have the background to work with related but more complex devices, and (iii) they will be able to produce innovations based on the background that they have obtained. There are "softer" outcomes that we also strive for. We would like the student to have an honest opinion of his/her own abilities in the field. Hopefully the course will move them from a "novice" to a "qualified" level. We hope that they will be actively involved in class attendance, assigned readings, and completion of homework assignments. The core concepts in the course should be very familiar to them so that they can perform well in exams without feeling the threat of time pressure. They should become familiar with using the graphical interface for ADS and see their design produce concrete products. They will learn how to use microwave measurement equipment to assess the performance of these products. In general, they will be comfortable using the computer facilities and measurement equipment available in our laboratories. Much of the learning will be done through interaction with their colleagues in class and in the labs. The course should help to build a cooperative climate among graduate students and their research faculty mentors, further stimulating interest in research. This should lead to the development of lifelong friendships. Finally, we hope that many course projects will grow into theses and research publications.

Acknowledgement

This is to acknowledge our debt to Dr. Robert M. Nelson of the University of Wisconsin-Stout for his contributions to the development of the electromagnetics courses at NDSU during the period 1989 to 2008. He continues to be an inspiration in our work.

References

1. Plonsey, R. and Collin, R. E. (1961). *Principles and Applications of Electromagnetic Fields*. New York, NY: McGraw-Hill.

2. Collin, R. E. (2001). *Foundations for Microwave Engineering*. New York, NY: IEEE Press.

3. Pozar, D. M. (2005). *Microwave Engineering*. Hoboken, NJ: Wiley.

4. Balanis, C. A. (2012). *Advanced Engineering Electromagnetics*. Hoboken, NJ: Wiley.

5. Gupta, K. C., Garg, R., and Chadha, R. (1981). *Computer-Aided Design of Microwave Circuits*. Norwood, MA: Artech House.

6. Ishimaru, A. (1991). *Electromagnetic Wave Propagation, Radiation, and Scattering*. Englewood Cliffs, NJ: Prentice Hall.

7. Agilent Technologies (2009). Advanced Design System. www.agilent.com.

Biographical Information

DAVID A. ROGERS is a Professor of Electrical and Computer Engineering at North Dakota State University (NDSU). He earned the B.S.E.E. and Ph.D. (E.E.) degrees from the University of Washington, the M.S.E.E. from Illinois Institute of Technology, and the M. Div. (Ministry) degree from Trinity Evangelical Divinity School. He is a Life Member of the American Society for Engineering Education.

BENJAMIN D. BRAATEN is an Assistant Professor of Electrical and Computer Engineering at NDSU. He earned B.S. and M.S. degrees in Electrical Engineering and the Ph.D. degree in Electrical and Computer Engineering, all from NDSU. He conducted post-doctoral research at South Dakota School of Mines and Technology.