Int. J. Engng Ed. Vol. 11, Nos 4 and 5, pp. 314–321, 1995
Printed in Great Britain.

0949-149X/91 $3.00+0.00

Development of a Modern Undergraduate Microwave Laboratory

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An electromagnetics and microwave teaching laboratory that utilizes modern, computer-controlled equipment that is used in conjunction with undergraduate classes in these areas was developed at the University of Kansas. The primary objectives of this laboratory are: (i) to improve teaching of basic concepts of electromagnetics and microwaves; (ii) to develop a set of classroom demonstrations using the advanced graphics capability of modern computer-controlled instrumentation; and (iii) to give students hands-on experience with modern measurement instrumentation. This paper outlines the experiments and demonstrations used in two undergraduate courses: a required course in electromagnetics and an elective course in microwave engineering.

INTRODUCTION

IN RECENT years there has been a trend throughout the USA toward reducing (or, in some cases, eliminating) electromagnetics as required courses in undergraduate electrical engineering curricula [1, 2]. There are a number of reasons for this, not the least of which is the constant pressure to include a greater diversity of course material in a four-year curriculum. Another factor is undoubtedly the perception among many students (and even faculty) that electromagnetics is a 'solved' problem and is no longer relevant to the majority of electrical engineers in an age of integrated circuits and computers.

At the University of Kansas, we have resisted this trend and have kept electromagnetics as an important part of both our undergraduate and graduate curricula. Although we too have faced the same pressure to cover a greater range of material during the course of the four-year undergraduate curriculum, we feel that an understanding of electromagnetic theory is no less important now than it has ever been. While we agree that some applications traditionally covered in electromagnetic (EM) courses may be less relevant to the majority of electrical engineers, there are also new systems and applications that cannot be understood without electromagnetics. Included in these are microwave and millimeter wave systems, fiber optic systems and devices, and semiconductor devices (including light-emitting diodes and lasers). Also, the advent of high-speed digital circuits has brought along with it the problem of electromagnetic interference (EMI), which can only be addressed using electromagnetic concepts.

Of course, electromagnetics is still a difficult subject for most students. One reason is that it is one of the few courses that requires them to think about the spatial layout of a device or system. Hence, the mathematical description of these effects can often be tedious. On the other hand, many of these same effects are quite simple to observe in a laboratory setting. This allows students to see first hand the relevance of electromagnetics, rather than depending solely upon the professor's opinion or a textbook.

At the University of Kansas we developed a modern microwave laboratory for undergraduate education. The basic objectives of this lab are: (i) to improve teaching of basic concepts of electromagnetics and microwaves; (ii) to develop a set of classroom demonstrations using the advanced graphics capability of modern computer-controlled instrumentation; and (iii) to give students hands-on experience on the modern measurement instrumentation. This laboratory supports two undergraduate courses in the electromagnetics and microwave area. One of these is a five-credit-hour required senior-level course and the other is an elective in microwave engineering.

The laboratory exercises for the required undergraduate course are designed to reinforce lectures on the basic concepts of transmission lines and electromagnetic theory and to provide hands-on experience on modern microwave instrumentation. In addition to these laboratory exercises, each student is required to complete a design project, which includes the analysis, design, modeling and measurement of a passive microwave circuit.

The laboratory exercises for our elective course in microwave engineering have similar goals, but the material is tailored for a higher level. Here, students concentrate on the characterization of various active and passive microwave components. This laboratory also culminates in a design project that requires them to design, analyze, build and test a device that uses active components.

In this paper we provide a brief overview of these laboratories and how we have used modern instruments to teach basic theory of microwaves through laboratory exercises and classroom demonstrations.

ELECTROMAGNETICS COURSES AT THE UNIVERSITY OF KANSAS

The following is a listing of all the undergraduate courses at the University of Kansas that involve electromagnetics:

EECS 255	Vector Calculus (sophomore level)
EECS 320	Electromagnetics I (junior level)
EECS 420	Electromagnetics II (junior level)
EECS 623	Microwave Engineering (senior/first-year graduate level)
EECS 628	Fiber Optic Communication Systems (senior/first-year graduate level)
EECS 622	Microwave Communication Systems (senior/first-year graduate level)

All undergraduate EECS students are required to take the two-semester sequence EECS 320 and 420. The first course is usually taken in the first semester of the junior year and covers the foundations of electromagnetic theory using the classical approach. The topics included in this 3 hr course fall within the areas of electrostatics, magnetostatics and Maxwell's equations for time-varying fields. Much of the course involves the development of the basic equations that describe electromagnetic effects, but we also emphasize the physical nature of these effects. By the end of this course, the students are well grounded in the nature of electromagnetic fields, Maxwell's equations and circuit applications such as inductance, capacitance and resistance.

The second required course, EECS 420, is a 5 hr class, consisting of 3 hr of lecture and 2 hr of laboratory. The topics covered in this course include transmission lines, planewaves, waveguides and radiation effects. Through these topics, the major applications of electromagnetic waves in high-frequency electrical systems are covered. An important sub-topic addressed throughout the course is the relationship between electromagnetic and circuit theories, and how circuit theory can be augmented through the use of equivalent circuits.

After taking the required courses in electromagnetics, students are then able to take a variety of courses that cover more advanced subjects in electromagnetics or that use electromagnetic concepts to describe various types of systems (such as fiber optics and microwaves).

LABORATORY FOR THE REQUIRED COURSE (EECS 420)

We developed the laboratory portion of the required course (EECS 420) to acquaint students with the physical nature of electromagnetic fields and devices. They perform ten experiments and complete a final project.

1. Introduction to the operating principles of a vector network analyzer.
2. Characterization of lumped elements. The students measure the impedance of low-frequency resistors and capacitors mounted on microstrip lines to see the effects of lead inductance and then derive simple equivalent circuit models based on their measurements. They compare these results with measurements of microwave chip resistors and capacitors.
3. Measurement of the characteristic impedance and propagation constant of a simulated transmission line.
4. Measurement of the loss and phase velocity of a variety of standard cables.
5. Measurement of the voltage standing wave ratio (VSWR) and impedance using a slotted line.
6. Measurements using a time-domain reflectometer. Students configure the network analyzer to function as a time-domain device and perform measurements to characterize various types of discontinuities on transmission lines.
7. Application of stub tuners (single and double) for impedance matching.
8. Measurement of cut-off frequency and group delay of a waveguide.
9. Measurements to study the relationship between the phase and group velocities in a waveguide.
10. Measurement of the antenna pattern and gain of a horn antenna.

In addition to these laboratory exercises, we developed some classroom demonstrations for use in the lecture portion of the class. These are listed below:

1. Lumped element characteristics at high frequencies. Figure 1 shows typical circuits and set-up for this demonstration.
2. Impedance matching using double-stub tuners.
3. How to use quarter-wave transformers to accomplish impedance matching.
4. The use of transmission lines sections to realize lumped inductances and capacitances at high frequencies.

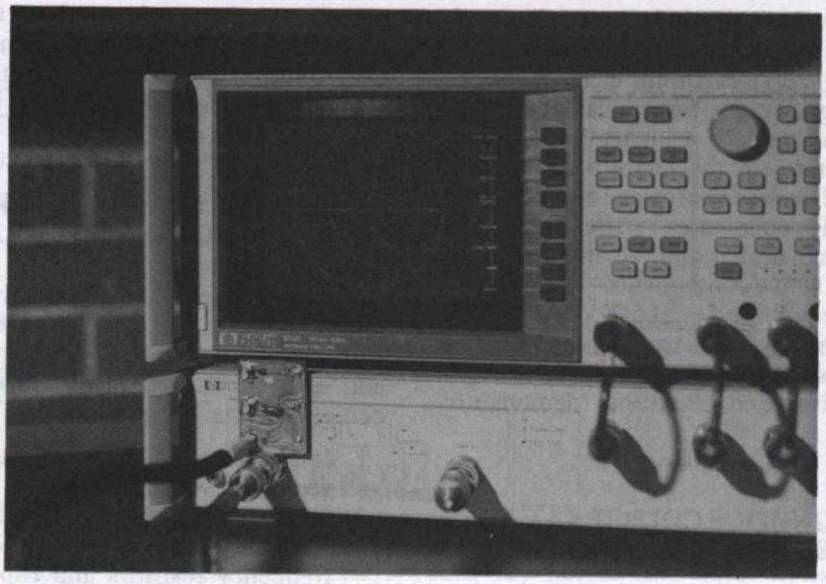

Fig. 1. Printed circuit board with lumped elements and set-up for demonstrating the frequency response characteristics of lumped elements at high frequencies.

Figure 2 shows the typical in-class set-up for performing these demonstrations. Here, a video camera is placed in front of the network analyzer screen, allowing the students to view the experiment on a large-screen television. Each demonstration is presented in a sequence of simple steps. For instance, in example 3, the Smith chart display of the reflection coefficient resulting from a 100 ohm load at the end of a 50 ohm transmission line is shown on the network analyzer. Next, a quarter-wave transformer is inserted in front of the load, and the students are able to see the operating point move to the center of the Smith chart, indicating a good match. Then, the network analyzer is operated in the frequency sweep mode, demonstrating how the match degrades over a finite bandwidth.

The approach we adopted throughout these experiments was to have students use modern microwave instruments (such as vector network analyzers), but we constructed the experiments in such a way that the basic nature of the measurements are not masked by the automated nature of the equipment. For instance, in experiment 3 the students perform measurements on a lumped load, artificial transmission line, just like the transmission line equivalent circuits used in transmission line analysis. Here, we developed the artificial transmission line by cascading 15 T sections made of lumped inductors and capacitors, as shown in Fig. 3. Although the most obvious way to analyze the performance of this line would be to measure the two-port S-parameters of the line, we chose to have the students do it the 'old-fashioned way', by measuring the impedance looking into the line when it is terminated in open and short circuits, respectively. Using these measured values at a number of frequencies, the characteristic impedance and propagation constant of the line are determined using the standard equations:

Fig. 2. Set-up for in-class demonstrations.

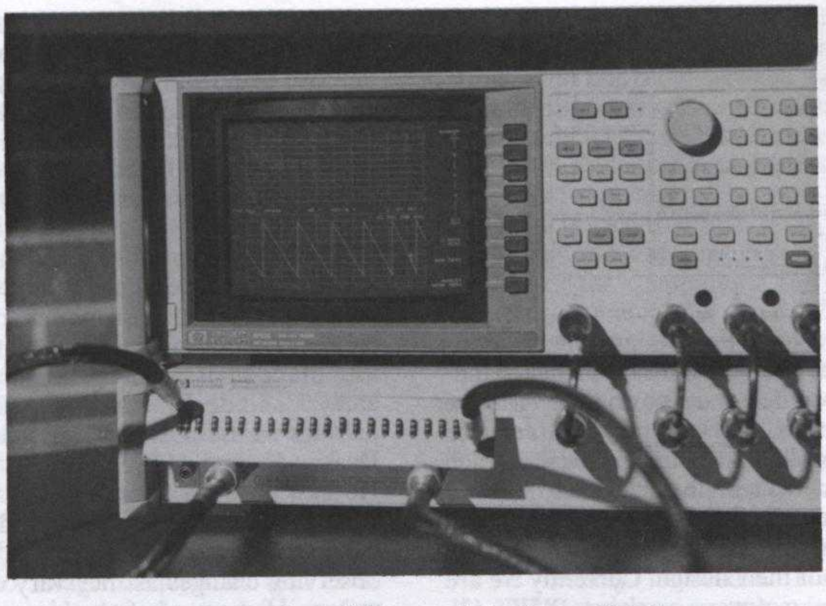

Fig. 3. Set-up for artificial transmission line experiment.

$$Z_o = \sqrt{Z_{ino}\,Z_{ins}} \qquad (1)$$

$$\gamma = \frac{1}{s}\tanh^{-1}\left(\sqrt{\frac{Z_{ins}}{Z_{ino}}}\right) \qquad (2)$$

where

Z_o = characteristic impedance
Z_{ino} = input impedance with output open-circuited
Z_{ins} = input impedance with output short-circuited
γ = propagation constant
s = line length

Another example is the measurement of standing wave ratio and impedance using a slotted line in experiment 5. Figure 4 shows the block diagram of the experiment. In this experiment, we generate the modulated signals needed for the slotted lines and power meters using the CW outputs of the network analyzers and pulse modulators that were designed by students in the microwave engineering course. These students used a prepackaged single-pole single-throw (SPST) microwave integrated circuit switch to provide the 1 kHz modulation necessary for the VSWR meter. The students designed the microstrip board to mount the switch, a digital board to drive the switch, and packaged the boards and power supply into a simple, self-contained unit. By using the network analyzers in conjunction with these in-house-built pulse modulators, we were able to eliminate the need to buy the expensive microwave signal generators needed for this experiment. Using the slotted lines, the students measure the impedance of an unknown load. They are then asked to compare these results with those measured directly with the network analyzer and explain any discrepancies. The experiment provides students an opportunity to compare the values obtained using different experimental approaches.

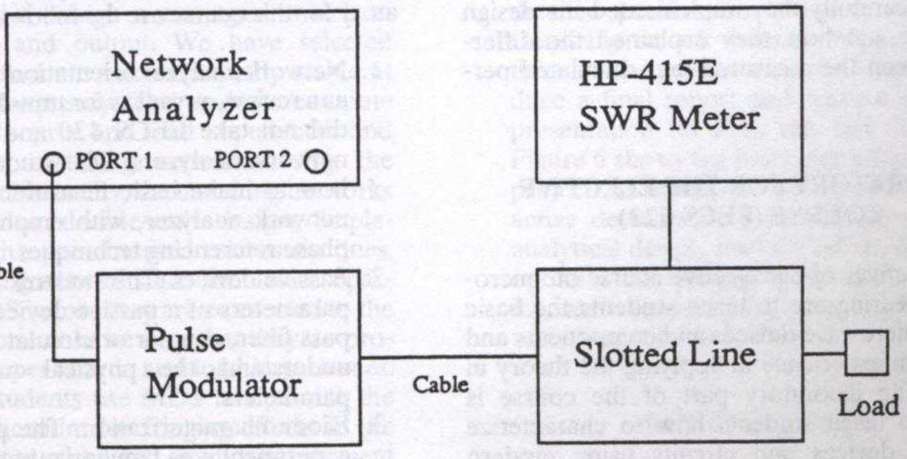

Fig. 4. Block diagram of the experimental set-up for measuring standing wave ratio and load impedance using the network analyzer as a source.

The last project of the semester in the 420 laboratory is a design project where the students are required to design, analyze, build and test a working microstrip device. Typically, the students work in groups of two or three and start by selecting their device from a list, which usually includes:

Low-pass or band-pass filters
Hybrid couplers
Directional couplers
Power dividers

Each project has a set of design specifications that are to be met, such as center frequency, bandwidth, coupling coefficient or return loss. They are then expected to go to the library and refer to microwave textbooks and learn the basic design procedures associated with their device.

Once they have completed a paper design, each group uses a microwave CAD program to analyze the performance of their design. Currently we are using a PC-based software package PUFF [3]. PUFF runs on standard PCs, is easy to use, and is capable of modeling the simple structures designed by the students. If the students find that their design does not conform to the specifications, they can use PUFF to refine their design quickly. Once they have a final design, each group builds their circuits out of standard printed circuit boards, using simple etching techniques. They then measure the performance of their circuit using the network analyzers.

During the last week of class, each group is expected to write a report on all aspects of their design, analysis, fabrication and testing. They also give a 15 min presentation on their project. Our experience has been that these presentations are one of the high points of the semester, both for the students and the faculty. It is here that the students gain a glimpse of the 'real world' of high-frequency design by seeing the problems encountered by each group and how they addressed them. When grading these reports we make allowances for the fact that the designs are, in most cases, far above the instructional level of the class itself. As a result, we look most closely at how well the outside literature was used, how carefully they implemented the design procedures, and how they explained the differences between the measured and calculated performance.

LABORATORY FOR THE ELECTIVE COURSE (EECS 623)

The objectives of our elective course on microwave engineering are to teach students the basic theory of microwave devices and components and to give them experience in applying the theory in practice. The laboratory part of the course is designed to teach students how to characterize microwave devices and circuits using modern microwave instrumentation. The equipment used in this laboratory consists of four vector network analyzers, two spectrum analyzers, a noise figure meter, three power meters and a frequency counter. Two of the four network analyzers operate over the frequency range from 300 kHz to 3 GHz, one operates from 300 kHz to 6 GHz, and the other operates from 100 MHz to 40 GHz. Both spectrum analyzers operate over the frequency range from 9 kHz to 22 GHz.

We designed the laboratory part of this course to reinforce theory learned in the classroom, provide hands-on experience on modern microwave instrumentation, and to give students experience in the use of computer-aided design (CAD) tools to analyze and design microwave circuits. The CAD package we utilize is Hewlett Packard's Microwave Design System (MDS), which was donated by Hewlett Packard for use in this course. The students gain an intuitive understanding of microwave circuits by modeling them on MDS and then observing changes as they vary component parameters. However, before they can use the CAD, they are first required to find approximate solutions to the problems analytically before they are allowed to use MDS. In this way, we try to remind them that CAD is just one of their tools, and cannot be used to replace thinking.

We assign several homework problems that use MDS, which are usually modified versions of problems from the class textbook. The first problem involves plotting the S-parameters (scattering parameters) of open- and short-circuited quarter-wave microstrip stubs and determining how the characteristic impedance of the stub affects its quality factor (Q). Later problems involve designing multisection quarter-wave transformers, impedance matching networks and coupled-line filters using the built-in optimization capabilities of MDS. Again, the students are required to complete an approximate analytical design before they are allowed to use the CAD package. We have found that it is better to start the CAD problems early in the semester so the students are familiar with MDS before they encounter the more difficult problems toward the end of the semester in the laboratory.

The experiments students perform in the laboratory for this course are the following:

1. Network analyzer orientation. This lab is used as a review, as well as for transfer students who did not take EECS 420 and have not used network analyzers. The students are taught how to make basic measurements using the network analyzer, with emphasis on proper phase referencing techniques.
2. Passive devices. The students measure the S-parameters of a passive device such as band-pass filter, coupler or circulator to help them understand the physical meaning of S-parameters.
3. Diode characterization. The purpose of this experiment is to familiarize students with how to DC bias microwave devices, design DC blocks and measure the S-parameters of a PIN

diode as a function of applied bias. Students input the measured data into MDS, design a simple microwave switch and plot the results.

4. Dielectric resonator. This lab explains to students how to characterize a microwave resonator by measuring the Q of a dielectric resonator. The students determine the loaded Q and coupling between the resonator and a microstrip line. They compare these Q measurements with those of simple microstrip resonators.
5. Spectrum analyzer. This lab teaches the basic operation of the spectrum analyzer and familiarizes the students with the spectra of amplitude- and frequency-modulated signals.
6. Mixer characterization. As an introduction to mixers, the students determine mixer conversion loss as a function of local oscillator drive level using the spectrum analyzer. They are introduced to image frequencies and then measure the third-order intermodulation distortion products of the mixer.
7. Transistor small signal characterization. Locally prepared test fixtures are used to introduce the students to error-correction techniques. After designing a resistive bias network for a bipolar transistor, the students use the test fixture to measure the transistor S-parameters over the operating frequency range of the network analyzer. The theory of error correction of S-parameter measurements is presented to the students as part of this lab. Students are taught how to use the built-in error-correction capability of the network analyzer to accurately determine S-parameters of the device under test.
8. Transistor amplifier design. The students use the measured S-parameter data from the previous experiment in a CAD program to analyze and design an amplifier to operate at 2 GHz. The students add models of their bias circuitry (usually quarter-wavelength stubs) to the measured S-parameters and use MDS to compute new S-parameters that include the bias stubs. They assume that the transistor is unilateral and design a conjugate match at both input and output. We have selected transistors that are unconditionally stable at the center frequency. The students compute the desired source and load impedances and then design matching networks using the Smith chart. Normally, the matching networks are single- or double-stub designs implemented with open-circuited microstrip lines. The matching networks are simulated separately in MDS before they are connected to the rest of the circuit to be sure that they do provide the proper source and load impedances. Then the students use MDS to optimize the circuits to account for fringing effects in the open-circuited stubs and small measurement errors in the Smith chart designs. If the results of the optimization are substantially different from the original design, the students are required to find the reason before they are allowed to proceed. At this point the matching networks are added to the transistor circuit, and the entire circuit is simulated to ensure that it works properly and the circuit is stable at all frequencies. The auto-layout feature of MDS is used to print a mask of the microstrip circuit on a laser printer so it can be fabricated.
9. Transistor amplifier measurement. The transistor amplifier is etched onto a printed circuit board and assembled.The circuit boards for the amplifier and other construction projects are created by copying the layout onto a transparent film and then transferring the image to the board using an iron [4]. The boards are then etched in ferric chloride. We have found that with patience and practice, line widths and gaps as narrow as 10 mm can be reliably fabricated. The students then solder their components onto the boards and measure the amplifier gain, input and output VSWR, and 1 dB gain compression point with the network analyzer. Figure 5 shows the experimental set-up and amplifier fabricated by the students. Finally students compare experimental results with those predicted by CAD. Generally we found that experimental results compare favorably with those predicted by MDS.
10. Noise figure. The students measure the noise figure of their completed amplifier using a Hewlett Packard noise figure meter. They then measure various combinations of amplifiers and attenuators in cascade to see the effects of gain and loss on the noise figure of cascaded systems.
11. Final project. The lab also includes a final project. The scope of the project is similar to that for the required course. However, students enrolled in the elective course are assigned a project to design the microwave components of an amplifier, a switch or a mixer. We assign this project to the students during the middle of the semester, and provide them with detailed specifications and goals of the project. Generally we ask them to work in groups of three on the project and require them to produce a final report and make a 15–20 min presentation on it to the rest of the class. Figure 6 shows the basic elements of a typical project. It involves characterization of an active device such as a transistor or diode, analytical design, use of CAD to analyze and optimize the design, layout, fabrication, testing, and comparison of experimental results with theoretical predictions.

CONCLUSIONS

We have developed a set of experiments for two courses involving electromagnetics and electro-

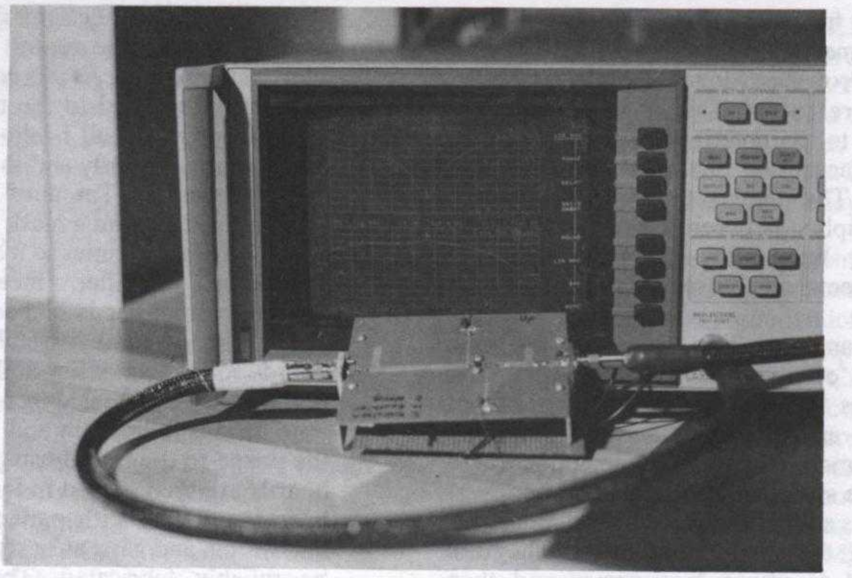

Fig. 5. Amplifier fabricated by students and experimental set-up for characterizing its response.

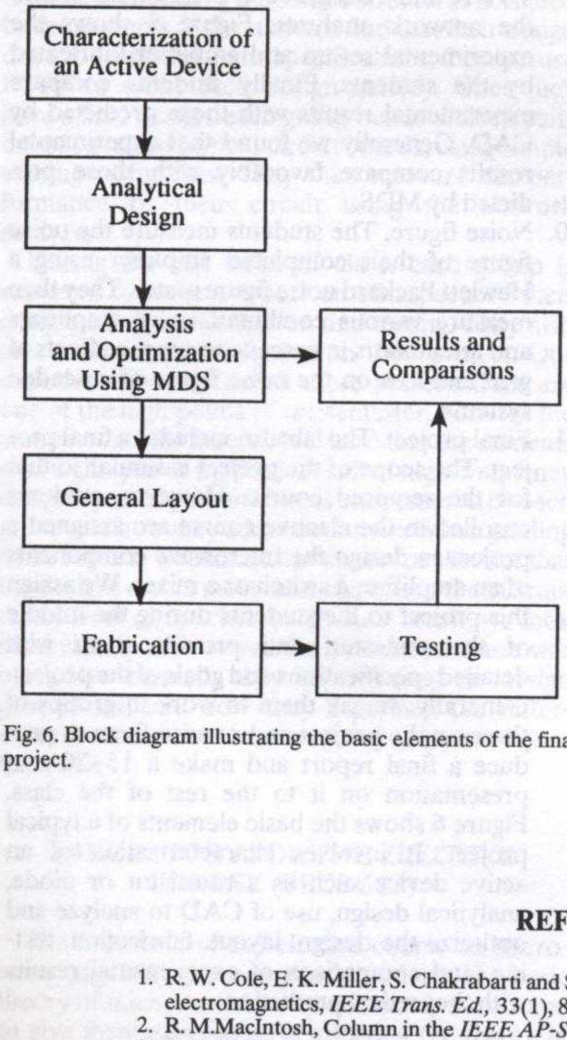

Fig. 6. Block diagram illustrating the basic elements of the final project.

magnetics applications that teach the basic principles of high-frequency engineering. Although these laboratories allow students to use modern, computer-controlled instruments, we have designed these experiments in such a way that they make measurements 'the old-fashioned way' whenever possible.

Based on student feedback and course grades, we feel that these laboratories have been successful in enhancing the learning process and show how electromagnetics is applied in engineering practice.

Acknowledgements—We would like to thank Duane E. and Marlene Dunwoodie for giving stock valued at $500,445 to the University of Kansas Endowment Association, which endowed the Dunwoodie Laboratory Equipment Fund in support of undergraduate and graduate microwave laboratories. We also want to thank Hewlett Packard, Inc. for donating an HP 8753C network analyzer, a power meter and 16 copies of the MDS software package. Tektronix, Inc. donated a spectrum analyzer. Allied Signal Foundation provided funds ($50,000) partially to underwrite the cost of purchasing the Wiltron network analyzer. The National Science Foundation provided the initial funding for the project through their Instrumentation and Laboratory Improvement Program with grant no. EID-895 1237. This grant provided further impetus for obtaining industrial support for this laboratory. Finally, we want to thank Tim Healy and his colleagues at Santa Clara University for sharing their experiences in developing a microwave and communications laboratory [5].

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