

ONGOING DEVELOPMENT OF A MODERN RADIO-FREQUENCY (RF) AND MICROWAVE ENGINEERING LABORATORY

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INTRODUCTION AND HISTORY

At North Dakota State University the RF and Applied Electromagnetics Laboratory has been significantly upgraded in order to give undergraduate and graduate students the opportunity to work with new and up-to-date professional measurement equipment and software. Begun almost a half century ago, the laboratory capabilities and student experiments were originally based on measurement equipment in the VHF, UHF, and X-bands. In the early years core experiments were based on use of the slotted line and General Radio equipment at the lower frequencies and the slotted waveguide and Hewlett Packard equipment in the X-band. In time, computer analysis and design of microwave devices was added.

STUDENT EXPERIMENTS IN THE EARLY YEARS

The applied electromagnetics laboratory of the 1970's included labs such as the following: (1) measurement of transmission-line characteristics, (2) microwave power measurements, (3) modeling capacitor fields with teledeltos (conductive) paper, and (4) impedance matching using transmission line stubs. The transmission line experiments had as objectives the measurement of line attenuation, characteristic impedance, and reflection coefficient for practical transmission lines. The creation of distortionless lines with the use of periodic loading coils could also be studied. Teledeltos paper is a two-dimensional paper with an approximately uniform resistance per square. A conductor is established by painting appropriate regions with conductive paint. Then a voltmeter is used to establish the surfaces of equipotential. The method of curvilinear squares (Hayt & Buck, 2006) could then be used to calculate the capacitance. Similar experiments were done at some universities using water in a tray as a replacement for the teledeltos paper and aluminum forms as models of the conductors. Related class demonstrations were performed using rubber-sheet models and fluid maps of potential fields (Rogers, 1954). In the fourth experiment, single- and double-stub tuners were used to match a generator to an unknown impedance. Using the slotted-line, this facilitated the visualization of standing waves along a transmission line, the measurement of the source frequency, and the measurement of the complex value of the load impedance as a function of frequency (Hayt & Buck, 2006). This latter measurement is very accurate, but can be tedious.

METALLIC WAVEGUIDE EXPERIMENTS

The experiments mentioned so far would be relevant today if the curriculum and its objectives permitted. By the 1980's and beyond, engineering students needed to be prepared for their professional lives by going beyond experimental studies that dealt only with improving student understanding of the basic engineering science. At some universities basic electromagnetics experiments were introduced in prerequisite physics courses, and such experiments still exist today. To meet the demands of the engineering profession, the laboratory in engineering electromagnetics added basic transmission line experiments in the UHF and microwave frequency ranges (Laverghetta, 1981). Another approach was to add a cluster of metallic waveguide experiments in the X-band. These experiments included the use of slotted lines or slotted waveguides for standing-wave characterization or measurement of complex impedance values in these bands. Students would also experience direct frequency measurement, dielectric-filled waveguides, isolators, attenuation and power measurements, waveguide bends and "tees", directional couplers, and other waveguide hardware. The key manufacturers of the day were General Radio and Hewlett Packard.

THE FREIRE-DINIZ MODEL OF THE APPLIED ELECTROMAGNETICS LABORATORY.

Almost 40 years ago, Frieire and Diniz (1973) published a textbook in Portuguese that was very significant for its intended audience (engineering students in Brazil) and for its time. The last chapter of the book dealt with suggested experiments for the electromagnetics course that could be found in American or European universities. The authors skillfully used their knowledge of electromagnetic theory to construct a set of experiments that required only a modest investment in laboratory equipment. This led to the following experiments:

1. Measurement of transmission line parameters
2. Use of the slotted transmission line to measure impedances
3. Impedance matching techniques
4. Study of the cutoff frequency of rectangular waveguides
5. Waveguide measurements using a slotted waveguide
6. Waveguides filled with dielectric material
7. Antenna pattern of the half-wave dipole.

Even today these experiments have continued usefulness. However, the pressures on the curriculum and the need to keep pace with current professional practice make it difficult to implement more than a few of the above experiments in a contemporary course. As attractive as it is, even the slotted transmission line or the slotted waveguide must be left for, perhaps, a classroom demonstration. Furthermore, the student will have to be content with a theoretical understanding of transmission line parameters. Antenna patterns remain of vital interest, so hopefully room for such a study will be made in the laboratory curriculum.

POZAR'S LABORATORY AS A MODEL

David Pozar's laboratory at the University of Massachusetts Amherst is a model microwave engineering laboratory. It combines significant theoretical and practical elements to improve student understanding as well as important experiences in professional development for students. Pozar and Knapp (2004) present the following set of experiments in an on-line manual:

1. The slotted line (*waveguide hardware, measurement of SWR, guide wavelength, impedance*)
2. The vector network analyzer (*one- and two-port network analysis, frequency response*)
3. Active devices (*the spectrum analyzer, power meter, mixers*)
4. Impedance matching and tuning (*stub tuner, quarter-wavelength transformer, network analyzer*)
5. Cavity resonators (*resonant frequency, bandwidth, frequency counter*)
6. Directional couplers (*insertion loss, coupling, directivity*).

This laboratory is usually associated with a second course for which the traditional undergraduate electromagnetics course is a prerequisite. However, some interesting features are present. In Pozar's first experiment, SWR and guide wavelength are considered in a waveguide context. This could also be done using traditional transmission lines and microstrip lines (Giarola & Rogers, 1978). Three experiments involve student use of network analyzers and the spectrum analyzer. Two experiments deal with impedance matching and insertion loss. These concepts and instruments should be included at least in introductory form in the first electromagnetics course.

BUDGET-PRICED INSTRUMENTS

The RF and microwave lab requires very expensive equipment and software. In situations where there are significant budgetary constraints, our students can benefit from new budget-priced RF and microwave measurement equipment and from instrumentation developed as part of senior projects. Related to this also are student-developed RF and microwave software packages for analysis and design (Fernandes, Giarola, & Rogers, 1983; Nelson & Islam, 2006; Bais & Rogers, 2008).

One example of a budget-priced instrument is the MJF Enterprises antenna analyzer (Hallas, 2005). This is not a precision instrument. However, it is priced under \$500 and easily demonstrates for the student the frequency dependent character of transmission-line circuits and basic circuit components. It gives reasonable estimates of voltage standing-wave ratio.

A PC-based RF spectrum analyzer (Tracy, 2005) and a PC-based RF network analyzer (Tracy, 2006) are also available. They are low-cost instruments (under about \$1,000). Their frequency ranges are limited (under 100 MHz and 260 MHz, respectively), but their accuracy is reasonable. Where only limited financial resources are available, instruments such as these could be the basis for a useful engineering lab experience.

CAD IN THE MICROWAVE ENGINEERING LABORATORY

In the 1970's and 1980's it was common in the microwave laboratory to introduce computer-aided design (CAD) and analysis, often using locally produced software such as PACMO (Fernandes, Giarola, & Rogers, 1983). These and similar packages could be used today, but they have often been replaced by student or trial versions of commercial software. Another package that was used at the time was MECAP, developed at the University of Maine Orono under the leadership of Dr. John C. Field (Field & Herrick, 1974). This package allowed the modeling of a wide range of transmission-line and microwave devices. A slightly more versatile package was MCAP (Gupta, Garg, & Chadha, 1981). The computer language used in PACMO, MECAP, and MCAP was FORTRAN. These were primarily analysis packages. MECAP could be driven by an optimization program that gave it a design capability. More recently, Nelson and Islam (2006) introduced MES, a Web-based package consisting of tools for analog filter design, impedance matching, and microwave network analysis. A related MATLAB-based package, CAMDS, incorporates microstrip design and analysis, waveguide analysis, impedance matching, microwave filter design, and microwave network analysis (Bais & Rogers, 2008).

In the modern lab the packages mentioned above are useful in providing an analytical solution for comparison with data taken in the lab and offer the user full access to the computer code. However, a commercial package like Agilent's Advanced Design System (ADS) is extremely useful especially since it offers the student design tools that weren't even dreamed of a few decades ago (Agilent Technologies, 2009).

A MODERN MICROWAVE LABORATORY

Recently the NDSU ECE Department made a commitment to significantly upgrade its RF and Applied Electromagnetics Laboratory. Today it consists of several design and measurement stations, each equipped with a computer and appropriate software. Four specialized stations provide the capability for making RF and microwave measurements of the following types: scattering parameters, time-domain reflectometry, spectral analysis, component characterization in the frequency domain, and electromagnetic interference. Currently, experiments dealing with some of these topics are integrated into the course in applied electromagnetics that is required for all undergraduate majors in Electrical Engineering or Computer Engineering. The lab is also used in the graduate courses in microwave engineering where, for example, students apply microstrip design concepts to practical devices using ADS software. Interest in the lab is further enhanced by use of the facility by senior design students. The RF and Applied Electromagnetics Laboratory is stimulating interest in a subject that is often challenging to students.

AN OUTLINE OF FOUR CURRENT MAJOR EXPERIMENTS

For the introductory undergraduate applied electromagnetics course, four major experiments are currently used at NDSU. A brief description of each is presented below, along with comments on the relationships that exist to the early experiments described above.

The **first experiment** (Fig. 1) is a coupled transmission lines or cross-talk experiment. This is an experiment that breaks away significantly from the experiments that were done earlier in the lab.

The content reflects interests in the department in signal transmission and electromagnetic compatibility. This experiment also reflects the general philosophy in use in the lab: the experiments are extensions of the course. The principal focus is not only to reinforce and explain theoretical concepts, but also to extend student learning beyond the lecture hall. Several types of coupled lines are studied: coupled open-wire lines, twisted pair, and coaxial lines, along with various types of grounding. The student experiences firsthand the transmission of signals through space and the potential problems this creates.

In a **second experiment** (Fig. 2) a study of discrete components is made. An impedance analyzer (Agilent 4395A) is employed to measure the impedance over a wide frequency range for several types of resistors, inductors, and capacitors. The student sees that one component can look like the other at different frequencies. This lab is also a departure from the experiments in use in the initial decades of the lab. On the surface it would seem that the measurements made would reinforce the theoretical studies done in the lecture hall of resistance, conductance, inductance, and capacitance. However, the student quickly learns that the mathematical models experienced in the textbook have severe limitations.

The **third experiment** (Fig. 3) employs a high-quality modern microwave network analyzer (Agilent E5071C) to study impedance matching using a double-stub tuner. This lab is closely linked to the experiments done by students in the lab three decades ago. The design and measurement goals are the same, but the instrumentation is radically different. The modern network analyzer produces very speedy results when compared to the earlier slotted-line approach. However, the student misses directly experiencing the standing wave on the slotted line. The students also use the network analyzer to measure the scattering parameters of microstrip devices (Giarola & Rogers, 1978). They thus experience a technology that has, for the most part, replaced the older metallic waveguide technology of the past.

Finally, in the **fourth experiment** (Fig. 4) a commercial spectrum analyzer (Agilent E4402B) is used along with wide bandwidth active antennas to explore the frequency spectrum experienced in the laboratory location. The students measure the radio frequency of several local broadcast stations. The analyzer also allows listening to individual stations after they are located in the ambient spectrum. This experiment introduces the students to antennas (Freire & Diniz, 1973) and to the spectrum analyzer (Pojar & Knapp, 2004). However, the primary objective is to help the students see the connection of the course material to the real world in which they live and work.



Fig. 1. First experiment station.



Fig. 2. Second experiment station.



Fig. 3. Third experiment station.



Fig. 4. Fourth experiment station.

Two other stations were also added at the back of the lab (Fig. 5). These stations are multi-functional areas. The equipment at these stations can be used for circuit board manufacturing, experiments and simulations. At this point these stations have been very helpful for groups of undergraduate students in Electrical and Computer Engineering who are completing required senior design projects (i.e., capstone projects). This space has also been used for graduate and undergraduate research in applied electromagnetics. In particular, software programs on the computers have been used to simulate the radiation from printed antennas, and the test equipment at these stations has been used to develop and test various flexible sensor networks being applied to phased-array antennas.

Fig. 5 also shows a very useful table located in the center of the south end of the lab. This table has been used for meetings between advisors and undergraduate and graduate students. This area has provided a nice forum for sharing ideas about projects openly and conveniently.



Fig. 5. Multi-functional stations.

CONCLUSION

The experience students have today in the RF and applied electromagnetics laboratory is the result of decades of development by many educators and researchers. The goal has always been to enhance student learning and to adequately prepare future engineers. The challenge has been and still is to choose those laboratory experiments that will be most helpful in the long-term. Some personal experience with electromagnetic waves and quality professional measurement equipment is a step in the right direction for today's students. This combined with the creativity and energy of students and instructors alike should produce the desired results.

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BIOGRAPHICAL INFORMATION

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