Hands-on Electromagnetics:
Microstrip Circuit and Antenna Design Laboratories at USU

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Abstract

New laboratories for microstrip circuit and antenna design have recently been developed at Utah State University. These laboratories are used to provide hands-on design, fabrication, and testing experience in two senior/graduate level design courses -- ECE 6130 Microwave Engineering and ECE 6170 Antenna Design. HP/EESOF Libra software and other available software is used heavily throughout these courses. New facilities for fabrication and testing have been developed, including a low-cost holder for connection of microstrip circuits to the network analyzer, use of an LPKF circuit-board mill to mill circuits, and simple methods to prototype designs using copper tape. Tutorials to quickly teach the students to use the HP/EESOF Libra software and HP measuring equipment are available on the web. The laboratory exercises, design of the low-cost holder, tutorials, and examples of completed student design projects are available on the web.

Introduction

Electromagnetics has often been taught as a mathematical science, where students may have little or no hands-on experience in most of their courses. With the availablity of lower-cost, more user-design software, fabrication facilities, microwave components and test equipment, this is changing. Excellent electromagnetics laboratory experiences are provided at many schools including University of Southern Florida [1], Brigham Young University [2], and University of Utah [3]. Laboratories like these that allow students to apply and test their knowledge greatly enhance the understanding of the principles taught in class. In addition, they teach things that instructors might consider obvious but students do not, such as how to connect a microstripline to a coaxial cable. Perhaps the greatest advantage, though, is the level of interest and excitement these labs generate among the students. Design competitions, research-based projects (some of which are potentially publishable), and real-world problems have a profound effect in energizing a class. This paper describes the first year in a five-year development phase of electromagnetics laboratories at Utah State University, including the development of facilities, software, tutorials, and lab experiments.

The Courses

Four electromagnetics semester courses are taught in the Department of Electrical and Computer Engineering at Utah State University using these facilities. These are:

ECE 3170	Introduction to Electromagnetics	60 students	Fall Semester
ECE 5130	Computational Electromagnetics	25 students	Spring Semester
ECE 6130	Microwave Engineering	25 students	Spring Semester
ECE 6170	Antenna Design	25 students	Fall Semester

In addition, several students have done or are doing senior projects, special topics courses (such as microwave amplifier design), or master's design projects using these facilities. The traditional graduate-level electromagnetics theory course is taught in the physics department so will not be using these facilities.

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Design Software

The use of HP/EESOF Series IV Microwave Design software is critical to the success of virtually all of the microwave design projects developed at Utah State University this year. This software is used to design passive microwave components such as filters and couplers, active devices such as amplifiers and oscillators, microwave circuits such as a distance measuring system and wireless local area network (WLAN). The Momentum package in the software is used to design microstrip antennas (patches of all shapes and sizes, microstrip, slot, or coaxial feed systems, arrays, even a patch with lossy material placed on top of it.). The Linecalc package is used to calculate the width and lengths of line for given frequency and electrical length. The software is used to replicate text examples (such as those given in Microwave Engineering, by David Pozar, and Antenna Engineering by C.Balanis), and to demonstrate the dependence on device performance with parameter alteration (using the "variable" feature). This same method is used to test the sensitivity of circuits to possible errors (such as milling error). This way the students know what part, if any, of their circuit is sensitive to error, and have an idea of what range of values to expect. Then when they measure their circuit, if it is outside of this range, they can check for other problems such as poor or broken connections or poor calibration. In addition, the HP/EESOF software is interfaced directly to the LPKF circuit board mill that is used to mill microstrip circuits. Part of the key to using this software in these courses (particularly the introduction to EM course) is to make it very quick to learn. This has been done with on-line tutorials, guiding the student through every key stroke. Four tutorials are presently on-line, and others will be on-line shortly. These tutorials are:

1. Single Stub Matching
2. Basic Patch Antenna with microstrip feed
3. Patch Antenna with coaxial feed, multilayers, and user-defined patch shape.
4. Using HP/EESOF to interface to the LPKF circuit board mill.

Other software has also been found to be very useful in these laboratories. In particular, the software TLINE by Jensen and Iskander is an excellent teaching tool for transmission line connections, Smith Chart analysis, and single and double stub matching networks. Particularly in the introduction to EM and the antenna design courses, students use it extensively.

XFDTD software was used for several projects in the antenna class, in-class demos in the introduction to EM course, and is presently being used for several senior design projects. It is sufficiently user-friendly that the students are able to use it for basic projects within an afternoon, with the help of another student familiar with the software who gives them a quick demo. This software will be used for projects in the computational EM course, and will probably be incorporated into homework projects in the introduction to EM course.

Fabrication Facilities

Microwave circuits have been fabricated three different ways at USU. These are acid etching, milling, and use of copper tape.

Acid etching has been done using both on-campus and off-campus facilities, but it requires the longest turn-around-time and the most equipment, and cannot be done by the students themselves, so is not presently our method of choice.

The most common method we use for prototyping is to convert HP/EESOF layout files to HPGL files that can be used directly by the LPKF circuit board mill. A tutorial is on-line for this process. The milling is overseen by an undergraduate lab assistant, but each student is able to take an active part in the process and to examine his circuit under a microscope to see the precision obtained. This method has been used with excellent success for both microwave circuits and antennas and is the most common method of fabrication we use. An exception is with very large or complicated circuits, such as a 3"x16" meander antenna designed last summer, because of the difficulty of keeping the circuit board material flat and stable throughout the whole milling process and problems with breaking milling bits if the panel was not completely flat. For this case, professional off-campus etching was used.

The third method of fabrication that proved to be especially effective in the antenna design course was the use of copper tape over fiberglass circuit board material. Fiberglass panels with no copper were initially used, and the backplane of copper was provided with stick-on copper panels available through the local craft store (used in stained-glass preparation). In future iterations, several different thicknesses of circuit-board material will be used, with copper already attached to one side. The microstrip antenna (patch, meander, loop, etc.) is cut out of the stick-on copper tape or sheets using scissors and simply taped to the fiberglass panel. SMA connectors were used for the driving point. Several types of SMA connectors are available. Connectors that have a small "tube" for a wire to be soldered into for the center conductor seemed to be the most durable for this method. Connectors that already have a center conductor gave more difficulty, with the center conductor commonly breaking off or breaking loose from the solder. To create shorting pins, holes were drilled through the board, and copper wire was soldered to top and bottom plates. No doubt the biggest advantage of the copper tape method of prototyping is that it is very quick and easy, so the students can try several design iterations in a few minutes. Another very interesting application of this method was in tuning of circuits. In the design of a single-stub matching network, for instance, the students could cut a small stub of copper tape, and place it copper-side down on their circuit. Then, using a pencil eraser, they could slide it along their circuit, observe the effect of the match, and choose and optimal point for matching. This method would not be optimal for long-term applications, as the copper begins to peel loose at the corners within a few days. For labs, this was actually an advantage. The fiberglass boards can be easily re-used.

Two different types of circuit board materials were used for all of these applications. The RT-Duroid products have proven to be the best for etching, as the copper was very tightly bonded to the substrate. They were difficult to use for our milling applications, however, as the mill would need to manually remove all of the unwanted material on the top of the circuit board, which used a lot of ($20 each) mill bits. The Gil Laminates eliminated this problem. The copper is well-attached to the substrate, but with some small effort can be peeled away by hand or with a craft knife. The LPKF circuit board mill would be used to mill the outline of the circuits, and students would peel away the exterior copper.

Testing Facilities

The testing facilities for microwave devices unfortunately require a substantial investment. The instruments most critical to our laboratories are:

1) Network Analyzer (HP 8510C or 8752)
2) 400 MHz - 3 GHz Microwave Source (HP ESG 3000A)
3) Spectrum Analyzer (HP 8593E)

A microwave holder was developed to hold microstrip circuit elements so that connectors did not need to be soldered to all circuits (the connectors are the most likely place for microstrip circuits to "fail", so eliminating this problem saves the students a great deal of difficulty). The design for this holder is available upon request. The holder has two aluminum blocks, each with two SMA connectors pre-soldered to a pair of parallel microstriplines. These lines can then be butted to the student's circuit and held in place with a clamp made of non-conductive nylon with copper "skis" to make electrical contact on the top of the microstriplines. These two aluminum blocks can be used independently or can be attached together, so that most configurations of circuits can be evaluated for S11, S22, S12, S21 parameters.

The network analyzer is calibrated for the microwave holder using the TRL calibration procedure. The "Thru", "Reflect" and "Line" are milled microstriplines. The "Reflect" is just an open-circuited 50-ohm microstripline, where the length of the line is not critical. The "Line" and " Thru" are also 50-ohm lines, and are 1/4 wavelength different in length. These calibration standards are obviously not going to be of the same precision that can be achieved in commercial applications, but they appear to be plenty sufficient for the circuit applications we have developed up to 3 GHz (the limit of the microwave source readily available to students in the lab.)

In the USU Microwave Laboratory, we do not have sufficient equipment to hold traditional laboratories with many students simultaneously making measurements. To overcome this limitation, labs are held sequentially, and students sign up for 1-2 hour blocks throughout the week. The lab TA is given a study desk in or near the lab, and helps the students get started on the lab and is available for questions but does not attend them for the full lab period. Consequently, the labs are written to be dominantly self-taught. Information on how to use the equipment is spelled out in minute detail (every key stroke) in tutorials or in the lab writeups themselves.

The Projects

Several microstripline projects have been developed in the electromagnetics courses. They are:

ECE 6130 — Microwave Engineering (all projects are software and hardware)
Course Final Project (using all subparts) : FSK WLAN
- Cable and connector test and measurement (loss, phase, dispersion)
- Microstrip design and test (straight, bent, coupled lines)
- Microstrip couplers (branchline, Wilkinson, etc.)
- Microstrip filters (coupled line, finger, etc.)
- Amplifier use and design
- VCO, oscillator use
- Mixer / Phase detector use

ECE 6170 — Antenna Design
Antenna radiation pattern measurement
Input impedance measurement
Dipole Array design (hardware and software)
Yagi, LPA array design (hardware and software)
Final projects: Microstrip antenna design
(Satellite Antenna, Implantable Antenna, Dipole Array
Yagi for HAM operation, Yagi and LPA for distance measuring
Moisture sensor)

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References

[1] University of Southern Florida http://www.eng.usf.edu/EE/people/dunleavy.html (see Teaching)

[2] Michael Jensen, Brigham Young University, Personal Communication

[3] Mark Baird, University of Utah, Personal Communication