A Review of Two Approaches to Teaching Applied Electromagnetics

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Introduction

Two different approaches to teaching the mandatory engineering electromagnetics course are reviewed. Using basic theories developed in the course, divergent applications were emphasized in different semesters of the course offering. The two separate applications covered were (a) radio frequency circuit design and (b) radar and antenna design. The general electromagnetic theory lectures were enhanced through laboratory experiences in the two different applications.

Experiments and design in the radio frequency applications made extensive use of vector network analysis. Microstrip lines were designed and analyzed for VSWR, transmission, reflection, and impedance matching. Agilent ADS software and Motorola impedance matching network were used in both applications to enhance and confirm designs.

Microwave Training Kit experiments gave a different, but equally useful, perspective on measurements of VSWR, microwave power, frequency, wavelength, load impedance, etc. Besides, familiarization with various microwave components was gained in this set of experiments.

An extension of antenna design theory beyond the confines of the course textbooks covered low frequency antenna design for submarine communications. Furthermore, antenna impedance matching to radio frequency circuitry demonstrated how electromagnetic theory can be coupled to a broad class of practical RF networks.

These approaches show how the same course material can be covered differently in terms of applications, thus enriching students' design capabilities in applied electromagnetics.

Course Structure and Execution

The Electrical Engineering Program at the University of San Diego, a primarily Liberal Arts University, is a 9-semester Undergraduate Program requiring 152 course units. Upon successful completion of broad-based course requirements, engineering graduates from the program receive dual BS/BA degrees.

The heavy graduation course requirements of the program place demands on efficient application of material in the engineering offerings. The required EE electromagnetics course is offered in the senior year of study and is structured with three hours of lecture and a three-hour laboratory each week. The primary prerequisite for the course is the second semester electronics circuit design course. The prerequisite course in itself has several prerequisites including upper-division mathematics courses, physics (electromagnetics), and a course in signal and systems analysis.

The very nature of electromagnetics requires development of strong theoretical foundations. For students, those foundations are oftentimes challenging and cannot be readily bridged to applications. By including a three-hour weekly laboratory to the course, important theoretical concepts can be applied to engineering implementations. Additionally, engineering design methodology for electromagnetics problems can be taught during the laboratory sessions. The lectures are then tailored to complement the laboratory exercises that can often include engineering design concepts.

The laboratory experience is enhanced through the use of design methods: analysis, simulation, fabrication, test, and iteration. In most instances, the iteration step is not possible due to time constraints. Therefore, data analysis is substituted for the iteration. The application of electromagnetic theory was applied to two classes of engineering problems in the laboratory portion of the course. In some semesters, the laboratory exercises resulted in radar- and antenna-based experiences, and in other semesters, RF circuit-based experiences. Laboratory and design exercises in both modes of electromagnetics laboratories are described in this paper.

Radio Frequency Circuit-Based Laboratory Experiences

Three different RF (Radio Frequency) Circuit-based laboratory exercises described here were written to be performed. Students designed various RF circuits and structures using software packages that included Agilent AppCAD, Agilent ADS, Motorola Microwave Impedance Matching Program (MIMP), and MathCAD. They then implemented and tested the RF circuits to confirm specified design goals.

The three exercises described here are:

1. Impedance Matching With A Double-Stub Tuner
2. High-Speed Digital Design Issues
3. Antenna Engineering Project

The first of the exercises builds on discussion in class and on previous laboratory experiences in

- Transmission lines
- Impedance of transmission lines
- Reflection and transmission coefficients

- Design with Smith Charts
- Single Stub-Tuner Laboratory Exercise
- Agilent ADS Program

A double-stub transmission line impedance matching network of Figure 1 is designed for given load components and the results simulated using the Agilent ADS simulation software package. Equivalent passive components are used in place of stubs and their results compared to the double stub tuner simulation results.

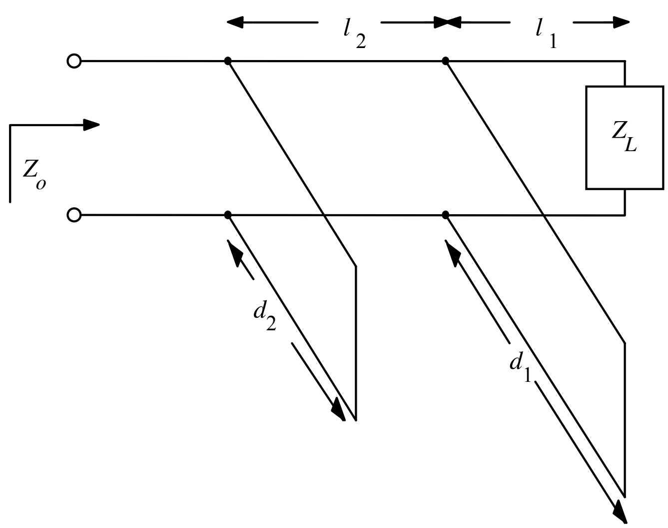

Figure 1. Double Stub Short Circuit Tuner

The design and laboratory goals were:

- Design a 50 Ω microstrip line double-stub transmission line impedance matching network to match a 50 Ω source and line to a load with a specified capacitive load impedance of resistance *R* in series with a capacitance *C*.
- Let the distance between the load to the stub closest to stub be $l_1 = 0.250\lambda$ and the short-circuit stub length closest to the load be $d_1 = 0.204\lambda$. The relative permittivity of the G-10 printed circuit board is $\varepsilon_r = 4.5$. Metal thickness of 1.37 mils (0.00137 inches) is typical for 1 oz. copper plating.
- Use a Smith chart to design the matching network at 965 MHz
- Verify the matching network (at 965 MHz) using the Agilent ADS software package. How reasonable will the match be at 500 MHz?
- Using Agilent ADS, plot S_{11} in both rectangular and Smith Chart formats, as well as the SWR.
- Re-design the matching network by replacing the stubs with lumped parameter passive components (inductors or capacitors) [1].
- Measure the Impedance Matched Network: Verify the re-designed matching network (at 965 MHz) using the Agilent ADS software package. How reasonable

will the match be at 500 MHz? Plot S_{11} in both rectangular and Smith Chart formats, as well as the SWR.

One particular aspect was emphasized in all laboratory exercises, mandating that all designs are frequency dependent. For example, the purpose of the double-stub tuner redesign of stub replacement with lumped parameter passive components (inductors or capacitors) was twofold:

1. Demonstrate that the Smith Chart can be used for lumped parameter design
2. Demonstrate that the stub lengths and lumped parameter values are dependent on operational frequency and material properties

The second exercise required students to design and investigate transmission lines for high-speed, short rise-time digital transmission that is important for high-speed digital design. In particular, the skill set required for the design of high-speed printed circuit boards (PCB) has migrated from simple tape layout to serious consideration of transmission line effects.

The design and laboratory goals for the high speed digital design experience were:

- Design a Split Terminated Trace: Using a driver and a receiver (using 74HC00 gates), design a split termination for a transmission line with Z_0 = 50 Ω using a G-10 single-sided metal clad board. Construct the following configurations shown in Figure 2 [2] and observe the rise times and ringing. Let the length of the transmission line run the length of the metal clad board.

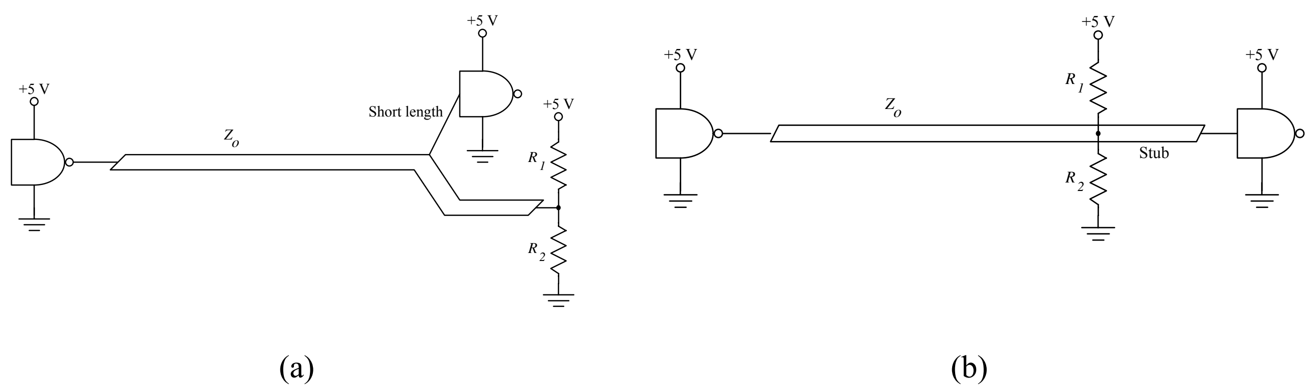

Figure 2. (a) The Right Way to Daisy-Chain and (b) The Wrong Way to Daisy-Chain

- Crosstalk Experiment: Using a 74HC00 driver, investigate crosstalk due to mutual coupling for transmission lines with Z_0 = 50 Ω using a G-10 single-sided metal clad board. Construct on the following configuration shown in Figure 3 and observe the crosstalk on trace ***CD***. Quantify Crosstalk and the *K* value.

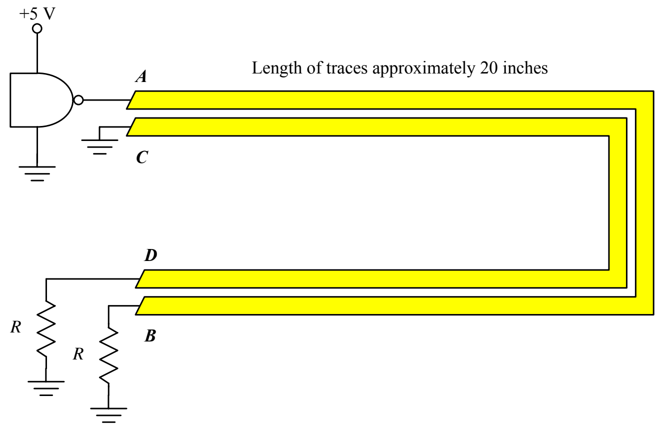

Figure 3. Mutual Inductance Experiment

The third example exercise requires students to design and develop antennas and associated driving transformers. Student groups of no more than two students per a group analyze, design, and test the following at the 2-meter amateur radio band as specified by the U.S. FCC:

- Half-Wave Dipole Antenna
- Helical Antenna
- Two-Element Quarter-Wave End-Fire Array
- Design and Development of 3-4 Baluns

The laboratory exercise design and development goals were:

- Analysis of the product chosen: Develop a theoretical understanding of the topic chosen. Perform required research. Use appropriate mathematical relationships and electromagnetic theory. The operational wavelength is the 2-meter amateur radio band (144.0-148.0 MHz) [3].
- Design the product: Use sound design techniques to develop the project chosen. The end result must be the electromagnetic product (e.g. antenna). Use appropriate design equations and software.
- Use appropriate means to test the product. Test appropriate parameters and compare to theory (radiation pattern, radiation resistance, and efficiency if possible).

In developing the antennas, students were required to design appropriate driving hardware interfaces. Radiation resistance was investigated and applied to optimal impedance matching designs. Some groups developed baluns of various ratios to act as impedance interfaces to antennas.

Low Frequency Antenna Design ($l >> \lambda$)

To introduce students to antenna design methods beyond the confines of the course textbooks [4, 5], design of long antennas (typically used in submarines) with accompanying exercises is covered. Besides, this gives the students a glimpse at an aspect of graduate-level antenna design.

Students are made aware, analytically, in the design process that practical application of such antennas is only possible when sea water ($\varepsilon = 81\varepsilon_0$ and $\sigma = 4$ S/m) behaves as a good conductor at low frequencies ($f <<$ 889 MHz), typically when $f \leq$ 100 Hz, for communication to be possible.

We start with the standard far E_θ – field expression from a center-driven linear dipole antenna of length l shown in Figure 4 [4]:

$$E_\theta = \frac{jk\eta e^{-jkr}}{4\pi r}[\sin\theta]U(\theta) \quad \text{with} \quad U(\theta) = \int_{-l/2}^{l/2} I(z)e^{jkz\cos\theta}dz \tag{1}$$

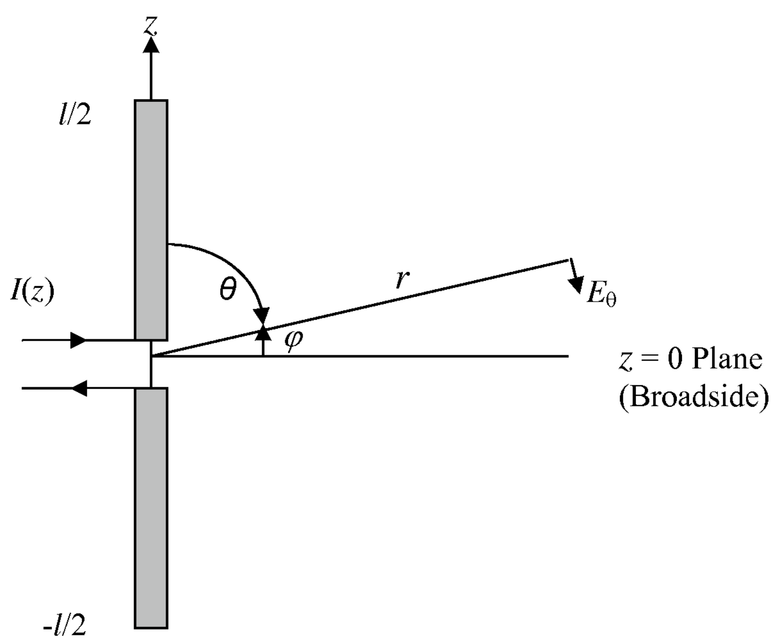

Figure 4. Center-Driven Dipole Antenna of Length l

Departing from the course textbook method, we transform equation (1) to the form:

$$E_\theta = \frac{jk\eta e^{-jkr}}{4\pi r}[\cos\varphi](\frac{l}{2})g(u) \quad \text{with} \quad g(u) = \int_{-1}^{1} I(\zeta)e^{ju\zeta}d\zeta \tag{2}$$

Equation (2) evolves from equation (1) as follows:

- $[\theta = \frac{\pi}{2} - \varphi]$ from Figure 4. Hence, the change $[\sin\theta]$ = $[\cos\varphi]$ from (1) to (2)
- $u = \frac{kl}{2}\cos\theta = \frac{\pi l}{\lambda}\cos\theta = \frac{\pi l}{\lambda}\sin\varphi$; and $\zeta = \frac{2}{l}z$ (a dummy variable)
- In equation (1) $U(\theta)$ is replaced by $U(\varphi) = \frac{l}{2}\int_{-1}^{1} I(\zeta)e^{jk\zeta\frac{l}{2}\sin\varphi}d\zeta$
- Substituting, we attain: $E_\theta = \frac{jk\eta e^{-jkr}}{4\pi r}[\cos\varphi]\,\frac{l}{2}\int_{-1}^{1} I(\zeta)e^{ju\zeta}d\zeta$ where:
- $\int_{-1}^{1} I(\zeta)e^{ju\zeta}d\zeta = g(u)$ (Similar to a Fourier Transform).

Note that choice of different amplitudes or functions of the antenna current $I(\zeta)$ results in the modification of $[\cos\varphi]$ by $g(u)$ in equation (2).

For a given current distribution $I(\zeta)$, the design process is reduced to evaluating $g(u)$ so that the corresponding antenna pattern can then be determined from equation (2). Thus, a design to given specifications may be accomplished, as illustrated briefly in the following exercise.

- For $I(\zeta) = I_0$ = constant, we find

  $$g(u) = \int_{-1}^{1} I_0 e^{ju\zeta}d\zeta = 2I_0\frac{\sin u}{u}$$

- Hence $E_\theta = \frac{jk\eta e^{-jk\zeta}}{4\pi r}[\cos\varphi]\,(l)(I_0\frac{\sin u}{u})$ and the Antenna Pattern (*AP*) is
- $AP = \left|[\cos\varphi]\frac{\sin u}{u}\right|$ where $-\frac{\pi}{2} \le \varphi \le \frac{\pi}{2}$ and $u = \frac{\pi l}{\lambda}\sin\varphi$

For long antennas ($l >> \lambda$), the beam width of the pattern is very narrow which implies $[\cos\varphi] \sim 1.0$. Hence, for an antenna with $I(\zeta) = I_0$ (uniform current distribution) the following design parameters apply:

- $(AP)_{dB} = 20\log_{10}\left|\frac{\sin u}{u}\right|$ dB
- Beam Width Between First Nulls (BWFN) = $\frac{2\lambda}{l}$
- 3-dB Beam Width or Half Power Beam Width (HPBW) = $0.88\frac{\lambda}{l}$
- First Side Lobe Level (SLL) = -13.2 dB

As a design example, if $\varphi = 3^\circ$ and $I(\zeta) = I_0$ the antenna length can be determined from the appropriate parameters above to be: $\underline{l = 38.2\lambda}$ (*i.e.* $l >> \lambda$).

Table 1 shows antenna design parameters for different antenna current distributions.

TABLE 1 Long Antenna ($l >> \lambda$) Design Parameters for Specified Antenna Current Distributions

Antenna Current Distribution $I(\zeta)$	BWFN	HPBW	SLL
I_0 (Uniform Distribution)	$\frac{2\lambda}{l}$	$0.88\frac{\lambda}{l}$	- 13.2 dB
$I_0 \cos\frac{\pi\zeta}{2}$	$\frac{3\lambda}{l}$	$1.21\frac{\lambda}{l}$	- 23 dB
$I_0 \cos^2\frac{\pi\zeta}{2}$	$\frac{4\lambda}{l}$	$1.44\frac{\lambda}{l}$	- 32 dB

Lab Experiments Using Microwave Training Kit

The two methods applied to the course have a common ground in labs requiring state of the art software packages (Agilent ADS, Motorola Microwave Impedance Matching Program (MIMP), and MathCAD) to design and analyze microstrip transmission lines with single/double stub impedance matching, dipole and monopole antennas.

Another aspect of the course is use of Microwave Training Kits [6] to familiarize the students with basic microwave measurements. Initially, students carry out simple animation experiments (Agilent Java Smith Chart Animation) to observe variations of VSWR for different load impedances, reflection coefficients, etc. and Smith Chart graphing. This prepared the students for the challenges of microwave measurements of waves propagating in rectangular waveguides. Specific lab activities included the following experiments from the Microwave Training Kits:

- Initial Set-Up Procedures
- Measurement of Microwave Power
- Measurement of VSWR
- Measurement of Frequency and Wavelength
- Measurement of Impedance
- Waveguide Attenuators
- Klystron Characteristics

Data analysis, processing, graphing and use of Smith charts are fully employed in this set of experiments. Students also become familiar with various microwave components which include:

- Power Supply/Thermistor & amplifier; Thermistor Mount; Solid State Oscillator
- Klystron Tube Mount; Frequency Meter; Slotted Line; Termination
- Waveguide Stands; Shorting Plate; Waveguides and Dimensions
- Variable Flap Attenuator; Tuning Probe; Detector Mount

One vital lesson students learn in Microwave Measurements is that unlike other labs involving lumped parameters, Microwave Measurements need Patience, Care and Precision due to the sensitivities of the Power Supply/ Thermistor, Solid State Oscillator, Tuning Probe, Slotted Line, etc.

Conclusions

We have shown how a dual approach to teaching applied electromagnetics can be effective to undergraduates. This is especially beneficial in the Department of Engineering at USD where there is only one mandatory course in electromagnetics. Therefore, rather than cover a course in field theory first (with no labs) before embarking on an applied electromagnetics course with labs, as is typical in most institutions, we are able to cover both theory and labs quite successfully, both in depth and breadth. The use of state of the art software such as Agilent ADS and the varied lab exercises, projects and design methods make it possible for students to acquire: (1) experience that could lead to promising RF careers in industry and (2) sound background for future graduate studies, especially with the addition of a more advanced elective course in RF design offered in the EE Program at USD by the second author.

Finally, although the lab experiences vary to some extent, the two methods are actually based on the same concepts of basic electromagnetic theory. Our experience is that the same course material can be covered differently in terms of applications, thus enriching students' design capabilities and experience in applied electromagnetics.

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