A Novel Microwave Engineering Course in a Collaborative Electrical Engineering Program

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In this paper, we describe a fairly innovative microwave engineering course with a concurrent laboratory. This course is offered in the context of a collaborative electrical engineering program among Salisbury University (SU), University of Maryland Eastern Shore (UMES), and University of Maryland at College Park (UMCP). In contrast to the traditional lineup of topics, we develop the course using circuit theory all the way through ABCD and Scattering matrices, transmission lines and impedance matching. Only then, about mid-semester, do we make our first reference to Maxwell's Equations and develop the theory of waveguides. In order to address the pedagogical concern expressed in the literature, we have retained the almost moribund slotted lines while concomitantly introducing the snazzy network analyzers in the laboratory experience. The need for designing such a course was motivated by the inexplicable - but welcome- presence of over half a dozen microwave companies concentrated in a narrow rural corridor on the lower eastern shore of Maryland coupled with a severe shortage of qualified engineers desperately sought by these companies.

I. Introduction

Microwave engineering and communications have rapidly and inexorably become a part of everyday life. It may well be that a nodding familiarity with these areas may be deemed indispensable for all electrical engineers and physicists in the very near future. For students and faculty at Salisbury University and UMES (University of Maryland, Eastern Shore) located on the lower eastern shore of Maryland, our neighborhood has been a veritable "microwave valley" for quite sometime. In addition to the collaborative Electrical Engineering program with University of Maryland Eastern Shore and University of Maryland College Park, Salisbury University offers a B.S. degree in physics. The need to expose our students to microwave engineering and communications is clear and present [1] – [3].

It is well known in the education community that adding new courses to an already bloated curriculum cannot be taken lightly or in a cavalier manner. If the addition of a course is exigent and justifiable then something has to give. The conventional wisdom is that we must resign ourselves to a tradeoff. Fortunately and serendipitously for us, we believe that we have stumbled upon an innovative idea that kills three birds with one stone. The traditional curricula in electrical engineering and physics require students to take at least one semester of an electromagnetics course. In our case this happens to be ENEE 380, which is equivalent to PHYS 315. Table 1 lists the catalogue course descriptions. This course introduces students to electrostatics, vector calculus, Gauss's law, Stokes's theorem and culminates with an introduction to Maxwell's equations. Many electrical engineering and physics curricula require students to follow this with a sequel that explores wave propagation, reflection, refraction, polarization phenomena, Poynting's theorem, and transmission lines. This course is invariably a prerequisite for students electing to take a microwave engineering course. Our experience has been that the traditional way of offering the microwave engineering course is inordinately abstract, and we feel that one needs to differ from the theoretical purist's clamor that an extensive and deep theoretical foundation must precede any introduction to the theory of transmission lines and the principles of microwave engineering. We believe that reversing the order of presentation and making them concurrent in the same course not only averts any tradeoffs but also, on the contrary, it engenders unexpected and welcome benefits.

Table 1: Course Descriptions

ENEE 204 Basic Circuit Theory — 3 cr.

Basic circuit elements: resistors, capacitors, inductors, sources, mutual inductance and transformers; their current-voltage relationships. Kirchoff's Laws. DC and AC steady-state analysis. Phasors, node and mesh analysis, superposition, Thevenin and Norton theorems. Transient analysis for first- and second-order circuits. Prerequisite: MATH 321. Co-requisite: 182H.

ENEE 206 Fundamental Electric & Digital Circuit Lab. — 2 cr.

Introduction to basic measurement techniques and electrical laboratory equipment (power supplies, oscilloscopes, voltmeters, etc.) Design, construction, and characterization of circuits containing passive elements, operational amplifiers, and digital integrated circuits. Transient and steady-state response. Co-requisites: ENEE 204 and ENEE 244.

ENEE 380 Electromagnetic Theory — 3 cr.

Prerequisites: MATH 212 and PHYS 263 and completion of all lower-division technical courses in the EE curriculum. Introduction to electromagnetic fields. Coulomb's law, Gauss' law, electrical potential, dielectric materials, capacitance, boundary value problems, Biot-Savart law. Ampere's law, Lorentz force equation, magnetic materials, magnetic circuits, inductance, time varying fields and Maxwell's equations.

ENEE 482 Microwave Engineering — 3 cr.

Introduction to Microwave Engineering. This course explores the theoretical underpinnings as well as the practical applications of Microwave Engineering. Laboratory experiments and theoretical principles will be seamlessly blended in order to maximize the learning and long-term retention efficiency. Simulation software will be used. Topics include: Transmission Lines, Smith Chart, Z, Y, T, S, and ABCD matrices, passive devices and filters, Maxwell's equations applied to reflection, refraction, and polarization of waves, Poynting's theorem, waveguides, antennas, and microwave amplifier design. **Prerequisite:** PHYS 315/ENEE 380 and PHYS 311/ENEE 206. **Four hours per week**.

II. Pedagogical Epistemology

Kolb's Experiential Learning Theory provides a holistic model of the learning process. There is widespread agreement among scholars and researchers that there are significant individual differences in taking in and processing information [4]–[5]. There are two ramifications of learning styles on the teaching-learning process. At a minor level there is a need for adjustment between learner and teacher: sometimes their preferences are complementary, sometimes adversarial, and of course sometimes collusive if they both tend to go for the same stages in the cycle. At a major level, neglect of some stages can prove to be a major obstacle to learning [6]. Broadly speaking, practitioners of creative disciplines, such as the arts, are found in the Divergent quadrant. Pure scientists and mathematicians are in the Assimilative quadrant. Applied scientists and lawyers are in the Convergent quadrant. Professionals who have to operate more intuitively, such as teachers, are in the Accommodative quadrant. These four broad quadrants are depicted in Figure 1.

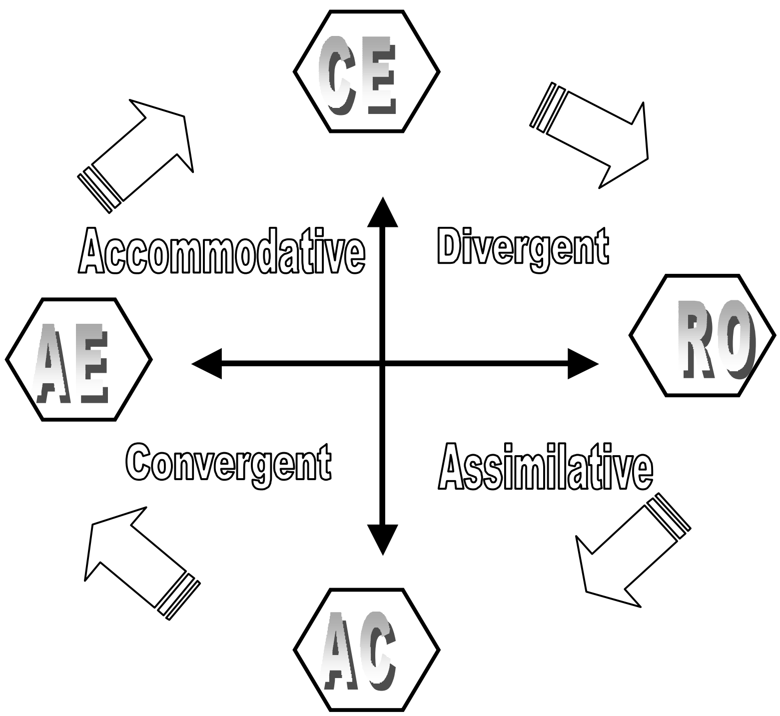

Figure 1: The Four Quadrants of the Kolb Experiential Cycle

In his experiential learning cycle, known as the Learning Styles Inventory, Kolb has delineated four major learning styles. These four categories are activists, reflectors, theorizers, and pragmatists. The Kolb Experiential Learning Cycle is shown in Figure 2.

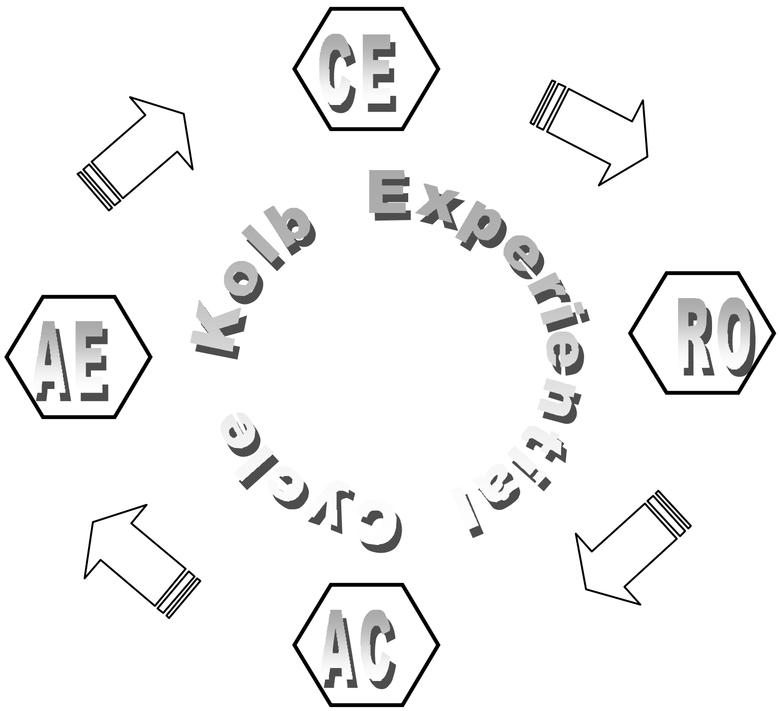

Figure 2: The Kolb Experiential Cycle

The four stages of learning are Concrete Experience (CE), Reflective Observation (RO), Abstract Conceptualization (AC), and Active Experimentation (AE). The vast majority of students find it difficult to formulate an abstract view of the phenomena (Kolb's "AC") until they have had an opportunity to grapple with the tangible and the concrete (Kolb's "CE" and "AE") and reflect on their experience (Kolb's "RO"). Hence the motivation to restructure the contents of the new microwave engineering course as follows:

- Circuit and networks precede the abstract electromagnetic theory
- A nodding familiarity with laboratory equipment and applications
- Simulation software for Smith Chart and Circuit Design

III. The New and Improved Microwave Engineering Course

Our new microwave engineering course departs from the traditional version in several fundamental ways. We develop the course from the perspective of circuit theory. In other words, we draw on the students' robust and concrete knowledge of circuit theory [ENEE 204 (circuit theory) and ENEE 206 (Electric and Digital Circuits Laboratory) both of which are equivalent to PHYS 311(Basic Electronics with a concurrent laboratory)] with minimal reference to electromagnetics (ENEE 380) and absolutely no reliance on electromagnetic wave propagation as a prerequisite. In order to pique the students' curiosity and whet their appetite, we review the history of microwaves and radar and point out the plethora of modern appliances like cell phones and the microwave oven. At this point we have the students' undivided attention and interest and not meaning to lose them by scary references to abstract formulations of Maxwell's equations at this early stage, we set out to develop the concepts of the transmission coefficient, reflection coefficient, maximum power availability, image impedance, impedance matching, and impedance and admittance matrices for N-port networks. The students are on terra firma as we make the gentle transition from network theory to microwave engineering. We conclude this topic with the derivation of the normalized impedance matrix and the equation

$$[Z] = [\,\overline{Z}\,]^{1/2}\,[\mathcal{Z}]\,[\,\overline{Z}\,]^{1/2}$$

We find it smooth sailing at this juncture to thoroughly develop the concept of the scattering matrix all the way to

$$[S] = \{[\mathcal{Z}] - [U]\}\,\{[\mathcal{Z}] + [U]\}^{-1}$$

We wrap it all up with the ABCD chain matrix representation and the relationships among the different representations. At this point we engage the students in a thorough analysis of the transmission line – still in the context of circuit theory! Concepts of the quarter-wave transformer and insertion loss round this off. At this point we make the first foray into rudimentary electromagnetics to lead an analysis of the stripline and the microstrip line. By mid-semester, we have thoroughly mastered the Smith Chart and introduced a couple of software packages [7]. A snapshot is depicted in Figure 3. Also, we have covered single and double stub matching, the 3-section Chebyshev transformer and tapered impedance matching.

It is now, and only now, that we begin the development of electromagnetic wave propagation assuming only a pre-requisite of a single semester of electromagnetics. We believe that the students have attained a level of maturity, enthusiasm, and confidence to masticate, digest, and assimilate the steady diet of abstract nourishment that will surely follow! An exposition of electromagnetic wave propagation in various media, reflection, refraction, polarization, skin effect, Poynting's theorem, and Brewster's angle exemplify the bitter pills swallowed in anticipation of rewards to follow. At this point students know, for instance, that no Brewster's angle exists for perpendicular polarization.

We are now eminently qualified to take the plunge into the venerable waveguides. An extensive development of rectangular waveguides is followed by a perfunctory but adequate analysis of circular waveguides and the coaxial cable. Maxwell's equations are depicted in all their glory and gory detail. A second pass of striplines and even and odd mode analysis of coupled transmission lines rounds this off nicely. We now take a stab at passive devices. This includes, but is not limited to, S-matrix formulation and design of power dividers and couplers, coupling coefficient in terms of even and odd mode characteristic impedances, and Q of cavity resonators. The penultimate topic is filters. Lumped element prototypes lead to microwave filters including maximally-flat Butterworth and the equal-ripple Chebyshev. The last topic that we barely squeeze in is active circuits and amplifier design.

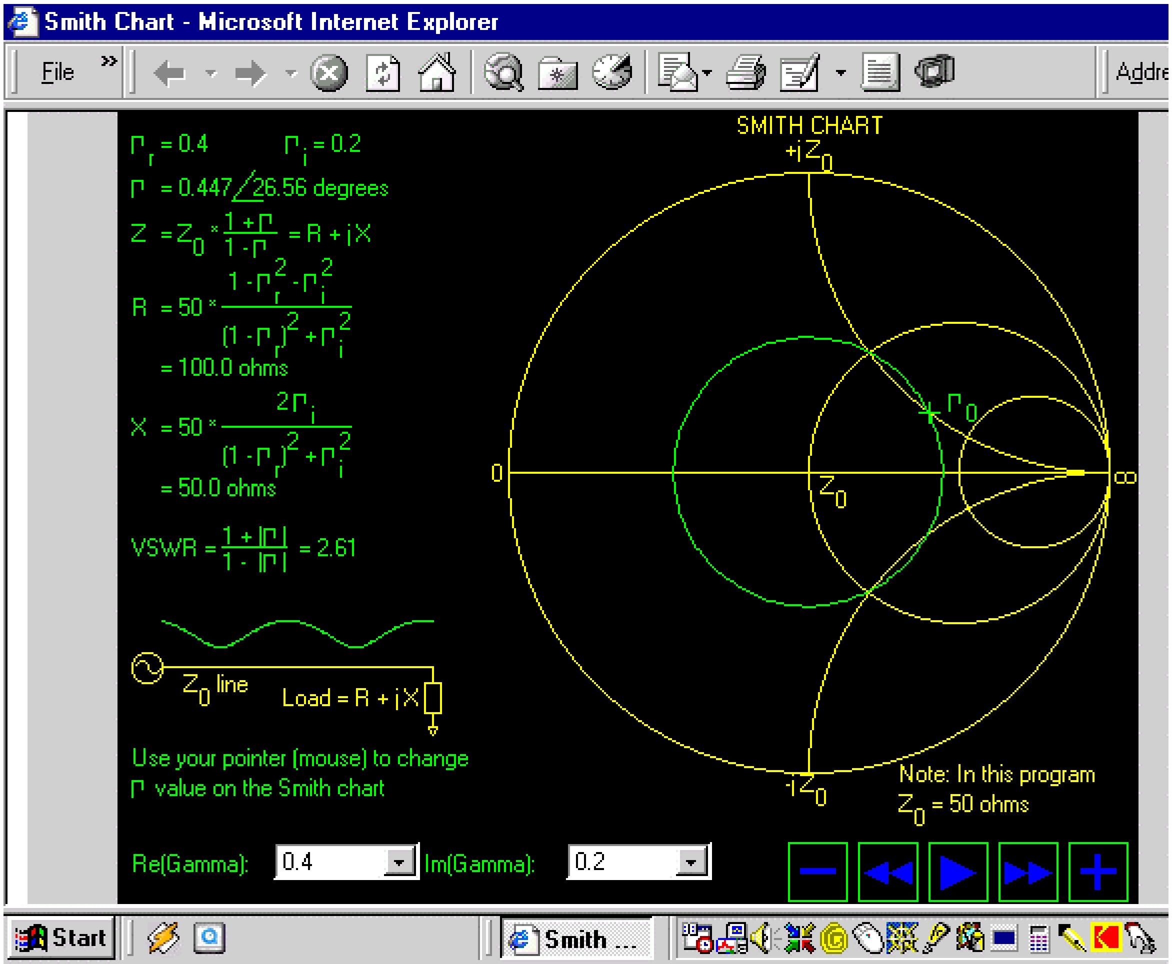

Figure 3: Snapshot of the Smith Chart Simulation Output

IV. Microwave Engineering Laboratory

A well-equipped microwave engineering laboratory supports and extends the hands-on, concrete experience precedes the abstract conceptualization philosophy of the new and improved microwave engineering course. In addition to state-of-the art equipment, a conscious effort was made to acquire many pedagogically instructive pieces of equipment that have been discontinued by major manufacturers. For instance, the slotted-line is so sorely missed by the educational committee that individuals have resorted to writing simulation software in order to provide the students with laboratory experience [8]. We were fortunate enough to get our hands on a few real slotted-lines before they become extinct. The laboratory is also used for capstone design projects by students who have already completed the prerequisite microwave engineering course. A representative but not exhaustive list of equipment includes the Agilent 8714 ES Network Analyzer, Agilent 8648C Signal Generator / Synthesizer, HP415ESWR meter, HP432A power meter, HP805C, slotted-line 0.5 – 4.0 GHz, HP809C / 817A / 447B X-band slotted line system, HP8350A / 83570A 18.0-26.5 GHz sweep generator, GR874-LBA General Radio Slotted-line, GR874-D20L Tuning stub, GR900-LB Precision Slotted-line, Narda 610B-100 Bolometer, Pasco WA-9316 / 9318/9319 Advanced Microwave Optics System, Tektronix R3131 Spectrum Analyzer, Tektronix TLA 601 Logic Analyzer, Tektronix TDS 3012 100 MHz DPO color oscilloscope, Tektronix R3754 Network Analyzer, Tektronix AFG 310 Arbitrary Function Generator. In figures 4 and 5, we show the microwave engineering laboratory.

We deliberately wanted to include a mix of the classic and the modern. Our experience has shown that for instructional purposes, an exclusive reliance on the state-of-the-art leaves much to be desired and we deemed it to be pedagogically unsound. A complete list of equipment and the vendors is available from the first author via e-mail at newton@ieee.org.

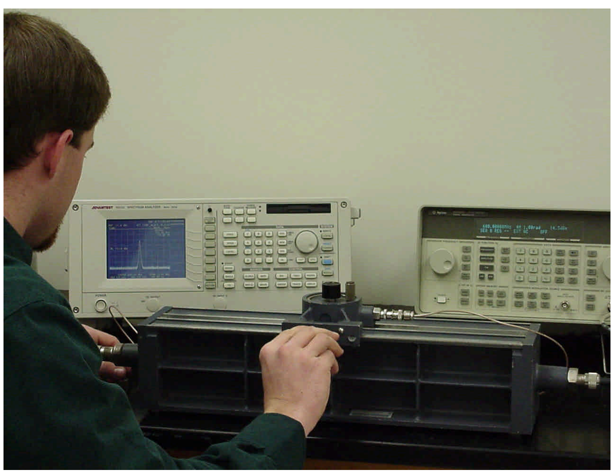

Figure 4: Slotted-Line and Signal Generator

Figure 5: Microwave Engineering Laboratory

V. Conclusion

An innovative microwave engineering course was described that develops the course from a foundational knowledge of circuit theory instead of electromagnetic theory. We reckon that the restructured format of the new and improved microwave engineering course affords the following advantages:

- No increase in graduation credit requirements
- Overall increase in the diversity of topics covered

- Increase in depth, breadth, and comprehension of material covered
- Addition of a useful course in the students' repertoire

At first blush this seems to be a paradox, which in our estimation falls under the " less is more" rubric. We do owe the skeptical inquirer more than a hand-waving explanation and are happy to do so. At the root of the resolution of this paradox is the Kolb experiential learning cycle as elucidated in this article.

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