

# Project Based Undergraduate and Graduate Electromagnetics Education

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**Abstract** — The paper describes a comprehensive project based EM program that allows for independent thinking, builds design and analytical skills and trains students in state-of-art design procedures. Such an approach is to mitigate the universal dislike that students have for Electromagnetics and make it more appealing while not sacrificing theory. This will require an early implementation of software projects and measurement techniques in the junior level course on wave theory and transmission lines in order to pique the students' interest and get them interested in EM graduate education. More complex software and hardware design projects are executed in graduate courses, to complement a rigorous theoretical education. The design projects provide the complete design experience that includes the development of analytical models in addition to the use of software modeling tools, construction and validation by measurements. The projects include some traditional ones in microstrip circuitry and antenna design and some others which demonstrate the relevancy of EM in related areas such as wireless communication, biomedical applications and digital systems. This paper demonstrates the feasibility of a student-friendly approach to EM education.

**Index Terms**— analytical skills, design procedures, modeling, antenna and microwave circuits

## I. INTRODUCTION

To improve and inspire student interest in Electromagnetics continues to be a challenge for EM educators. Emerging technologies such as wireless communication, mixed signal circuits and bio-electromagnetics have made Electromagnetics increasingly important. Teaching methodologies for Electromagnetics have evolved from pencil and chalk to computer mouse and multimedia. The most notable changes in how we teach EM are the visualization and animations of fields through software and instrumentation, which have strongly impacted the way, students learn Electromagnetics and its applications, today. There are several software tools, some that illustrate the fundamentals of EM theory, others that use MATLAB for microwave circuit design and antenna design and those that are very elaborate commercial software packages. Students learn best when theory is accompanied by experimentation, in particular, design, construction and testing of microwave circuits and antennas. The available software and hardware tools are making project-based instruction increasingly popular. Elaborate as they are, these

can be implemented as early as the Undergraduate courses and finally culminating in graduate project based courses. Unique software and laboratory experiences at the junior level are discussed with illustration of basic wave concepts, the primary intent being to make abstract concepts easier to understand by relating theory to measurable quantities [1, 2]. In the graduate program, following courses on microwave circuit theory and antenna theory, design of experiments is illustrated to characterize or measure specific quantities, working with the constraints of measurable ones using the vector network analyzer, in conjunction with the development of closed form analytical expressions. In addition, meaningful design projects can be executed with projects ranging from simple to elaborate designs of microwave circuits and antennas. The complete design process includes the development of analytical models in addition to simulation with software modeling tools, construction and validation by measurements. This paper summarizes a program of the kind described above.

## II. EM WAVES AND TRANSMISSION LINES

This section contains software projects and a set of experiments conducted in the junior level course on EM waves and transmission lines. Fortunately a large majority of undergraduate EE programs have a mandated course in wave dynamics followed by a transmission lines course that is mandated in some programs and a senior elective in others. Software projects can be executed to enhance the understanding of abstract theoretical concepts. Although several software projects can be conducted, selection of the projects should be such that theory is taught alongside and simulated results can be compared with hand calculated results and validated with measurements.

Following are examples of software projects that can accompany a typical junior level EM course. A microstrip transmission line circuit configured as a cascaded and as a branched system can be designed in Ansys Designer. Reflection and transmission can be characterized through return loss, SWR and insertion loss Figure1. Dispersion in rectangular waveguides can be illustrated by Ansys' HFSS (figure2). Radiation characteristics of a dipole antenna can be analyzed using GNEC (figure 3). A planar inductor in silicon can be modeled in SONNET for its inductance and Q (figure 4). All these software tools are elaborate with a steep learning curve. While graduate students can successfully navigate through these tools, undergraduate students require step-by-step instructions so that they do not get lost in the

intricacies of the modeling but get to the results easily. Examples of these handouts are shown in the author's website [www.rit.edu/kgcoe/eta](http://www.rit.edu/kgcoe/eta).

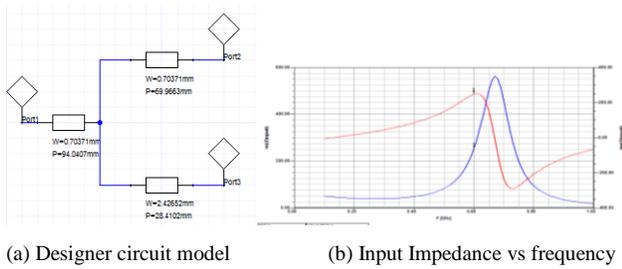


Figure 1 Branched transmission lines in Ansys Designer

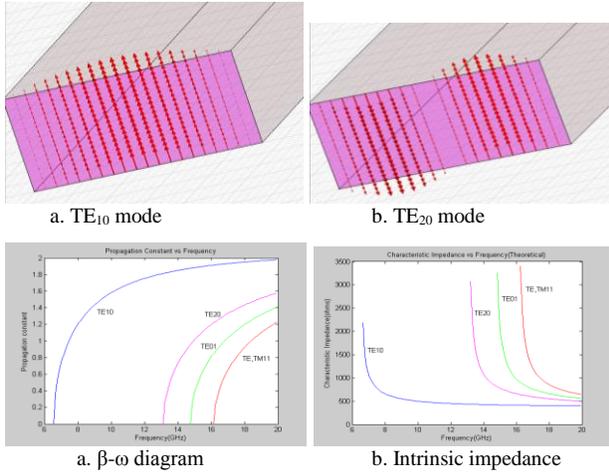


Figure 2 Rectangular Waveguide in HFSS

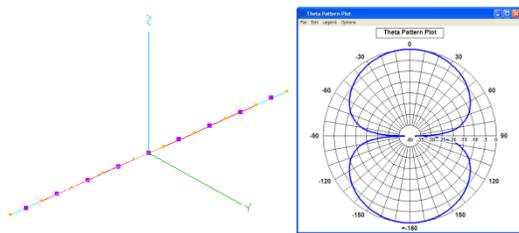


Figure 3 Dipole antenna in GNEC

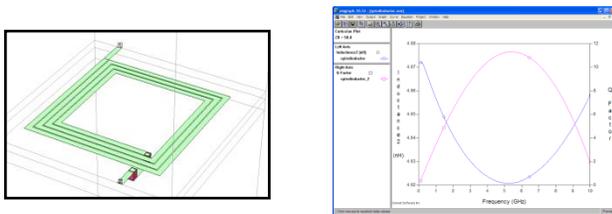


Figure 4 Inductance and Q of a Spiral Inductor on Silicon in SONNET

The pre-laboratory exercises of analytical formulations, hand calculated and simulated, are validated through experiment. At RIT, the undergraduate lab has 5 stations each equipped with a vector network analyzer, a computer and slotted co-axial lines which have been automated by a student senior project. Each experiment has been written with step-by-step instructions for the network analyzer front panel key operation to overcome it's steep learning curve. The entire EM program is described in the author's website

[www.rit.edu/kgcoe/eta](http://www.rit.edu/kgcoe/eta). In the age where automated instrumentation and computers dominate our lives, the slotted coaxial line and the Smith Chart are a sanity check, remaining as the greatest pedagogic tools that help students understand the intriguing behavior of electromagnetic waves. Various types of calibration procedures are investigated for measurements in the time and frequency domains. The experiments are designed to complement the theoretical discussion such as step excitation of coaxial lines, standing wave patterns and impedance matching using a single stub tuner, figure 5 (click on figure for a video demo).



Figure 1a Co-axial slotted line and the vector network analyzer



Figure 1b Time domain

Figure 1c Single stub tuning

Figure 5 Transmission Line Concepts

### III. DESIGN OF EXPERIMENTS

The motivation for the design of experiments comes from the fact that, often times, measurements are needed where there is no well-defined methodology. It also adds a new dimension to the theory for the students. At first, one needs to develop an analytical formulation in terms of quantities that can be simulated and measured. Basically it is the [S] matrix displayed in a variety of forms such as return loss, insertion loss, SWR, input impedance etc. Following are a few examples of designing experiments for measurement of a specific quantity.

#### (i) Dielectric constant measurement:

Characterizing a dielectric for its permittivity often times is very important and necessary. The following experiment can be designed. Placing the dielectric sample in a rectangular waveguide and backing it by a short and then by an open allows the thickness of the sample, 'd', to be eliminated in the analytical expression for dielectric constant. In each case, the impedance  $Z_{AA}$  (or  $Z'_{AA}$ ) at the input plane are measurable quantities, figure 6. The student would be required to develop the methodology and derive the following equation. Results are compared with measurements using the Agilent dielectric probe kit 85070E, figure 7.

$$\epsilon_r = \frac{(120\pi)^2}{Z(AA)Z'(AA)} + \left(\frac{f_{c0}}{f}\right)^2 \quad (1)$$

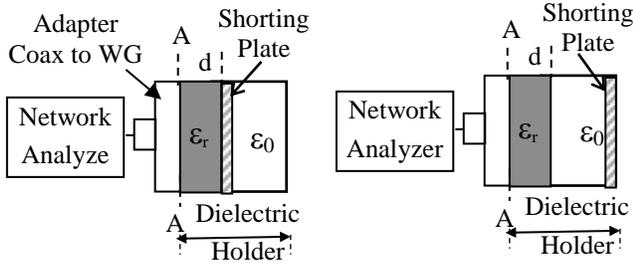


Fig 6 (a) Dielectric sample backed (Measure  $Z_{AA}$ )  
(b) Dielectric sample backed by an open (Measure  $Z'_{AA}$ )



Figure 7 Agilent 85070E dielectric probe kit

(ii) Characterizing Phase Shift:

In any high frequency circuit phase shift (desired or often times undesired) needs to be characterized and assessed. Working with the [S] matrix of each component in a microwave circuit, it is possible to develop an analytical formulation for the transmission and reflection characteristics of the circuit, which are measurable quantities. The example in figure 8, shows a waveguide hybrid Tee with movable shorts placed on the E and H arms. As the lengths  $l_E$  and  $l_H$  are varied the phase between ports #1 and #2 can be measured and compared to theoretical predictions (Click on figure for a demo). The following analytical expression can be developed from the [S] matrix of the hybrid Tee.

$$\text{Phase } \phi_{12} = -\beta (l_E + l_H) + \pi/2 \quad (2)$$

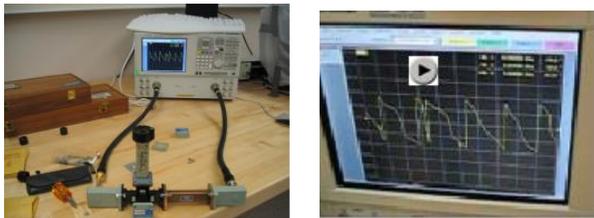
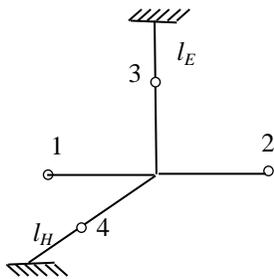


Fig. 8 Assessing phase change between ports #1 and #2 of a waveguide hybrid Tee

(iii) Modeling Discontinuities:

Discontinuities appear in microwave circuits and cavities in the form of probes or irises which add a shunt susceptance. These often lead to undesirable effects such as shifting the resonant frequency or causing a mismatch. Figure 9 shows a methodology for measuring the susceptance and developing the following analytical expression in which the standing wave ratio SWR is the measurable quantity.

$$b_{eq} = \pm \left[ \frac{SWR - 1}{\sqrt{SWR}} \right] \quad (3)$$

where  $b_{eq} = \frac{B_{eq}}{Y_0}$  and  $Y_0 = \frac{1}{\eta_{TE_{10}}}$

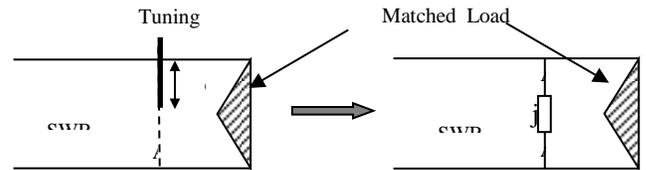


Figure 9 Modeling discontinuities

(iv) Cavity Resonances: Cavity resonances have a wide range of applications. In some cases, such as filters, frequency, microstrip circuitry these are desirable resonances whereas resonances introduced by discontinuities or in power plane cavities are undesirable. Predicting and measuring the resonant frequency is important and can be done as illustrated in fig.10.

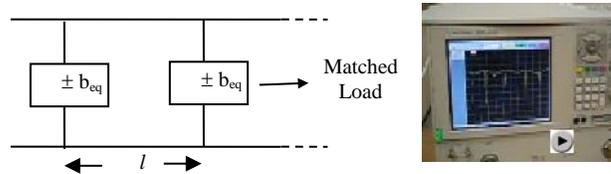
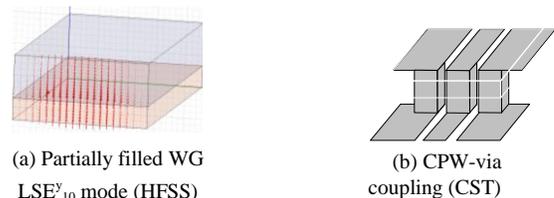


Fig. 10 Transmission Cavity Resonances

IV. EM MODELING PROJECTS

A variety of software projects can be conducted in EM graduate courses that deal with EM propagation characteristics, microwave circuit design and antenna design. Examples include TE and TM modes in rectangular and circular waveguides, LSE and LSM modes in partially filled guides (figure 11a), HE and EH modes in dielectric guides using full wave solvers such as Ansys' HFSS. Using CST, co-planar waveguide (CPW)-via coupling can be analyzed (figure 11b). Antenna design can be conducted with GNEC (for wire antennas) and HFSS (for microstrip antennas).



(a) Partially filled WG LSE<sub>10</sub> mode (HFSS)

(b) CPW-via coupling (CST)

Figure 11 Some examples of software projects

V. DESIGN PROJECTS

Following a training of the kind described above, meaningful design projects can be executed as part of graduate course work. The complete design process includes the development of analytical models in addition to the use of software tools, construction and validation by measurements. Student projects can range from simple to elaborate designs of microwave circuits and antennas. Some unique graduate student projects from RIT are described in the following sections.

A. Size Reduction of Microstrip Quadrature and Ring Hybrids (by David Hudson and James Aclub, RIT)

This project examines size reduction techniques as applied to the microstrip quadrature and ring hybrids. Artificial transmission lines (ATLs), compensated spiral compact microstrip resonant cells (CSCMRCs), photonic band-gap structures (PBGs), and complementary split ring resonators (CSRRs) are suggested structures for size reduction of microwave circuitry [3, 4]. Initial design and preliminary results are obtained through Ansys Designer, and a more thorough analysis in HFSS. The design frequency ranges between 1.5 and 2.0GHz, Couplers have been constructed and the design validated through simulation and measurement. As examples, the ATL topology for the Quadrature hybrid resulted in a 60% size reduction (figure 12) and the CSCMRC topology for the ring hybrid resulted in an 80% size reduction (figure 13).



Figure 12 Microstrip Quadrature Hybrid with Artificial Transmission Lines (ATL) with 60% size reduction

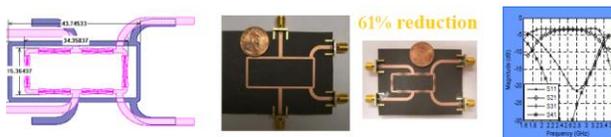
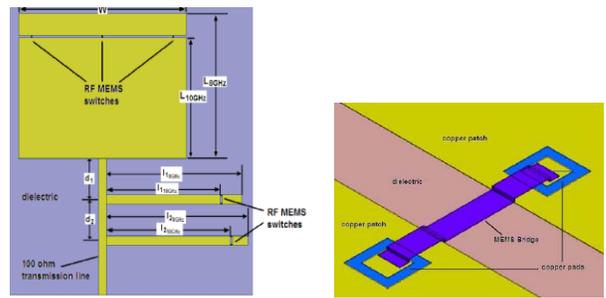


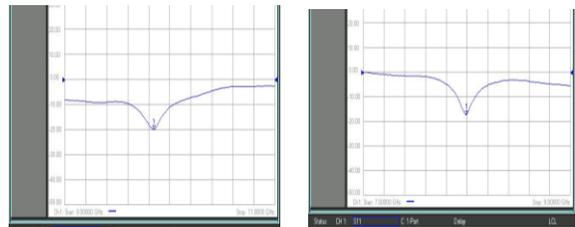
Figure 13 Microstrip Ring Hybrid with compensated spiral compact microstrip resonant cells (CSCMRCs) (60% size reduction).

B. Reconfigurable Dual Frequency Microstrip Patch Antenna Using RF MEMS Switches (by Jessica DeSignor, RIT)

In this project, a reconfigurable dual frequency microstrip patch antenna is created by reconfiguring its size using two rectangular patches that are connected together via RF MEMS switches (figures 9a and 9b) based on [5, 6]. Two antenna configurations are considered where the switches are open for resonance at 10 GHz and closed for resonance at 8 GHz. A double stub tuner provides matching for each of the antennas reconfigured with two sets of stub lengths that correspond to each frequency. Finally, the performance of the dual frequency patch antenna is validated through construction and measurement (Figures 9c and 9d).



(a) Antenna with matching circuit (b) RF MEMS switch model (HFSS)

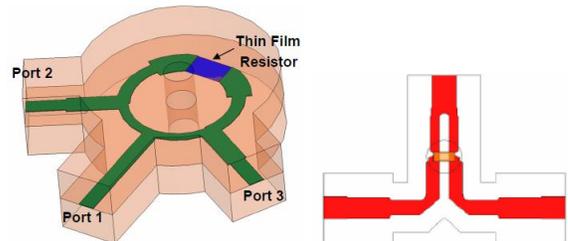


(c) Measured return loss (10 GHz antenna). (d) Measured return loss (8 GHz antenna)

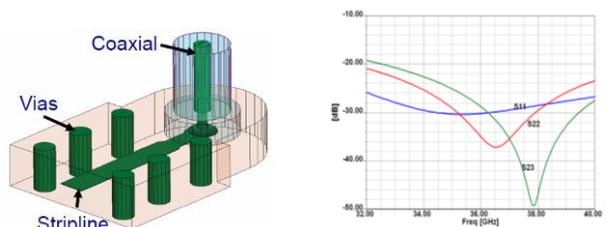
Figure 9 Dual frequency reconfigurable microstrip patch antenna

C. Ka-Band Wilkinson Power Divider with Integrated Thin Film Resistor (Stefan P. Bukowski & Franz Orban, RIT)

Designing a Wilkinson power divider using surface mount chip resistor technology is a relatively deterministic process at frequencies where dimensions of the resistor are electrically small [7, 8]. At Ka-band frequencies, it becomes necessary to account for the electrical length of the resistor in addition to addressing the effects of the anisotropic substrate due to the chip resistor package and its surrounding cavity. This project involves the design of a 3dB Wilkinson power divider for the Ka-Band using a thin film resistor integrated within the substrate. Omega-Ply® technology is implemented to ensure that the dielectric permittivity is isotropic throughout the stripline circuit, thereby maintaining consistent line impedances.



(a) 3-d model of Wilkinson power divider with an integrated resistor (b) 3-d model of Wilkinson power divider with chip resistor



(c) Stripline to coaxial connector (d) Return Loss (HFSS)

Figure 10 Ka-Band Wilkinson Power Divider

D. 4x4 X-Band Butler Matrix for Antenna Beamforming  
(By Joel Barry, Mia Mujezinovic, Amanda Kristoff and Michael Pecoraro)

The Butler Matrix allows for beam steering by providing a different phase progression at the output depending on which input port is energized. It consists of four  $90^\circ$  hybrids [9] and  $45^\circ$  (Schiffman) phase shifters [10]. In figure 11a, the desired phase progression is  $-\pi/2, 3\pi/2, -3\pi/2, \pi/2$  at output ports.

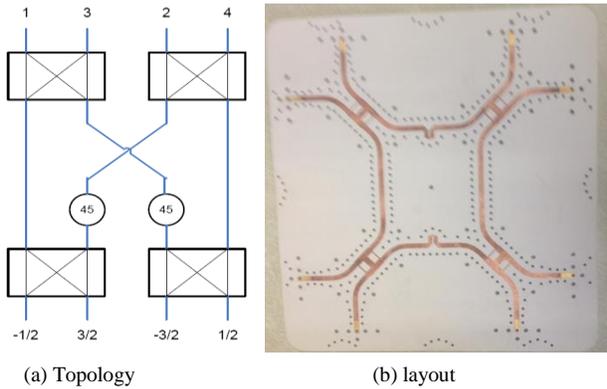


Figure 11 Feed system with  $90^\circ$ Hybrids

The return loss (figure 12) simulated at all four input ports is less than  $-16\text{dB}$  over a frequency range 9.5 to 13 GHz. The phase difference between the output ports were close to the required values. Results as a class project are acceptable.

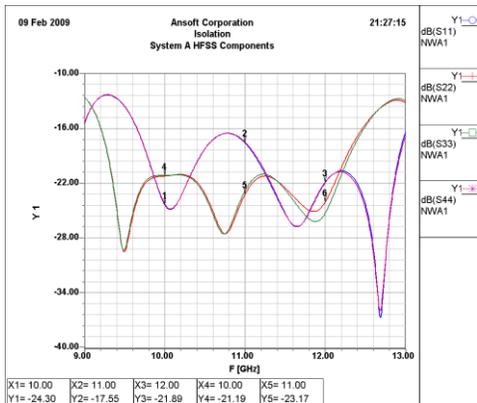


Figure 12 Return loss at the four input ports

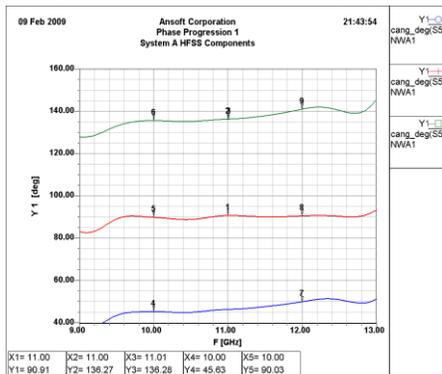


Figure 13 Phase at the four output ports

VI. CONCLUSION

This paper describes a comprehensive project based EM program that begins with incorporating software projects and measurement techniques in a junior level course on wave theory and transmission lines and leads to more complex software and hardware projects including designing experiments in graduate courses. The complete design experience is utilized that includes the development of analytical models in addition to the use of software modeling tools, construction and validation by measurements. Some examples of student projects have been presented to show the level to which EM education can be taken.

VII. REFERENCES

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