AC 2010-66: DESIGNING PRINTED CIRCUIT BOARDS FOR MICROWAVE ENGINEERING APPLICATIONS: A TEACHING TOOL FOR ENGINEERING TECHNOLOGY STUDENTS

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Designing Printed Circuit Boards for Microwave Engineering Applications: a Teaching Tool for Engineering Technology Students

Abstract

This paper will present the results stemming from an undergraduate course in Microwave Engineering Technology at the University of Massachusetts, Lowell. An opportunity to experience the complete process of designing a microwave circuit with printed circuit board (PCB) technology was made possible by a grant provided by the Electrical and Computer Engineering Technology Department Heads Association (ECETDHA). The financial support has allowed the students to apply the theory that is part of the class syllabus to a practical design challenge designed to mimic real–world applications such as wireless phones or GPS devices. Each student was challenged to meet similar, yet unique design specifications. A collaborative environment was fostered. Each student submitted a technical report along with a short presentation to the class as part of their final evaluation. Students were also asked to respond to an on–line questionnaire aimed at evaluating their experience. Responses were tabulated to measure students' feedback in 3 major areas: their understanding of microwave theory of distributed components; their understanding of the PCB technology applied to microwave design; and their challenges related to the execution of their project.

This paper is organized as follows: the main features of the course are outlined first to provide a context within which this project was developed. An outline of the educational approach taken by the author will follow. Then, a description of the projects and challenges faced by the students will be sketched out. A review of the students' feedback on their experience will be described and discussed. Some suggestions on how to improve this experience will be made before concluding the paper.

The Microwave Engineering Technology Course at the University of Massachusetts, Lowell

The University of Massachusetts, Lowell, is located in an area where high technology companies are often competing in securing new graduates. At the same time, a need for continuing education of their workforce has often brought back to the University their professionals interested in advancing their technical education. Within this local context, microwave engineering is of particular importance and a course on microwave engineering has been established by the author in spring 2008.

The course is entitled *Foundations of Microwave Design* (course # 17.403) and it is an elective course that the students may take either as part of their undergraduate program; or as individual class. Engineering Technology courses last 14 weeks and consist of a single 3 hour long class per week; all activities, such as a laboratory section, must fit within the allotted weekly time. The prerequisite to *Foundations of Microwave Design* is *Circuits II and Laboratory* (course # 17.214) which deals with circuits under sinusoidal excitation. However, the University does not require

students to have successfully completed a prerequisite course in order to attend a class. For this reason, the student population may possibly be of any level: for instance, at the time of this project, the class was attended by both freshman and senior students.

Its syllabus has originally been conceived to cover two major aspects of microwave engineering:

1. linear distributed components; and
2. basic circuits for wireless communication

Item 1 is considered a core constituent of the course[1] and addresses a major pedagogical objective – the introduction of typical microwave engineering concepts such as wave propagation, wavelength and discontinuities in the signal path to name a few. The analysis of transmission lines is the subject elected to introduce the students to these fundamental ideas. To facilitate the students' understanding, great emphasis is made on the application of transmission lines: Smith chart, scattering parameters, matching circuits, substrates are some of the keystones[2] of this course.

Item 2 is introduced to the students in the context of typical microwave systems such as General Positioning Systems (GPS) and wireless phones. Because of the ubiquity of cell phones, it is easy to focus the students' attention to the concepts of down and up-conversions, electrical noise, radio-frequency power and the basic metrics used to characterize a radio transmission[3]: power gain, noise figure, 1dB compression point, etc.

This balanced approach between theory and applications has received good feedback from past students as it meets both the curiosity of the young students and the needs of the professionals.

In January 2009, the Electrical and Computer Engineering Technology Department Heads Association (ECETDHA) funded a proposal by the author to allow the students of the spring 2009 *Foundations of Microwave Design* class, to design, layout, manufacture and characterize a printed circuit board for microwave applications. This project has been executed by the students with tools that are industry standards – Agilent's Advanced Design System (ADS) software for design, simulation, layout; and a vector network analyzer (VNA) for testing. Only manufacturing has been outsourced to a commercial vendor located in Canada, in line with common practices of this industrial sector.

The pedagogical approach

The opportunity provided by ECETDHA demanded a review of the current syllabus in order to maximize the students' understanding of the class topics through the execution of a real–world project within the standard 14 weeks.

The experiential learning approach[4] is considered with great favor by the author as a guideline[5] *a*) for teachers to facilitate the student's understanding of a subject; and *b*) for students to learn through experience how to handle unforseen challenges that cannot be taught through textbooks.The author's teaching experience aligns with scholarly research that a broad range of

ways of taking and processing information exists among individuals[6]. In order to meet the students' diverse – and certainly unknown at the start of the class – approach to learning, the syllabus was modified to accommodate the PCB project in terms of both content and schedule. Indeed, the project requirement of focusing on the design, layout and characterization of a microwave circuit imposes reconsidering the syllabus structure and content in order to answer the question *What topics should be taught to the students for them to fully appreciate the PCB project?* Further, a successful execution of the project can be achieved only if the sequence of the subjects to be taught is also reviewed – the question to address is: *When should a particular topic be scheduled for presentation in relation to the other subjects and to the project?*

The author's answers to the *what* and *when* questions have been based on a pedagogical approach that attempts to balance theory with practice; and aims at demonstrating to the students that theoretical models are key to guide the design of practical applications to a successful outcome. A strong theoretical component becomes an integral part of the student's practical experience as it helps the students evaluate the outcome of a decision against the expected result. These considerations provide an indication on which subjects ought to be taught in order to support the execution of the PCB project (the answer to the *what* question); and to sort the subjects correctly (the answer to the *when* question). Therefore, the lectures have been reshaped to time the following topics within the allotted 14 weeks:

Topic	Sample of subjects discussed in class
1. Initial review	· Sinusoidal sources · Complex numbers · Impedances
2. Transmission lines	· Lumped vs. distributed electrical components · Wave equation in the frequency domain · Propagation constant k
3. The boundary conditions	· Incident and reflected waves · Changing reference system ($x = l - d$) · Reflection coefficient Γ
4. The scattering matrix $\mathbf{S}$	· Scattering matrix $\mathbf{S}$ of a transmission line · Obtaining S_{ij} (general case) · The Smith chart
5. Practical transmission lines	· Ideal vs. real transmission line · Microstrip line · Introduction to microstrip models
6. Matching circuits with distributed elements	· Single stub match · Displaying the effect of a stub on the Smith chart · Quarter wavelength transformer
7. Designing the PCBs	· The substrate · The board (via–holes, corners, etc.) · Other components
8. Circuits and their characterization	· Defining linearity $\rightarrow$ compression point · Noise basics and measurement · Mixers $\rightarrow$ image frequency
9. A microwave approach to measurement	· The Vector Network Analyzer (VNA) · De–embedding · Calibration procedure
10. Board characterization with VNA	· Executing the measurement with a VNA · Exporting data (Touchstone format) · Evaluating the results

The 10 topics outlined above require about 1 class each for their presentation. The remaining weeks were used to carry out the design and for the student evaluation as discussed later. Not mentioned in the list above are the discussions on Agilent's ADS software, which has been integrated seamlessly with the lectures. Indeed, ADS has been introduced and described to the students as a modern evolution of the Smith chart: a tool to simplify the complexity of microwave circuit analysis and design! It should be noted that many microwave programs may be available nowadays to support design and analysis of microwave circuits, some even for free. Agilent offers its ADS software at very competitive prices to Universities through its University program – a license for commercial activities may be worth many tens of thousands of US dollars, depending on which features of the software are made accessible. A free program may certainly appear attractive at first, since it alleviates some of the instructor's constraints in organizing a hands–on

project. However, from the students' standpoint, it is certainly more valuable to acquire highly marketable skills that are sought out by employers: this was the author's purpose when selecting the software tool for this project.

The projects were presented, explained to and selected by the students around topic #6, *Matching circuits with distributed elements*. The execution of the project lasted 4 weeks and a hard deadline was clearly set in order to allow *a)* the manufacturing of the boards by a third party vendor; and *b)* the shipment of the boards from the vendor's location to the University . During these 4 weeks, the students were exposed to those ADS features useful to the execution of the design and layout of the boards. In this period, students were able to gain an appreciation of *a)* the sophistication of specialized software supporting the design and the layout of complex microwave designs; *b)* the attention to details demanded by a manufacturable layout; and *c)* the constraints that a real–world implementation imposes . For instance, the specifications of the projects included the board size. Its dimensions were constrained by the vendor's fabrication capabilities vs. pricing options. While the students were not made aware of actual costs, the constraint was very real and they were reminded of it many times!
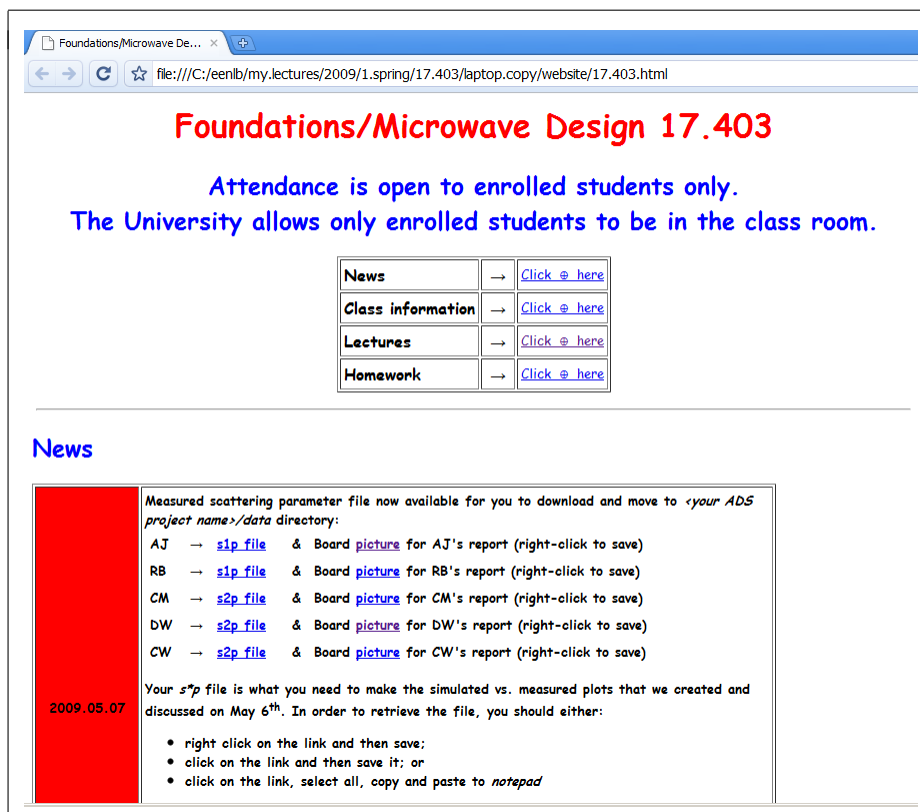

Figure 1: Class website: students were able to access the website from any computer, on or off–campus. The *News*, *Lectures* and *Homework* sections were updated on a regular basis.

Since the individual pace of the students to process the information was different as expected, each student would interact with the author either in person or by email with a number of very different questions. While reminders to discuss tips and design challenges during and after class were regularly made, it became clear that questions generated by individual students could be of

interest to everyone. The sharing of information was addressed by improving the class website, Fig. 1, that the author would update after each lecture with *a*) a description of the topics discussed in class; *b*) material (such as slides or ADS examples) used during that class; and *c*) homework supporting the lectures and tailored to clarify the projects . The improvement, Fig. 2, consisted of listing in the *News* section, suggestions and tips aiming at facilitating their design task and their use of ADS. Hypertext links within the page were used to direct students to homework, lecture material, ADS examples that relate to a particular issue. The goal was to make the website the *knowledge center* for the students to consult before bringing the issue up in class or directly with the author.
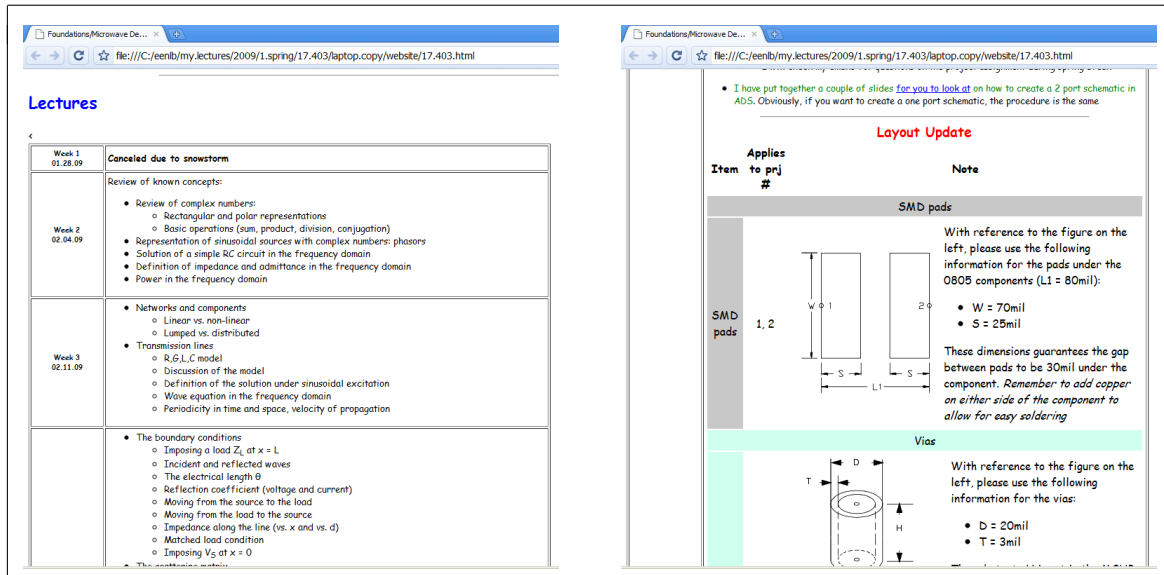
Figure 2: Screen–shots of the *Lecture* section (left); and of the *News* section (right). The website has 4 sections, hyperlinked at the top of the webpage, Fig. 1. Students were reminded to check out the website regularly before contacting the author with their questions as new hints and suggestions related to the execution of the project were being posted on a regular basis.

Student evaluation was also tailored to the unique environment offered by the PCB project. Typically, a total of 4 evaluations are offered during the semester. These evaluations consist of two multiple choice quizzes; one midterm exam; and one final exam. The quizzes are 30 minute long, multiple choice questionnaires and they aim at providing an estimate of the student's understanding of the topics covered up to that point in time; they are scheduled halfway through the two periods defined by the midterm exam. Both midterm and final exam consists of a design problem (e.g. design a matching circuit with ideal transmission lines) followed by technical questions.

The opportunity presented by the PCB design called for an overhaul of the final exam: the students were asked to submit a written report and give an oral presentation of their results to the class. Indeed, the author believes that it is important for undergraduate students to have the opportunity – often the first one – to address an audience of their peers as part of the experiential pedagogical approach. In light of the fact that this was indeed the very first presentation for most students, the final grade was solely based on the written report.

It may be worth stress out at this point that many Universities offer this type of hands–on microwave projects to students. However, as the reader may be aware, the tools involved in executing this type of projects are primarily found in Universities with an established tradition of graduate and post–graduate research activities in the microwave area. These activities provide the necessary know–how and funding to support a microwave laboratory, whose instruments alone cost in the tens of thousands of US dollars. Indeed, this paper describes the author's attempt to bring his Institution closer to the high standards set out by other US Campuses.

The projects

The projects consists of the design, simulation, layout and characterization of a matching circuit with microstrip lines at the design frequency $f_o = 1.5$GHz on a given substrate, Fig. 3. The projects aim at letting the students appreciate the physical effects that take place when the electrical wavelength of the signal the circuit is processing, is comparable with the physical dimensions of the circuit itself. Proper selection of design frequency and PCB substrate material enable the successful execution of the projects. The following considerations have guided the author towards the definition of the projects:

- *have the students place their projects within a familiar context*: commercial GPS systems are ubiquitous nowadays. Their operation is centered at 1.57542GHz;
- *find a correct balance between board size and its cost*: the larger the board, the easier the layout, the higher the fabrication costs. However, small dimensions are generally associated with microwave and wireless applications and the projects must match this expectation;
- *mix distributed and lumped components on the same board*: students should verify first hand that a number of technologies may coexist to deliver the expected performance.

The *flame retardant 4* (FR4) substrate is widely used for electronic applications, including microwave circuits such as GPS and wireless phones, and provides a cost effective solution in the low GHz range. Depending on the substrate in use, a $\lambda/4$ transformer in microstrip is in the order of 1in in length. Therefore, the board size was selected to be 2in $\times$ 2in to meet the vendor's requirements and the project's needs. The board layer structure is *1oz copper–substrate–1oz copper* to support microstrip lines – a widely used implementation of transmission lines. In order to support the discussion of lumped vs. distributed components, surface mount devices (SMD) of manageable dimensions (0805 size, 80mils $\times$ 50mils) were used[7].

The fundamental effect[1] of an ideal, lossless transmission line when applied to a load Z_L is to change the phase of its reflection coefficient proportionally to the line's physical length l:

$$\Gamma_{in} = \Gamma_L \cdot e^{-\jmath 2kl} \tag{1}$$

where k is the propagation constant; Γ_L is the reflection coefficient associated with Z_L at $x = l$; and Γ_{in} is the reflection coefficients associated with the input impedance Z_{in} at $x = 0$. The relationship between impedance and reflection coefficient is:

$$\Gamma = \frac{Z - Z_o}{Z + Z_o} \tag{2}$$

Figure 3: Final assignments of the projects to the students as described on the class website. The topology of the matching circuit was selected by the students.

where Z_o is the characteristic impedance (typically 50Ω). Both k and Z_o depend on the substrate material; in particular, the line's physical width directly affects Z_o. The product $\theta = 2kl$ is called *electrical length* and it is measured in either degrees or radians. The propagation constant is inversely proportional to the guided wavelength λ_g:

$$k = \frac{2\pi}{\lambda_g} \tag{3}$$

If the electrical length $\theta = 2kl = 4\pi l/\lambda_g$ can be neglected in (1) because $l \ll \lambda_g$ (for instance, $\theta \leqslant 10°$ is verified), then $\Gamma_{in} \approx \Gamma_L$ and the line is effectively an ideal wire; if θ cannot be neglected because l is comparable to λ_g, then the line behaves like a transmission line. In general, the ratio l/λ_g is key to set the boundary between the concepts of distributed and lumped components.

The purpose of a matching circuit is to allow the transfer of the available power from a source to a load (for instance, from an antenna to an amplifier). The use of a compass and a ruler on a Smith chart[8,9] allow an easy visualization of the effects of (1) in the design of matching circuits; and a great simplification of the math involved to match the known load $Y_L = 1/Z_L$ to a given reflection coefficient – ideally $Z_{in} = Z_o = 50\Omega \leftrightarrow \Gamma_{in} = 0$. A standard solution[10] with lossless transmission lines consists of:

1. adding a transmission line of electrical length θ_1 to the load Y_L such that the real part G_1 of the new admittance $Y_1 = G_1 + jB_1$ is equal to $1/50\Omega = 20$mS; and
2. adding an open or short circuited stub to resonate out the susceptance $B_1 = \Im m\{Y_1\}$.

Other circuit solutions can be devised: for instance, a stub can resonate out $B_L = \Im m\{Y_L\}$ first; and then, a $\lambda/4$ transformer can make the real part $R_L = \Re e\{Y_L\}$ equal to 50Ω. Although solutions are equivalent at the design frequency f_o, their frequency response is often key for the selection of the matching circuit topology.

In order to differentiate the projects, the board would have either one or two ports. In the case of a one–port network, the load Z_L consisted of a lumped SMD resistor $R = 100\Omega$ in series with a SMD capacitor $C = 1pF$ connected to the ground plain by via holes. The impedance value associated with the load is $Z_L = R + 1/j\omega_o C \approx (100 - j106.1)\,\Omega$, where $\omega_o = 2\pi f_o$. In the case of a two–port network, the same impedance value Z_L was generated by an ideal line of given width and length to be placed between a plane $P - P'$ and an external 50Ω load connected to port 2 of the two–port network (Fig. 4). The external 50Ω load is provided by the VNA at the time of measurement; edge mounted SMA connectors were used for easy testing[7]. Length and width of the ideal transmission line were provided to the students by the author in order not to burden them with unnecessary complications; however, the students were to take this information, determine the corresponding dimension of the microstrip line and lay it out on the FR4 board as seen fit.

The students were to design the matching circuit and its layout with ADS. The layout was then exported as a Gerber file and passed on to the vendor for manufacturing after a final check made by the author. The delivery of all the information required to manufacture a circuit in a given technology is known as *tape–out*: in this case, the tape–out consisted of the delivery of the Gerber file. The author provided the students with a simple ADS template in order to facilitate their task of meeting the tape–out deadline. The template guided the student through the following basic steps:

1. use standard theory to design the required matching circuit to achieve $\Gamma_{in} = 0$ with lossless transmission lines and a Smith chart and verify it with ADS;
2. use ADS to calculate widths and lengths of the real transmission lines (microstrip lines on the FR4 substrate);
3. enter the data into the ADS microstrip models and re–simulate Γ_{in};
4. layout of the circuit within a 2in × 2in board.

When these steps are completed, the Gerber file is generated. It is important to recognize that the projects' starting point is an ideal matching circuit designed on a standard Smith chart, Fig. 4. From an educational stand–point, the students can experience the link between theory and
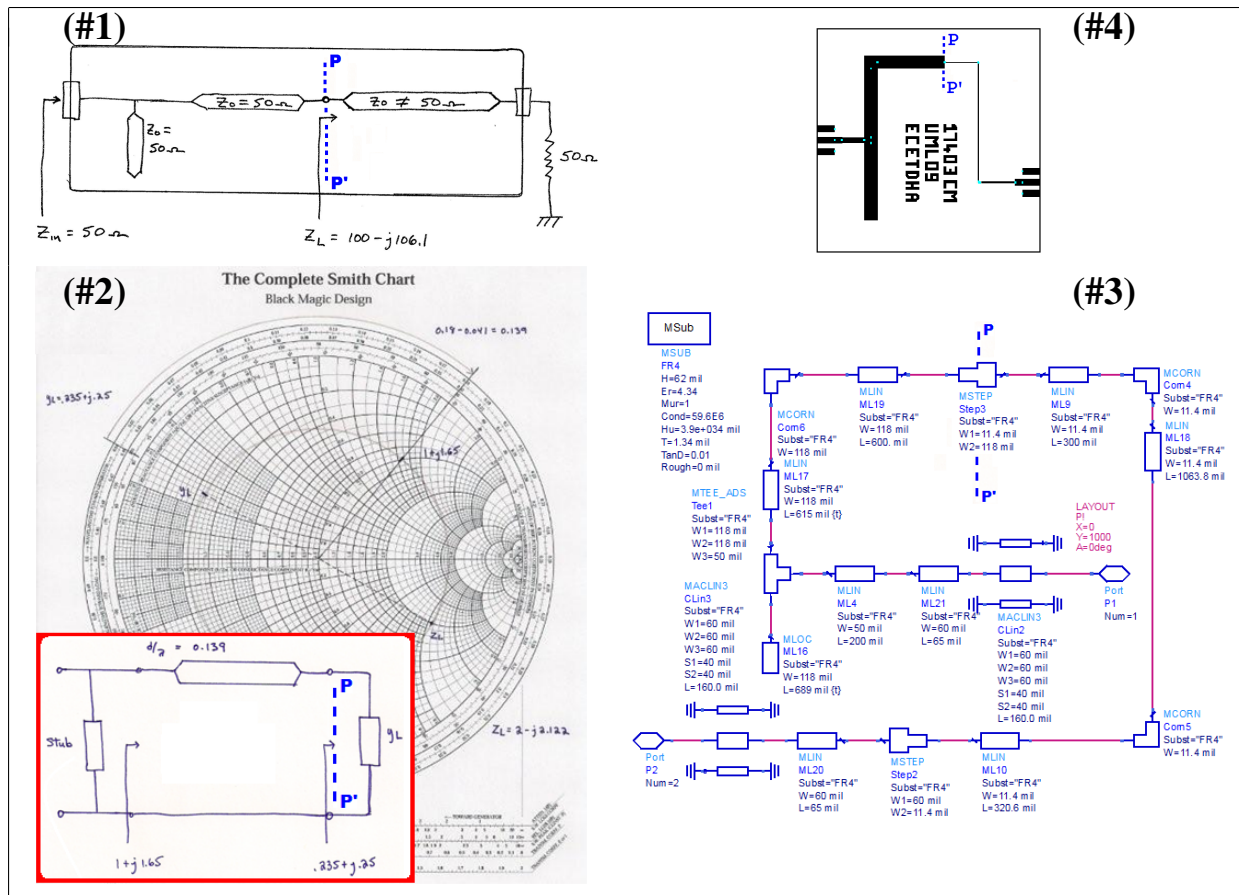
Figure 4: The basic problem of matching a given load $Z_L = 1/Y_L$ to a known input impedance Z_{in} as correctly executed by CM. From the top: (#1) $Z_L = (100 - \jmath 106.1)\,\Omega$ is matched to $Z_{in} = 50\Omega$ with the standard solution *transmission line–stub*. Z_L, located at the internal plane $P - P'$, is generated by an ideal line with characteristic impedance $\neq 50\Omega$. (#2) CM used the Smith chart to design the matching circuit after normalizing the load to $Z_o = 50\Omega$ ($y_L = Y_L \cdot Z_o \approx 0.235 + \jmath 0.250$). (#3) The circuit is simulated in ADS with microstrip models on a FR4 substrate. (#4) The board layout generated by CM. The dependance of Z_o on the line's width is clearly visible.

practice provided by a real–world circuit simulator; and the importance of a theoretical framework (transmission line theory; Smith chart; etc.) within which the students can manage design challenges and deliver a manufacturable circuit. In this context, students understand that step 3 and 4 are taken iteratively: as new microstrip models (e.g. corner, stub end–effects, width steps, etc.) are added to the circuit, both layout and electrical performance may be affected. For instance, connecting two lines orthogonal to each other, requires a metal square (a corner or a T connection) to provide electrical continuity. Then, the circuit must be resimulated and its performance verified. This is valuable experience for the students to acquire.

Following a lecture devoted to the measurement of the scattering parameters[2] and the calibration procedure[11], a standard VNA was used to characterize the manufactured boards. Standard VNAs have the ability of transferring the measured data back to the simulation software and allow an
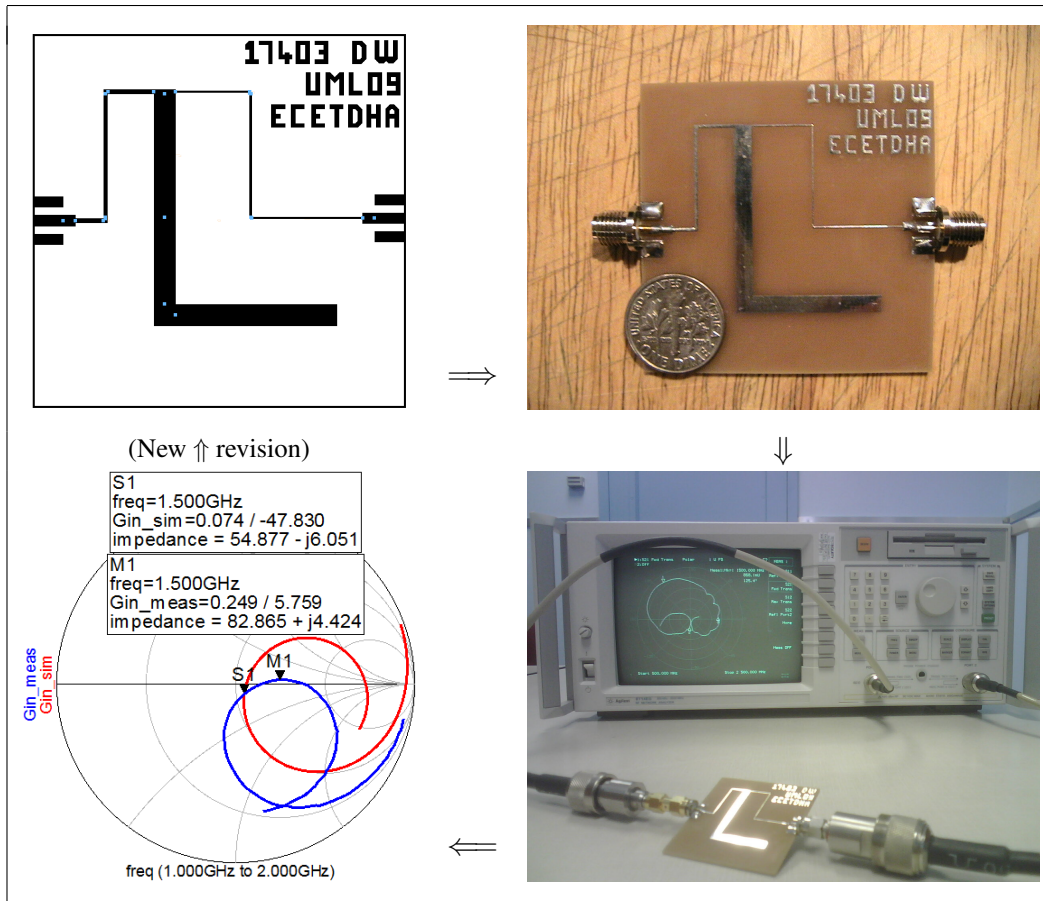
Figure 5: The logical steps required to complete the projects, consisting of a loop linking design, fabrication, test and verification. From the top left, clockwise: layout of the designed board provided by the student at tape–out; the manufactured board delivered by the vendor; characterization of the board with a vector network analyzer; and comparison between measured (blue line, M1 marker) vs. simulated results (red line, S1 marker) executed in the ADS environment. The shift of the measured (blue) trace can be demonstrated to be caused by the SMA connectors, which were not accounted for in the simulation for sake of simplicity.

easy comparison of measurement vs. simulation. Fig. 5 visualizes the logical steps required for the successful execution of the projects – from design to measurement. This is the typical loop that may be reiterated with a new revision of the circuit for further tuning of the design if the performance of the fabricated circuit does not meet the simulated response.

Students' feedback

Students were asked to provide feedback on their class experience at the end of the semester in order to evaluate the contributions of projects and lectures separately. The feedback was voluntary and it had no bearing on the students' final grade. The feedback consisted of an on–line form, Fig. 6, for the students to complete at their convenience.

Figure 6: On–line feedback form: scrolling the on–line form from the top, it consisted of an introductory explanation (left) preceding the actual questions (right) for the students to answer.

The feedback form was organized in three groups of questions, each group focusing on a different subject. The three subjects are:

1. the microwave theory of distributed elements (9 questions);
2. the PCB technology applied to microwave design (10 questions); and
3. the student's feedback on his/her execution of the PCB project (7 questions).

It should be noted that the nature of the questions was not technical. Indeed, the questions were devised to probe the student's understanding of microwave theory before and after the class; and the student's personal experience of this class. All but the last question in each group required the selection of an answer among multiple choices – e.g. either *Yes* or *No*; or a rating ranging from 0 to 10. The last question, *Further comments/inputs you may have on this topic*, allowed the student to enter a response in their own words. The decision of constraining the answers available to the students was made in order to tabulate and evaluate quantitatively the students' responses. The last question was intended to give the students an opportunity to expand their responses. The appendix shows the questions and the responses of the feedback form.

The feedback form is certainly open to criticisms as it could have been structured differently or composed by different questions – the author gladly concedes that some questions may sound more obvious than their answers! Indeed, the goal of the feedback form is to *a*) establish an initial baseline; *b*) have a sense of what the students thought of the course; and *c*) have a sense of what they gained out of it. For instance, question 1_1 was important to ask as some students may already be working in a microwave lab and have some understanding of matching circuits and distributed components. Indeed, as mentioned earlier, many microwave companies involved in activities as diverse as wireless phones or radars for military applications are located within few miles of the University of Massachusetts at Lowell.

The students' feedback highlights the fact that the students did not rely on previous knowledge of distributed components (question 1_1, 1_2) but they knew about their existence (1_3). The theory

of transmission lines relies on complex numbers for its explanations, with heavy use of trigonometric functions. Surprisingly, this aspect of the lectures was not an issue (1_4). However, the complexity of the subject required some effort to be understood (1_5) and a considerable amount of time (6 hours/week in average) was devoted to this class (1_6). Overall, the lectures were received well and the project was appreciated as a tool for the comprehension of microwave engineering (1_7, 1_8).

The students' background in electrical circuit theory and its application is mixed (2_1, 2_3). Interestingly, 2 students indicated (2_2) prior involvement with microwave circuits, despite previous statements (1_1 and 1_2). Experience with circuit simulation software did not include ADS (2_4, 2_5), which was found relativity complex to master, with some appreciable differences among students (2_6). The goal of the PCB project – to explain the real–world challenges related to a microwave design – has been achieved (2_8), and the students have clearly made the connection (2_7) between PCB technology and microwave engineering. However, (2_9), a slight majority failed to understand that the PCB technology is just one of many microwave technologies.

The students have been satisfied with the content (3_1), the pace (3_2) and the balance between theory and practice (3_3). This is a very rewarding result for the author, which can be linked to the author's planning efforts prior to the class. Further, the students appear to agree on the fact that the PCB project provides added value to the class (3_6) and it is a tool for the understanding of microwave engineering (3_4) since the majority would suggest to attend this class even if the project was not part of it (3_5).

Looking back to the experience, some considerations and suggestions can be drawn for the future:

- the student's understanding of a complex subject such as microwave engineering can be enhanced with a simple, yet practical project;
- the experiential approach can be enhanced by a theoretical framework that complements it and guides the student towards a successful completion of the project;
- providing a solid review of the math behind the analysis of transmission lines under sinusoidal excitation (e.g. trigonometric functions, complex numbers) will facilitate the task of understanding the physics of guided wave propagation;
- lectures should not be structured around the project, rather the project should be considered as an opportunity to introduce the students to both standard and modern tools necessary to the completion of the design – in this context, the microwave software becomes the modern evolution of the graphical approach based on the Smith chart;
- making the projects simple but as close to a real–world design as possible is key for a successful fruition of the project by the students: the goal is to expose the students to the requirements of real–world applications, rather than having them focus on the project itself;
- the lecturer should not limit the class content to the project, rather take advantage of the opportunity to broaden the students' horizon to other technical subjects.

One key challenge for the lecturer is to avoid being put off by the details of software operation, while keeping in mind that its simulation and layout capabilities are just tools in the student's hands. Indeed, it is easy to transform the lectures into a course on how to use the software: this

should not happen as there is no one single industry standard. The lecturer must find the right balance between what subjects ought to be part of the lectures, and what topics ought to be left to the students' curiosity, while aiming at achieving the pedagogical objective of the course.

Conclusions

This paper has presented and discussed a project for the design and fabrication of a PCB board in a microwave engineering technology class at the University of Massachusetts, Lowell. The project has been funded by ECETDHA. Information on the changes made to the standard class syllabus in order to accommodate the execution of the project has been provided. A description of the projects and how the students have tackled their design has been presented. A review of the feedback form and a discussion of the results to gauge students' reaction and understanding of the project within the broad area of microwave engineering have been made. The students' feedback to this project has been positive, as it appears that the right balance between theory and practice has been struck. Suggestions stemming from this project have been outlined. The experience is easily reproducible and rewards the students' commitment with a lot of additional, marketable value.

Appendix: Feedback form

Feedback forms were completed by $N = 5$ students. Average $\overline{x}$ and standard deviation σ_x are calculated as follows

$$\overline{x} = \frac{1}{N} \sum_{n=1}^{N} x_n$$

$$\sigma_x = \sqrt{\frac{1}{N} \sum_{n=1}^{N} (x_n - \overline{x})^2}$$

The feedback form consists of a number of questions collected in 3 groups or *components*. Questions are labeled *<component>_<#>*. Responses are tabulated below and the tallying is self–explanatory. The component's last question, always *<component>_<0>*, allowed the students to enter additional feedback in their own words: when provided, they are listed out at the end of each component.

Component 1: the microwave theory of distributed elements		
1_1	Did you know what the microwave theory of distributed elements was before attending this class?	NO = 5 YES = 0
1_2	Would you have been able to explain to your peers what a distributed element is before attending this class?	NO = 4 YES = 1
1_3	Were you aware of the existence of distributed components as electrical component?	NO = 1 YES = 4
1_4	Have you been able to follow the math behind the theory of distributed transmission lines?	NO = 0 YES = 5
1_5	How much effort were you required to put in to understand the theory of distributed transmission lines? 0 = no effort; 10 = a lot of effort.	$\overline{x} = 7.20$ $\sigma_x = 0.75$
1_6	How many hours per week have you spent in average on the subject of the theory of distributed transmission lines? Available choices: 2, 4, 6, 8, 10 hours.	$\overline{x} = 6.00$ $\sigma_x = 1.26$
1_7	Do you think this class has been able to provide a comprehensive description of what microwave engineering is about?	NO = 0 YES = 5
1_8	Would your comprehension of microwave engineering be less/same/more if you had not been involved in the PCB design project funded by ECETDHA?	LESS = 4 SAME = 1 MORE = 0

Question 1_0: *Further comments/inputs you may have on this topic*

1. *I took Emag 1 before this class which helped, it should be encouraged or required*
2. *It would be nice to have lecture notes before the lecture*
3. *I really enjoyed the design project, as well as learning about the theory taught in this class. I would like to know MORE!!! about microwave engineering - there are a lot of topics that we didn't have time for in the class that are interesting to me. In general the course really provided a good introduction and start to this study.*
4. *Although I feel my learning about TX lines did not improve from the Project, I thought the project was excellent! The REAL PROBLEM here was the amount of time we had to acquaint ourselves with the simulations and layout using Agilent ADS.*

Component 2: the PCB technology applied to microwave design		
2_1	Had you ever designed an electrical circuit of any type prior to attending this class?	NO = 2 YES = 3
2_2	Had you ever dealt with microwave circuits prior to attending this class?	NO = 3 YES = 2
2_3	Had you ever been exposed to PCB technology prior to attending this class?	NO = 2 YES = 3
2_4	Had you ever used simulation software to design an electrical circuit prior to attending this class?	NO = 1 YES = 4
2_5	Had you used Agilent Advanced Design System (ADS) prior to attending this class?	NO = 5 YES = 0
2_6	How challenging has the use of ADS been? 0 = no challenge; 10 = extremely challenging.	$\bar{x} = 6.40$ $\sigma_x = 2.42$
2_7	How clearly has the theory of distributed components been linked to PCB technology? 0 = not clear at all; 10 = very clearly.	$\bar{x} = 8.60$ $\sigma_x = 0.49$
2_8	How would you rate the design of the board as a tool to explain real world challenges related to the design of microwave PCB circuits? 0 = useless tool; 10 = indispensable tool.	$\bar{x} = 9.60$ $\sigma_x = 0.80$
2_9	Would you agree with the following sentence: microwave applications cannot exist without PCB technology?	NO = 2 YES = 3

Question 2_0: *Further comments/inputs you may have on this topic*

1. *I think a little more time on learning ADS would have made the design process less labor intensive.*
2. *I think some extra time on learning ADS would have made the design process easier.*
3. *I did not like the idea of the project at first. Having done this course. I think it is a very good idea.*
4. *I don't really know about the answer to 2.9! I think many or maybe even most microwave applications currently might use PCB technology, but I can imagine that some other kind of microwave circuit fabrication does exist or will exist!? I think there are 3-dimensional integrated circuits being developed, for instance.*

Component 3: your feedback on the execution of this project		
3_1	Has the class met your expectations?	NO = 0 YES = 5
3_2	Has the pace of the class been too slow/just right/too fast?	TOO SLOW = 0 JUST RIGHT = 4 TOO FAST = 1
3_3	Has the hands-on time (i.e. access to the lab and ADS) been too little/just right/too much compared to the time allocated to theory?	TOO LITTLE = 1 JUST RIGHT = 4 TOO MUCH = 0
3_4	Do you think that your understanding of microwave theory and its applications has benefited from the design and fabrication of a PCB board?	NO = 0 YES = 5
3_5	Would you suggest a fellow student to take this class if you knew that the class does not include the fabrication of a PCB microwave circuit?	NO = 2 YES = 3
3_6	How much value would you say the PCB project adds to this this class? 0 = no additional value added; 10 = overwhelming additional value.	$\overline{x} = 8.40$ $\sigma_x = 1.50$

Question 3_0: *Further comments/inputs you may have on this topic*

1. *I had to put more time (beyond class time) to complete the design but I really feel the project made me more marketable as an engineer. The final report reinforced the project.*
2. *Doing a project really helps with understanding. It shows you what you understand and what you do not.*
3. *I would say the project added a lot of value to the class. However I think the class would be interesting even without the project. It definitely took some extra time that could also be used to explore additional topics. In the end, I think the project was the more rare and valuble experience. Perhaps more topics could be covered in the course, even while doing a project design; or a second course on the subject could be introduced.*

Bibliography

1. G. Gonzalez, *Microwave Transistor Amplifiers: Analysis and Design*. Prentice Hall, 2nd ed., 1996.
2. Hewlett Packard Application Note 95, *S Parameters... Circuit Analysis and Design*. Palo Alto, CA, Sep 1968.
3. D. Pozar, *Microwave Engineering*. Addison Wesley, 1990.
4. D. Kolb, *Experiential Learning: Experience as the Source of Learning and Development*. Prentice Hall, 2000.
5. A. Shakur, P. Pramanick, A. Eydgahi, I. K. Dabipi, and M. Fotouhi, "A novel microwave engineering course in a collaborative electrical engineering program," *Proceedings of the 2003 American Society for Engineering Education Annual Conference and Exposition*, 2003. Session 1332.
6. A. Knox, *Helping Adults Learn*. San Francisco: Jossey–Bass, 1986.
7. Digi-Key, *Digi–Key Catalogue*. Digi–Key Corporation, 2009.
8. B. C. Wadell, "Smith charts are easy. I," *IEEE Instrumentation & Measurement Magazine*, vol. 2, No. 1, pp. 37–44, March 1999.
9. B. C. Wadell, "Smith charts are easy. II," *IEEE Instrumentation & Measurement Magazine*, vol. 2, No. 2, pp. 45–47, June 1999.

10. R. Collin, *Foundation for Microwave Engineering*. McGraw Hill Inc., second ed., 1992.
11. Hewlett Packard Company, *HP8510 Network Analyser – Operating and Device Manual*. Palo Alto, CA, 1985.