AC 2008-777: WEAVING A MICROWAVES THREAD THROUGH THE CURRICULUM

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Weaving A Microwaves Thread Through The Curriculum

Abstract

A set of educational materials being spread across the electrical and computer engineering curriculum at Montana State University to help students develop an increasingly deep and broad understanding of high frequency electronics is described. The materials are being developed to be integrated in several courses taken by undergraduate students beginning in freshman year and include lecture demonstrations, laboratory exercises and design projects. The development of these materials is motivated by the need for engineers well-versed in high-frequency electronics, the desire to cast common concepts learned at the foundation of the curriculum in terms of practical engineering applications and to introduce students to one of the many specialties in electrical engineering. Particular attention is given to materials developed for the freshman level introductory course.

Introduction

A meaningful educational experience for an undergraduate intending to pursue a career in high-frequency / microwave electronics requires involvement in a curriculum that both stresses fundamental concepts and provides thorough exposure to modern design tools and techniques routinely used by experienced practitioners in the field. To meet this need, several universities have developed courses that allow students to design, simulate and test microwave components. However, there are two key areas in which many of these courses could be further developed: (1) students should be given an opportunity to use their newly developed component-level design capabilities toward a system-level problem and (2) students should engage in activities that prepare them for emerging trends in the field. The senior-level course in microwave circuits at Montana State University has been redesigned using this philosophy based on materials developed at another university as described by Furse et. al..[1] Even those electrical engineering students pursuing specialties other than microwave electronics can benefit from rudimentary knowledge of high-frequency effects. For example, an understanding of transmission line and other high-frequency effects is of vital importance for engineers involved in high-speed digital design.

This paper describes educational materials that integrate key concepts in high-frequency electronics into several courses within the electrical and computer engineering curriculum. The materials developed for the lower-level courses take a fundamental topic from the course and expound upon it using a concept relevant to high-frequency electronics. In addition to helping students learn the fundamentals in terms of modern engineering applications, the newly developed materials are intended to introduce students to an increasing important specialty in electrical and computer engineering. For those students developing sufficient interest in high-frequency electronics, as mentioned previously, the senior-level elective in microwave electronics has been revamped to reflect best practices in the field. A similar vertical integration scheme that involves materials related to other specialties within electrical engineering is being considered.

Motivating the Study of Waveforms In The Freshman Electrical Engineering Course

Our introductory electrical engineering course, EE 101 – Fundamentals of Electrical Circuits Laboratory, has recently undergone a significant revision and now guides students in learning the basics of circuit theory, characteristics of electronic components and electrical measurement techniques as students assemble microcontroller-based robots.[2] As revealed through student surveys regarding their experiences in the revised course, the robot-based activities have been very well received. Having taught the current version of EE 101 several times, both the author and another faculty member teaching the course, while generally viewing the course as a significant success, felt that the it could be further improved by introducing students to areas of focus within the general discipline of electrical and computer engineering other than robotics. As the author's primary area of scholarship is high-frequency electronics, this seemed a natural starting point. Not wanting to dramatically change course objectives or delivery methods, but only to introduce an interesting concept from high-frequency electronics into the current structure of the course, one 50 minute lecture and one two-hour laboratory session per week, the author chose the following course outcome statements upon which to focus.

Given a sketch of a sinusoidal waveform, I am able to write an equation that properly describes its amplitude, frequency and phase shift with respect to a reference sinusoid.

I am able to determine the amplitude, frequency, period and phase shift of a sinusoidal signal using an oscilloscope.

To provide the instructor a baseline appreciation of the educational background of students and to ensure students' awareness of the instructional objectives, the author introduces a list of instructional outcomes for the course through the use of a day one anonymous survey that asks students to rate their proficiency in meeting the instructional objectives. As the course assumes only a college algebra background, it is not uncommon to have a few students respond as having come to the class with some knowledge of a couple of the course outcomes.

The primary opportunity for students to work with sinusoids in EE 101 comes in a lab in which each student is to measure the change in magnitude and phase shift as a function of frequency between an input voltage signal and the output voltage defined as that across a capacitor in a simple resistor-capacitor circuit (single pole RC). Students are then to describe what they feel is meant by a lowpass circuit. Looking for a compelling means to emphasize the importance of frequency and phase shift to students, while simultaneously introducing students to a topic germane to high-frequency systems, the author chose to develop materials to introduce students to phase-array antennas. The materials include a chapter written for the course note set and hardware for a lecture demonstration.

The chapter written to introduce students to antennas and antenna arrays states that:

After reading this chapter you should:

(1) Be able to identify two common types of antennas
(2) Understand how to interpret a simple antenna radiation pattern

(3) Understand how the radiation pattern of a single antenna may be altered using additional antenna elements
(4) Have an appreciation for an application of your knowledge of frequency, wavelength, phase shift and electrical length

To achieve these goals, the chapter briefly introduces the dipole antenna and then focuses on the planar microstrip ("patch") antenna, as this is the type used for the in-class demonstration. Figure 1 is a photograph of one of the patch antennas described in the note set. Students are reminded of the relation between frequency and wavelength, the notion of electrical length is introduced earlier in the note set, and led through the calculation of the wavelength of a 2.4 GHz signal in the dielectric material (λ_d) used to realize the antenna.

Figure 2, another taken from the note set, illustrates the simulated 3D antenna radiation pattern of the patch antenna. The idea of shaping the antenna pattern and controlling its primary direction is suggested to the student and the use of such techniques to increase capacity in a wireless communication system is noted.

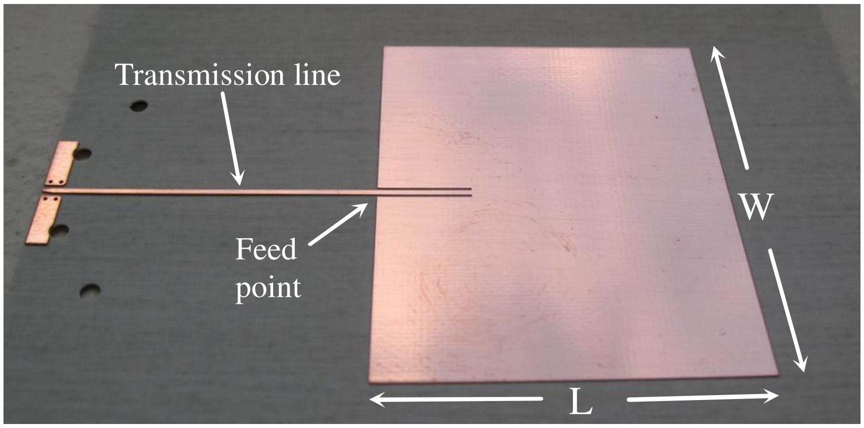

Figure 1: Photograph of a so-called "patch" antenna realized on a dielectric substrate. While not shown in the photograph, the backside of the substrate is completely coated with copper metalization. The length (L) of the patch is chosen to be approximately equal to $\lambda_d/2$ at the design frequency of 2.4 GHz.

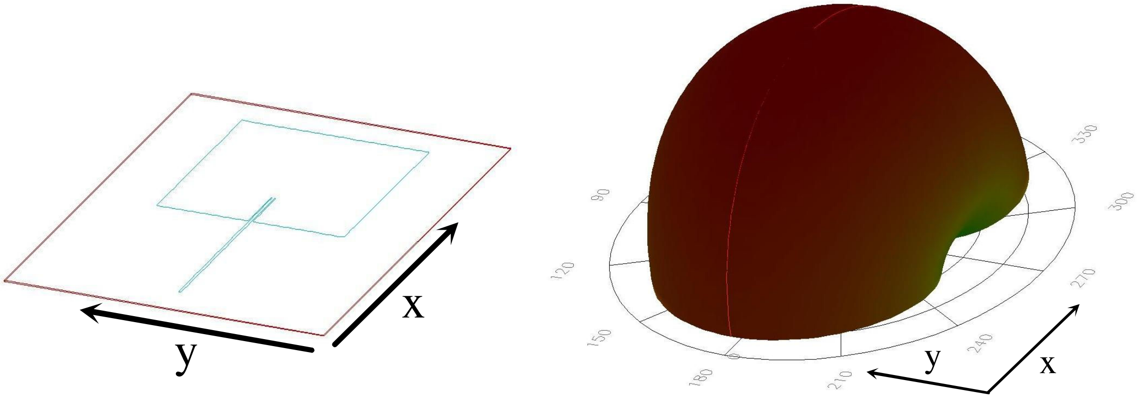

Figure 2: Sketch of the patch antenna and its predicted 3D radiation pattern.

The in-class demonstration utilizes two-element linear arrays to show how phase shift between equal amplitude signals may be used to steer an antenna beam. To help prepare the students for the demonstration, the chapter introduces an example two-element array and how its antenna pattern can differ greatly from that of a single antenna. Figure 3 describes a theoretical in-phase fed two-element array in which the antennas are separated by a distance L_{sep}, and Figure 4 shows the 2D antenna pattern of a single antenna and that resulting from a two-element array in which L_{sep} is equal to one wavelength. Both Figures 3 and 4 are taken from the course note set. Clear from Figure 4 is the ability of an array to increase the directivity of the radiation pattern. Also of interest in the array's pattern are the nulls 30 degrees on either side of the maximum. Using simple geometric arguments, students follow calculations demonstrating 180^{o} of phase difference between the signals launched from the antennas as observed at points distant from the antenna and at 30^{o} from the normal to the antenna surface. The 180^{o} phase difference results in destructive interference.

Returning to the idea of electrical length, the students must then calculate the phase delay between signals entering the two antennas if a longer transmission line is used to feed one of the antennas. By controlling the phase difference between the signals fed to the antennas, the primary beam of the array may be steered and/or nulls may be placed where desired. Prior to coming to class, students are to calculate the location of nulls in the radiation pattern of two arrays with different phase excitation schemes. A photograph of the arrays used in the class demonstration is given in Figure 5.

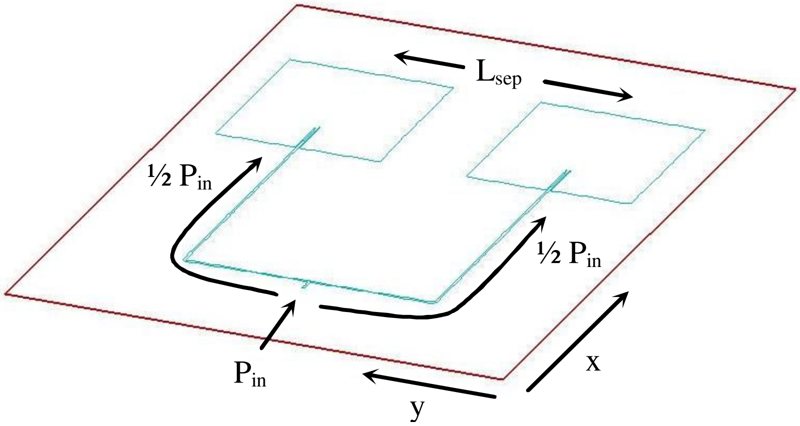

Figure 3: Sketch of a two-element patch antenna array. In this configuration ½ of the input signal arrives in-phase at both elements. The center-to-center separation distance between the antennas is denoted L_{sep} and P_{in} refers to the input power.

The two arrays use different delay lines to achieve 90^{o} and 180^{o} degrees of phase shift (at the design frequency of 2.4 GHz) between the antennas of the individual arrays respectively. As mentioned previously, students are to come to class having calculated the location of the nulls of the radiation patterns for the two arrays. Figure 6, again provided in the note set, aids the student in setting up the calculations to locate the nulls. A sample calculation for the array on the left of Figure 5 is given below. The effective dielectric constant used in the transmission line calculation is denoted ε_{eff}.

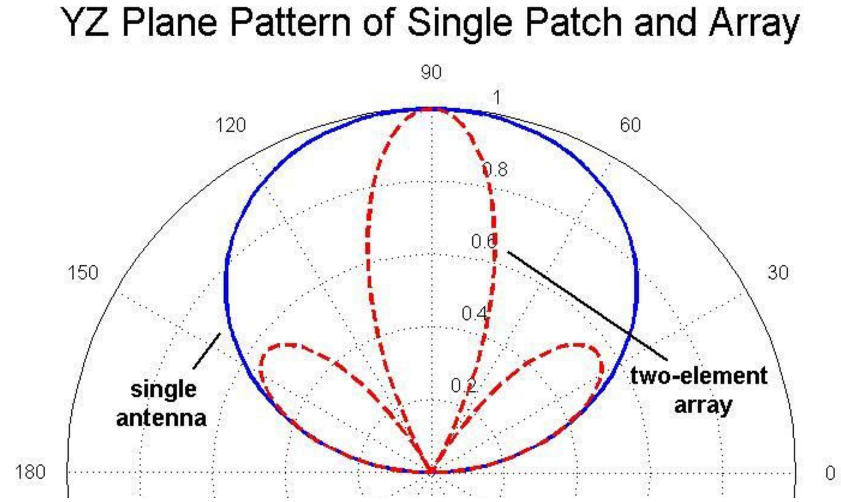

Figure 4: 2D radiation patterns of a single patch antenna and a two-element patch antenna array in which the two patches are fed with equal amplitude in-phase signals. The array elements are spaced such that $L_{sep} = \lambda$.

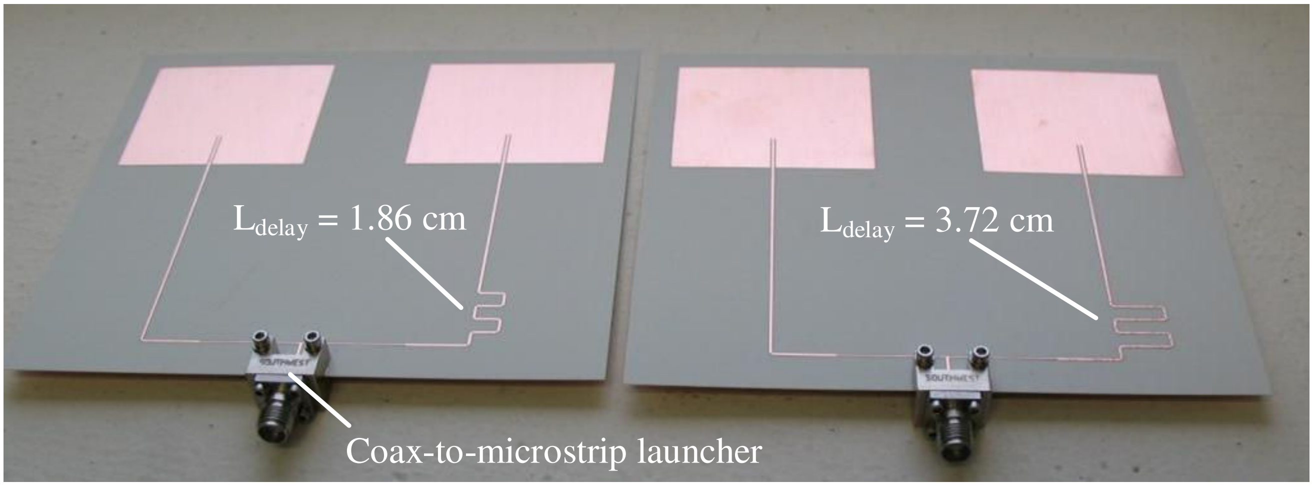

Figure 5: A photograph of the two two-element patch antenna arrays used for an in-class demonstration of an application of phase shift between sinusoids in high-frequency wireless systems. In each case, a 2.4 GHz signal is introduced on the board using a coaxial-to-microstrip launcher. The array on the left uses a 1.86 cm delay line to introduce a 90^o phase shift between signals arriving at the two antennas and the array on the right doubles the delay to introduce a full 180^o of phase shift between signals fed to the antennas. In both cases $L_{sep} = \lambda/2$.

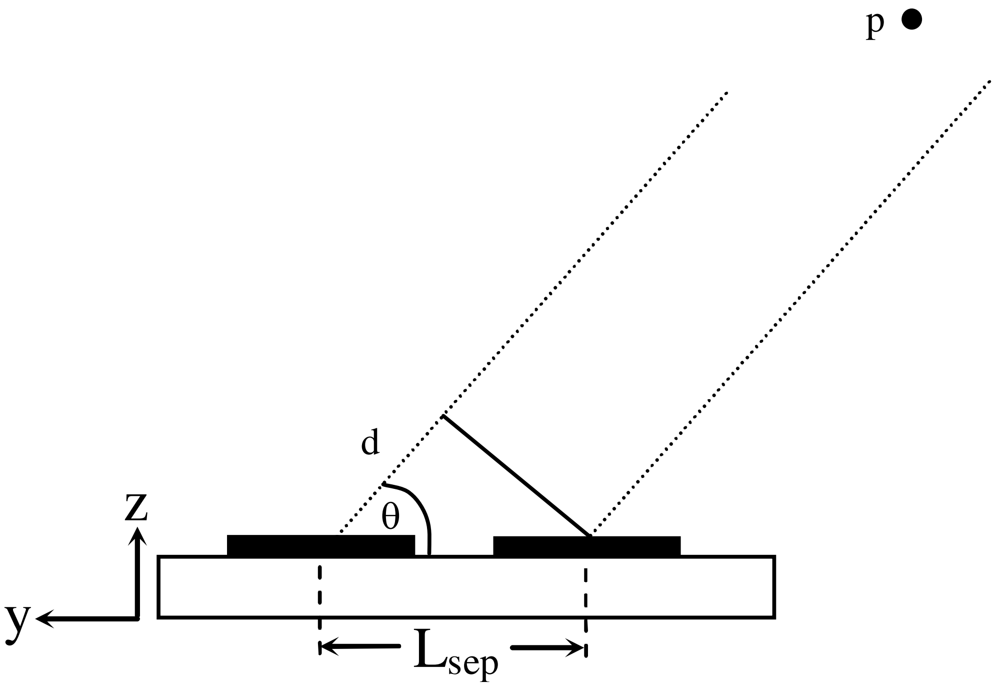

Figure 6: Sketch of a two-element array with a distant observation point 'p'. When the observation point is sufficiently far from the antennas, rays drawn from each patch to the observation point are approximately parallel. In such a case, the distance labeled 'd' amounts to the path difference between the rays to the observation point.

- The guided wavelength, λ_g, on the transmission line at 2.4 GHz:

$$\lambda_g = \frac{c}{f\sqrt{\varepsilon_{eff}}} = \frac{2.998 \text{ x } 10^8 \text{ m/s}}{2.4\text{x}10^9\text{Hz}\sqrt{2.82}} = 7.44 \text{ cm}$$

- Phase delay introduced by longer transmission line of the antenna array:

$$\text{phase delay} = \frac{1.86 \text{ cm}}{7.44 \text{ cm}} \text{ x } 360^\circ = 90^\circ$$

- Amount of additional phase delay to introduce a null = 90°

- Value of d in terms of wavelengths to introduce the necessary additional = $\lambda/4$

- Angle at which the necessary value of d is obtained

$$\theta_{cancel} = \arccos\left(\frac{d}{L_{sep}}\right) = \arccos\left(\frac{\lambda/4}{\lambda/2}\right) = \arccos\left(\frac{1}{2}\right) = 60^\circ$$

Following a similar set of steps, it is easy to show that the null for the array on the right in Figure 5 (L_{delay} = 3.72 cm) should be at 90°, that is, normal to the plane of the antennas!

The first use of the demonstration occurred in the two lecture sections during the fall 2007 offering of EE 101. The 2.4 GHz signal necessary to stimulate the transmit antenna (a single patch antenna) was realized using a commercially available voltage controlled oscillator (the ZX-95-2650-S+ from Minicircuits, Inc) biased using a bench-top DC supply and exhibited an output power of about 1 mW. The receive antenna array was placed approximately two feet from transmit antenna with the received signal monitored by a spectrum analyzer (typical received power at maximum in radiation pattern ~ -35 dBm). The measured null locations, as determined with a simple protractor by student volunteers, was within a few degrees of what was predicted. For further validation of the correspondence between theory and experiment, the students were shown results such as those depicted in Figure 7 taken in the electromagnetically quiet environment of an anechoic chamber.

The first offering of the antenna demonstration was successful from the point of view of the instructor and through feedback received from the students. Further effort is being expended on the demonstration hardware and experimental setup such that it is more effective for use in a large classrooms (having a large readout of the spectrum analyzer proved difficult in the classrooms used) and so that it may be used in other environments such as junior colleges and high schools as an example of the importance of understanding waveforms. In the spring of 2008, we plan to use a USB power meter that connects to a laptop and ultimately to a video projector to improve the visual impact of the demonstration. To obviate the need for a spectrum analyzer or commercial power meter for schools interested in adopting the demonstration, but without access to such expensive test equipment (about $2300 for the power meter, $20,000 for the spectrum analyzer), we are currently developing circuitry that provides an audible cue relating the frequency of the sound to the power received. To further reduce cost, we also intend to design antennas that can be made from the empty soup cans instead of utilizing antennas realized through printed circuit board manufacture. Realizing antennas in this manner also opens the possibility of an in-class antenna construction exercise.

A question may arise as to the appropriateness of requiring students to understand the notion of electrical length as freshmen. Since an understanding of electrical length requires application of frequency and wavelength and little else, it is not a tremendous hurdle to overcome. Having students appreciate electrical length and signal speed through a circuit at the freshman level has the additional benefit of helping to address the common questions the author has received during class regarding when various events happen in a circuit. To inform students that electrical length is one of the course objectives, the following course outcome statement has been added to the course syllabus and initial outcomes questionnaire: *I understand the concept of "electrical length" and can calculate a component's electrical length given its physical length and the operating frequency.*

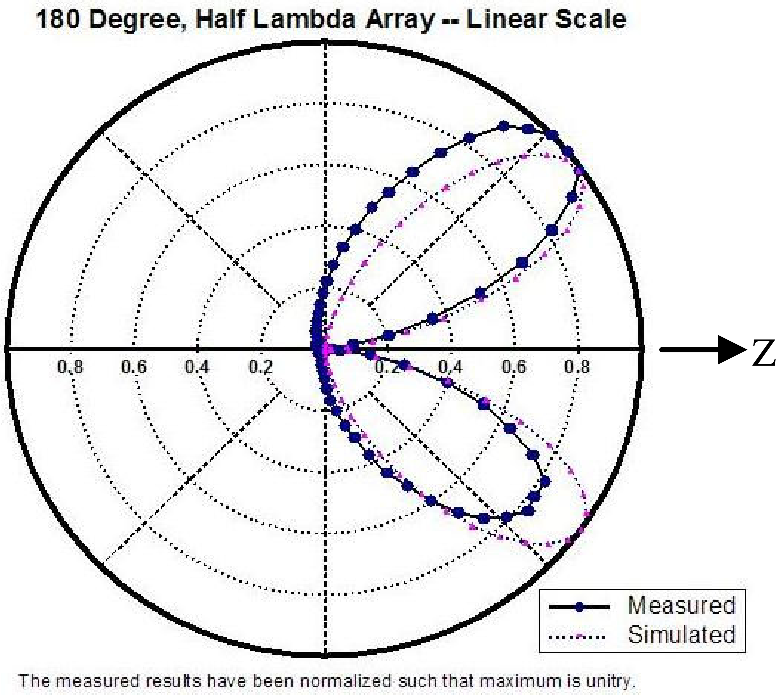

Figure 7: Measured and simulated radiation pattern of the 180^o two-element patch antenna array. The patterns show that the array has a null in the plane normal to the array (the location of the maximum for a single patch).

Using Non-Idealities of Lumped Elements To Reinforce The Concept of Resonant Frequency in a Sophomore Circuits Course

The second discipline specific course that students take in the electrical and computer engineering curriculum at Montana State University is EE 206 – Circuits I. The course explores fundamental concepts in electrical circuits including a review of the circuit laws learned in EE 101, nodal and mesh analysis methods, RC, RL and RLC response, steady state AC circuits and three phase circuits. The non-ideality of lumped elements at radio frequencies was chosen to serve as a vehicle to further explore the standard topics of frequency response and resonance covered in EE 206. The author has noted in many of the department's capstone senior design projects that entail printed circuit board layout for high frequency systems, students are ill-prepared to account for component and board parasitics as well as transmission line effects that arise at radio frequencies and above. Indeed, as circuit speed of both analog and digital circuits constantly increases, the need for proper accounting of high-frequency effects is now commonplace. Such "advanced" considerations are typically left to upper division elective courses and thus are often missed by undergraduates completely. By introducing the basics of electrical length in EE 101 and non-ideal lumped elements in EE 206, students should be able to develop an appreciation for practical considerations in circuit design relevant to activities they may face in their capstone projects and beyond.

In the laboratory experiment of EE 206, entitled "Frequency Response," students use a function generator and oscilloscope to study the frequency response of simple RC, RL and series RLC circuits in terms of input and output voltage amplitude and phase. Some of this material is clearly a review from EE 101. To provide students an additional opportunity to consider the material, an addendum to the lab was written and will be auditioned in Spring 2008. The additional exercise is entitled, *When a capacitor isn't capacitive – parasitics and resonance in a lumped element* and asks students to (1) consider the measured impedance of a standard 100 pF ceramic capacitor mounted on a printed circuit board, (2) develop a simple two-element lumped equivalent circuit of the component, and (3) address how the actual behavior of the capacitor will affect the performance of a simple lowpass filter studied earlier in the lab if the filter's cutoff frequency is shifted to beyond the capacitor's self resonant frequency. A photograph of a 100 pF ceramic capacitor mounted on a printed circuit board with a coax-to-microstrip transition is shown on the left Figure 8. A similar measurement setup is utilized by students in the senior-level microwave electronics course for an advanced component modeling exercise. The measured data are to be made available on the course website for use in the software package MATLAB which is an integral part of the curriculum. It was decided for the first offering of the exercise that students not make the measurements themselves as this would require use of an instrument such as an impedance or network analyzer (an N5230A Vector Network Analyzer was used for the measurements) capable of performing accurate measurements in the MHz range and our department currently has only a few such capable instruments. The output magnitude response in which the measured capacitor is used in a hypothetical single time constant lowpass circuit with cutoff frequency of approximately 160 MHz, along with the ideal response are shown on the right of Figure 8. Clearly, the response is tremendously different providing a key take home message regarding the realities of practical implementation.

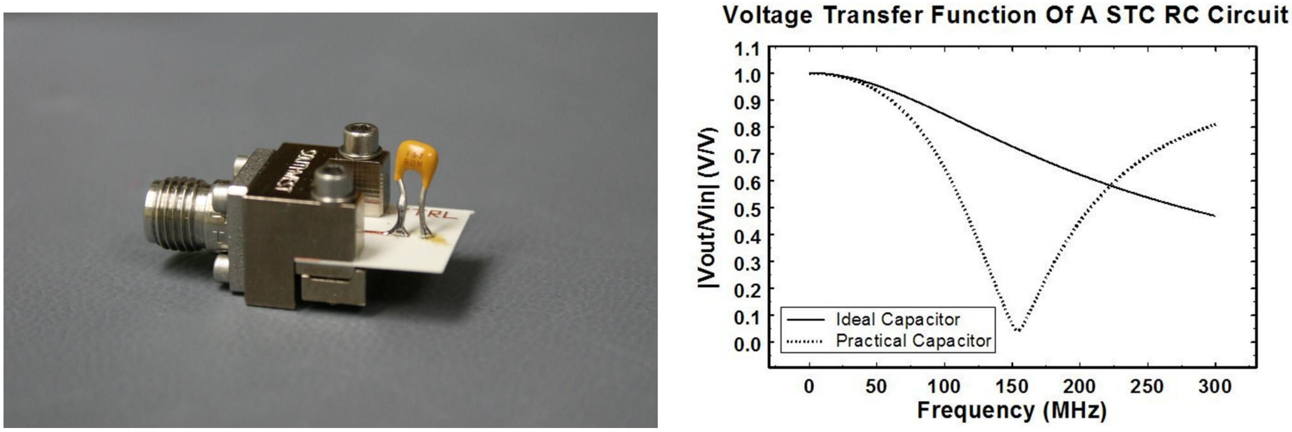

Figure 8: LEFT: Photograph of a 100 pF ceramic capacitor mounted on a printed circuit board ready for one-port impedance measurement. RIGHT: Simulated results of the output magnitude response of a single time constant RC circuit in which the output is taken across the capacitor. The "ideal" response assumes an ideal capacitor whereas the "practical" response uses the measured impedance of the 100 pF ceramic capacitor.

Mode Scattering Parameters In An Analog Electronics Course

A junior/senior level electronics course such as EE 411 – Advanced Analog Electronics at Montana State University provides an ideal vehicle to introduce concepts from high-frequency electronics by simply taking a fresh look at standard topics within the course. EE 411 covers current mirrors, differential pairs and differential amplifiers, frequency response, feedback and stability as well as active filters and oscillators. In uncovering the fundamentals of feedback, students review basic two-port network descriptions such as impedance and admittance parameters which can be used to analyze various feedback topologies. An alternate network description, the scattering matrix, is often introduced in a microwave electronics course. The scattering matrix is of vital interest in high-frequency electronics as, unlike impedance and admittance parameters, scattering parameters are readily measureable at microwave frequencies. Again, as the operating frequency of analog and digital circuits increases, those students whose specialty is analog (or digital) electronics should be conversant in the language of high-frequency electronics.

In the Spring of 2008, a set of materials will be auditioned in EE 411 that focus on so-called mixed mode scattering parameters and their application in the measurement of the properties of differential amplifiers. Mixed mode scattering parameters describe the response of a network to both common mode and differential mode signals, and thus are particularly relevant in the study of differential blocks in analog circuits whose primary function is to discriminate between the two types of excitation. To help students grasp the meaning of mixed mode scattering parameters an in-class demonstration of differential-to-common mode conversion will be given using coupled lines such as those shown in Figure 9. An extra length on one of the coupled lines (another demonstration of the importance of electrical length) can tremendously affect mode conversion – a generally undesired phenomenon. A check of the network's mixed-mode scattering parameters can quickly quantify the amount of mode conversion. Armed with this background information, students will be able to appreciate the use of mixed-mode measurements to later evaluate the common mode rejection ratio (CMRR) of differential amplifiers which they design.

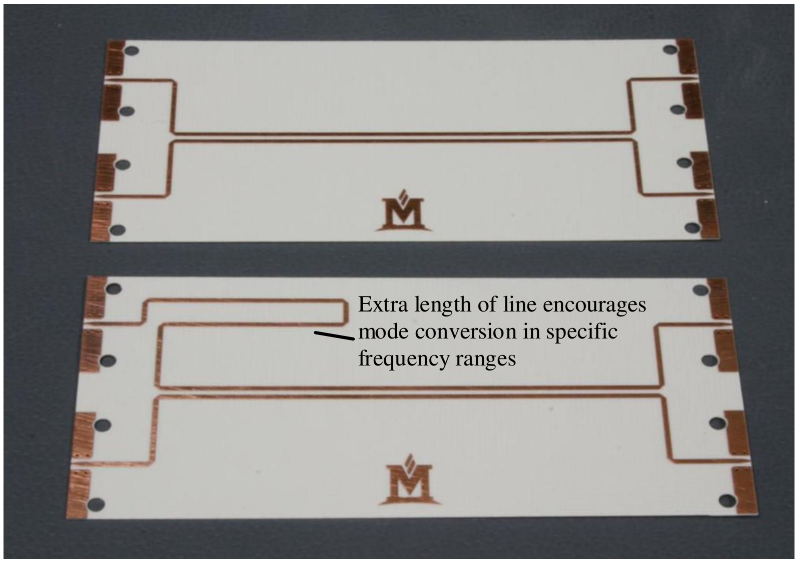

Figure 9: Photograph of two coupled line experiment boards designed to provide differing mode conversion responses to help demonstrate the use of mixed-mode scattering parameters to describe differential devices. The extra length of transmission line for the coupled-line experiment in the lower board greatly increases mode conversion at frequencies in which the extra length amounts to an odd multiple of 180°.

A four-port vector network analyzer such as the Agilent N5230A is ideal for making mixed-mode scattering parameter measurements and will be used for the experiments described herein. Such instruments are now of great interest in industry and academic research labs, but are rarely used in the classroom as they are relatively new and expensive instruments. With the continued migration from single-ended circuitry, historically that utilized in microwave design, to fully differential design, it is expected that four-port network analyzers will become more common. That being said, standard two-port network analyzers can be used for most mixed-mode measurement applications by implementing a simple matrix transform on the single-ended parameters.[3]

Component-To-System Level Design In A Microwave Circuits Course

The senior-level elective, EE 433 – Planar Microwave Circuit design at Montana State University has recently undergone significant revision to begin to bring more system-level content to the course. Previously, the course focused almost exclusively on component-level design. The current rendition of the course has largely adopted the approach described by Furse et al.[1] in having students design, simulate and test a matching network for a radio frequency diode, 2.4 GHz and 2.6 GHz bandpass filters, and a 3 dB power divider to be used as part of a simple frequency shift keyed receiver. Figure 10 is a photograph of some of the circuit boards designed and tested by students in the fall of 2007 course. While several of the technical details of our implementation of the material described by Furse et al. differ, instead of describing these details, this section will focus on plans to further develop the course based on our experiences and the nature of our department.

A challenge in a smaller department such as electrical and computer engineering at Montana State University with a modest faculty size (thirteen tenure track positions) is the difficulty in consistently offering a series of advanced undergraduate and graduate level courses in a given focus area such as microwave electronics. Thus instead of having three upper-division/graduate level courses in microwave electronics as some large departments are able to consistently offer, we have one undergraduate course offered every year specifically in microwave electronics (i.e. EE 433) and an antennas course offered at the graduate level every other year. This provides added incentive for us to craft a class such as EE 433 in a manner that provides students with sufficient background to understand the nature of the field, to provide the practical skills that they are likely to be called upon to use in industry and yet sufficient academic understanding to enable self-study of more specialized topics if necessary later in their careers. Very few students taking EE 433 for example, will design coupled-line bandpass filters once leaving the course, yet this topic can take considerable time to develop the proper theoretical background for sufficient understanding. This suggests the idea of removing the material on the nuances of bandpass filter design and rather focus on guiding students in choosing among existing products to effect the best system-level design. Indeed, with the aggressive development of small feature size, low-cost microwave components that are now readily available, the topic of distributed filter design might be better left for a graduate-level course. With these thoughts in mind, EE 433 will undergo further redesign in removing much of the materials related to the details of filter *design* and other more esoteric topics in favor of spending additional time on system-level calculations and board-layout considerations. For example, in the future, students will be able to choose between pre-designed filters with differing specifications and then must justify their choices based on system-level calculations. In another planned system-level exercise for EE 433, students will be asked to predict the performance of a Doppler radar and then test their calculations against measurement. Specifically, one of the fall 2007 EE 433 graduates is completing his undergraduate degree pursuing an independent study in which he is modifying the Doppler radar module that was his capstone design project. His completed module will form the case study for future EE 433 students. Once the final design of the Doppler radar is completed and tested experimentally against system-level calculations, a thorough description of this case study is planned.

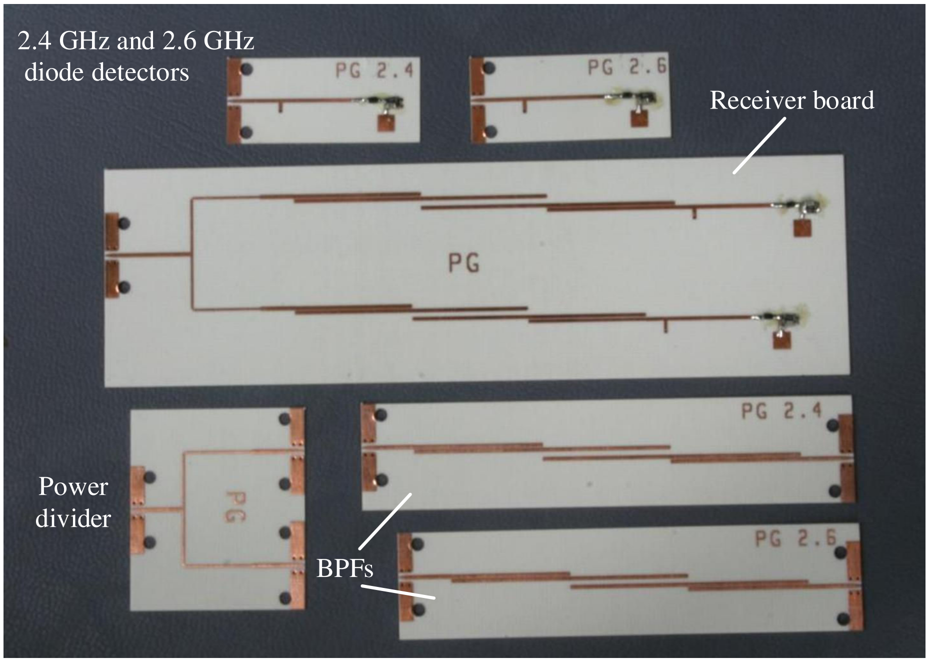

Figure 10: Photograph of a simple frequency shift keyed receiver along with constituent parts designed and tested by students in EE 433. The receiver consists of a 3dB power divider, 2.4 GHz and 2.6 GHz bandpass filters (BPFs) and 2.4 GHz and 2.6 GHz matched diode detectors. Some boards, not shown, included a surface mount amplifier. Each board has an integrated transition for a coaxial adapter (see Figure 8) that allows for ease in testing with a network analyzer, or in the case of the receiver, for connection to an antenna for wireless testing.

Conclusions

This paper describes a set of educational materials that cast common concepts learned within a typical undergraduate electrical and computer engineering curriculum in terms of high-frequency electronics. The goals of spreading these materials across the curriculum instead of reserving them for a single upper division course include providing practical engineering examples motivating common mathematical concepts learned at the foundation of the curriculum and to introduce students to one of the many specialties within electrical and computer engineering. Students within the electrical and computer engineering department at Montana State University have the opportunity to take a senior-level elective course in microwave electronics that takes advantage of the students' developing knowledge of the field to provide a system-level design experience. Additional work is underway to fine tune the materials, and the development of 'thread' materials involving other specialties within the curriculum is being considered.

Acknowledgements

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