AC 2010-1521: DEVELOPMENT OF A DOPPLER RADAR EXPERIMENT BOARD FOR USE IN MICROWAVE CIRCUITS AND ELECTRONICS COURSES

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Abstract

The development of a Doppler radar experiment board and associated course content, observations from their first implementation in the fall 2009 offering of the microwave circuits course at Montana State University and plans for their revision and use in an upper division analog electronics course are described. The motivation for incorporating the experiment board into the microwaves course is to provide students a bridge between their understanding of the basics of microwave component design and the implementation of components into a microwave system. The trend toward higher levels of abstraction in the microwaves field suggests the growing importance of system-level understanding, as fewer students will continue on to component-level design in industry. A continuous wave Doppler system was selected as a vehicle for the component-to-system level transition due to the relative simplicity of the system and its common use in speed monitoring applications. The attempt to combine both component and system-level experiences into a single course was necessitated by the fact that the Electrical and Computer Engineering Department in which the concept is being deployed has the resources to offer but a single course in microwave engineering. Thus it is expected that programs which seek to provide students a rather broad sampling of microwave circuitry and systems in a single course may benefit from the chosen approach.

Introduction

Students enrolled in the Electrical and Computer Engineering Department at Montana State University chose from a variety of upper division discipline-specific courses to satisfy their "professional electives" requirements. One of the upper division electives, taken both by senior-level undergraduates and graduate students, is EE 433 – Planar Microwave Circuits Design. Due to the relatively small size of the department (undergraduate and graduate population of approximately 300 students), EE 433 is the only course available to the students in the field of microwave circuits. For this reason, the course has tried to sample a significant number of topics from the field of microwave circuits, though in the past the course was almost entirely devoted to component-level design.

Over the last several years, a popular microwave engineering text[1] has been used for the course, and prior to the fall of 2009, the content of the course could be summarized by the lecture topics and lab exercises listed in Table I. The fact that system-level knowledge is of value to students and implementation of system-level projects can be a motivational tool in a microwave course has been recognized by others.[2,3] Indeed, the lab exercises devoted to detector design, power divider design and filter design were fashioned so that the components designed for each experiment were ultimately assembled to develop a primitive frequency-shift keyed (FSK) receiver.[2,4]

Table I: Course Topics For EE XXX Prior To Fall 2009

LECTURE TOPICS
Introduction to microwave theory and applications
Transmission line theory
Microstrip and coplanar transmission lines
Transmission line discontinuities
The Smith chart
Lumped and distributed impedance matching
Computer aided design of microstrip circuits
Matrix representation of multi-port networks (S-,Z-,Y- and ABCD parameters)
Calibration of coaxial and in-fixture VNA measurements
The diode at radio and microwave frequencies
Microstrip filter design
Power dividers, combiners and couplers
Even and odd mode analysis
Scattering parameter design of transistor amplifiers
Linear dynamic range, noise figure and noise calculations for microwave systems
LAB / DESIGN EXERCISES
Introduction to the vector network analyzer (VNA) and basic transmission line theory – Students measure the reflections from a series of open circuit transmission lines of different lengths and at different frequencies and compare measurement to theory.
Passive component characterization using the VNA – Students measure the scattering parameters of a capacitor, inductor and a diode using thru reflect line calibration and develop equivalent circuit models for the components.
Diode detector design and impedance matching – Students design a matching network for the diode for use as a small signal detector operating at 2.4 GHz.
Power divider design – Students design a Wilkinson power divider at 2.4 GHz.
Filter design – Students design a series of microstrip filters for operation at 2.4 GHz.

While the course consistently received positive evaluation from students who enjoyed the course's design projects, it was felt by the instructor that the course needed additional system-level content. An often-mentioned interest of students taking the course has been radar and so it was decided that a senior design project be commissioned to develop a continuous wave Doppler radar module for use perhaps as a case-study demonstration for the course. Figure 1 shows a photograph of the product of the senior design project.

The Doppler radar module shown in Figure 1 was designed to operate at 5.8 GHz and utilizes commercial components save for the single in-house designed component – a nominal 10 dB coupler used to split the signal from the voltage controlled oscillator (VCO) to serve both as a transmit signal and as the local oscillator (LO) for the mixer. The radar operates on the principle that, when scattered by a moving target, the transmitted signal is shifted in frequency by an amount dependent on the target's velocity relative to the radar. The simple equation that relates the Doppler frequency, f_d, to the target's radial velocity, v, the transmitted frequency, f_o, and the speed of light, c follows.[1]

$$f_d = \frac{2vf_o}{c}$$

Assuming the 5.8 GHz transmitted signal frequency (f_o) and an anticipated range of velocities up to 100 mph (that specified for the senior design project), one can quickly find that the maximum Doppler shift corresponds to a frequency of approximately 1.7 kHz. Using the Doppler radar shown in Figure 1 and an oscilloscope connected to the radar's intermediate frequency (IF) output, one could easily see evidence of the motion of a person in the transmit antenna's main beam more than ten feet from the radar. The nominal transmit power was 10 dBm and the antenna gain approximately 7 dBi.

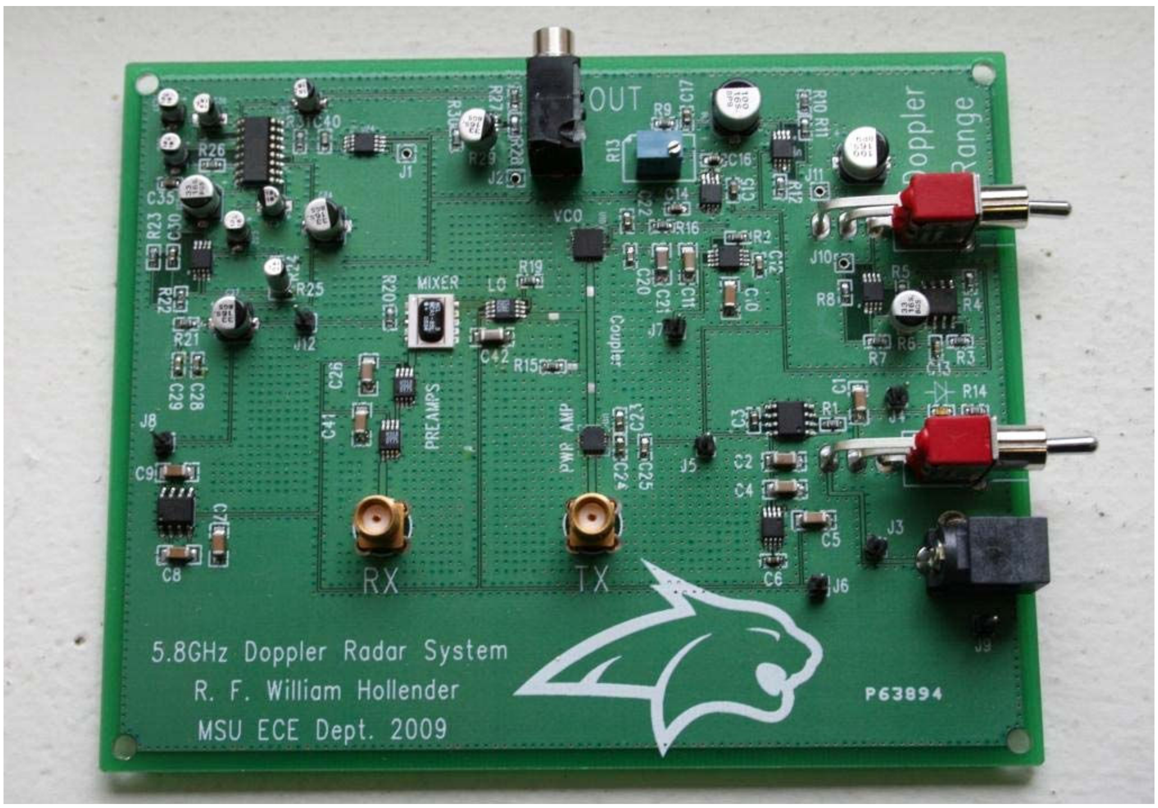

Figure 1: Doppler radar developed as a student's senior design project. The radar, having both velocity detection and ranging capabilities, was developed using commercial components save for the 10 dB coplanar coupler near the center of the board.

The remainder of this paper discusses the changes that have been made to the microwave circuits course to implement the Doppler radar module, briefly noting a preliminary assessment of the effectiveness of the approach as measured by student sentiment. An outline of how the Doppler module is being used in the spring 2010 offering of an advanced analog electronics course is provided and finally a few remarks are made as to how the work will be carried forward in future offerings.

Modification of Lecture Content For Fall 2009

The implementation of a radar project into an undergraduate course has been described by others. Specifically, Jensen et al.[3] had students design a standard microstrip divider and a patch antenna array and used these components to realize a Doppler radar. They found that typically, students "are enthused about their useful system," and go on to state that, "these system level design experiences can significantly enhance the student educational experience and help them gain a more thorough appreciation of the physics upon which the electrical engineering discipline is based." Our goals in implementing a Doppler radar experiment board into the microwaves course included helping students become able to identify the key figures of merit at the component level that affect the Doppler system as a whole as well as provide a small sampling of distributed circuit design and an introduction to board layout techniques for circuits operating at GHz frequencies. As topics devoted to system-level considerations weren't meaningfully addressed in prior offerings of the course, decisions had to be made with regard to what material to remove from the lecture to make room for discussing the Doppler system.

As noted previously, students in the offerings prior to the fall of 2009 designed various microstrip filters. These included stepped impedance low pass filters, multi-section coupled line bandpass filters and low pass filters using a series of microstrip stubs. Preparing students to understand and tackle these design tasks required devoting several lectures to distributed element filter design theory in which, for example, Richard's transformation and Kuroda's identities[1] were introduced. While such topics are certainly germane to a course in microwave theory, our intent is to move the course in a direction in which the typical student at Montana State University will find most benefit in terms of using the material later in their careers and so these somewhat esoteric topics were removed from the course. Based on one of the author's experience in teaching students at Montana State over the last eight years, and in following what many of the EE 433 students do after graduation, the most common tasks that align with potential content for EE 433 include RF/microwave board layout, component selection, and circuit-level and system-level calculations. It is interesting to note that not one student has indicated that he/she is involved with distributed filter design. In place of the lectures devoted to the theory of distributed element filter design, time in lecture was opened for discussing the fundamentals of Doppler radar, the radar range equation, antenna figures of merit and component nonlinearity and how nonlinearity impacts a system. As is discussed later in this paper, further adjustment of the lecture content is needed to achieve the goals set forth in introducing the Doppler experiment board. This was to be expected as we developed both the lecture content and revised the Doppler experiment board during the fall of 2009 without ample time to test the entire process beforehand.

The EE 433 Doppler Radar Experiment Boards and Associated Laboratory Experiments

While the Doppler radar shown in Figure 1 worked well, we decided to redesign the board to accommodate one or more student-designed elements for its use in EE 433. Figure 2 shows a circuit block sketch of the RF portion of the Doppler radar from which we considered what element(s) could be designed by the students and connected to an experiment board to make a functional continuous wave Doppler. It should be noted that the senior design board also had ranging capabilities which contributed significantly to the component count and complexity of the printed circuit board that were not to be part of the simple continuous wave Doppler module for EE 433.

The microstrip coupler that served to split the signal from the VCO was an obvious choice. This component serves a similar function as the microstrip 3dB Tee junction described in the paper by Jensen et al.[3] though the use of the coupler allowed us another “knob” to adjust, through the coupling factor, to hit the desired pump power of the mixer. Another potential choice was the mixer itself, which is the heart of the system. Finally, one could imagine that one or more of the amplifiers could be designed using microwave transistors. While several of the course lectures have been devoted to the scattering parameter design of transistor amplifiers, and in the past a final project was directed toward the simulation and design, but not fabrication and testing of an amplifier, it was quickly decided that the complete design, layout, fabrication and testing of one or more amplifiers that would provide reasonable gain and noise figure would be beyond the scope of what could reasonably be achieved in this introductory microwave circuits course. It was decided that an experiment board that could accommodate a student-designed coupler and mixer as well as various commercial amplifiers would be made. In addition, a board with connections for only an external mixer was developed. A photograph of the full experiment board is shown in Figure 3 and a list of the primary components used to populate the board is given in Table II.

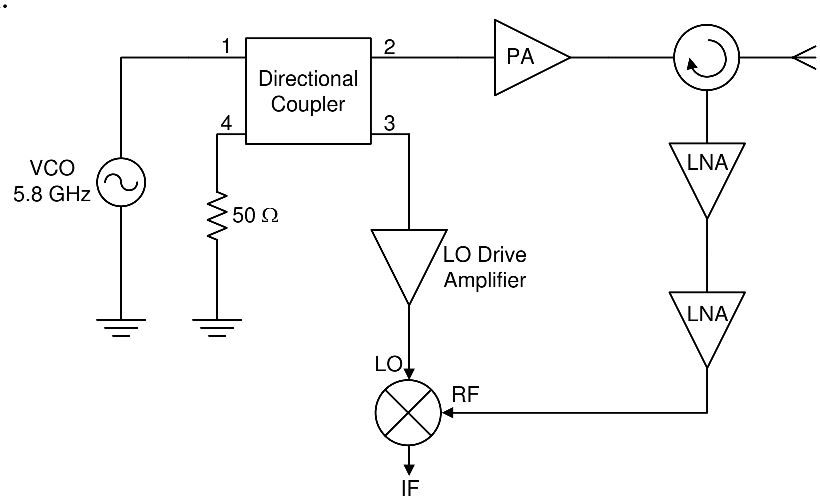

Figure 2: Circuit block diagram of the EE 433 Doppler radar. While it is suggested in the sketch that a circulator was used to permit single antenna operation, the use of separate transmit and receive antenna was also possible as shown in Figure 3.

Table II: Key component used in the EE 433 Doppler Experiment Board

Component	*Manufacturer*	*Model Number*
Voltage Controlled Oscillator	Hittite Microwave Corporation	HMC431LP4
Local Oscillator Drive Amplifier	Hittite Microwave Corporation	HMC320MS8G
Power Amplifier (PA)	Hittite Microwave Corporation	HMC717LP3
Low Noise Amplifier (LNA)	Hittite Microwave Corporation	HMC318MS8G
Mixer	Minicircuits	MCA1-85L+
Circulator	Ditom Microwave, Inc.	D3C4080

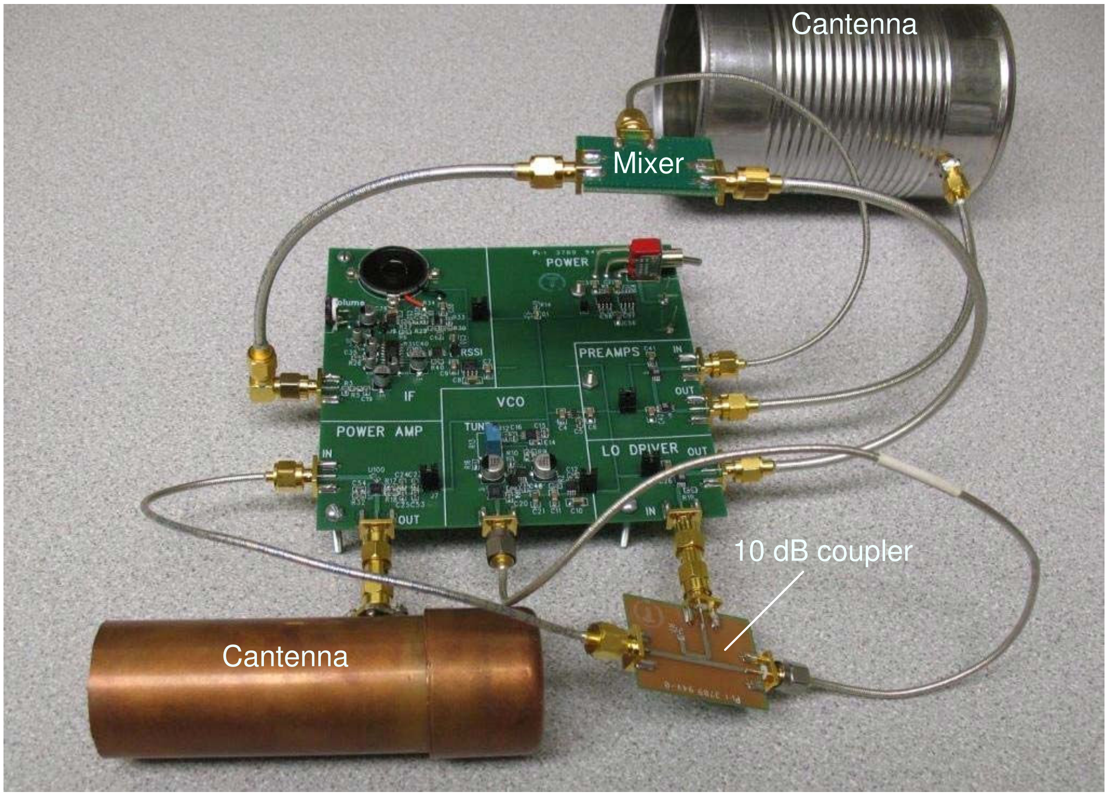

Figure 3: Photograph of the Doppler Radar experiment board. The board was built to accommodate various components that are student-designed, for example, the mixer (shown upside down) and a 10 dB coupler that splits the power received from the VCO between the mixer's LO input and the power amplifier used for signal transmission. "Cantennas" may be used for the transmit and receive antennas and are also be readily designed and manufactured by students. A speaker is included on the board to provide an audible cue of the relative speed of a detected target.

Ultimately, two laboratory exercises were developed during the fall of 2009 around the Doppler radar. The first was a simple passive component characterization in which students used a vector network analyzer (VNA) to measure the scattering parameters of a coupler, a circulator and a cable that would be used to connect external components to the board. Images of the directional coupler and the cables can be found in Figure 3. From measurements of these three components, and based on an evaluation of datasheets for the amplifiers and the commercial mixer used in the radar system, the students were instructed to carry out simple calculations to determine, among other things, the optimal pump power for the mixer (found from the component's datasheet), the optimal output power of the VCO (found from considering the mixer's required pump power, the gain of the LO drive amplifier and the measurement of the directional coupler's coupling factor) and the expected power at the input to the transmit antenna (found from the optimal VCO output power, the insertion loss of the coupler and circulator and the gain of the power amplifier). In addition, students were asked to consider potential problems that could arise in the receiver based on operating amplifiers at their various bias settings as well as speculate on any problems that might arise due to the finite isolation of the circulator which they measured using the VNA.

It turns out that based on the expected power at the input to the circulator (approximately 18 dBm) and the finite isolation of the circulator (approximately 25 dB), power compression was likely in the second LNA of the receive path thus suggesting that, due to the improved isolation between the transmit and receive paths, separate transmit and receive antennas would be a better choice than using a single antenna and circulator for this particular system. The photograph in Figure 3 shows separate "cantennas" used for the transmit and receive sections. While not part of the course in fall 2009, the assembly of such cantennas is rather straightforward and has been used as a project for high school students visiting Montana State University[5].

The second lab required students to design their own single-balanced mixer around a rat-race hybrid. While mixer design itself could be the subject of an entire course, a simplified design that ignores both impedance matching of the diodes and nonlinear analysis was found to be well within the grasp of most students. Figure 4 contains a photograph of one of the student-designed mixers as well as the commercial mixer used in the experiment board. A successful design required students to be able to develop a simple microstrip rat-race hybrid at 5.8 GHz, a single-section coupled line filter to block DC/IF content from leaking through the RF and LO ports and an open circuit stub placed at the IF port for isolation between the IF signal and the LO and RF signals. Based on the expected Doppler shift of less than 2 kHz, the stub was found to be sufficient without the need for a more complicated filter. Naturally, since the lecture content devoted to distributed filter design was removed from the course, only the most basic filtering schemes could reasonably be adopted. The following commentary was given with regard to the LO/RF and the DC/IF blocks to guide the students in their designs:

RF/LO BLOCK

Design Philosophy and Specifications

• The IF port should be built using a 50Ω transmission line and a properly located and sized stub (the stub need not be 50Ω). The impedance looking into the IF port from the ring should present the LO and RF signals with an open circuit. While the RF should be within 2 kHz of the LO and thus extremely closely spaced, the VCO is subject to some drift (on the order of 10 MHz, or less) and thus the LO will not stay precisely pegged at 5.8 GHz. Therefore, do your best to broaden the bandwidth of the RF/LO block though your ability to do so may be limited.

• Isolation at 5.8 GHz must be greater than 30 dB.

• Make certain to account for all the relevant microstrip discontinuities.

DC/LO BLOCK

Design Philosophy and Specifications

• Both the LO and RF ports are to include simple coupled line sections that block low frequency signals (i.e. DC and the 2 kHz IF) and yet allow maximum transfer of the LO and RF signals. Remember, the hybrid itself is chosen to give the required LO/RF isolation! An entire class of microwave filters is built around the coupled line concept and the Pozar text covers distributed filter design in great detail. Our goal is not to explore complicated multisection filter design, rather only to utilize a single coupling section to build a bandpass filter centered around the LO.

• The filter is to reject signals up to 10 kHz with better than 100 dB attenuation.

• The filter is to exhibit an insertion loss less than 1 dB at 5.8 GHz.

The students were to use the industry-standard microwave CAD tool, The Advanced Design System (ADS)[6] to design the mixer and all its components and to provide simulation evidence of the success of their designs. They were to assume a set of substrate characteristics based on standard 31 mil thick FR-4, design rules based on anticipated fabrication capabilities and to model all discontinuities. Finally, once they had demonstrated design success as evidenced by simulation, they were to include microstrip-to-coax transitions to complete their layout for fabrication. Their designs were then fabricated using a circuit board milling machine housed in the department.

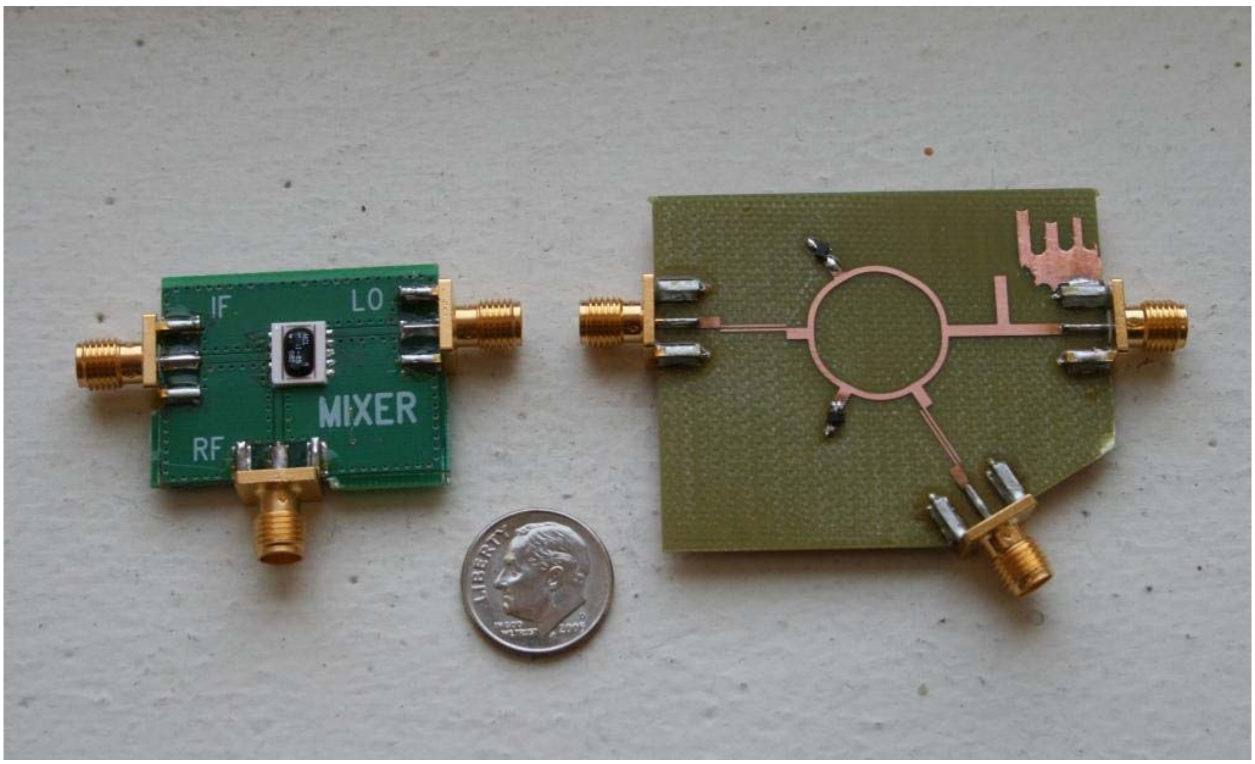

Figure 4: Photograph of both a commercial mixer (LEFT) and a student-design version (RIGHT) that could be used in the EE 433 experiment board.

Observations Based on the Initial Deployment Of Experiment Board

Generally speaking, the materials were well received by the students and they agreed that the incorporation of the Doppler radar content was of value for the course. Among the student comments as recorded on the course exit questionnaire were:

"…using the Doppler radar as a design concept helped apply the microwave theories covered in the course."
"…many concepts taught in class apply to the Doppler radar concept."
"…actually designing with a whole system in mind makes for a better understanding of the individual components."
"I would have liked to spend more time on it."

As the materials were developed while the course was in session and due to unexpected issues delaying the fabrication of both the experiment board and the student designs, student testing of the full Doppler system was not completed. It is unsurprising then that a student would note the desire to spend more time on the system. Perhaps the most positive comment regarding the incorporation of the material related to Doppler radar in the course came from a student who was in the midst of interviewing for fulltime employment. He noted that during an interview he was asked to describe what he was learning in the microwaves course and that the recruiter expressed pleasant surprise that such material would be covered in an undergraduate course – something he had not heard of before.

Based on characterization of one of the student-designed mixers, it was found that the simple design was capable of achieving a conversion loss of around 9 dB at a pump power of approximately 7 dBm. While the performance of the commercial mixer is better (7 dB conversion loss with a pump power of 4 dBm), the student-designed version may certainly be used in the Doppler system. The fact that the optimal pump power of the student version is not that of the commercial version would suggest the radar could benefit by being modified to achieve the additional 3 dBm drive should the student designed mixers be used. In theory this could be achieved by finding a VCO with additional output power, increasing the coupling factor of the directional coupler, or adding more gain between the coupler and the mixer. Based on these observations and the desire to realize a system whose performance approaches that predicted by the radar range equation and simple receiver noise calculations, several changes are proposed to the implementation strategy as described in the next section.

Plans for Future Developments in the Microwaves Course

Based on our experience in the fall of 2009, we collect in Table III a list of the proposed lecture topics for the fall 2010 offering of the course as well as the proposed lab experiments. Of particular note is the removal of much of the content on the scattering parameter design of amplifiers in favor of a higher-level discussion of amplifiers, oscillators and mixers. It is expected that the change will save approximately three fifty-minute lectures while introducing students to key active components through the analysis of datasheets and how component performance impacts the Doppler system. Content on the scattering parameter design of amplifiers will be posted on the course website for students interested in learning more about the topic.

The labs pertaining to the introduction to the VNA, passive component modeling and diode detector design are to remain largely unchanged. The lab tentatively entitled, "Doppler Radar System Calculations and Evaluation" will combine what was done in the fall 2009 offering in terms of measurement of the passive elements comprising the Doppler system and the associated system calculations, along with measurement of a fully integrated Doppler system. The system will be complete in so far as no external components, save for possibly a circulator will be used. Students will then be asked to compare their measurements on the system (range for a given target size/distance/velocity, minimum detectable signal, etc.) with appropriate calculations. By having a fully integrated system, it is hoped that calculations will match reasonably well with measurements. To make this lab feasible the content regarding the Doppler will be moved to earlier in the semester and an additional Doppler board will be constructed. This board will be fully integrated and will seek to improve the phase noise of the integrated VCO using additional bias filtering as it is believed that phase noise associated with the VCO limited the performance of the fall 2009 EE 433 Doppler system.

Table III: Course Topics For EE 433 For Fall 2010

LECTURE TOPICS
Introduction to microwave theory and applications
Transmission line theory
Microstrip and coplanar transmission lines
Transmission line discontinuities
The Smith chart
Lumped and distributed impedance matching
Computer aided design of microstrip circuits
Matrix representation of multi-port networks (S-,Z-,Y- and ABCD parameters)
Calibration of coaxial and in-fixture VNA measurements
The diode at radio and microwave frequencies
Power dividers, combiners and couplers
Even and odd mode analysis
Nonlinear elements – gain compression, distortion and mixing
Overview of amplifiers, oscillators and mixers
The radar range equation and antenna basics
Noise analysis of microwave systems
Linear and spurious-free dynamic range
LAB / DESIGN EXERCISES
Introduction to the vector network analyzer (VNA) and basic transmission line theory – Students measure the reflection from a series of open circuit transmission lines of different lengths and at different frequencies and compare measurement to theory.
Passive component characterization using the VNA – Students measure the scattering parameters of a capacitor, inductor and a diode and develop equivalent circuit models for the components.
Diode detector design and impedance matching – Students design a matching network for the diode for use as a small signal detector operating at 5.8 GHz.
Doppler Radar System Calculations and Evaluation – Students to carry out an assortment of system-level calculations based on an analysis of components comprising the system as well as test the system as a whole.
Directional Coupler design – Students to design a coupler for maximum coupling factor based on substrate characteristics and fabrication design rules.
Mixer Design – Students to design a single-balanced mixer with additional isolation

components and experimentally characterize their fabricated designs.
Doppler Radar System Integration and Layout – Students are to integrate their coupler with their mixer as well as layout the system to include pads for the LO drive amplifier, the power amplifier and an low noise amplifier.

The lab pertaining to mixer design will be largely unchanged. Students will be required to measure their mixers to determine the optimal pump power to minimize conversion loss. Finally, to give students additional practice with printed circuit board layout at GHz frequencies, students will be required to integrate a coupler with their mixer as well as an LO drive amplifier, power amplifier and LNA. The students will use commercially available (and stocked in the microwave lab) amplifiers in their design. This final project will require layout considerations to maximize isolation between the transmit and receive paths. Thus constructed, the students design will be nearly a complete Doppler save for the VCO (perhaps the most difficult portion) for which the students will use a precision RF/microwave signal generator. While the additional lab / design experiments may seem to significantly add to the burden on the students, moving some of the required design work to displace existing homework and utilizing the saved lectures appropriately should allow the set of proposed experiments to be completed within the expectations of the three-credit course.

Plans for Implementation of the Doppler Board in An Analog Electronics Course

In spring semesters students have the opportunity to take EE 411 Advanced Analog Circuit Design which focuses on differential and multistage amplifiers, frequency response and feedback as well as the design of active filters. The course addresses design primarily using discrete transistors for frequencies up to approximately 1 MHz, though both concepts relevant to design at the integrated transistor level and the level of operational amplifiers are discussed. While the RF/microwave portion of the Doppler radar is not suitable for in-depth discussion in the analog circuits course, the low frequency portion of the radar board provides an interesting opportunity for exploration in the course. Toward that end, for the spring 2010 offering of the analog electronics course a design project is being deployed in which students will have to design the intermediate frequency (IF) gain stages that take the IF signal from the mixer and condition it for ready viewing on the oscilloscope. The design will require students to realize the necessary gain (approximately 60 dB) and frequency response (to be determined by the students based on the specified range of target velocities) in the minimum number of stages. Students will also need to consider appropriate biasing of the stages to provide good noise matching as well as choose between two discrete transistor types based upon noise performance. Such a design fits well within the current format of the course and is to be done using discrete devices and assembled on a breadboard, requiring no background in RF/microwave electronics. It is expected that the project will not only reinforce course concepts through a meaningful design experience, but also create interest in the microwaves course.

Conclusions

The development of a Doppler radar experiment board and associated curricular materials for the Planar microwave circuit design course at Montana State University have been discussed. Plans for further development of the materials and for the use of the Doppler radar in a senior-level course on analog electronics have been noted. While students sentiment was quite favorable with regard to the incorporation of the Doppler radar content into the course, significant revision and addition to the material is required for the educational goals to be fully achieved.

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