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2000-11-01

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Original Publication Citation

Jensen, M. A., D. V. Arnold, and D. E. Crockett. "System-Level Microwave Design: Radar-Based Laboratory Projects." *Education, IEEE Transactions on* 43.4 (2): 414-9

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<https://scholarsarchive.byu.edu/facpub/586>

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System-Level Microwave Design: Radar-Based Laboratory Projects

Michael A. Jensen, *Member, IEEE*, David V. Arnold, and Donald E. Crockett

Abstract—Two laboratory projects—a Doppler radar and a synthetic aperture radar (SAR)—designed to augment traditional electromagnetics education are proposed. The projects introduce students to component and system level design and expose them to modern computer-aided design (CAD) tools, microstrip and surface mount fabrication technologies, and industry standard test equipment and procedures. Additionally, because the projects result in a working radar system, students gain new enthusiasm for the electromagnetics discipline and directly see its relevance in the engineering field. Implementation of these laboratories within the curriculum have proven to be highly motivational and educational and have even contributed to increased enrollments in upper division electromagnetics courses.

Index Terms—Electromagnetics laboratory, microwave engineering, radar.

I. INTRODUCTION

DESPITE the maturity of electromagnetics as a discipline within electrical engineering, curricular approaches for teaching electromagnetics seem to be in continual flux. For example, although the fundamental principles in electromagnetic theory are well established, the community continues to produce new textbooks that highlight the relevance of high-frequency effects for modern applications. Additionally, the rapid improvement of computational technologies has led to new educational approaches that facilitate conceptualization through enhanced visualization of physical phenomena [1]–[10].

When considering changes to pedagogical approaches for electromagnetics education, it is important to include revisions to the teaching laboratory [11]–[16]. When properly planned and executed, the tangible experiences provided in the laboratory reinforce physical principles and mathematical descriptions offered in the course. Additionally, good experiments can foster student motivation and enthusiasm as well as facilitate exposure to modern analysis, design (both component and system level), fabrication, and test procedures. This concept is consistent with recent recommendations that educators introduce fundamentals within the context of engineering applications [17].

Several excellent laboratory approaches and experiments have recently been proposed [11]–[15]. This work adds to the body of possible laboratory projects by introducing system level design experiences based upon microwave radar applications. This application area has been chosen because: 1) radar design is an area of strength within the department's

research program, allowing a positive laboratory experience to be provided for students; 2) radar instruments contain a wide variety of microwave components and do not require sophisticated intermediate frequency (IF) subsystems; and 3) radar baseband data interpretation does not need to be accomplished in real time. Two different C-band projects—a Doppler radar and a synthetic aperture radar (SAR)—are proposed. Students use modern computer-aided design (CAD) tools coupled with planar technology and surface mount components in the project design and fabrication. They also gain valuable experience using standard test equipment to troubleshoot their designs and evaluate component and system performance.

This paper offers information concerning the infrastructure required to accomplish these laboratories and provides details regarding the system designs. Procedures for component design, fabrication, and testing, as well as system integration—which have been developed through several iterations of the projects and which prove to reduce student frustration and instructor time commitment—are suggested. It is noteworthy that these techniques are applicable to many other potential laboratory projects, such as communications systems, and therefore this paper is relevant to those wishing to develop other microwave design laboratories. Methods and results of system deployment are highlighted. Finally, observations concerning the educational impact of the projects are offered as conclusions.

II. LABORATORY GOALS AND INFRASTRUCTURE

Before providing a detailed description of the proposed projects, it is helpful to discuss the goals to be accomplished by the chosen experiments. In the laboratory courses, the priorities are as follows:

- 1) reinforce the physical principles and engineering techniques taught in the accompanying course;
- 2) motivate the relevance of high-frequency phenomena in engineering application;
- 3) introduce students to modern CAD tools, fabrication technologies, and test procedures;
- 4) facilitate exposure to both component and system level design;
- 5) foster the attitude that electromagnetics is enjoyable.

Understood in these goals is the fact that the student-designed system should accomplish a useful and observable function without requiring excessive additional laboratory work (such as low-frequency circuit design or excessive computer programming) that does not contribute to reinforcing the principles learned in the classroom.

Manuscript received September 27, 1999; revised May 5, 2000.

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Publisher Item Identifier S 0018-9359(00)10088-3.

TABLE I
REQUIRED EQUIPMENT AND SUPPLIES FOR IMPLEMENTATION OF THE DOPPLER AND SAR PROJECTS. THE EQUIPMENT FOR THE SAR IS IN ADDITION TO WHAT IS LISTED FOR THE DOPPLER

Item	Possible Solution	Estimated Cost
Doppler System Equipment		
Milling Machine	LPKF ProtoMat 91s	\$10,000
Surface Mount Solder Station	OK Ind. SMT-1160	\$500
6 GHz Oscillator		
Network Analyzer		
Spectrum Analyzer		
Antenna Pattern Measurement Facility		
Microwave Circuit Simulation Software		
Doppler System Supplies		
Coax to Microstrip Transitions	Johnson Components	\$8
Circuit Board	GIL-1000	\$10/square ft
Mixers	Mini-Circuits SKY-7G	\$17
Amplifiers	Mini-Circuits ERA-3SM	\$2
Mill Bits	LPKF	\$25
SAR System Equipment		
Arbitrary Waveform Generator	LeCroy LW410A	\$10,000
2-Channel Sampling Oscilloscope	LeCroy LC334A	\$12,000

To accomplish these goals, radar systems have been targeted since these projects offer several advantages as outlined in the introduction. However, despite these advantages, implementation of such labs clearly comes at the cost of significant infrastructure. Table I shows the basic equipment and supplies required to support the two projects outlined in this paper along with some rough cost estimates. No cost estimates are provided for some of the basic test equipment due to the wide range of products available to address these needs. For example, the source can be as simple as a \$50 voltage controlled oscillator (since an absolute frequency reference is not required) or as complex as a \$30 000 synthesized sweeper. Fortunately, much of this infrastructure is already in place in many high-frequency laboratories, and there are many grant and donation opportunities which aid in the acquisition of additional equipment. Also, simulation software is readily available to educational institutions for little to no cost. In the laboratory, the agile advanced design system (ADS) design and layout software is used.

In addition to this required infrastructure, each student laboratory station includes a digital sampling oscilloscope, a power supply, a microwave sweep generator, and a low-frequency function generator. This equipment aids during the testing phase of the components and systems. Also, a track (roughly \$1200 in material costs) for deployment of the SAR had to be constructed. Finally, a cost of approximately \$10 per student in consumables (substrate, solder, mill bits) and replacement components is incurred. Naturally, this cost can be assessed as a lab fee if necessary.

While the undergraduate courses associated with these laboratories focus on transmission lines and linear passive structures, the design projects require active and nonlinear devices such as amplifiers and mixers. In first implementations of these laboratory projects, students were given the information sheets concerning the available surface mount components and were expected to design a single-board radar system. With this approach, however, it was extremely difficult to troubleshoot systems after fabrication. Additionally, while surface mount amplifiers are relatively inexpensive, passive mixers are typically more costly, and it became difficult to reclaim these components

for use in subsequent years since the surface mount removal process often damaged the device.

As a remedy for the problems associated with single-board systems, a modular design approach was adopted where each individual component is fabricated on its own board and terminated with coax (SMA connector) to microstrip transitions designed specifically for end-launching on printed circuit boards. If properly connected, these transitions offer an adequate match for most radar applications, with voltage standing wave ratios (VSWRs) typically below 1.2. Given this approach, large numbers of amplifier and mixer modules, with the coaxial connectors soldered to the board, have been fabricated and are provided to the students for their project. Student fabricated components are then fitted with similar connectors which have been modified with a thumb-screw so that the connectors can be attached and removed easily. Velcro strips are glued to the back of each component, and the modules are connected together and pressed onto a rigid wooden integration board coated with mating Velcro material. This modular approach allows students to test their individual components before assembling them into the final system. Additionally, considerable cost was saved by being able to reclaim the amplifiers and mixers each semester.

III. LABORATORY PROJECTS

A. Doppler Radar

In the junior-level laboratory course, the design of a 6-GHz Doppler radar system was introduced. Fig. 1 shows a block diagram of the system used. A microwave signal generator supplies the 10-dBm 6-GHz carrier which, after passing through the power splitter, is amplified and broadcast through the transmit antenna array. If an object (such as a hand or corner reflector) is placed in front of the system, the signal reflected by the object is detected by the receive antenna array. When this signal is mixed with the copy of the transmitted waveform, the resulting IF voltage will be at the Doppler frequency f_d (produced from movement of the reflecting object) and can be observed on an oscilloscope. The velocity of the object in the direction normal

Fig. 1. Block diagram for the C-band Doppler radar system.

Fig. 2. Simulated S-parameters versus frequency for the microstrip tee used in the Doppler radar system.

to the plane of the radar system is then computed using the expression [18]

$$v = f_d \lambda / 2 \quad (1)$$

where λ is the free-space wavelength of the excitation signal.

The student design effort focuses on the 3-dB power splitter and the four-element microstrip patch array antenna. The design of the power splitter, which is simply a microstrip tee junction followed by single-section quarter-wavelength matching circuits on the tee output legs [19], reinforces their understanding of impedance matching and provides exposure to practical microstrip design. Students perform a paper design of this component, simulate its performance in a schematic window of the ADS software package, and tune the design to compensate for the microstrip discontinuities. The software is then used to create a microstrip layout file which is transferred to the milling machine for fabrication. The coax to microstrip transitions are attached to the final board, and the device performance is tested on a network analyzer. Fig. 2 shows the simulated S-parameters for this component.

The design of the microstrip antenna proceeds in a similar fashion. In this case, students use simple curves to create a preliminary design of a single radiating element [20]. They then use the moment method simulation capabilities of the ADS suite to analyze and tune the antenna. To facilitate the later integration of the antenna into the corporate-fed array, the design is typically made for an input impedance of 100 Ω . The single element antenna is fabricated, and the input match and radiation pattern are

Fig. 3. Photograph of the completed Doppler radar system.

measured using the test facilities. The students then incorporate the antenna into the four-element array using microstrip tees and again test the input match and radiation pattern. To save costs, the students only fabricate one of the necessary arrays while a second array is provided for them.

While the students do not fabricate their own amplifier and mixer modules as part of the laboratory, we do want to provide them with some basic understanding of device parameters. To facilitate this, basic models have been created of the amplifiers and mixers used in the laboratory within the ADS simulation suite. Students are then given the assignment to perform amplifier simulations where the input power is swept so that they can visualize the meaning of 1-dB compression point and gain saturation. They also perform simulations on the mixer to assess the meaning of conversion loss. Since this is a beginning class, more advanced nonlinear behaviors are not emphasized. However, this may be suitable in a senior-level course where the project may be used.

The final portion of the course involves system integration and testing of the complete radar. Fig. 3 shows the final integrated radar system, where the student-fabricated tee and other connectorized components are visible. To measure the radar range capability, one student moves a corner reflector back and forth at various locations while a second records the voltage level observed on the oscilloscope as a function of the mean distance to the corner reflector. To test the system accuracy, one student runs at a constant speed toward the radar, and the velocity derived from the observed Doppler frequency is compared to that obtained using a distance over time ratio. Typically, students are enthused about their useful system and will see how small of an object they can observe or how fast or slow a speed they can detect.

The entire laboratory project requires approximately three to four (depending on the amount of testing performed at each step and of ancillary simulations required) three-hour laboratory sessions. The design is robust and has consistently worked for approximately 150 students over the past three years in the laboratory.

B. SAR

The project in the senior-level laboratory course, a 6-GHz SAR, is somewhat more ambitious than the Doppler radar of the previous section. A block diagram of this system appears in Fig. 4. For this project, the 6-GHz tone produced by the microwave generator is mixed with a pulse created by an arbitrary

Fig. 4. Block diagram for the C-band SAR system.

waveform generator. The pulse is 1 μ s in duration and is characterized by a linearly ramped frequency from 30–100 MHz. This resulting “chirped” signal is filtered to remove the upper sideband before transmission. The branch-line coupler provides the local oscillator (LO) for the down conversion to in-phase (I) and quadrature (Q) components by generating two replicas of the carrier signal offset by 90°. Other required power splitters are implemented as Wilkinson dividers. The antennas are implemented as eight element microstrip patch arrays. However, because the students have already experienced antenna design during their junior year, previously fabricated arrays are provided for them.

The student design effort for this project focuses on the Wilkinson power dividers, the branch-line coupler, and the bandpass filter which is implemented as a microstrip coupled line filter [19]. These components are again designed using the principles taught in the accompanying course and are subsequently implemented within an ADS schematic window for S-parameter simulation and tuning. The components are fabricated as previously described and tested on the network analyzer. System integration is then performed and the radar is tested in the laboratory before final deployment at the test location. Figs. 5 and 6 show typical student-fabricated components and an integrated SAR system (without the transmit array).

The SAR deployment occurs on a length of track (constructed from channel iron designed for industrial hanging doors—see Fig. 7) installed along the edge of the roof of the engineering building on the Brigham Young University campus. A small cart has also been constructed to sit on the track, and a garage door opener fitted with a long chain is used to move the cart at a relatively constant speed of 0.35 m/s. The cart is loaded with the arbitrary waveform generator, the microwave generator, and the sampling oscilloscope which samples the baseband I and Q signals at 500 Msample/s and stores the data for post processing. During the measurement, the pulse repetition frequency (PRF) is set to 4 Hz with no signal averaging. The radar images the roof of an adjacent building which has a number of metal objects that provide a strong return to the radar.

Fig. 5. Photographs of student-fabricated Wilkinson power divider, branch-line coupler, and coupled-line filter.

Fig. 6. Photograph of a complete SAR system (without the transmit antenna).

Fig. 7. Photograph of the track used for the SAR system deployment.

The sampled data from the deployment is transferred to a computer for processing using Matlab routines. A 30-min lecture is offered at the beginning of four consecutive laboratory sessions in order to educate students concerning the signal processing required to compress the raw data to obtain a high-resolution image [21], [22]. Given the frequency bandwidth of $f_B = 70$ MHz and the antenna dimension of roughly $L = 20$ cm, the range and along-track resolution are given, respectively, as [21]

$$\delta_R = c/2f_B \approx 2 \text{ m} \quad (2)$$

$$\delta_A = L/2 \approx 10 \text{ cm} \quad (3)$$

where c is the speed of light.

Figs. 8 and 9 show a photograph and a radar image, respectively, of the scene observed by the SAR. All of the large metal structures on top of the roof are clearly identifiable in the radar image. Students are expected to physically measure the size and distance between targets and compare with the data obtained in their images. They provide written reports in which they not only document their design, fabrication, and deployment, but also provide physical reasons for any discrepancies between

Fig. 8. Photograph of the scene imaged by the deployed SAR system.

Fig. 9. Grayscale representation of the image measured using a student-deployed SAR.

their theoretical predictions and actual measured responses. In both laboratory projects, the students perform their laboratory work in pairs, but work individually on their written reports. Grades are assigned according to the project functionality and the quality of the report.

IV. OBSERVATIONS AND CONCLUSIONS

These projects have been used now for three consecutive years in the curriculum at Brigham Young University. From a quantitative point of view, introduction of the SAR resulted in an increase in enrollment in the senior-level class from 15–36 from one year to the next. From a more subjective standpoint, the faculty have observed considerable enthusiasm in the students. Frequently during instruction in the course, students will request a more thorough explanation of phenomena they observe in the laboratory. As such, the majority of the students appear more motivated to tackle the difficult theoretical and physical principles in the course as they become more aware of their relevance in engineering application.

When coupled with traditional electromagnetic laboratory exercises that emphasize the physics of electric and magnetic fields, transmission line properties, and wave behavior, 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. Students observe practical issues not covered in the classroom, and gain confidence in their abilities to utilize high-frequency principles for useful applications. As such, laboratory projects such as these help to make the educational experience more enjoyable and to better prepare students to contribute in the scientific advances of the discipline.

REFERENCES

- [1] O. de los Santos Vidal and M. F. Iskander, "Multimedia modules for electromagnetic education," *Comp. Appl. Eng. Educ.*, vol. 5, pp. 257–267, 1997.
- [2] J. Fabrega, S. Sanz, and M. F. Iskander, "New software packages and multimedia modules for electromagnetics education," in *Proc. 1998 IEEE AP-S Int. Symp. Dig.* Atlanta, GA, June 21–26, 1998, vol. 4, pp. 2292–2295.
- [3] S. E. Fisher and E. Michielssen, "An integrated online environment for antenna education," in *Proc. 1999 IEEE AP-S Int. Symp. Dig.* Orlando, FL, July 11–16, 1999, vol. 1, pp. 78–81.
- [4] K. W. Whites, "Visual electromagnetics for Mathcad: A computer-assisted learning tool for undergraduate electromagnetics education," in *Proc. 1998 IEEE AP-S Int. Symp. Dig.* Atlanta, GA, June 21–26, 1998, vol. 4, pp. 2288–2291.
- [5] M. Righi, W. J. R. Hoefer, and T. Weiland, "Virtual field-based laboratory for microwave education," in *Proc. 1998 IEEE MTT-S Int. Microwave Symp. Dig.* Baltimore, MD, June 7–12, 1998, vol. 2, pp. 555–558.
- [6] M. Piket-May, "Learning interactively: Electromagnetics case study," in *Proc. 1997 IEEE Frontiers Educ. Conf.* Pittsburgh, PA, Nov. 5–8, 1997, vol. 2, p. 796.
- [7] S. L. Broschat, J. B. Schneider, F. D. Hastings, and M. W. Steeds, "Interactive software for undergraduate electromagnetics," *IEEE Trans. Educ.*, vol. 36, pp. 123–126, Feb. 1993.
- [8] V. L. Hall and Z. J. Cendes, "Introducing real world design problems into the undergraduate electromagnetic curriculum," *IEEE Trans. Educ.*, vol. 36, pp. 279–283, May 1993.
- [9] R. W. Scharstein, "Visualization and interpretation for the electromagnetic derivation of Snell's laws," *IEEE Trans. Educ.*, vol. 41, pp. 286–292, Nov. 1998.
- [10] B. Beker, D. W. Bailey, and G. J. Cokkinides, "Application-enhanced approach to introductory electromagnetics," *IEEE Trans. Educ.*, vol. 41, pp. 31–36, Feb. 1998.
- [11] L. P. Dunleavy, H. C. Gordon, R. E. Henning, and T. M. Weller, "Wireless circuit and system design: A new undergraduate laboratory," in *Proc. 1997 IEEE Frontiers Educ. Conf.* Pittsburgh, PA, Nov. 5–8, 1997, vol. 2, pp. 757–760.
- [12] T. M. Weller, P. G. Flikkema, L. P. Dunleavy, H. C. Gordon, and R. E. Henning, "Educating tomorrow's RF/microwave engineer: A new undergraduate laboratory uniting circuit and system concepts," in *Proc. 1998 IEEE MTT-S Int. Microwave Symp. Dig.* Baltimore, MD, June 7–12, 1998, vol. 2, p. 563.
- [13] L. P. Dunleavy, T. M. Weller, P. G. Flikkema, H. C. Gordon, and R. E. Henning, "Versatile test bench for wireless RF/microwave component characterization," *Microwave J.*, vol. 41, pp. 304–312, May 1998.
- [14] C. Furse, "Hands-on electromagnetics: Microstrip circuit and antenna design laboratories at USU," in *Proc. 1999 IEEE AP-S Int. Symp. Dig.* Orlando, FL, July 11–16, 1999, vol. 1, pp. 66–69.
- [15] E. W. Bryerton, W. A. Shiroma, and Z. B. Popovic, "An active microstrip circuits lab course," in *Proc. 1997 IEEE AP-S Int. Symp. Dig.* Montreal, PQ, Canada, July 13–18, 1997, vol. 4, pp. 2490–2493.
- [16] M. A. Jensen, D. V. Arnold, and D. E. Crockett, "Microwave engineering design laboratories: C-band rail SAR and Doppler radar systems," in *Proc. 1999 IEEE AP-S Int. Symp. Dig.* Orlando, FL, July 11–16, 1999, vol. 1, pp. 82–85.
- [17] R. Bansal, "Teaching fundamentals of electromagnetics in the context of engineering practice," in *Proc. 1997 IEEE AP-S Int. Symp. Digest* Montreal, PQ, Canada, July 13–18, 1997, vol. 4, pp. 2482–2485.
- [18] N. Levanon, *Radar Principles*. New York: Wiley, 1988.
- [19] D. M. Pozar, *Microwave Engineering*, 2nd. ed. New York: Wiley, 1998.
- [20] R. C. Carver and J. W. Mink, "Microstrip antenna technology," *IEEE Trans. Antennas Propagat.*, vol. AP-29, pp. 2–24, Jan. 1981.
- [21] S. A. Hovanesian, *Introduction to Synthetic Array and Imaging Radars*. Boston, MA: Artech House, 1980.
- [22] W. G. Carrara, R. S. Goodman, and R. M. Majewski, *Spotlight Synthetic Aperture Radar: Signal Processing Algorithms*. Boston, MA: Artech House, 1995.

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