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Application of Active Learning in Microwave Circuit Design Courses

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I. Introduction and motivation

Microwave Circuit Design is a fairly well established topic for senior undergraduate and graduate courses and many good textbooks are available[1]. Topics that are covered vary but typically include some fundamentals of electromagnetic wave propagation, transmission lines (TL), effects of matching and reflection on TLs, various passive circuits (matching, filters, couplers, etc), linear amplifiers (usually a low-noise amplifier), mixers and power amplifiers. Distinction is usually made between RF circuit design which primarily uses lumped passive elements (RLC) while microwave circuit design utilizes transmission lines and other distributed elements. Active devices are typically transistors but microwave circuits operate at high frequencies, which narrows down choices of active elements considerably. For the sake of convenience, we will use frequency of 1 GHz as a transition from RF to microwave domain. In most electrical engineering programs it is difficult to set up any sophisticated labs due to very high cost of instrumentation. In addition, microwave measurements are difficult to properly setup and perform, and there is dearth of practical information outside of instrumentation companies' application notes. Simulation tools are widely used but some old-fashioned design techniques, especially graphical ones using Smith-chart, are used in conjunction.

Our Microwave Circuit Design I and II courses are senior or first year graduate electives and are required in Analog/Microwave track. Two quarters last 10 weeks each and the first quarter is primarily devoted to passive components, including: lumped passive components and resonators (2 weeks), transmission lines (2 weeks), matching and Smith charts (2 weeks), L-, T- and Π-circuit matching, 2-port devices and measurements (1.5 weeks), lumped and microstrip filters (1.5 weeks). The tenth week is devoted to work on projects, typically a filter design using SMD and/or microstrip techniques. Weekly lab activities include: characterization and modeling of SMD components; using TDR response to determine line properties (2 weeks); examining reflections using TDR and VNA; designing and testing λ/4 and single-stub matching circuits; two-port measurements on VNA; deembedding of fixtures. During the 9th week students are asked to watch a webcast on a technical topic and write a summary. During the term students also work on two simulation assignments which utilize Agilent ADS software.

The second quarter deals primarily with active circuits, including: passive power combiners; active devices, gain, and stability; design for gain and noise; using ADS in amplifier design; transistor biasing; nonlinear effects and their measurement; power amplifiers; mixers; complete receiver design. Weekly lab activities include: design and test of Wilkinson and quadrature-hybrid combiners; active devices and their DC and S-parameter characterization; design of amplifier matching circuits; LNA design and layout; noise figure measurement of amplifiers and other devices; using ADS to design amplifiers; on-wafer measurements using probe stations. Emphasis during this term is on producing a working prototype of an active circuit, e.g. designing, fabricating and testing an LNA using procedure given by Payne[10]. Both courses heavily rely on hands-on, lab-based exercises, simulation assignments and a culminating (group) project. Typical enrollment is 15-20 students with 2:1 ratio of undergraduates to graduates.

We have recently expanded our teaching labs to include four 20 GHz Vector Network Analyzers (VNA) and four high-speed (17ps rise time) Time Domain Reflectometry (TDR) oscilloscopes. They were obtained for junior electromagnetics labs but this opened up opportunities for more hands-on approaches to teaching and learning microwave circuit design. Figure 1 illustrates the layout of the lab. Student can now perform measurements at true microwave frequencies, i.e. between 1 and 20 GHz. They can also use TDR oscilloscope to quickly determine characteristic impedance of the lines and to debug circuits.

Figure 1 Inside of the lab used for electromagnetics and microwave circuit design courses. There are 8 stations: four with 20 GHz VNA-s and four with high speed (17ps rise time) TDR oscilloscopes.

Given this infrastructure, the next question is how to best leverage it. One approach would be to design a set of separate labs with well defined procedures and goals, and have it run by a teaching assistant. This would provide students with skills in the area of instrumentation usage and give them an opportunity to test the theory given in class. This approach, however, does not address some important issues:

- There is little opportunity to provide students with <u>immediate</u> feedback since this is typically done through grading after they submit their lab reports.
- Students are not given an <u>opportunity to fail</u>. If we want them to be creative and try out different solutions then failure should be allowed and not be disproportionately penalized.

- In general, we felt that over the years we have erected artificial barriers between lecture and lab, while in reality we should strive to integrate the labs and lectures.
- Many of our past labs were hands-on in the name only. We should strive to make lab experience as authentic as is practicable.

II. Active learning in classroom and lab setting

In addition to difficulties associated with designing traditional labs, we also faced a question of how to best utilize face-to-face time in classroom, i.e. during lectures. There is plenty of literature[3] confirming that traditional lecture format is not very effective and that “active learning”, in its many forms, is more effective and efficient way for students to learn and for us to teach. We will use the following working definition of active learning[2]: “any class activity that involves students in doing things and thinking about the things they are doing”. Other authors have reported on various approaches on bringing hands-on and project-based learning into similar courses[5-8]. From our own experience we were also aware of the fact that students prefer to produce something tangible as a “product” of their work.

All of these considerations led us to the following guidelines:

1. Doing should replace listening during face-to-face classroom time
2. Students should produce something tangible
3. Students should be engaged in their learning
4. Make immediate feedback a priority
5. Provide multiple ways to retrieve recently learned concepts
6. Push students into using higher cognitive functions, but
7. Provide appropriate scaffolding
8. Have multiple opportunities for design cycle: design → build → test → redesign

Most, if not all, of these are part of research-based principles of teaching articulated by Ambrose et al.[4]. These are fairly generic and can be applied to other courses that are design oriented. In practical terms, we set these specific goals:

a) Emphasize complete design cycle, from “paper” development, to simulation, to prototype development and testing, followed by more advanced prototyping, testing and redesign (items 2, 3, 6, 8 above). Example: students first design, build and test a filter in “sticky-tape” technology and follow that up with production of a real PCB in a foundry.
b) De-emphasize face-to-face lecture and emphasize in-class activities and peer interaction (items 1, 3). Example: introduction of Learning Catalytics in-class interaction system.
c) Provide students with as much immediate or early formative feedback as possible (items 1, 3, 4, 5, 7). Examples: observation and interaction in lab section while students are going through design cycle of a device or circuit, such as matching network; using Learning Catalytics.

d) Reinforce student learning by having "lab" and "lecture" merge into one so that concepts can be immediately put to practice instead of waiting for assigned lab time. This means that as many designs from item a) should be attempted during class/lab time so that instructor can provide immediate feedback (items 2, 4, 5, 6, 8). Example: students measure surface-mount devices (SMD) and wire-lead components on LCR meter and we discuss how to deduce what the components are, what parasitics they exhibit and how to model them.

We then settled on specific high-level course outcomes and topics for both courses, i.e. students should be able to:

- Design, build and test passive circuits (microstrip and SMD)
- Design, build and test active circuits (low-noise amplifier, mixer, power amplifier)
- Design circuits using simulation tools
- Measure real circuits at microwave frequencies and apply de-embedding and calibration
- Write good quality reports
- Read, comprehend and explain technical literature

More detailed explanations of outcomes are provided in study guides, which are distributed to students. We also asked the following research questions:

1. How can we demonstrate benefits of active learning?
2. What are the most appropriate and effective implementation techniques to bring active learning to Microwave Circuit Design courses?
3. Based on course assessment, how do we improve the course and what are the lessons learned that can (potentially) be generalized?

The existing literature on design and assessment of microwave courses addresses some of the issues related to hands-on and project-based activities[5-8] but it is short on assessment data and rationale for introduction of various teaching techniques. One useful conceptual framework for discussing microwave education was provided by Gupta[9]. Our work provides a fresh look at how to design the courses and why, as well as providing initial data to support decisions and course refinements, as outlined below.

III. Implementation of the new courses

We will first report on our experience with classroom response system from Learning Catalytics since this can be readily implemented by interested instructors. For each lecture we looked into possible conceptual problems that students have exhibited in the past and tried to find appropriate questions and/or activities that would bring that up for discussion[*]. One area of considerable difficulty is the concept of matching, reflections and how Smith chart is to be used.

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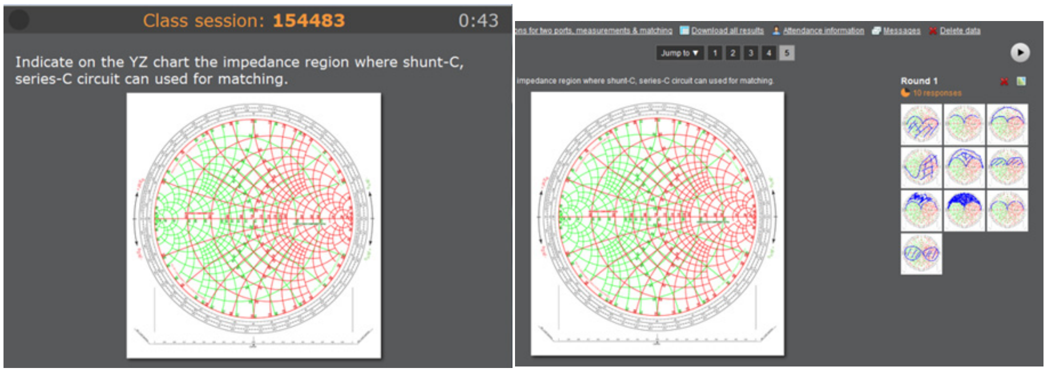
[*] Having a "concept inventory" set of questions would be very useful but none appears to be readily available.

Figure 2 presents a question screen on the left (as seen by students) and student answers on the right. It is immediately clear that several students are having difficulty and may even be completely lost. In such a case, we need to stop the lecture and: a) have peer discussion, or b) pose a different question, or c) explain the material in more depth. Some of the fundamental concepts can be tested in this way and class progress adjusted accordingly.



Indicate on the YZ chart the impedance region where shunt-C, series-C circuit can used for matching.

impedance region where shunt-C, series-C circuit can used for matching.

Figure 2 Illustration of an in-class problem with graphical component for posing the question and for student response. On the left is the question and on the right are student answers.

Note that students are asked to visualize and give their answers in graphical format which is a significant advance provided in the latest response systems. Similarly, students can provide quick sketches of circuit schematics which can then be discussed, providing immediate feedback and interaction.

Another valuable type of question is related to ordering of given items. This comes up any time we are dealing with procedural knowledge, such as design process for a matching circuit. The steps are usually well defined and by asking students to order them we draw not only on memorization of the procedure but also understanding why they are organized in a certain order. This type of activity helps students organize their knowledge[4].

Here are some of our initial observations regarding use of this response system:

Upside:	Downside:
• Goes beyond multiple choice questions • Graphical and TeX capabilities • Immediate formative feedback • Wide range of devices (laptop, smartphones, tablets) • Enables peer interaction and competition	• Significant investment in time to build a “database” of questions or problems • Inelegant handling of complex numbers • It takes a couple of weeks for students to get used to it and regularly bring devices

Every week there was one lab which typically involved design of a given circuit, e.g. transmission lines, matching circuits, power dividers etc., laying it out using sticky copper tape[6], measuring it and comparing predicted results with actual ones. Students had to cut copper tape, solder SMD components, drill vias, etc. and use simulation tools while in the lab to accomplish the tasks. After each lab they were asked to write a report and answer some questions. The latter were intentionally left vague to force students to think about their answer before typing it up. In the last section of the report they were asked to comment on what were the two most interesting things they found during that week that are related to class material but not necessarily covered in class. For example, they may have discovered a new microstrip line calculator, or an article on use of some filters. The intent was to enhance student metacognition through reflection. Feedback, in the form of annotated word files, was provided weekly.

Towards the end of the class, students were asked to watch and summarize a one hour long technical webcast on a topic related to class but not directly covered. The intent was to expand students' technical skills by forcing them into unfamiliar, but related, territory and making them use their knowledge in a different context. Finally, during the 2nd half of the courses pairs of students were engaged in class projects on filter and LNA design. A written report and working prototype demonstration were required. Midway through the term, students start working on two simulation assignments which utilize Agilent ADS software.

IV. Assessment

In addition to the usual items used for grading, such as exams, lab and project reports, at the end of each term we ran a survey with questions given in Table 1. The first four questions were designed to address research question 1 on benefits of active learning. The rest of the questions addressed research question 2 regarding the most appropriate and effective teaching technique.

Table 1 Student survey questions.

I am confident that I can:	I found this technique to be:
1. Design microwave circuits 2. Build and test microwave circuits 3. Write good quality reports 4. Read and understand technical publications	5. Building and testing circuits 6. Running circuit simulations 7. Doing in-class exercises and problems 8. Solving homework problems 9. Class project (filter design, simulation, build, test) 10. Listening to lectures in-class 11. Watching recorded videos of lectures (Echo 360) 12. Watching pre-recorded videos (special topics) 13. Working with teammates 14. Class project
Scale: Strongly Agree, Agree, Neutral, Disagree, Strongly Disagree.	Scale: Very helpful, Somewhat helpful, Neutral, Not helpful, Waste of time.

There were 14 responses out of 15 students after first term, and 8 out of 12 after the second term. The first survey was administered before grades were posted and the second after they were posted. Figures 3, 4 and 5 present histograms of student responses. Note that these are raw numbers which will suffice for qualitative discussion below.

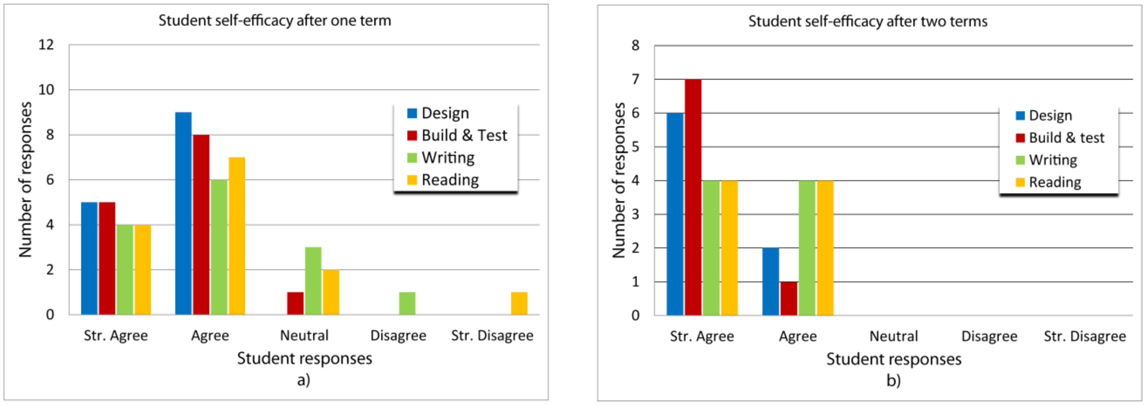


Figure 3. Student self-efficacy in the areas of designing circuits, building and testing, writing reports and reading technical literature: a) after the first term, and b) after the second term.

It is obvious that after the second quarter students felt more confident across all four categories. We can speculate that this can partially be attributed to attrition of students who were not that interested in the class. Based on student comments at the end of survey, however, it is also clear that their self-efficacy did improve from the first to second term. By the end of the 2nd term students were very confident in their Design and Build & Test abilities but the improvement in Reading and Writing was noticeably smaller.

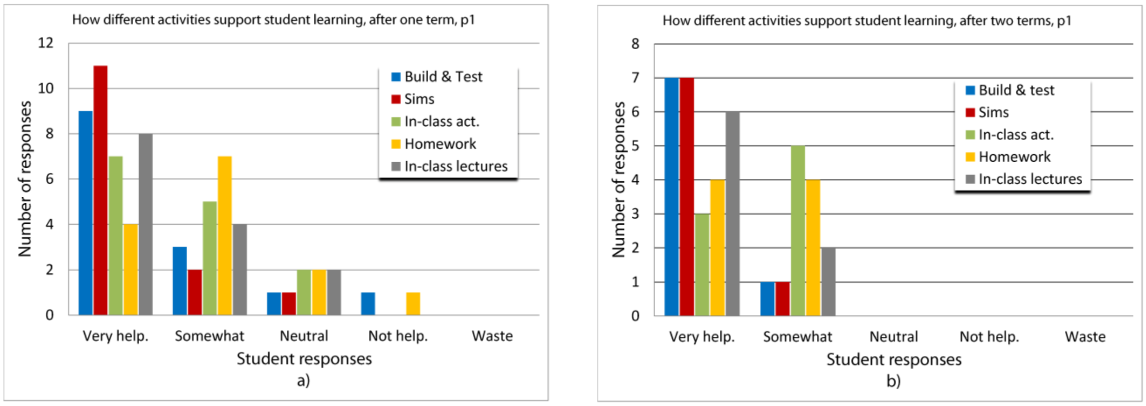


Figure 4 Student assessment of how well various class activities contributed to their learning: a) after the first term, b) after the second term (part 1).

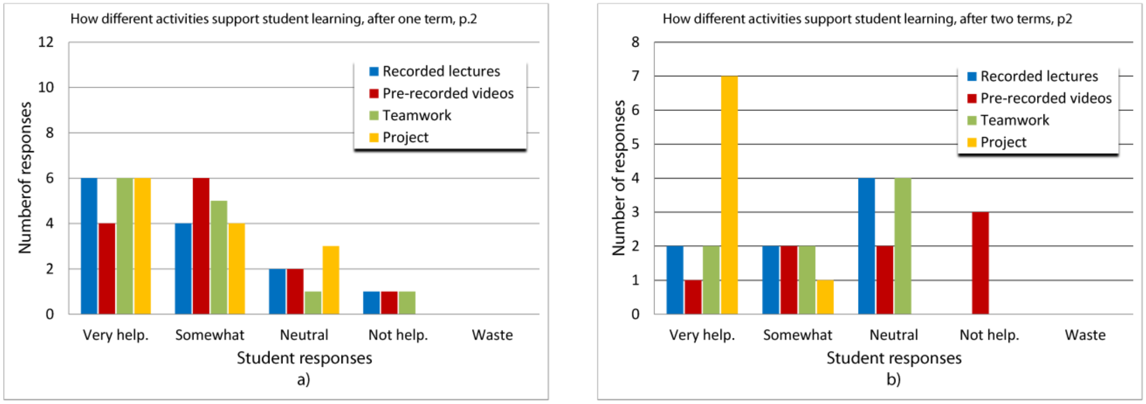


Figure 5 Student assessment of how well various class activities contributed to their learning: after the first term, b) after the second term (part 2).

Next, we attempted to evaluate the effectiveness of various components of the course, as judged by the students. Building and testing circuits and their simulations were perceived as most useful, as shown in Figures 4 and 5. Such high ranking for simulations was a surprise and, as a result, we will introduce simulations earlier in the course. In-class activities were, in general, deemed effective but there is room for improvement. Somewhat surprisingly, in-class lectures were deemed even slightly more effective than in class activities. However, we may need to clarify or eliminate this question since it is possible that students are not clearly separating the activities from listening to instructor lecturing. Our attempts to introduce video materials, either as recordings of live lectures or as videos covering special topics, were not very effective. Working with teammates appears to not have worked well in the 2nd term but that seems contradicted by the results for the class project which was judged to be effective in both terms.

V. Lessons learned and future work

Based on the results presented above, we drew some preliminary conclusions and observations:

- Students feel more confident in their technical skills than in “soft skills” of writing reports and reading technical literature. We will address this by a different approach to writing assignments where students will be asked to submit revisions of the drafts, instead of moving on to the next report. Requirement for reflection on their learning will be emphasized more strongly and we will provide additional reading assignments.
- Design, build, test cycle was successfully implemented with good results. Simulation part will be introduced earlier and more practice provided.
- We need to further improve our design and selection of in-class activities. In particular, we will implement a more stringent structure where students first work on the activity individually, followed by discussion with neighbors, followed by discussion of overall results. We will also introduce a required preparation before the class which will be tested at the start of lectures or labs.

- Recording of lectures is of limited use in the active learning environment. However, foreign students find these very valuable due to language barrier.
- Our attempt to provide some additional materials as pre-recorded videos did not work as well as some other techniques. We attribute this to relatively poor quality and excessive duration. These will have to be planned better, last no longer than 10-15 minutes, and directly address students' misconceptions and/or difficulties.
- Homework assignments were de-emphasized in this round, but students still need more practice and we will re-introduce some of it in the few critical areas.
- There seem to be some issues related to teamwork but these were not apparent during the lab sessions. We will address this through a mid-term survey.
- Our observation of student work in all phases of the design cycle was invaluable for adjusting the pace and content of class topics and activities.
- We need to combine some objective assessment (based on student work) with self-reporting assessments. For this to happen, we will have to develop rubrics for various course outcomes. Currently, only writing and presentation rubrics have been developed.

Overall, we believe that this was a successful first iteration of introducing active learning in all aspects of the course, as demonstrated by assessment data. Having access to a very sophisticated lab is, obviously, very useful but we have presented rationale and techniques that should be transferable to other environments. Our assessment data has provided us with sufficient initial feedback to refine the courses and evaluate effectiveness of different teaching techniques. It is our belief that the traditional separation of courses into labs and lectures is getting in the way of effective student learning. We have attempted, with some success, to blur that line. We have also attempted to provide some theoretical grounding for various changes and course design choices.

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