SoC FPAA Immersed Junior Level Circuits Course

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Abstract—We present our junior level class implementation moving from classical discrete circuit concept towards system level design. This approach was enabled using large-scale Field Programmable Analog Arrays (FPAA) (ECE 3400). The approach enables a first junior level transistor circuit course to build and verify system level designs. This course heavily utilized remote FPAA designs for their hands-on projects; the resulting class data usage generated by this system gives some information on class behavior. This discussion presents the implementation, analysis, and early assessment data for this first semester class.

At the beginning of my junior level circuits class this semester, I explained this semester will be different from previous semesters. I was teaching this class exactly thirty years after I took a similar class. When I took that class[1], it seemed nearly 20 years out of date. A usual junior level circuits course seems about explaining every traditional transistor (and vacuum tube) topologies in a couple of classical audio amplifier configurations. Each program assumes this historic approach presents the clearest understanding of circuits, while students almost never develop the simple circuit intuition, believing mindlessly deriving equations is doing circuits. One would not be surprised why only a few students have any interest in circuit design.

This paper discusses our junior level class implication of large-scale Field Programmable Analog Arrays (FPAA) (ECE 3400), particularly the resulting circuit education and design implications from these approaches. Figure 1 summarizes our FPAA concept, described in other papers as well as its implementation. An understanding of historical circuit techniques may be valuable for some students, and such courses would easily follow after our approach. First, the discussion will continue through overviewing the opportunities enabling a first junior level transistor circuit course presenting a system level perspective. Second, the discussion will explain the use of the remote FPAA system in this course, and resulting class data usage generated by this system. Third, we will discuss other aspects of this first semester class, including other initial assessment data. Finally, we will summarize the approaches with some final thoughts.

Utilizing FPAA devices enabled a bold shift towards system-level design, further illustrated by Fig. 1. Previous papers have discussed the introduction of FPAA devices, such as the SoC FPAA [1], into a graduate course (Analog VLSI, ECE 6435) at Georgia Tech [2], [3], [4], including early discussions on assessment. These educational efforts are continuing to be

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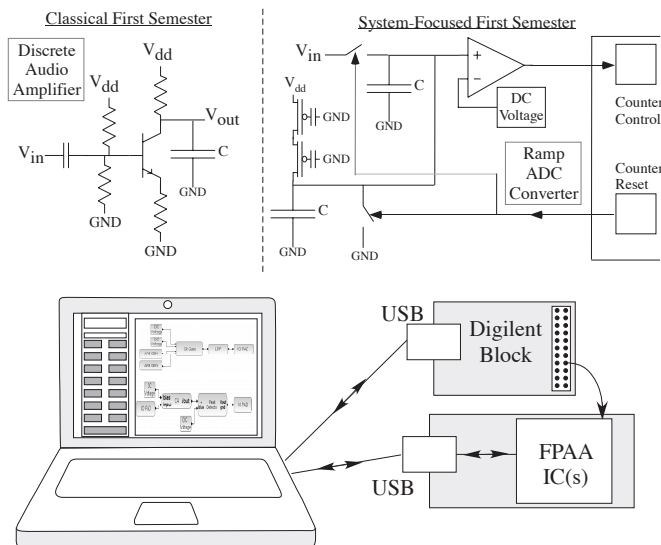[1]I took EE 334 (Transistor Circuits) from Dr. DeMassa at Arizona State University (ASU) Fall 1986

Fig. 1. Moving from classical discrete circuit concept towards system level design, empowered by FPAA devices. A typical classical first junior level transistor circuits course focuses on learning many forms of a traditional audio amplifier. The focus is on design with discrete parts, where the transistor is the difficult element. The system-focused first junior level course covers many of the same circuit fundamentals, and results in students designing a system component (e.g. a Ramp ADC). FPAA concepts empower the ability to move towards a system level course as well as a hands-on circuits course. The FPAA structure just requires a board connected (through USB) to a student laptop with our open-source Virtual Machine.

developed [7]. The technology had become stable enough to enable patient graduate students a unique educational experience, opening the opportunity to utilize FPAA devices earlier in the curriculum. This study opens up the opportunity for wider FPAA deployment in undergraduate curriculums.

I. JUNIOR LEVEL CIRCUITS: FROM AUDIO AMPLIFIER TO ON-CHIP IC DESIGN

Fall 2016 was the first full implementation of ECE 3400 as a hands-on, design, devices-to-systems course. This course implementation started with three key objectives to enable hands-on measurement of multiple circuits, enable students to design different circuits and experimental measure these components, and enable students to experimentally utilize on-chip system design concepts rather than classic discrete design approaches. The roots of these approaches build from the inspiration of Caltech CNS 182 (Analog VLSI and Neural Systems) as well as the ECE 6435, building on the experimental topics that connect to traditional circuits topics. The CNS 182 (and follow-on) approach(es) was heresy in the classical circuit community in the 1990s, similar to digital VLSI techniques
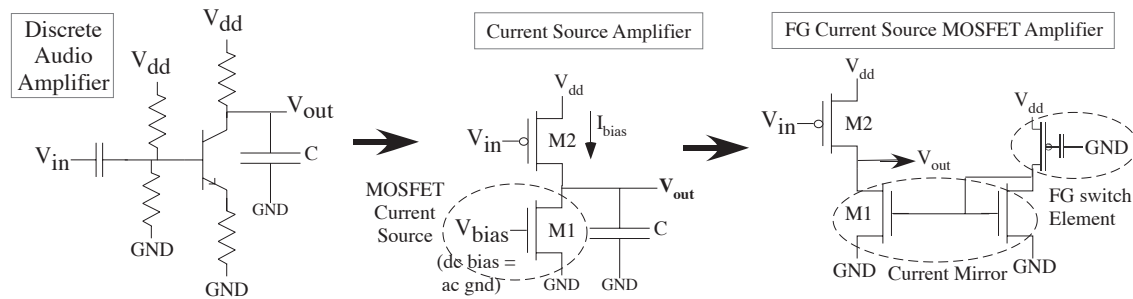
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Fig. 2. The flow moving from a classical amplifier discussion, like the discrete circuit version of an audio amplifier, towards a reusable, programmable and configurable circuit block. Classically, an on-chip solution would require getting either discrete transistors as well as having equipment for setting fine-voltage biases (e.g. Olin: Introduction to Microelectronic Circuits), or a custom fabrication process for the students to use in a later semester. Utilizing on-chip Floating-Gate (FG) transistors, a key part of the FPAA design, enables the student to simply program a desired current, through a current mirror, for the same circuit. Issues of biasing are simply and directly handled. The circuit on the right was used as part of the second project this semester.
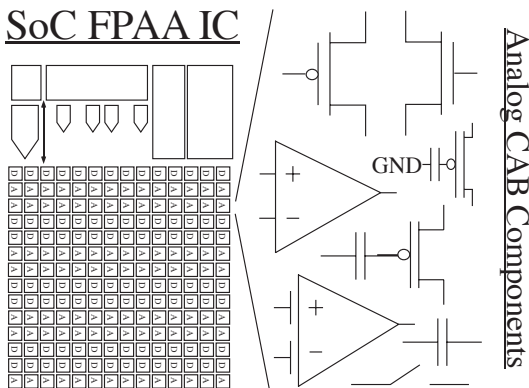

Fig. 3. A focus on the Computational Analog Block (CAB) components in an SoC FPAA device. The SoC FPAA device is a combination of analog and digital components, including on-board uP and Memory. The potential devices are transistors, transmission gates, capacitors, FG transistors, Transconductance Amplifiers (TA) that use FG devices to set bias currents, and Transconductance Amplifiers (TA) that use FG devices for the input transistors and bias currents.

Fig. 4. On-chip IC design focuses on MOSFET transistors. For a fixed bias current (I_{bias}) at the source and drain terminals, we have a (large-signal, static) linear relationship between gate, source, and drain. Drain current versus Drain voltage shows the MOSFET is a gate-controlled current source. From the linear relationship, one gets *four* fundamental circuits by fixing one terminal, apply the input to one terminal, and the resulting equilibrium terminal is the output. σ is the Early effect, or channel length modulation, or Drain-Induced Barrier Lowering (DIBL) parameter characterizing the ideality of the MOSFET current source.

Assignment	Topic	Day
Project 1	Sub and Above Threshold Transistors	22
Project 2	Two transistor and transconductance Amplifiers	43
Exam	Review of Core Circuit Concepts	51
Project 3	Design your own FPAA Op-Amp	77
Project 4	System Analog Project: LNA + Filter or ADC	102

Fig. 5. Summary Table of Junior Level Circuits Class Topics and Flow

was heresy in the 1970s. Some techniques used in this course were attempted in various forms over the previous decade with the best available options; an experimental design experience for undergraduates has been nearly impossible until using the techniques in this class. The material for this course is available on-line[2].

The approach moves towards using programmable transistors acting as approximate current sources. Figure 2 shows the necessary shift from a discrete circuit based approach to a programmable on-chip approach. The classical circuits perspective assumes that students struggle with using transistors as current sources until they have far more circuits knowledge (e.g. look at the presentation in classic IC design textbooks [8], [9]). The FPAA infrastructure utilizes Floating-Gate (FG) transistors throughout its architecture enabling programmability, even utilizing routing switch elements. Figure 3 shows the flavor of components available for students. Some blocks are abstracted in the Xcos tools; for example, the dc voltage block sets a DC output voltage that compiles to a single Transconductance Amplifier (TA) that use FG devices
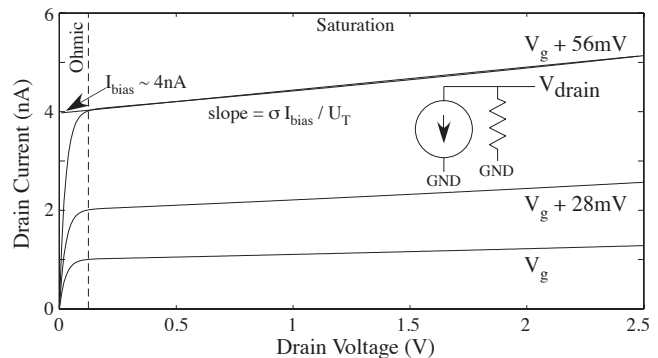
for the input transistors and bias currents. Figure 4 shows the MOSFET current source is the natural device on-chip, and the number of potential devices available is huge, compared to resistive and inductive parasitics; capacitances to a fixed potential are available almost everywhere, and two-terminal capacitances are also available.

II. USING REMOTE FPAA FOR HANDS-ON CIRCUIT DESIGN

Figure 5 shows the core structure with our course. The course centered on four projects, one exam, and an optional
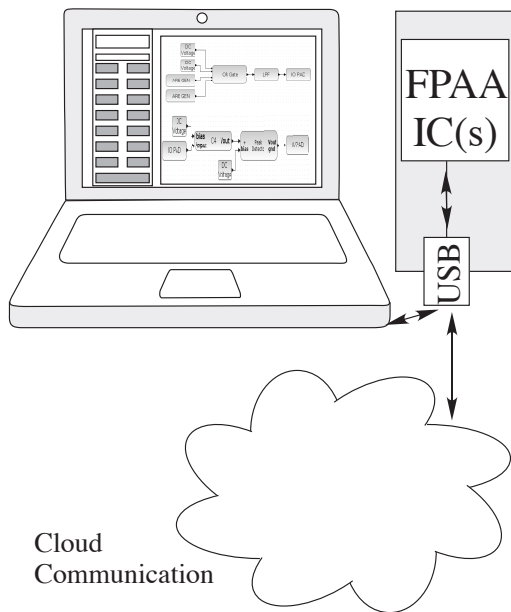
Fig. 6. Summary picture for the remote test system implementation. The design toolset in Xcos/Scilab allows the user to "send email" in addition to "program FPAA", allowing the file sent to an email address that is POP-ed off the server, the resulting programming files are extracted and executed, the resulting data measurement is performed on the device, and the results are sent back by email to the original sender. A simple USB digital interface enables the FPAA to appear like as a typical digital peripheral.
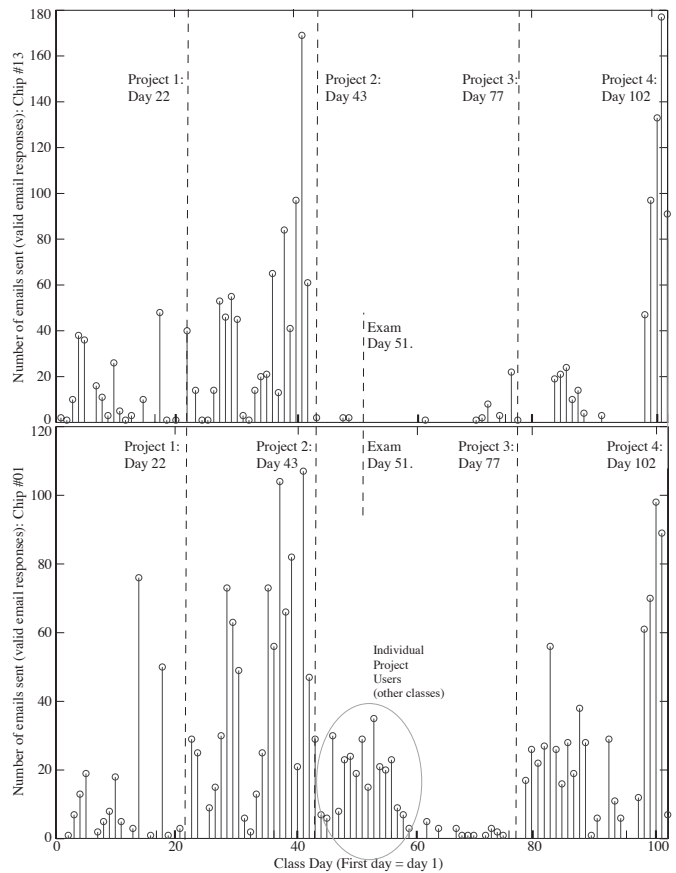

Fig. 7. Number of email replies sent by the remote system by day through the class. We utilized two remote systems, designated chip 1 and chip 13 during the semester. One sees the highest activity happened just before projects were due, in particular project 2 and 4. Significant activity after the second project on Chip 01 was due to separate undergraduate and graduate special problems classes using the FPAA system.

final exam. The course was originally set up, with allocated resources, for students to connect physical boards to their laptops as well as using the remote FPAA system. Unfortunately, an administrative issue occurred only allowing students to use the remote system; future years will allow for multiple opportunities. Figure 6 shows the basic concept for the remote FPAA system [6].

Our unique situation resulted in excellent data on the students using the remote system, as well as enabling to find (and correct) issues with this system. Figure 7 shows the student use of the two FPAA boards the students had access during the semester. Project 1 only lightly used the remote system, but focused on students learning the rest of the system (e.g. simulation [11]). Project 2, 3, 4 expected heavy use of the remote system. One notices heavy activity mostly a few days before an assignment was due, as well as students started to just coast through after the second project / exam until the beginning of the fourth project, when the students were encouraged that they needed to build back to the original work ethic. The second project focused on projects that mostly required repeating given examples with slight modifications. Almost all groups achieved the desired results. The third and fourth project focused on a particular circuit design. Several groups achieved good results on the fourth project, particularly the groups assigned to build a ramp ADC. The groups assigned to build filters had more struggle, probably because they were overconfident of their knowledge.

III. WHAT WAS LEARNED FROM THE FIRST CLASS IMPLEMENTATION

Figure 8 shows the results from the student survey shown at the end of this one semester class. Going forward, we will take the survey at the beginning and end of the course, as well as comparisons with traditional offerings of this course (e.g. Spring 2017 semester[3]). The students all believed their knowledge of MOSFET transistors, transistor circuits, and analog system knowledge significantly increased throughout the semester. Looking at the rubric data from grading the four projects, as well as results from the one exam, a large percentage of students routinely solved these projects. The students seemed comfortable designing multiple transistor circuits, including some confidence at 5-8 transistor level circuits, although nervous at greater than 10 transistor circuits. This result, coupled with graded assignments, indicates some success on our objective to enable students to focus at a system level. Our expectation that students in a traditional course would have no confidence beyond a single transistor circuit,

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[3]We will discuss preliminary findings at the conference and present the comparison in a later paper

Question (Abreviated)	Mean
MOSFET transistor knowledge significantly increased	1.64
transistor circuit knowledge significantly increased	1.48
analog system knowledge significantly increased	1.77
comfortable designing circuits, 2-4 transistors	1.18
comfortable designing circuits, 5-8 transistors	0.41
comfortable designing circuits, 10-15 transistors	-0.23
comfortable designing circuits, 20-30 transistors	-1.05
increased circuit design ability this semester	0.81
exp. measurements important learning circuit design	2.05
circuit abstraction essential for building systems	1.52
knowledge of circuit tools / simulation has increased	1.05
Simulation helpful, not sufficient learning circuits	0.14

Fig. 8. Results of assessment questions asked on the last day of class after all projects had been submitted. The values were averaged from a 1 to 7 score (subtracted from the center = 4). Twenty-three (of 24) students responded.

a hypothesis we will test through future surveys. Further, the students clearly understood the need for doing experimental measurements for circuit design as well as abstraction being important for building systems, all explicit course objectives. From other survey results, the students wanted access to FPAA boards in hand in addition to the remote system, which was our original intent, but unfortunately was not available due to administrative issues. The students also asked for improved documentation and organization of documentation going forward, particularly earlier in the semester for documentation on the remote FPAA system. Given this course was in its first full offering, this result is not surprising. Documentation improved throughout the course. Some issues were not anticipated beforehand, including emphasizing what on-line resources we made available. The first semester showed some positive movement, although this effort is just at its start, both in implementation and assessment.

The assessment data is supplemented by our observations and issues for the semester class. The first project, curve fitting MOSFET devices and building a well matched (EKV [10]) simulation based on this data, proceeded much smoother than previous uses of these approaches given the Xcos / Scilab circuit simulation tools recently developed [11]. The second project proceeded smoothly typical to similar components utilized in our graduate course (ECE 6435), this time entirely using the remote system. The third project reflected the resulting student effort; the students worked through the design efforts and started with the simulations, but ran out of time to verify (either in simulation or experimentally) their design performance. The fourth project multiple students simulated, compiled and measured their complete system. Both the third and fourth project showed the time efficiency of experimental measurements versus multiple numerical simulations for circuits over 10 transistors.

IV. SUMMARY THOUGHTS OF FPAA-BASED, SYSTEM-LEVEL JUNIOR-LEVEL CIRCUITS COURSE

This discussion showed our junior level class implementation moving from classical discrete circuit concept towards

Design Concept	implication(s)
Subthreshold	simple expressions,
MOSFET design	widely used in modern design
Programmable FG	Current source
current sources	design
FG OTA inputs	increase linear range
	enables high V_{T0} mismatch design
	direct solutions
FPAA framework	enables rapid prototype
	rapid experimental measurements
	built in testing infrastructure

Fig. 9. Fundamental circuit changes, enabled with on-chip IC design, enable a new paradigm for circuit teaching.

system level design, enabled using FPAA devices. One always has a place for historical circuit design classes, such as the brilliant audio engineering course, started and taught by Marshall Leach in 1969, that can follow on after such a class. These classes are specializations, not fundamental for system-level IC design. The classroom implementation did not require any specialized laboratory spaces, additional human resources, or other technology other than the FPAA boards. Figure 9 shows the fundamental concepts enabled by the FPAA technology, and their resulting impact for moving towards a first junior-level system design course. Although one assumes that undergraduate engineering classes, unlike say topics in liberal arts, are not able to to utilize higher forms of learning (e.g. synthesis), the experience in this class tells a different story that when we actively look to build the infrastructure and culture, engineering students are fully capable and will rise to the opportunity to achieve these higher learning concepts.

REFERENCES

[1] S. George, S. Kim, S. Shah, J. Hasler, M. Collins, F. Adil, R. Wunderlich, S. Nease, and S. Ramakrishnan "A Programmable and Configurable Mixed-Mode FPAA SOC,"

[2] M. Collins, J. Hasler, and S. George, "Analog Systems Education: An Integrated Toolset and FPAA SoC Boards," *Microelectronic Systems Education*, May 2015.

[3] J. Hasler, S. Kim, S. Shah, F. Adil, M. Collins, S. Koziol, and S. Nease, "Transforming Mixed-Signal Circuits Class through SoC FPAA IC, PCB, and Toolset," *IEEE European Workshop on Microelectronics Education*, Southampton, May 2016.

[4] Michelle Collins, J. Hasler, S. Shah, "An Approach to Using RASP Tools in Analog Systems Education," *FIE*, October 2016.

[5] M. Collins, J. Hasler, and S. George, "An Open-Source Toolset enabling Analog-Digital-Software CoDesign," *Journal of Low-Power Electronics Applications*, January 2016.

[6] J. Hasler, S. Kim, S. Shah, I. Lal, M. Kagle, and M. Collins, "Remote FPAA System Setup Enabling Wide Accessibility of Configurable devices," *Journal of Low-Power Electronics Applications*, October 2016.

[7] M. Collins, J. Hasler, and S. Shah, "An Approach to Using RASP Tools in Analog Systems Education," *FIE*, October 2016.

[8] P. Gray and R. Meyer, *Analysis and Design of Analog Integrated Circuits*, Wiley, 1993.

[9] P. Allen and D. Holberg, *CMOS Analog Circuit Design*, Oxford University Press, 2002.

[10] C. C. Enz, F. Krummenacher, and E. A. Vittoz, "An analytical MOS transistor model valid in all regions of operation and dedicated to low-voltage and low-current applications," *Analog Integrated Circuits and Signal Processing*, vol. 8 no. 1, 1995, pp. 83-114.

[11] A. Natarajan and J. Hasler, " Modeling, simulation and implementation of circuit elements in an open-source tool set on the FPAA," *Analog Integrated Circuits and Signal Processing*, January 2017.