

Tinkering With CMOS Circuits at the Lunch Table With MOSbius

Experimental validation is a critical step in any engineering discipline and doing lab experiments is an essential part of the formation of an engineer. Creating relevant experiments to train integrated-circuit designers has become difficult due to the lack of appropriate components. We designed the MOSbius chip and adapter PCB so learners can perform circuit labs with MOS transistor topologies that are relevant to modern transistor-level IC design. With MOSbius, students can experiment with customized CMOS circuits early on – without the challenges, delays, and cost of designing a custom integrated circuit. Yet, MOSbius serves as a great steppingstone towards full custom IC design courses.

Motivation

Many of today's students are primarily exposed to transistor-level circuits through computer simulations. Few have experience with tinkering with transistors as it often comes with logistical or financial challenges of obtaining components or accessing test equipment. Attention spans also have reduced, so it is paramount that students see things happen in their circuit right away. For microcontrollers, the Arduino platform [1] has significantly lowered the threshold for building microcontroller-based experiments, even for students or hobbyists with limited training. They obtain results quickly with pre-

made examples. This spikes the student's interest to dig deeper and start experimenting on their own. Similarly, FPGAs offer an accessible way to learn digital system design using hardware description languages and verify the design in hardware. The goal of the MOSbius project is to enable a similar experience for MOS transistor circuits.

Design and Analysis ⇄ Simulation ⇄ Measurement

A seasoned IC designer is well versed in theory, uses simulation to verify their designs, and proves correct functionality and performance using measurements (see Figure 1). Any student with an Internet connection can access an extensive set of (open) teaching materials to learn theory. Powerful open-source or free simulation tools [2] are available and can be run on affordable laptops. But, until recently, doing electronic lab experiments was largely limited to university or industry laboratories. The availability of low-cost, all-in-one USB instruments (e.g., [3] and [4]) now bring lab experiments to any lunch table.

The key missing component at this point is access to adequate MOS devices to build IC-relevant CMOS test circuits so that students can learn how to use theory and simulation to design and verify custom MOS transistor-level circuits. The CD4007 [5] and ALD1107/8 chips [6] offer MOS signal transistors, but the available device sizes are limited and the number of transistors per package is small so that building, e.g., a Miller-compensated

OTA requires many chips, leading to an overly complex breadboard.

MOSbius Platform

The MOSbius platform allows students to perform MOS circuit labs at the lunch table (Figure 2). The kit is robust and easy to use. Premade examples (Figure 3) freely available at [7] ensure that stimulating results are obtained quickly. The MOSbius chip (Figure 4) is a custom IC that contains MOS circuit blocks like common-source amplifiers, current mirrors, differential pairs, one-stage OTAs, and inverter stages. The chip is mounted on an *adapter-PCB* that plugs into a solderless breadboard. The PCB has some bias and protection circuits. The students add external components like resistors, capacitors, diodes, or sensors on the breadboard. Connections can also be made on the breadboard, or students can use the on-chip programmable switch matrix to wire up their circuit from a spice schematic or a *connections* file. The chip can be programmed with a microcontroller (Figure 3) or digital pattern generator.

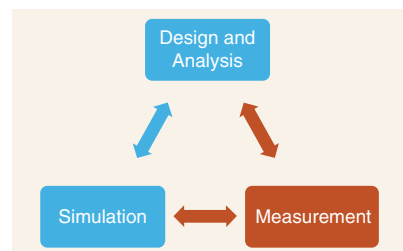


FIGURE 1: MOSbius offers easy access to interesting measurements on MOS transistor-level circuits so students can practice the “Design and Analysis ⇄ Simulation ⇄ Measurement” validation loop.

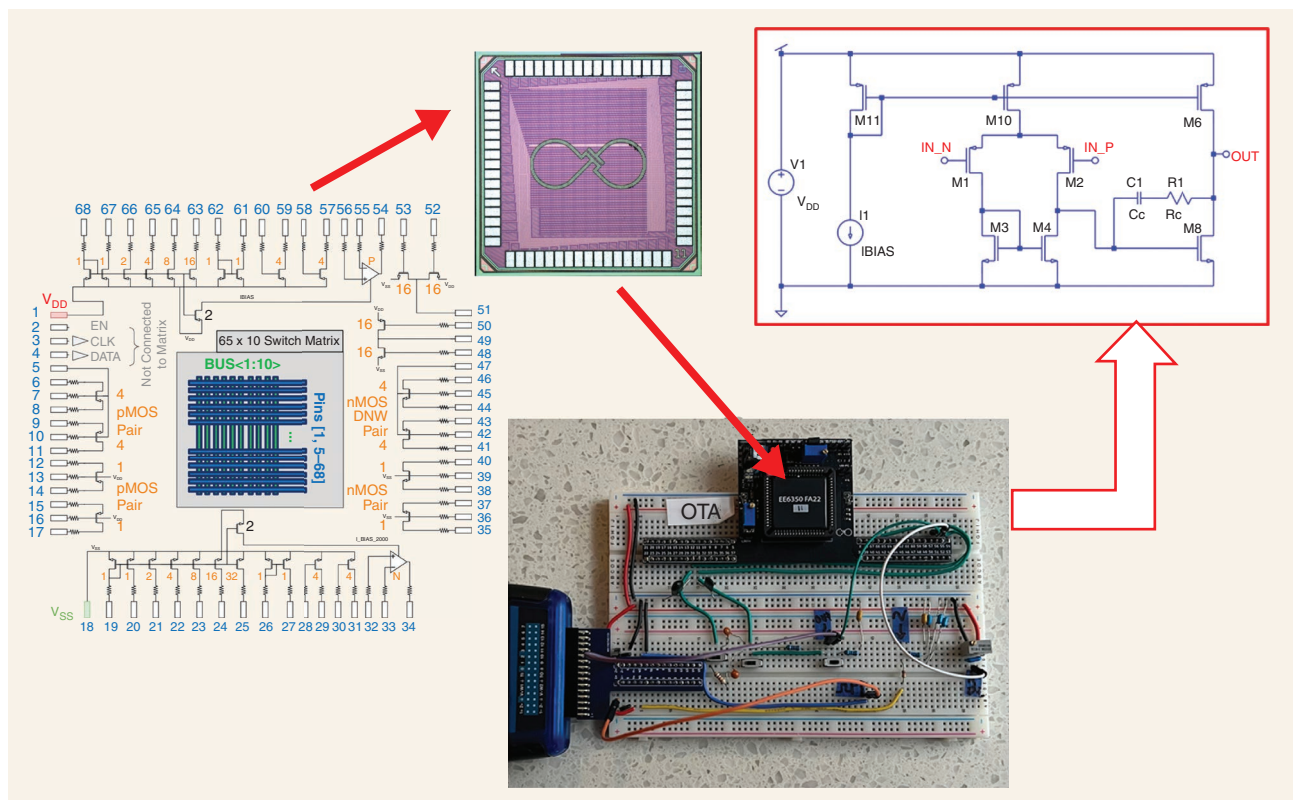


FIGURE 2: An overview of the MOSbius platform. Students design and realize transistor-level MOS circuits using on-chip-style topologies and evaluate them experimentally.

This setup makes *internal nodes* of the MOS circuit accessible for measurements. Measurements can be conducted with affordable, yet powerful, all-in-one USB instruments [3], [4] that have power supplies, oscilloscopes, waveform generators, and digital input-output and logic analysis. The whole experimental setup with a laptop fits easily on the lunch table. The setup is portable so that experiments can easily be done, even outside of a formal electronics lab.

The MOSbius website [7], <https://mosbius.org>, has extensive documentation and tutorials, and the project has a public discussion board.

MOSbius Chip

The MOSbius chip was designed with a 65-nm CMOS foundry process using 2.5-V thick-oxide devices and is packaged in a 68pin plastic leaded chip carrier package. Students are encouraged to use a (gm/I)-based design methodology. The W/Ls of the *unit* (1x) nMOS and pMOS transistors have been chosen so that the devices oper-

ate with a V_{ov} of ~ 200 mV and a (gm/I) of $\sim 8/V$ when biased with $100 \mu A$. All other devices are sized relative to the 1x transistor. The typical external resistor values are 10's K Ω s. With external capacitors in the order of nFs, unity-gain bandwidths of tens to hundreds of kilohertz are achievable. This keeps the effect of breadboard parasitics (typically a few picofarads) negligible so that good correspondence is achieved among measurements, simulations, and calculations.

Simulations

A custom LTspice [8] library (see Figure 5) is available for users to draw circuits and simulate them. Openly available model cards for 0.25- μm CMOS transistors give good results for simulation explorations.

Programming the On-Chip Switch Matrix

The registers that are used to program the switches in the switch matrix are arranged in a 650-stage shift register that is easily programmed using a clock (CLK) and

data (DATA) signal. The enable (EN) signal is pulled low by default on the chip to disconnect the switch matrix if users do not want to use it, and to program the registers; after programming, when the EN is pulled high, the on-chip switches close to make the connections between the pins.

The student can describe their circuit connections using a simple JavaScript Object Notation (JSON) file or can use Python scripts (Figure 6) to extract the connections from their circuit spice netlist. The connections JSON

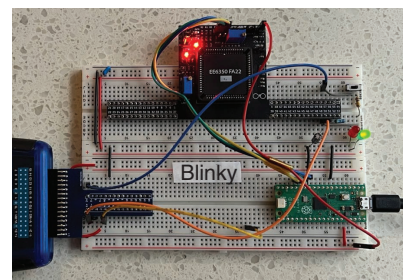


FIGURE 3: Physical setup of the "Blinky" experiment with the MOSbius chip and adapter board on top, the USB instrument plugged into a breadboard adapter in the lower left corner, and a microcontroller in the lower right corner.

file can be uploaded to the microcontroller (e.g., a Raspberry Pi PICO [9]) running microPython, or converted to comma-separated value files to drive a digital pattern generator.

Using MOSbius From “Introduction to Electrical Engineering” to Graduate “IC Design” Courses

We now illustrate how MOSbius can be incorporated into electrical engineering curricula at all levels, from the undergraduate to the graduate level.

Introduction to Electrical Engineering and Electronics I

From “Blinky”-style experiments to single-stage transistor amplifiers, differential pairs, current mirrors, or transistor-level digital circuits like latches, flip-flops, and basic logic gates, many experiments can be devised to complement entry-level circuit classes.

Students progress from building-block-level thinking to transistor-level realization (Figure 7) and can verify

their understanding through simulations and measurements (Figure 8). They can practice reconciling design calculations, circuit simulations, and measurements (Figure 2) considering component variations, simulation modeling limitations, and measurement inaccuracies.

Device Courses

I-V characteristics can easily be measured, even with basic USB instrumentation, to learn about devices

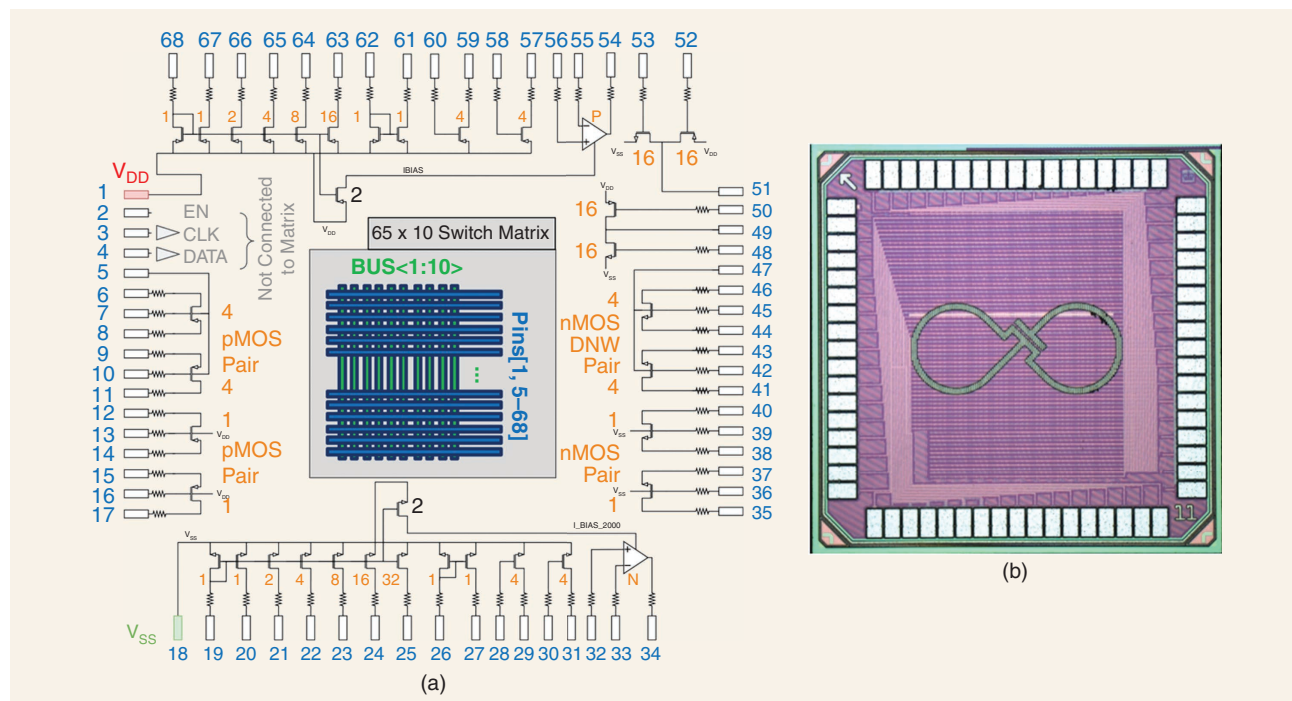


FIGURE 4: (a) A conceptual schematic and (b) microphotograph of the MOSbius chip.

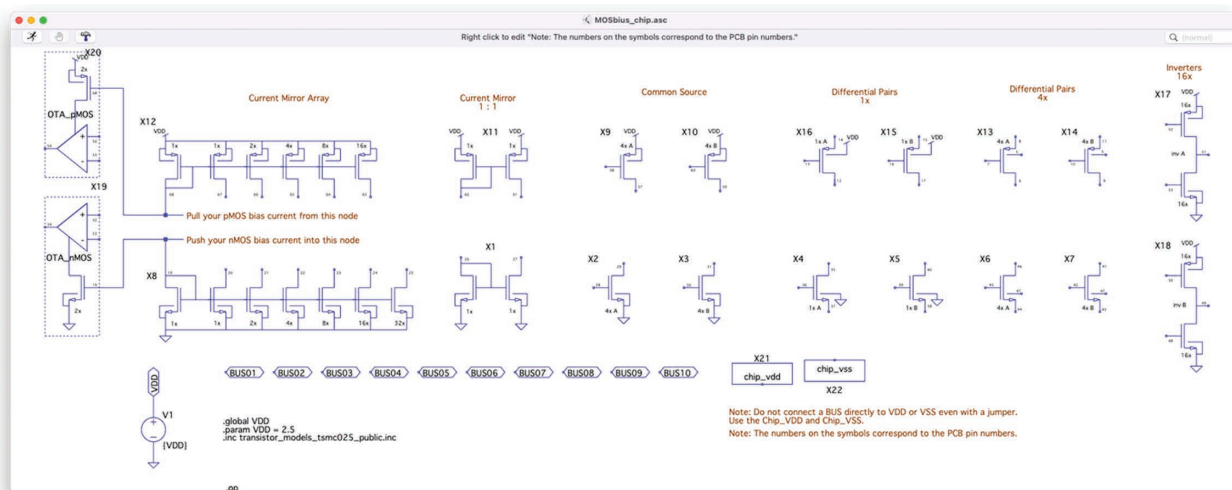


FIGURE 5: A screenshot of the custom LTspice library to draw MOSbius circuits. After making connections, a circuit can easily be simulated before building it on the breadboard.

(see Figure 9). It's one thing to see I-V characteristics in a book or in simulation, it's a whole different experience seeing the characteristics drawn out in front of your eyes. The differential nature of the USB oscilloscope channels makes current measurements quite easy with a resistor. The measured data can further be exported to extract custom models or to make comparisons to simulations.

Analog Electronic Circuits Courses

Many undergraduate circuit curricula follow the junior-level *Electronics I* course with a senior-level *Analog Electronic Circuits* or *Electronics II* course focused on OTA-based circuits using feedback, including stability and frequency compensation, and on basic transistor-level OTA design. MOSbius offers great support for labs to see all the principles of those circuits in action. Uniquely, all circuit nodes are available so that even internal signals can be probed and studied. All resistors and capacitors, including load and compensation capacitors, need to be added to the breadboard. This offers the student the opportunity to change their values and observe the effect of frequency-domain (Bode plot) and time-domain (step response) behaviors.

Figures 10 and 11 show the setup for a two-stage OTA. Students measure the response of the individual stages and then compute the required components for various compensation strategies. In Figure 12, the step response of the OTA in a unity-gain-follower configuration is measured with no compensation, dominant-pole compensation, and Miller compensation. All transistors and their biasing are identical between the measurements, clearly demonstrating the speed advantages of Miller compensation over dominant-pole compensation. The USB instrument software [3], [4] can also measure Bode plots (Figure 12) and the connections between the frequency-domain characteristics of the loop gain and the resulting time-domain closed-loop response can be explored

and checked against calculations and simulations.

Graduate Courses: Filters, ADCs, DACs, ...

MOSbius can be used in graduate-level courses as well. For instance, using the transistors on MOSbius, several OTAs can be built to make biquads for continuous-time filter experiments. Another example is continuous-time delta-sigma modu-

lators (DSMs). Figures 13 and 14 show the implementation of a first-order DSM using an active-RC integrator, a continuous-time comparator, and a D-flip-flop. It uses up all the transistors on the MOSbius chip and only requires an external CLK and analog input signal.

This type of circuit exposes students to advanced concepts and can be an opportunity to learn about more advanced measurements like

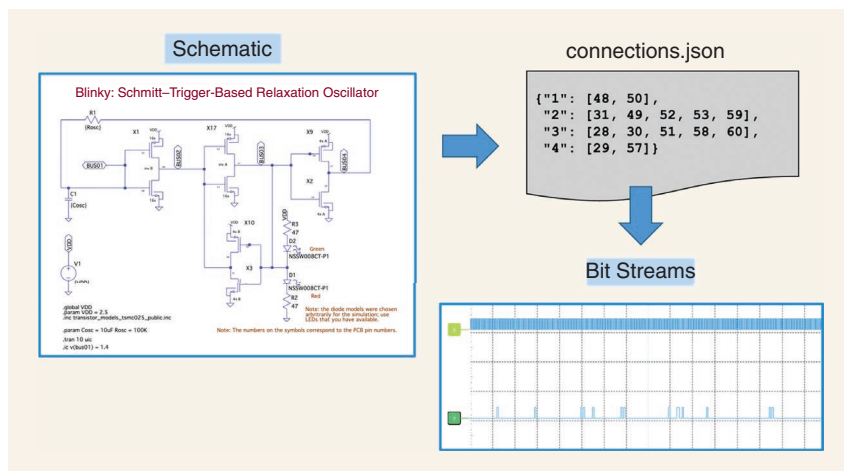


FIGURE 6: Python scripts in the 'MOSbiusTools' extract the connections realized with the on-chip switch matrix from the circuit schematic and generate the necessary CLK, DATA, and EN (not shown) bit streams to program the MOSbius chip.

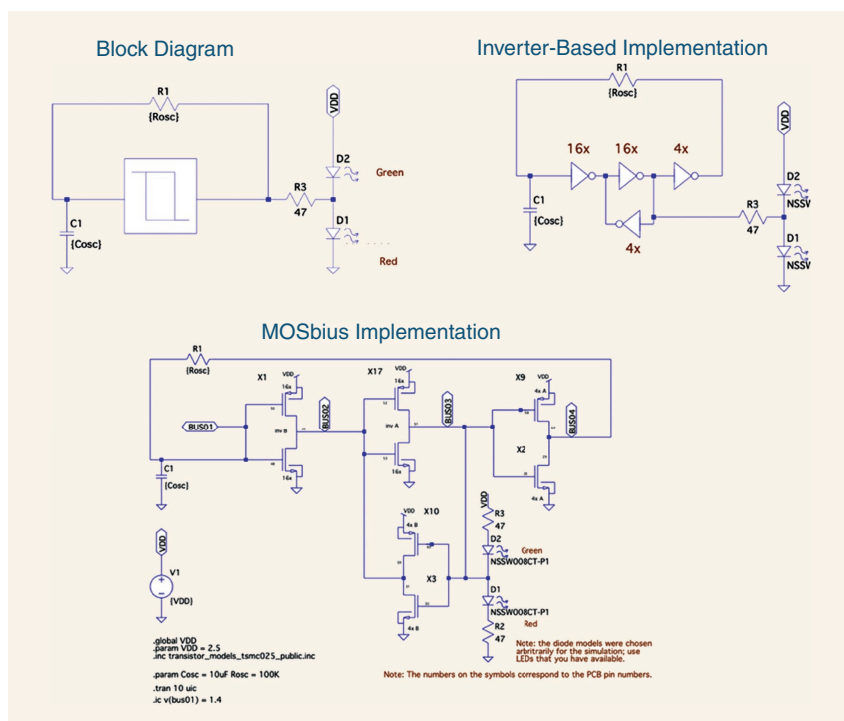


FIGURE 7: Inverter-based realization of a Schmitt-Trigger relaxation oscillator (Blinky) using MOSbius, showing the progression from a building block implementation to a custom transistor-level realization.

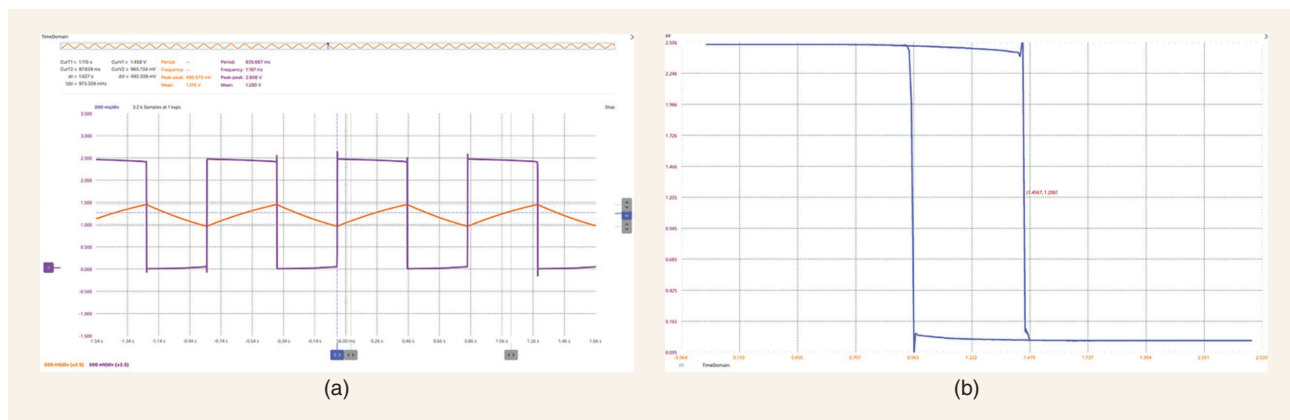


FIGURE 8: (a) Students can measure the transient waveforms of the Blinky relaxation oscillator, as well as the (b) Schmitt-Trigger input-output characteristic (X-Y), to gain insight into the circuit operation and compare it to simulations and calculations.

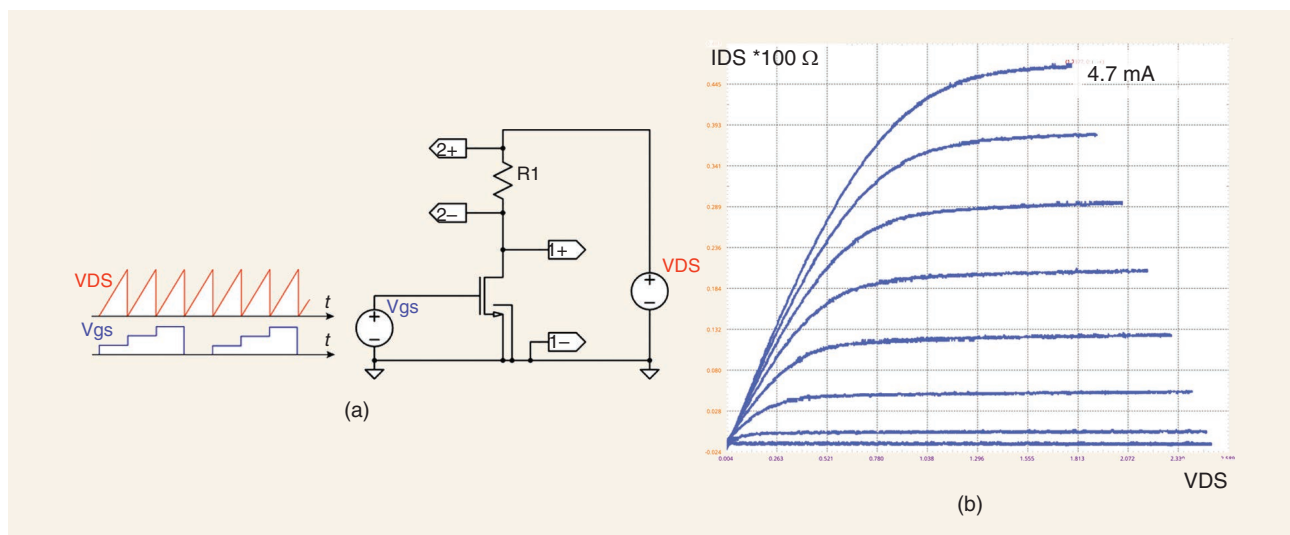


FIGURE 9: The basic setup used to measure I-V characteristics of the 4x nMOS transistor. The gate and drain sweep signals can easily be generated with a USB waveform generator; thanks to the differential inputs of the USB scope, the drain current and drain voltage can be accurately measured.

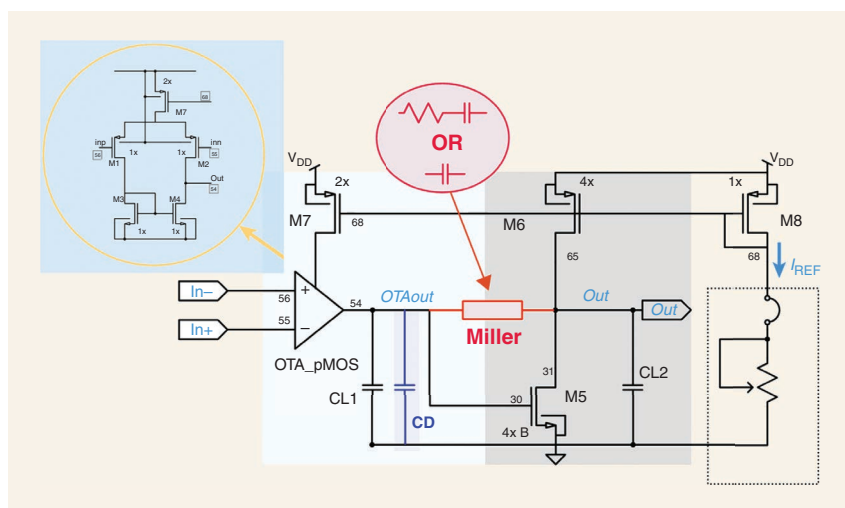


FIGURE 10: The single-ended, two stage, Miller-compensated OTA is easily built with the MOSbius chip; different types of compensation networks can be added externally on the breadboard.

SNR, SNDR, or ENOB. The USB instruments include a logic analyzer so that a digital output can be captured and digitally postprocessed. Alternatively, the spectra of the signals can be reviewed using the USB instrument to understand basic operations, as shown in Figure 15.

Preparation for a VLSI Design Lab Course With Tape Out

MOSbius is a great tool to prepare students for IC lab courses, where they conceive, design, tape out, and characterize their own full custom IC [10]. Through MOSbius experiments, they get exposed not only to transistor-level design techniques but also gain an appreciation of

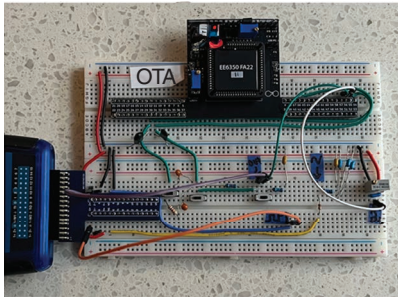


FIGURE 11: This setup for two-stage OTA experiments relies fully on external connections and does not need the on-chip switch matrix; different frequency-compensation networks and different feedback configurations can be selected with the switches.

the measurement techniques (and challenges) that they will need to evaluate their own chip. They are also introduced to basic biasing techniques or to how to program the shift-register-based serial-parallel interfaces that are ubiquitous on prototype chips.

Other Opportunities

We envision that MOSbius can further be used for hackathons, conference design contests or training sessions, senior projects, and so on and look forward to the opportunity to support such events.

Conclusions

MOSbius is a novel platform that brings MOS circuit experiments to any lunch table. It aims to broaden access to experiential learning of circuit measurements so that students can explore the nexus between design and analysis, simulation, and experimental results. The project website [7], <https://mosbius.org/>, provides extensive documentation and ready-made lab experiments so that instructors can easily adopt the labs into their curriculum. Chips and ready-made kits can be obtained through <https://mosbius.org/ordering.html/>. We look forward to collaborating with users to expand the portfolio of lab experiments.

We further encourage designers to consider designing their own MOSbius-like chips. The 2025 IEEE Solid-State Circuits Society Chipathon has MOSbius

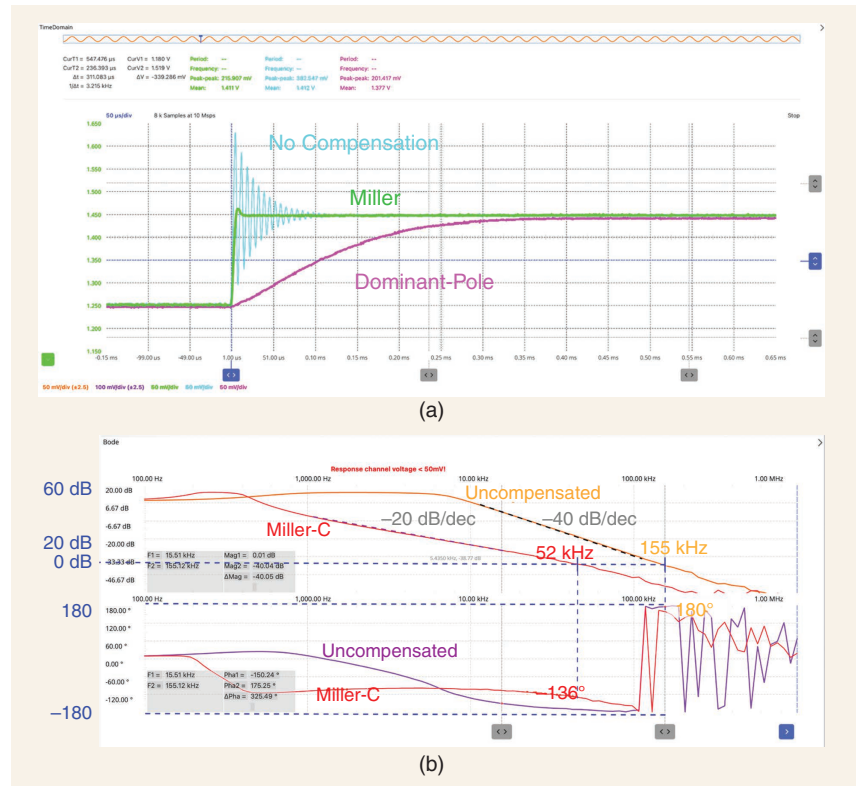


FIGURE 12: (a) The step response for the OTA in a unity-gain-follower configuration and (b) measured Bode plots for the loop gain with no compensation and Miller compensation.

as one of the topic areas to encourage designers all over the world to design open source MOSbius-like chips to broaden access even further.

Nothing can replace the “aha moment” when your circuit finally starts working and you see its operation before you own eyes. That experience will stay long after the equations and analysis are forgotten.

—Peter Kinget

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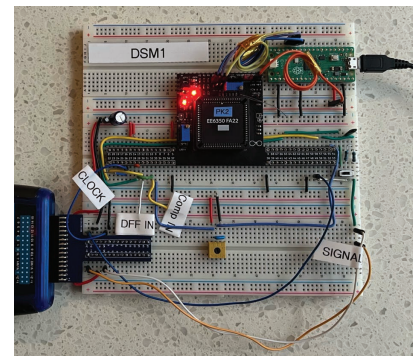


FIGURE 13: The first-order DSM setup uses a microcontroller (upper right) to program the on-chip switch matrix; the USB waveform generators (lower left) provide the external CLK and analog input signals, and the USB scope channels measure the outputs of various stages.

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—Peter Kinget 

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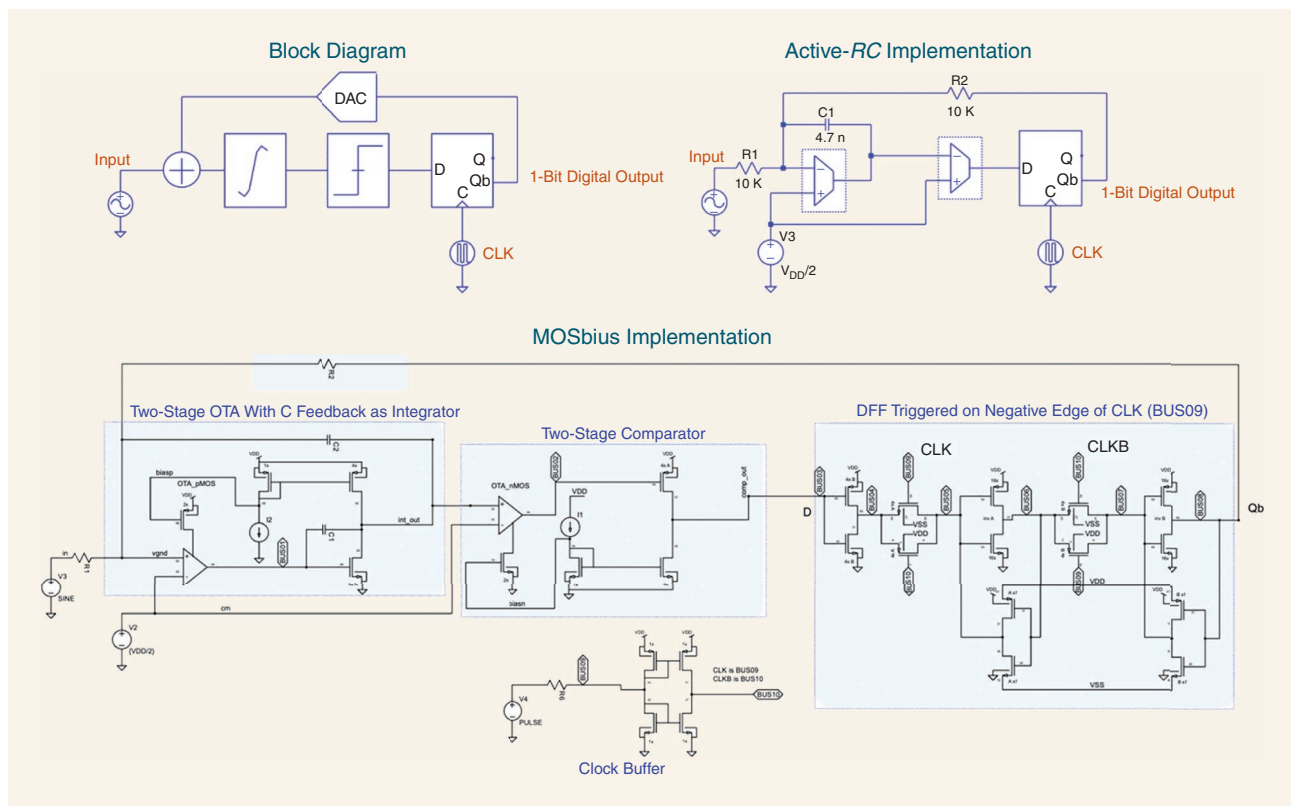


FIGURE 14: Realization of a first-order DSM using MOSbius.

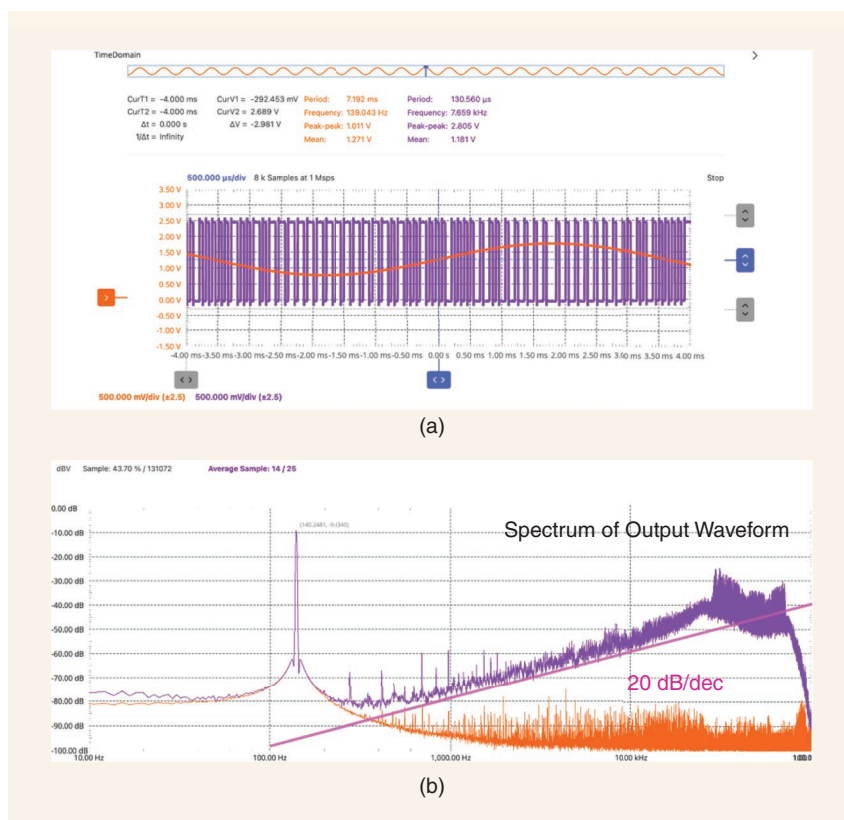


FIGURE 15: (a) The measured time waveform and (b) spectrum of the analog sinusoidal input signal and the digital output of the first-order DSM ($f_{IN} = 139$ Hz; $f_{CLK} = 100$ Ksps); for more accurate measurements the digital output can be processed in the digital domain.

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