U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

ASI Advanced Sensors and Instrumentation

Development of a Radiation-Tolerant Front-End Digitizer

Advanced Sensors and Instrumentation (ASI)
Annual Program Webinar
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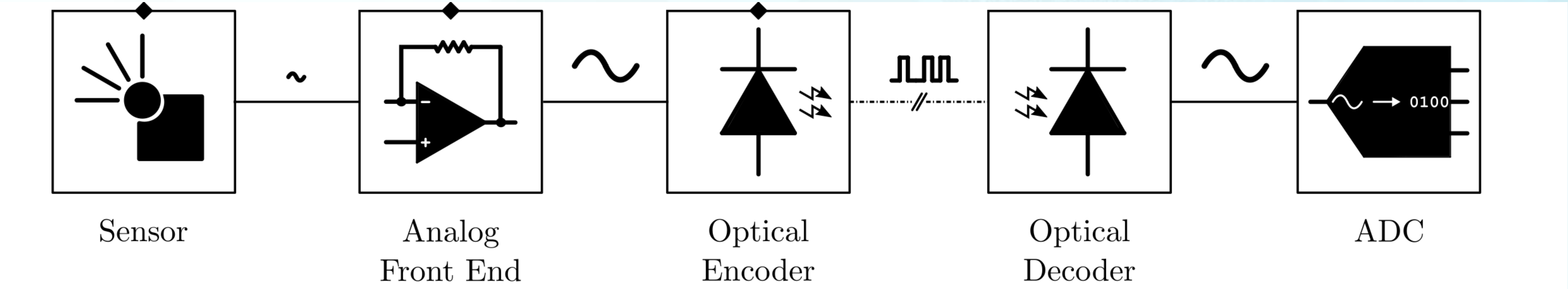
What is FrEnD?

- Goal: Read out entire I&C suite at a single experimental location over one fiber optic cable (or cable bundle)
  - Thermocouples, SPNDs, SPGDs, RTDs, fission chamber (stretch goal)
- FY22: Benchtop prototype design, fabrication, testing
- FY23: Irradiation/field testing of prototype, revisions, radiation hardened prototype



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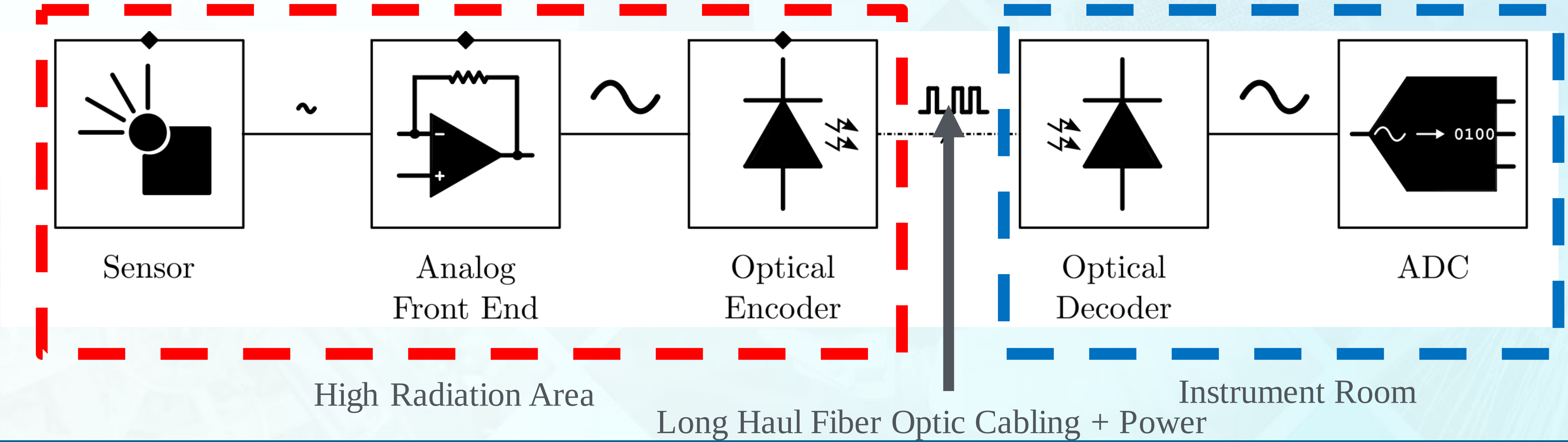
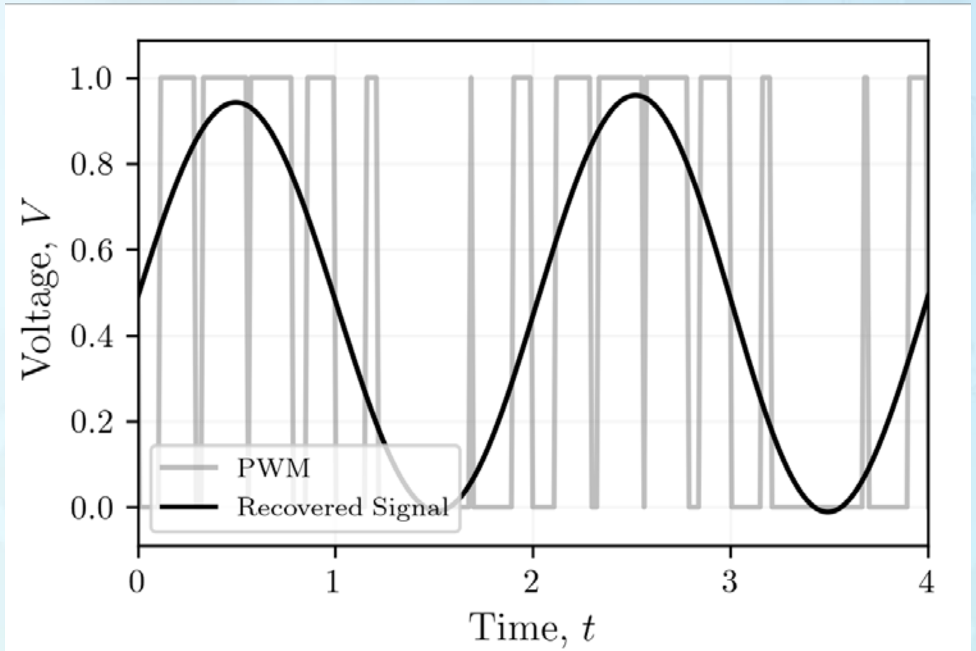
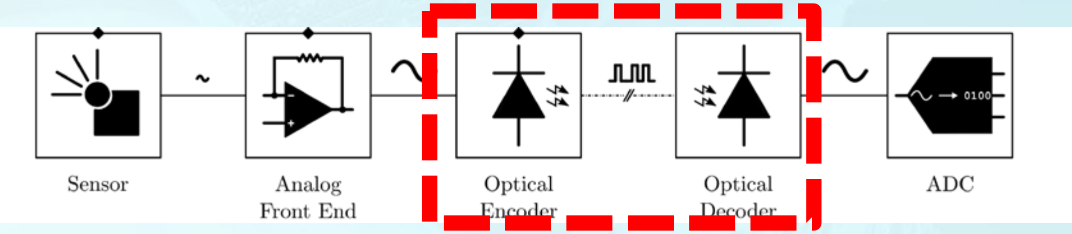


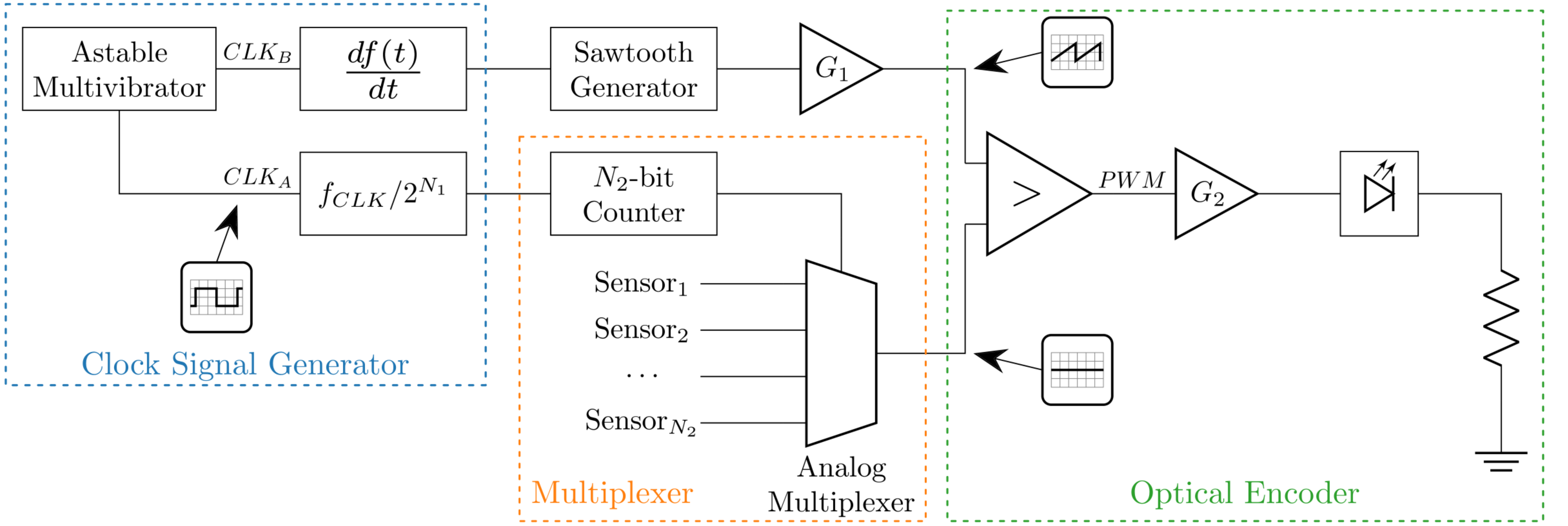
Pulse Width Modulation for Radiation Resistance

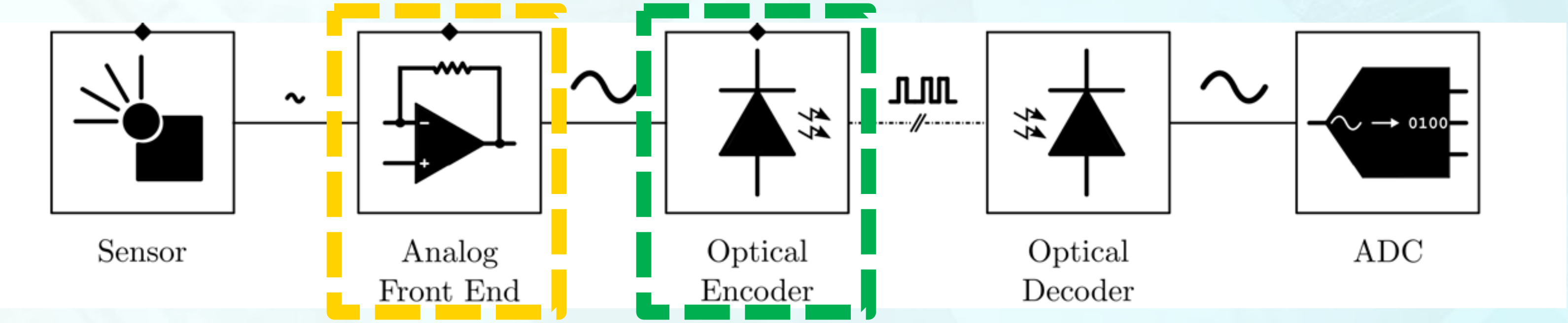
- Pulse Width Modulation (PWM) - temporally encodes sensor amplitude into a continuous time digital signal
- Convert electrical signal to optical – transmit via LED over rad-resistant fiber optic cable
- Encoding in time – confers resistance to radiation-induced fiber darkening
- Multiplex – multiple signals over one fiber
  - Exception: fission chamber in pulse mode
- Data rate resolution directly related to clock speed of carrier signal: clock/duty cycle





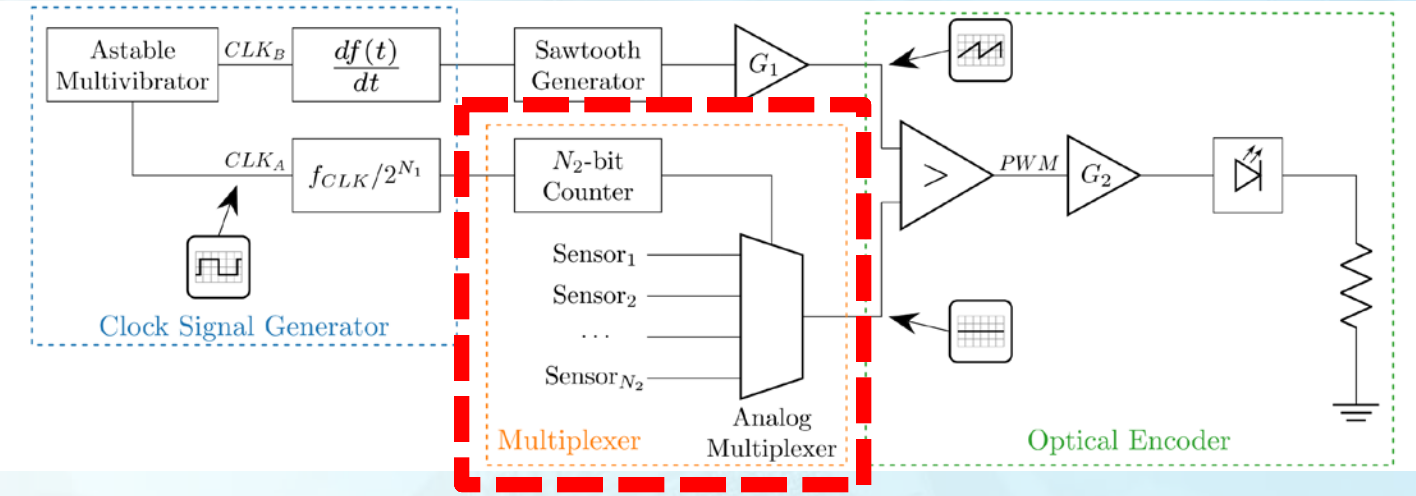
Front End Block Diagram

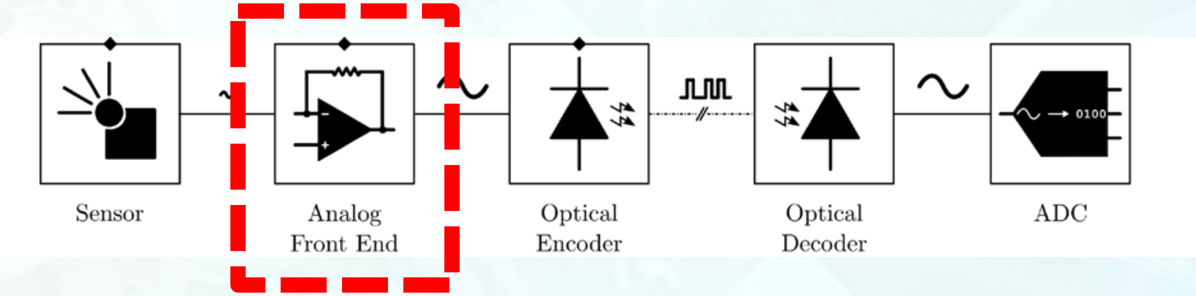


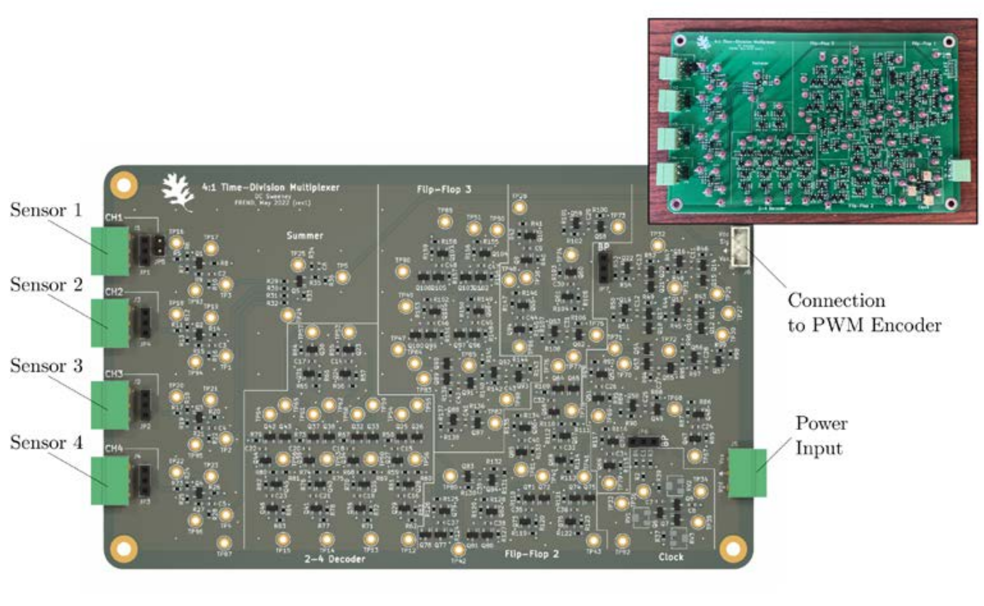


Analog Front End – Time Division Multiplexer

- Talks to instrumentation and time division multiplex (TDM) signals
- For inside radiation zone (ionizing radiation)
  - JFET semiconductors
  - Minimize number of components
- Sensor Sampling Time: 250 Hz
- Input: 4 sensors
- Output: Time-division multiplexed signal

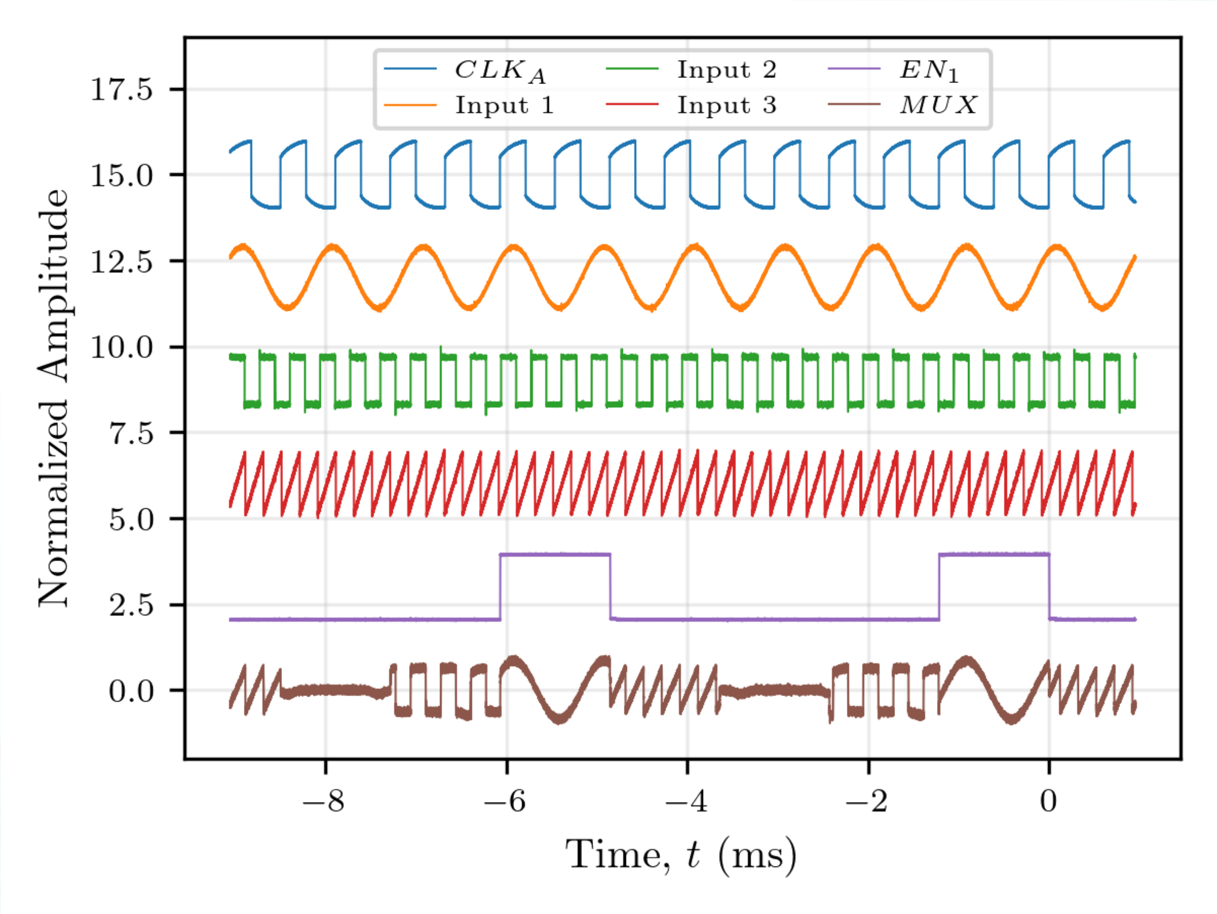


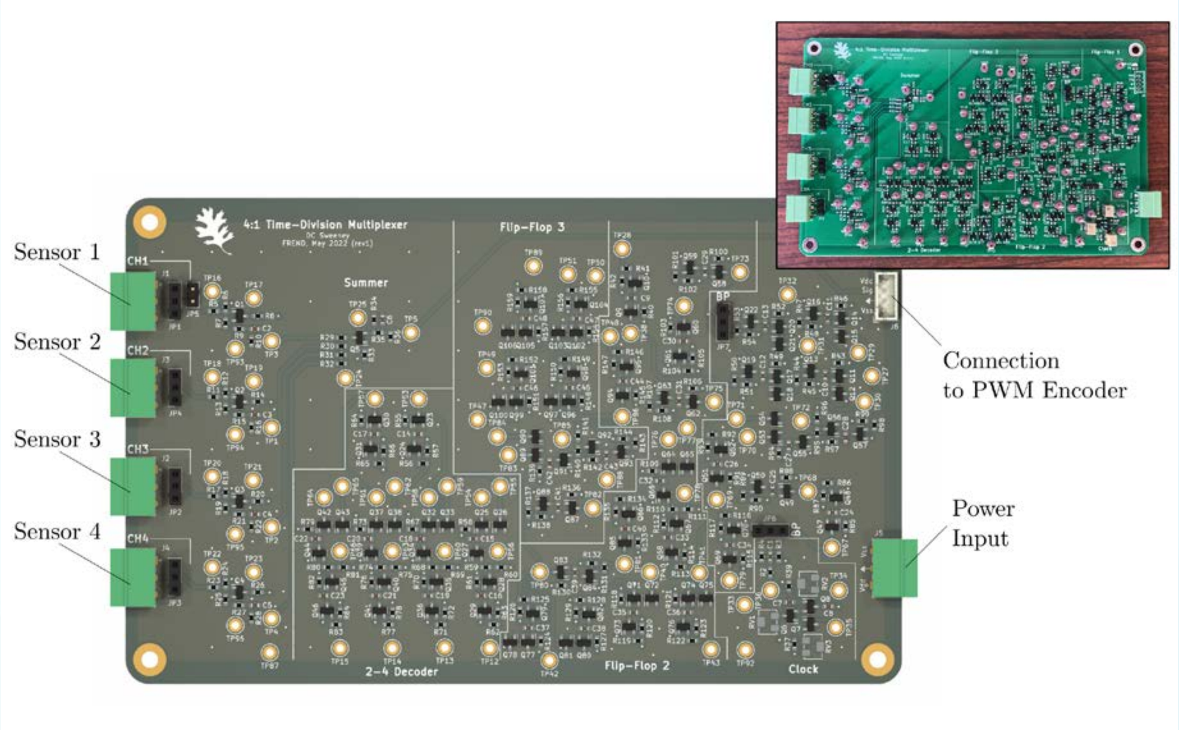


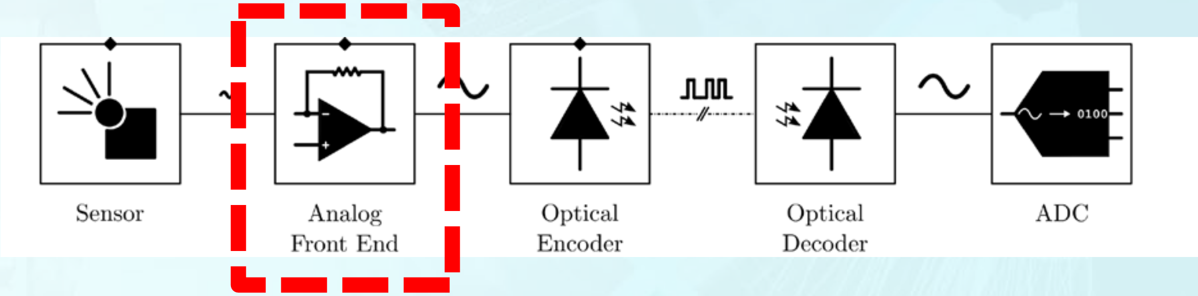


Analog Front End – Time Division Multiplexer

Input/Output of TDM:

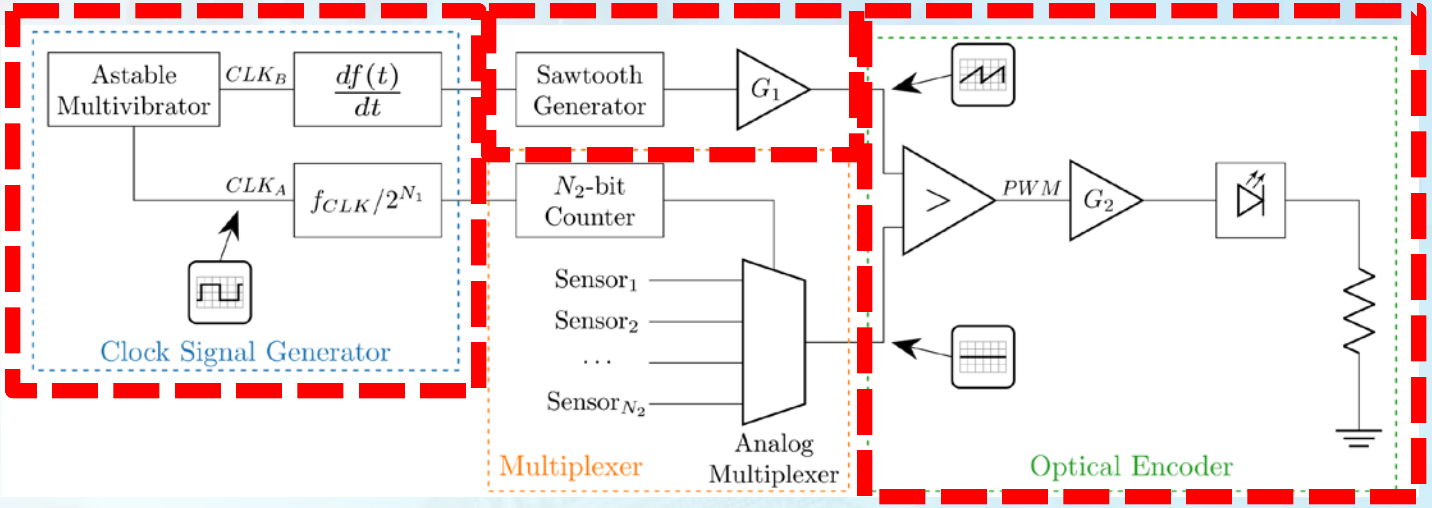


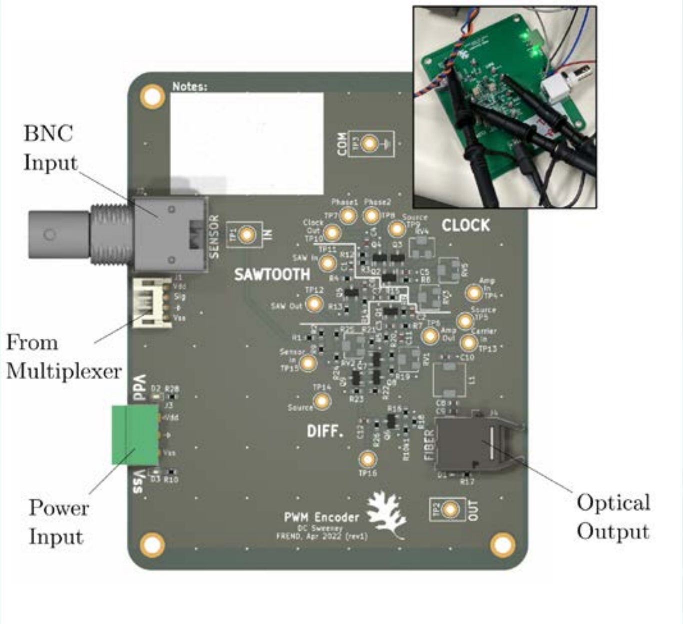


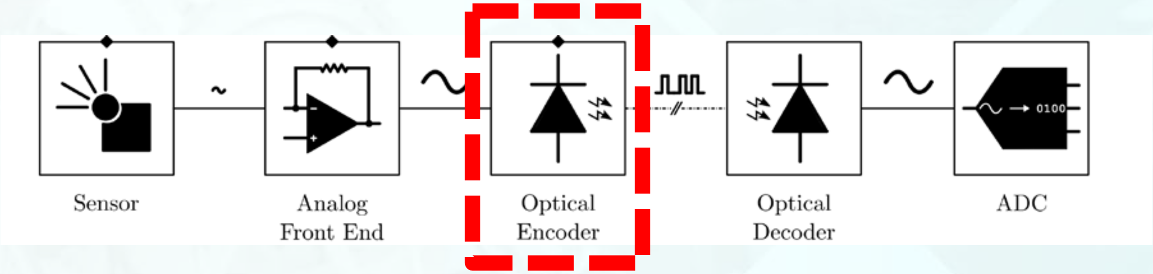


Analog Front End - PWM Encoder

- Inside radiation field - JFETs, minimum number of components
- Astable multivibrator (sample clock), sawtooth generator (carrier signal), comparator (TDM input to carrier), LED (optical output)
- Duty cycle directly related to voltage from input sensor

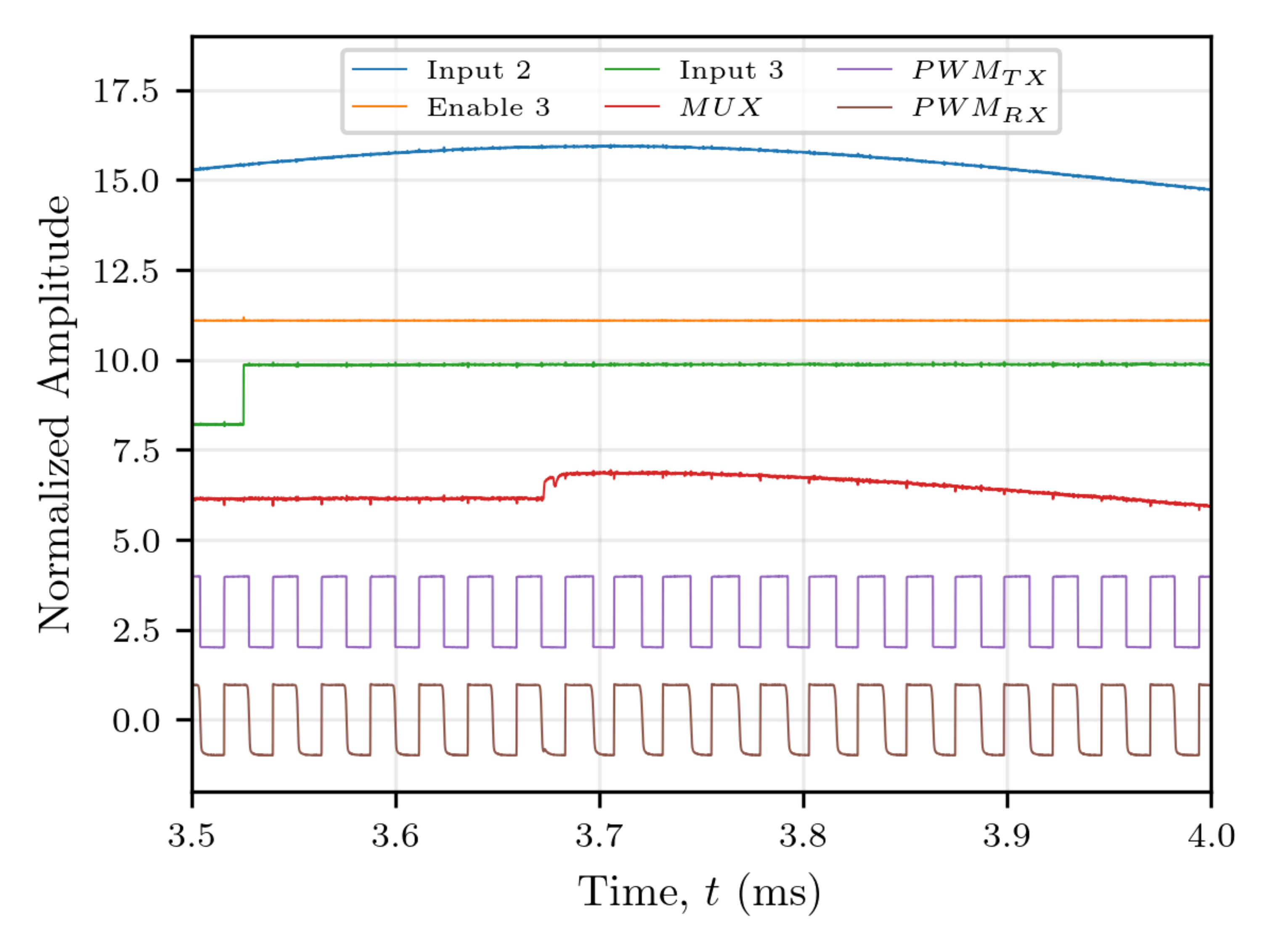


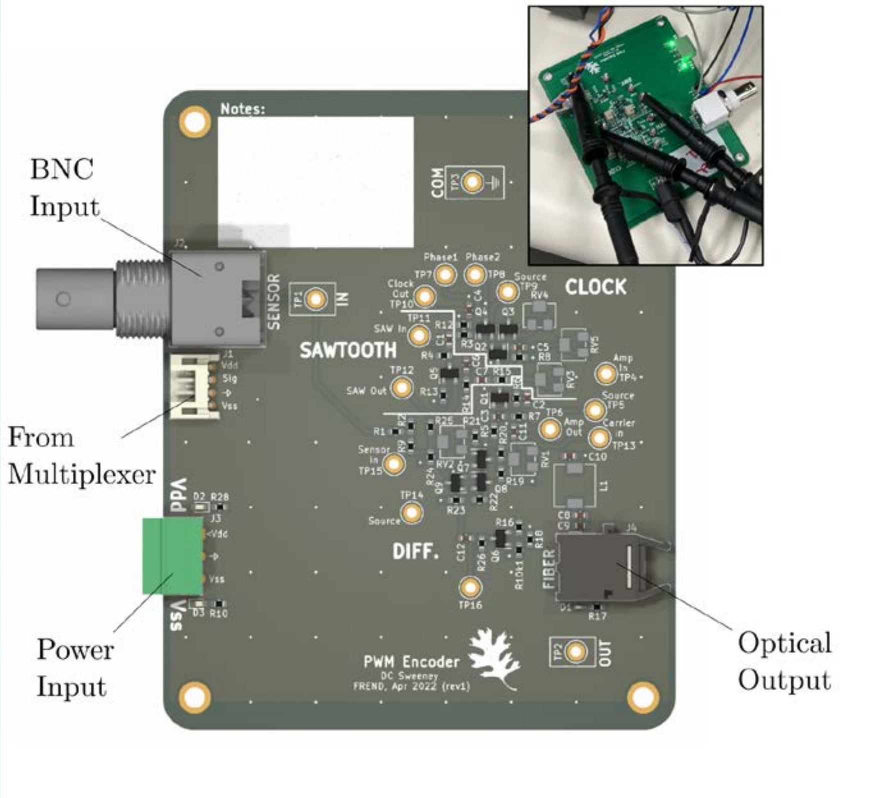




Analog Front End - PWM Encoder

Acquired Signal:

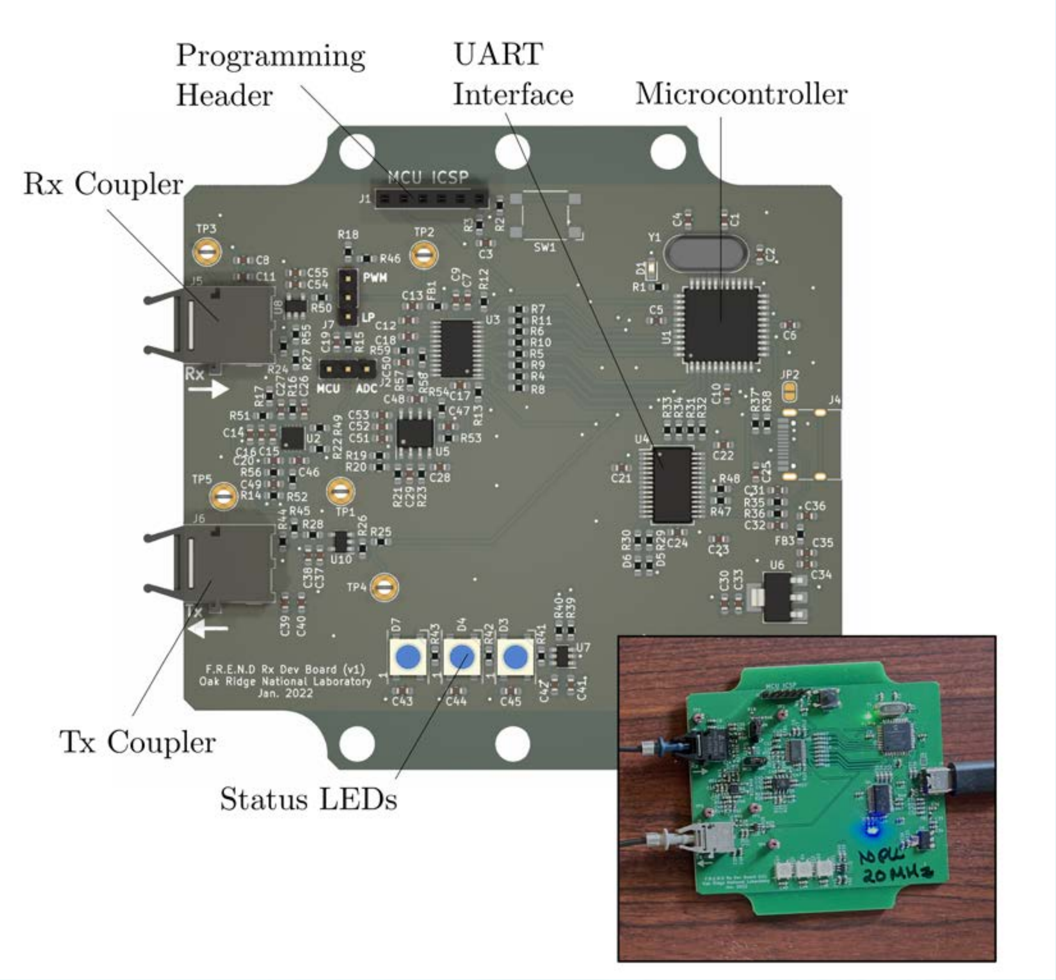


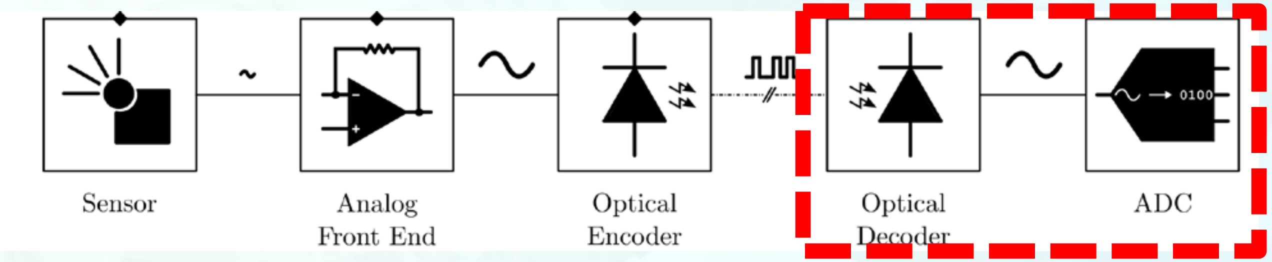


$$D = \frac{t_{on}}{t_{on} + t_{off}}$$

Fiber Optic Communication Development Platform

- Test transmit and receive circuitry, acquisition on one board
- Printed circuit board (PCB) integrates optical fiber Tx/Rx with data acquisition
  - 3 acquisition modes to identify most appropriate method
  - Optical fiber Tx/Rx circuitry to logic level
  - Benchtop form factor easy testing
  - Optical fiber output using microcontroller (MCU) PWM peripheral

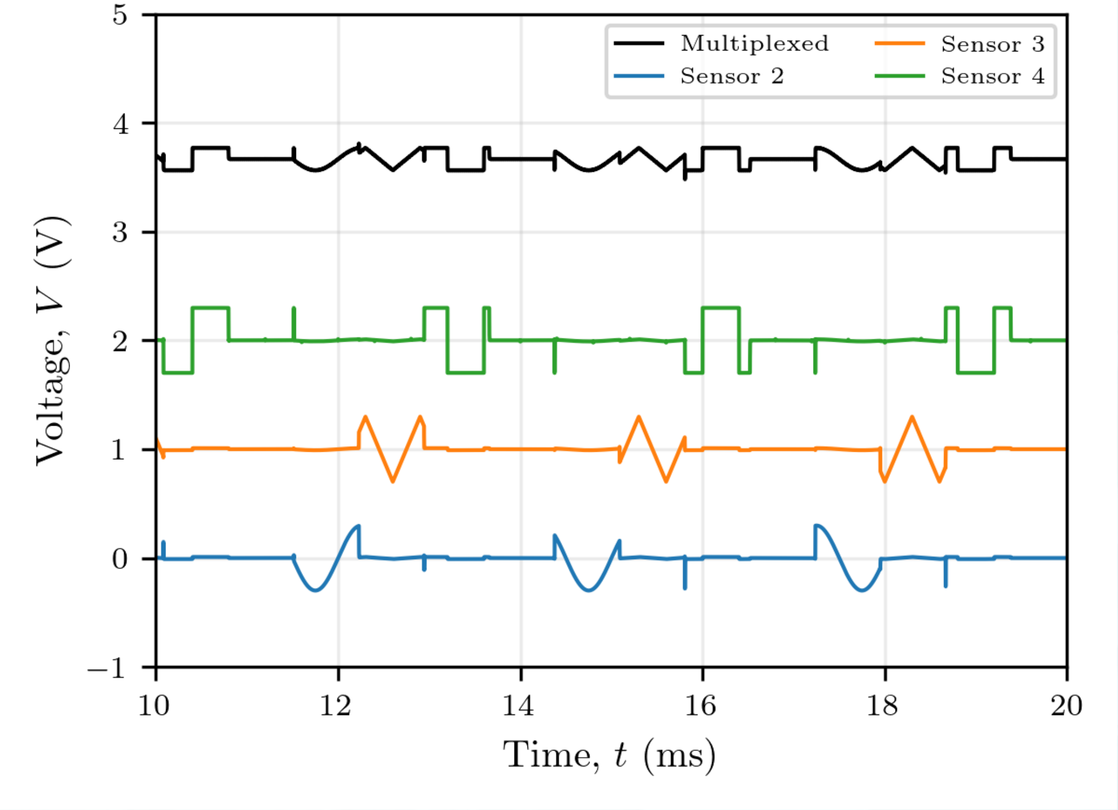




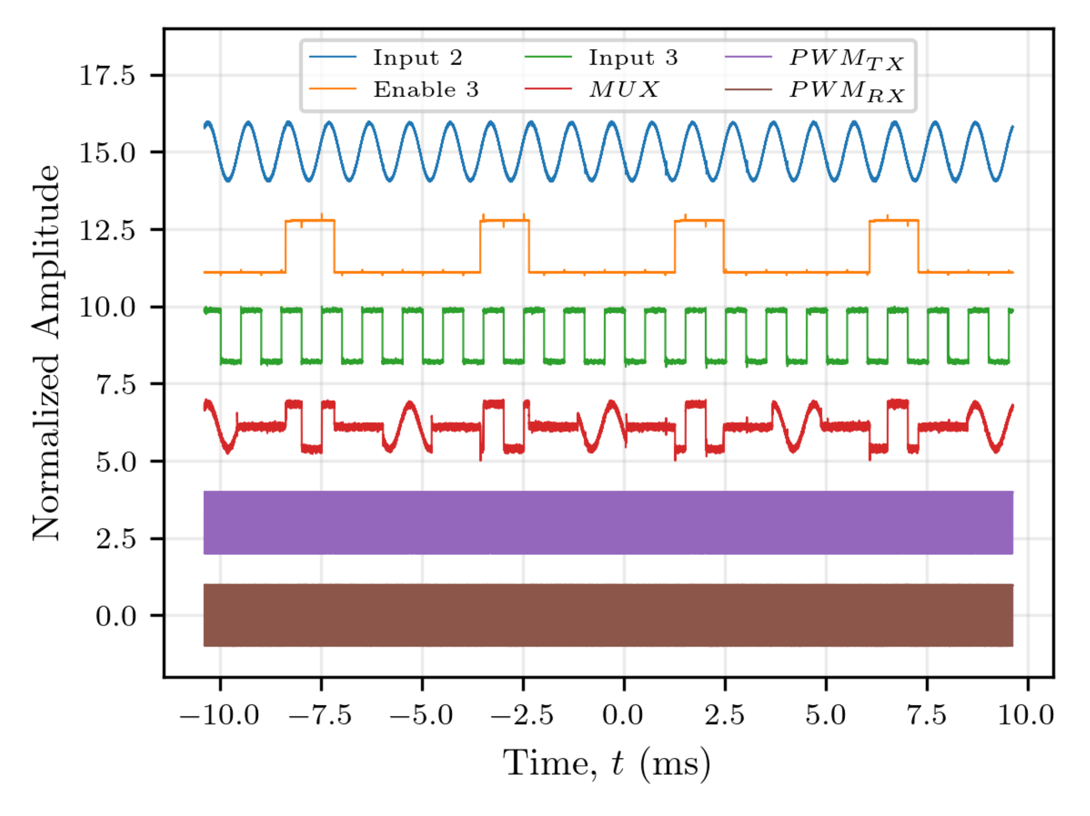
Benchtop Characterization – AFE/TDM

- Provide 3 inputs from function generators – mimic 3 pieces of I&C
- Monitor output of TDM on AFE board
- Good agreement with simulation
- Simulation shows “spurs” – artifacts, due to model lack JFET capacitance

Simulated:

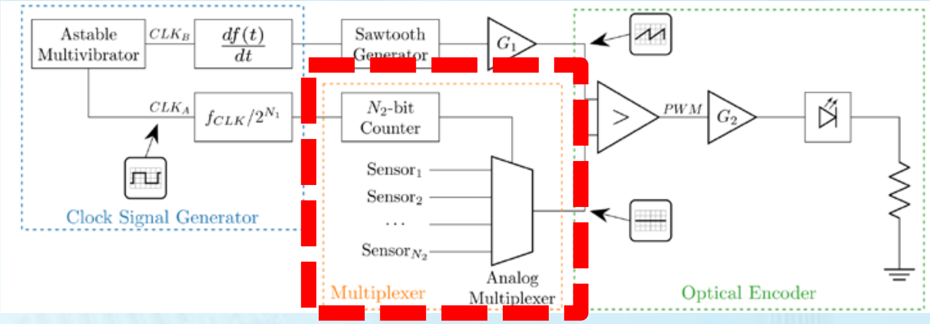


Experimental:

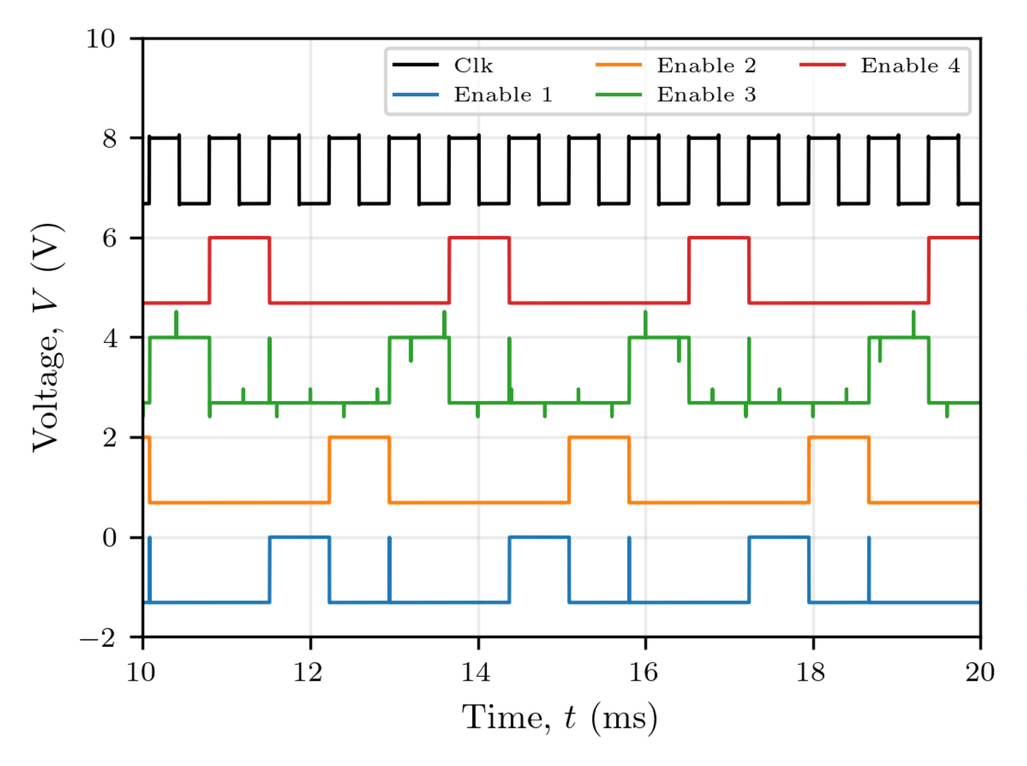


Benchtop Characterization – Binary Decoder

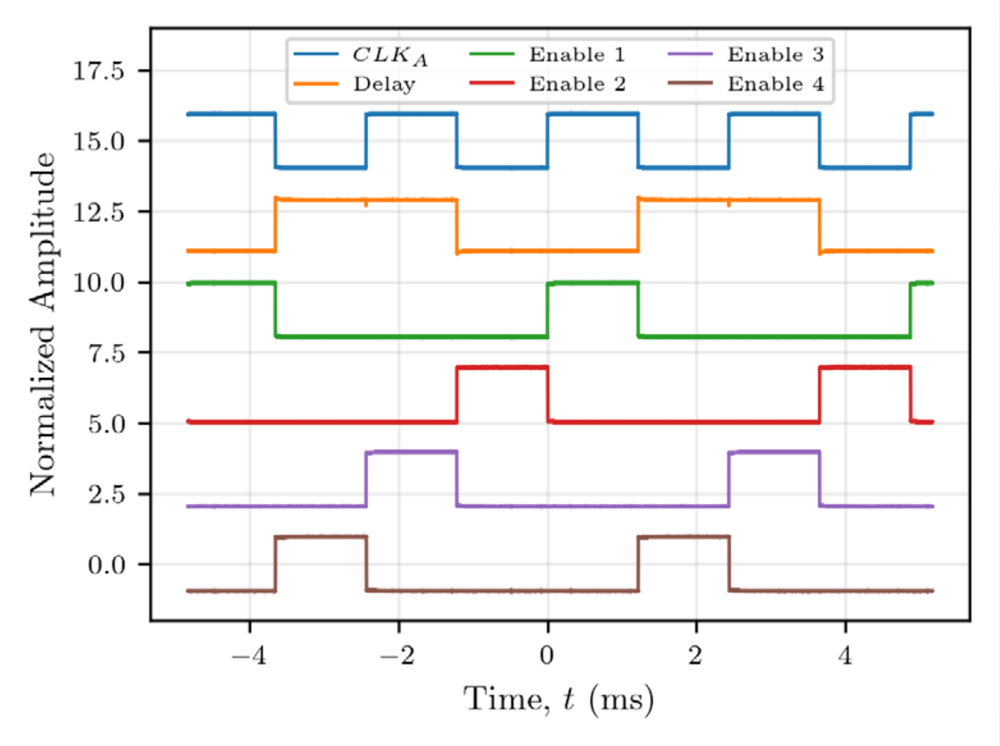
- 2 to 4 decoder in AFE
  - Part of AFE gives signal selection for analog multiplexer
  - Counts time – enables collection on each channel in turn
- Composed of AND gates



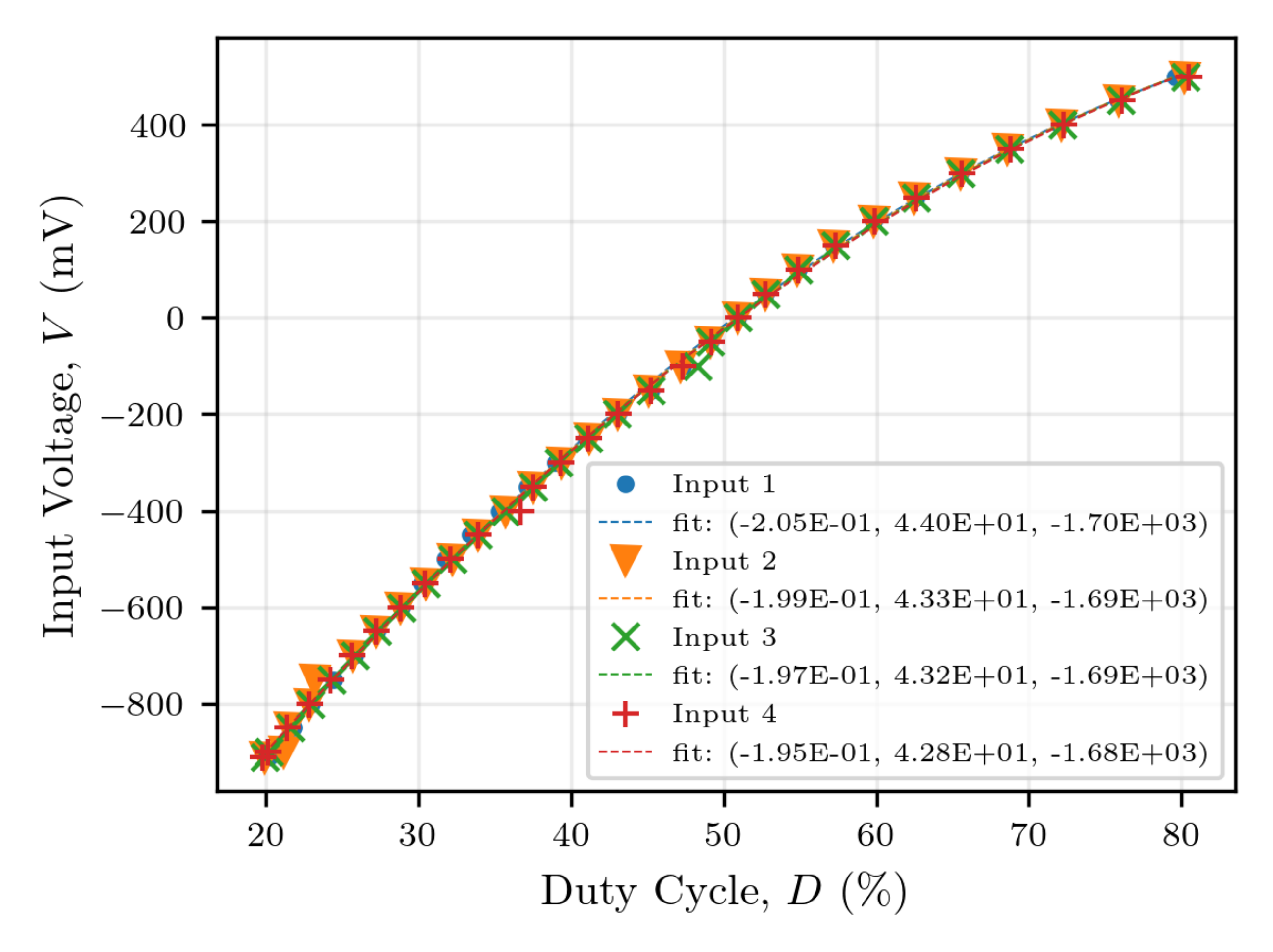
Simulation



Experiment

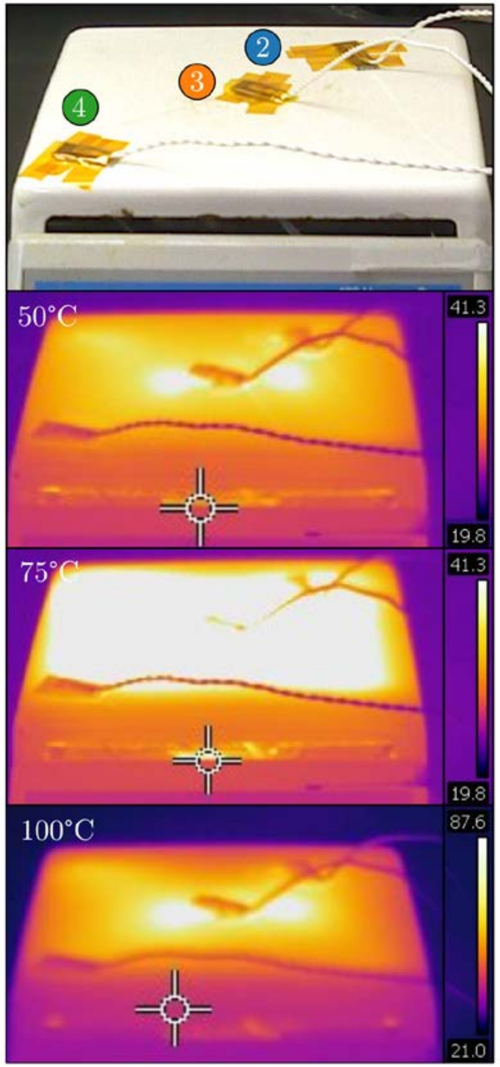


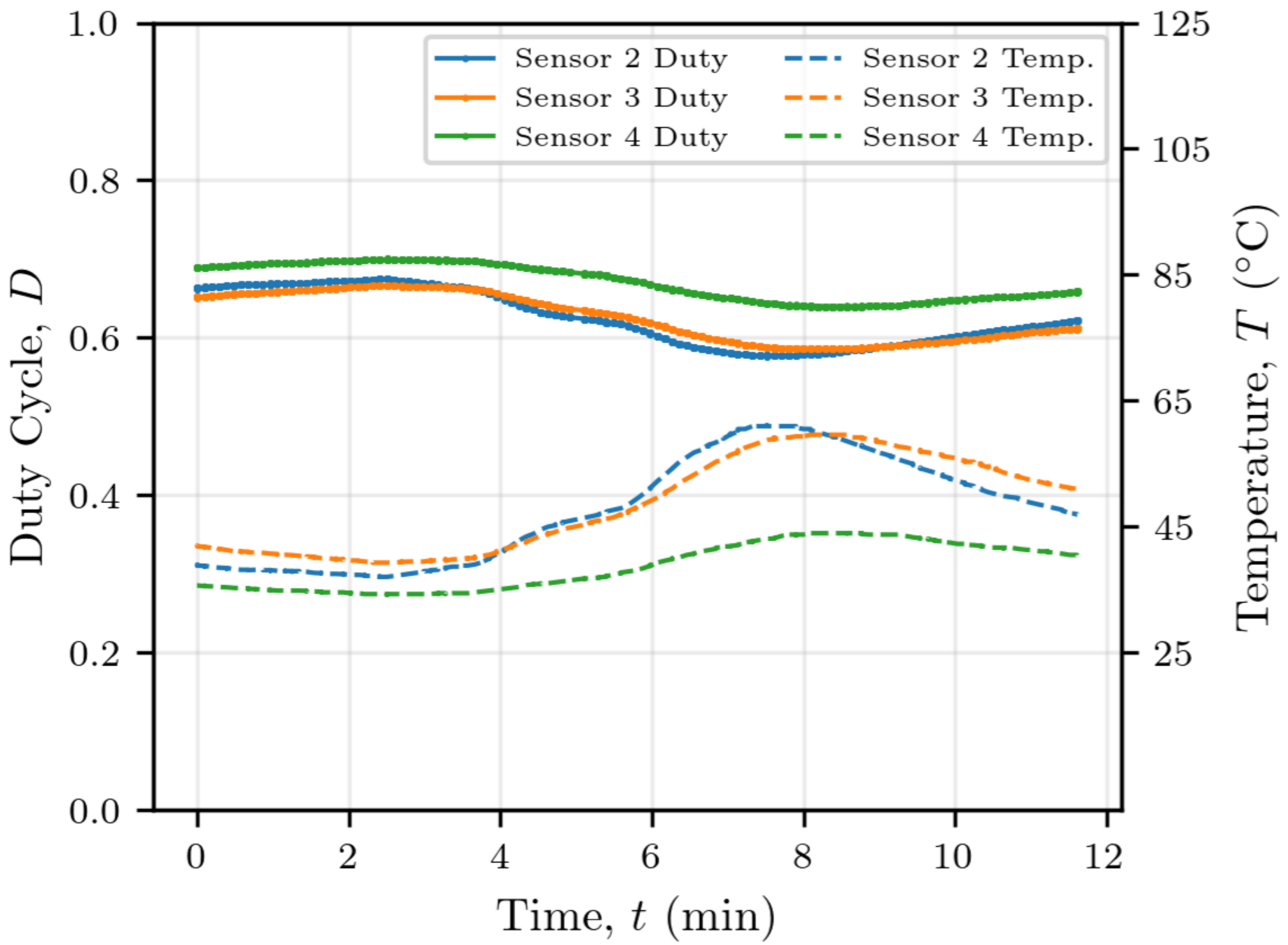
Benchtop Characterization – Linearity of Channels



- Examine Relationship between duty cycle and input voltage for each channel
- Vary input voltage from -900 mV to +500 mV on each channel
  - 20%-80% of full duty cycle available
- 2nd order polynomial fit (not linear)
  - Under investigation
- Similar behavior across channels

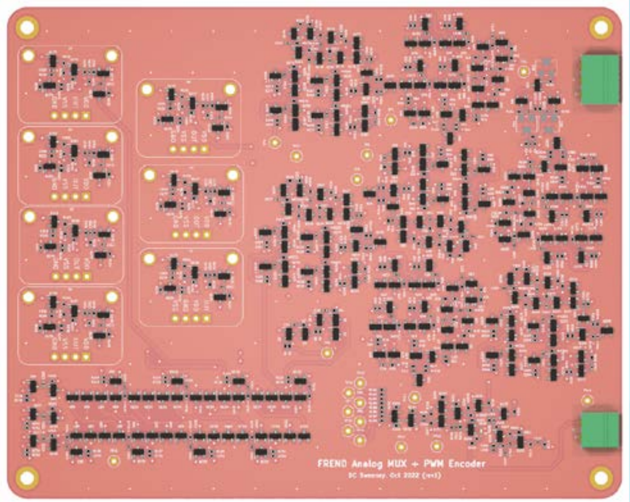
Full System Benchtop Test – 3 Thermistors

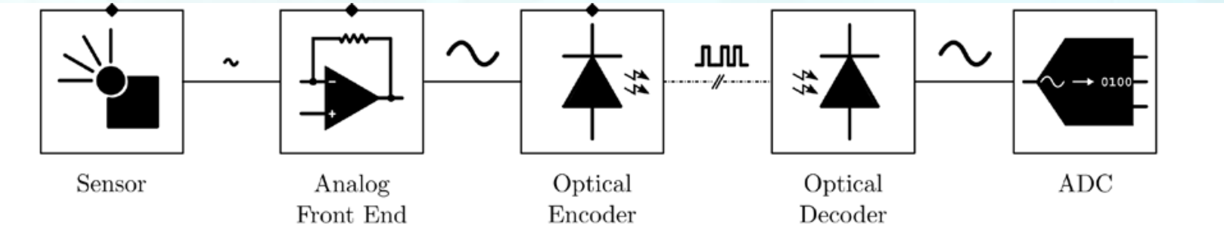




Next Steps – FY23

- Irradiation Planning – neutron, gamma, neutron/gamma
  - Plan to start irradiations around start of calendar year (pending funding)
  - Instrumented irradiation of system components (logic) and full system
- Board/Acquisition Revisions
  - More compressed board for irradiation
  - Increase number of input channels from 4 to 8
  - Added synchronization
  - Reduce channel cross talk
  - Updated component values
  - “real time” data acquisition and analysis
  - sensor signal conditioning needed for some detector types





Conclusions

- Prototype fabricated, characterized
- Full system benchtop testing with 3 thermistors
- AFE is designed using only JFETs, backend more flexible in component choice
- Algorithm implemented on microcontroller on receiver circuit for acquisition
- Irradiation analysis and planning underway
- Invention disclosure selected for provisional patent
- Interest from Cubresa for patent optioning
- 5 FrEnDs made to date!

Thank You

FrEnD Solves 4 Issues with Traditional I&C

- **Problem #1:** Reactors are noisy environments
  - I&C signals are small (nA - uA range)
  - cables are sensitive to EMI (noise on top of already small signal)
- **Solution: Early signal Preamplification and digitization**
  - Amplify signal as close as possible to measurement
  - Amplified signal is immediately digitized (within a few meters)
  - Signal transmitted via optical fiber (EMI/EMF blind)
- **Problem #2:** Extreme reactor environment necessitates long cables resulting in signal loss
  - **Solution**: close to experiment site, optical transmission
- **Problem #3:** Reactors are high radiation environments
  - **Solution**: Radiation resistance by design
- **Problem #4:** Traditional methods require many penetrations into reactor containment
  - **Solution**: MUX over single fiber optic cable or fiber optic cable bundle

FrEnD Solves 4 Issues with Traditional I&C

- **Problem #1:** Reactors are noisy environments
  - **Solution**: early preamplification and digitization
- **Problem #2:** Extreme reactor environment necessitates long cables resulting in signal loss
  - Long cables are lossy, small signals can be lost to noise, traditional cabling hard to drive (capacitance)
- **Solution**: Place FREND as close as possible to experiment site to preserve signal strength and transmit over optical fiber
  - Optical fiber virtually lossless
  - No introduced EMI over optical
- **Problem #3:** Reactors are high radiation environments
  - **Solution**: Radiation resistance by design
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- **Problem #2:** Extreme reactor environment necessitates long cables resulting in signal loss
  - Solution: close to experiment site, optical transmission
- **Problem #3:** Reactors are high radiation environments
  - Electronics prone to failure
  - Optical fiber darkens
- **Solution**: Radiation resistance by design
  - Limit number of components
  - Use rad-resistant components where needed (JFET)
  - Transmit signals encoded in time (Pulse Width Modulation) over fiber (limits issues due to darkening)
- **Problem #4:** Traditional methods require many penetrations into reactor containment
  - **Solution**: MUX over single fiber optic cable or fiber optic cable bundle

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  - Solution: close to experiment site, optical transmission
- **Problem #3:** Reactors are high radiation environments
  - **Solution**: Radiation resistance by design
- **Problem #4:** Traditional methods require many penetrations into reactor containment
  - Each instrument requires its own cable
- **Solution**: Multiplexed signals over fiber optic cable
  - Only need 1 fiber optic cable or fiber optic cable bundle to extract full suite of instrumentation at one experimental location