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

ASI Advanced Sensors and Instrumentation

Acoustic Sensors

Advanced Sensors and Instrumentation (ASI)

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Boise State University

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Project Overview

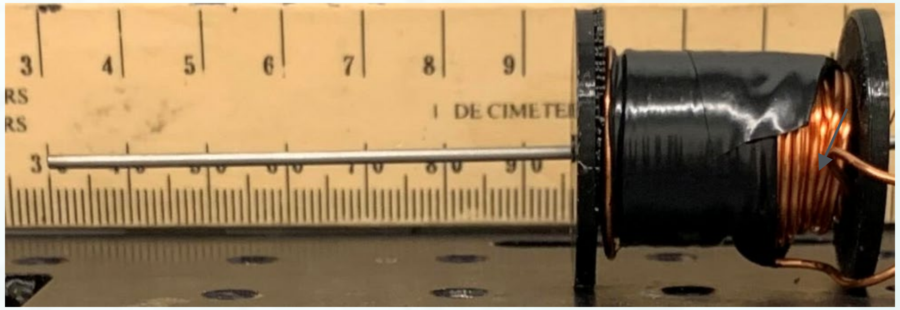
Motivation: Structural health monitoring enabled by advanced acoustic sensors is crucial for existing nuclear reactor fleets and next-generation reactors

Needs:

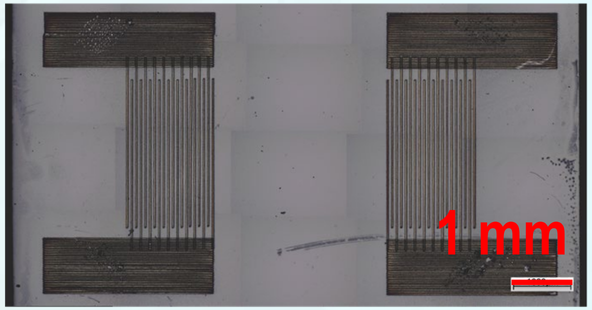
- Acoustic sensors for in-pile monitoring that can survive in high temperature and radiation
- Multiphysics modeling of advanced sensors enabling predictive maintenance

Objective: Develop sensors whose acoustical properties (e.g., speed of sound, attenuation) varies due to ambient environments or structural defects.

Longitudinal Wave



Surface Acoustic Wave



Lamb Wave

Project Team

INL Lead: Josh Daw

Boise State Co-PI: Dave Estrada

Graduate Students: Nicholas McKibben (Ph.D.), Drew Keller (M.S.), Takoda Bingham (M.S.), Amanda White (M.S.)

Undergraduates: >8 students from Boise State

#1: Longitudinal Waveguide Transducer

Acoustic Sensor #1: Magnetostrictive ultrasonic waveguide thermometer

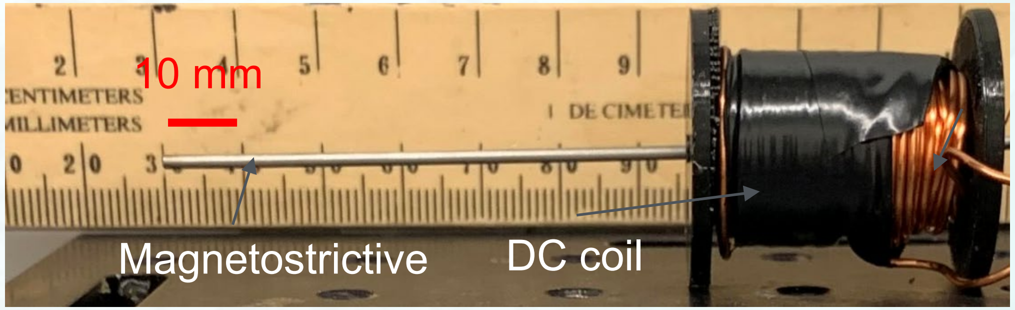
Working Principle:

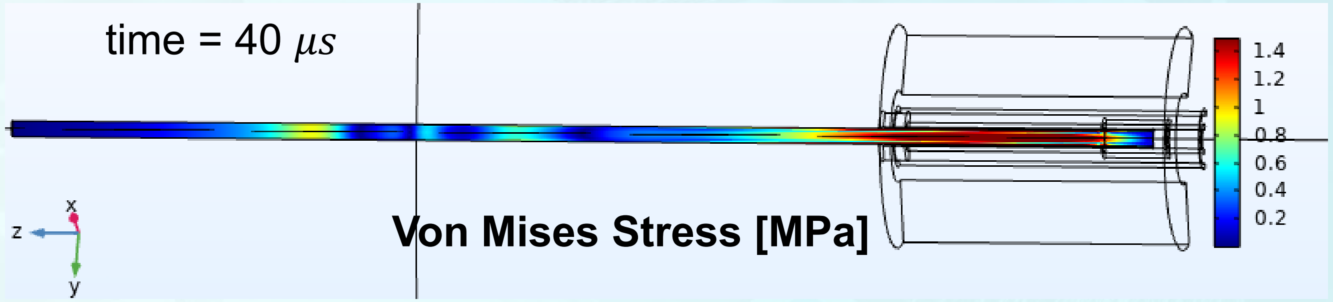
- Magnetic field generated by an electromagnet induces impulsive acoustic waves in waveguide
- Acoustic wave reflections cause electrical voltage across the same electromagnet
- The time-of-flight of acoustic signals depends on waveguide temperature

Objectives:

a) Enhance signal-to-noise ratio

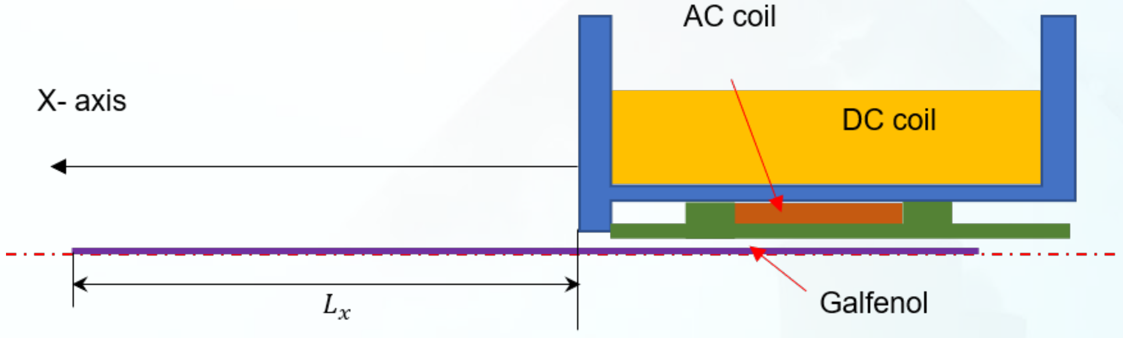
b) Achieve reliable signal post-processing

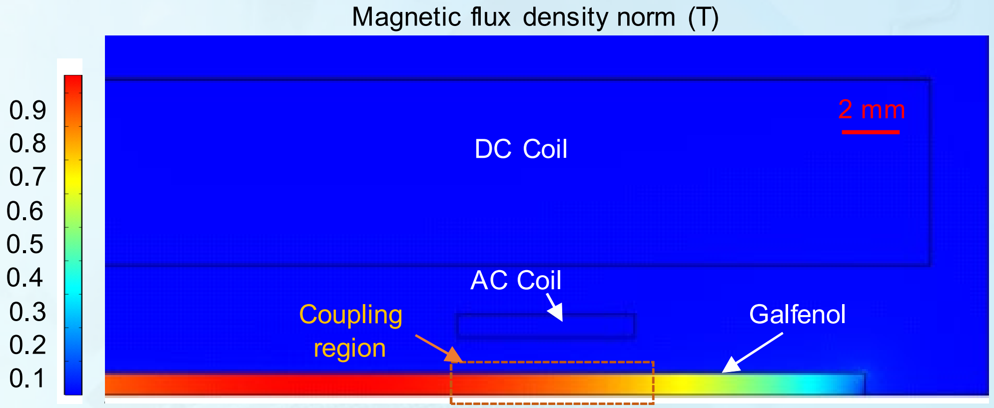


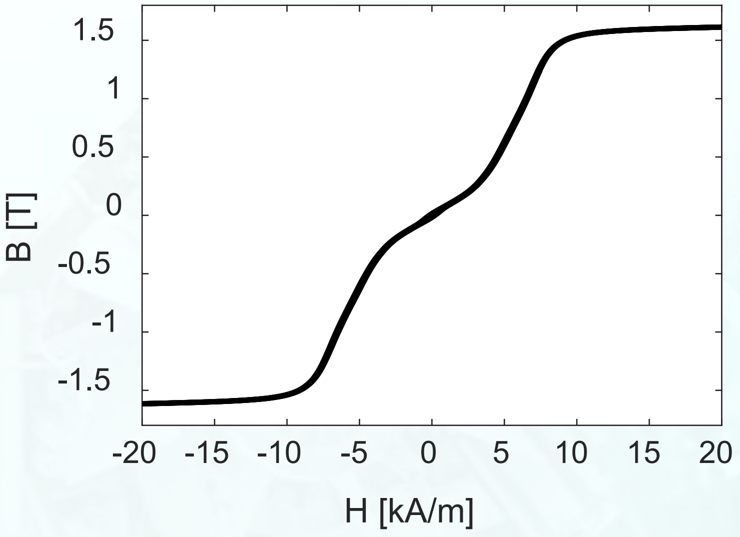


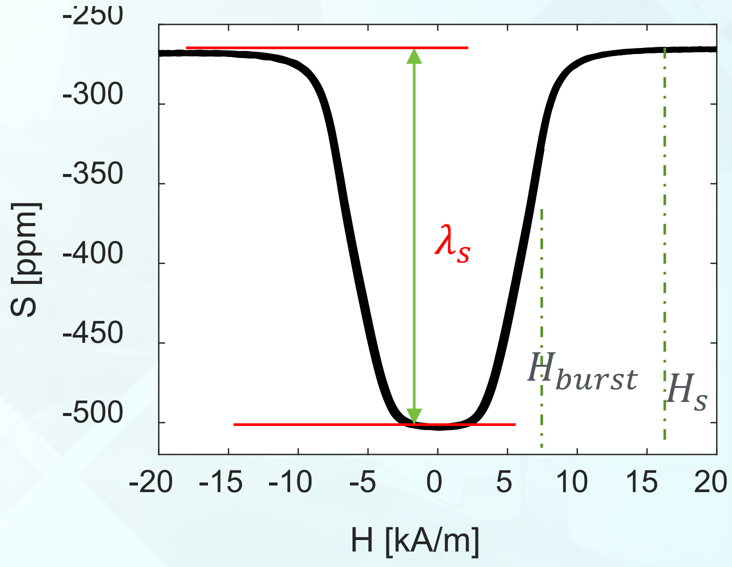
#1-1: Signal-to-noise Ratio

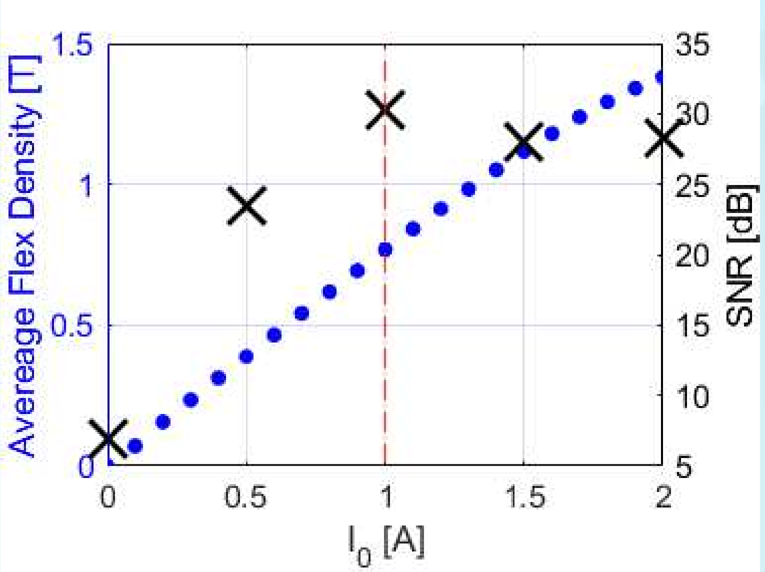
Task 1: Optimize the bias magnetic field to operate in material's burst region





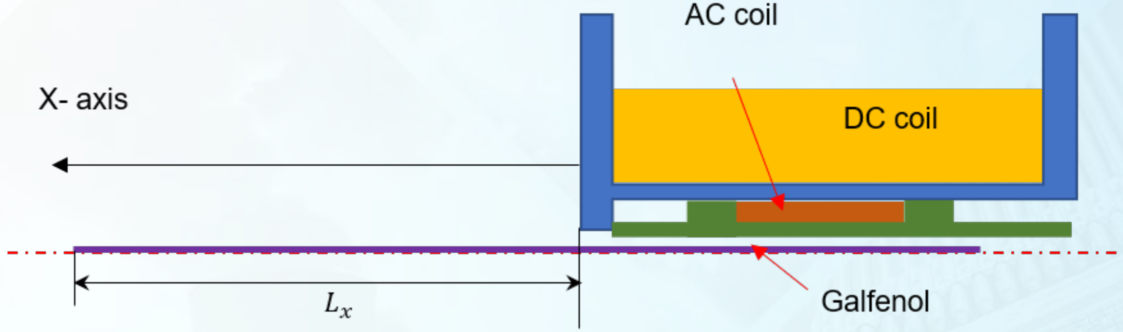


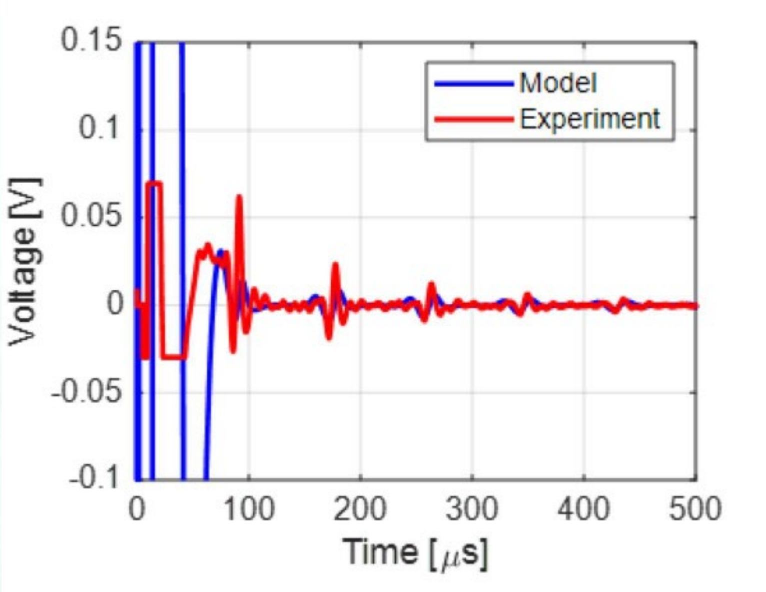


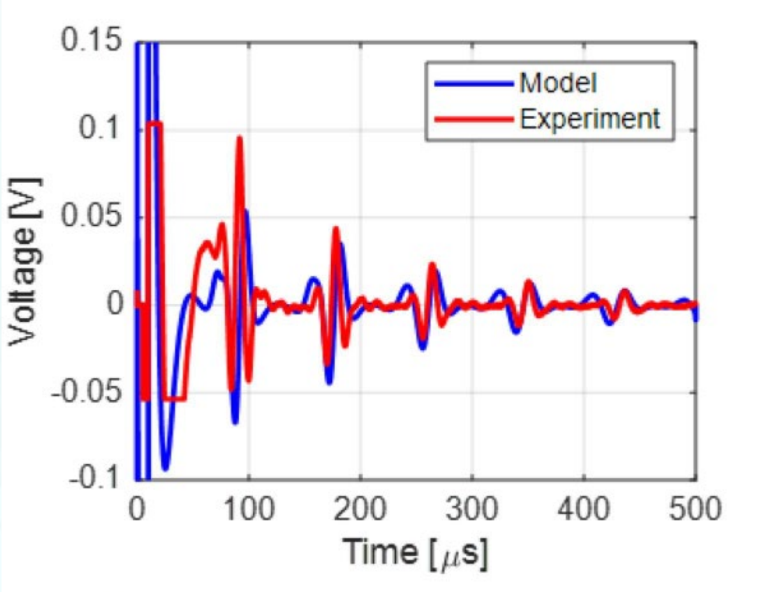


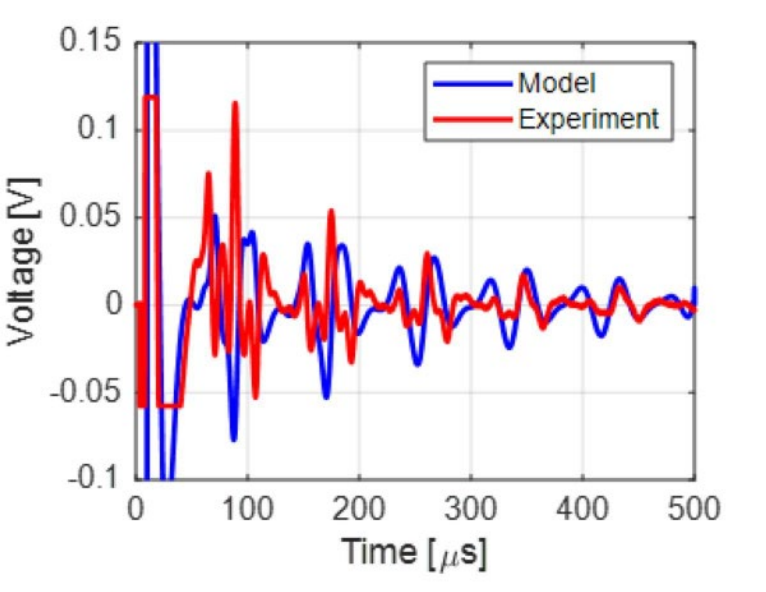
#1-1: Signal-to-noise Ratio

Task 2: Optimize the transducer location



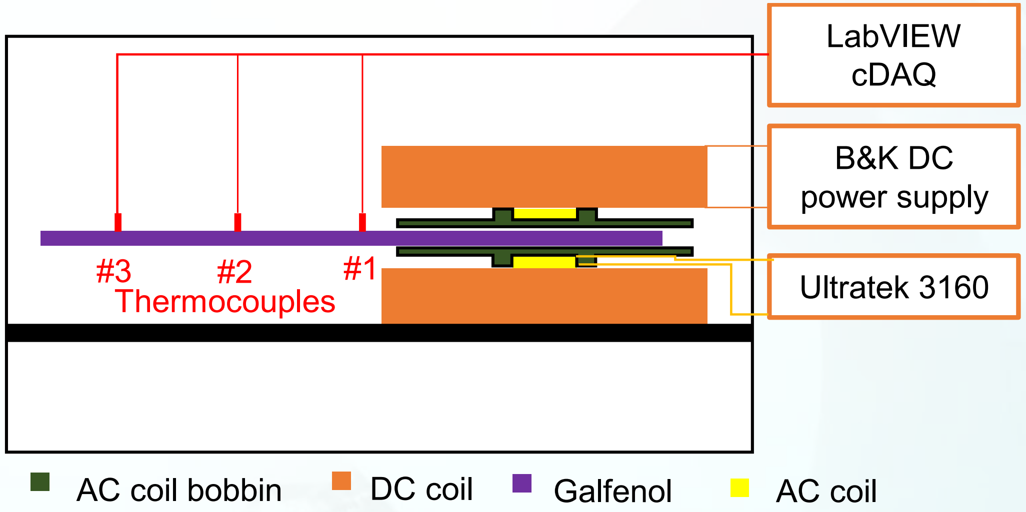


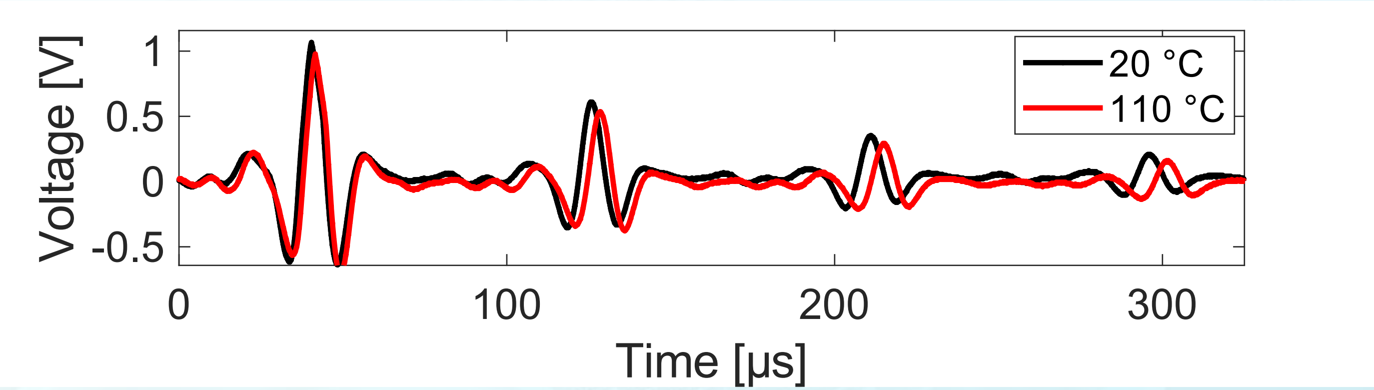


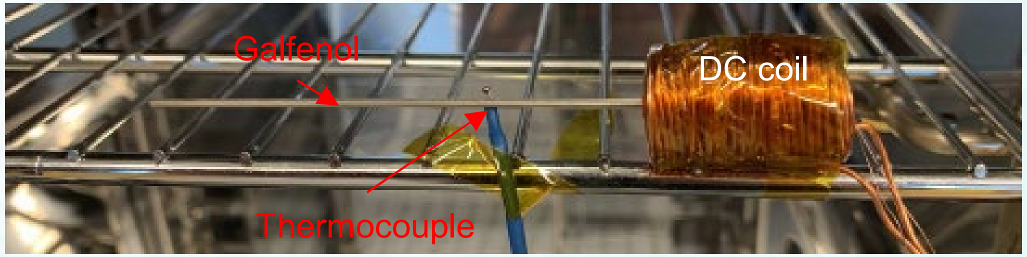


#1-2: Signal Processing

Task 3: Validate thermometer in an oven

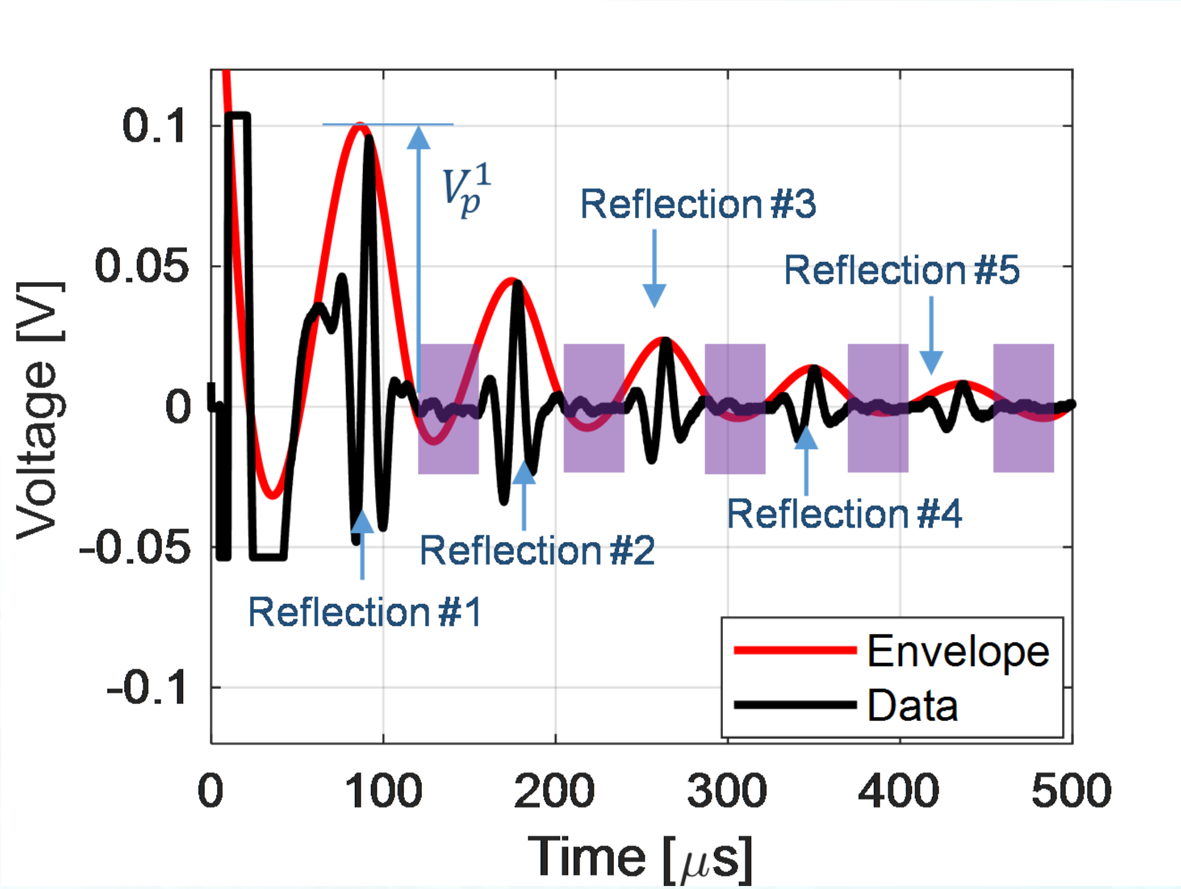


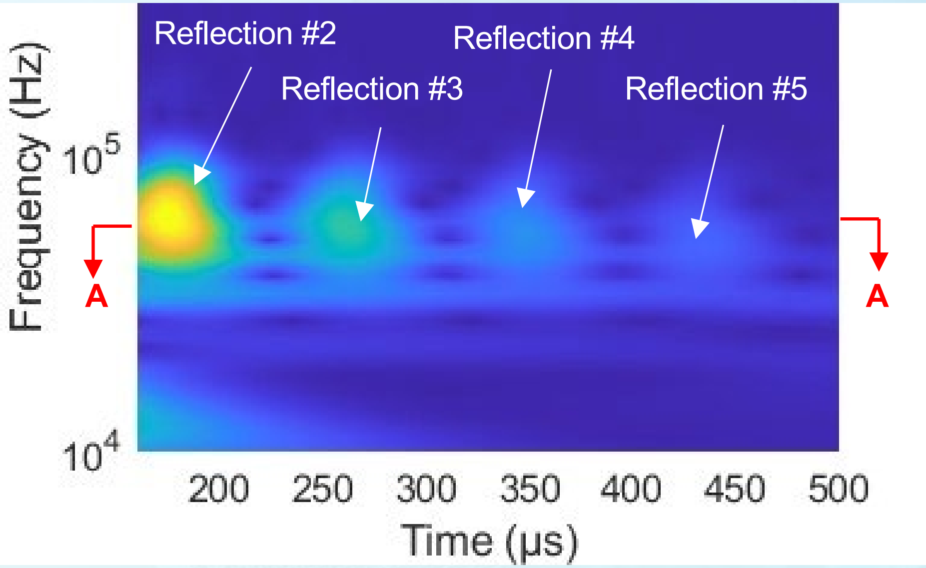


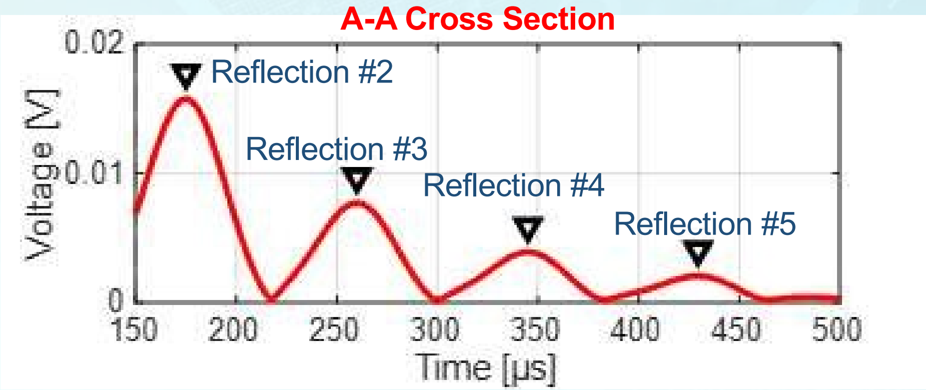


#1-2: Signal Processing

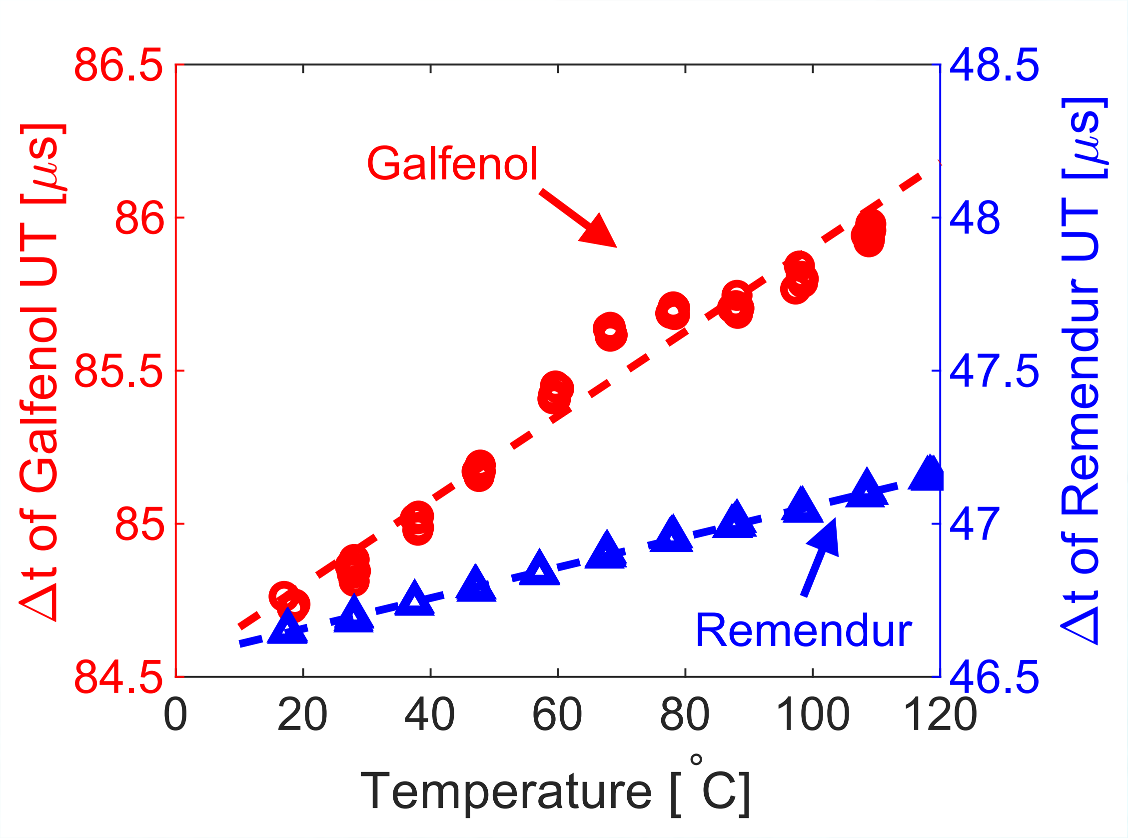
Task 4: Process signals in time and frequency domains

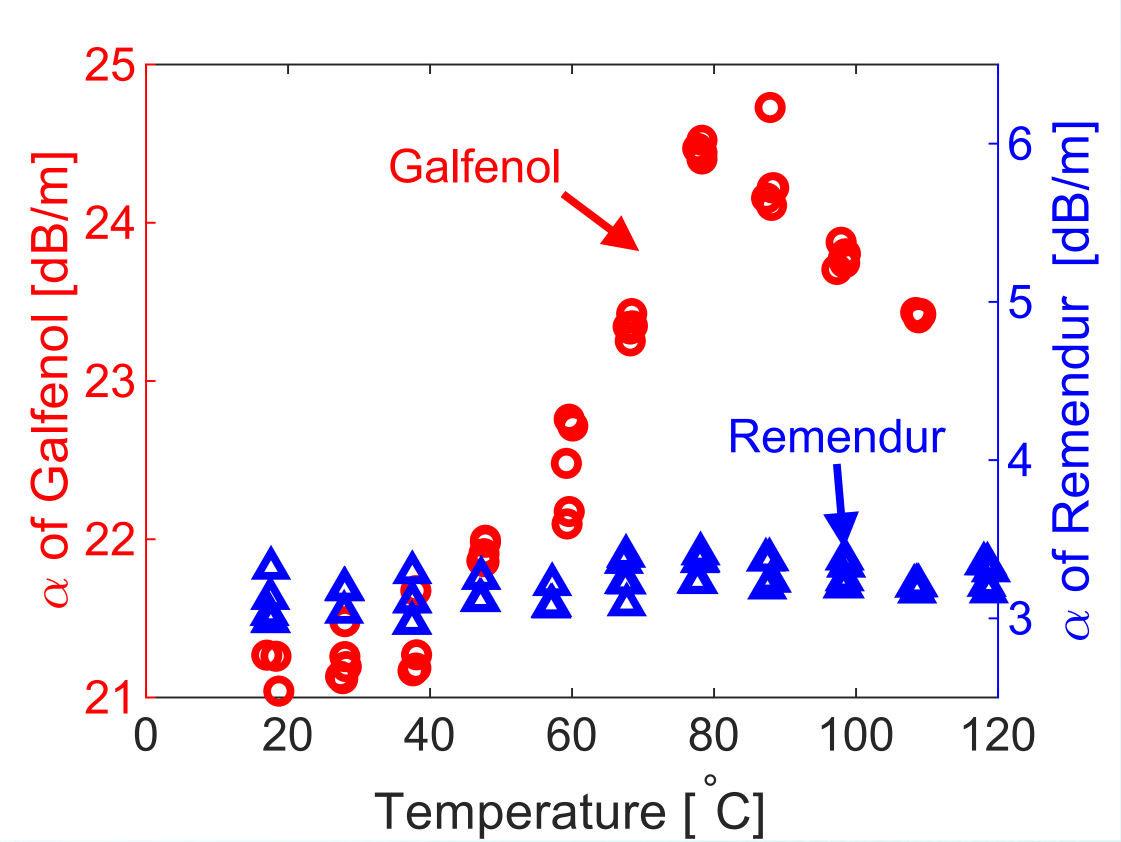






Task 5: Validate the waveguide thermometer at high temperatures





#2: Surface Acoustic Wave Transducer

Acoustic Sensor #2: Piezoelectric Surface Acoustic Wave (SAW) thermometer

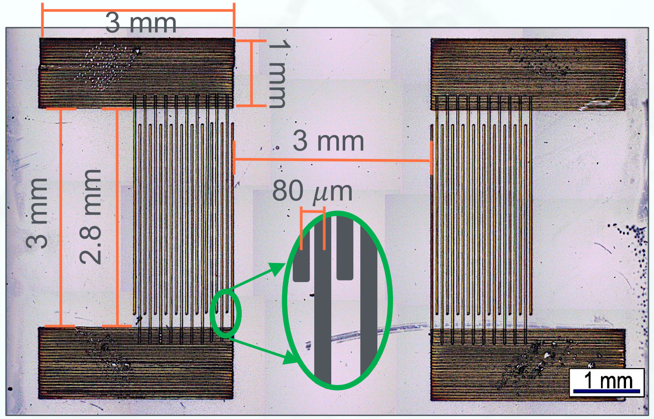
Working Principle:

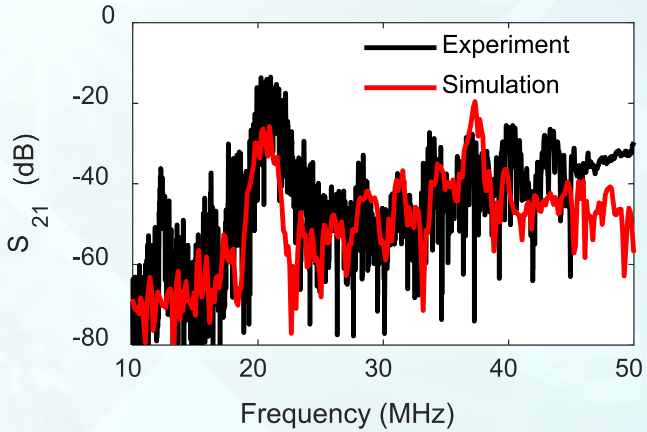
- Electrical field across interdigitated electrodes (IDTs) deforms the piezoelectric substrate
- SAW induces electrical voltage across the IDT
- SAW wave frequency and time-of-flight depends on the physical properties of substrate

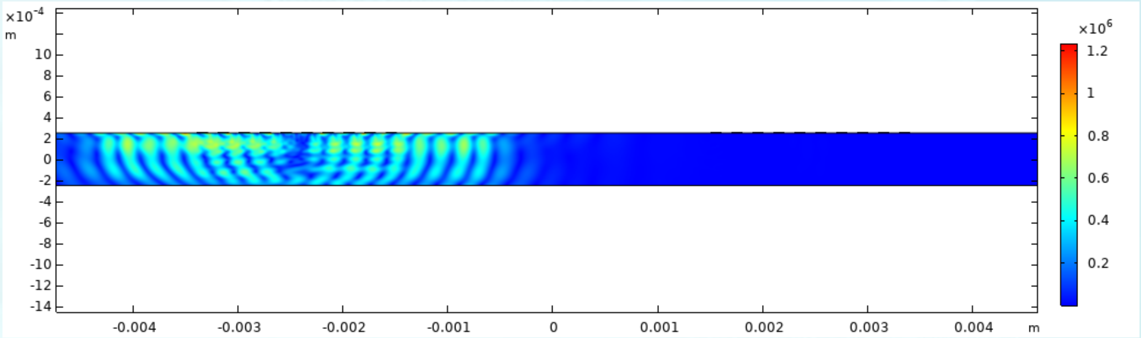
Objectives:

a) Print the SAW thermometer

b) Model the SAW thermometer

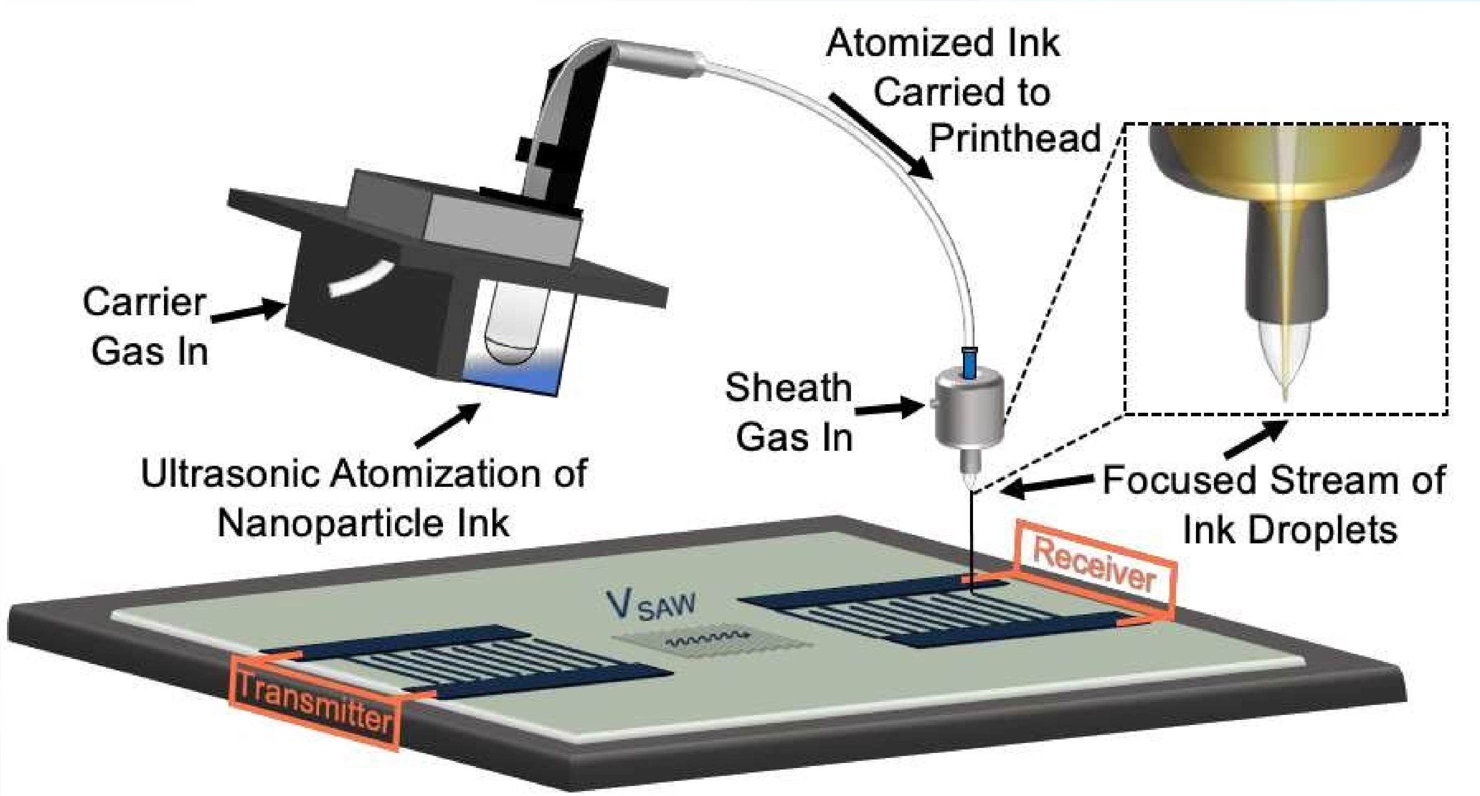


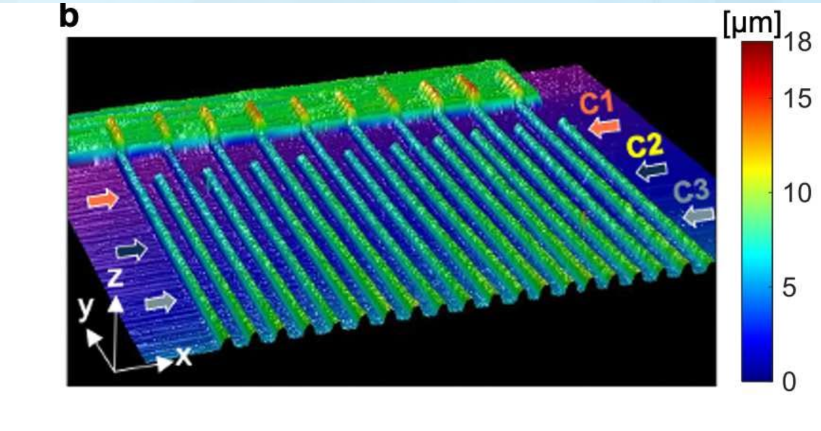


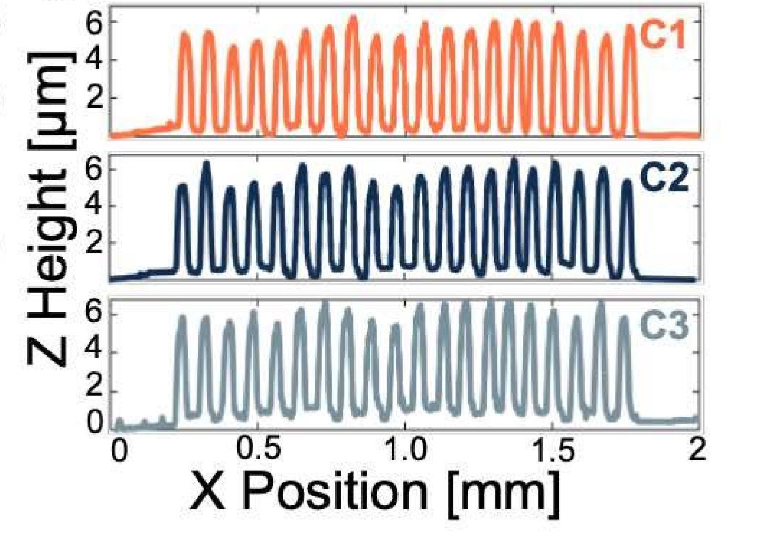


#2-1: Print SAW Thermometer

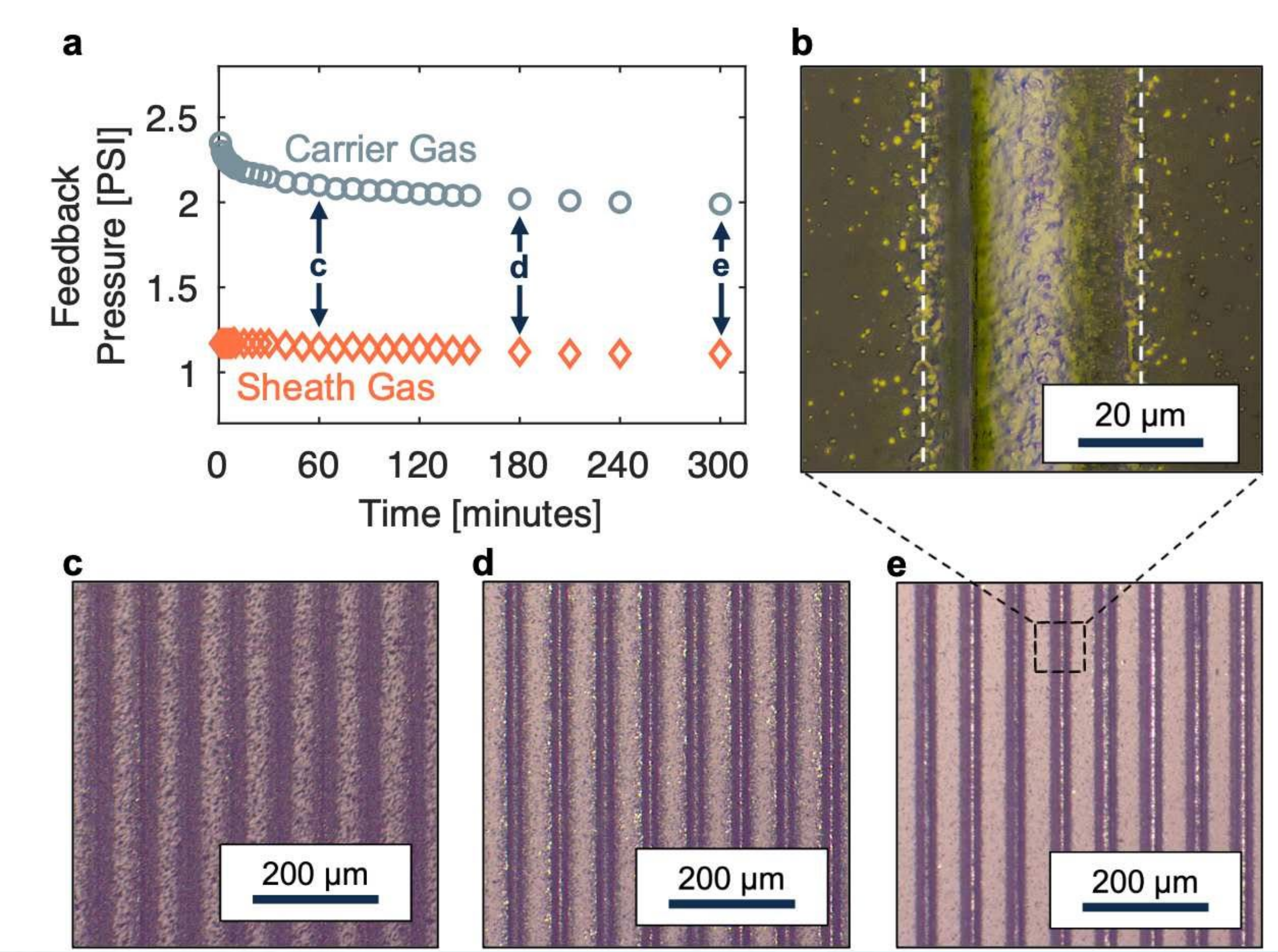
Task 1: Use aerosol jet printing to fabricate SAW devices



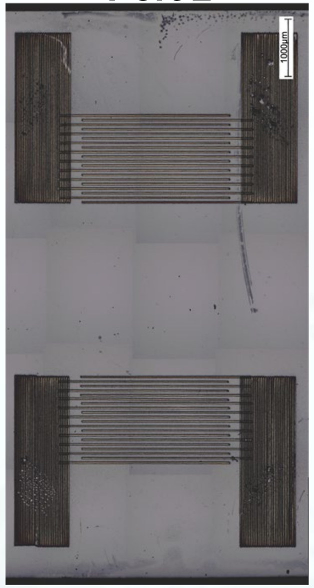


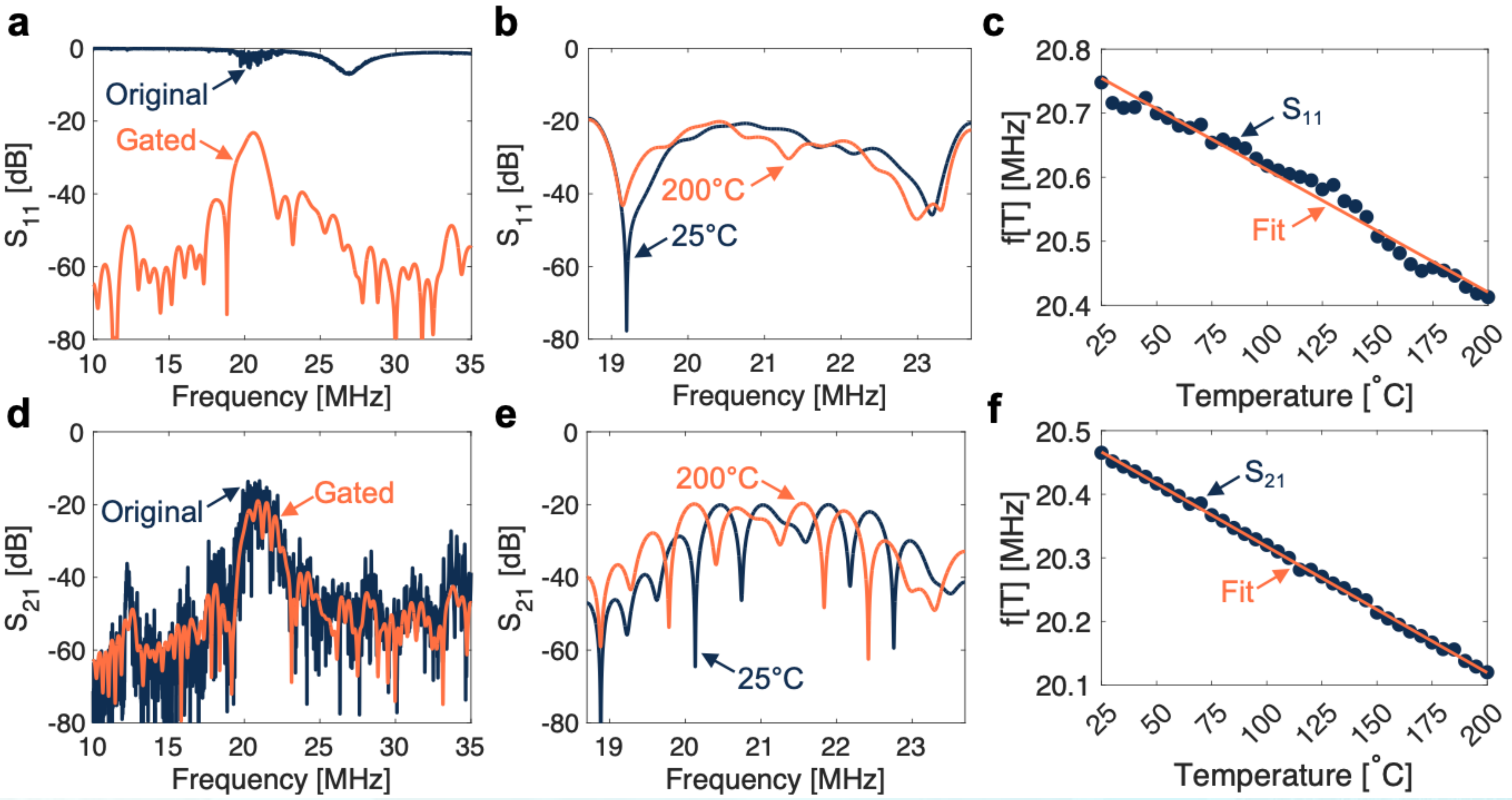


Task 2: Optimize the silver line printing process



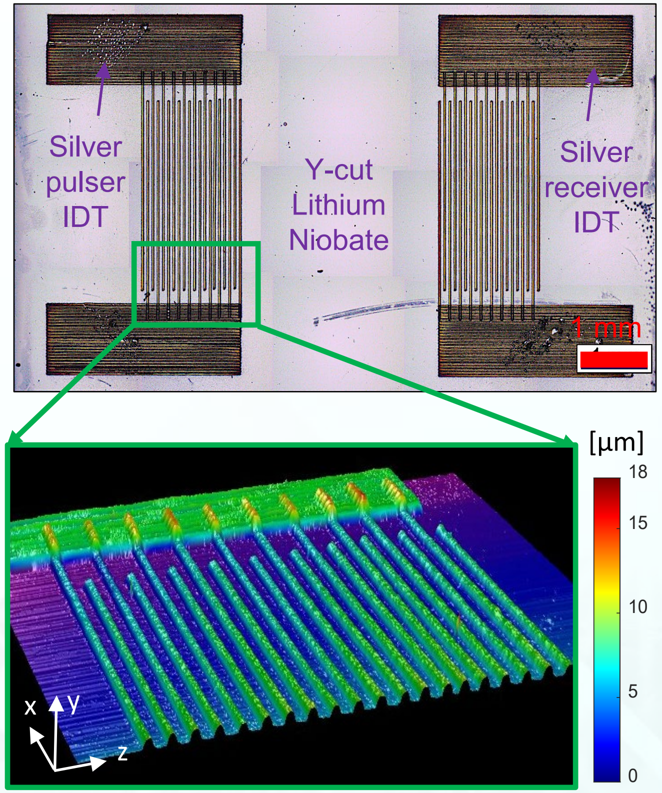
Task 3: Validate the SAW thermometer





#2-2: Model SAW Thermometer

Aerosol-jet-printed SAW sensor

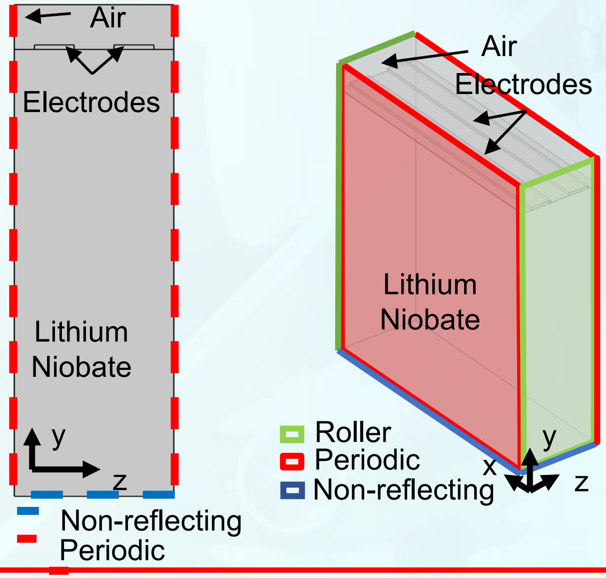


Multiphysics SAW modeling

Temperature-varying Constitutive Model

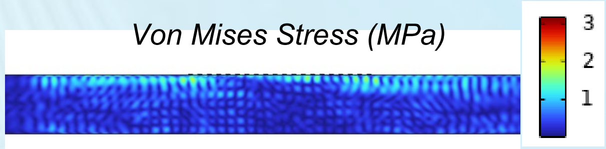
$$\boldsymbol{S}_i(\Delta T) = \boldsymbol{d}_{ij}(\Delta T)\boldsymbol{E}_j + \boldsymbol{C}_{ij}(\Delta T)\sigma_j + \boldsymbol{\alpha}_i \Delta T$$

Finite Element Model

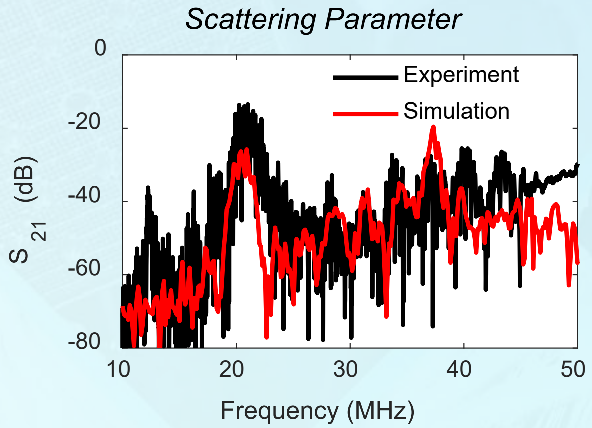


Modeling Results

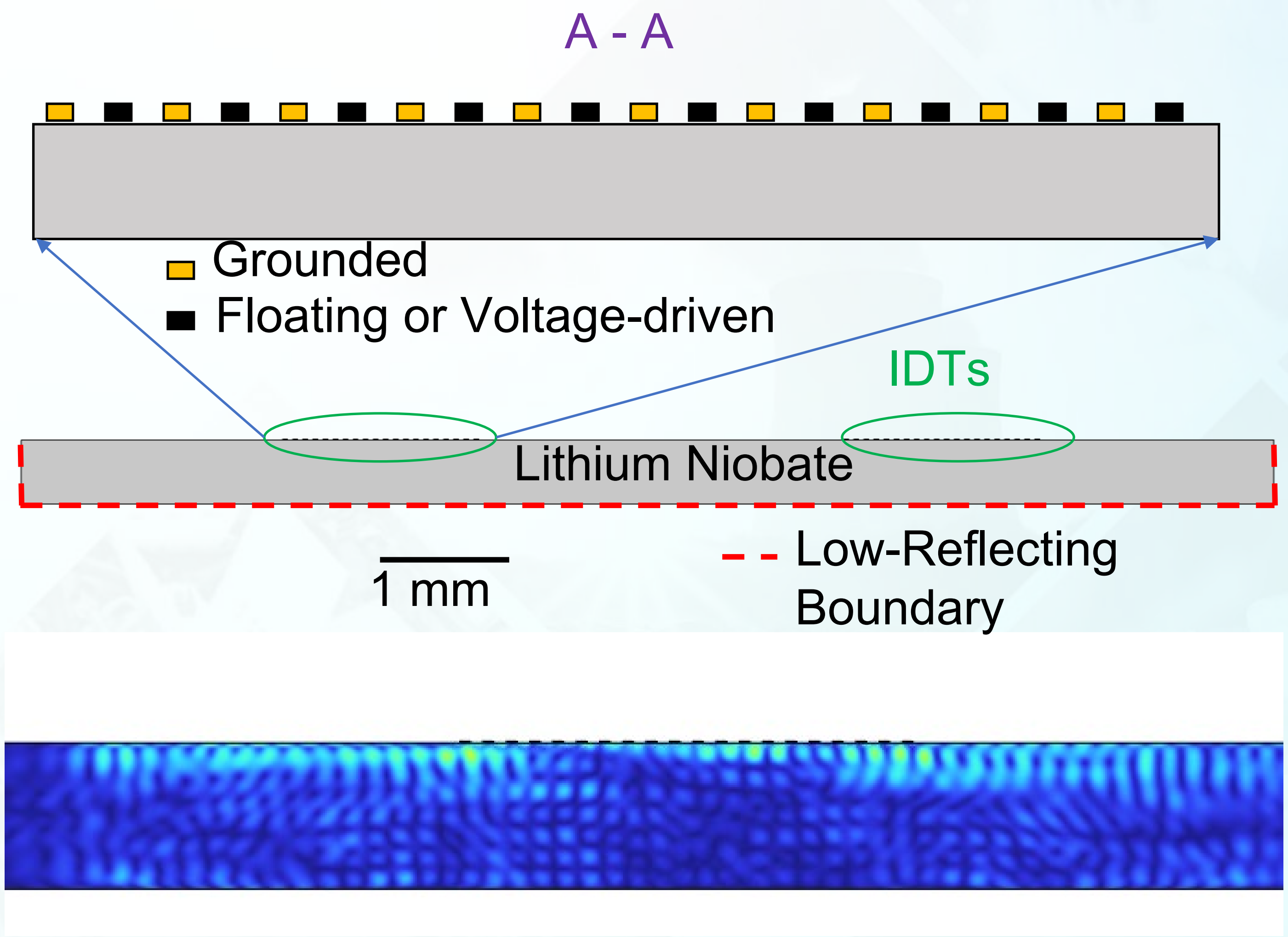
Time-domain

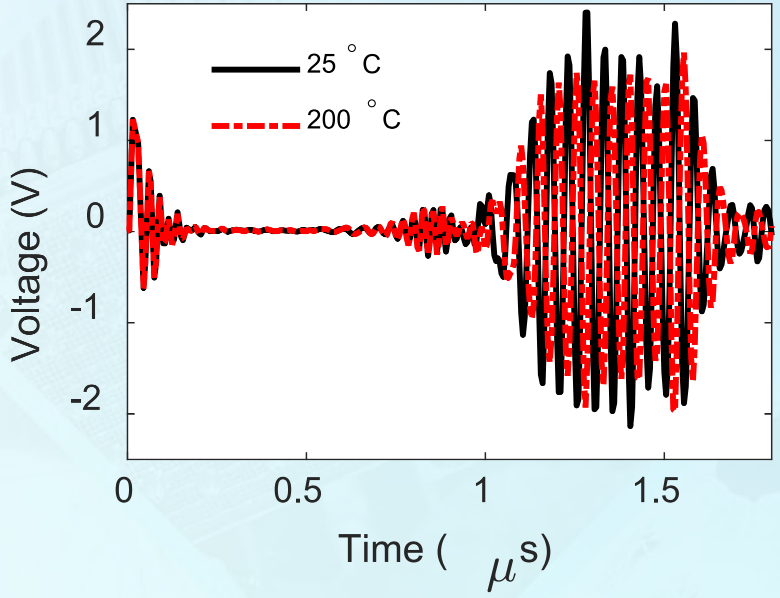


Frequency-Domain

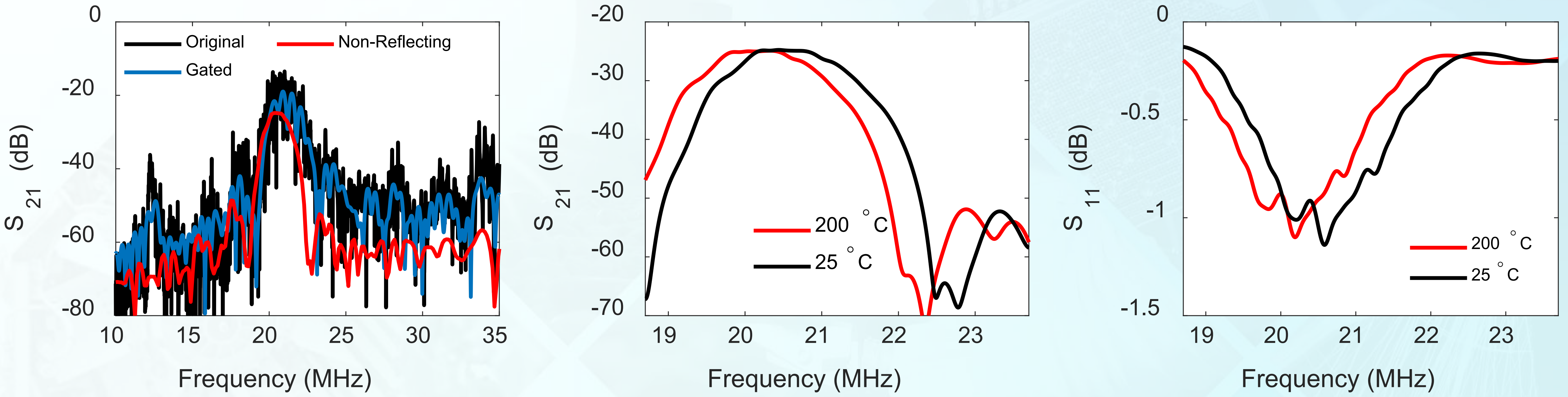


Task 4: Simulate the time-dependent SAW propagation

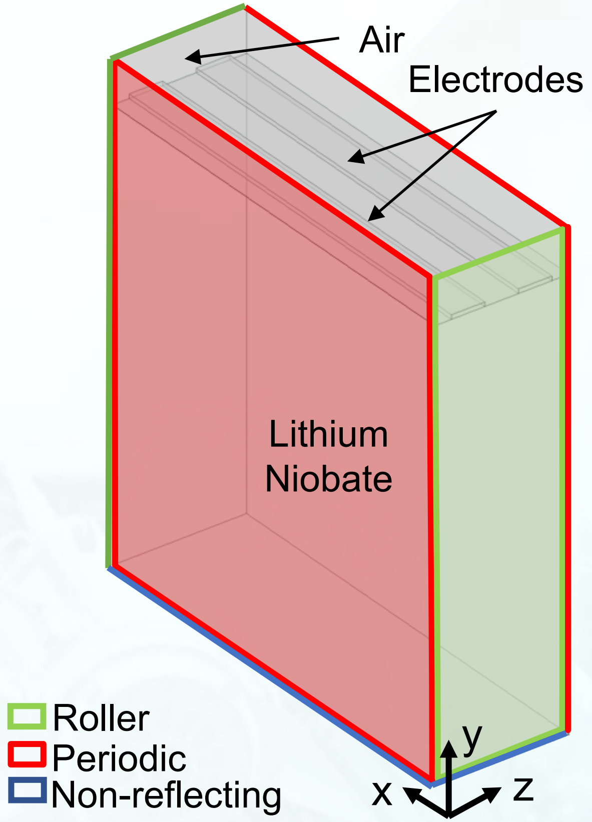


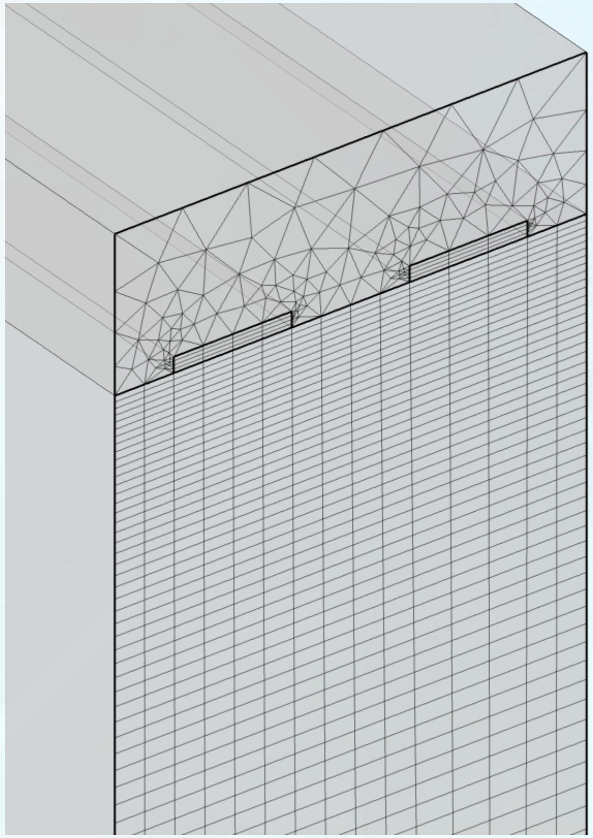


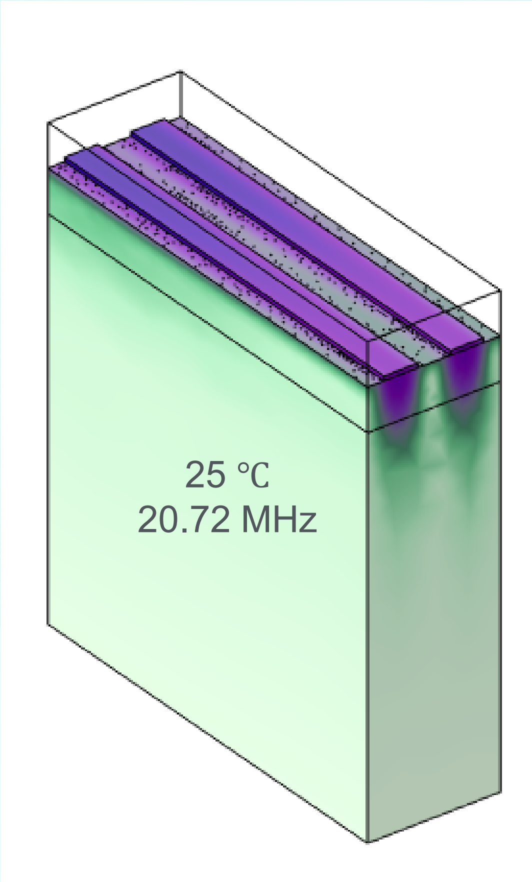
Task 5: Simulate the scattering parameters of SAW thermometer



Task 6: Simulate the SAW thermometer in frequency domain







Concluding Remarks

Publications

1. N. McKibben, B. Ryel, D. Estrada, J. Daw, and Z. Deng*. "Aerosol jet printing of piezoelectric surface acoustic wave thermometer." *Microsystems & Nanoengineering*. (in print)
2. A. Draper, N. McKibben, and Z. Deng*. "Multiphysics modeling of printed surface acoustic wave thermometers." *Sensors and Actuators: A. Physical*. (in print)
3. A. Keller, B. Robinson, A. Draper, A. White, J. Daw, and Z. Deng*. "Magnetostrictive ultrasonic waveguide transducer for in-pile thermometry." *IEEE/ASME Transactions on Mechatronics*. 27(6), 2022.
4. A. Draper* and Z. Deng. "Simulation of printed surface acoustic wave thermometer." In *Proceedings of Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*, 12046:53-60. 2022. (online)
5. N. McKibben*, B Ryel, A Draper, D. Estrada, and Z. Deng, "Additive manufacturing and characterization of surface acoustic wave devices. " *The Minerals, Metals, and Materials Society (TMS) Annual Meeting & Exhibition*, Anaheim, CA, USA, Feb. 2022.
6. Z. Deng*. "Additive manufacturing of smart materials." *The Minerals, Metals, and Materials Society (TMS) Annual Meeting & Exhibition*, Anaheim, CA, USA, Feb. 2022
7. Shane Palmer*, A. Draper, and Z. Deng, "Magnetostrictive ultrasonic waveguide transducer for in-pile thermometery." NPCI&HMIT 2021.
8. S. Palmer* and Z. Deng. "Additive manufacturing of magnetostrictive thin film sensors." In *Proceedings of Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2020*, Vol. 11379: 113791P, Los Angeles, CA, 27 April – 8 May, 2020.

Thank You