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

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Direct Digital Printing of Passive Wireless Sensors for Nuclear Energy Applications

Advanced Sensors and Instrumentation Annual Webinar

October 29, November 5, November 12 , 2020

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Oak Ridge National Laboratory

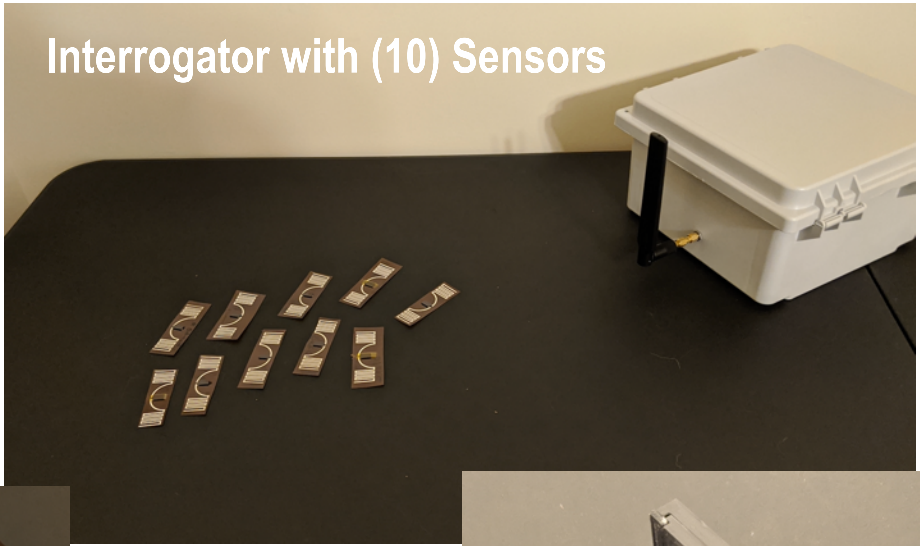
Project Overview

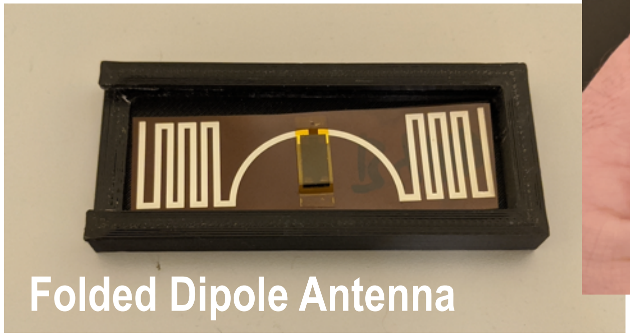
- Goal and Objective
  - Develop a prototype passive wireless sensor network including surface acoustic wave (SAW) sensors, or other printed electronic devices as needed for measurement of voltage, current and hydrogen. The sensors will be made by advanced additive manufacturing (AM) technologies for functional materials (FM) developed by ORNL
- Participants (2020)
  - Tim McIntyre, Pooran Joshi, Jim White, Stephen Killough, DaHan Liao, Timothy McKnight, Tolga Aytug, Bruce Warmack, Ben LaRiviere (all ORNL) and Don Malocha (U. of Central FL)
- Schedule
  - Remaining Schedule:
    - End of Q1 2021: Field demo of multisensory wireless network at partner location.
    - End of Q2 2021: Extended field deployment at partner location.

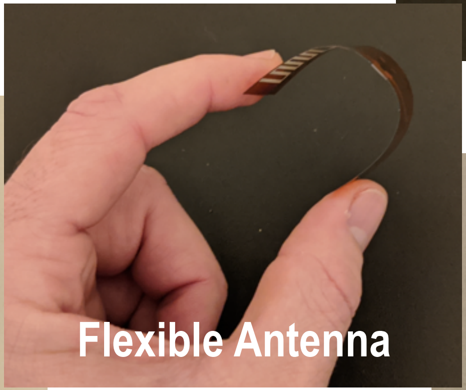
Project Overview - Technologies

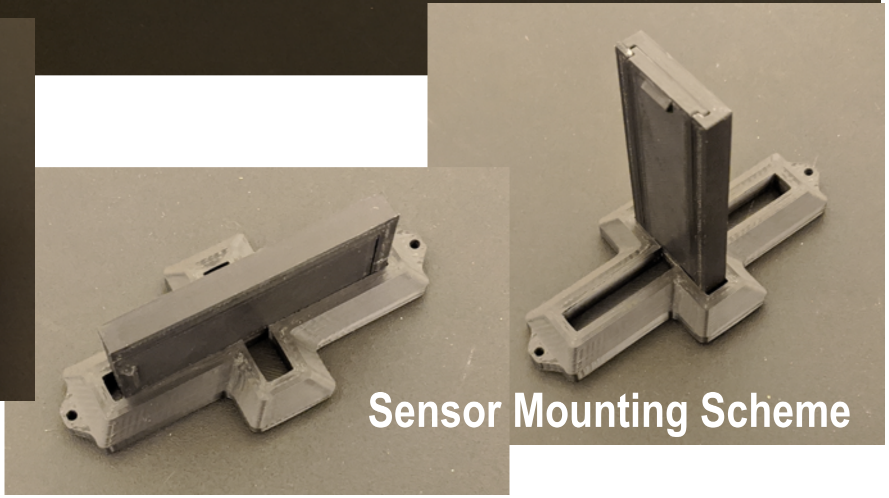
Project Technology Development Areas

- Surface Acoustic Wave (SAW) sensor fabrication
- Orthogonal frequency coding (OFC); unique ID
- Antenna design & integration
- Interrogator hardware & software
- Signal processing
- Functionalizing coatings
- Sensor & interrogator packaging
- The deployed sensor network



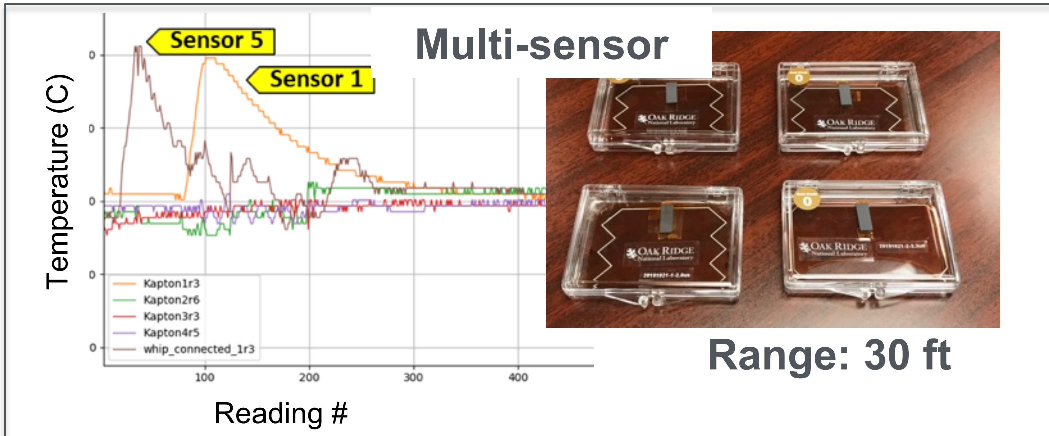


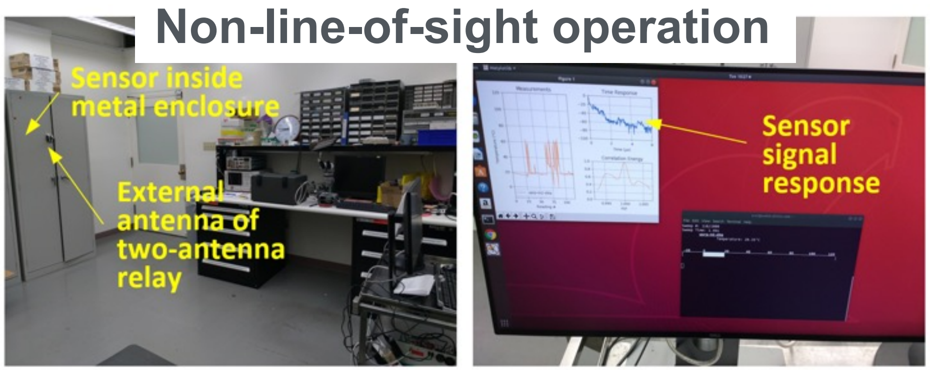


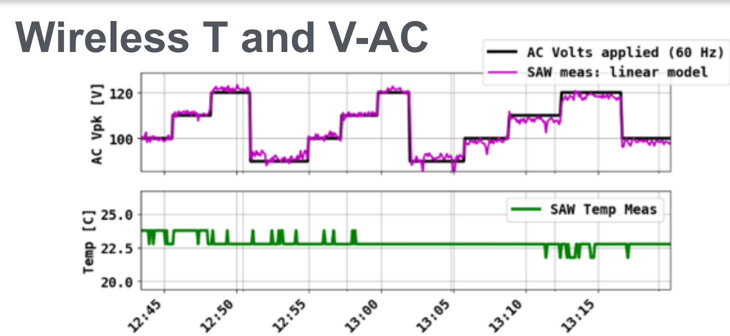


Summary of accomplishments (1/2)

1. Sensor Network Integration and Testing in the Laboratory - 12/31/2019; completed ahead of schedule for 4 sensor network; testing is ongoing as sensors are added and differing types of sensor are added (Temp., H_2, V, and I)
2. Multi Sensor Network Operates Autonomously Outside Laboratory - 3/31/2020; completed October (outside) and via demo at Southern Company mid-November, 2019
3. Expanded Sensor Suite to Include Temperature and Hydrogen Leak Detection - 6/30/2020
4. Multi-sensor Network Extended Duration Testing - 9/30/2020; delayed by COVID. Now shooting for Q2 in FY21.



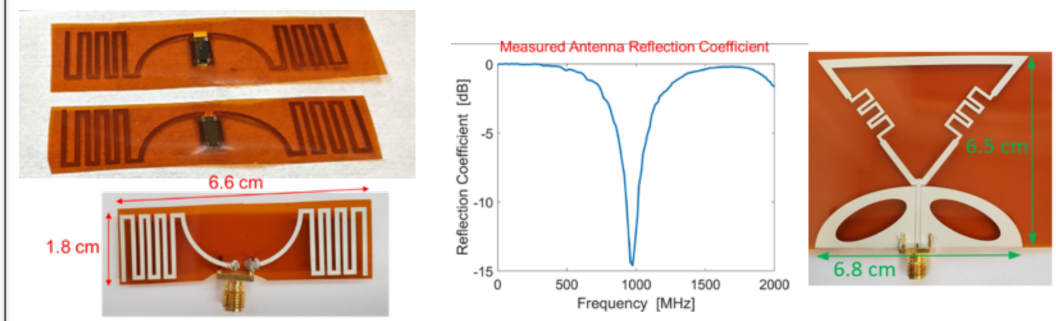




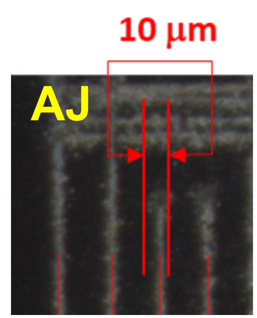
Summary of accomplishments (2/2)

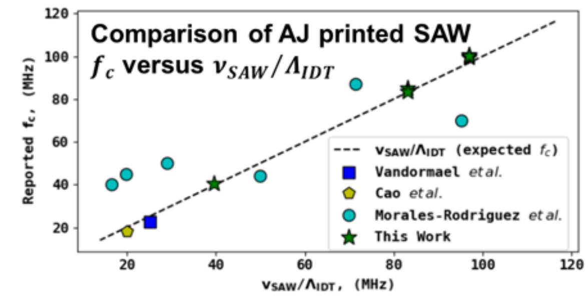
5. Antennas for Printed Hybrid SAWs – Optimized designs of silver-on-polyimide layered structures
6. Deterministic printed devices - demonstrated improved theory vs experiment agreement for printed SAWs compared to prior work
7. Use of higher harmonics of printed SAW devices – enables frequency operation approaching 1 GHz – first demonstration in the literature
8. Sensing beyond temperature – Voltage and resistance sensing with printed impedance sensitive devices.

Flexible optimized 915 MHz Antennas

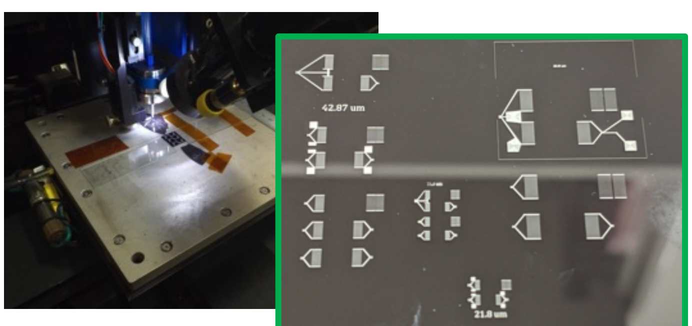


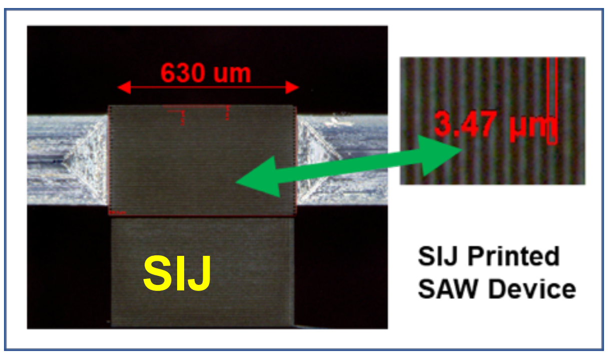
Advanced state-of-the-art for printed SAWs

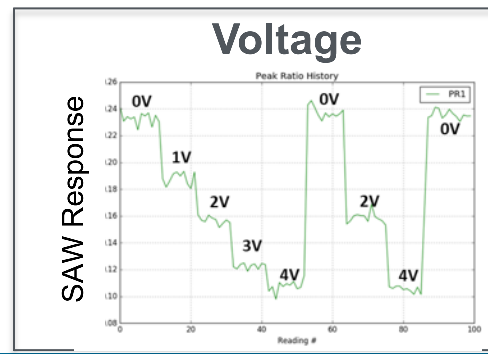




Printed Devices







Technology Impact

This technology:

- Enables a new paradigm for low cost, passive, wireless, highly reconfigurable, multiparameter sensor networks critical for nuclear power plant measurement needs
- Impacts the nuclear industry by making autonomous, ubiquitous sensing feasible economically and logistically: low cost; radiation tolerant; no wires or batteries; miniature
- Advanced sensor technology that impacts the DOE mission of resilient, reliable and cost-effective energy supply for the nation.
- Collaboration with Southern Company, EPRI and commercial sensing companies is being pursued to refine technology performance criteria and perform field demonstration
- Supports the DOE-NE research mission by pushing the state-of-the-art for applications of additive manufacturing to NE

Background

Pushing the Limits of Additive Manufacturing

The visionary premise is printing everything needed to be a passive wireless sensor.

Some fundamental challenges to be overcome along the way, include:

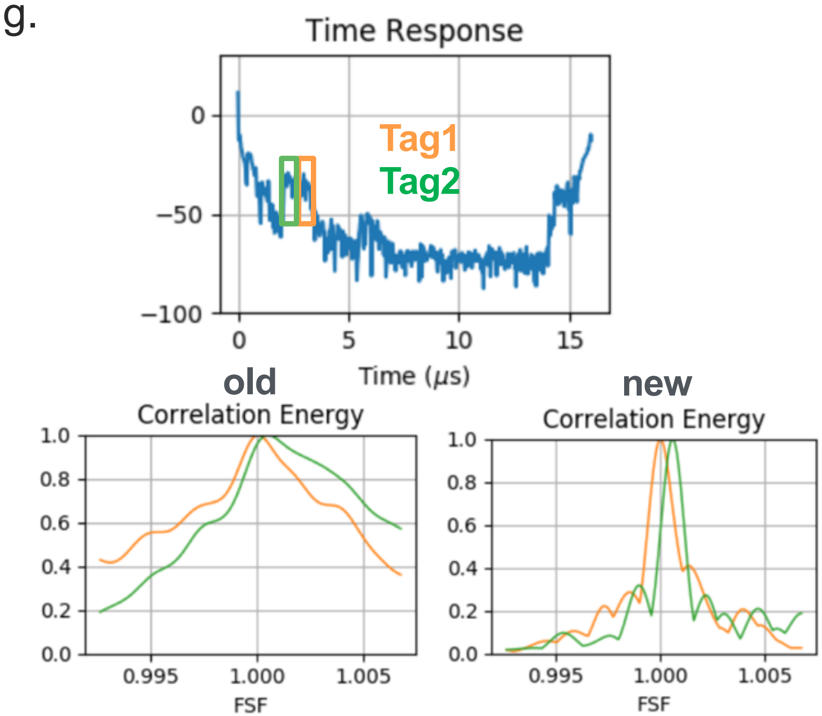
- Printing the SAW sensor – spatial feature size
  - Then: 20µm feature size
  - Now: 1.0 to 5.0µm – need to go smaller
- Printing the antenna
  - Then: Only Redux of conventional antennas (10-20cm x 2cm)
  - Now: Dipole (10cm x 1cm); folded micro-patch (2.5cm x 0.5cm) @ 915MHz
- Printing the functional coatings
  - Then: None available
  - Now: Wide selection of solution, nano-particle and carbon nano-tube based inks with unique chemical and physical parameters
- Printing the sensor package
  - Then: None available
  - Now: Concepts emerging – Sensors packaged in traditional AM printed structures, sensors embedded in components during manufacturing, or sensors printed on items (smart label), etc.

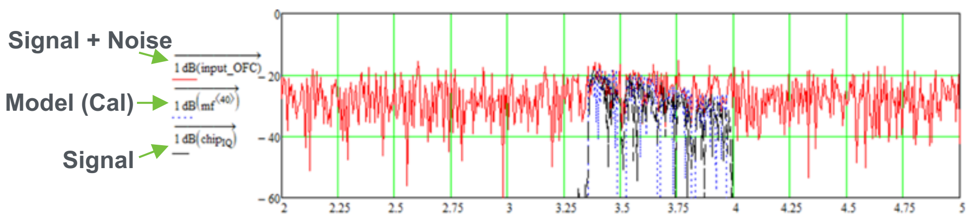
Accomplishments (1/4)
Improvements in Signal Processing

Recent Progress: Signal Processing

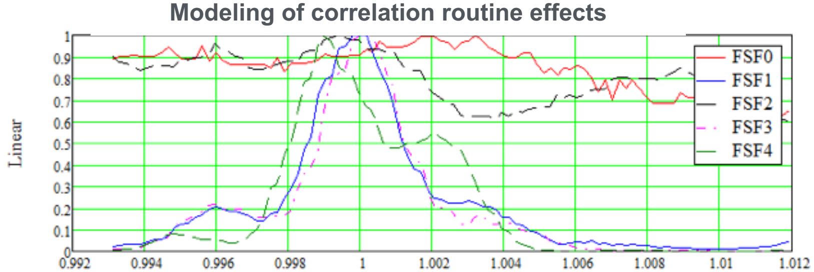
- ➢ Accuracy of extraction of SAW sensor parameters improved for higher fidelity calibration → filtering of signal at low SNR → improved measurand accuracy and distance
- ➢ Modeling of impact of various filtering approaches indicates correlation routine changes can increase sensor selectivity → address inter-tag sensitivity → increase sensor # density
- ➢ Two new designs for evaluating these algorithms on sensor networks with 10 simultaneous tags have been fabricated – experimental evaluation ongoing.

Experimental evaluation of calibration and correlation developments





Modeling of correlation routine effects

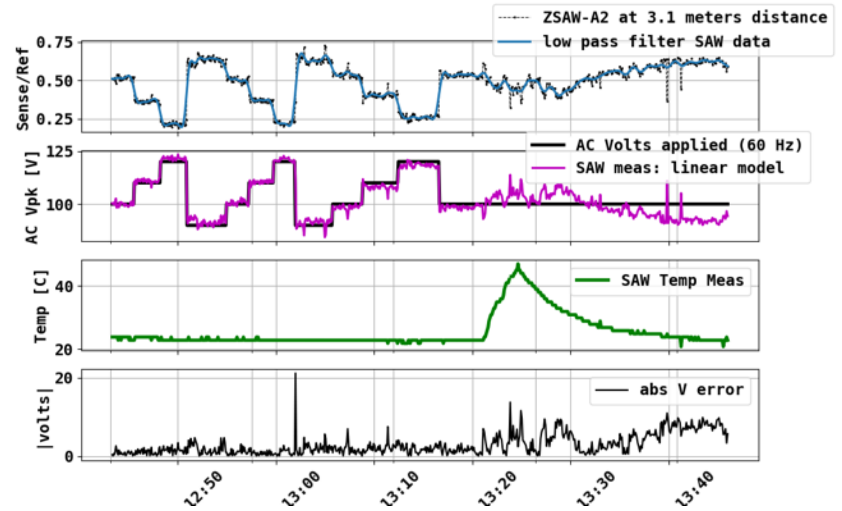


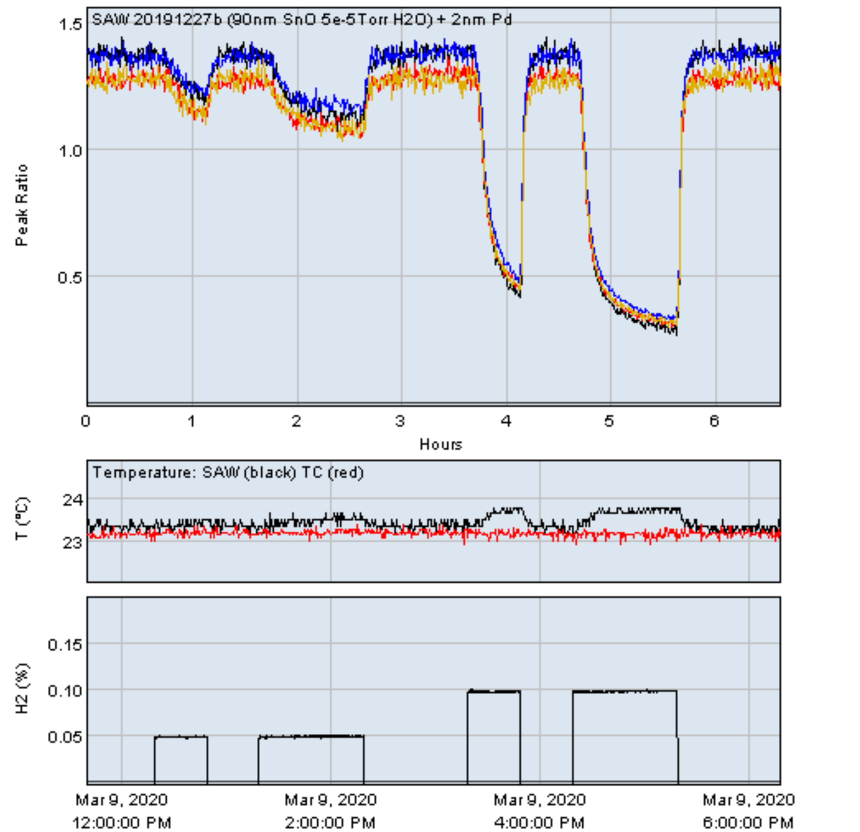
Accomplishments (2/4)

Passive wireless sensor networks:

- Implemented printed hybrid passive electronic sensor network with 5 temperature sensors; 8+ sensor network in progress.
- Ag/Polyimide antennas integrated with SAW chips for flexible, robust sensors
- Passive “look-around” RF-opaque obstructions using passive antenna relays
- Long range (100+ ft) comms for optimized setup
- Multiparameter: Temperature and Voltage, Temperature and Hydrogen,
- Reliability and degradation study of H_2 sensitive nanostructures
- Novel approach to coding reflections for passive voltage and current sensing (in disclosure process)

IP In-progress: Invention Disclosure ID# : 202004741, DOE S# S-162,155, "PASSIVE SAW TRANSPONDER WITH MULTI-CODE, ELECTRICAL IMPEDANCE LOADED SENSOR REFLECTORS“ (Elected by UT-Battelle)

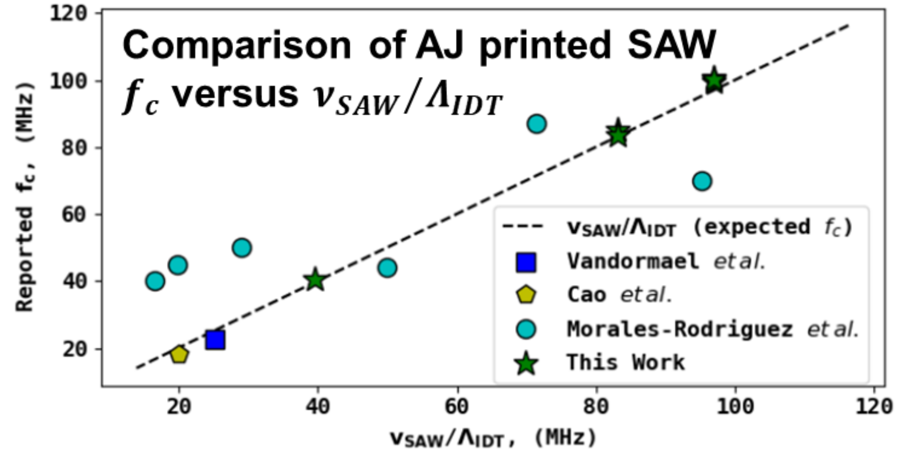




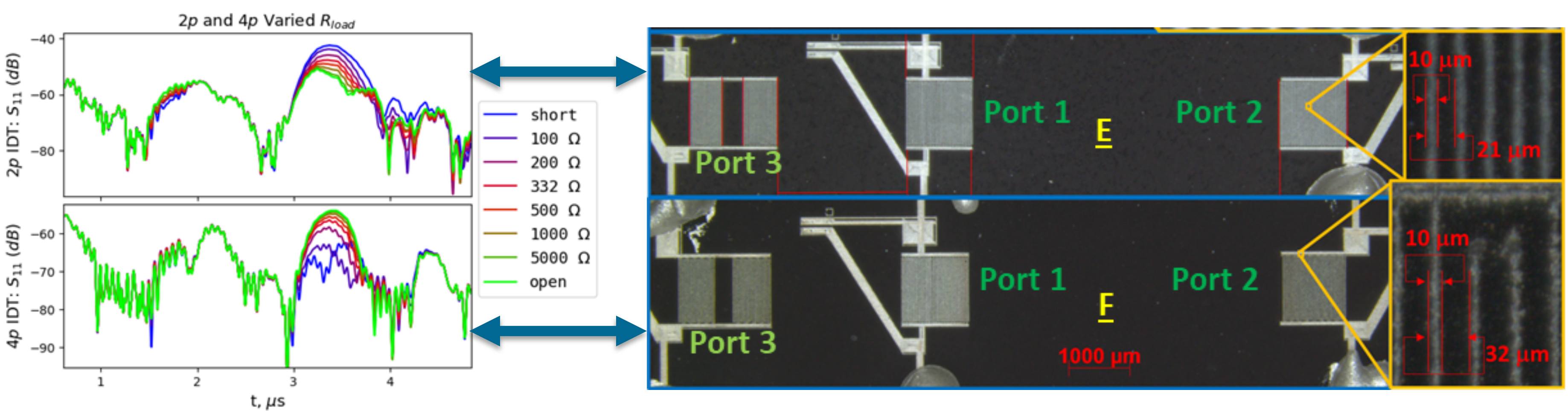
Accomplishments (3/4)

- For aerosol jet (AJ) printing fabrication:
  – Marked improvement in measured f_c versus v_{SAW}/Λ_{IDT}: The first demonstrations of deterministic SAW device design up to the resolution limit of AJ technology
  – First demonstrations of impedance sensitivity and use of alternative IDT designs to enable voltage sensing

Advancing the state-of-the-art for printed SAWs

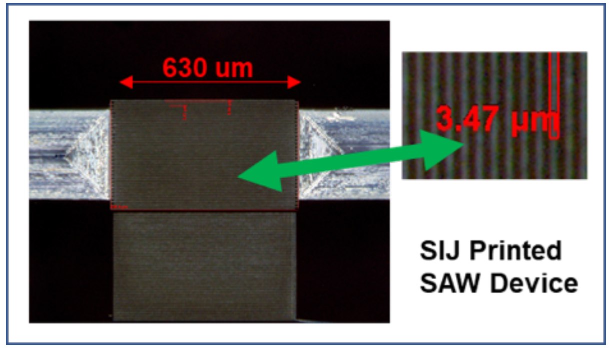


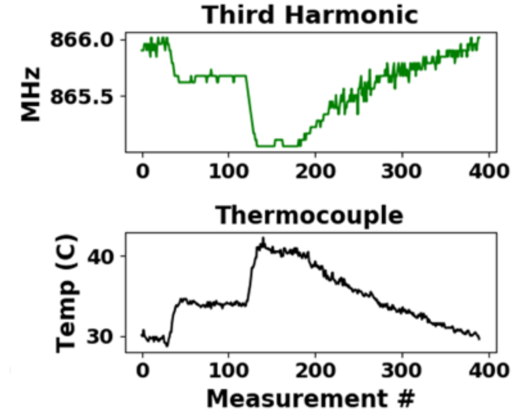
Modulation of Printed SAW Device Responses via Passive Load:

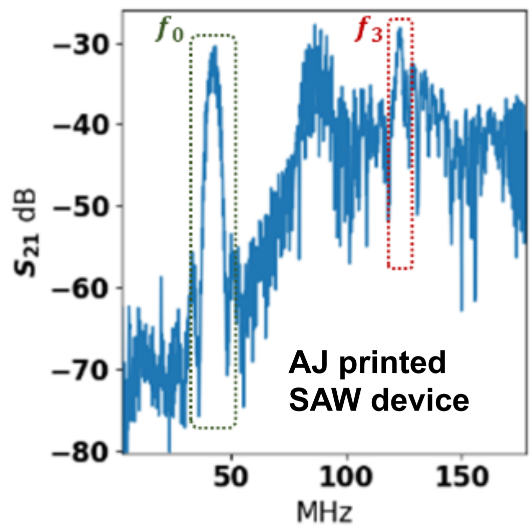


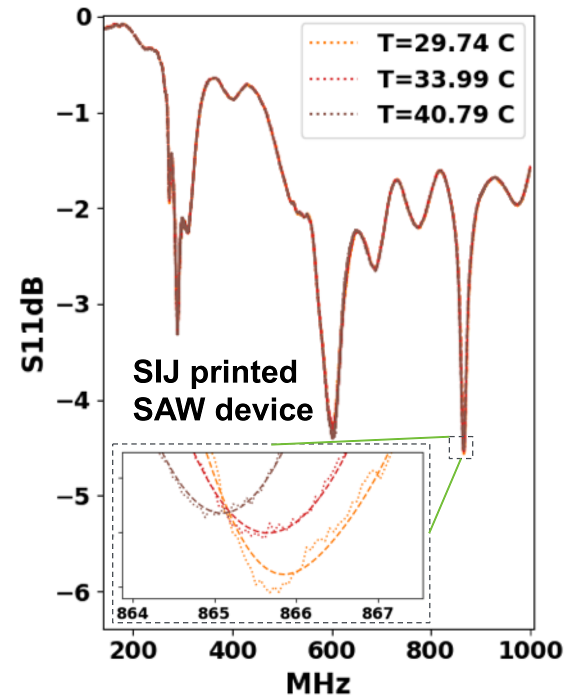
Accomplishments (4/4)

- Utilization of harmonics to increase operating frequency:
  - First demonstrations of approach for printed SAWs
  - Harmonic operation of SIJ-fabricated temperature sensitive resonator to 865MHz
  - Operation of AJ printed T-sensor to 123MHz









Recent Publications:

– B. LaRiviere *et al.*, “*Surface Acoustic Wave Devices Printed at the Aerosol-Jet Resolution Limit*” (Submitted to IEEE Access Q1 2021)

Conclusion

- We have developed passive (no batteries) wireless sensors based upon radio frequency (RF) surface acoustic wave (SAW) technology.
- We have demonstrated the ability to monitor multiple miniature passive sensors simultaneously.
- Relying on additive manufacturing, complete sensors can be printed.
- These sensors can be functionalized to monitor multiple parameters simultaneously such as temperature, hydrogen, voltage and current.

Questions?

Email contact information for any additional questions: Tim McIntyre:
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