U.S. DEPARTMENT OF ENERGY
Office of Electricity

GMLC SAW Sensor Field Validation

TRAC Program Review

US Department of Energy, Office of Electricity

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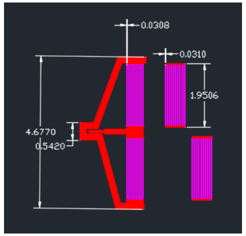
Project Overview

Project summary

- Low-cost and highly sensitive physical and chemical sensors developed to monitor transformer state-of-health.
- Novel, direct digital printed (DDP) radio frequency (RF) surface acoustic wave (SAW) technology for detection of dissolved gases caused by electrical, thermal and mechanical stresses are monitored during operation.
- On-line monitoring provides real-time tracking of transformer component degradation.
- Costly dissolved gas analysis by gas chromatography is currently used to collect diagnostic information.
- Concentrations of hydrogen (H_2), methane (CH_4), acetylene (C_2H_2), and other gases dissolved in transformer oil are monitored on large and very expensive transforms found in substations.
- Low cost sensor technologies enable fault diagnosis on large transformers and smaller distribution system transformers.



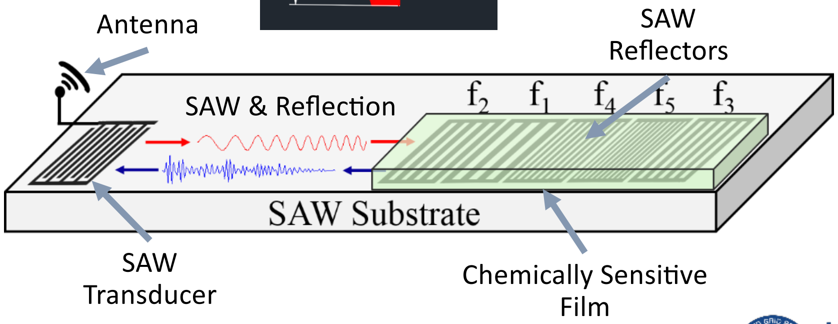
Single port, dual channel RF/SAW sensor – channel 1 temperature reference – channel 2 sensor of interest.

Total value of award (federal + cost share)

$1,500k(fed) + $50k (in-kind support of field testing)

Period of Performance

10/1/2016 to 9/30/2019 – no cost extension, 6 months

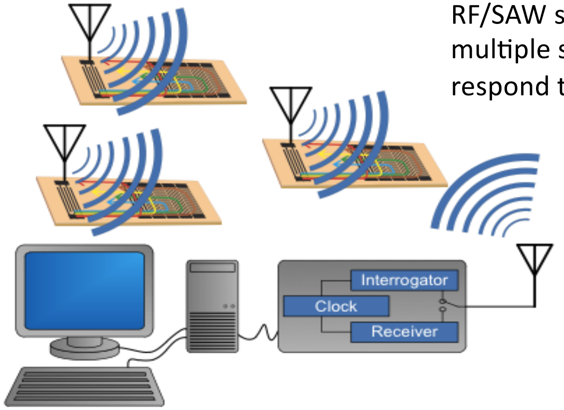


Project lead and partners

ORNL, Southern Company, EPRI

Context concerning the problem being addressed

- Background information & context in which the research problem exists.
  - ➢ Technology supports grid resiliency and optimizes efficient use of assets. On-line transformer monitoring and diagnostics enables proactive and event driven maintenance and repair.
- Economic or societal concerns associated with this research?
  - ➢ Economics: Large substation transformers are very costly to replace and have long lead-time for replacement. Due to their high cost, on-line DGA systems costing $50k or more can be justified. Low cost (<$5k), on-line diagnostics enables less costly monitoring on a much larger (utility pole) scale.
  - ➢ Societal concerns: Unanticipated or extended outages have significant impact on public health and increases avoidable cost that can become burdensome to customers.
- Environmental implications? Impacts on human health & wellness?
  - ➢ Environmental implications: Transformer fire caused by unidentified internal faults can release noxious chemicals into atmosphere.
  - ➢ Human health & wellness: Loss of electrical service can have serious health impact to citizens in need of medical support systems and HVAC.

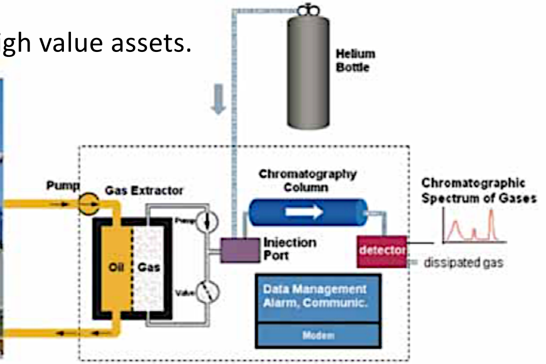


RF/SAW sensor architecture; multiple sensors simultaneously respond to interrogator

State of the art approaches for addressing the problem

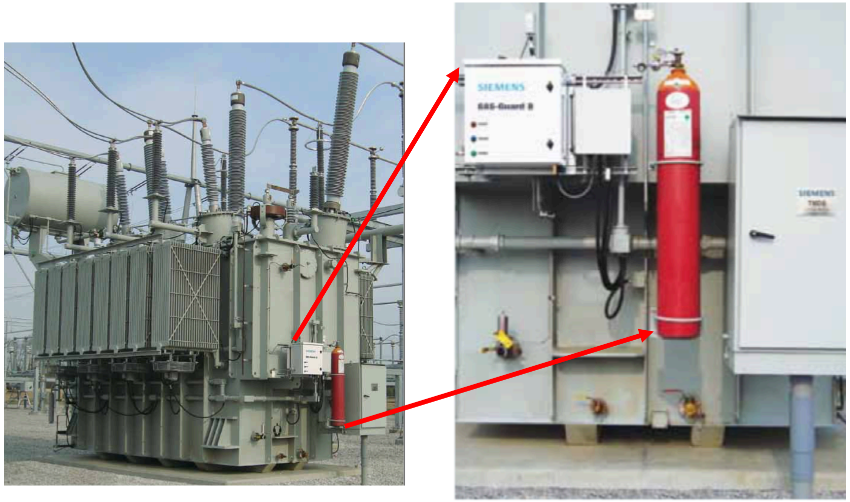
<u>Commercial equipment:</u> Siemens, Thermo Fisher Scientific, Agilent Technologies and others offer on-line diagnostic instruments.

System Integration with high value assets.



Gas		Accuracy[1]	Repeatability[2]	Range[3]
Hydrogen	H_2	+/-5% or +/-2 ppm	<2%	2-3,000 ppm
Oxygen	O_2	+/-5% or +30/-0 ppm	<1%	30-5,000 ppm
Methane	CH_4	+/-5% or +/-10 ppm	<1%	10-5,000 ppm
Carbon Monoxide	CO	+/-5% or +/-3 ppm	<1%	3-10,000 ppm
Carbon Dioxide	CO_2	+/-5% or +/-5 ppm	<1%	5-30,000 ppm
Ethylene	C_2H_4	+/-5% or +/-3 ppm	<1%	3-5,000 ppm
Ethane	C_2H_6	+/-5% or +/-5 ppm	<1%	5-5,000 ppm
Acetylene	C_2H_2	+/-5% or +/-1 ppm	<2%	1-3,000 ppm

Accurate and repeatable measurement of eight (8) critical fault gases.



<u>Merits:</u> These systems are highly sensitive to many gases.

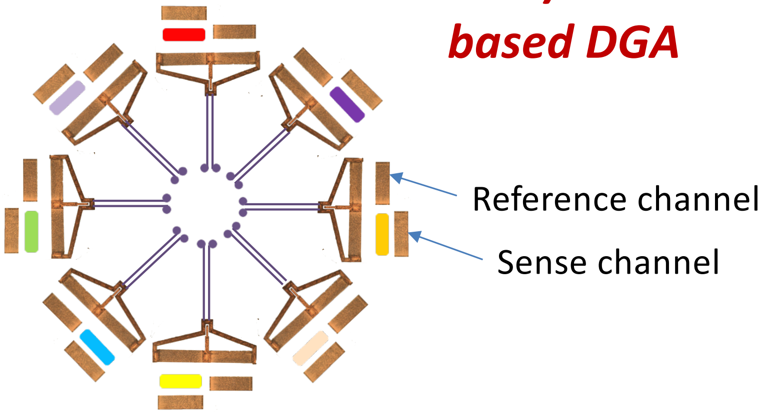
<u>Drawbacks:</u> High cost to purchase and maintain ($50k + $1-3k/yr.).

Uniqueness of the proposed solution

What separates this solution from others that have been proposed or tested?

- Technology - Novel sensors, antenna and packaging by DDP
- Integrated - Sensor system via roll-2-roll processing, easy scale-up
- CapEx - Sensors are very low cost (<$1/sensor)
- OpEx - Sensors are passive; no batteries required; energy comes from interrogator; if the sensor stops working, replace it; interrogator also low cost (<$1k/system)

MOONSHOT: Pursue RF/SAW-based DGA



Eight (8) single port, dual channel gas sensor DGA

What are the unique advantages?

- Sensor diversity - Can be functionalized to measure many things (H_2, CH_4, C_2H_2, CO_2 (many other gases), humidity, temperature, strain, pressure, pH, etc.
- Roll-2-roll printing enables fabrication diversity of sensors with little to no change in process.

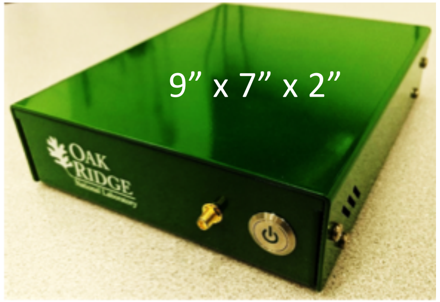
Significance of the results, if successful

When successful, how will the project outcomes be utilized?

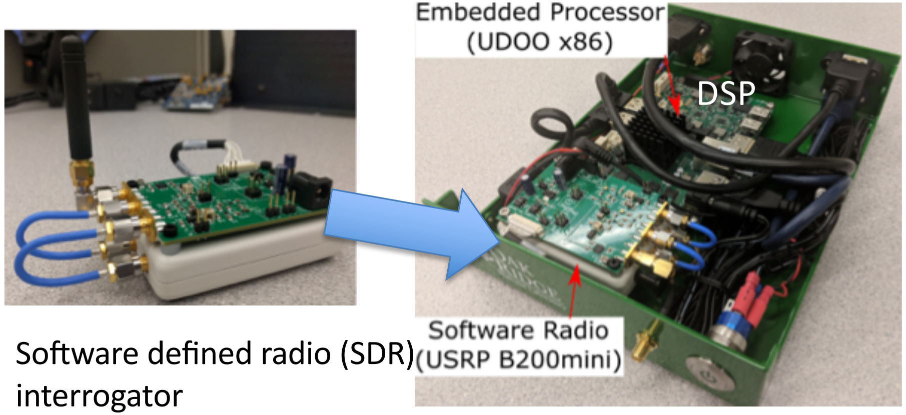
- Sensor systems will replace much higher cost technology
- Sensors will be deployed in new applications in which current technology is too costly and difficult to maintain

What will change, with regard to the problem and its larger context, once these research results are available?

- Increased asset visibility enables:
  - ➢ Reduced maintenance
  - ➢ Increased reliability & resiliency



ORNL Interrogator
- Cost < $1k
- Portable/mobile
- Reconfigurable



Software defined radio (SDR) interrogator

All commercial components + ORNL DSP (data-2-info)
Communication to the enterprise network

Asset visibility >> System Agility >> Reconfigurability

Specific research questions being addressed

Research questions we are addressing include:

- Are there low-cost sensor options currently available that enable ubiquitous measurements? NO
- Is there a path to low-cost sensors? YES
- Can we improve grid reliability and resiliency by sensor enabled analytics? YES
- How will reliability and resiliency be impacted?
    - ➢ Real-time asset visibility
    - ➢ Asset state-of-health
    - ➢ System state-of-health

ORNL interrogator ruggedization build-out in progress

Play Video

Inquiries being made >> Transformer State-of-Health (SoH) - Can we perform high-fidelity dissolved gas measurements for a fraction of the cost of current technology?

What exactly does this project seek to clarify or better understand?

- ➢ Real-time transformer SoH using very low cost printable sensors.

Technical explanation of the proposed approach

PWSTs using DDP represents a novel approach to very low cost sensors.

Process to obtain research results is:

✓ Step 1: Utilize conventional photolithography fabrication methods to demonstrate baseline passive wireless sensor technology (PWST)

✓ Step 2: Develop DDP capabilities to demonstrate "printed" PWSTs

✓ Step 3: Utilize DDP to print sensor films to functionalize PWSTs

✓ Step 4: Integrate sensors with printed RF antenna for remote communication

Step 5: Utilize DDP to package interrogator and RF/SAW sensors

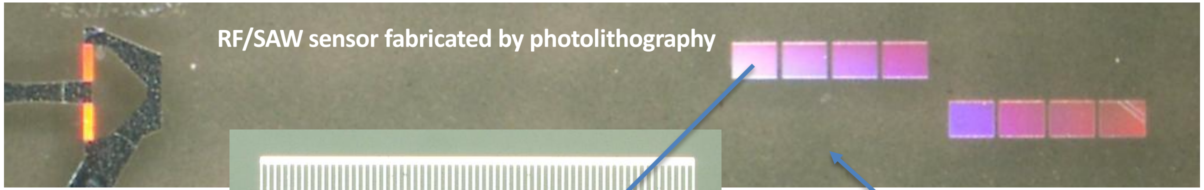
Step 6: Operate system to demonstrate:

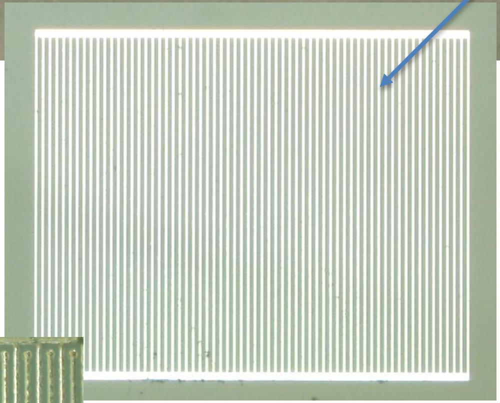
- Remote communication ✓
- Passive sensing ✓
- Simultaneous operation of multiple sensors ✓
- Detection of parameters of interest

Technical explanation of the proposed approach, continued

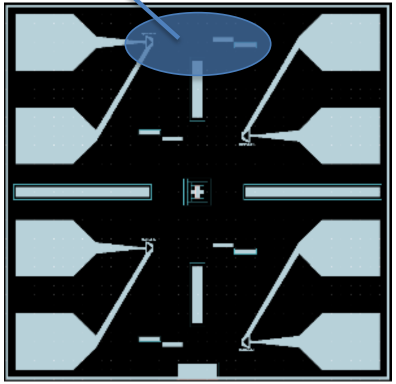
There are many R&D thrust areas coming together to make this technology successful.

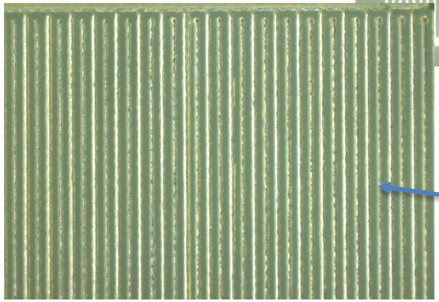
- Surface Acoustic Wave (SAW) sensor fabrication
- Orthogonal frequency coding (OFC); unique ID
- Antenna design & integration
- Interrogator hardware & software
- Signal processing
- Functionalizing coatings
- Sensor & interrogator packaging
- The deployed sensor network



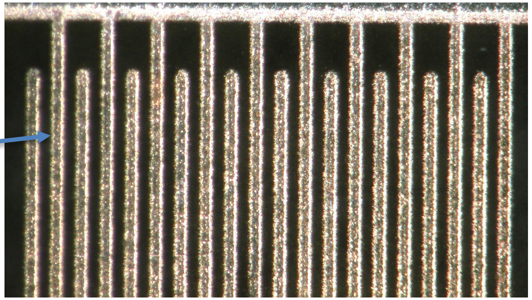


Bragg reflector element with 0.8µm feature size





Printed Bragg reflector with 1µm feature size



Printed IDT with 1µm feature size

The rationale for the approach is to start with a fabrication technology that is mature and capable of producing structures with the needed feature size (benchmark), then transition to the new DDP approach

Technical explanation of the proposed approach, continued

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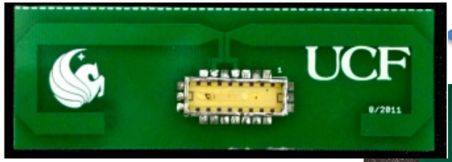
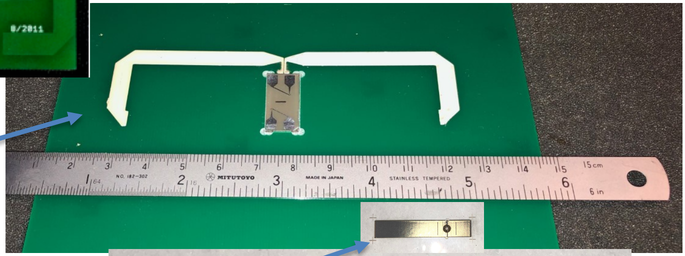
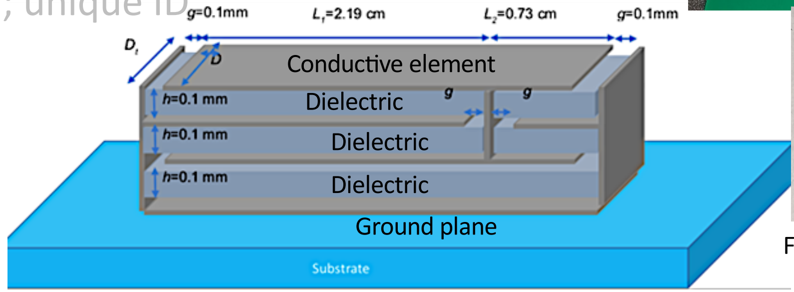
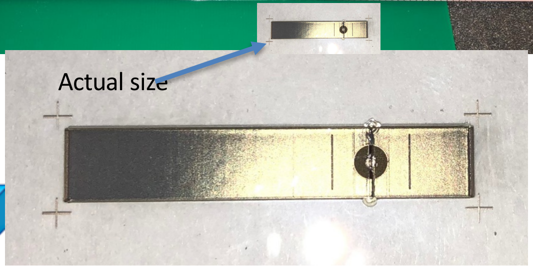


Commercially available 915MHz quarter wave dipole antenna with SAW chip package

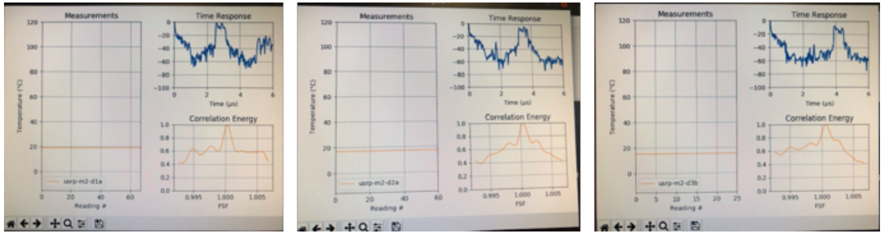


DDP 915MHz quarter wave antenna

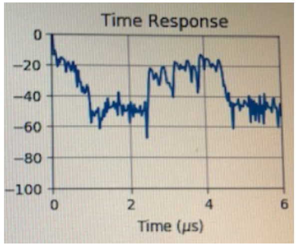




Folded micro-patch antenna (bottom view), showing the access port to the embedded conductor.



RF echo signal returning from SAW sensor; 3 sensors with time diversity



RF echo from 3 sensors simultaneously

Technical explanation of the proposed approach, continued

There are many R&D thrust areas coming together to make this technology successful.

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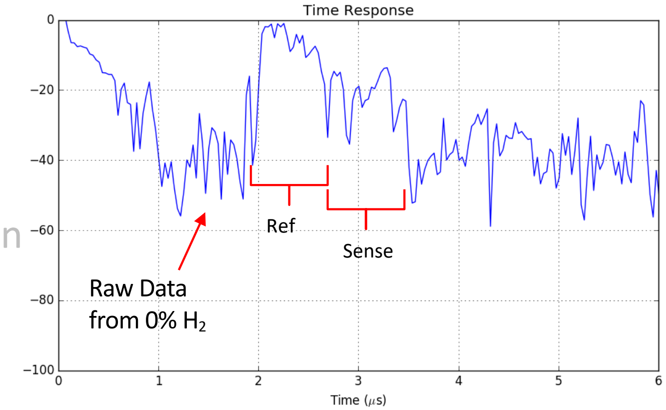
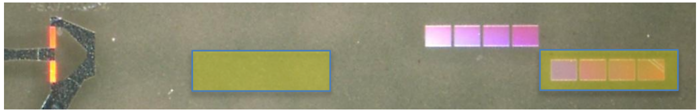
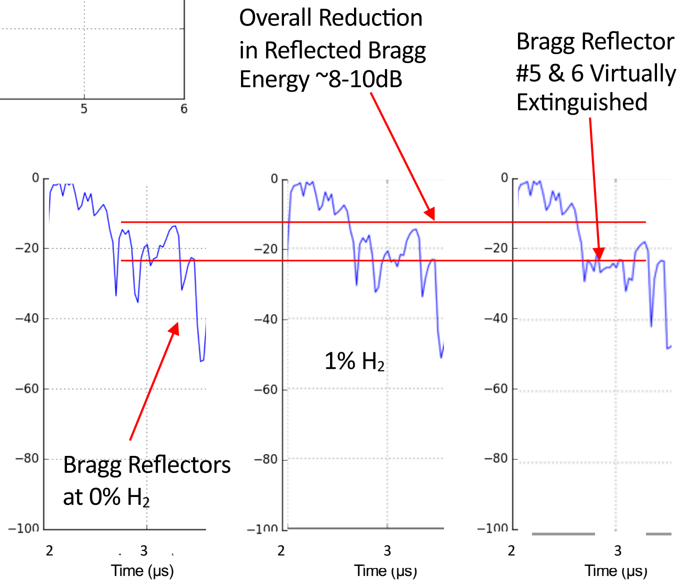


Hydrogen sensor data using SnO/Pd coatings in channel



In channel vs. on Bragg reflector



Project schedule, deliverables, and current status

Project Schedule

Ruggedized Interrogation System Design and Demonstration	October 2018	Design Complete Demo not
Report Technical specification between ORNL and utility for SAW temperature sensor deployment	January 2019	Complete
Report results from ORNL asset deployment of SAW temperature sensor	April 2019	In Progress
Report results from utility owned asset deployment of SAW temperature sensor. Discussions with utility on future deployment of SAW sensors.	July 2019	In Progress

Deliverables

- RF/SAW sensor designs for measuring methane, hydrogen and acetylene
- Interrogator design for rugged environments
- Letter report on sensor network testing results with project partner
- Test plan for testing a multisensory RF/SAW network in the field

Funding Summary

FY18 Carryover	FY19 Funds Received	FY19 Funding Authorized	Current Quarter Spending	YTD Spending	Committed	Balance Remaining
$766K	$0K	$766K	$194K	$205K	$2K	$559K

Note: Total project budget = $1,555,722

Anticipated challenges and risk mitigation strategies

- Printer capabilities – decrease feature size to achieve operating frequency of interest (function in license free spectrum; 902-926MHz ISM band)

Risk mitigation strategy – continue partnerships with printer OEMs and explore additional partnerships

- Availability of material formulations to perform measurements of interest
  - Inks for high performance device operation & substrate compatibility
  - Printable materials to functionalize sensors to measure specific

Risk mitigation strategy – identify new sources of inks that enable sensor functionalization and partner with manufacturers to develop new formulations

- Improve interrogator/system performance to extend range of operation and expand palette of physical and chemical measurements

Results & Next steps

Continued development is needed is many areas

Results

- Printed RF/SAW sensors
  - Continue to reduce feature size (^Hz)
  - Improve print quality to improve SNR
- Printed antenna(s)
  - Dipole & Folded micro-patch
- Fine-tuned interrogator; improved SNR by 20dB
  - Reduce size, weight & cost
  - Broaden scope of impact
- Achieved successful hydrogen and methane detection
  - SAW frequency shift (~0.5%) - methane
  - SAW amplitude shift (~0.1%) - hydrogen
- Characterizing new fab tools
  - Laser writer – 600nm resolution
  - Super ink jet – 900nm resolution
  - Advanced aerosol jet - (5µm res.)

Publications & Inventions

- Invited paper at 9th International PWST Workshop, Ottawa, Canada
- IP – (3) disclosures; (1) issued

Next Steps

Look Ahead (30 day/60 day/90day):

- 30 days: Continue optimizing system
  - Multiple sensors
  - Increased range
  - Signal processing to improve detection limits
  - Investigate acetylene sensor constructs
- 60 – 90 day: Optimize hydrogen selective coating on prototypic sensor platform.
  - Improve methane & hydrogen detection
  - Characterize new acetylene sensor constructs
- Beyond 90 days
  - Continue developing additional sensors toward SAW-based DGA

Broader Impact

- NASA/ORNL are the founding members of the Passive Wireless Sensor Technology (PWST) Workshop (9th year, Ottawa Canada, October 16-18th, 2019)
- Through PWST, there is international engagement in the development of PSWT
- ORNL has engaged multiple DOE offices (AMO, VTO, BTO, OE, BER) regarding printable sensors, electronics, etc.
- This GMLC project is uniquely focused on developing direct digital printing methods for ultra-low cost wireless sensors
- There have publication, conference proceedings and IP disclosure on this project.
- Working with OEMs to improve fab capabilities through AMO Tech Collaboration Program

- Discussions are underway with a wind turbine manufacturer and oil & gas companies interested in remote monitoring of caped oil and gas wells (methane leak detection). Work is ongoing with DOE/NE.

Contact Information

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RF – well known - RADAR

SAW devices - well known – Cell phones

Antennas – well known – everywhere

Tagging – well known - RFID

DSP – well known - <1 SNR

Functional Materials Additive Manufacturing DDPrinted RF/SAW Sensors - <10yrs.

We're just getting started

New inks

Better printers

Flexible substrates

Nano-materials

Roll-2-roll processing

Functionalization

Thin films