WAIC SAW SDR System and New Technology

4.3 GHZ Passive Wireless Sensor System

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University of Central Florida
CAAT

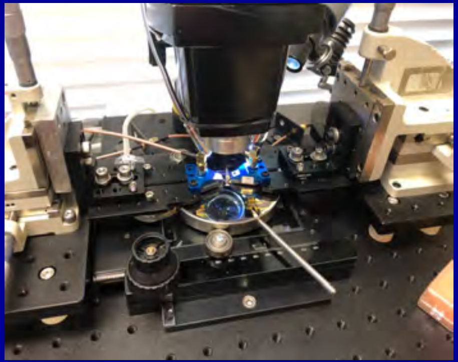
PWST 2019
IEEE WiSEE

Pegasense, LLC

Company started in 2016
Partners have over 60 years of academic and industry device and system research and development experience

Projects:

- **4.3 GHZ Passive Wireless Sensor System, NASA SBIR-II**
- **Multiband-Multiplatform Wireless Sensor System, NASA STTR-I**
- **SAW GHz Radiation Sensor NASA, Phase-III**
- **Programmable GHz SAW correlators, DARPA SPAR-III**
- **Acoustoelectric Amplification, DARPA SPAR-III**
- **GHz OFC SAW passive wireless sensor system**

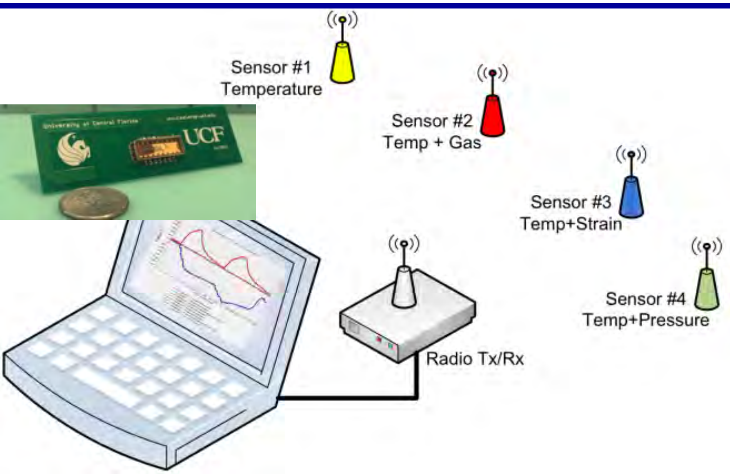


PARTNER/SUBCONTRACTOR

- Center for Applied Acoustoelectric Technology at the University of Central Florida (UCF), Orlando.
  - Dr. Arthur Weeks, Director
  - Pegasense supports UCF post-docs and a PhD graduate students
  - UCF device fabrication
  - Collaborative Hardware System Development
  - Collaborative Software System Development

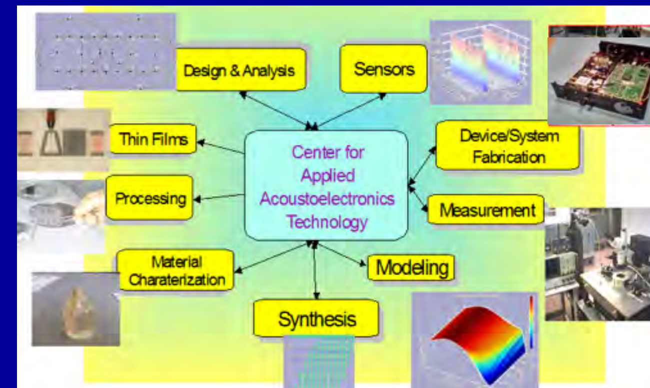
UCF Acoustic Device Rapid Prototyping and Test

Wireless Multi-Sensor Concept



Highlights

- **Solid state**
- **Piezoelectric**
- **Freq: 0.1 – 5 GHz**
- **Temp: 0.1 – >1000K**
- **Filters, correlators, & sensors**
- **RF systems and device development**



UCF Fast Prototyping Mask (0.8 um lines) to System
<1 week from idea to device prototype

915 MHz Systems

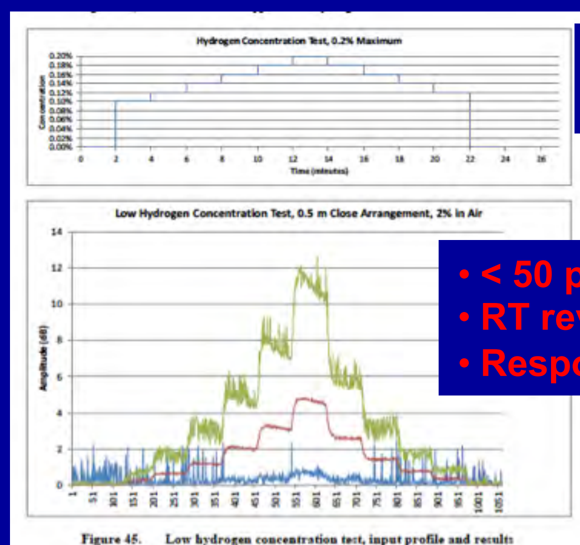
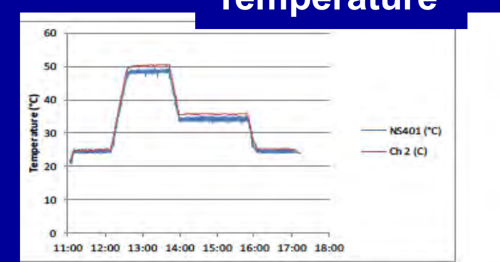


Figure 45. Low hydrogen concentration test, input profile and results

Wireless H_2 Gas

- **< 50 ppm**
- **RT reversible**
- **Response <1s**

Wireless Temperature



Temperature test results; blue trace: SAW sensor; red trace: thermocouple

<.01 C acc.
0.1-500 K range

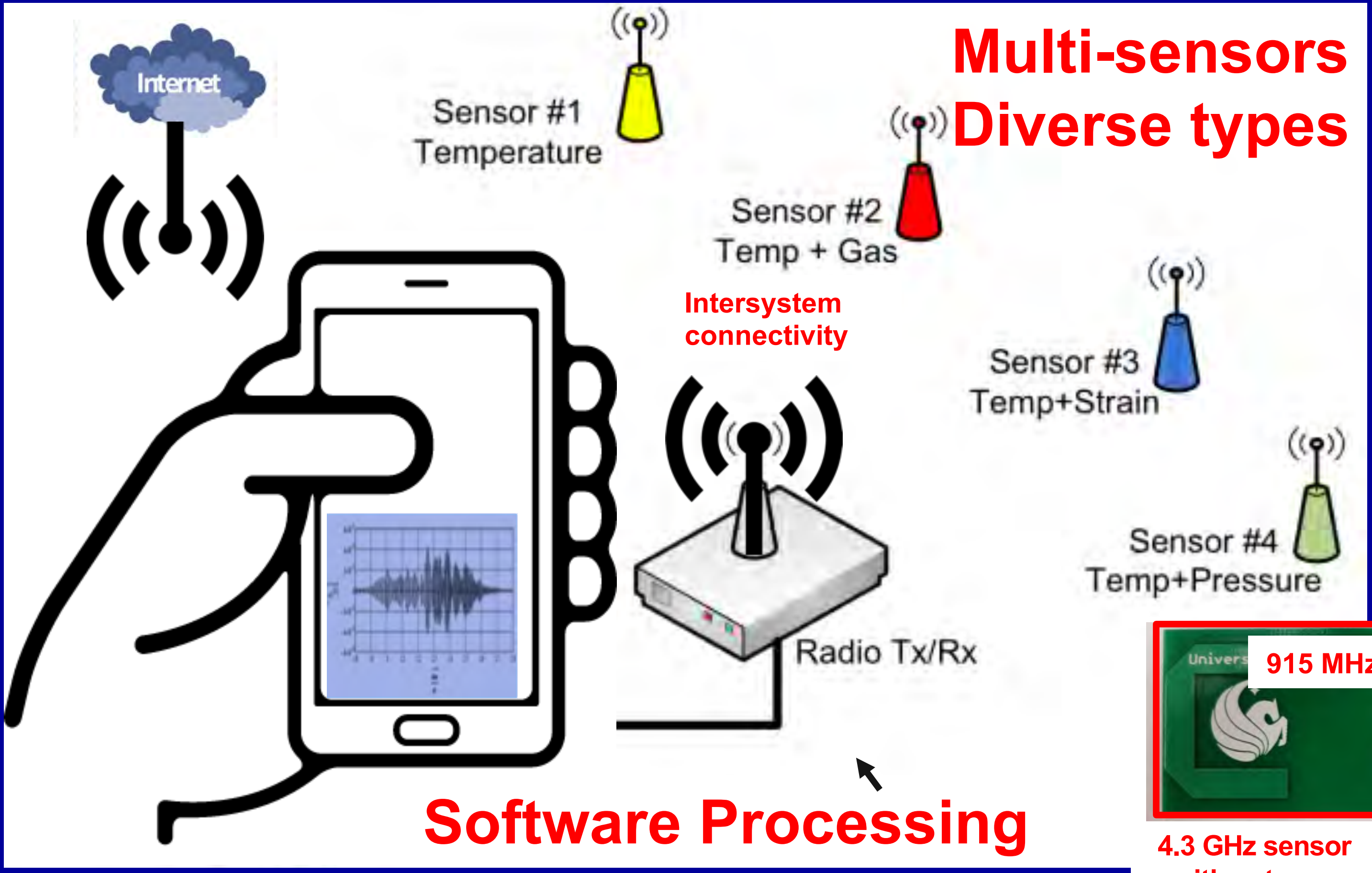
Handheld w/ processor and display display

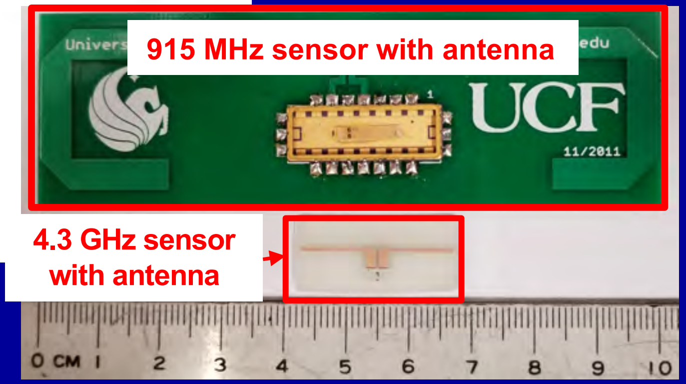
Goal: WAIC Sensor System

- Develop prototype SAW sensor system at 4.3 GHz – @ WAIC band
  - Software Design Radio (SDR)
    - Universal Software Radio Peripheral (USRP)
      - Ettus USRP, low cost, COTS, made in USA
      - Develop a 4.3 GHz, RF front-end board
      - Switchable bands over 200 MHz BW
  - SAW multi-sensor development
    - Build on Phase I demonstrations
      - temperature and strain sensors
  - Antenna integration – SAWtenna
  - Post-processing built on previous efforts and further optimized

Wireless Passive Sensor Concept

RFID Wideband Multi-sensor System in WAIC band





Sensor size contrast

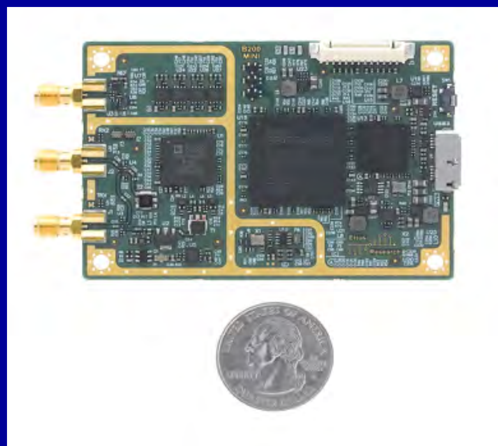
4 Major Technical Tasks

- TxRx development
  - RF motherboard design and build
  - System optimization for best range and SNR
- 4.3 GHz SAW sensor devices –temperature and strain
  - Analysis, design and fabrication
  - Integration, packaging and sensor
- Antenna and packaging
- Software
  - TxRx – FPGA control
  - Digital post processing

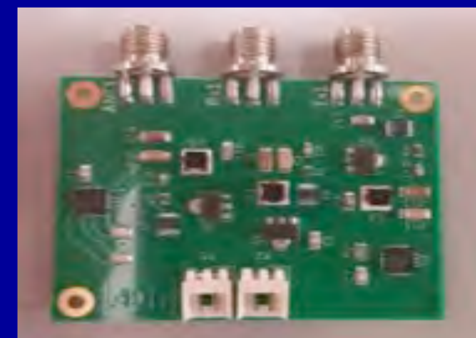
Issues to Consider

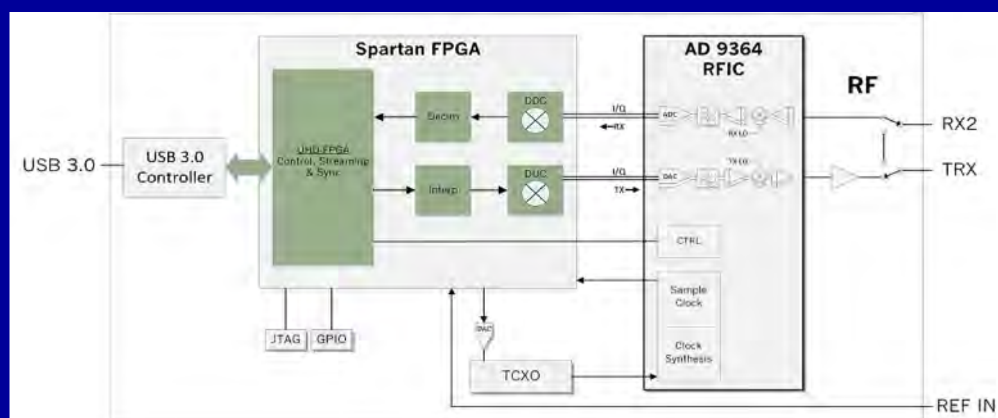
- Transceiver (SDR)
  - 4.3 GHz components
  - Output Power, range, etc.
  - Operational bandwidth – 200MHz => four 50 MHz bands
- Sensor
  - Type: SAW resonator, OFC, CDMA, mixed, other
  - Fabrication
  - Losses
- Antenna and packaging
  - Gain-Bandwidth
  - Size, polarization, PCB, on-die structures, embodiment feasibility
- Software control and post processing
- System losses, range and SNR
  - TxRx components
  - EM Path loss
  - SAW and antenna

Ettus B200mini SDR (top) and block diagram (bottom) from Ettus WEB page.



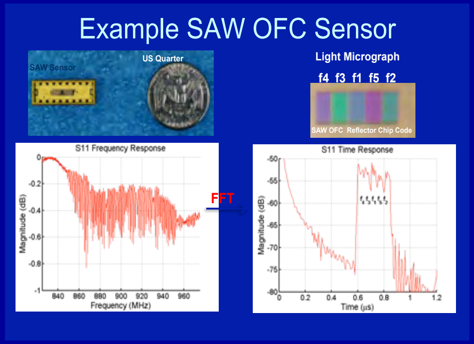
Custom designed 915 MHz RF front-end for SDR transceiver. Phase II will have similarly designed 4.3 GHz RF section.



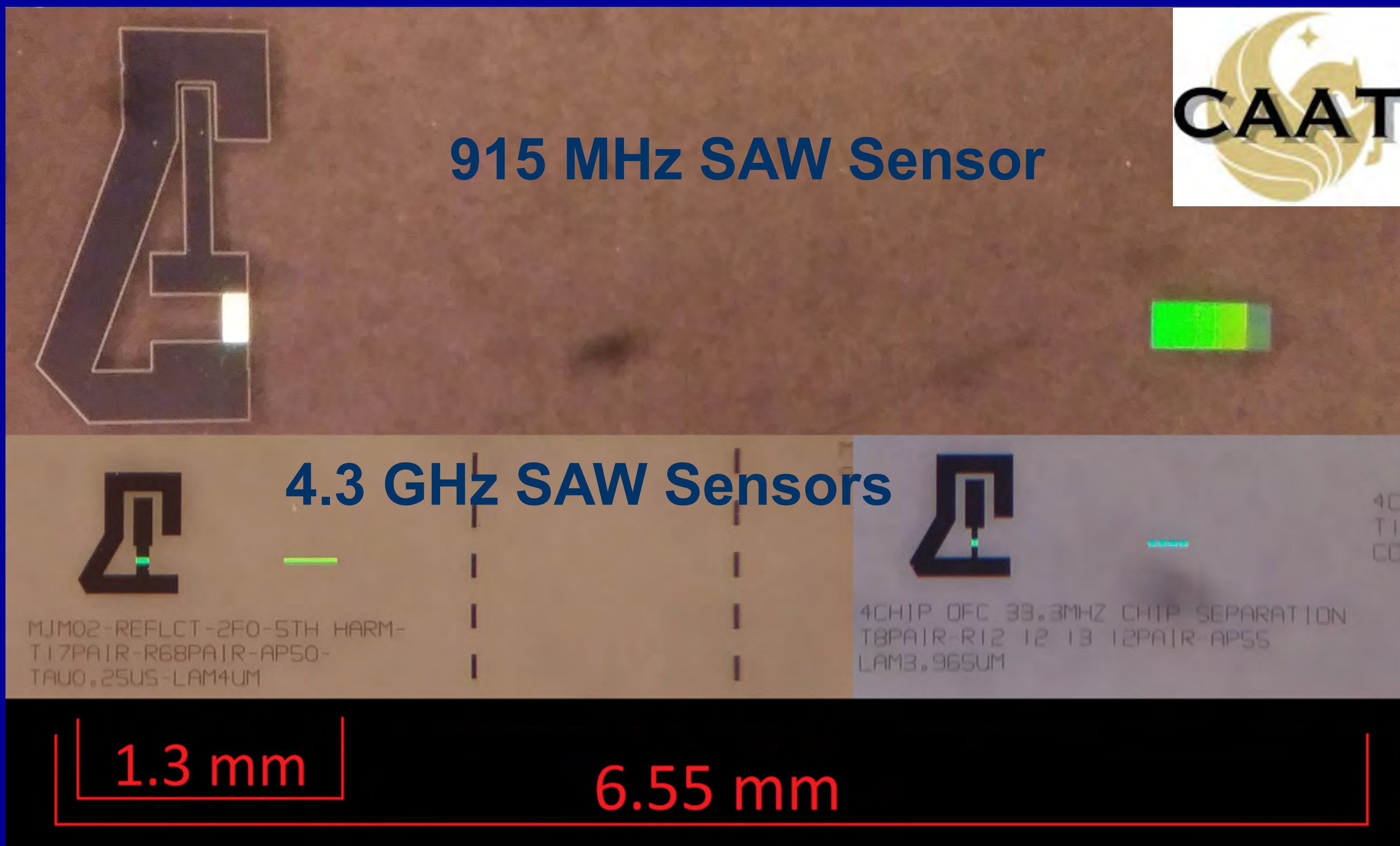


SAW Sensor Challenge

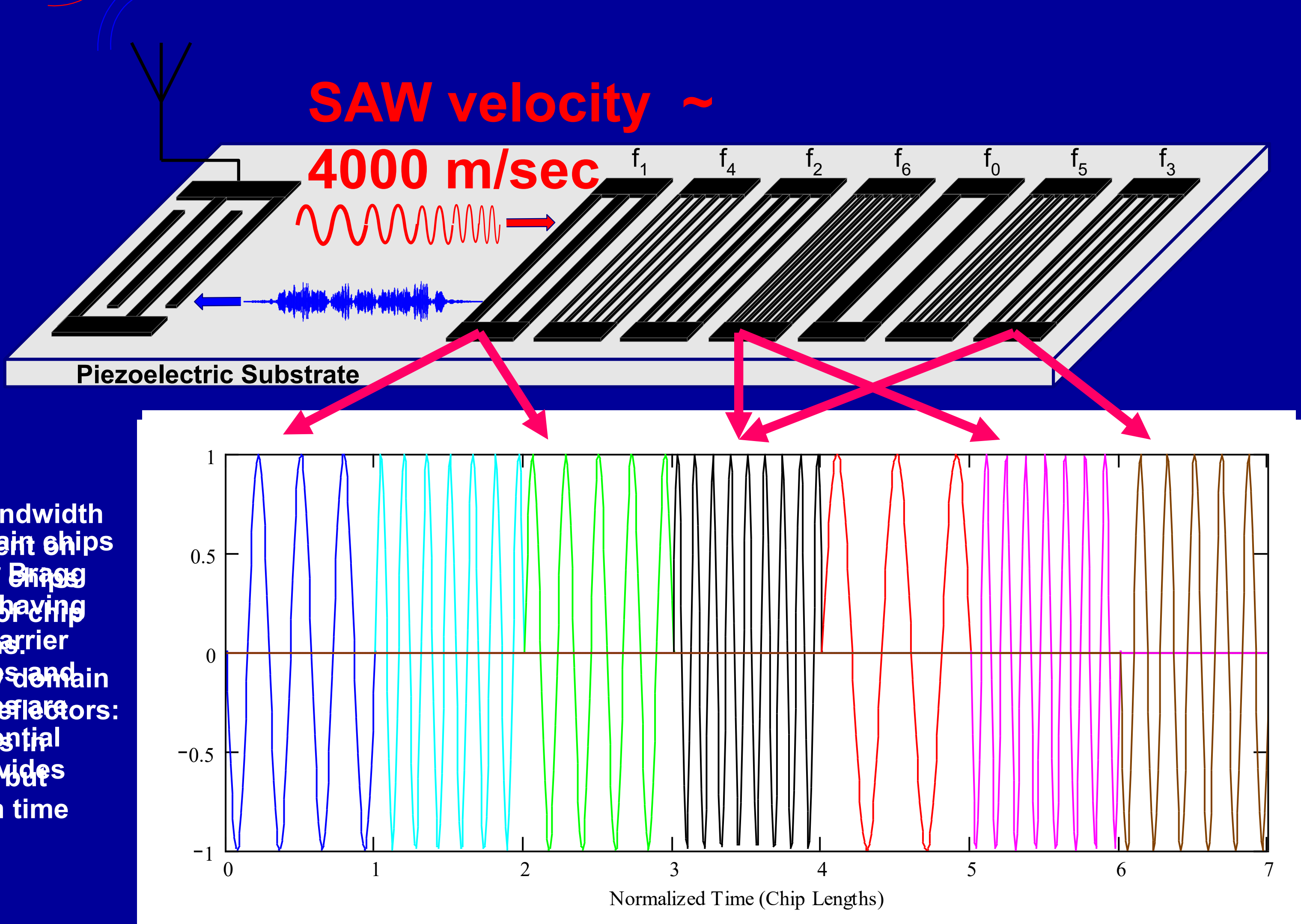
- Fabrication Approach:
  - YZ Lithium Niobate
  - Fundamental linewidth too small
  - Harmonic SAW device design
    - 3rd harmonic –
      - Line width~ 0.6um is well within commercial fab
    - 5th harmonic
      - Line width ~1 um is even better for commercial fab



Die Size Comparison:
915 MHz vs 4.3 GHz SAW Device



OFC SAW Sensor - Transduction and Reflectivity

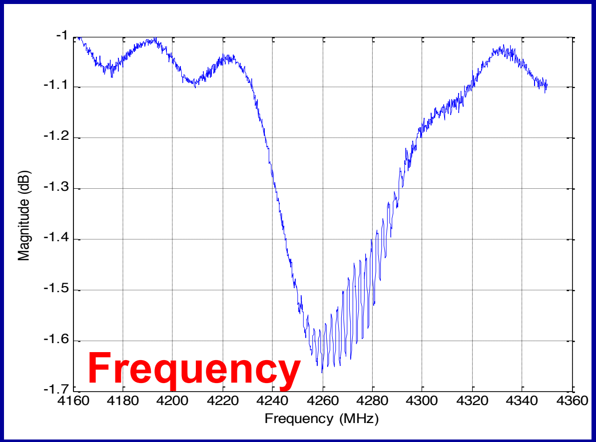


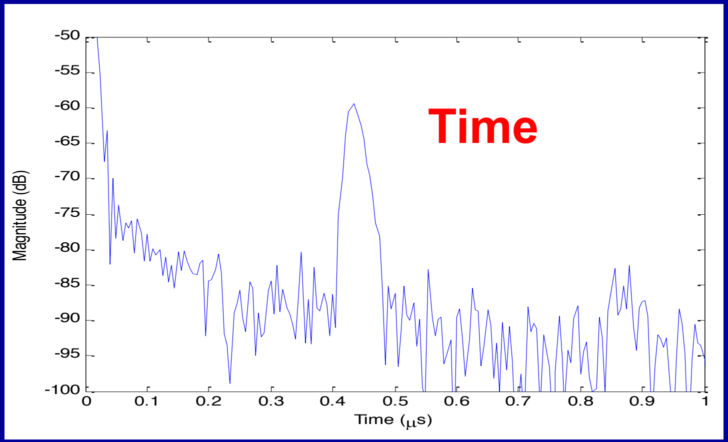
Sensor bandwidth is dependent on number of chips and sum of chip bandwidths.

Frequency domain of Bragg reflectors: contiguous in frequency but shuffled in time

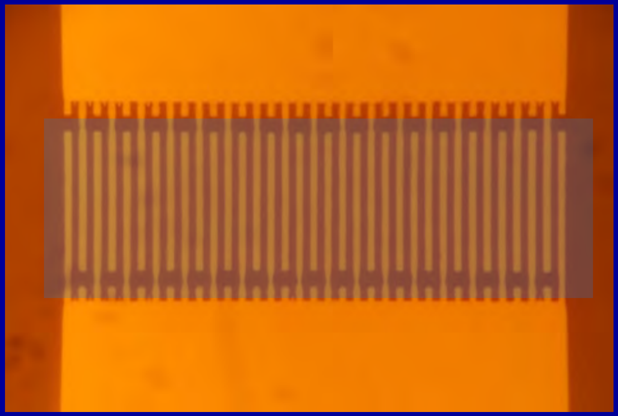
Time domain chips realized in Bragg reflectors having differing carrier frequencies and frequencies are non-sequential which provides coding

S11 Sensor Configuration Reflective Delay Line Phase I





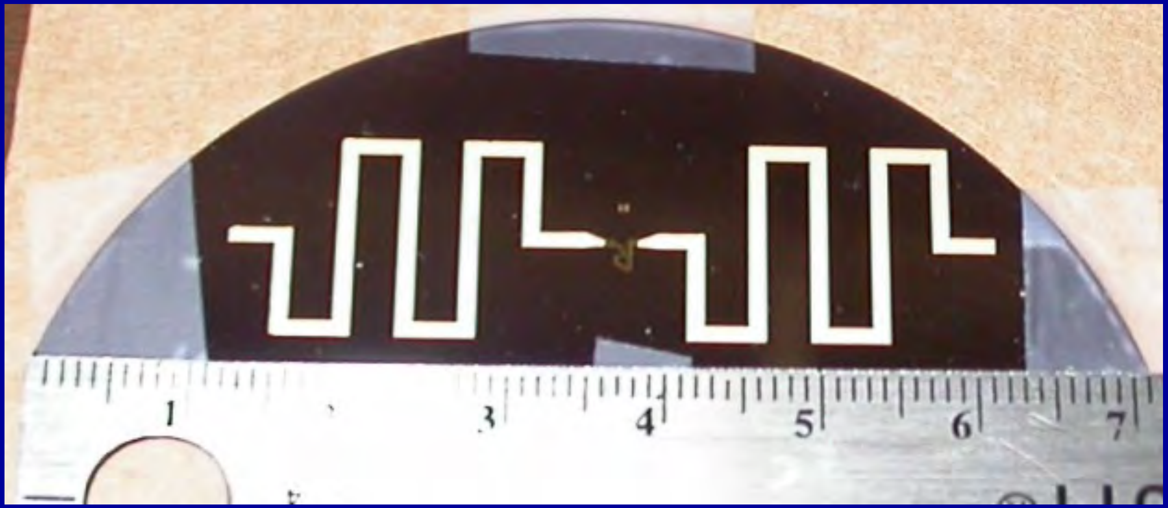
1-port Reflector response



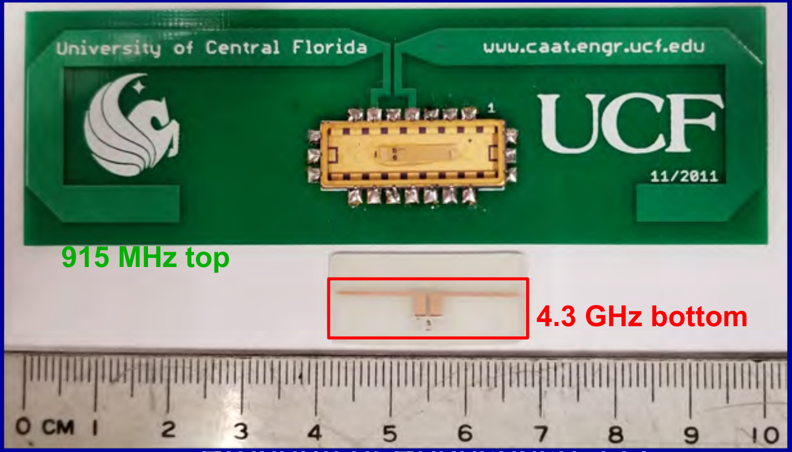
Antenna

- EM wavelength=7cm @ 4.3 GHz
- %BW=4.65 – narrow band
- Using electrically small antenna (ESA) approximation G_{ant}~10dB, for 2.5 cm
- Antenna on SAW device: G_{SAW}~20dB
- TxRx antenna larger with 30dB gain for Tx and Rx, respectively.
- Total system antenna gains: ~ 80dB

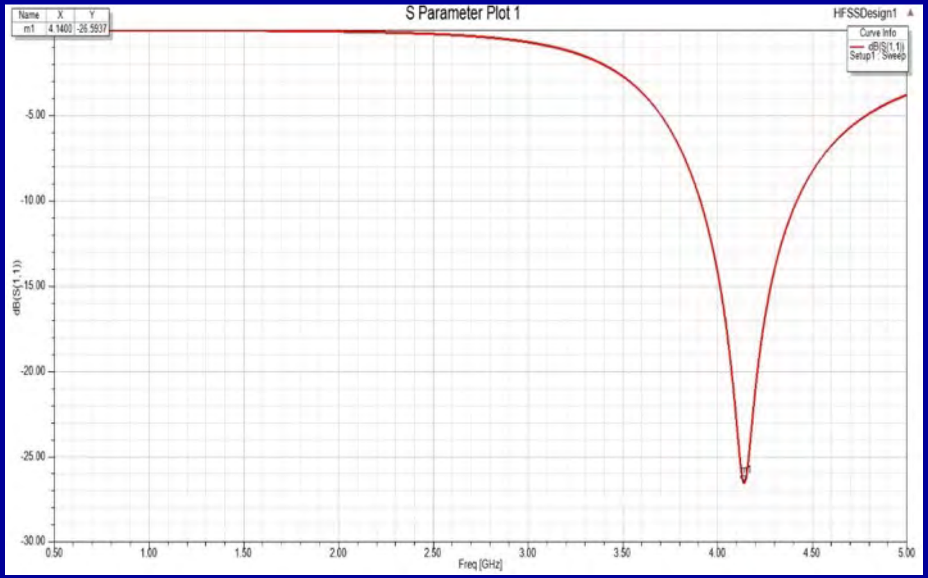
On Wafer 915 MHz SAWtenna

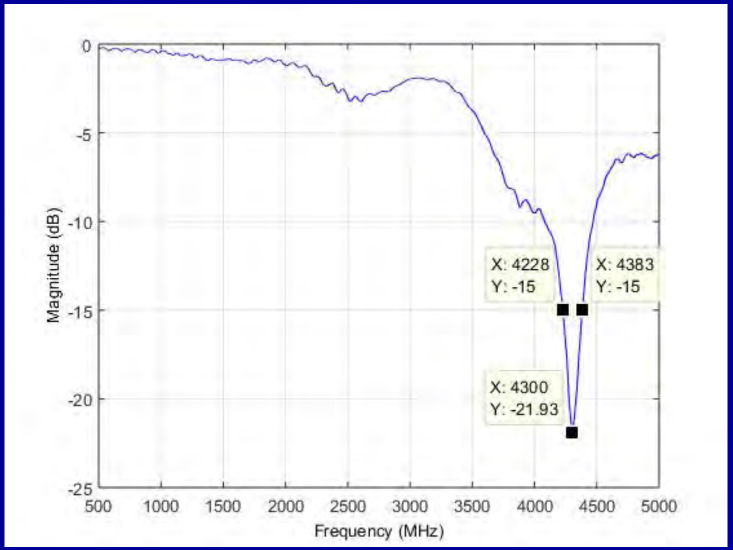


PCB Dipole Antennas



4.3 GHz PCB Sensor Antenna





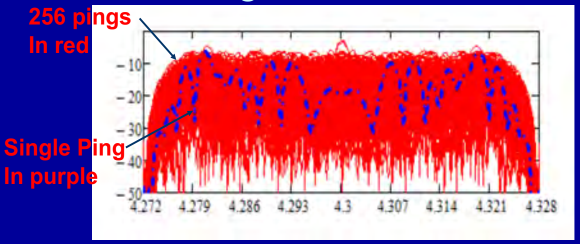
Simulated S11 for Phase I, 4.3 GHz dipole. Simulated response was adjusted for 4.14 GHz to achieve 4.3 GHz response after fabrication.

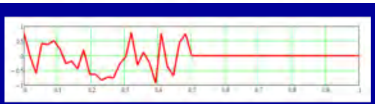
Measured S11 for Phase I, 4.3 GHz dipole. Simulated response was adjusted for 4.14 GHz to achieve 4.3 GHz response after fabrication.

Software Control and DSP

- RFID decode and optimize SNR
- Spread spectrum signal
  - Minimizes energy at any given frequency
  - Minimize interference between systems
- Noise-like interrogation signal
  - Excites all sensors every ping
- Software control of center frequency
  - Four - 50 MHz bands, 200 MHz total
  - Offers greater diversity while optimizing BW
  - Spatial+frequency isolation
- Synchronous control and integration

Random number generation in simulating Tx FPGA to DAC





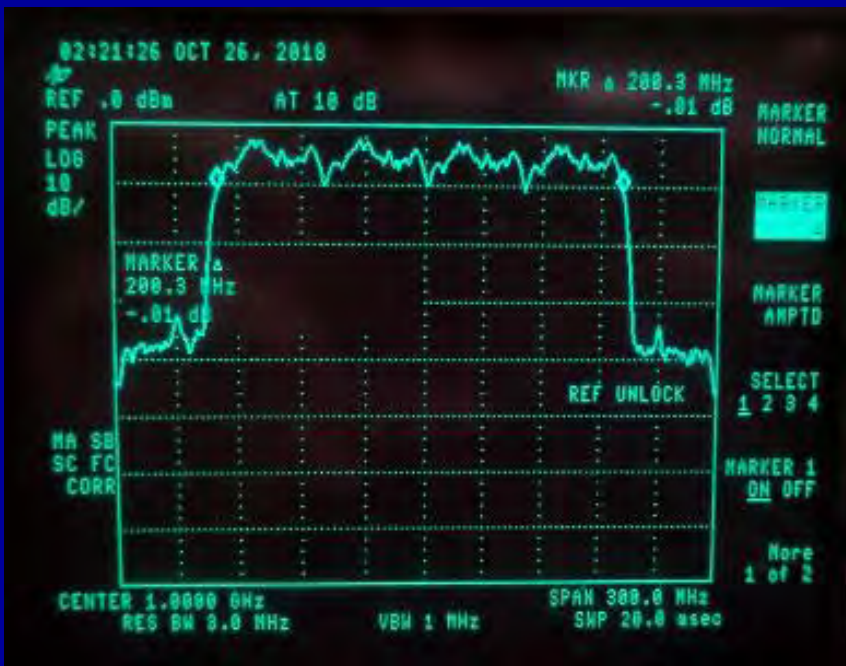
Single ping in time domain at baseband

Multi-Band Software Defined Radio Sensor System

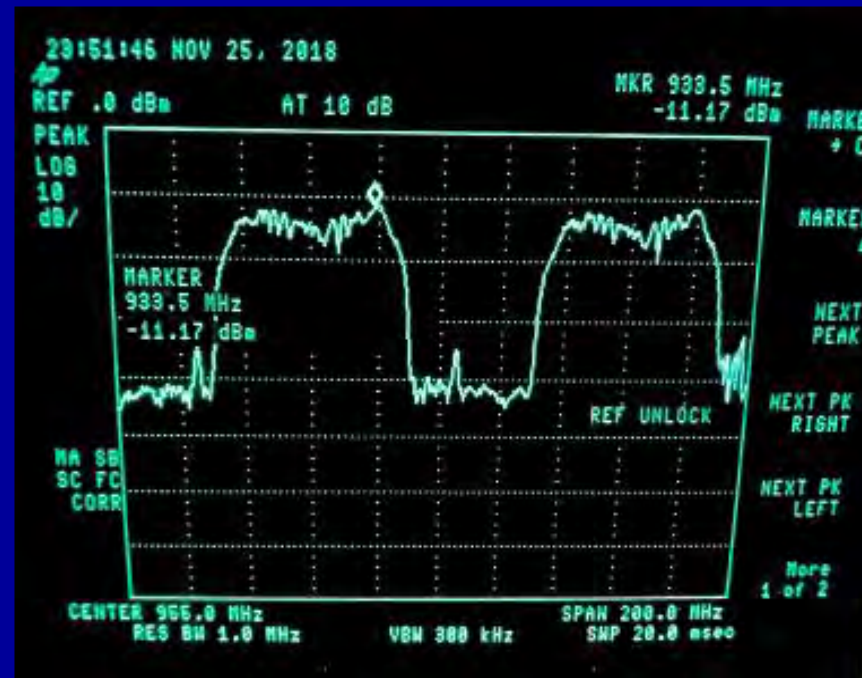
- Agile multiband transceiver for reconfigurable sensor systems
- Simultaneous wireless interrogation of multiple passive sensors operating in user-defined frequency bands.
- Transceiver architecture allows adding or removing sensors, via software modification, without any hardware changes
- Diverse wireless sensor technologies can be employed:

  SAW, BAW and dielectric resonators, SAW OFC sensors, etc.
- Sensors simultaneously measuring different physical quantities, such as temperature, strain, pressure, radiation, hydrogen, etc., at differing bands and embodiments

Frequency hopping examples:
Peak_Sweep_Hold spectrum at the USRP Tx port

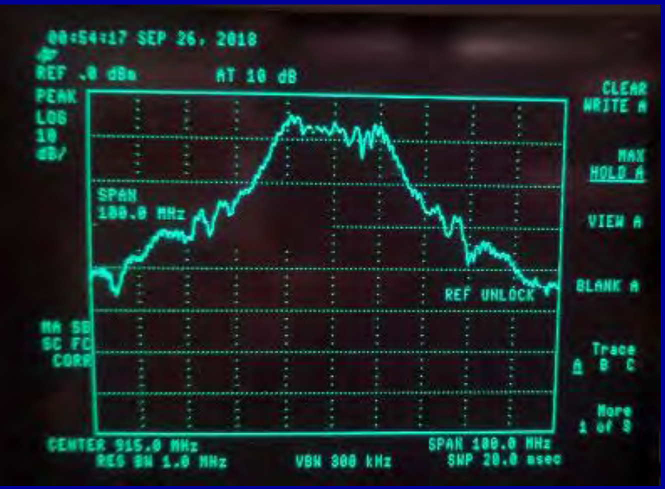


Adjacent bands,
overall bandwidth = 200MHz

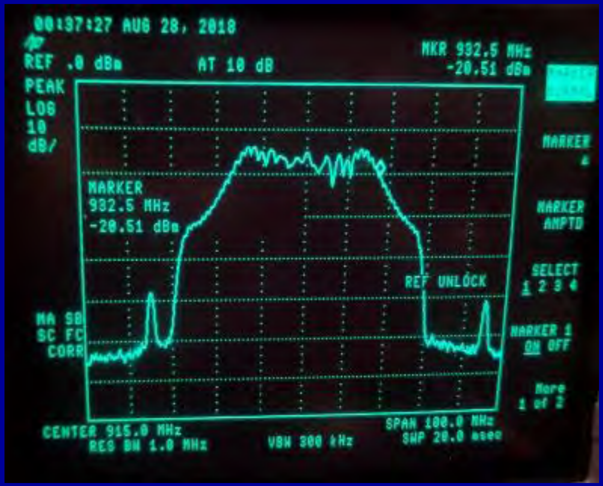


Two bands 915 MHz and 1015 MHz

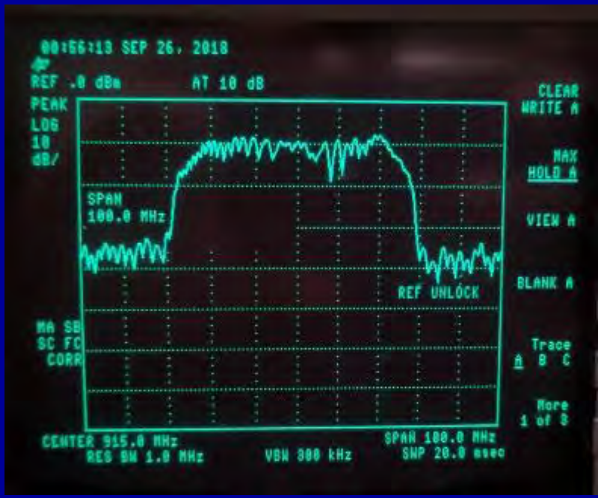
Variable bandwidth examples: Peak_Sweep_Hold at the USRP Tx port



25 MHz bandwidth

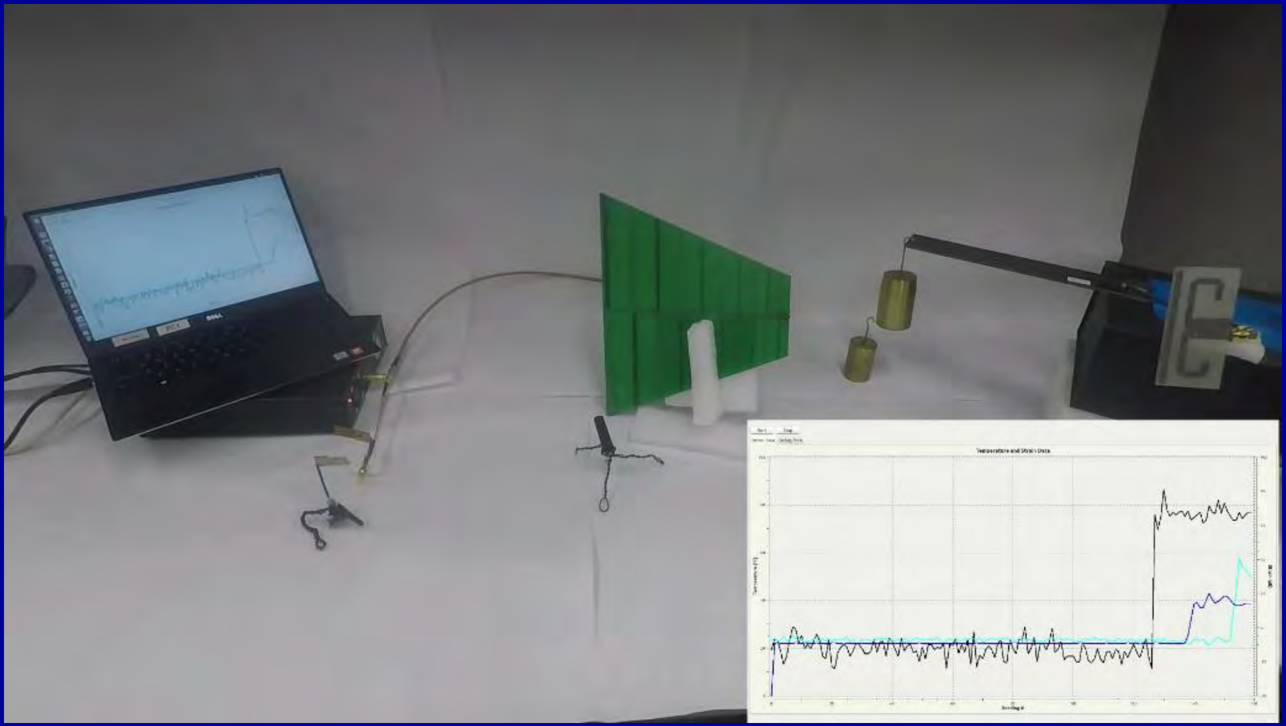


35 MHz bandwidth



50 MHz bandwidth

Three band operation: temperature and strain measurements



Test setup with the measurement screen showing measurements results over time: black – 915MHz strain sensor, light blue – 433MHz temperature sensor, dark blue – 2.55 GHz temperature sensor

Acoustoelectric (AE) Amplifier
65 years of R&D

- **1953 – AE effect first discussed,** **Parmenter, R. H. (1953). "The Acousto-Electric Effect", Physical Review.**
- **1961 – AE amplification,** **Hutson, A. R. and McFee, J. H. and White, D. L," Ultrasonic Amplification in CdS", Phys. Rev. Lett.**
- **1969 - combined medium amplifier and the separated medium amplifier,** **K. M. Lakin and H. J. Shaw, "Surface Wave Delay Line Amplifiers," in IEEE Transactions on Microwave Theory and Techniques.**
- **1969 to present – 100's of publications on AE effect and amplification.**
- **2012 – AE effect in graphene,** **V. Miseikis, J. E. Cunningham, K. Saeed, R. O'Rorke, and A. G. Davies, "Acoustically induced current flow in graphene." Appl. Phys. Lett.**
- **2019 – 9.8 dB asymmetry between forward/reverse AE wafer bonding,** **S. Ghosh, "FDSOI on Lithium Niobate Using Al2O3 Wafer-Bonding for Acoustoelectric RF Microdevices," 2019 20th International Conference on Solid-State Sensors, Actuators and Microsystems & Eurosensors.**

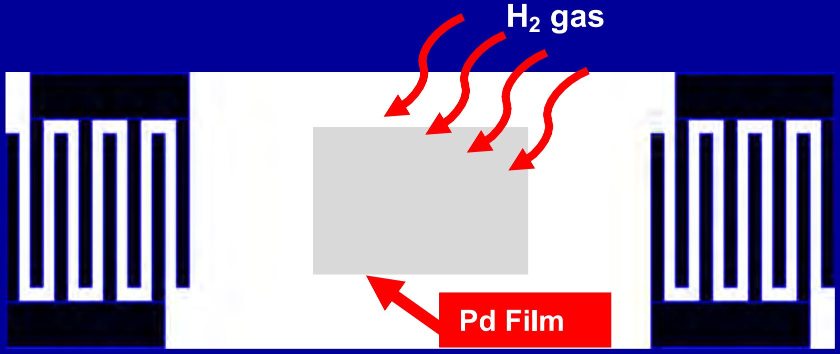
Elusive Properties of a SAW AEA

- **Manufacturable and scalable to high volume**
- **AEA insertion gain**
- **CW operation**
- **Low DC bias power**
- **Monolithic**
- **Low cost**
- **High frequency operation**
- **Low noise**

Acoustoelectric Effect

Passive Attenuation Mode

Responds to gas via film resistivity change



Optimized film shows huge attenuation

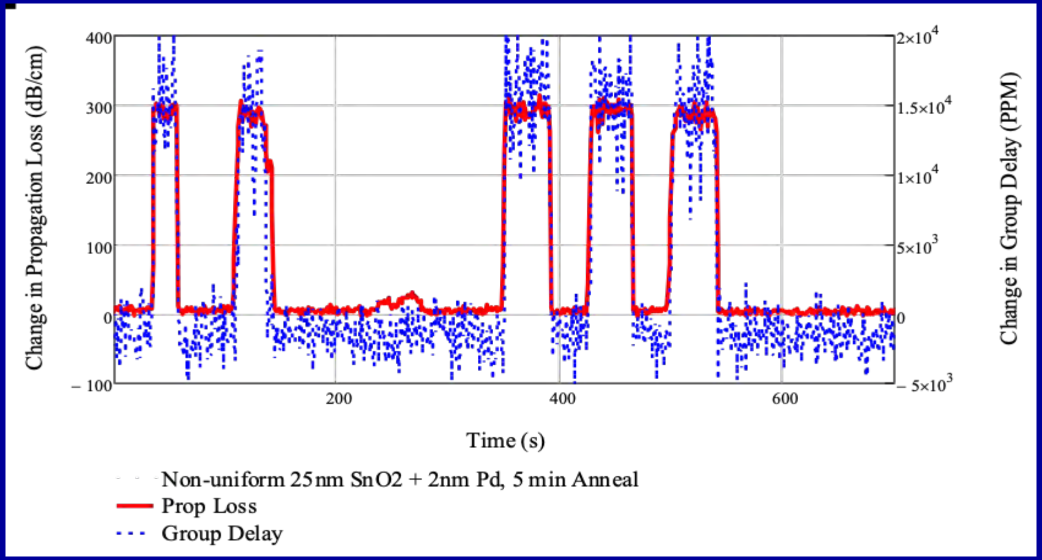
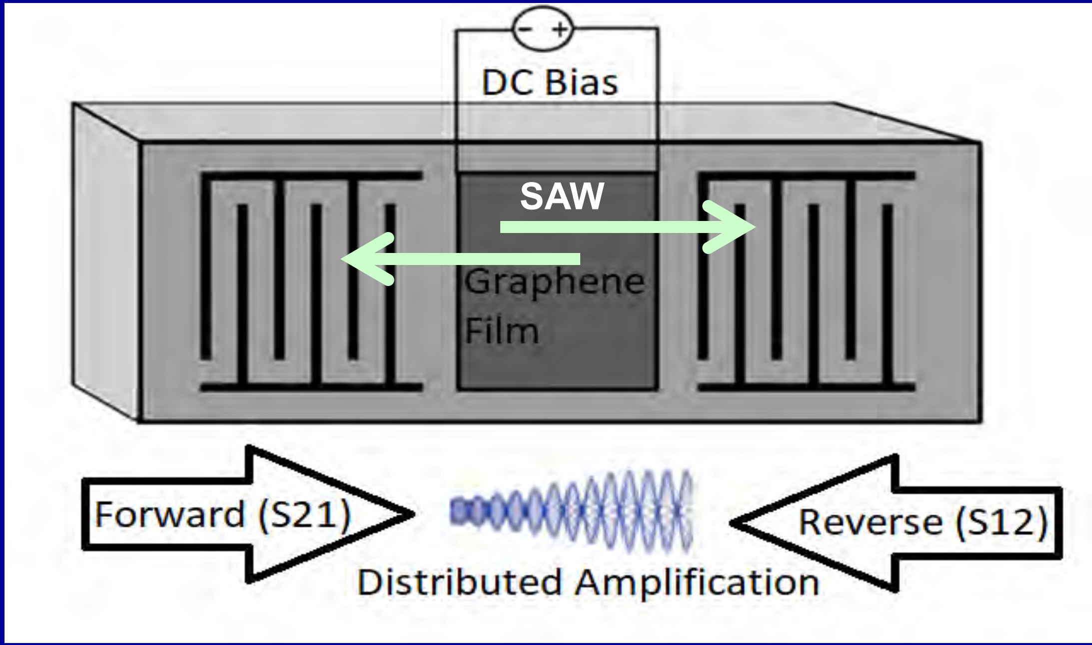


Figure shows the propagation loss and group delay change when a non-uniform 25nm SnO_2 +2nm Pd film is exposed to H_2 gas. The film is annealed for 5 minutes. The group delay increase during H_2 exposure because the wave velocity slows due to the decrease in sheet resistance toward the short circuit case.

B. Fisher PhD Thesis, 2012

Acoustoelectric (AE) Amplification

SAW S21 = forward gain

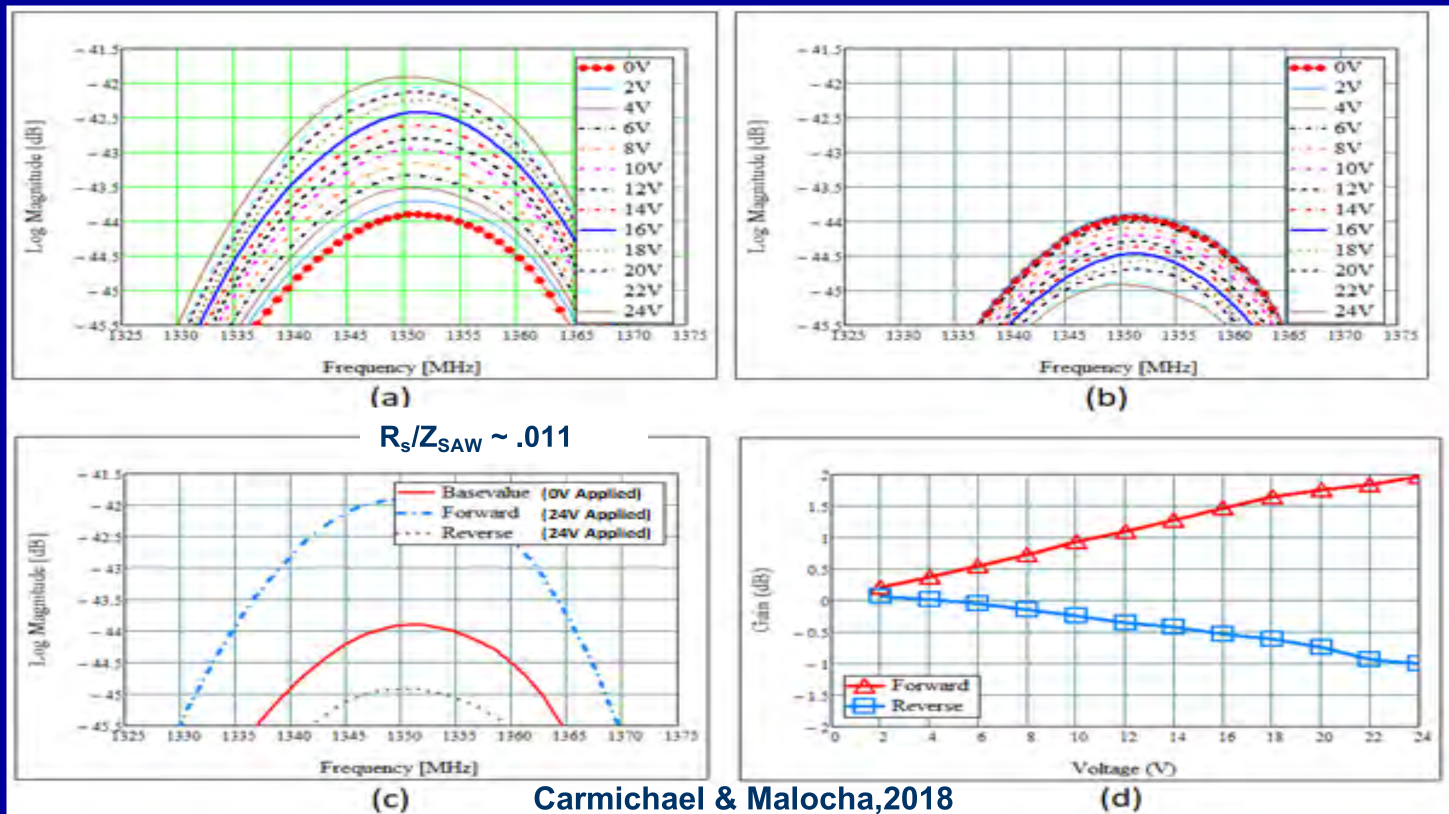


SAW S12 = reverse gain

Schematic of a simple SAW delay line with an AE amplifier using graphene film.

- **Coupling between the thin film surface charge and the travelling SAW potential.**
- **Asymmetric gain in opposite SAW propagation directions.**

Measured forward and reverse gain (in dB)



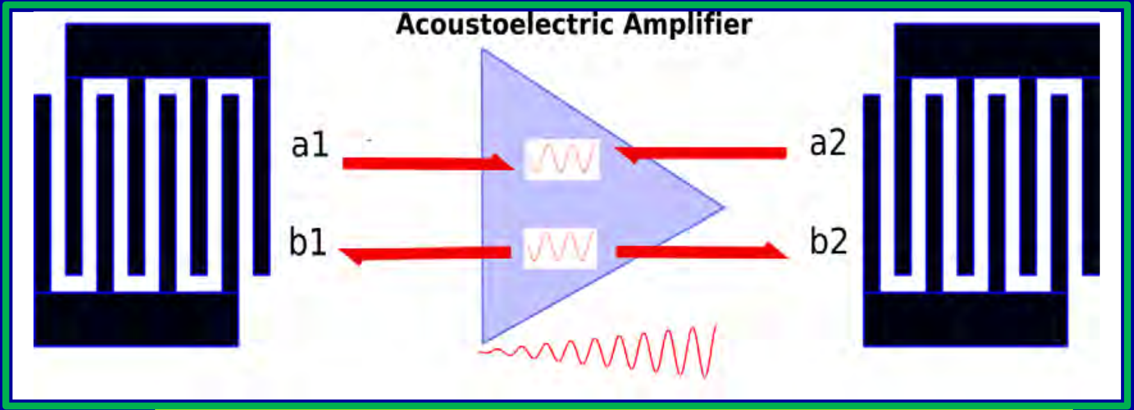
(a) Forward SAW frequency response with varying applied DC field to graphene film, (b) Reverse SAW frequency response with varying applied DC field to graphene film, (c) Forward and Reverse SAW frequency responses with 0V and +24V applied to graphene film, (d) Plot of the forward and reverse SAW peak value versus applied DC voltage to graphene film.

- 128-LN wafers, k^2=0.056, v_{SAW}=3980m/s.
- Acoustic beam width:~132 lam. @1.35GHz
- AE film: 0.864 mm length by 0.39mm width
- Film sheet resistance ~5 kohms/square.

Acoustoelectric Amplifier (AEA) with 3.6 dB Insertion Gain

168 MHz Delay Line, Monolithic, CW operation

128 Lithium Niobate, P_{DC}~86 mW

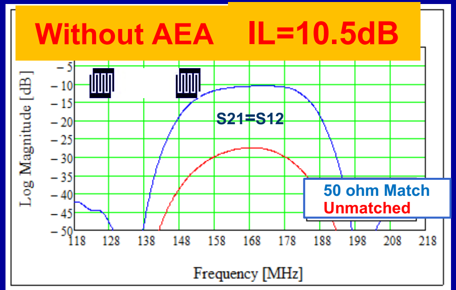


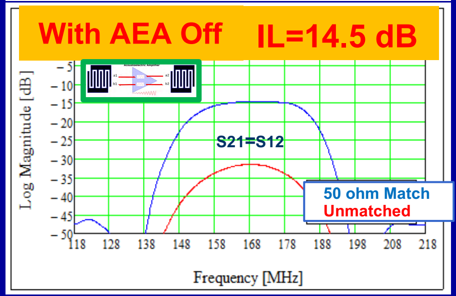
AEA Insertion Gain = 3.6 dB

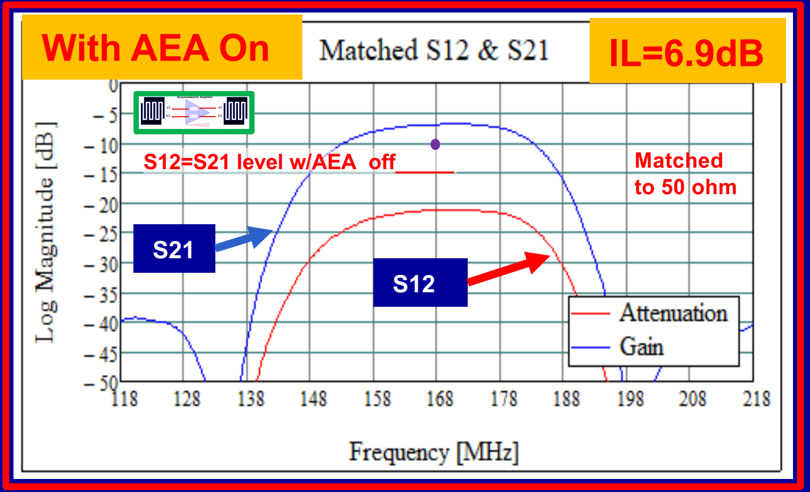
S21=7.6dB **S12=-6.7dB**

S21/S12=14.3dB

Measured Data







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Pegasense, LLC
Patent Pending

New AE Embodiment

- New SAW active components
  - SAW filters with gain
  - Programmable correlators
  - Integrated oscillators
- NEW passive SAW embodiments
  - Opens new material opportunities
- Other type of acoustic mode amplification

WAIC SAW SDR System and New Technology

Opportunities for:

1. Research
   - Transceivers
   - Sensors and Devices
   - Materials
   - Antennas
   - Systems & Networking
2. Development
3. Commercialization