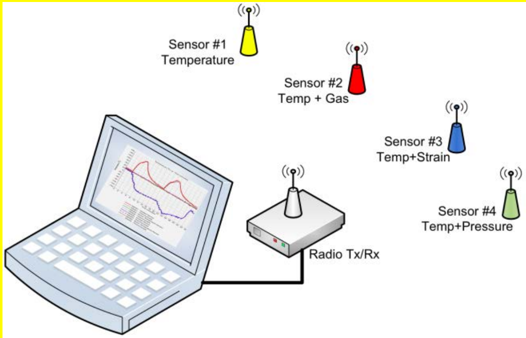
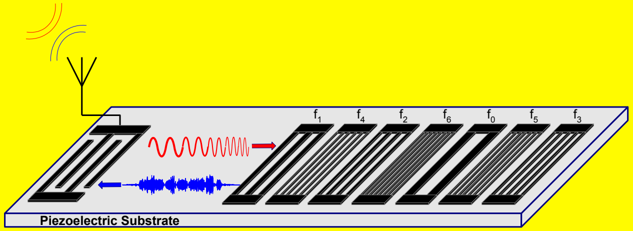
Passive RFID Wireless Sensor Technology





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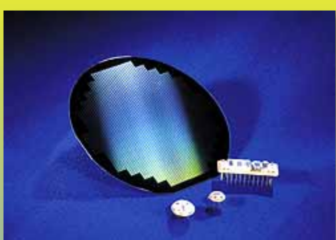


- Approximately 4-5 billion SAW devices are produced each year
- If you have a cell phone, you own multiple solid state acoustic devices

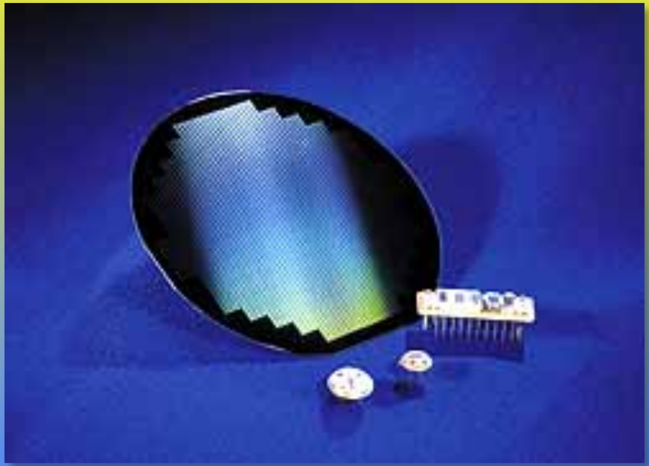
CAAT

2016 IEEE RFID COnference

May 3-5, 2016 Orlando, FL.

What is a Surface Acoustic Wave Device

- A solid state device
  - Converts electrical energy into a mechanical wave (~4000m/sec) on a high-Q, low-loss, single crystal substrate
  - Provides very complex signal processing in a very small volume
- Approximately 4-5 billion SAW devices are produced each year



Applications:

- **Cellular phones and TV (largest market)**
- **Military (Radar, filters, advanced systems**
- **Currently emerging – sensors, RFID**

Motivation: Multiplexed, Wireless, and Passive SAW Sensors

This work originated in 2002 with a Shuttle request for passive sensors that could be located under the Shuttle tiles and accessed wirelessly. These sensors would have to survive in space and reentry. No applicable technology existed, so an STTR program was established to seek solutions.

Several universities tried to solve this problem, but the best approach came from the University of Central Florida (UCF) who advocated surface acoustic wave sensors and demonstrated an orthogonal frequency code (OFC) wireless multiplexing scheme in 2005. We at KSC decided to support this SAW approach.

See NASA Tech Brief on SAW Sensor

Jim Nichols – KSC/NASA
Licensing Manager
NASA Techbriefs Webinar
Sept 19, 2013

UCF CAAT Sensor Research since 2004

<u>Major Student Fellowships:</u>

5- GRA Research Program
Fellows: = $410K

2- McKnight: = $160K

1-NSF:= $65K

2-FSGC: = ~$40K

<u>18 Contracts:</u>

9 - STTR/SBIR Phase I = $410K

7- STTR/SBIR Phase II = $1.92M

2 – DoD = $1.13M

Other = $750K

<u>7 – UCF Patents</u> on SAW based sensors and systems & several pending

NASA Tech Briefs

Monday, 01 December 2014

Named in NASA's Hot 100 Technologies: Sensors

Coherence Multiplexing of Wireless Surface Acoustic Wave (SAW) Sensors

This integrated, multi-sensor network quickly identifies gaseous leaks in extreme environments in ground systems, spaceflight, and space exploration by utilizing a chemical sensing film located on a piezoelectric substrate that wirelessly transmits the data collected through pairs of antennas located on the sensor. The multiplexed system is unique because it allows multiple sensors to communicate simultaneously without incurring degradation through returning signal echoes. www.techbriefs.com/2014NASA100/AcousSens

Activity at UCF Center for Advanced Acoustoelectronic Technology (CAAT)

- RFID and Sensors
  - Orthogonal frequency coded SAW RFID concept
  - Developed adaptive matched filter, synchronous coherent transceiver concepts
  - Demonstrated first 915 MHz SAW multi-sensor system and continually refining
  - Demonstrated physical, gas, liquid, cryogenic and high temperature sensor embodiments

Why SAW Passive Sensors?

- A game-changing approach
- Wireless, “infinite-life”, and multi-coded
- Single communication platform for diverse sensor embodiments
- Broad frequency range of operation and range (.25-2.5 GHz)
- Many different embodiments
- Can operate over large temperatures, radiation hard and robust in harsh environments
- Semiconductor **(Si)** can not function or meet requirements
- Multiple sensor operations on a single chip
  - Physical
  - Gas
  - Liquid

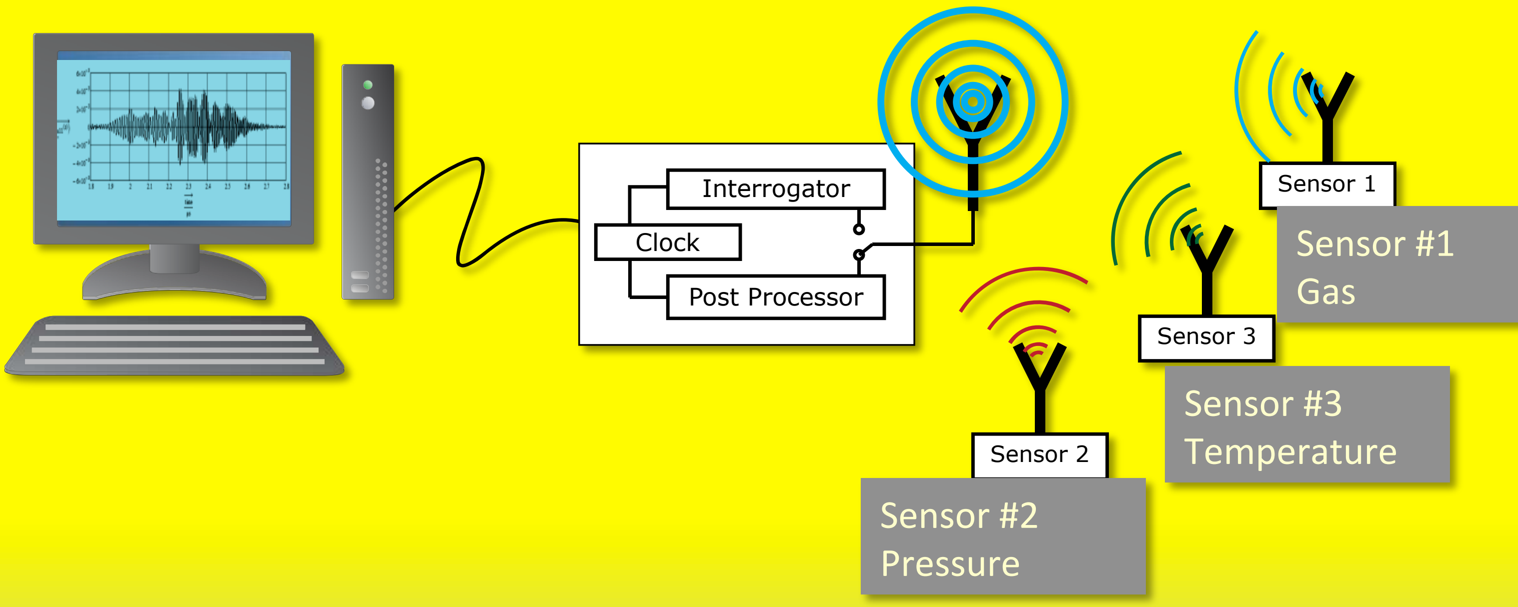
Applications

Reduces wire, installation, weight, maintenance, etc.

- NASA & Aerospace
  - Space vehicles
  - Space Exploration
  - Space Habitats
  - Satellites
  - Helicopters
  - Plane wings & fuselage
  - Structural health monitoring
- Commercial/Industrial
  - Energy conservation
  - Power grid
  - Motors
  - Rotors
  - Structural health monitoring – bridges, roads, building
  - Transportation
  - Oil fields

The Goal

Basic Passive Wireless SAW System



Basic Goals:

- Interrogation distance: 1< range < 1000 meters
- # of devices: 2 – 100's - **coded and distinguishable at TxRx**
- Single platform and TxRx for <u>differing</u> sensor combinations
- Can operate over a wide temperature range.

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Licensing Manager
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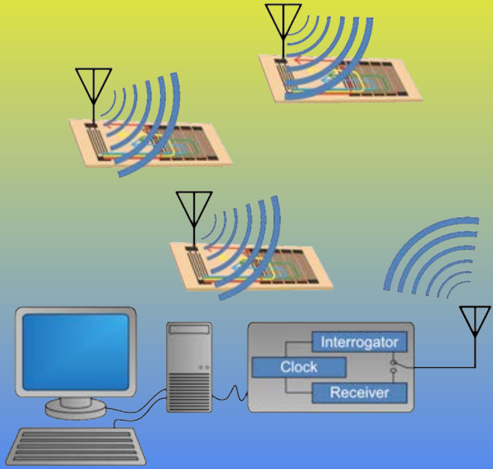
- Can operate over large temperatures, radiation hard and robust in harsh environments
- Multiple sensor operations on a single chip
  - Physical
  - Gas
  - Liquid
  - other



Confluence of Technology

- **RF receiver technology – fast, small & cheap**
- **Digital Hardware – fast, small & cheap**
- **Post-processing – fast, small & cheap**
- **SAW design, analysis and simulation**
- **SAW sensor embodiments**
  - **On-board sensors**
  - **Off-board sensors**

SAW Advantage
Size, Cost Performance

$V_{SAW} \approx 3000\ m/sec$ $\qquad$ $V_{EM} \approx 3 \times 10^{8}\ m/sec$

$$\frac{V_{SAW}}{V_{EM}} \approx \frac{3 \times 10^{3}}{3 \times 10^{8}} = 10^{-5}$$

$$\lambda f = \upsilon$$

λ vs f

	f = 10MHZ	f = 1GHZ
λ_{SAW}	$300\,\mu m$	$3\,\mu m$
λ_{EM}	$30 m$	$.3 m$

τ_D vs LENGTH $\qquad$ τ_D = time delay

FOR $\tau_D = 20\,\mu sec$ $\qquad$ $L_{SAW} \approx 6 cm = 2.4''$

$L_{COAX} \approx 6000 m = 3.75 mi.$

Four Principal SAW Properties

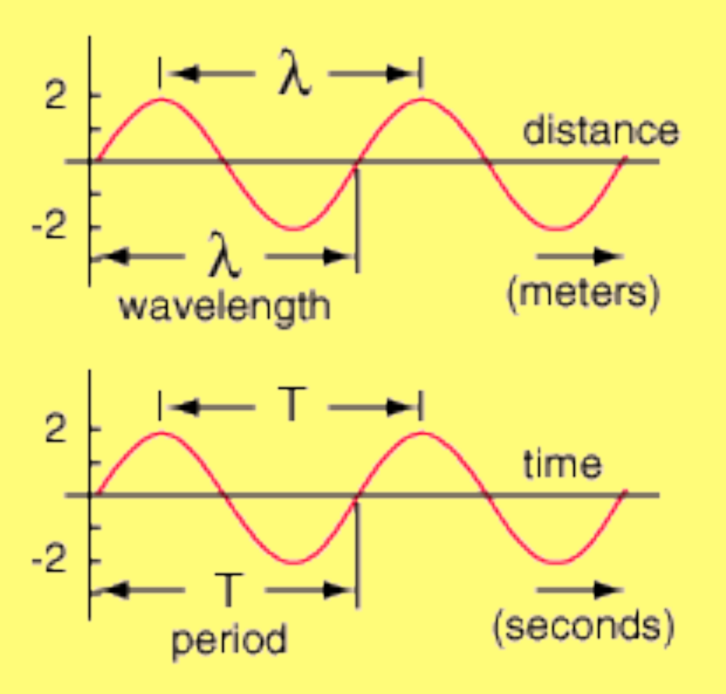
- _ *Transduction*
- _ *Reflection*
- _ *Re-Generation*
- _ *Non-Linearities*

- All SAW devices implement or exhibit one or more of these fundamental acoustic/ electrical properties

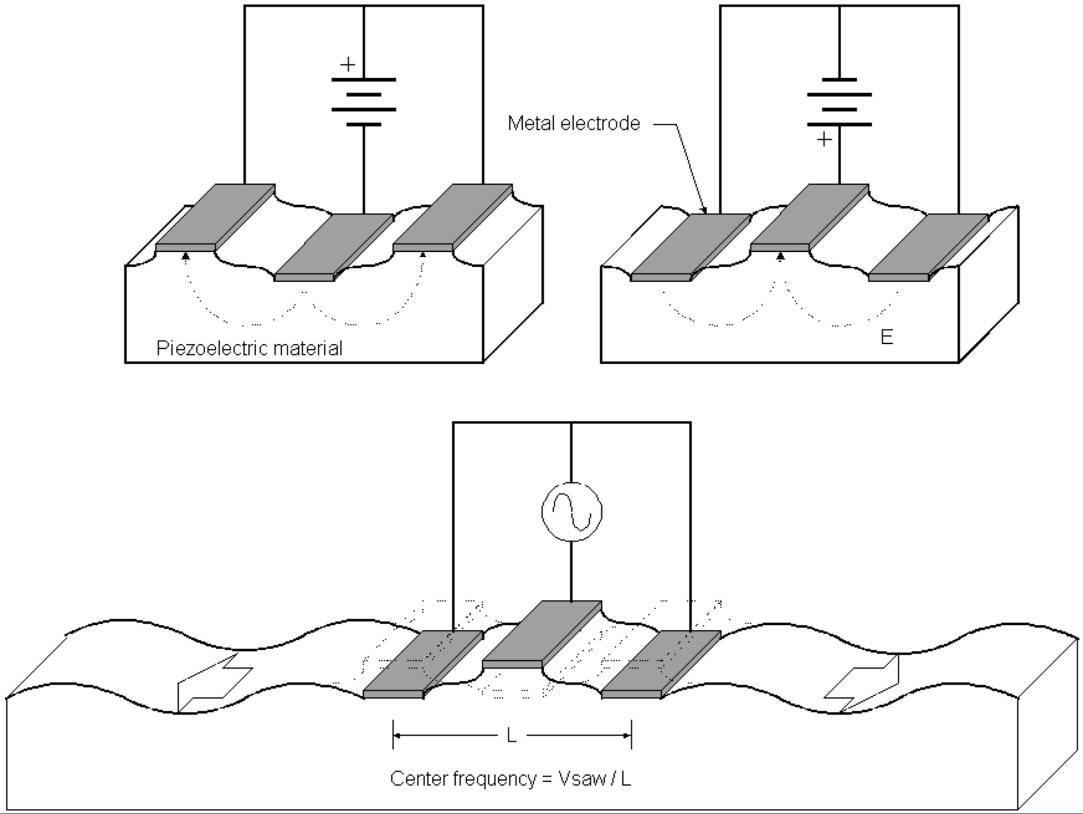
Basic Operation of a SAW Electromechanical Transducer

Velocity*time=distance

Velocity=distance/time= λ/T

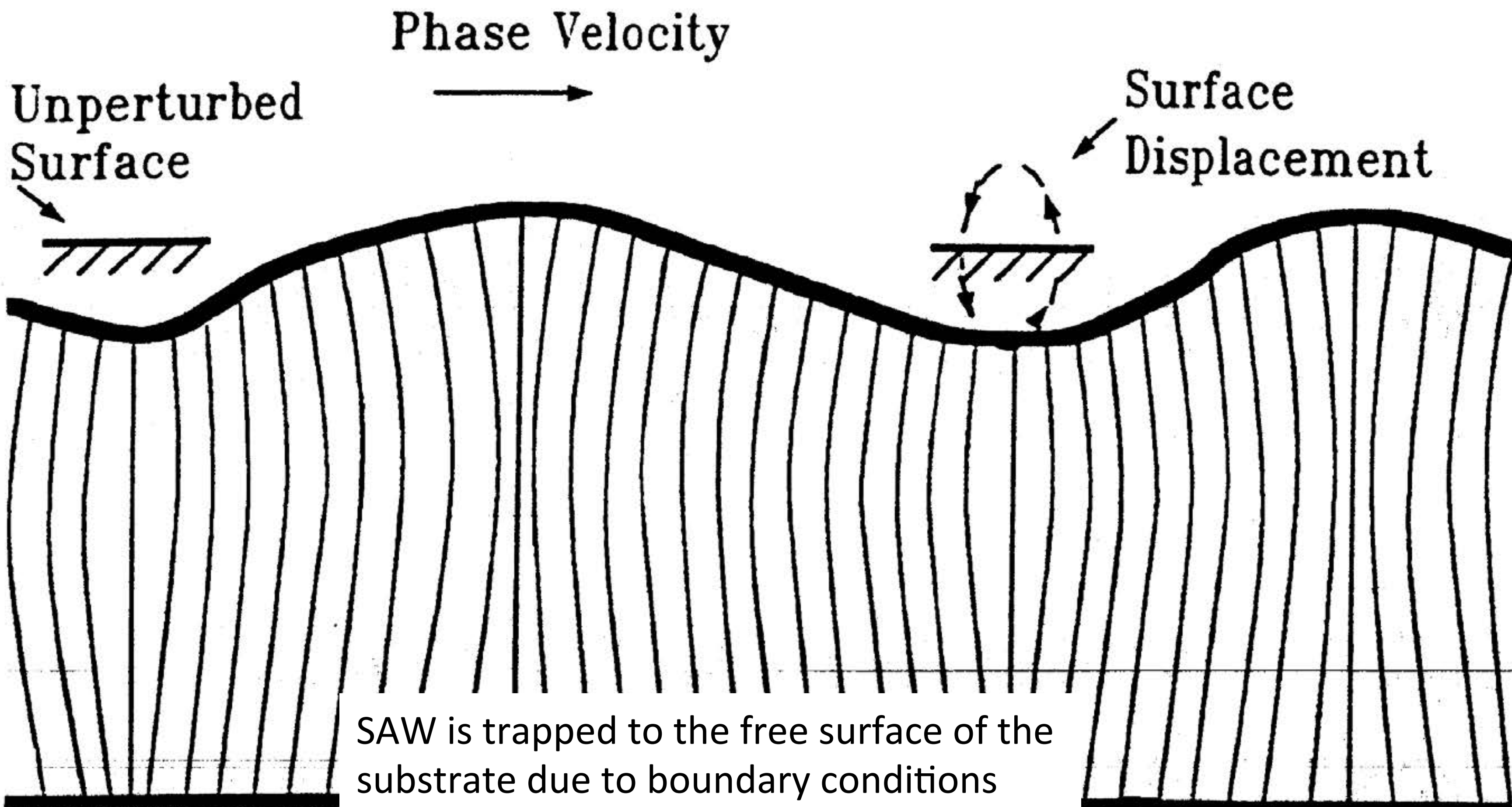


A SAW transducer is a mapping of time into spatial distance on the substrate



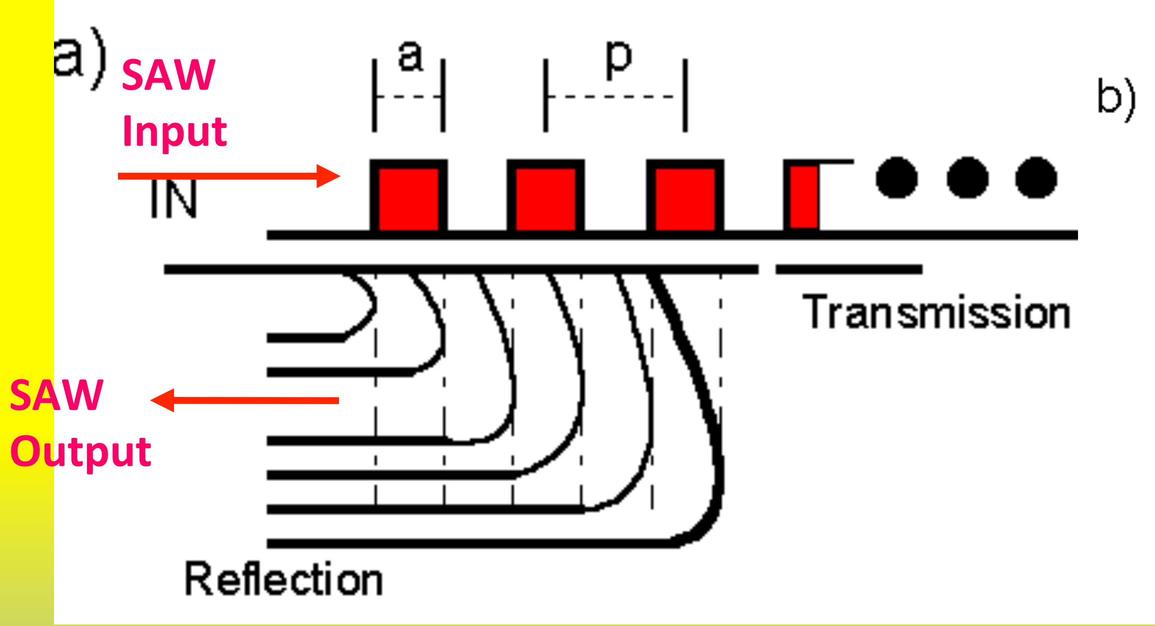
What is a SAW?

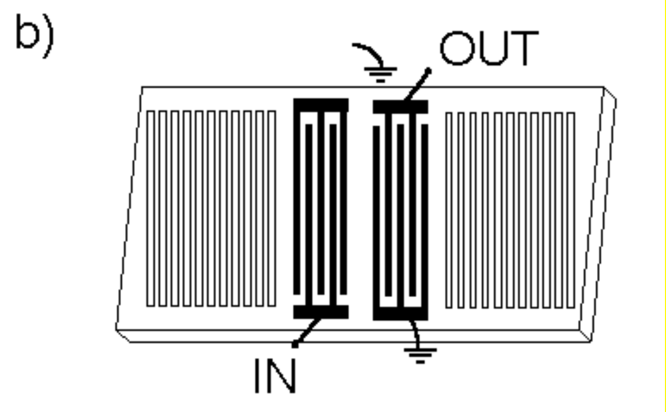
Surface Wave Particle Displacement



SAW is trapped to the free surface of the substrate due to boundary conditions

Basic Operation of a SAW Reflector Array



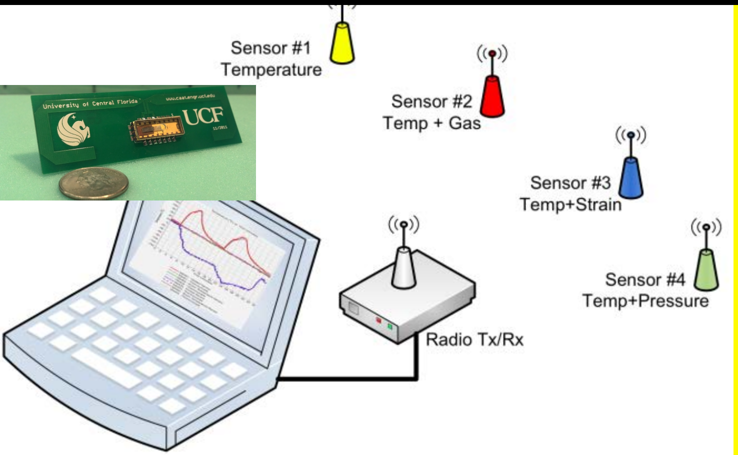


SAW 2 port resonator

With ¼ wavelength electrodes, all reflections add in phase (synchronous) which makes a distributed reflector. This is an acoustic mirror. Perturbation at each electrode is small which minimizes losses and mode conversion (BAW generation)

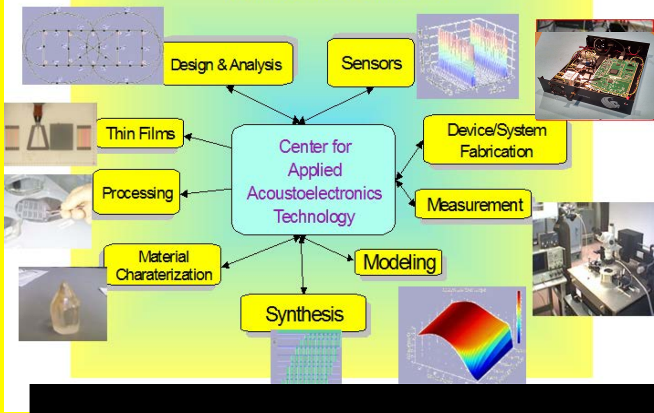
UCF Acoustic Sensor Rapid Protyping and Test

Wireless Multi-Sensor Concept



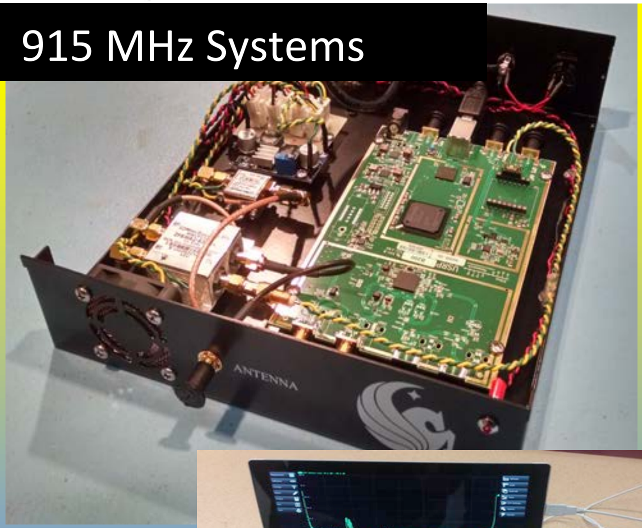
Highlights

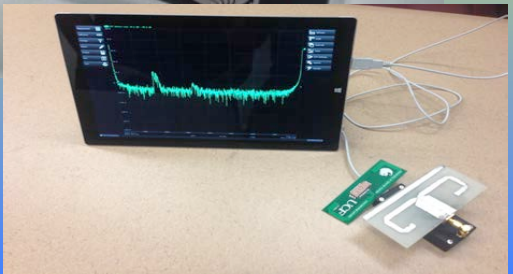
- Solid state
- Piezoelectric
- Freq: 0.1 – 2.4 GHz
- Temp: 0.1 – >1000K
- Filters, correlators, & sensors
- RF systems and device development



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

915 MHz Systems





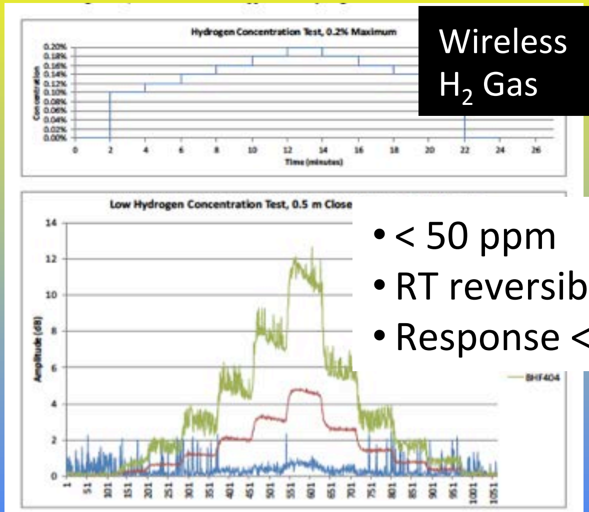
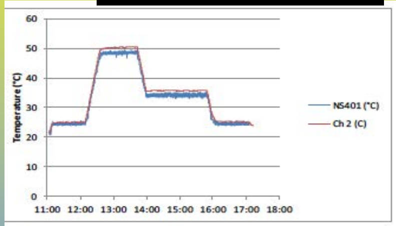


Figure 45. Low hydrogen concentration test, input profile and results

Wireless H_2 Gas

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

Wireless Temperature

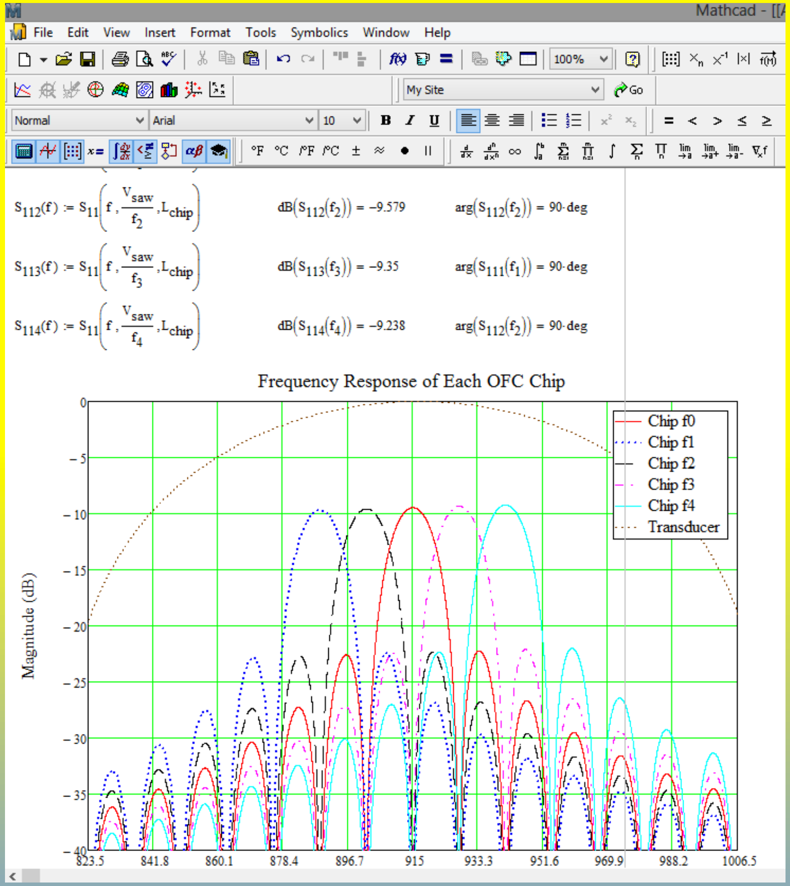


Temperature test results; blue trace: SAW sensor; red trace: thermocouple

<.01 C acc.
0.1-500 K range

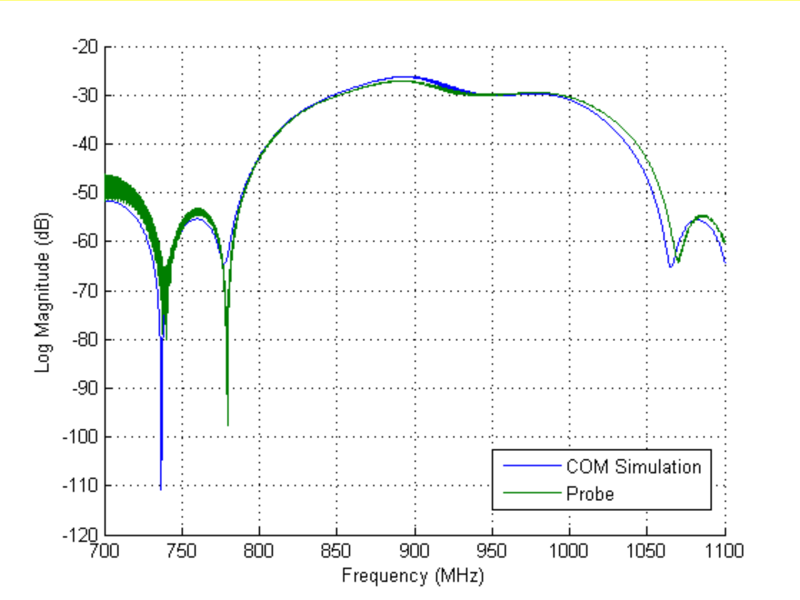
Concept

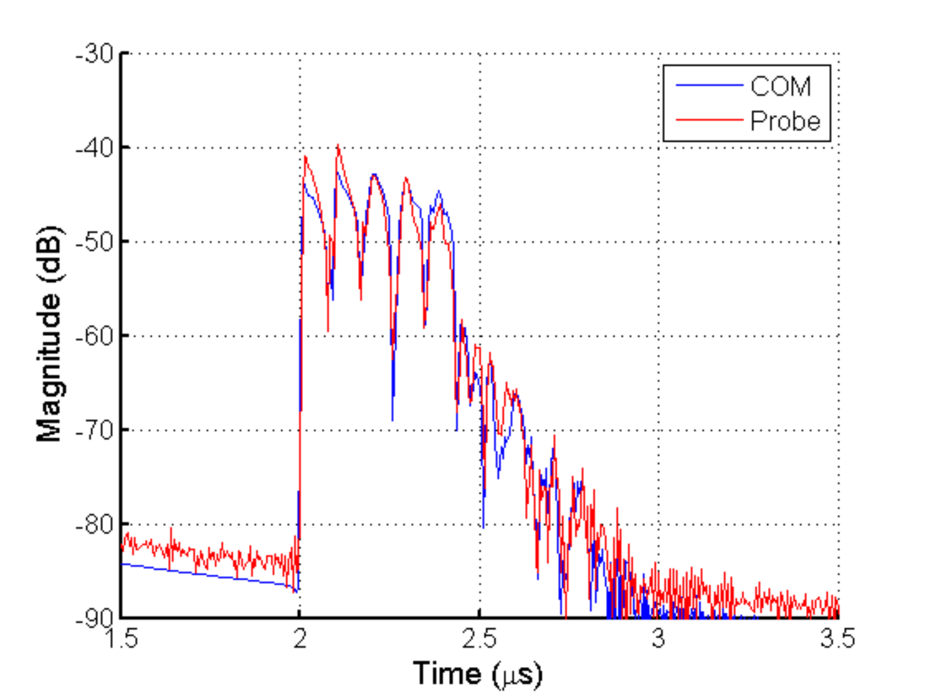
- Simple device modeling to predict performance
- New design approaches



Fast, Complex SAW Simulator

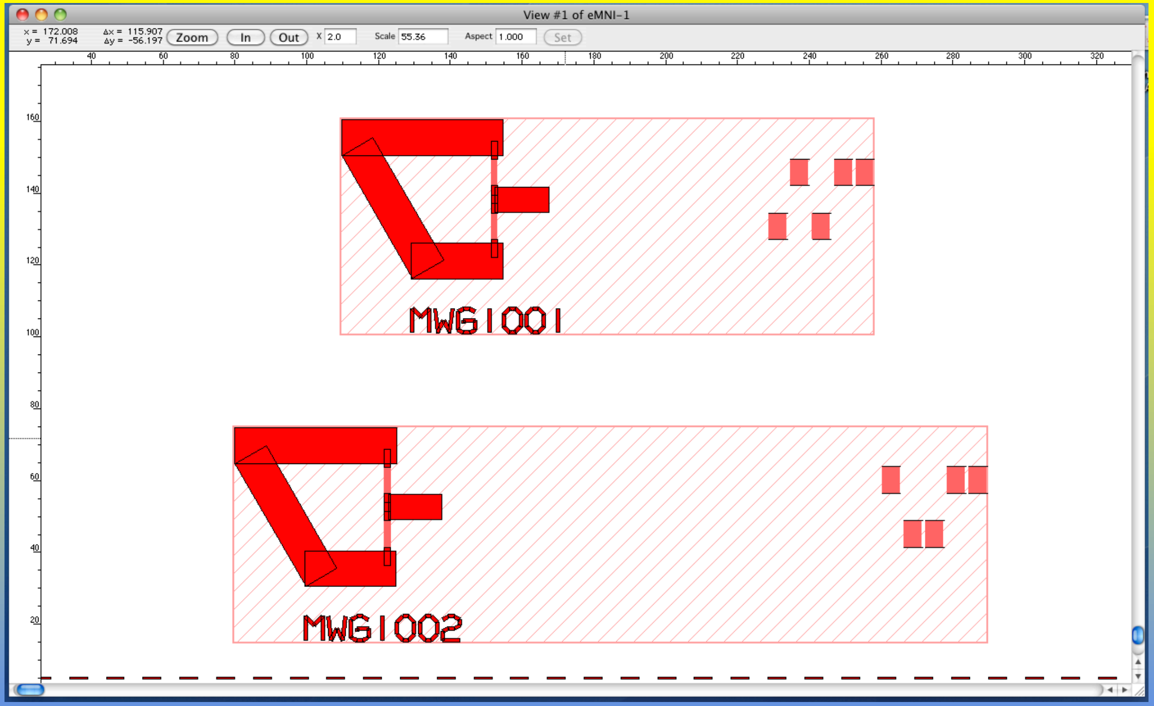
- Coupling of Modes (COM) Model for SAW Simulation
  - Accurate predictions of SAW device performance
  - Developed at UCF over 25 years





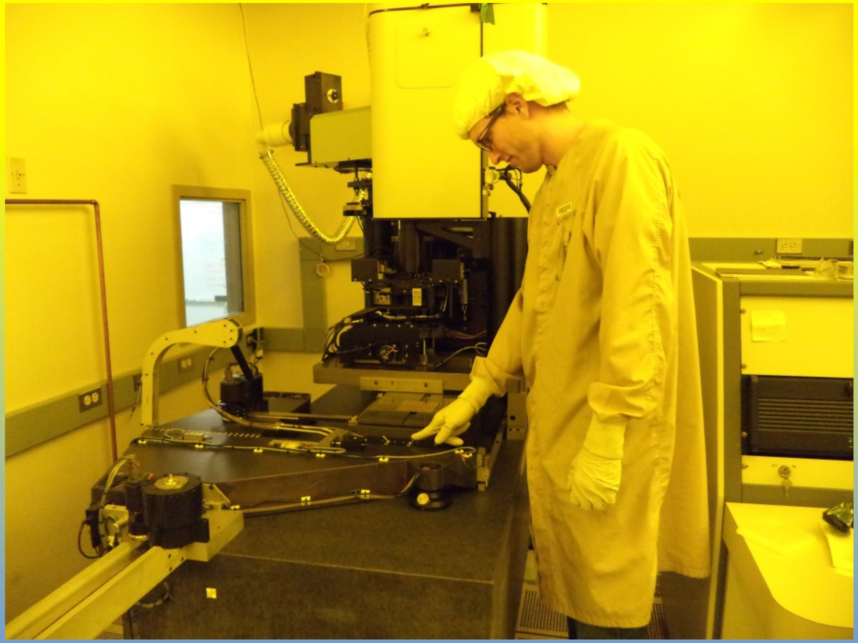
Accurate and Rapid Device Analysis Design and Layout Tools

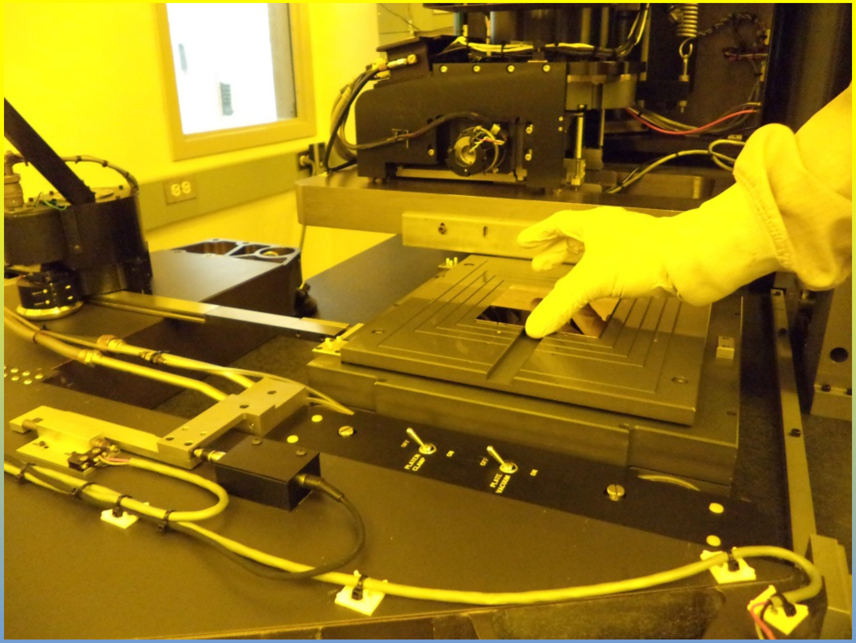
- Custom analysis and synthesis tools
- Custom Layout and Pattern Generator (PG) Tools



SAW Sensor Fabrication

Mask Fabrication for Photolithography
Pattern Generator - ~0.7 um Resolution



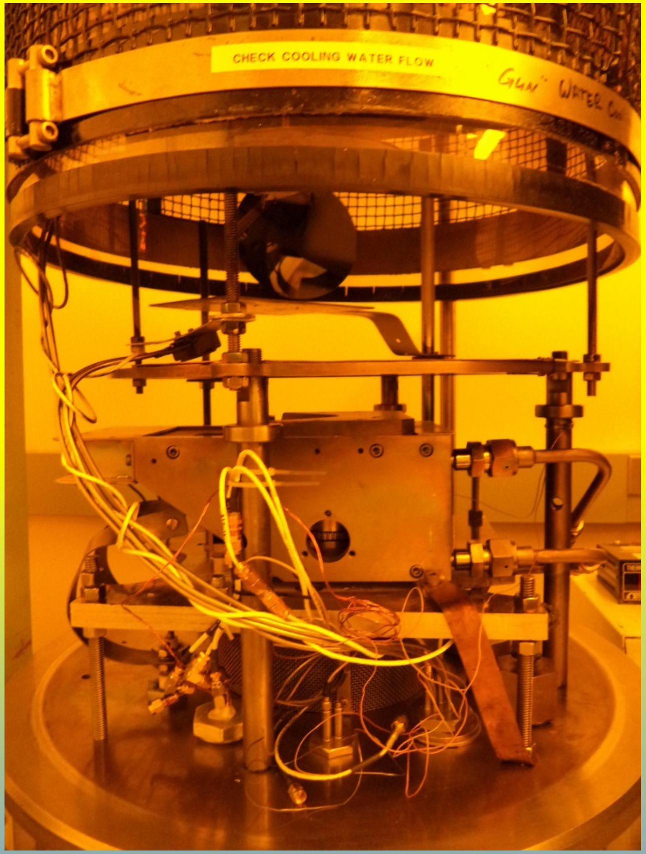


Photolithography

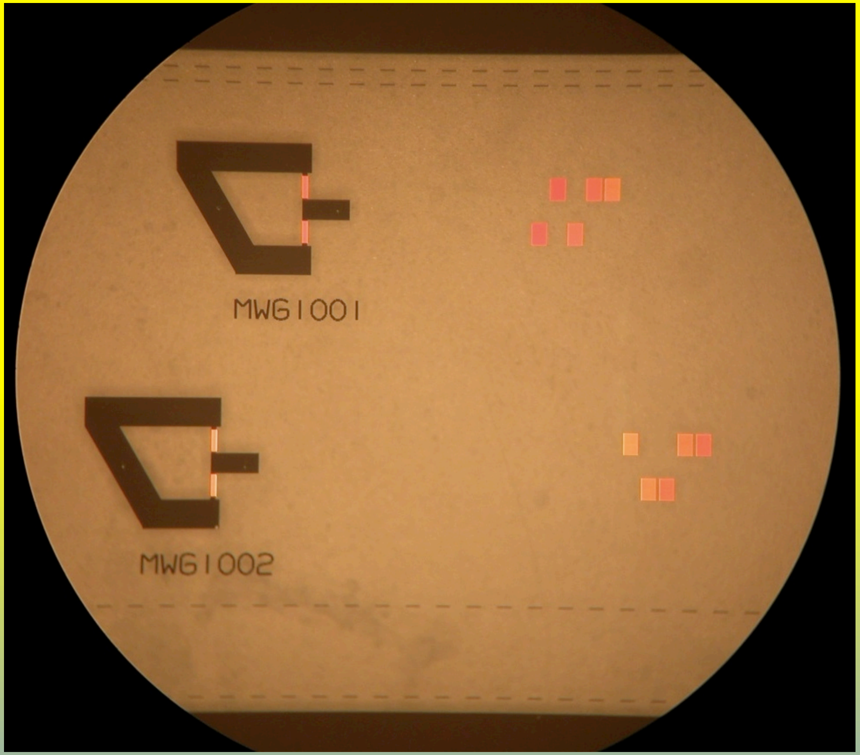
Submicron capability (~0.7um)

Thin Film Deposition

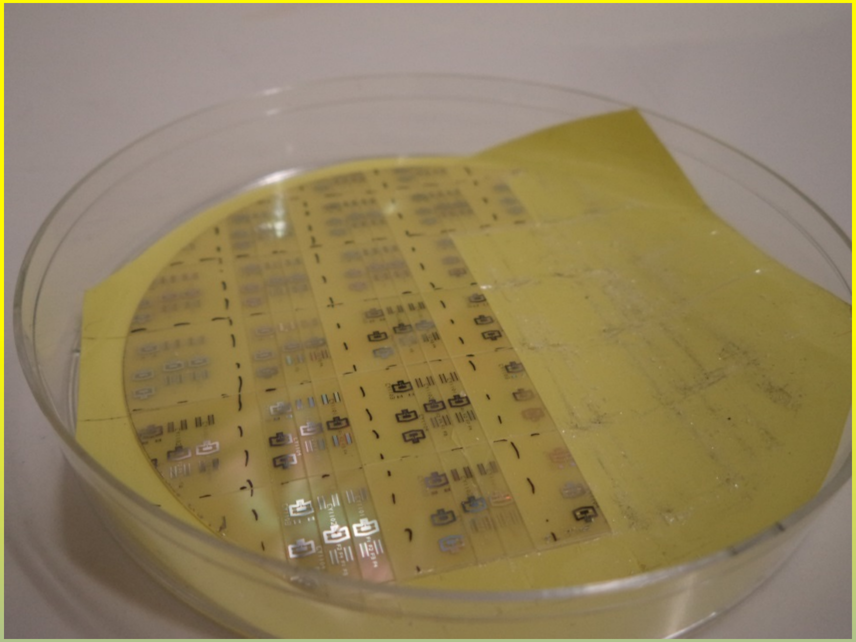
< 50 Ang. Accuracy



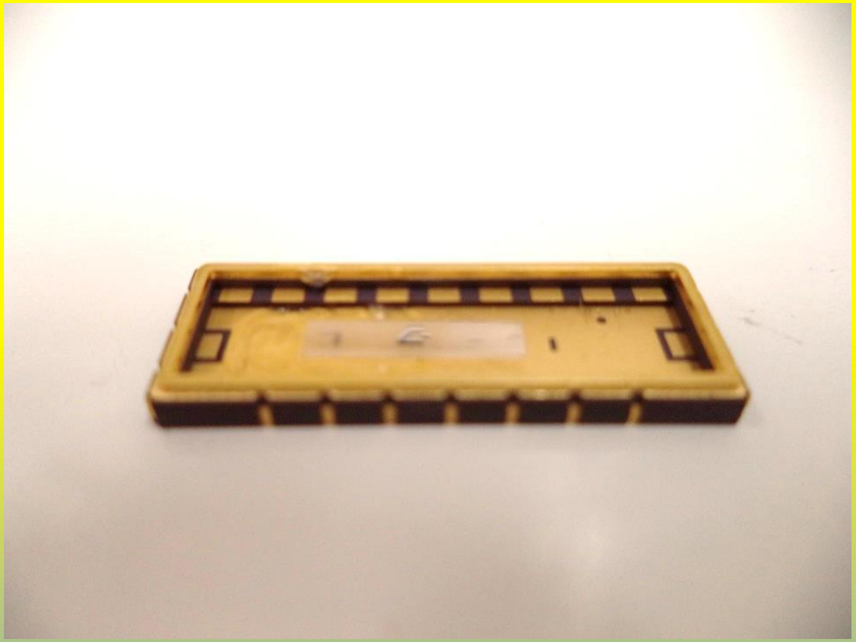
On Wafer Device Probing

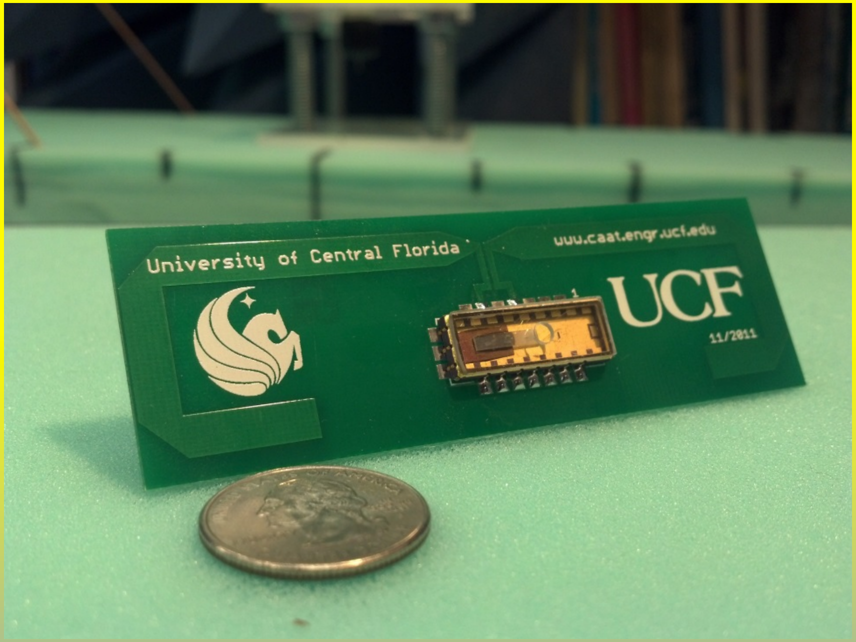


Wafer Dicing

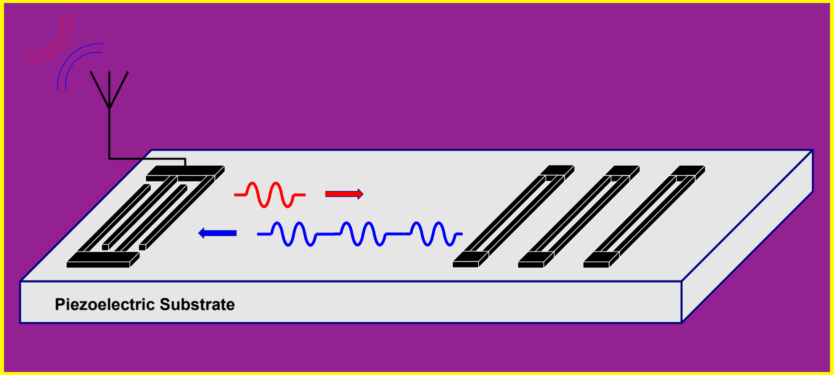


Packaging and Final Device Implementation





SAW Sensors



- External stimuli affects device parameters (frequency, phase, amplitude, delay)
- SAW sensor
  - Passive
  - Wired
- Coded devices allow for operation of multiple sensors
- Small, rugged devices offer low-cost solution for operation in harsh environments
- Frequency range ~10^2-10^3 MHz
- Monolithic structure fabricated with current IC photolithography techniques

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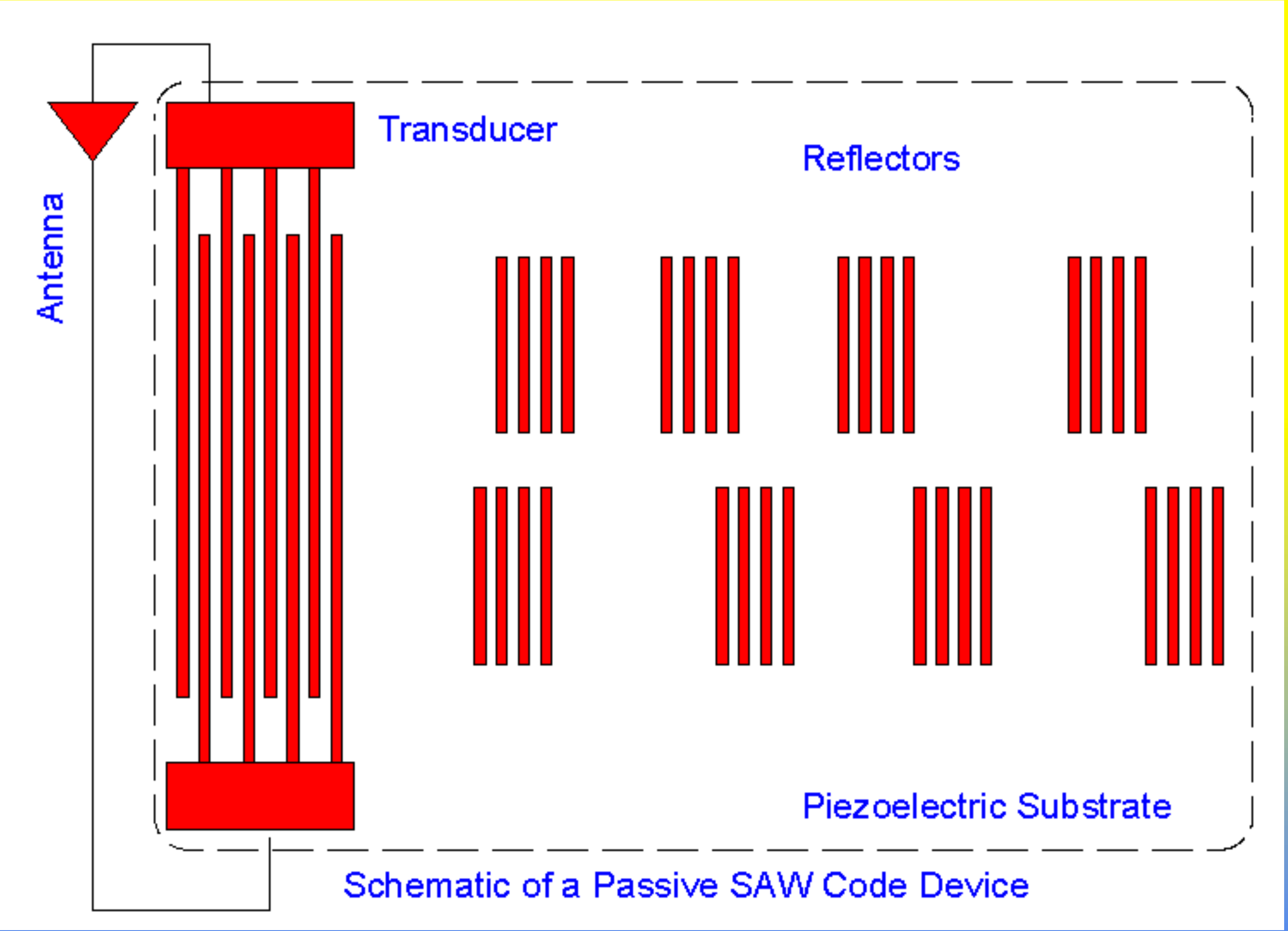
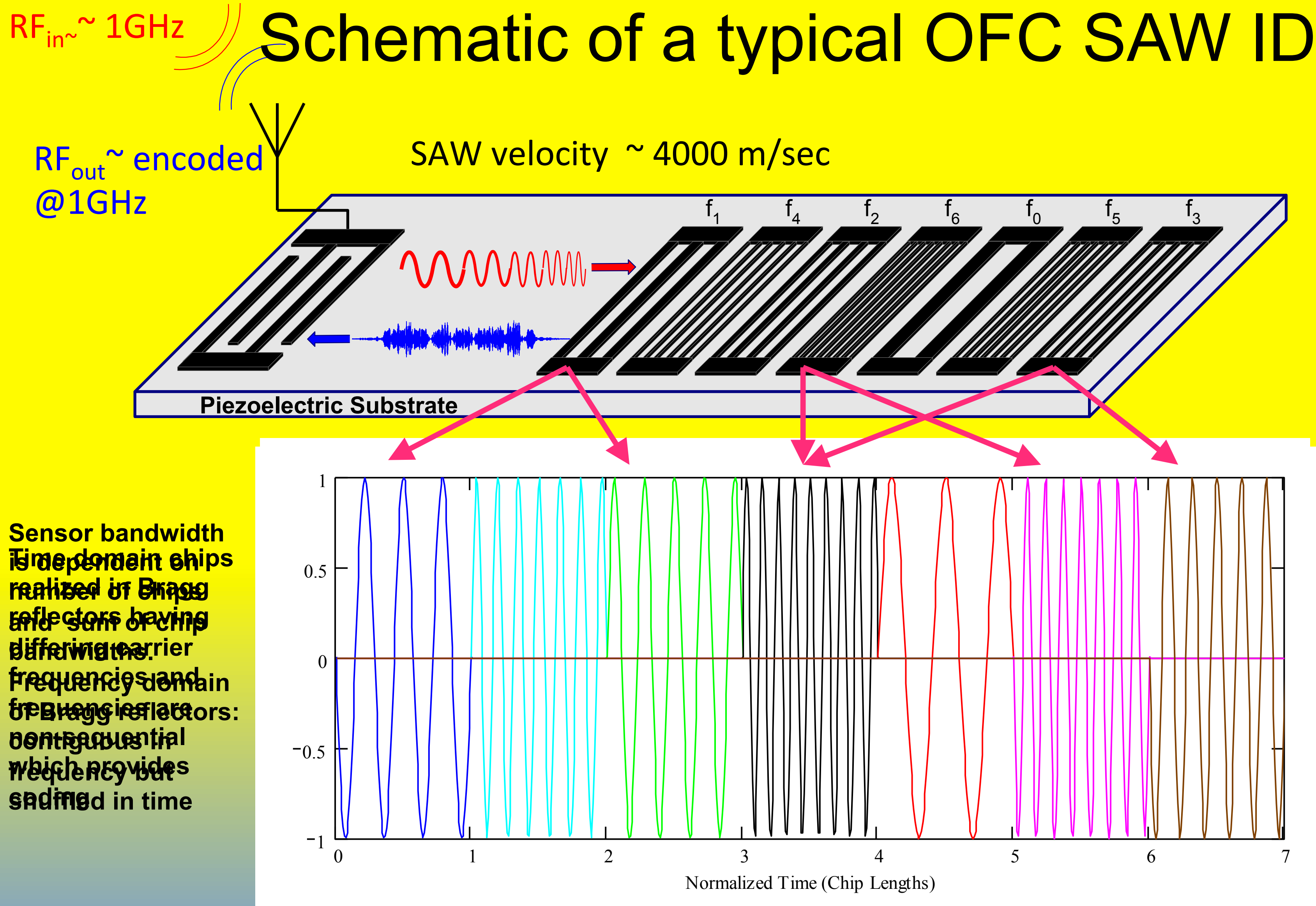
Example of a Multi-reflective Passive SAW Code Device



Wireless OFC Demonstration

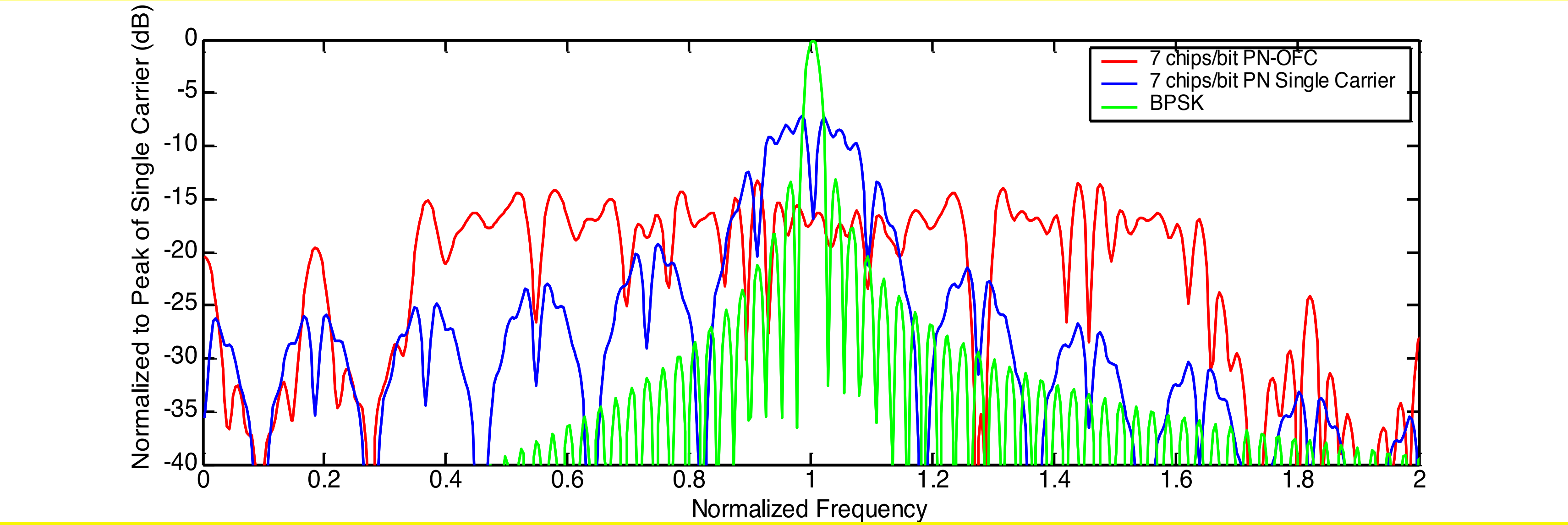
Schematic of a typical OFC SAW ID Tag

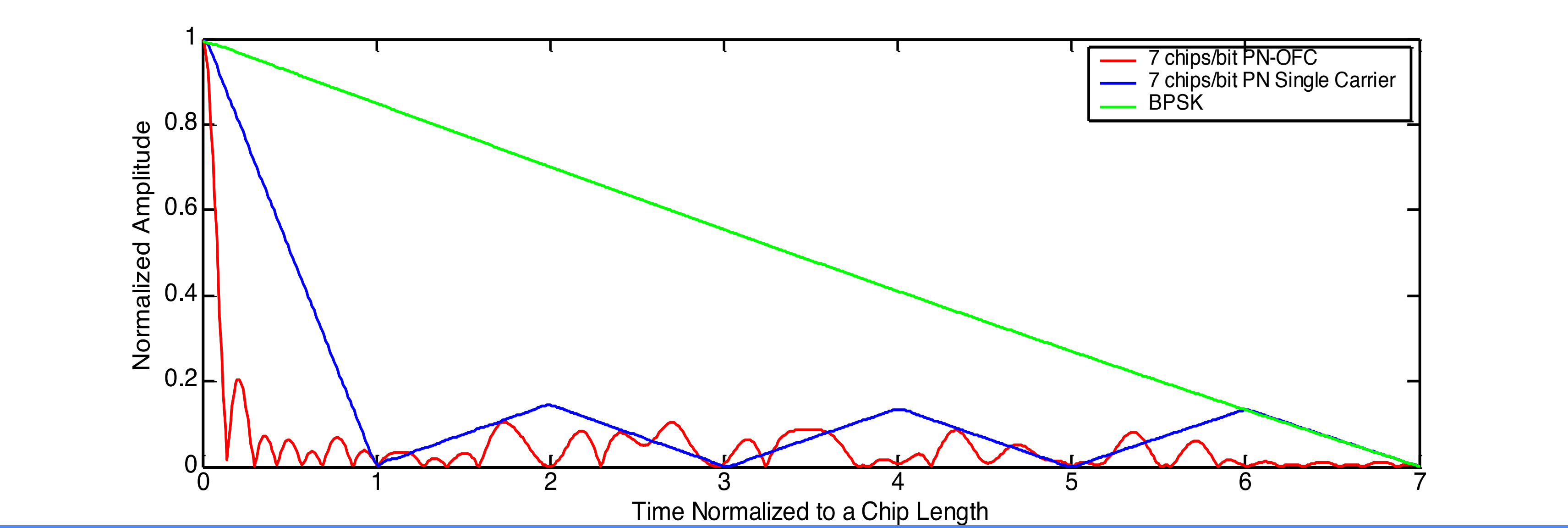


Sensor bandwidth is dependent on number of chips and sum of chip bandwidths. Frequency domain of Bragg reflectors: contiguous in frequency but shuffled in time

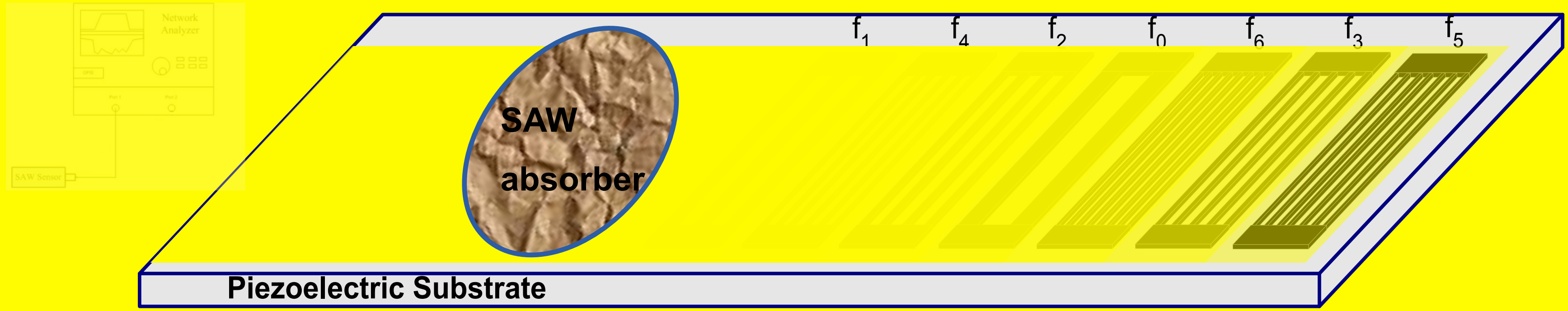
Time domain chips realized in Bragg reflectors having differing carrier frequencies and frequencies are non-sequential which provides coding

Bit, PN, OFC Signal Comparison

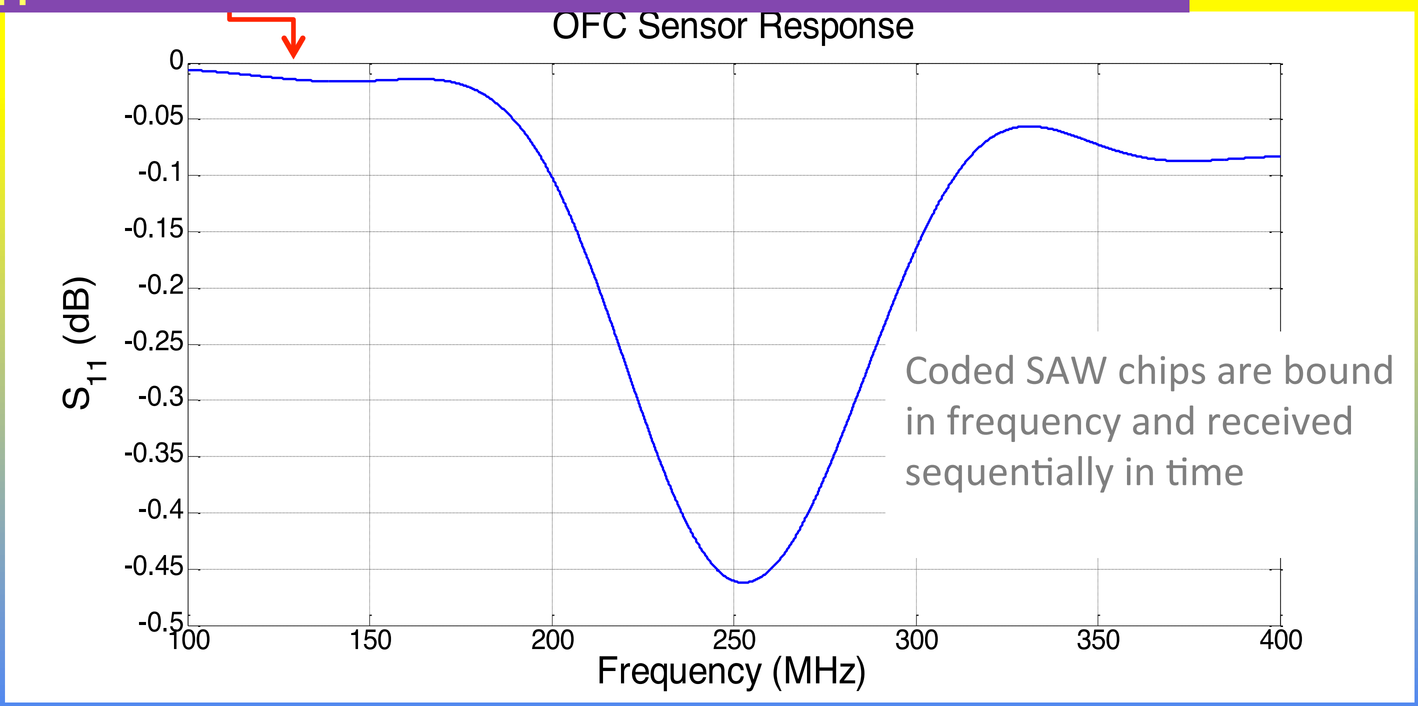




SAW OFC RFID signal – Target reflection as seen by antenna

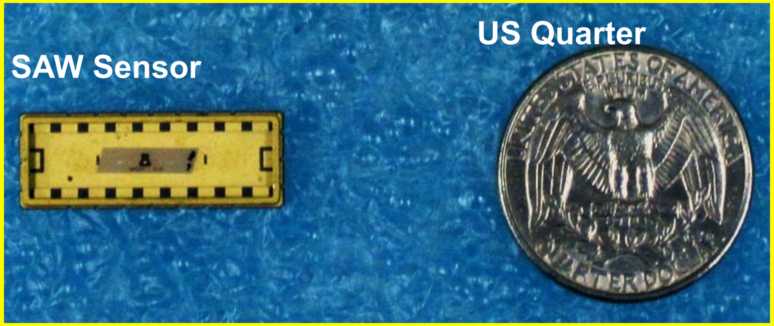


S_{11} w/o absorber and w/ reflectors

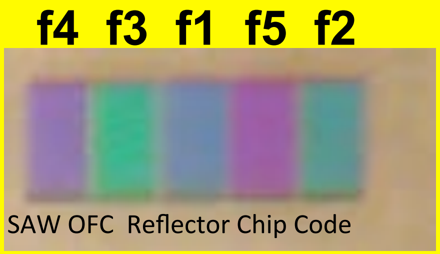


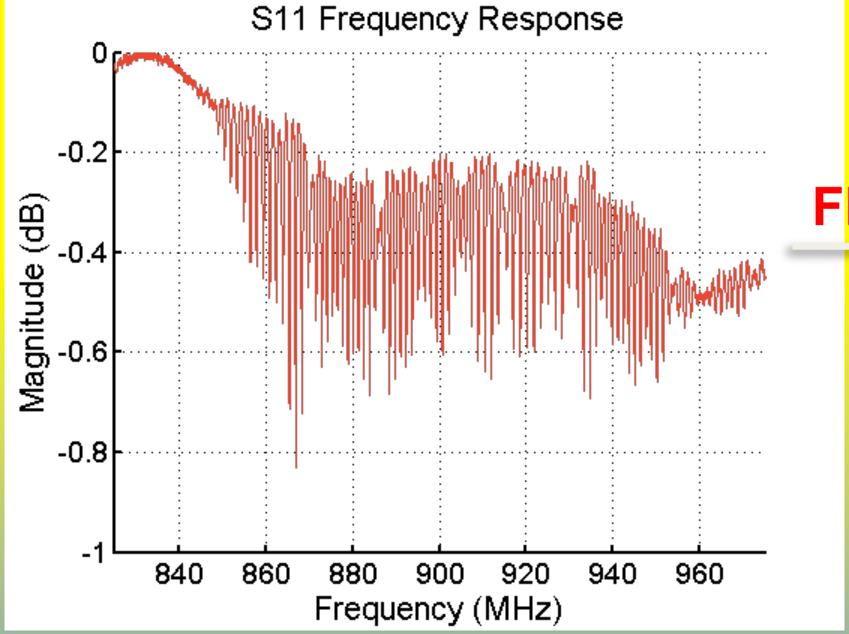
Coded SAW chips are bound in frequency and received sequentially in time

Example 915 MHz SAW OFC Sensor

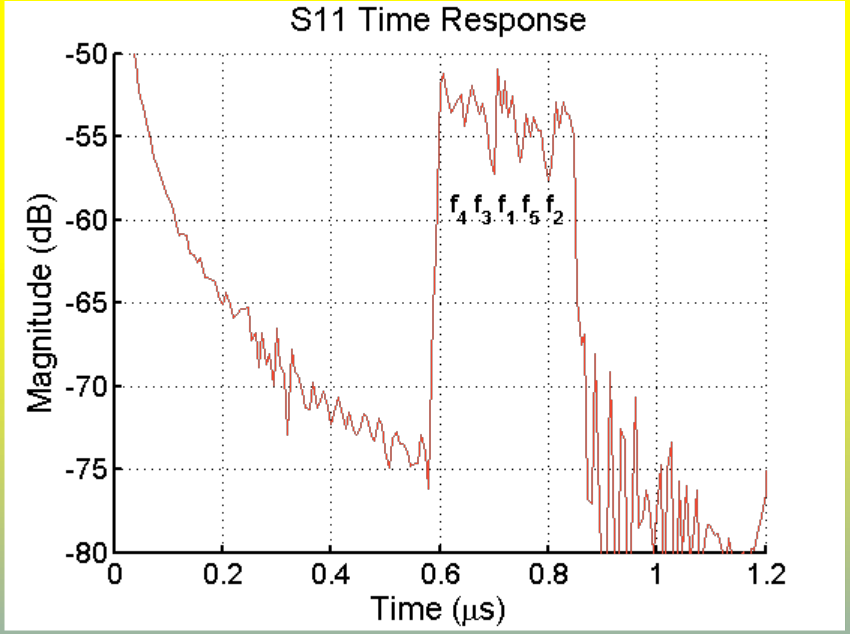


Light Micrograph

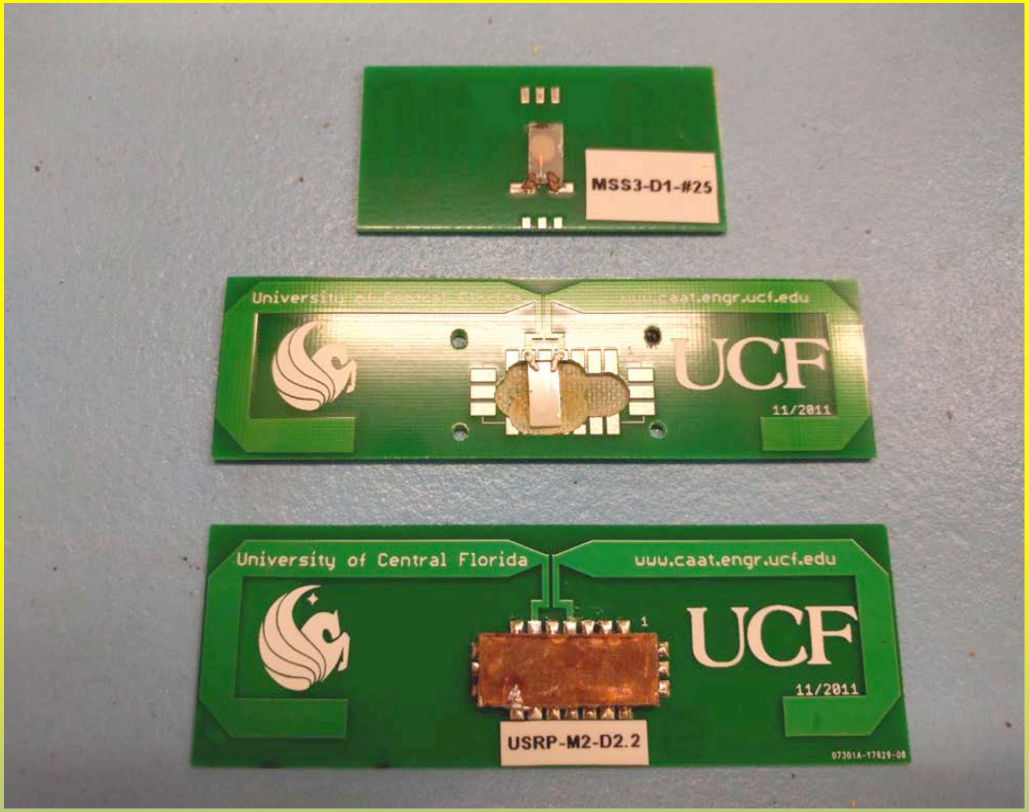




FFT



SAW Sensor + Antenna



Photograph of various SAW gas sensor embodiments. The design evolution is from bottom to top. The upper device has an embedded sensor and a small PCB antenna. Miniature antenna with exposed device (top), folded dipole antenna with embedded SAW die (middle), and folded dipole antenna with packaged SAW device (bottom).

TxRx Multi-Sensor Concept

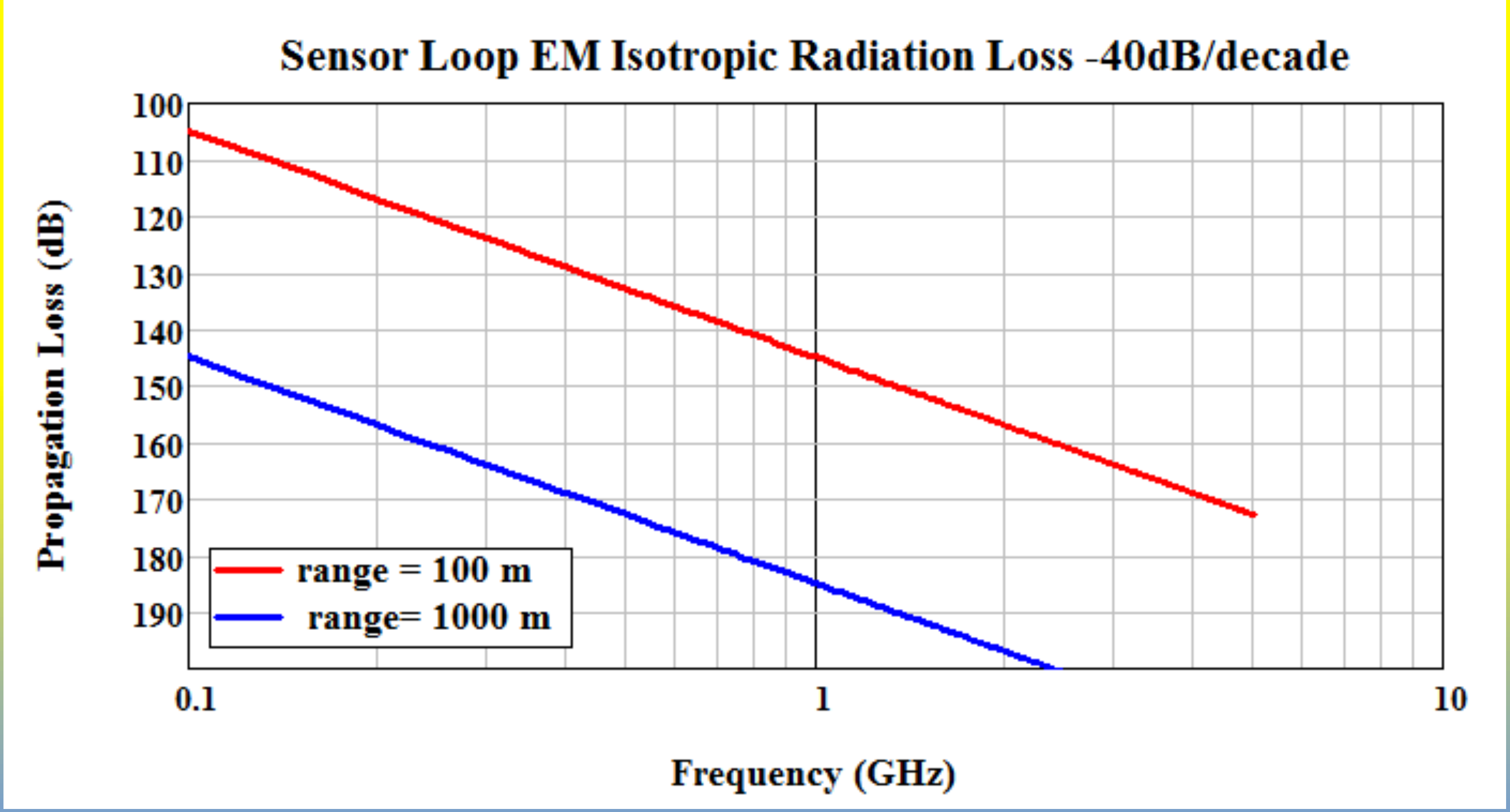
- Bandwidth can be either shared or partitioned
  - Output power is Watt/Hz or dBm/Hz
- Time window can be either shared or partitioned
  - Output power is in Watt/usec or dBm/usec
- Sensors can be partitioned either in time, in frequency, or can share both domains
  - Inter-sensor interference is eliminated by partitioning in one domain
  - Inter-sensor interference is problematic if overlap in **BOTH** time and frequency domain occurs
  - Code orthogonality helps inter-sensor interference

Most Transceiver Developments

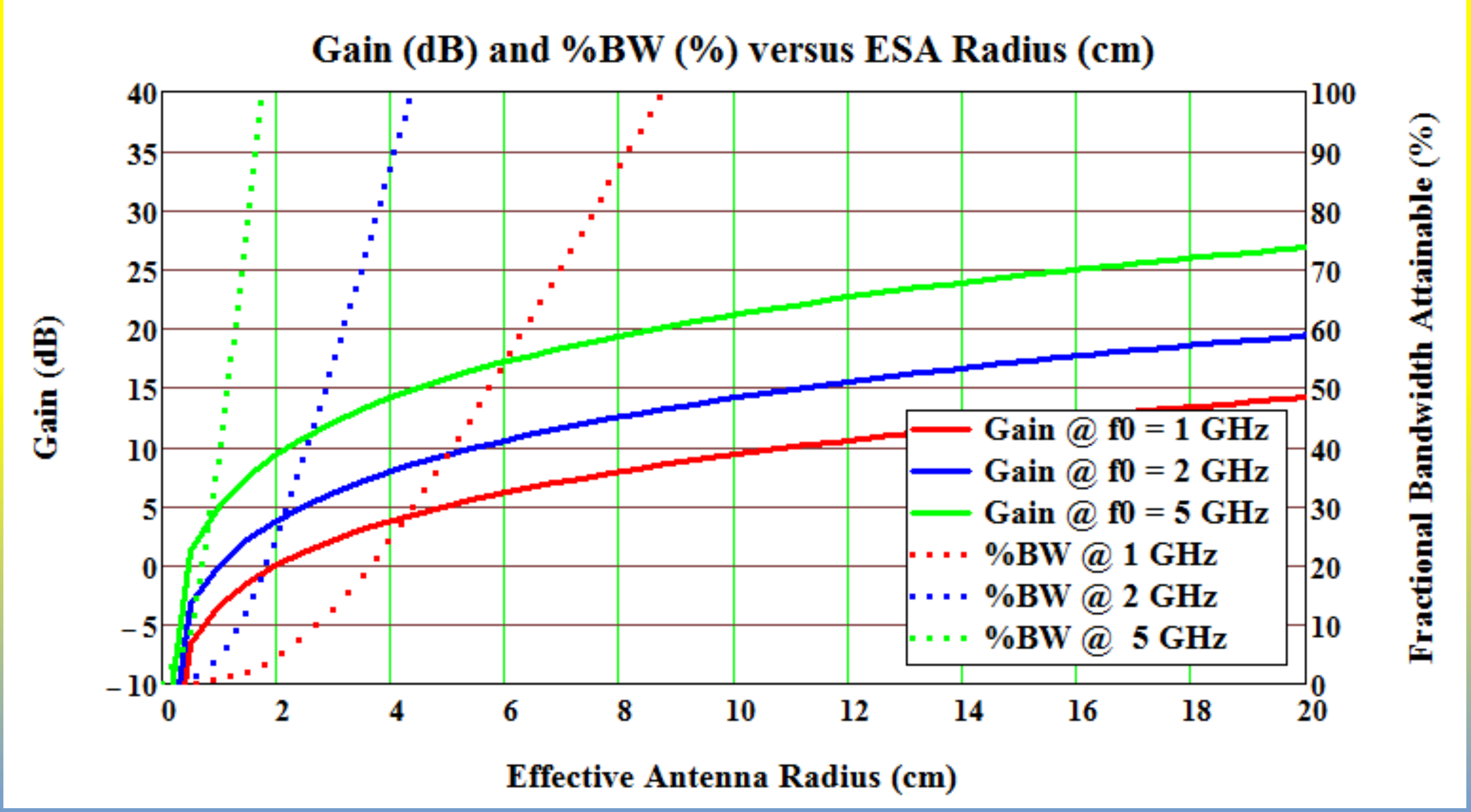
It's all about S/N Ratio for any sensor system

- Interrogation signal:
  - –Time windowed, all sesnors frequency bandwidth
- Transceiver:
  - –usually time duplexed mode, opposing on-off state.
  - –usually synchronous mode for switching and integration.
  - – usually ADC to a post-processing software

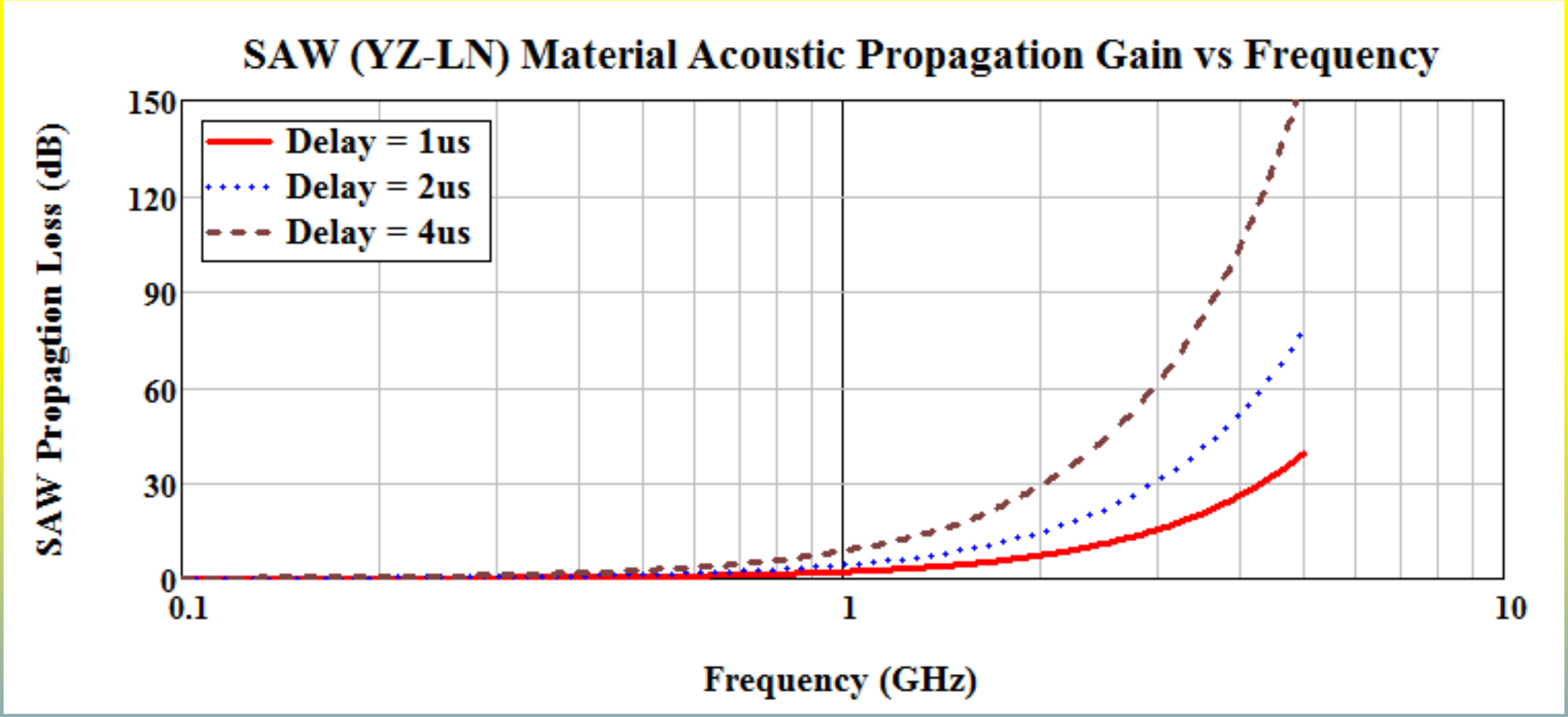
Any Passive Sensor

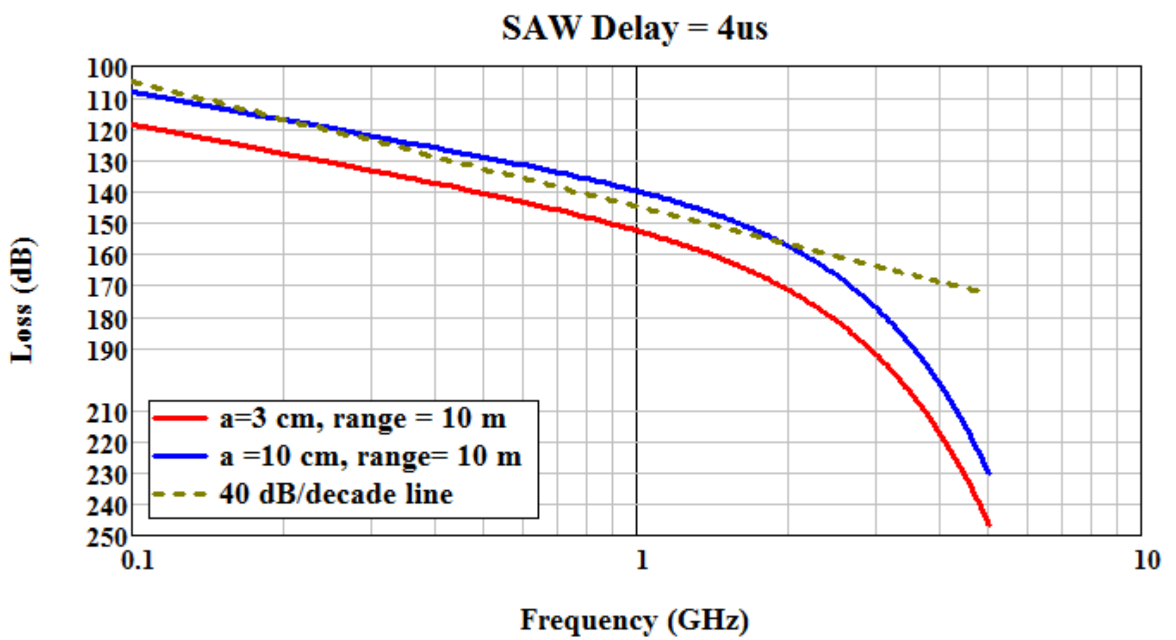


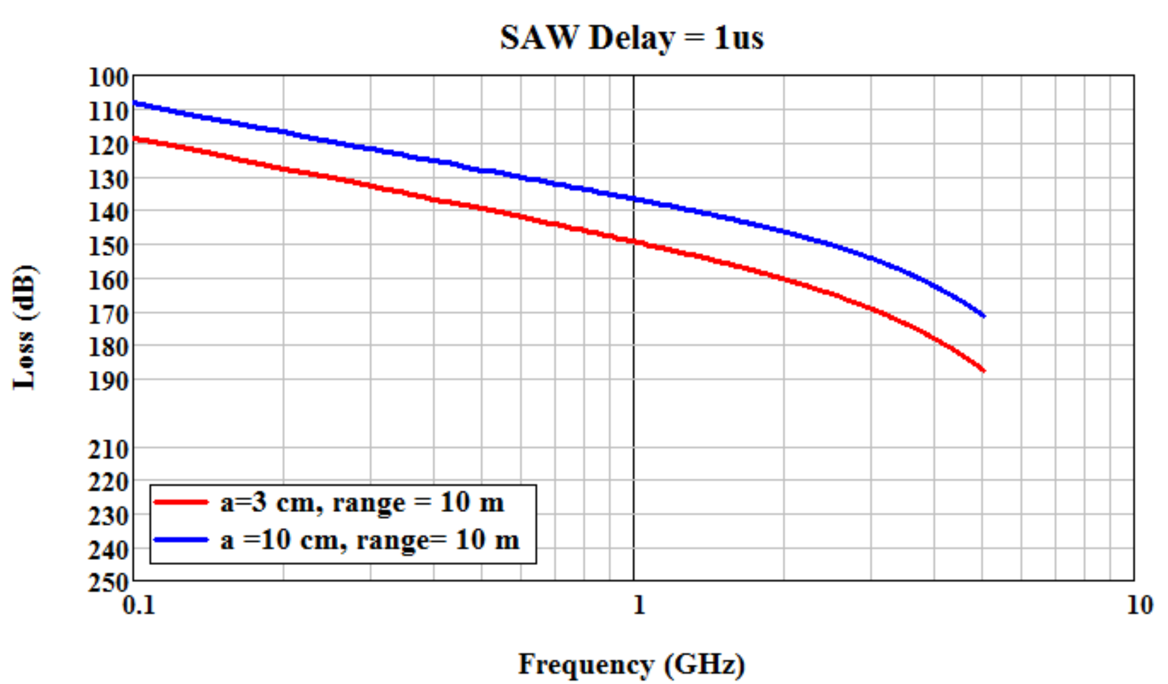
Any Electrically Small Antenna (ESA)



SAW Propagation Loss vs Frequency







Predicted Loss vs frequency including antenna, SAW propagation and free space Propagation for 4 usec and 1 usec delays

Does not consider bandwidth

Signal-to-Noise Ratio (SNR)

Condensed Version

$$SNR=\left[\frac{V_r^2 \cdot N_{Sum}}{V_{MDS}^2}\right]\cdot\left[G_{Sensor}\cdot G_{Tx\text{-}ant}\cdot G_{Rx\text{-}ant}\right]\cdot PL^{-1} \qquad (1)$$

or

$$S/N=G_{TR}\cdot G_P\cdot G_E \qquad (2)$$

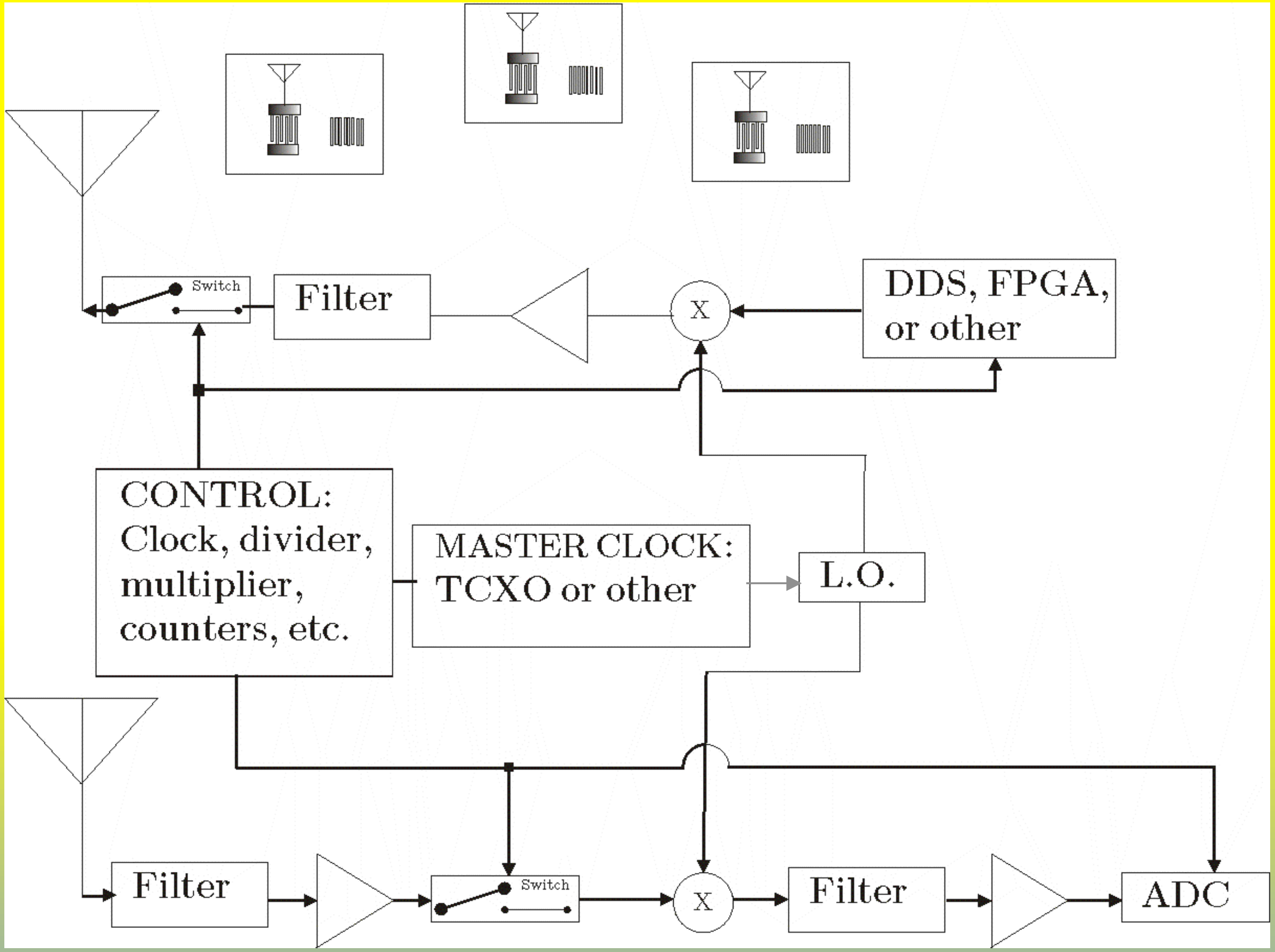
where $G_{TR}=\left[\frac{V_r^2 \cdot N_{Sum}}{V_{MDS}^2}\right]$, $G_P=\left[G_{Sensor}\cdot G_{Tx\text{-}ant}\cdot G_{Rx\text{-}ant}\right]$

and $G_E= PL^{-1}$.

V_r is the transmit voltage level and V_{MDS} is the voltage level detectable at the ADC, PL =Path Loss= $[v_{EM}/(4\cdot\pi\cdot R\cdot f_o)]^{-4}$, R=range

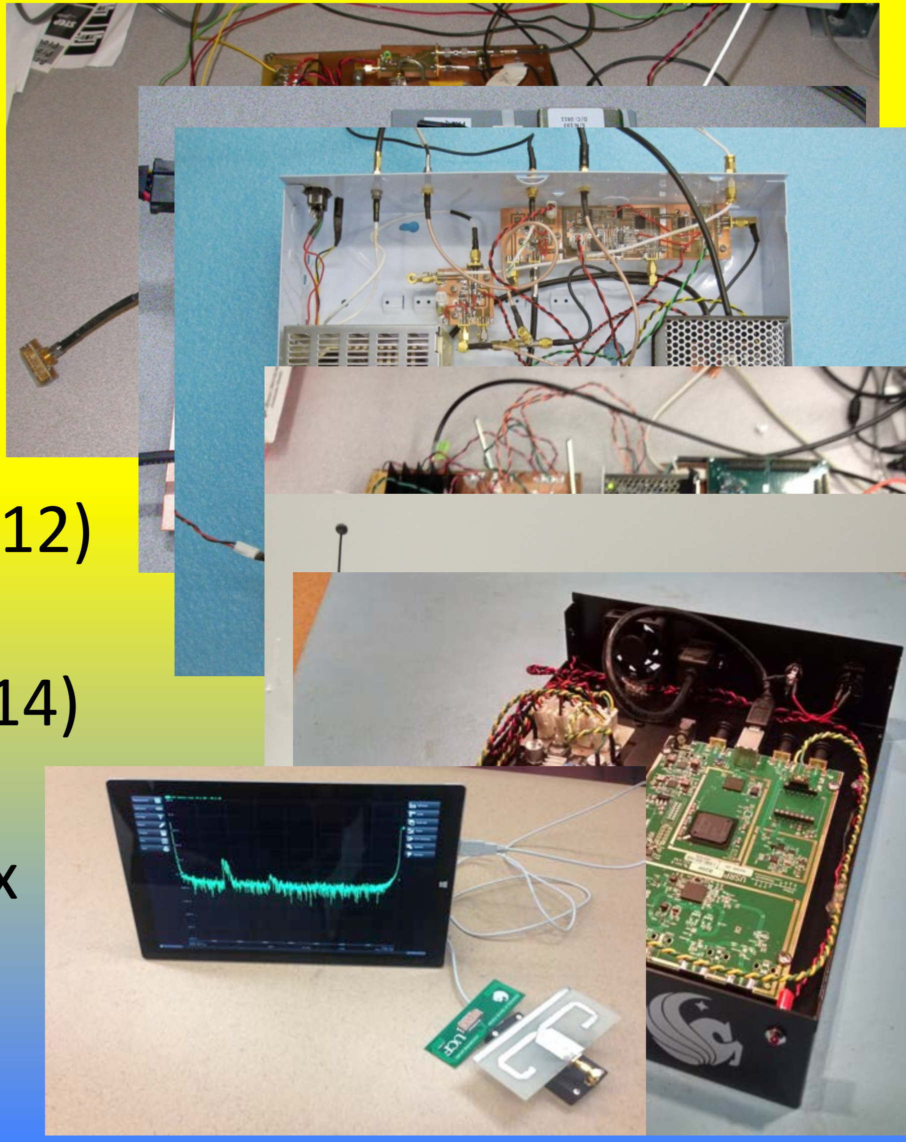
Example:

Hardware Synchronous Coherent TDM Pulsed Transceiver



RF Synchronous Coherence Transceiver Prototype Development

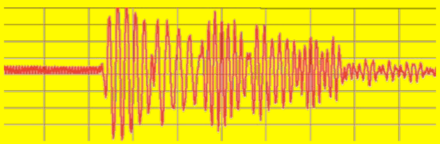
- 250 MHz
  - First Prototype (multiple boards) (2008)
  - Second Prototype (two main boards) (2009)
- 915 MHz Pulsed (2011)
- 915 MHz Noise Coherent(2012)
- 915 MHZ Wideband (2013)
- 915 MHZ FCC compliant (2014)
- 915 MHz SDR (2015)
- Wireless handheld mini-TxRx

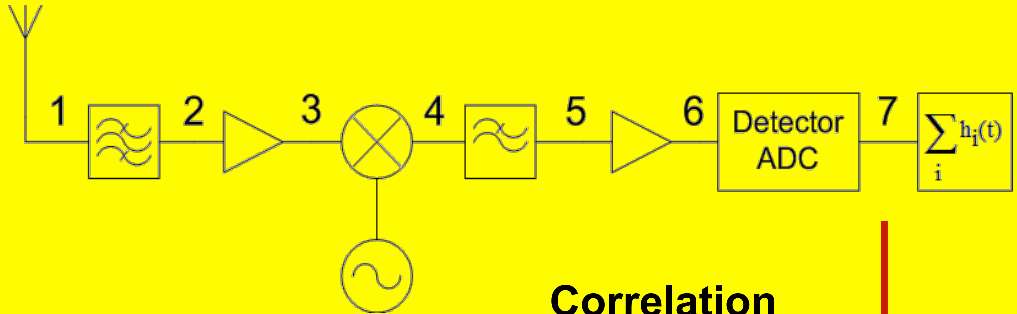


UCF Synchronous Correlator Receiver

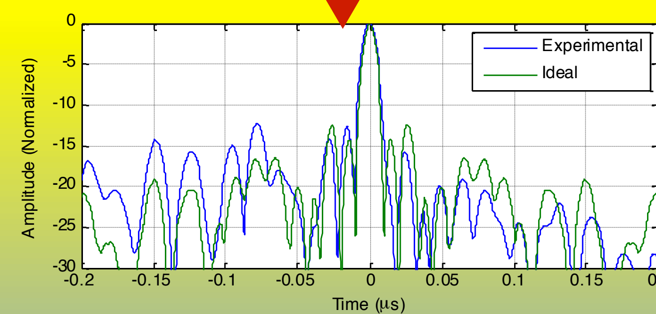
Block diagram of a correlator receiver using ADC

OFC Single Sensor Signal

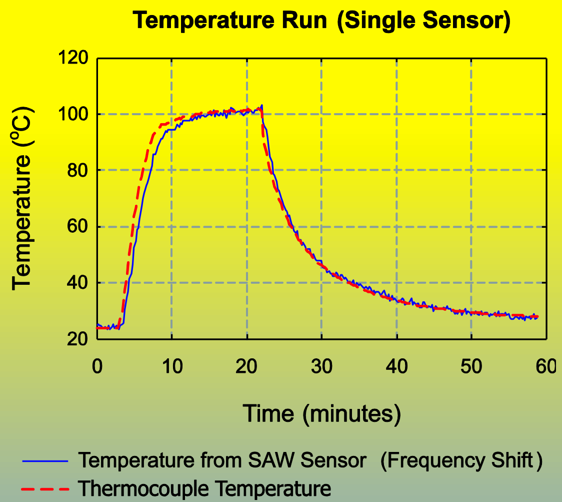


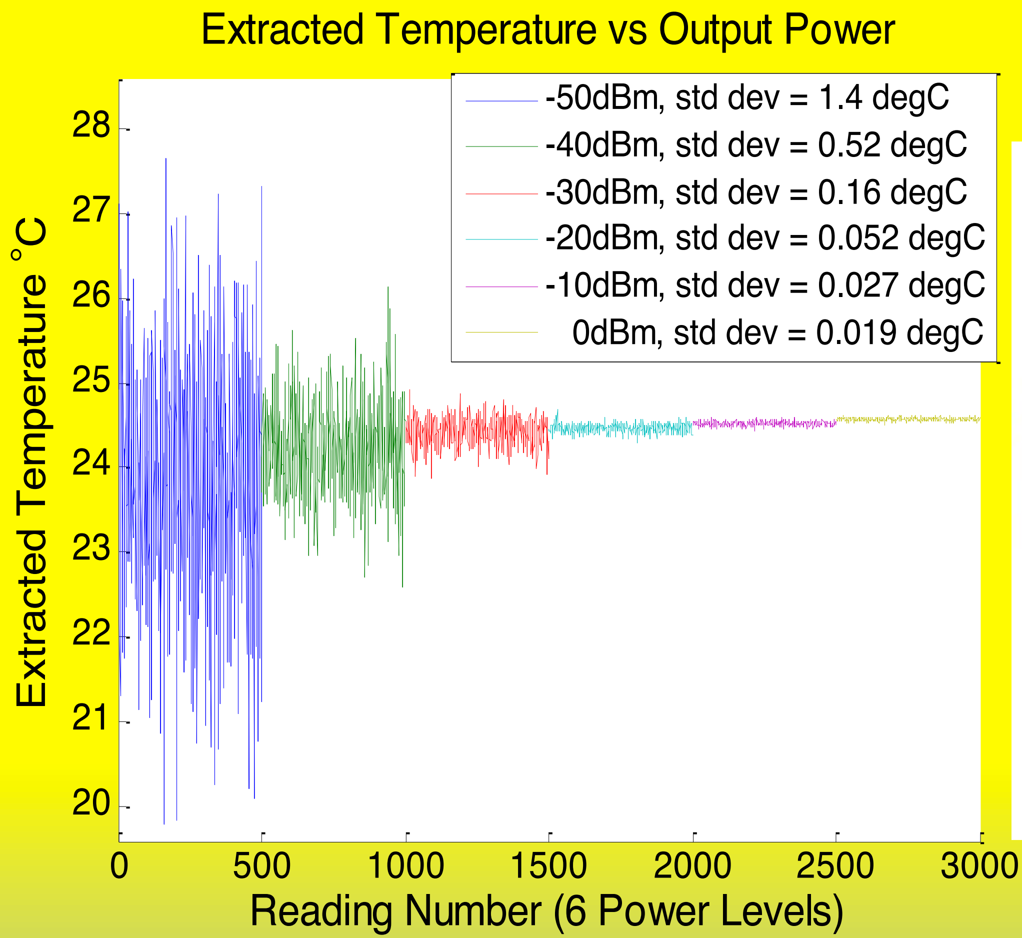


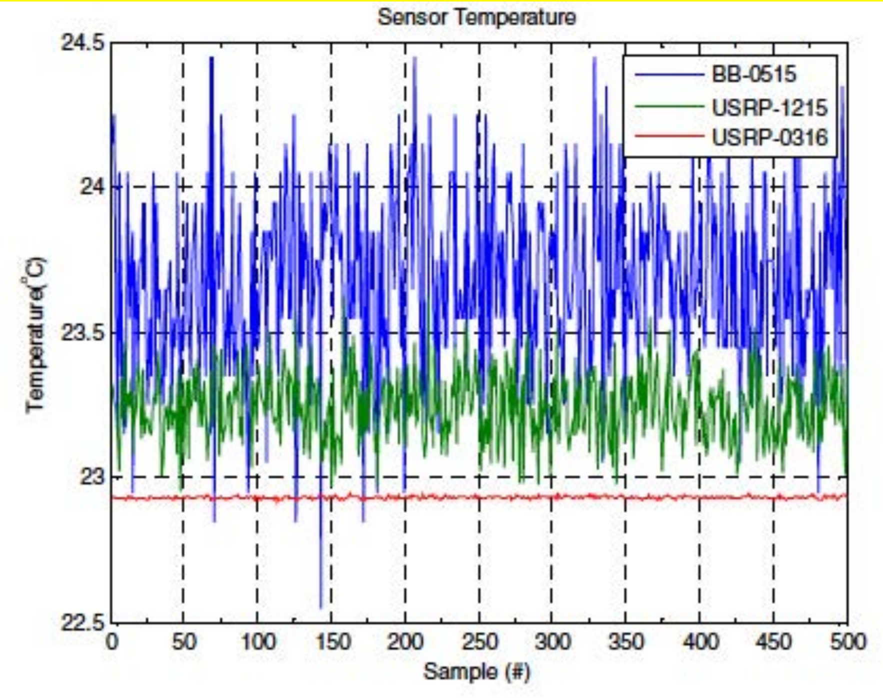
Correlation Output



Temperature Extraction



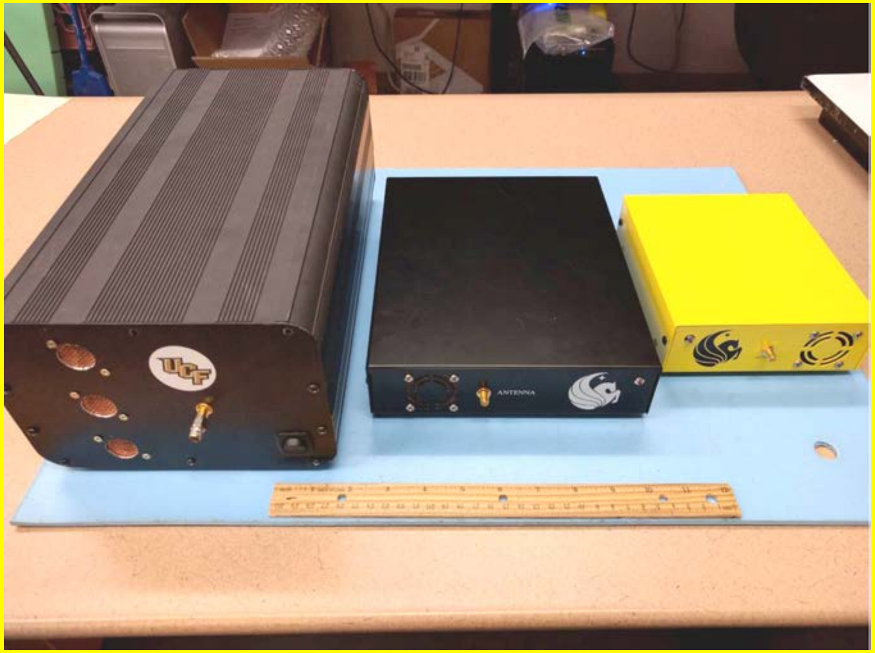


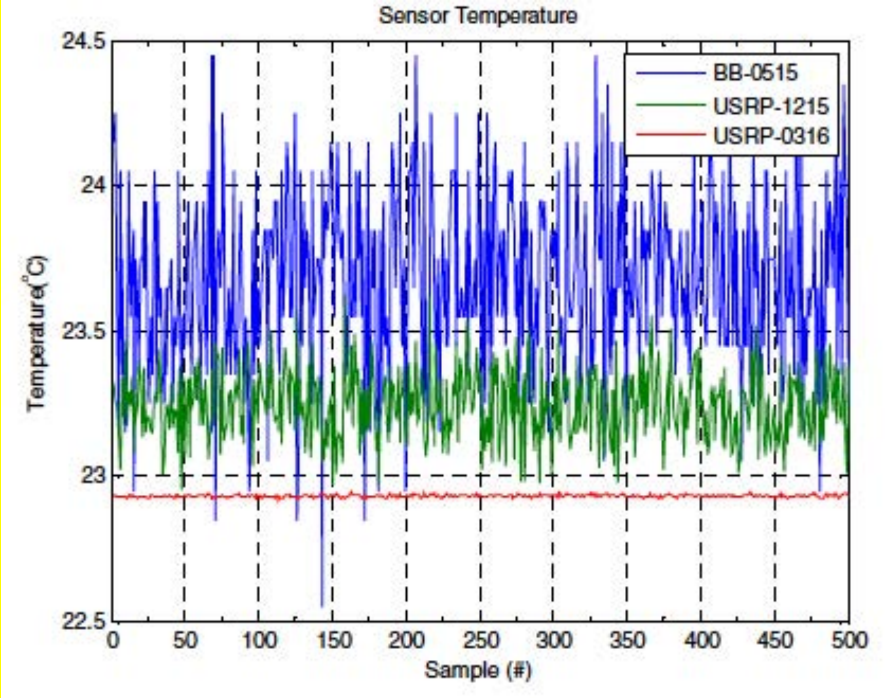


Temperature measurements showing the precision as a function of interrogation signal power in a controlled environment.

The corresponding reading number (RN) for the 6 power levels are: RN 1-500, -50dBm; RN 501-1000, -40dBm; RN 1001-1500, -30dBm; RN 1501-2000, -20dBm; RN 2001-2500, -10dBm; RN 2501-3000, 0dBm.

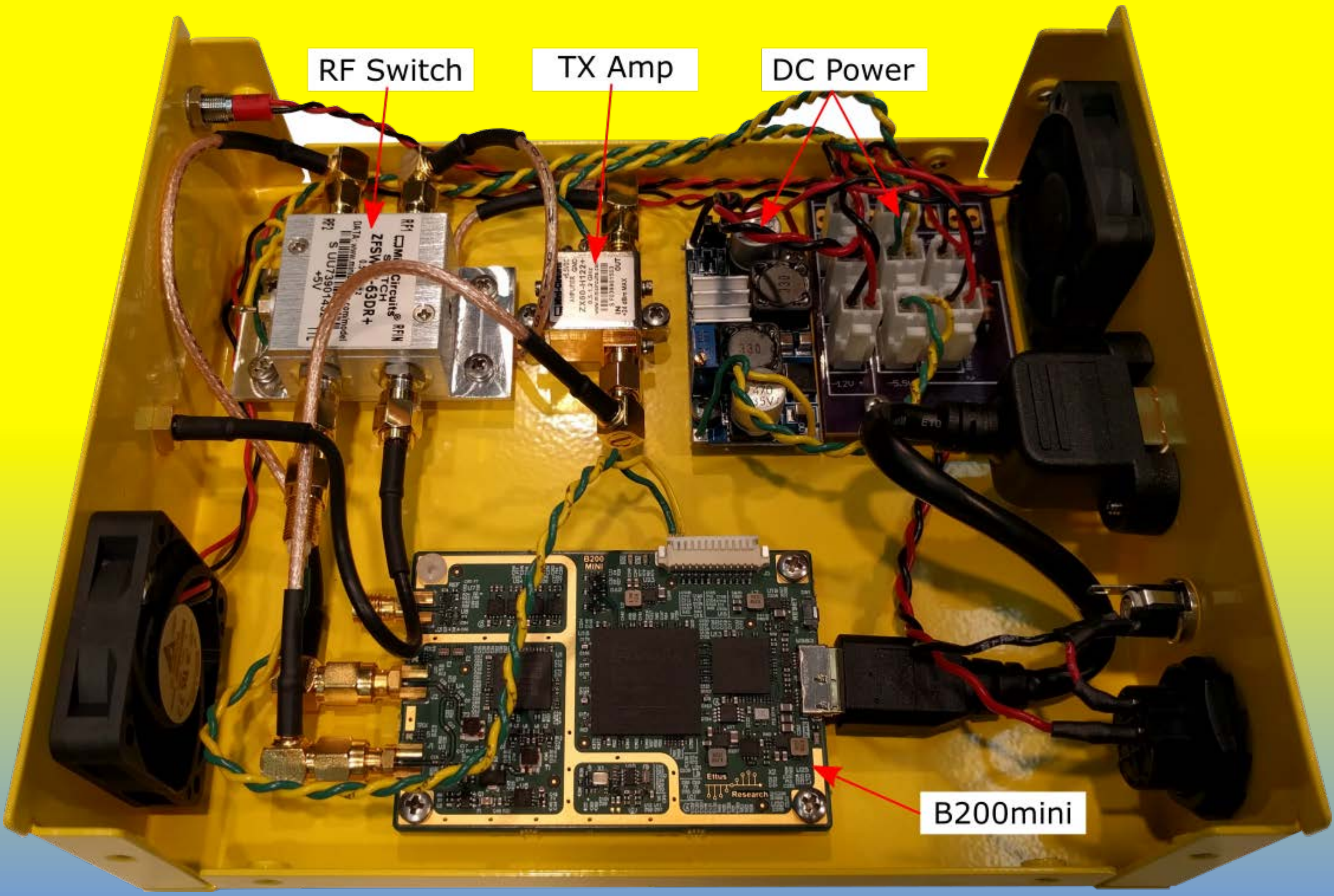
Plots of 3 differing transceivers having similar I/O specifications but have both hardware and software optimization





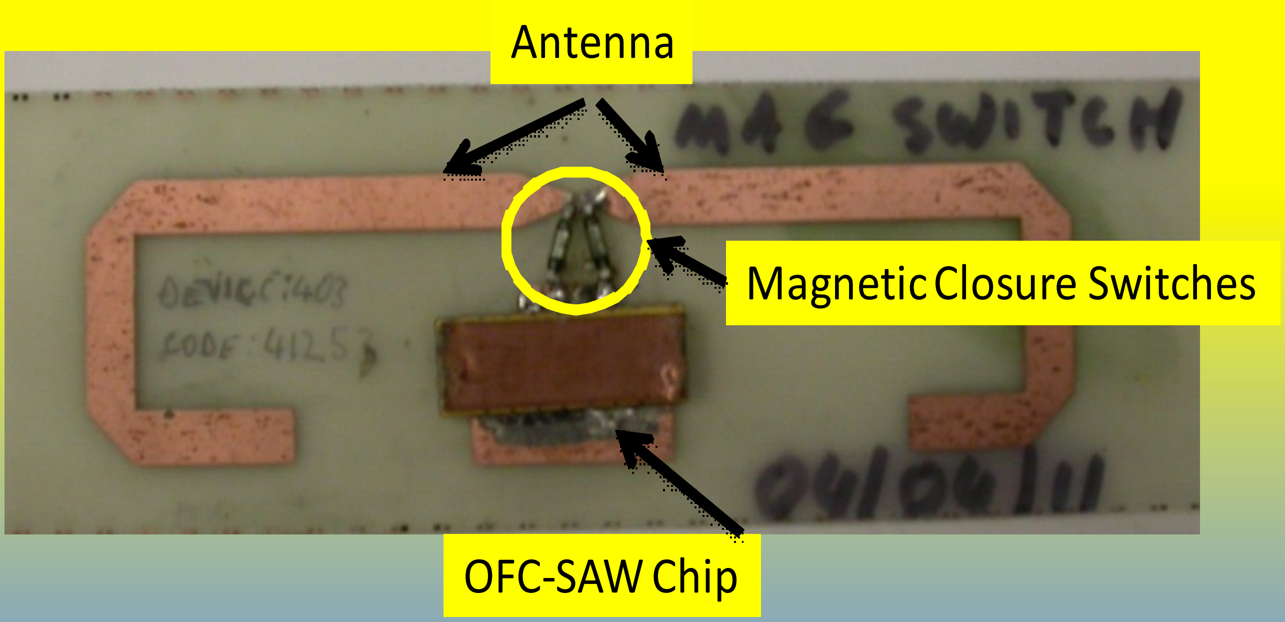
Photograph of 2015 noise coherent system (left), SDR based system (middle), and miniature SDR system (right). The system SDR systems have advantages in all aspects with respect to performance, size, cost, and power. Starting in 2016, all efforts have been focused on the SDR Reader approach for wired and wireless sensing.

Integration, Embedded Processor, Display, Etc.



Off-die: Wireless Magnetic Sensor

- SAW is used as RFID link and external device provides sensing
- Sensor between antenna and SAW



➢ **on-off ratio >30dB**
➢ **Multi-track**

Multiplexed Passive SAW Sensors Liquid Level Applications

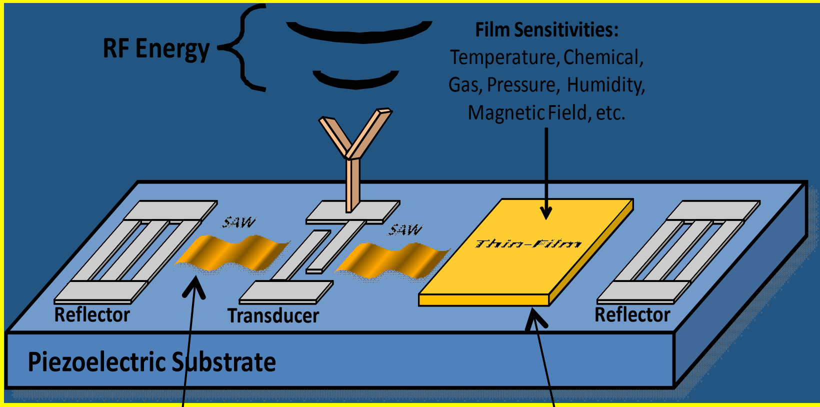
NASA needs improved methods for monitoring the liquid level in cryogenic tanks, and wireless passive technology is ideal due to the limited heat load introduced by the sensing system.

Devices operate from ~250C to 0.1 Kelvin

A set of six, coherence multiplexed, liquid level SAW sensors.

Hydrogen Gas Sensor using Acoustoelectric Effect (AE)

Motivation



Reference track

Active sensor track

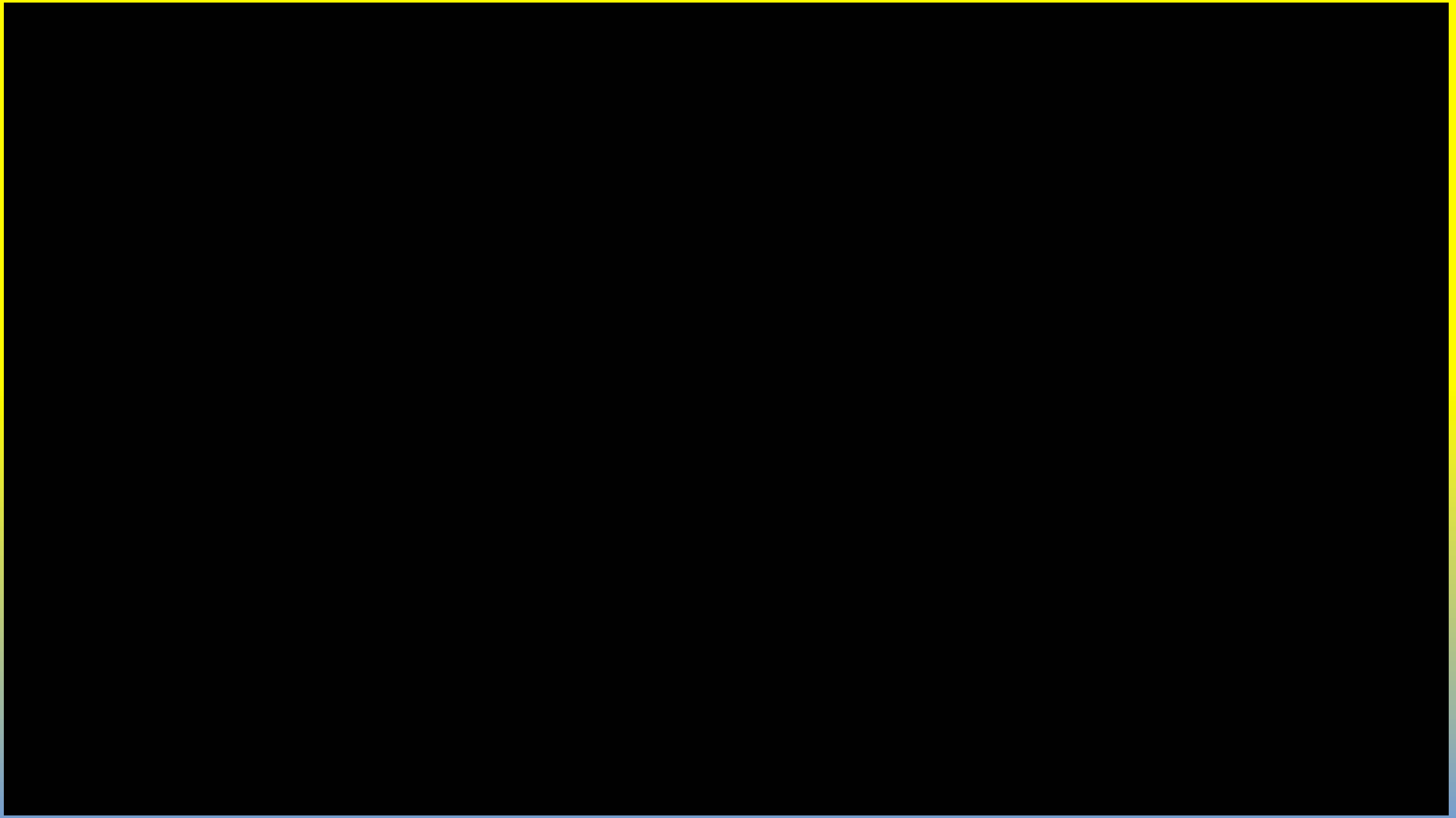
Build a wireless, passive, room-temperature, reversible, sensitive hydrogen gas sensor

High frequency Ultra thin films
•Nano-clusters
•New conductivity and dielectric property materials

Accomplishments:

- Rapid-response <1 sec
- 10 ppm sensitivity
- RT reversible in secs
- Low aging

SAW H_2 Gas Video



NASA-KSC Wireless Test: Hydrogen Gas Sensor 0.2% max H_2 0.02% concentration steps

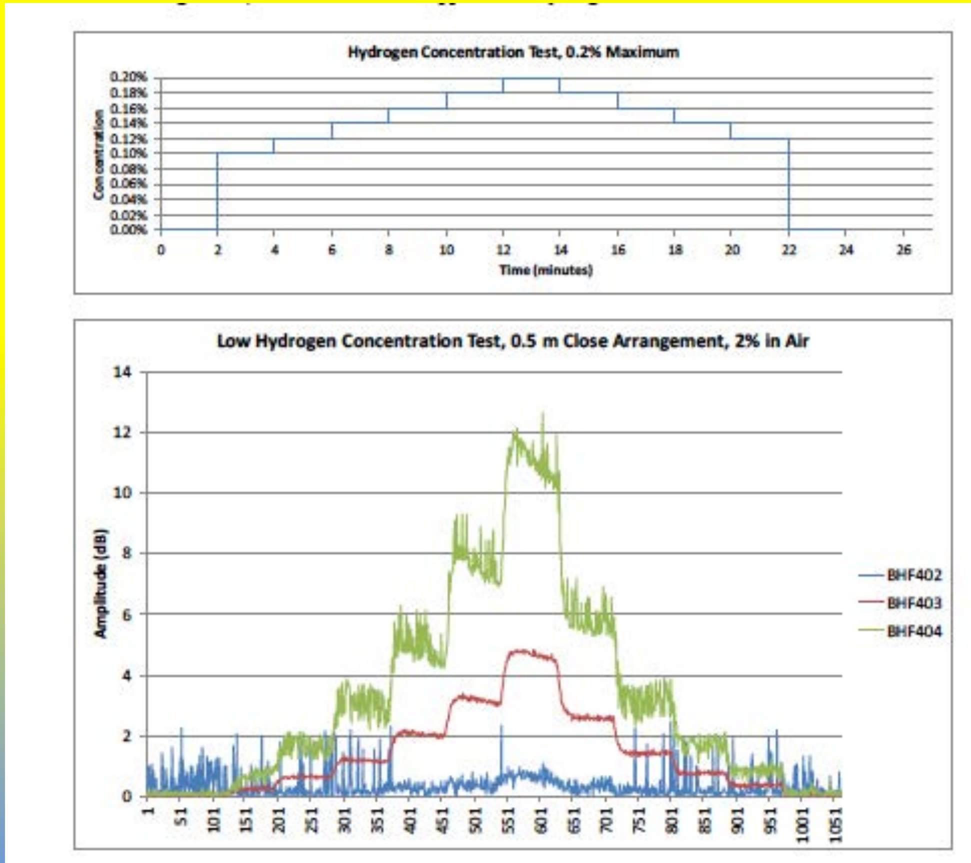
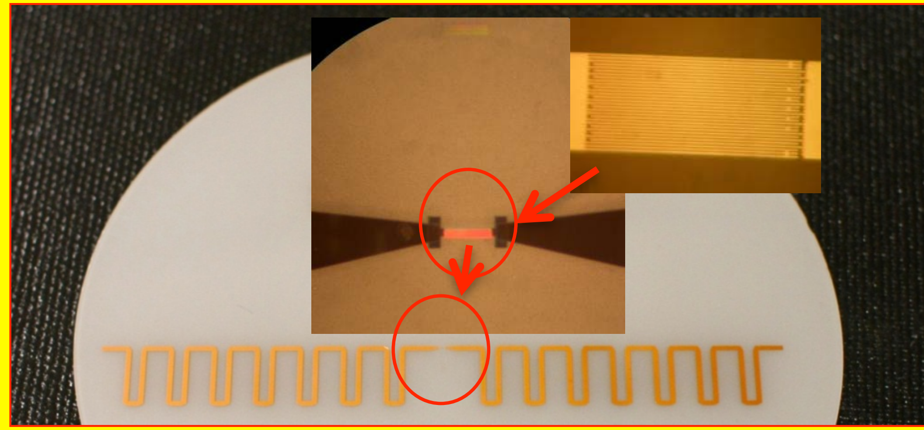


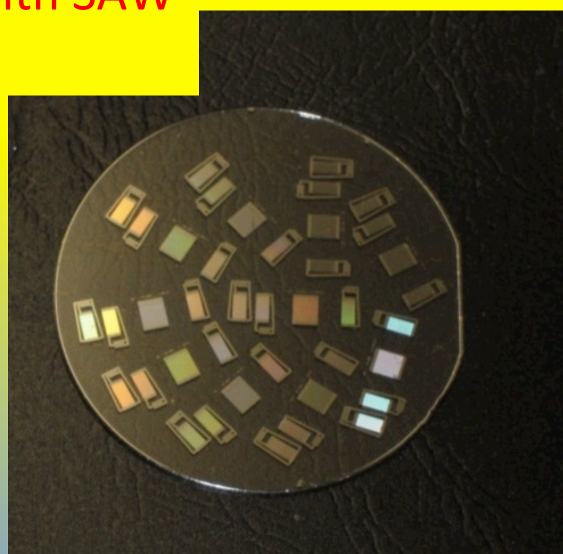
Figure 45. Low hydrogen concentration test, input profile and results

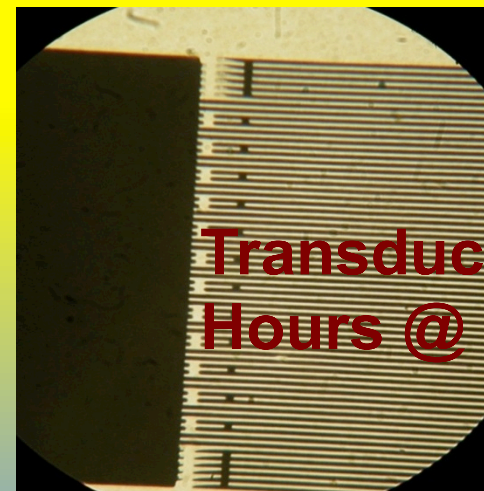
High Temperature Sensors

- SAW devices on Langatate (LGT)
  - LGT stable up to melting temperature of ~1450ºC
- Platinum thin/thick films under investigation
- Sawtenna development



LGT Wafer with SAW pin-wheel





Transducer after 2 Hours @ 700ºC

Observations

- SAW technology can be adapted to application specific wireless systems
- A host of sensor platforms are possible
- Teaming will advance the technology
- Regulatory issues need to evolve with sensor technology
- Single platform, multiple embodiments
- Narrow- , wide- , ultra wide– band have all been demonstrated with SAW OFC

Current Research

- Wireless gas sensing
- Wireless strain sensor
- Miniature low-cost hand-held TxRx
- High data rate acquisition
- Wired handheld POC diagnostics for biological liquid sensing

Future Research

- Higher frequencies
- NASA space qualification
- Handheld wireless TxRx
- Biological POC handheld system
- Networking of multi-node multi-sensor TxRxs

- **Former Students and Associates**
  - Rick Puccio
  - Nancy Saldanha
  - Matt Pavlina
  - Nick Kozlovski
  - Brian Fisher
  - Daniel Gallagher
  - Matt Gallagher
- **Current Students and Associates**
  - Trip Humphries
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  - Jose Figueroa
  - Roman Grigarov
  - Scott Smith
  - Chris Carmichael
  - Marc Lamothe
  - Art Weeks

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Thanks for your attention!