Wireless Passive SAW Sensors using Coded Spread Spectrum Techniques

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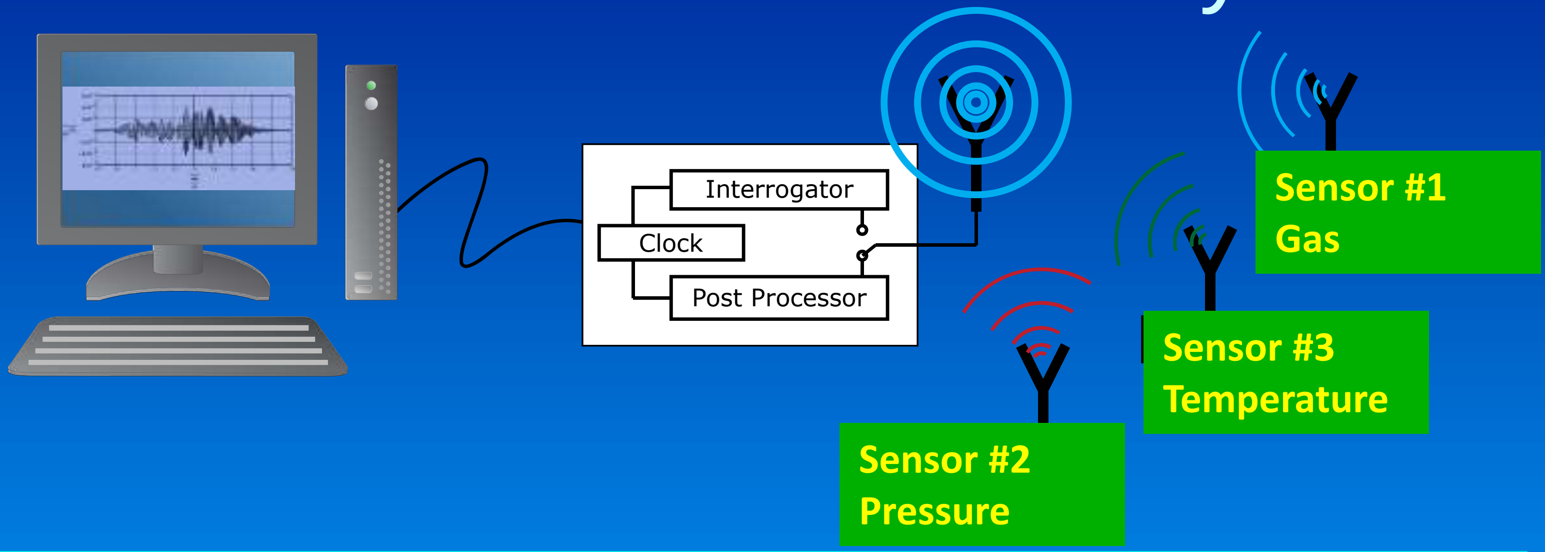
VISION

Basic Passive Wireless SAW System



Basic Goals:

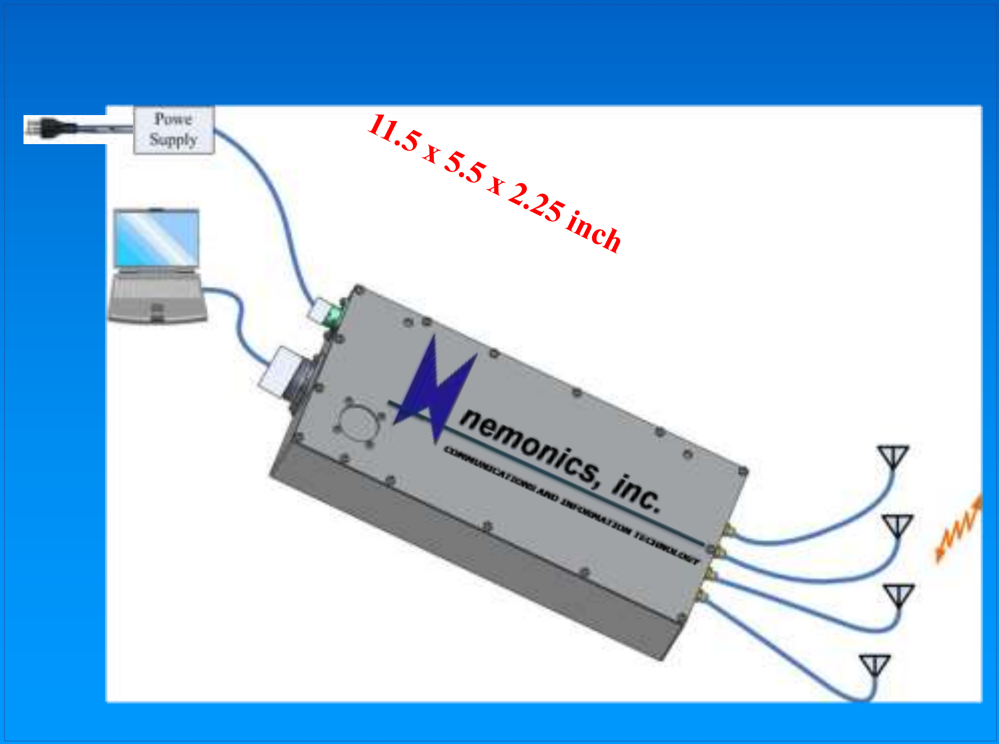
- **Interrogation distance: 1< range < 500 meters**
- **# of devices: 2 – 100's - coded and distinguishable at TxRx**
- **Single platform and TxRx for <u>differing</u> sensor combinations**
- **Wireless backhaul networking**

Wireless RF SAW Interrogator

- *Mechanical Housing*
- *Hardware*
- *Software*
- *DSP*
- *Antenna/Sensor*

First Generation

Second Generation



Wireless RF SAW Interrogator- 2nd Generation

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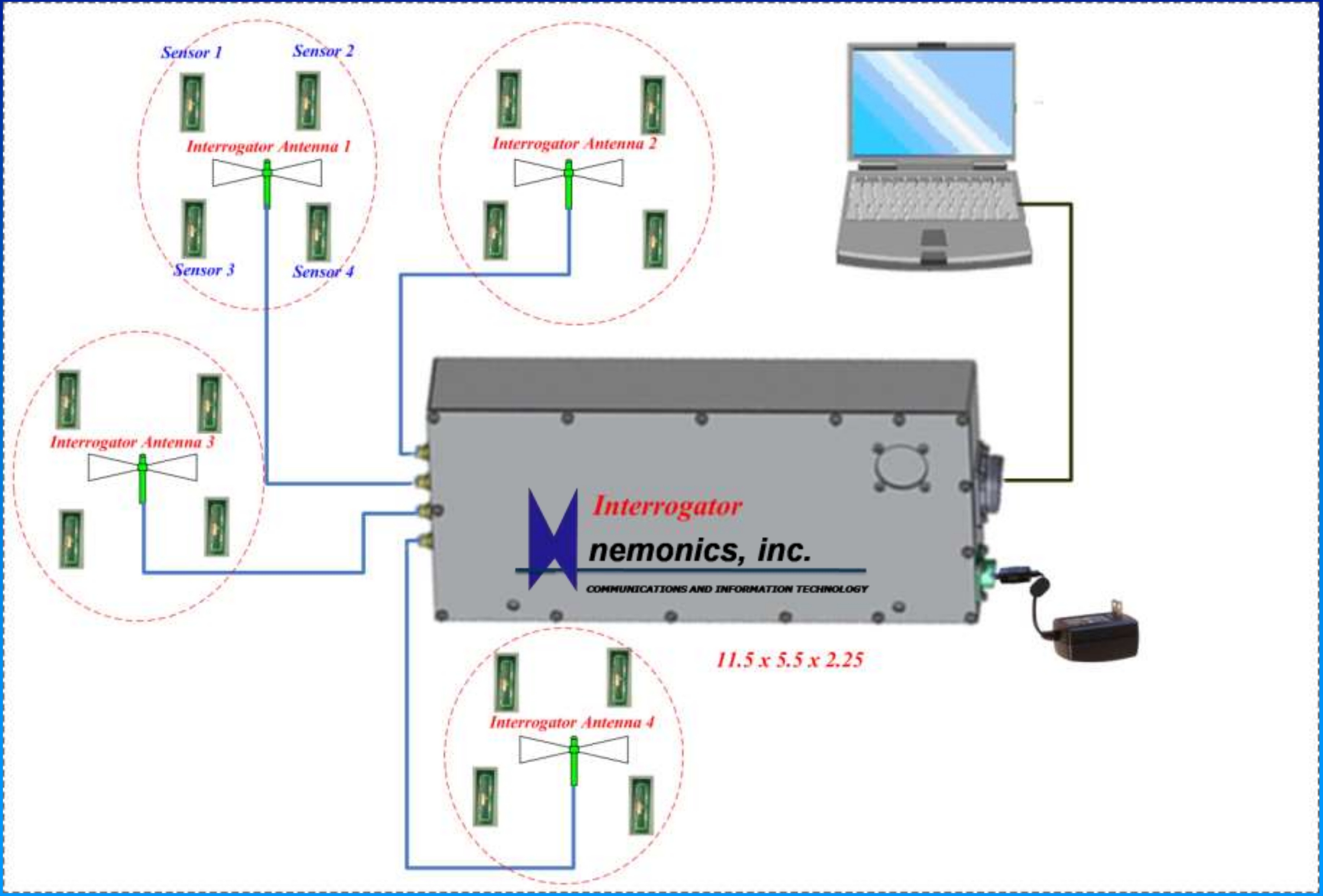
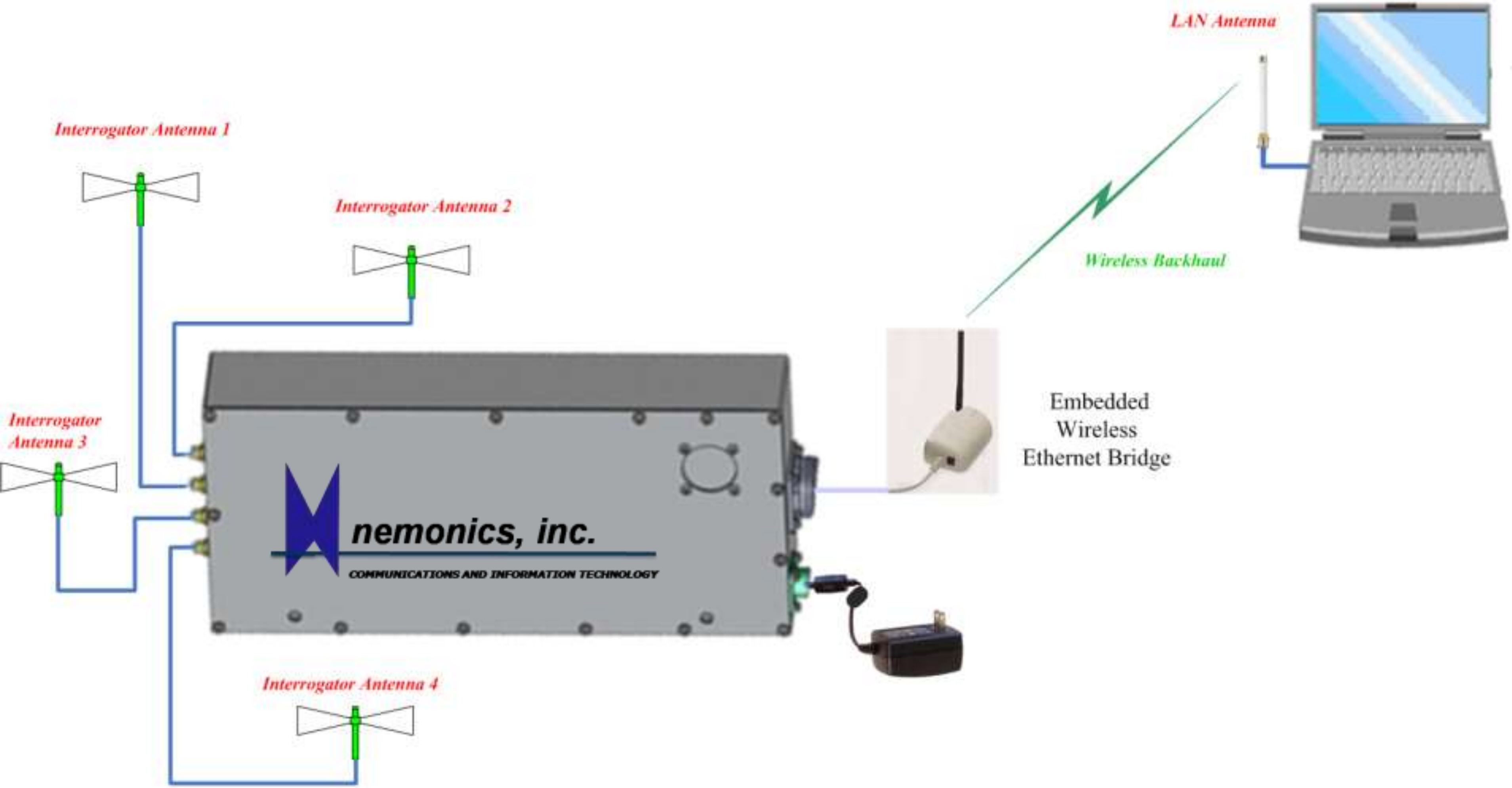
COMMUNICATIONS AND INFORMATION TECHNOLOGY

Wireless RF SAW Interrogator- 2nd Generation

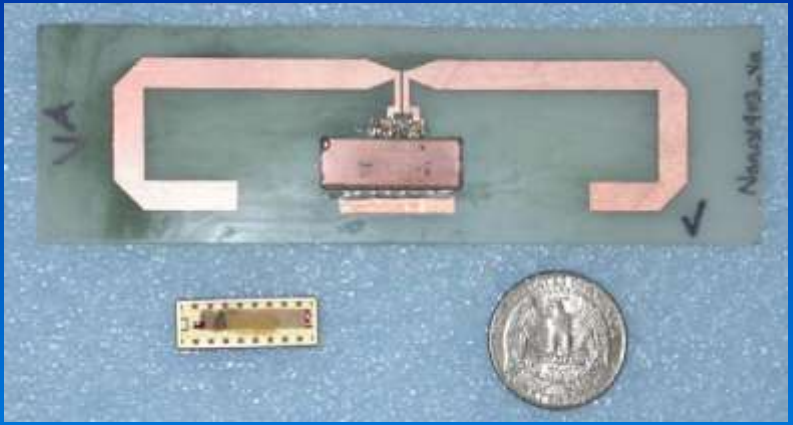


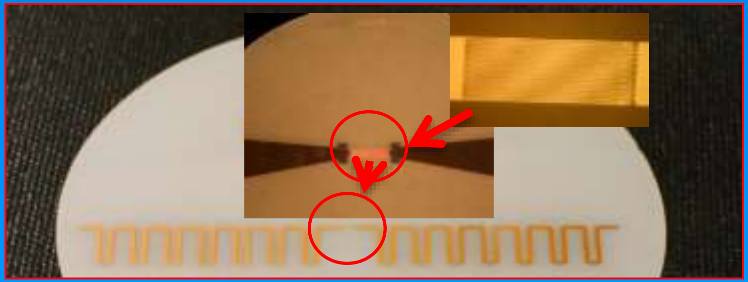
Wireless RF SAW Interrogator- 2nd Generation With Wireless Backhaul Option



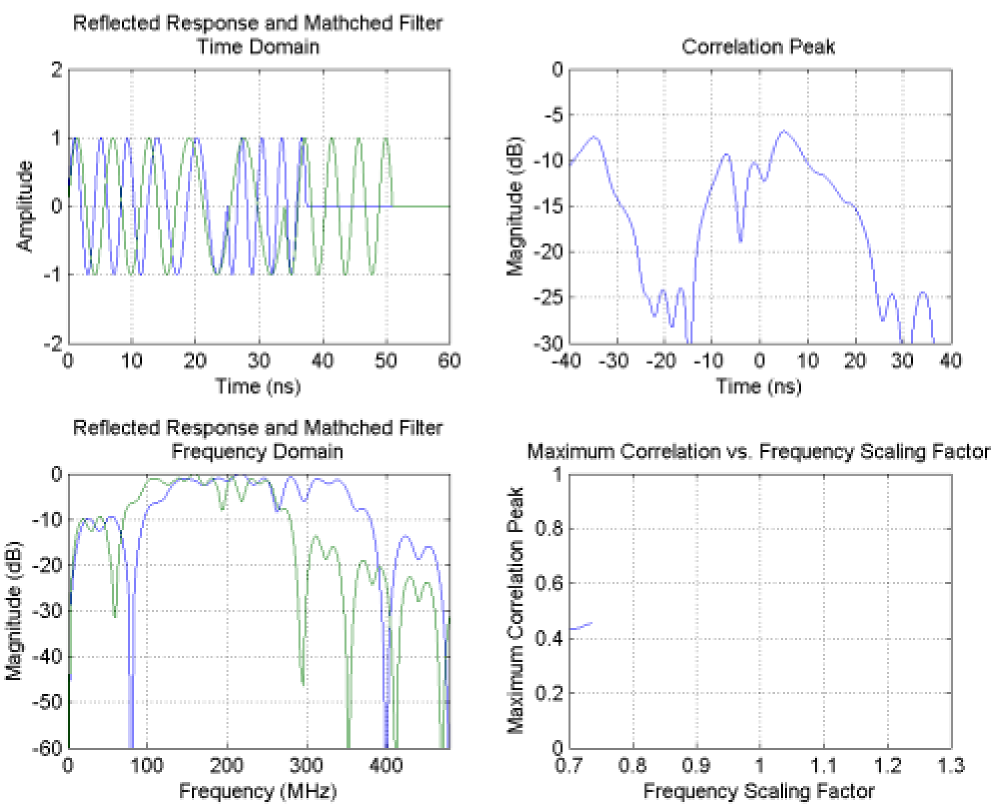
Wireless RF SAW Multi-Node Network

915 MHz Wireless Passive SAW System Demonstration



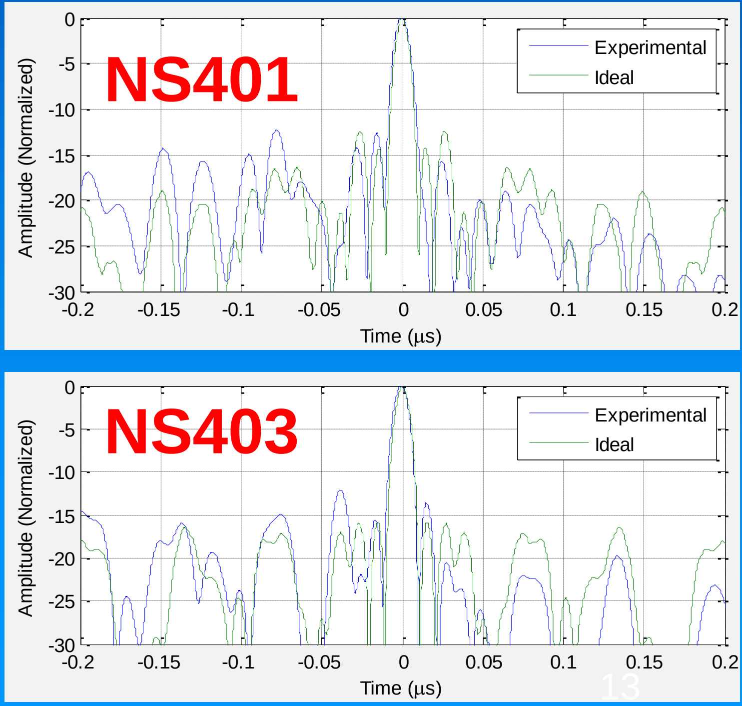


Temperature Extraction Using Adaptive Correlator



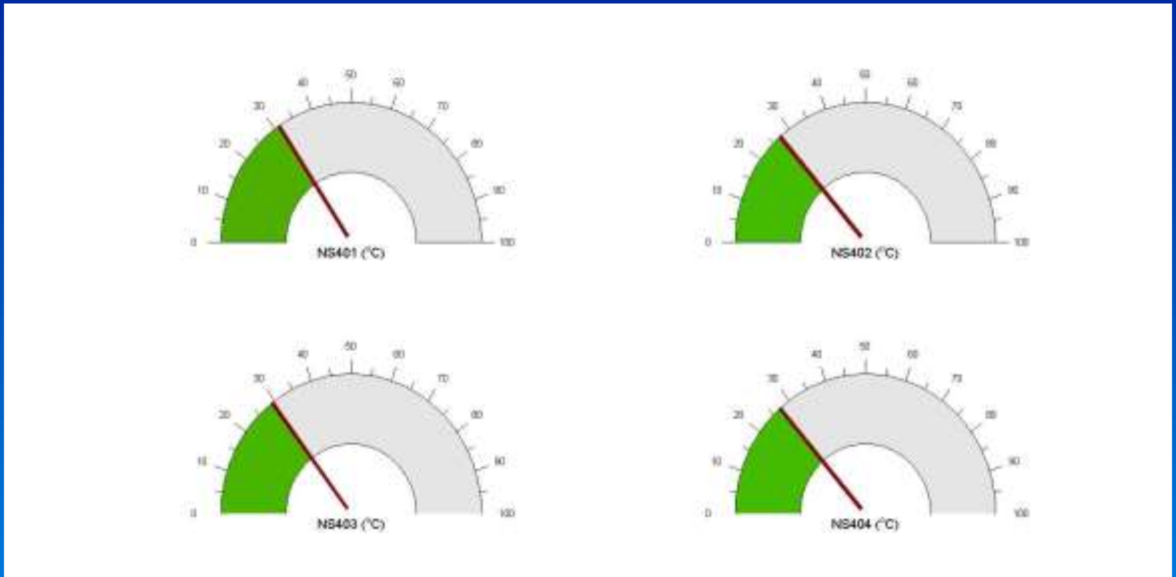
Comparison of ideal and measured matched filter of two different SAW sensors : 5-chip frequency(below)

Normalized amplitude (dB) versus time

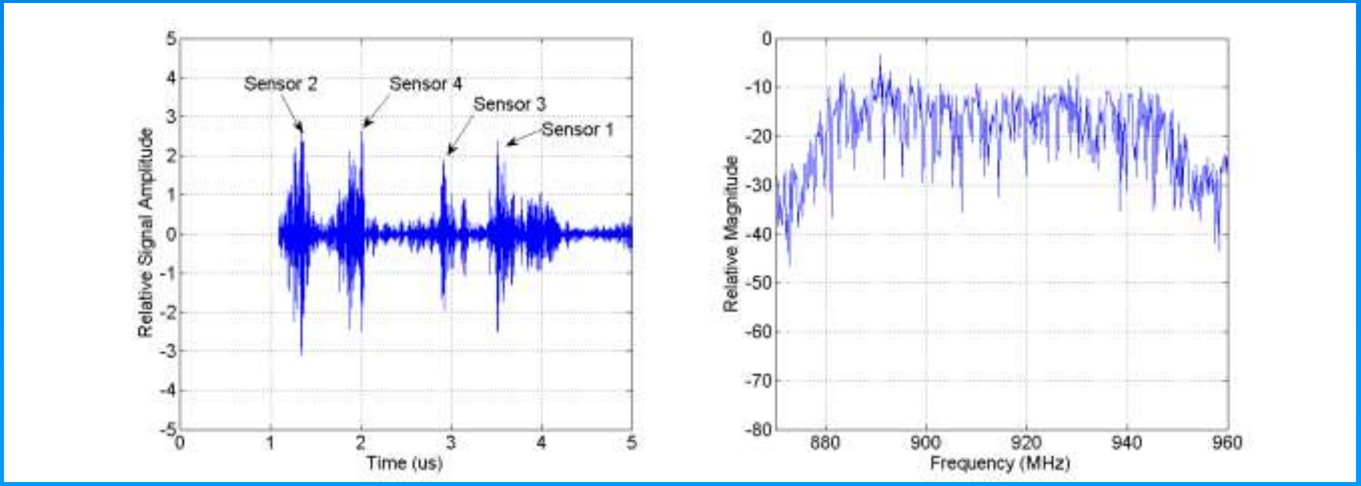


Stationary plots represent idealized received SAW sensor RFID signal at ADC. Adaptive filter matches sensor RFID temperature at the point when maximum correlation occurs.

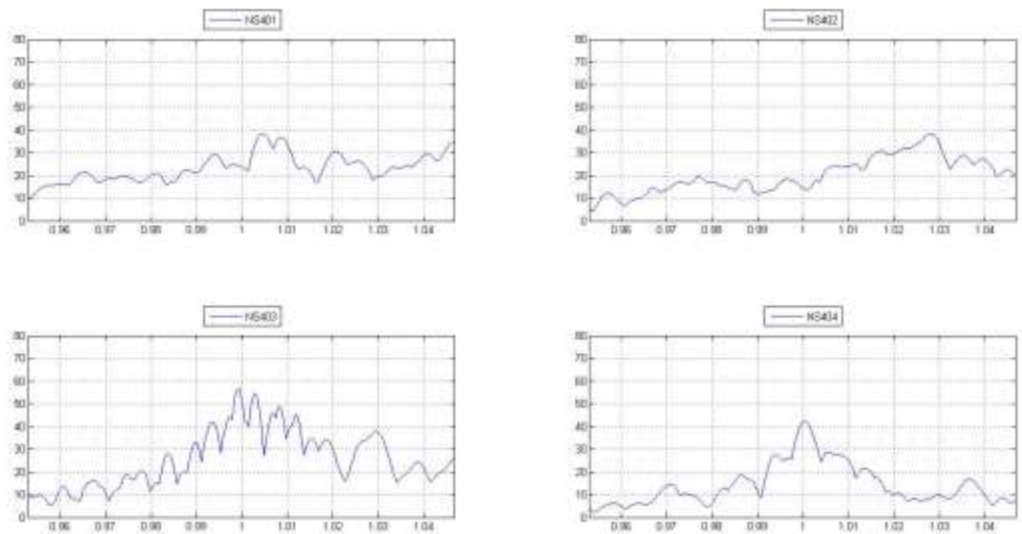
Wireless RF SAW Interrogator- 2nd Generation Software Display

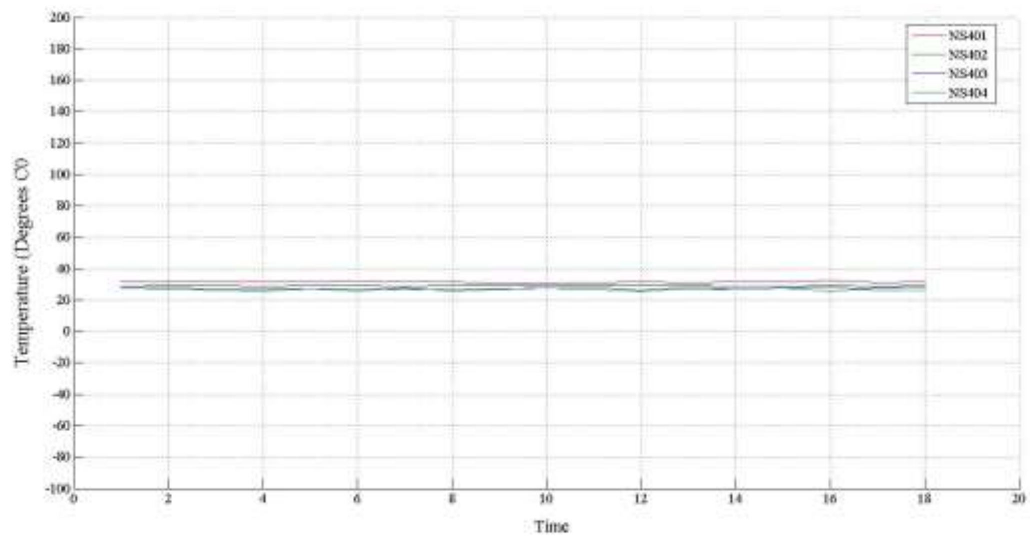


2nd Generation Diagnostic Mode Software



Wireless RF SAW Interrogator- 2nd Generation DSP





General SAW Background

- **SAW RFID Tags - integrated or external sensors**
  - ❑ **Passive – powered by interrogation signal**
  - ❑ **Radiation hard**
  - ❑ **Operational temperatures ~ 0 - 700^{+} K**
  - ❑ **Various sensor platforms**
  - ❑ **Coded multi-sensors**

Why Use SAW Sensors and Tags?

- Frequency/time are measured with greatest accuracy compared to any other physical measurement (10^{-10} - 10^{-14}).
- External stimuli affects device parameters (frequency, phase, amplitude, delay)
- Frequency range (practical) ~100 MHz – 3 GHz
- Monolithic structure fabricated with current IC photolithography techniques, small, solid state
- Complex signal processing

What is a typical SAW Device?

- A solid state device
  - Provides very complex signal processing in a very small volume
- Approximately 4-5 billion SAW devices are produced each year

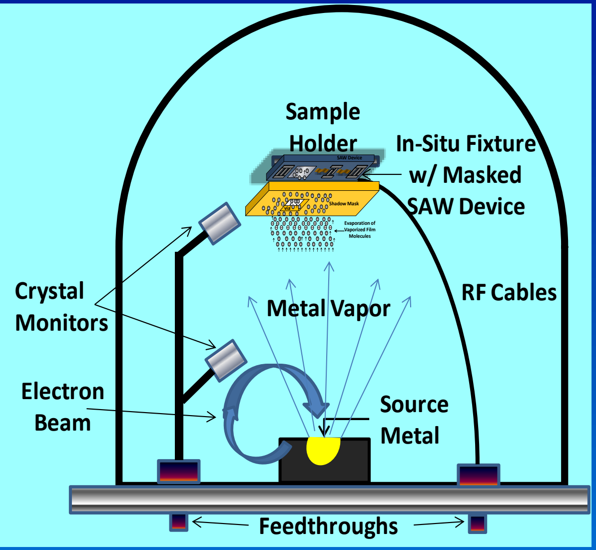
Applications:

Cellular phones and TV (largest market)

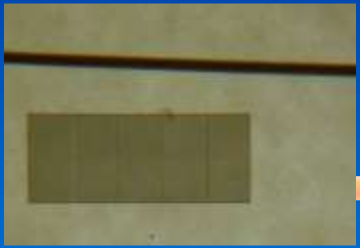
Military (Radar, filters, advanced systems

Currently emerging – sensors, RFID

SAW Fabrication Techniques



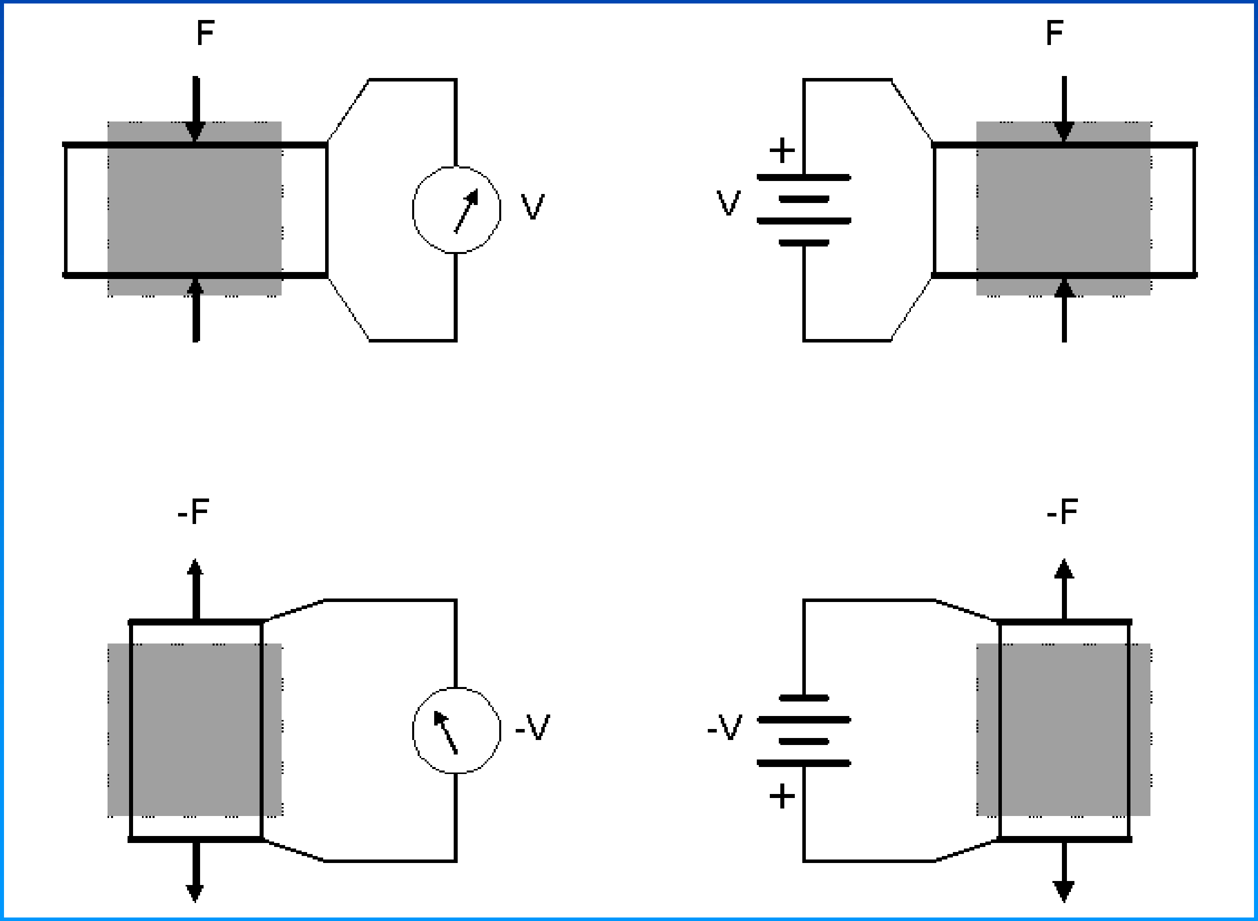
The dark line in micrograph is a 23 um gold wire



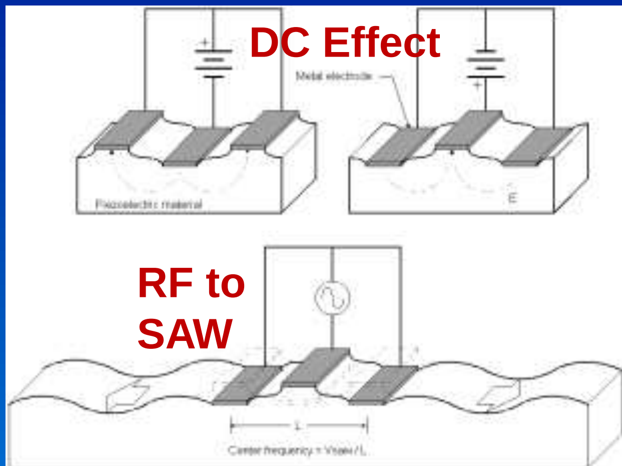
- **SAW devices @ 1 GHz require submicron lithography.**
- **Standard IC thin films, photolithography and processing are used.**

SAW Principle - Piezoelectricity

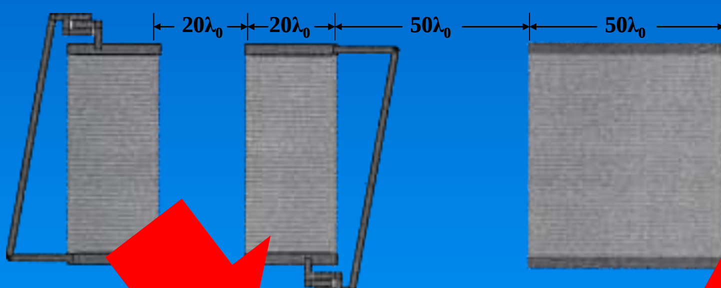
I. A voltage can compress or dilate a piezo-crystal.
II. Squeezing a piezo-crystal creates a voltage.

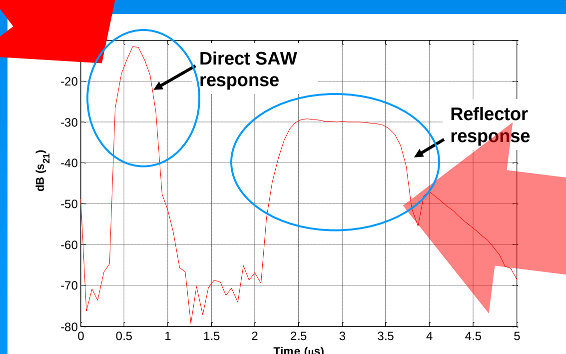


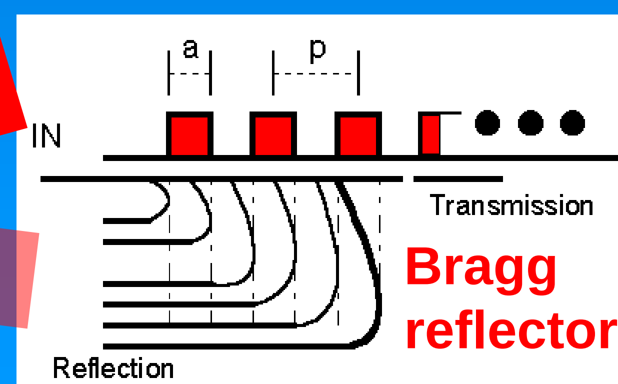
SAW Basics
Transduction & Reflection fro SAW Sensors



- SAW - mechanical wave trapped to the surface
- Transduction via piezoelectric effect
- Velocity ~ 3000 - 4000 m/sec
- Wavelength @ 1 GHz ~ 3 um
- Line resolution at 1 GHz ~ .75 um
- Reflection via Bragg reflector structure







RFID and SAW Comparison

Wireless Passive RFID Sensor

Any passive RFID sensor = a frequency dependent optimized passive radar target.

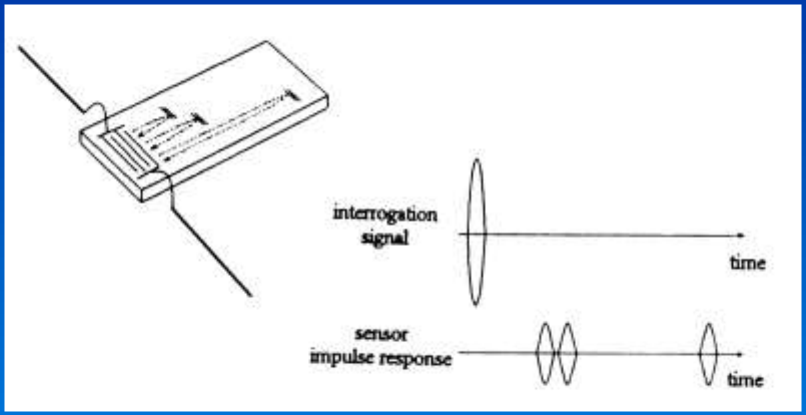
Two primary system functions:

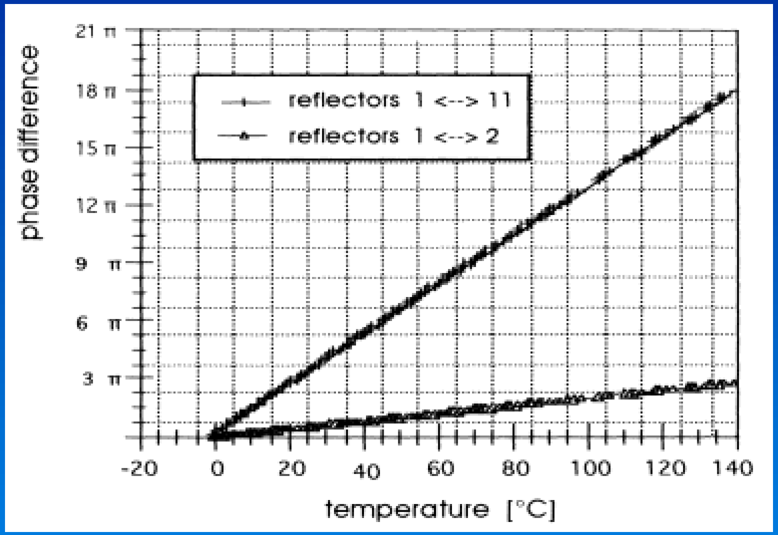
RFID acquired first - quantized/discrete: 1-yes or 0-no

The measurand extracted – analog quantifiable information.

- RFID Acquisition
  - Priority for system
  - Function of System Parameters
- Measurand Extraction
  - RFID is acquired
  - S/N ratio
  - Accuracy
  - Acquisition rate

Reflective Time Delay Line Sensor
Single device - No Coding



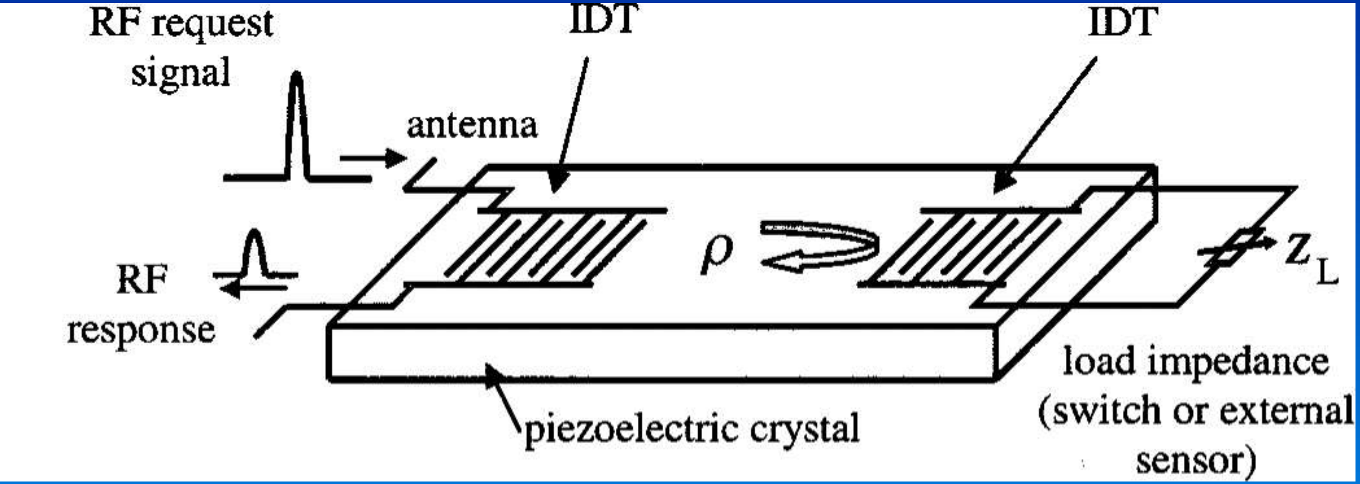


"Wireless Interrogator System for SAW-Identification-Marks and SAW-Sensor Components",

F. Schmidt, et al, 1996 IEEE International Frequency Control Symposium

- First two reflectors define operating temperature range of the sensor
- Time difference between first and last echoes used to increase resolution of sensor
- No coding as shown

Impedance SAW Time Delay Sensors- Single device No coding



"State of the Art in Wireless Sensing with Surface Acoustic Waves",

W. Bulst, et al, IEEE UFFC Transactions, April 2001

- External classical sensor or switch connected to second IDT which operates as variable reflector
- Load impedance causes SAW reflection variations in magnitude and phase
- No discrimination between multiple sensors as shown

SAW Frequency Chirp Sensor Single device – No Coding

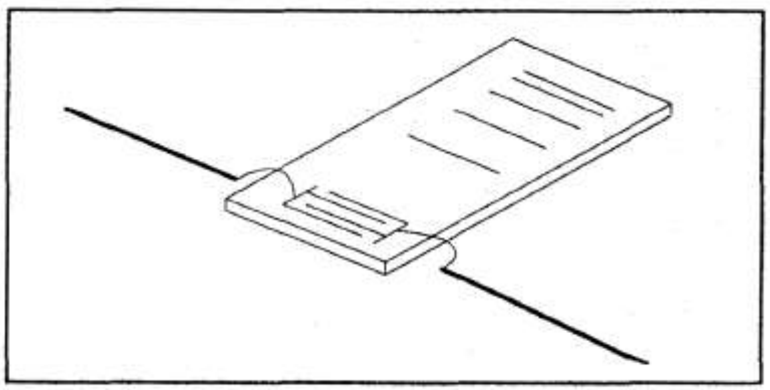
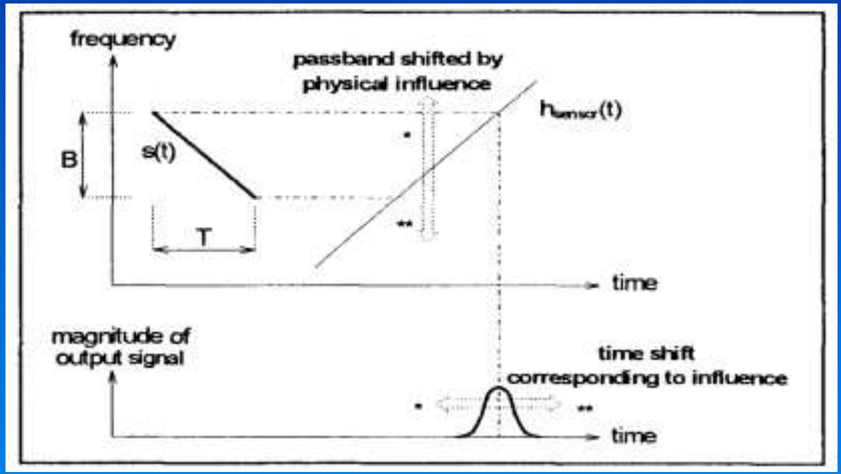


Fig. 2: Symbolic drawing of a dispersive one-port SAW sensor (up-chirp)



"Spread Spectrum Techniques for Wirelessly Interrogable Passive SAW Sensors",

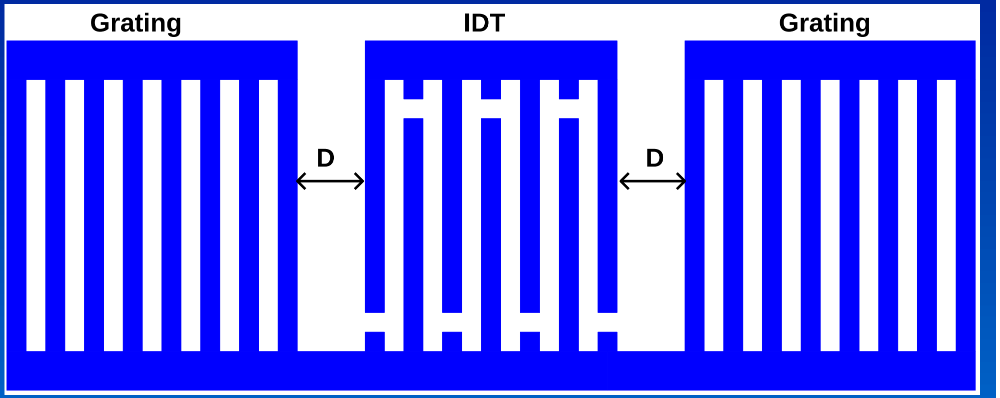
A. Pohl, et al, 1996 IEEE Symposium on Spread Spectrum Techniques and Applications

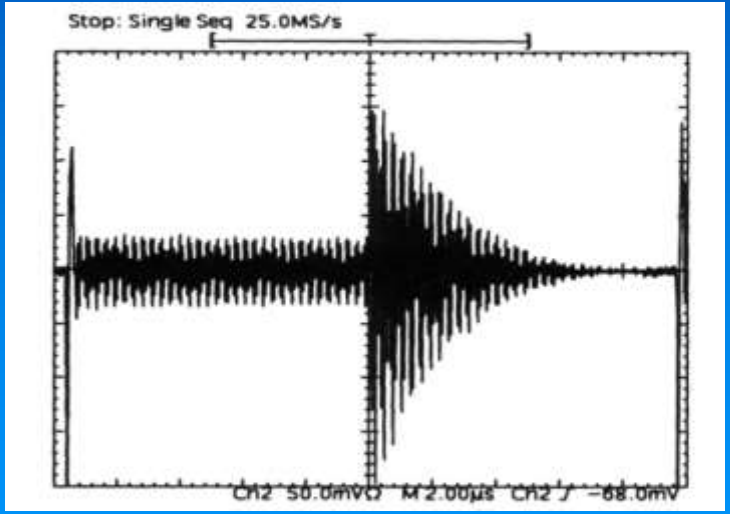
- Increased sensitivity when compared with simple reflective delay line sensor
- Multi-sensor operation not possible due to lack of coding

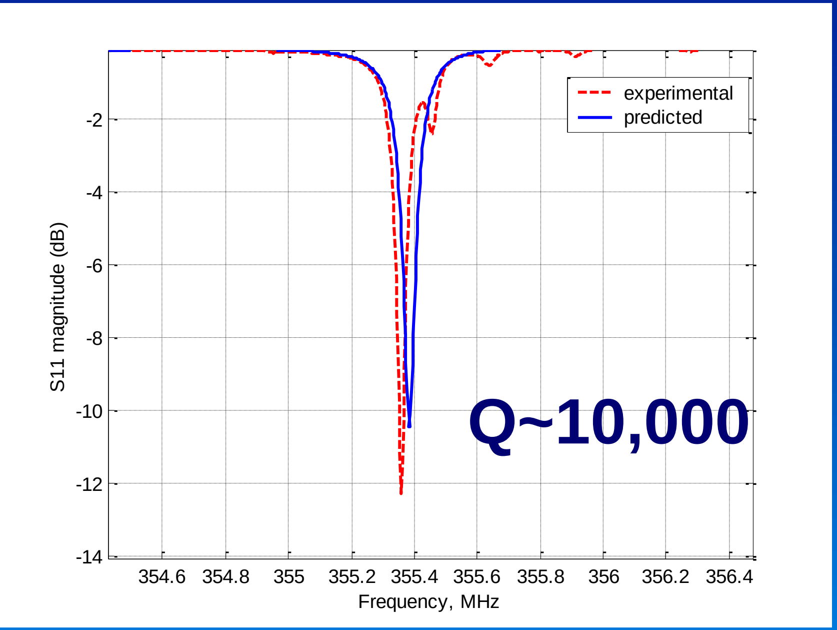
SAW RFID Practical Approaches

- **Resonator** - Frequency
  - Fabry-Perot Cavity
  - Frequency selective, SAW device Q~10,000
- **Code Division Multiple Access** (CDMA)- Time
  - Delay line – single frequency Bragg reflectors
  - Pulse position encoding
- **Orthogonal Frequency Coding** (OFC)- Time&Frequency
  - Delay line, multi-frequency Bragg reflectors
  - Pulse position encoding
  - Frequency coupled with time diversity

SAW Resonator - Frequency





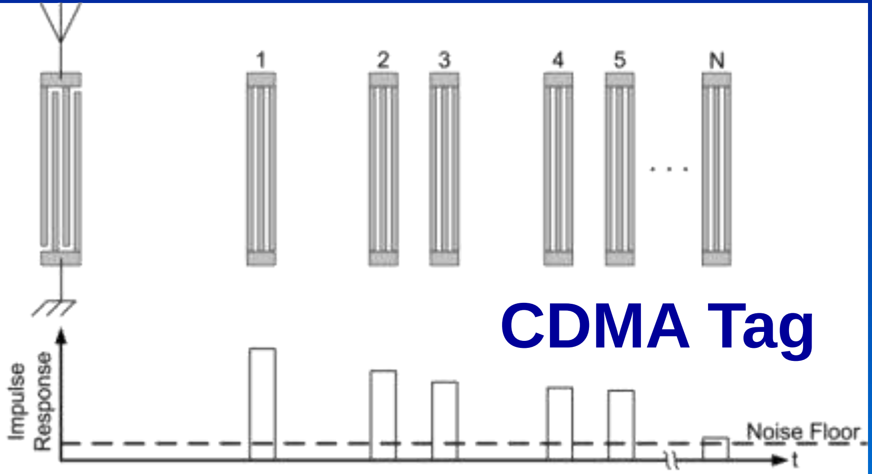


"Remote Sensor System Using Passive SAW Sensors",

W. Buff, et al, 1994 IEEE International Ultrasonics Symposium

- Resonant cavity
- Frequency with maximum returned power yields sensor temperature
- High Q, long time response
- Multi-device coding via frequency domain by separating into bands
- Frequency variation encodes information

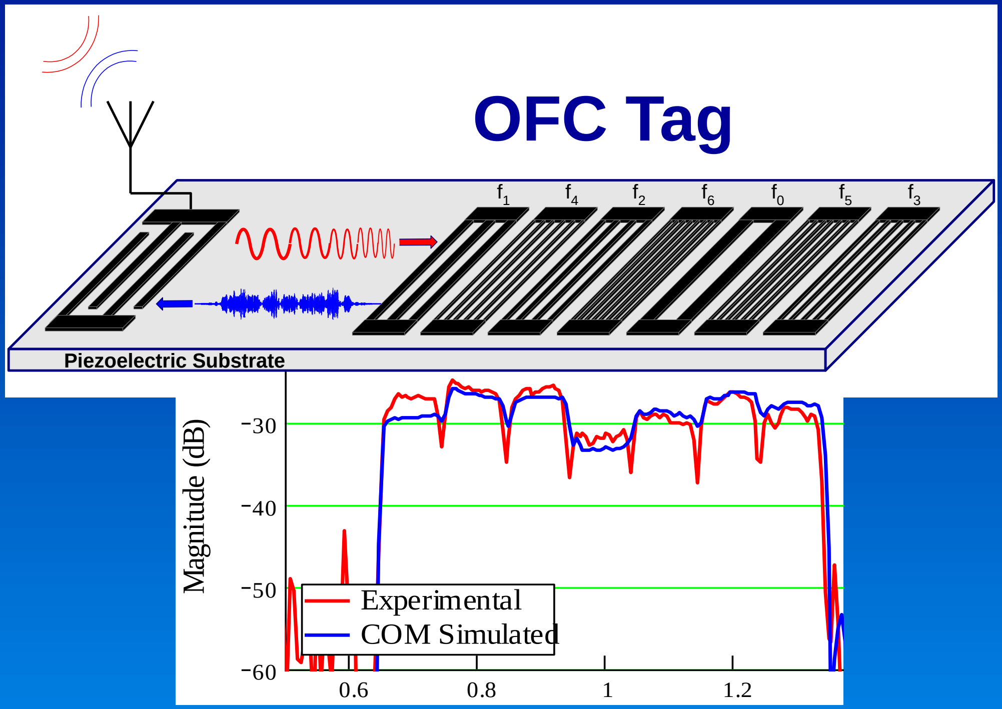
SAW CDMA Time Delay Line

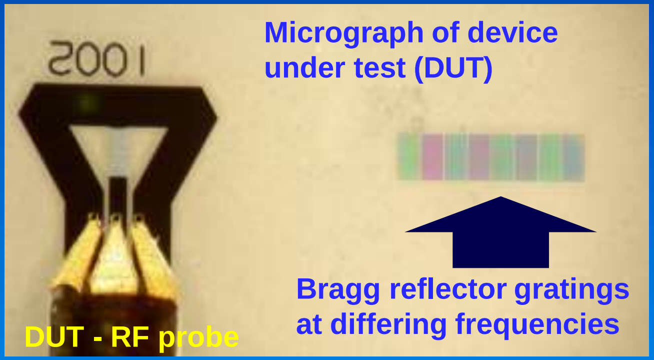


CDMA Tag Concept

- Single frequency Bragg reflectors
- Coding via pulse position modulation
- Large number of possible codes
- Short chips, low reflectivity - (typically 40-60 dB IL)
- Early development by Univ. of Vienna, Siemens, and others

SAW OFC Delay Line Time &Frequency

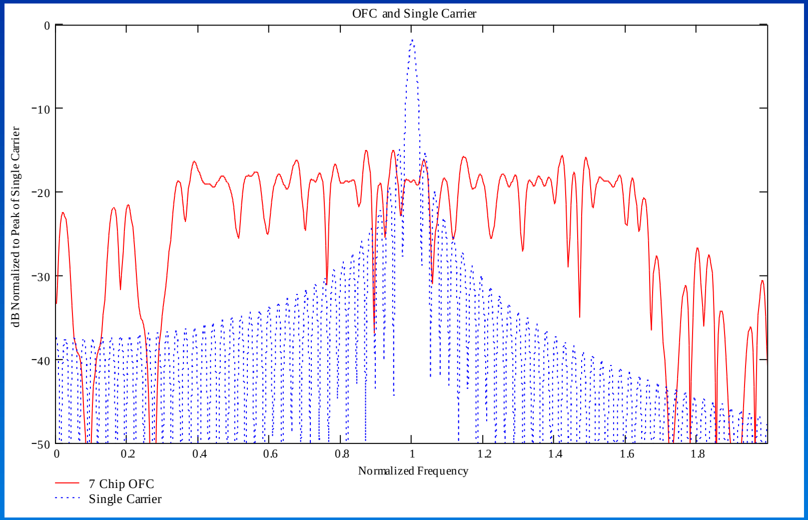




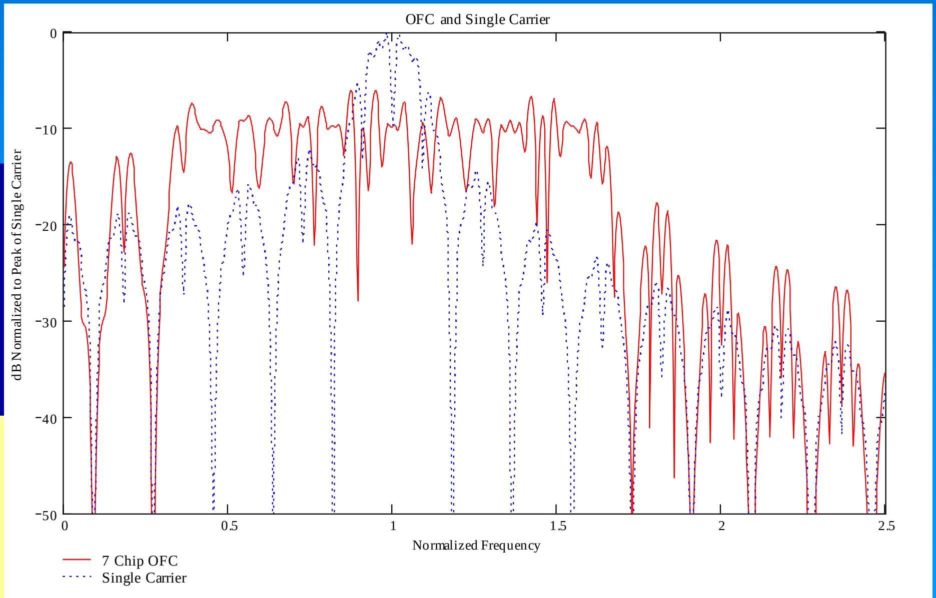
OFC Tag

- Multi-frequency (7 chip example) - large number of codes
- Long chips, high reflectivity
- Orthogonal frequency reflectors –low loss (6-10 dB)
- Example time response (non-uniformity due to transducer)

PN-OFC vs. Single Carrier Single Carrier CDMA



OFC 7-Chip vs. Single Carrier Frequency Response

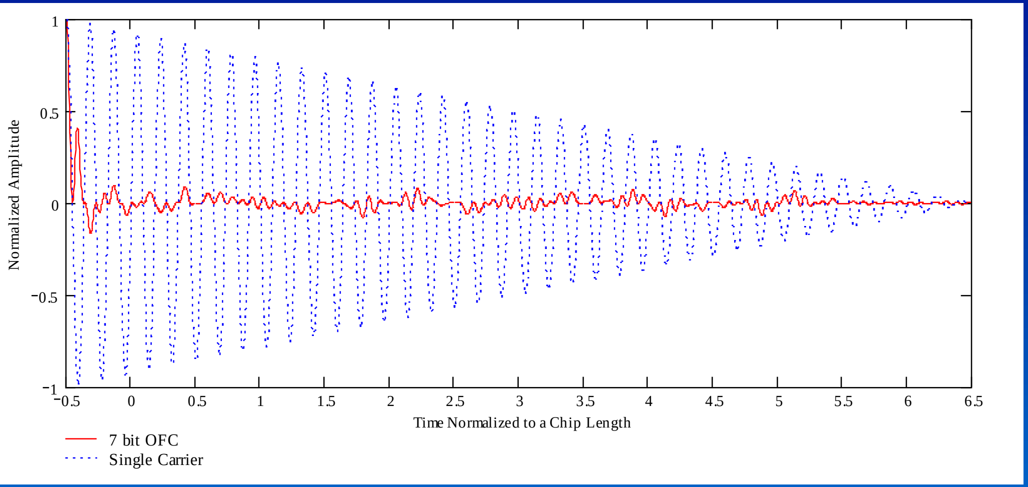


OFC 7-Chip vs. Single Carrier CDMA PN Code Frequency Response

For PN, PG=7

For OFC, PG=49

Time Autocorrelation Comparison

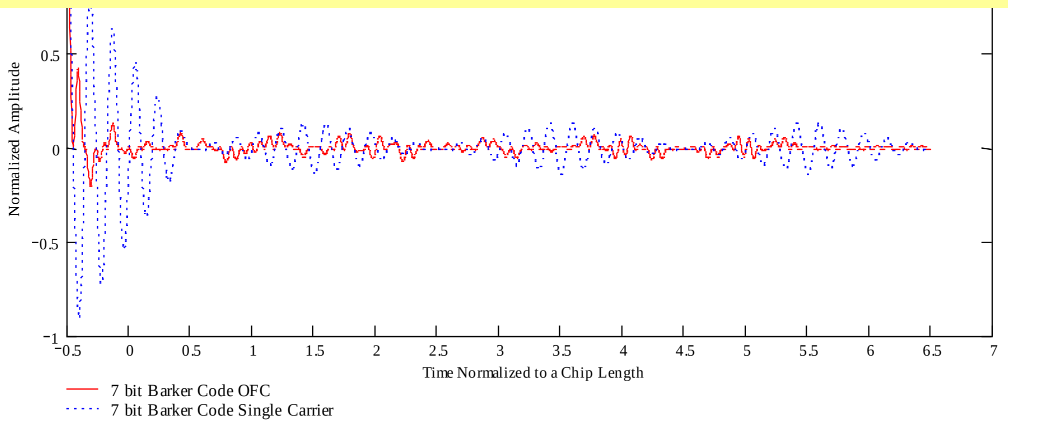


OFC 7-Chip vs. Single Carrier
Time Autocorrelation

For PN, compressed pulse width is 2 chips

For OFC, compressed pulse width is 0.29 chips

OFC vs. Single Carrier CDMA PN with 7 Chip Barker Code -
Time Autocorrelation

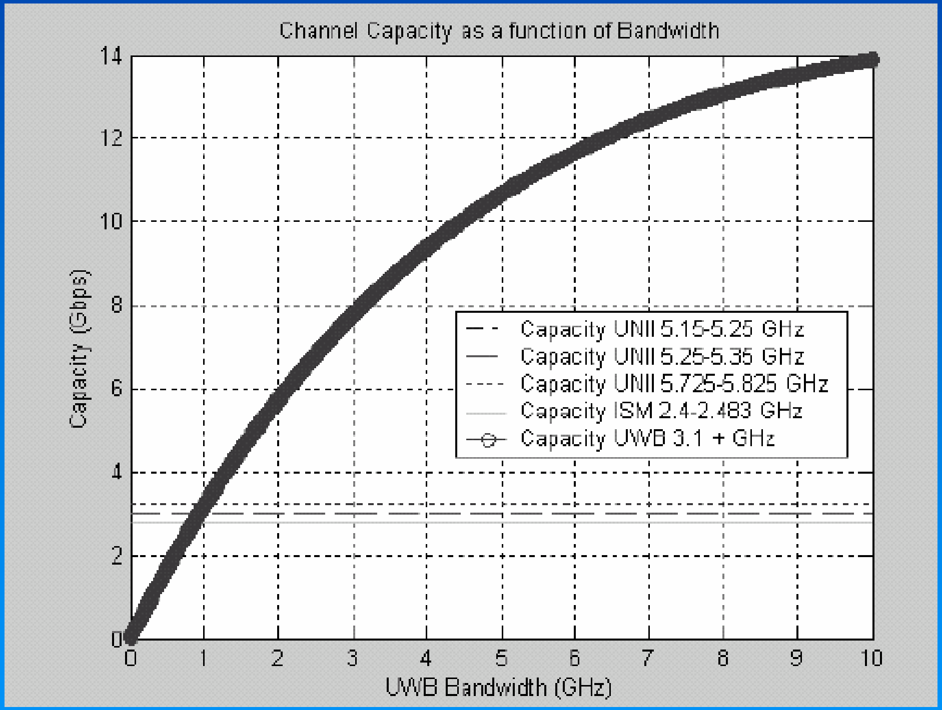


UWB vs. "Narrowband" Communication Systems

From: IEEE Ultra wideband Presentation October 21, 2003, Jim Silverstrim

Consider Shannon's capacity equation – Capacity increases faster as a function of BW than a function of power.

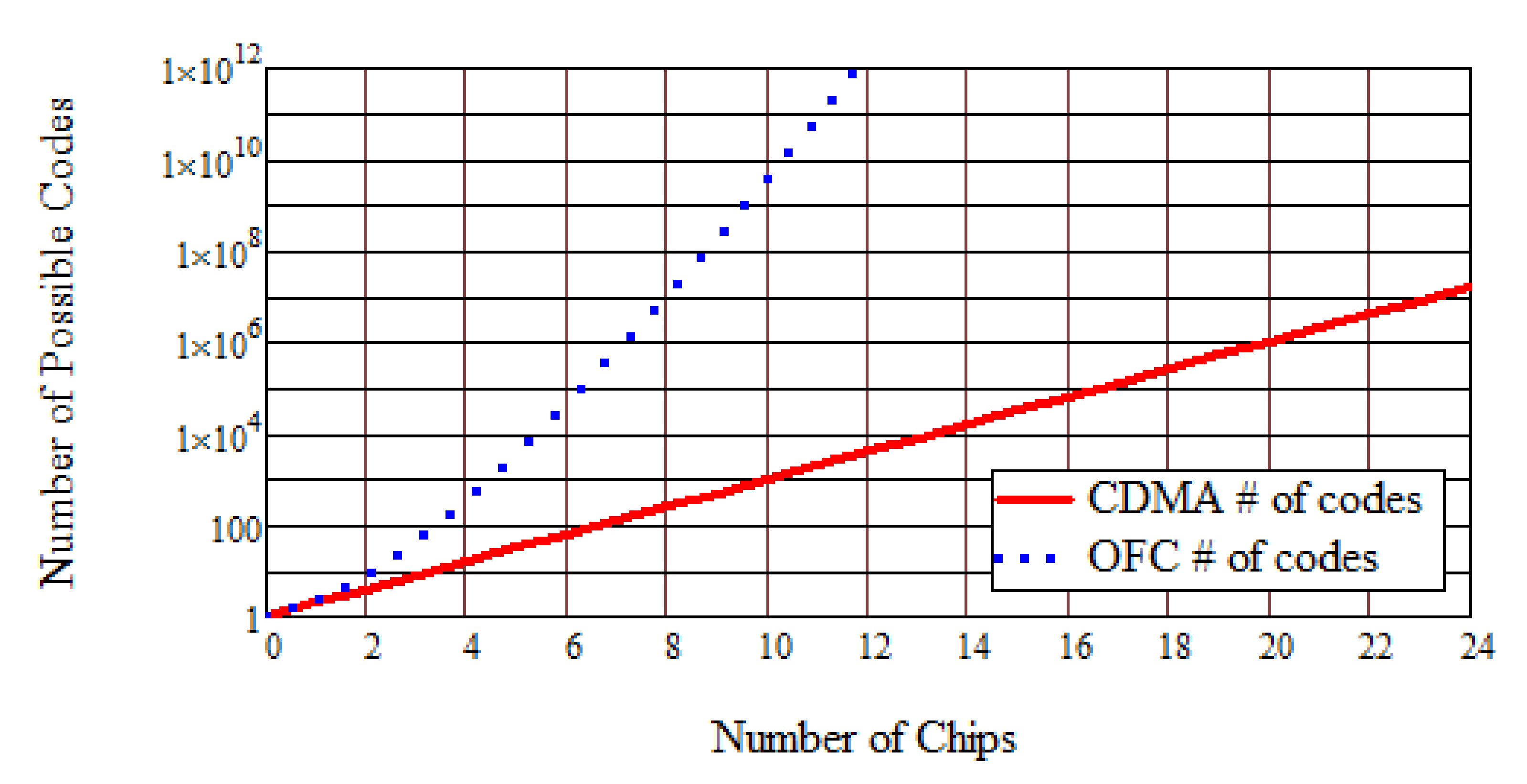
$$C = B \log_2 \left(1 + \frac{P}{BN_0}\right)$$



where : ***C = Channel Capacity (bits /sec)***
B = Channel Bandwidth (Hz)
P = Received Signal Power (watts)
No = Noise Power Spectral Density (watts /Hz)

OFC vs CDMA

Number of possible codes versus number of chips for same chip configuration



CDMA: # codes=2^N

OFC: # codes=$N!*2^N$ where N= #chips

Discussion

Resonator, CDMA, and OFC embodiments have all been successfully demonstrated and applied to various applications. Devices and systems have been built in the 200 to 2400 MHz bands by differing groups.

Resonator

- Minimal delay
- Narrowband PG~1
- Fading
- Frequency domain coding
- High Q – long impulse response
- Low loss sensor

CDMA

- Delay as reqd. ~ 1usec
- Spread Spectrum
  - Fading immunity
  - Wideband
  - PG >1
- Large number of codes using pulse position modulation (PPM)
- High loss

OFC

- Delay as reqd. ~ 1usec
- Spread Spectrum
  - Fading immunity
  - Ultra Wide Band
  - PG >>1
- Large number of codes using PPM and OFC
- Moderate loss

Regulatory Discussion

- Industry will need to drive regulatory changes as applications evolve
- Faraday cage applications
- No regulations for space exploration applications & other
- UWB regulations (FCC 15.503) do not directly address sensors –surveillance systems possibly
- %BW>10% desired

SAW OFC Sensor Embodiments & Details

Why OFC SAW Sensors?

Advantageous

- Frequency & time offer greatest coding diversity
- Single communication platform for diverse sensor embodiments
- Radiation hard
- Wide operational temperature range

1st Demonstrated

- UWB : %BW > 25%
- $\%BW_{MNI}$ ~9%
- Devices with 3-9 OFC chips
- Devices tested between 250-1600 MHz
- Multi-device coding techniques

RFID SAW Sensor
Engineering + Science

Radar

+

Communication

+

SAW

+

Microwave

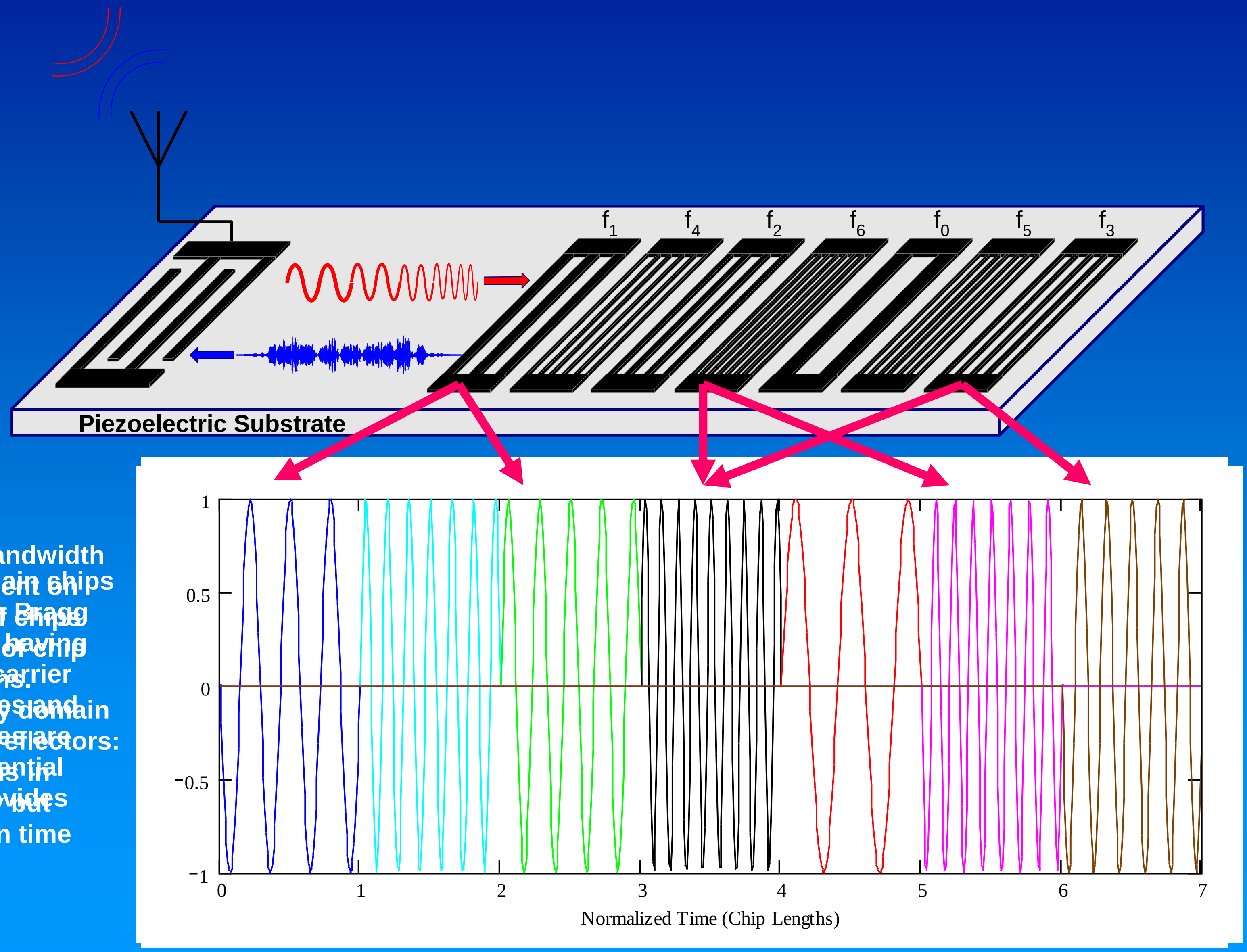
+

Physics

+

Chemistry

Schematic of OFC SAW ID Tag

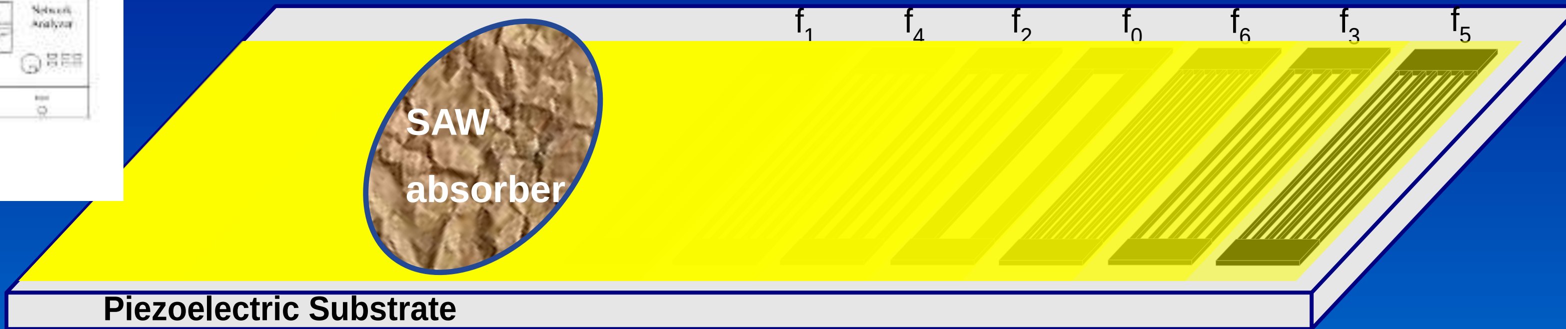


Sensor bandwidth is dependent on number of chips and sum of chip bandwidths.

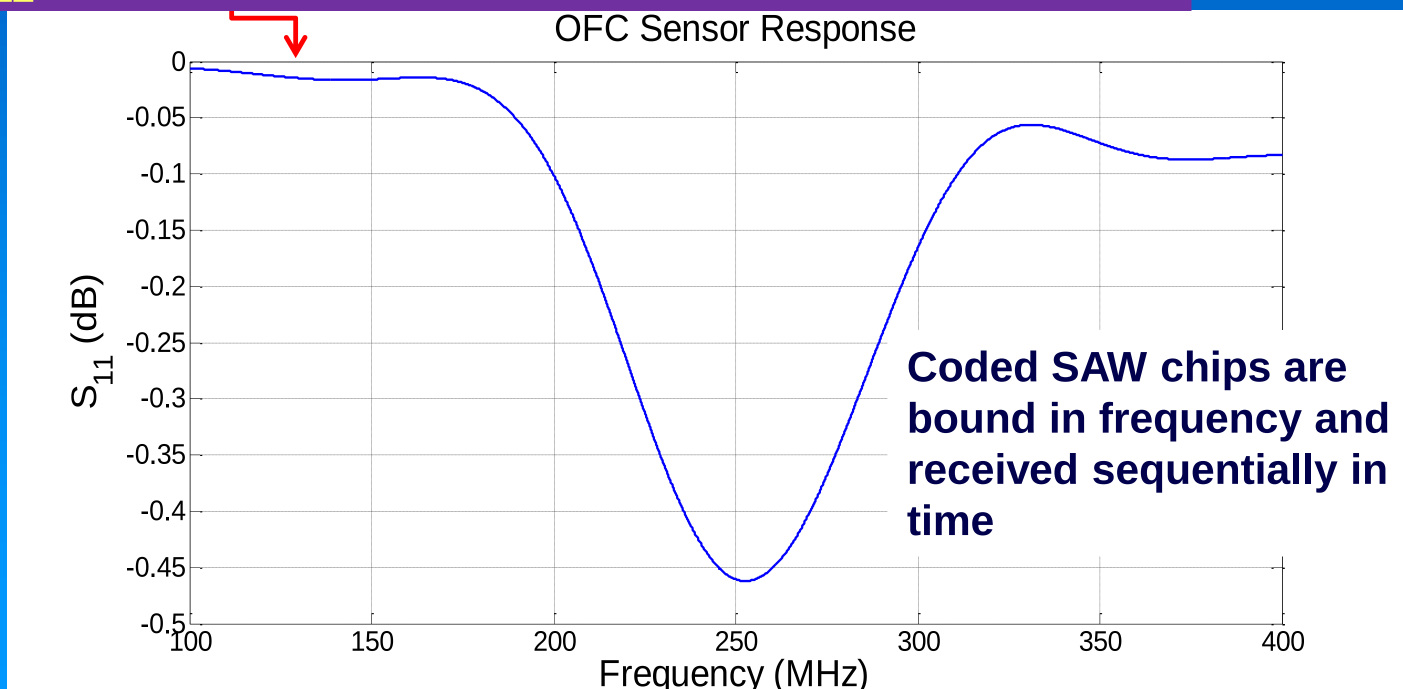
Frequency domain of Bragg reflectors: contiguous in frequency but shuffled in time

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

SAW OFC RFID signal – Target reflection as seen by antenna

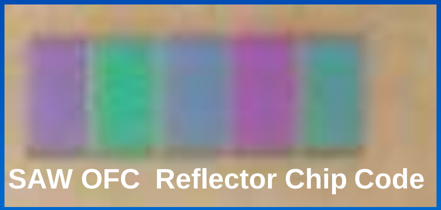


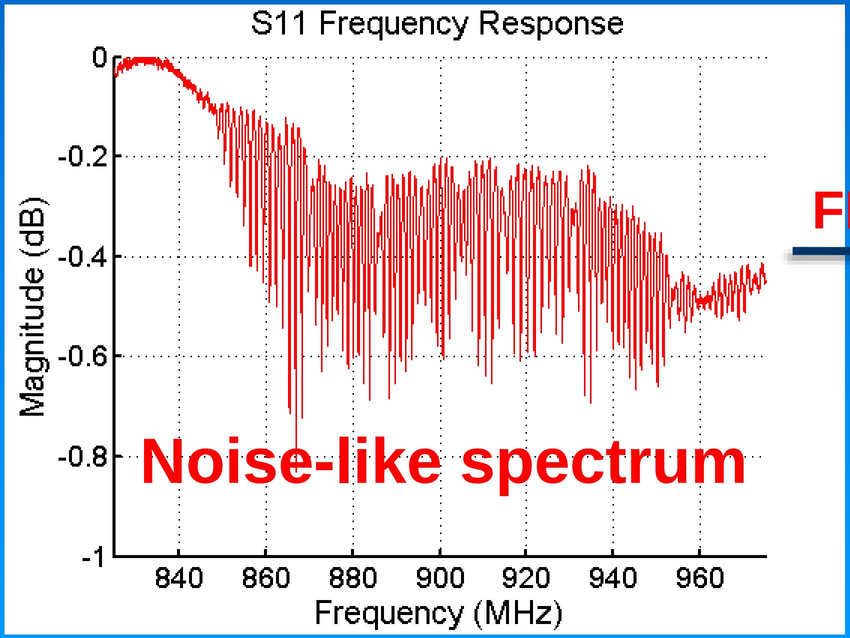
S_{11} w/o absorber and w/ reflectors



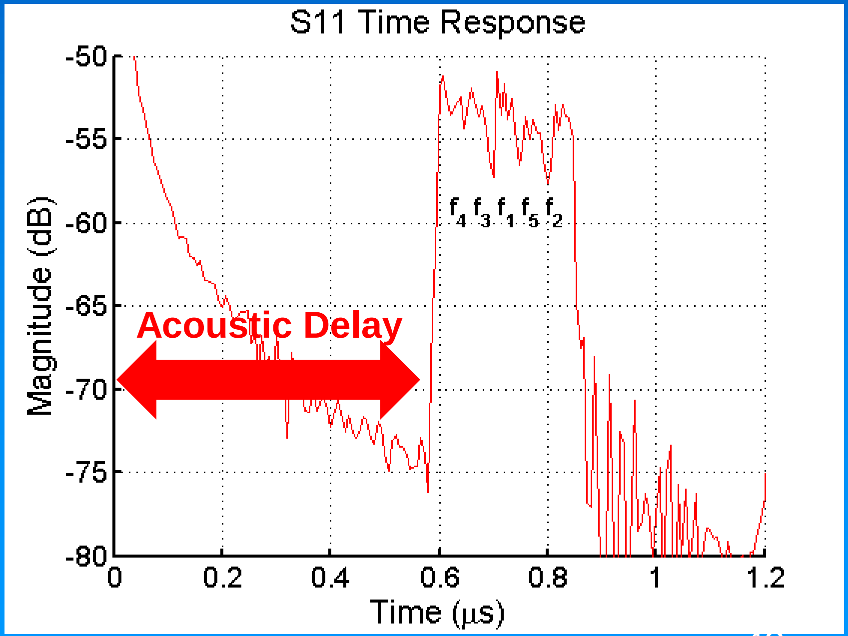
Coded SAW chips are bound in frequency and received sequentially in time

Example 915 MHz SAW OFC Sensor





FFT



SAW RFID Considerations

Givens:

Finite SAW substrate length where coding occurs.

Rate *Time=Distance

Problem:

How to fit the most diverse codes in the limited space-time window allowed and ensure the ensemble of sensors due not produce unacceptable code collisions?

Solution:

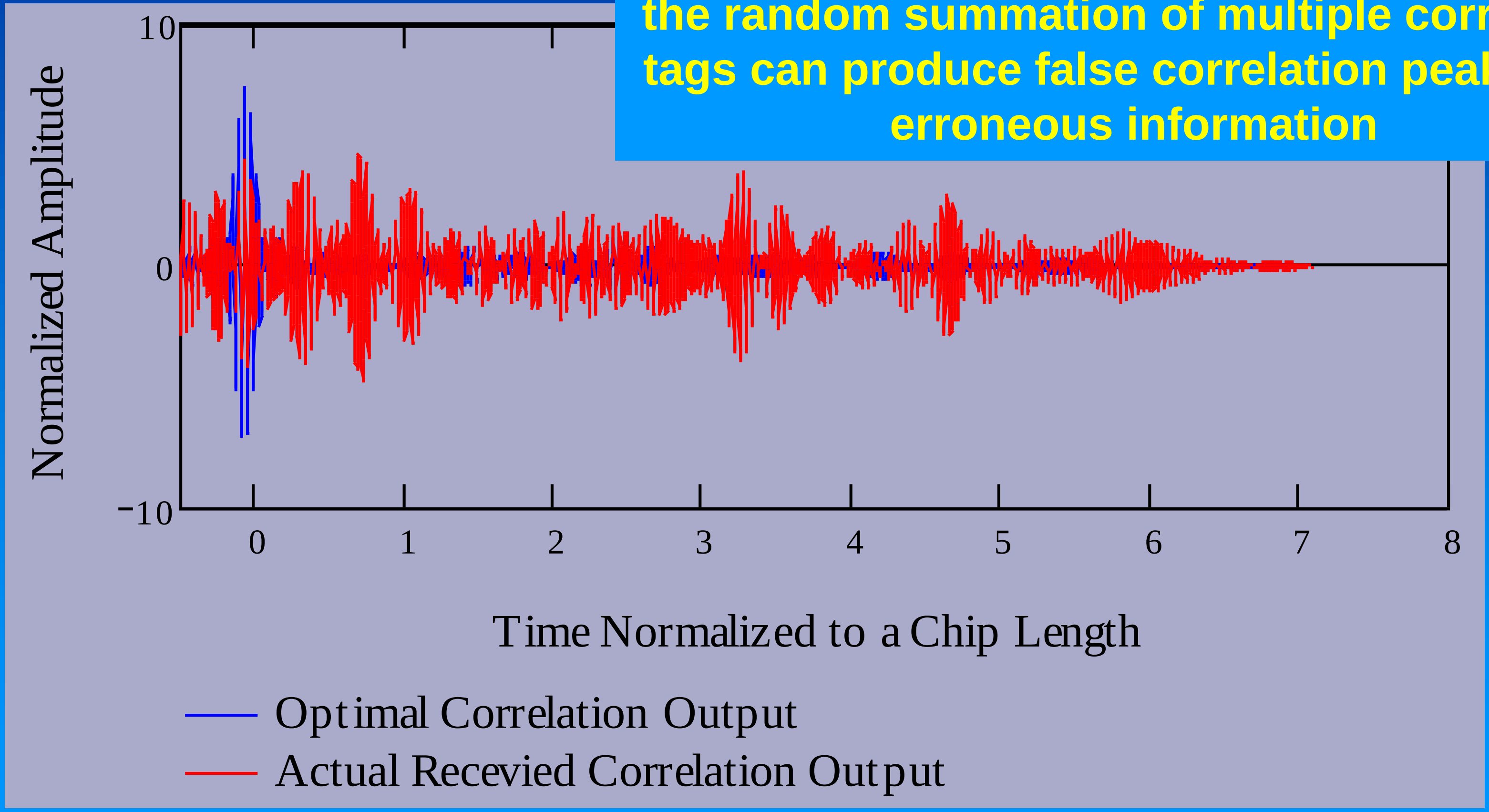
Use an optimum set of codes using frequency and time diversity.

OFC Diversity for Identification

- Frequency Spectrum Diversity per Device
- Time Delay per Device
- Spatial Diversity – device placement
- Sensor & Tx-Rx Antenna Polarization
- Use combinations of all to optimize system

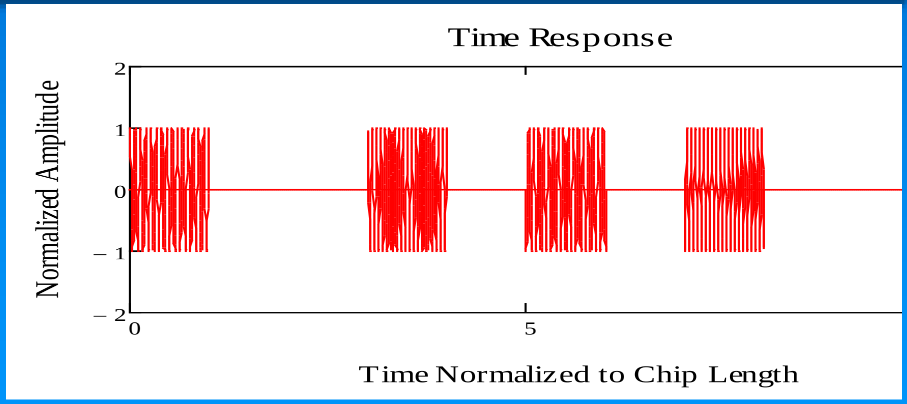
Effect of Code Collisions from Multiple SAW RFID Tags –Simulation 32 codes

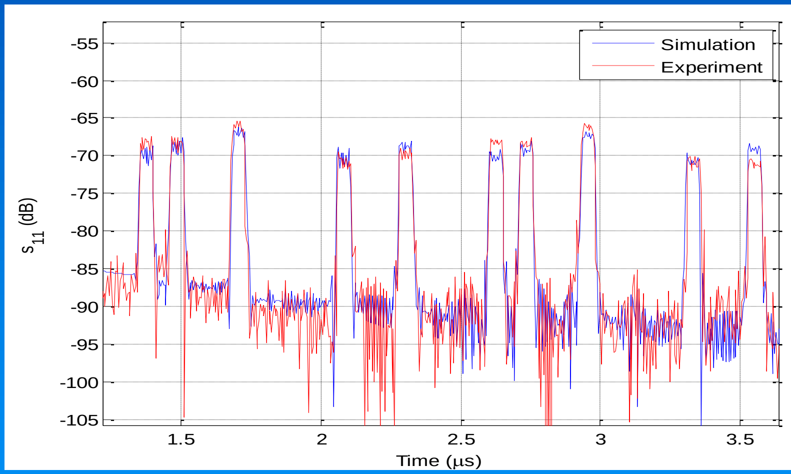
Due to asynchronous nature of passive tags, the random summation of multiple correlated tags can produce false correlation peaks and erroneous information



OFC Coding

- Time division diversity (TDD): Extend the possible number of chips and allow delay and phase modulation
  - – # of codes increases dramatically, M>N chips, $>2^M*N!$
  - – Reduced code collisions in multi-device environment



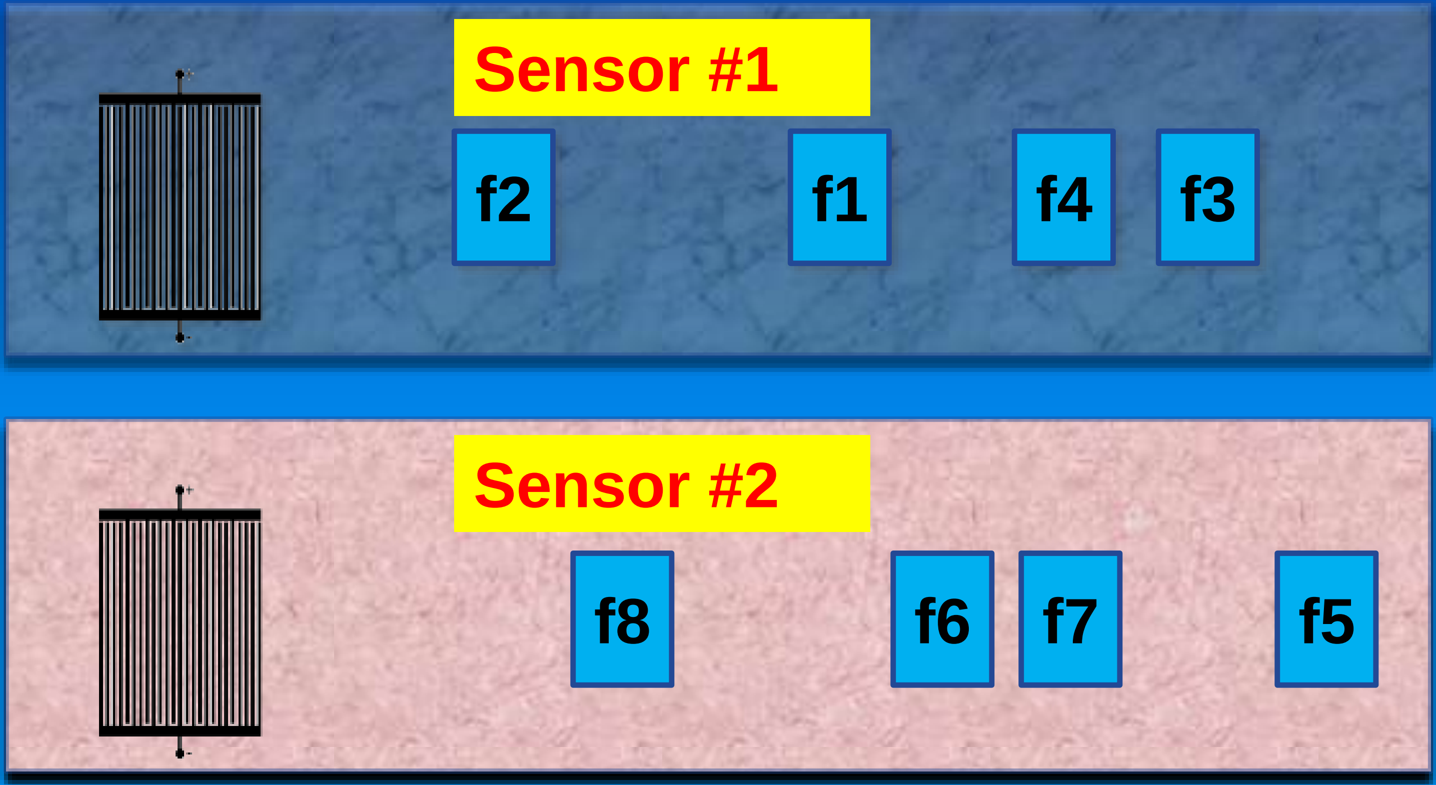


456 MHZ SAW OFC TDD Coding

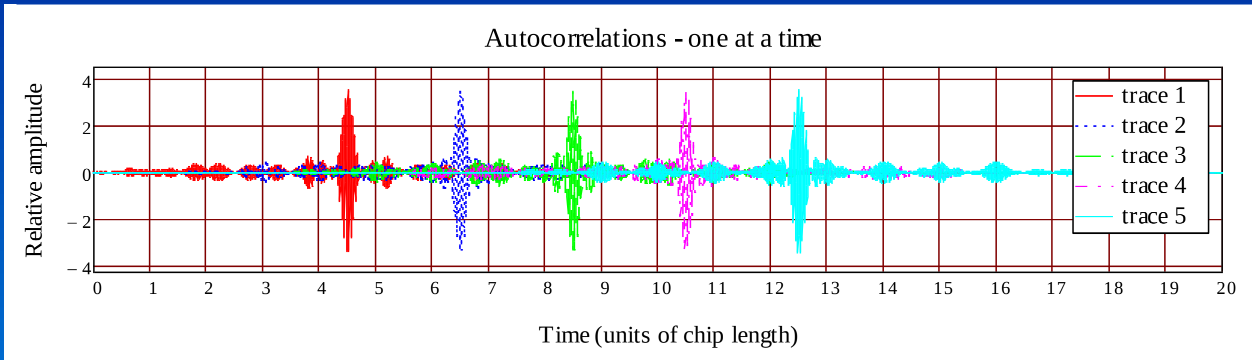
CAAT

OFC FDM Coding

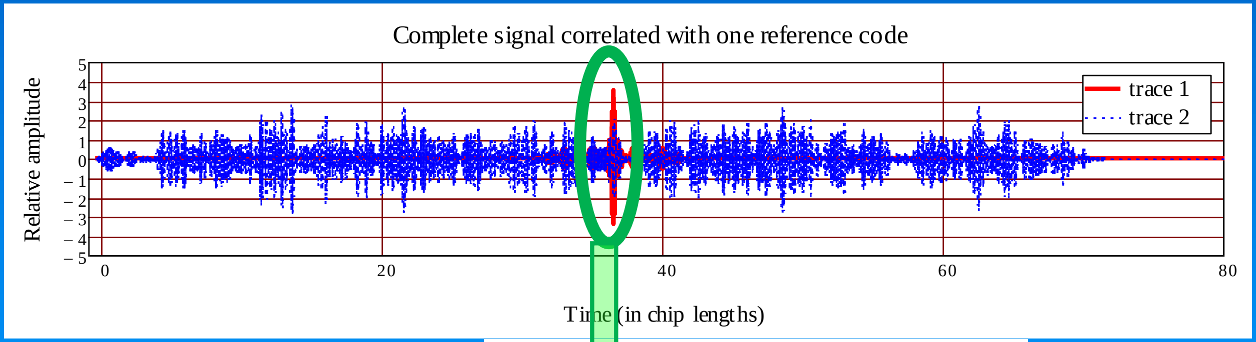
- Frequency division multiplexing: System uses N-frequencies but any device uses M < N frequencies
  - System bandwidth is $N*Bw_{chip}$
  - OFC Device is $M*BW_{chip}$
    - Narrower fractional bandwidth
    - Lower transducer loss
    - Smaller antenna bandwidth

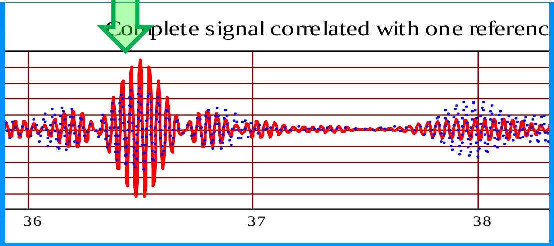


Coding Examples using OFC with Time Diversity



A. 5 chip OFC code autocorrelations which can also be repeated due to time diversity





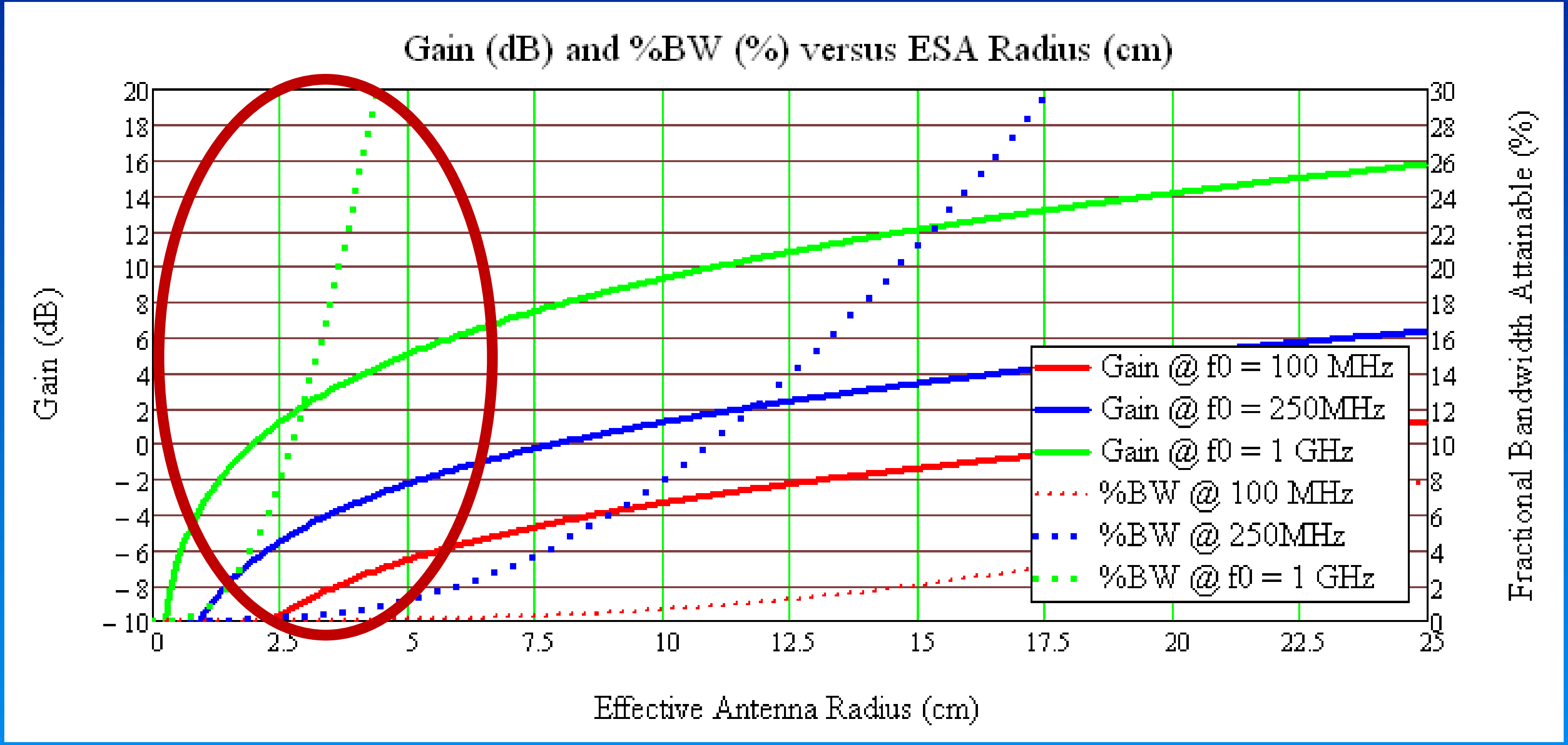
B. 32 OFC codes with one code autocorrelation
Each code = 1 OFC sensor

C. Code diversity must be maintained over temperature

Antenna and SAW Sensor Design Considerations

- Need small antenna with required bandwidth and reasonable gain
- Operational environment considerations
- Integrated antenna and SAW sensor

Electrically Small Antenna Gain and Bandwidth



The plots show that there is a minimum size at a given frequency to attain a desired fractional bandwidth.
As the frequency increases, a larger fractional bandwidth is achievable for a smaller antenna size.
As the effective size of the antenna increases, the gain and bandwidth both increase.

SAW TARGET – SAW + ANTENNA

UCF Initial Design

250 MHz Disk Monopole Antennas

OFC Device

US Quarter

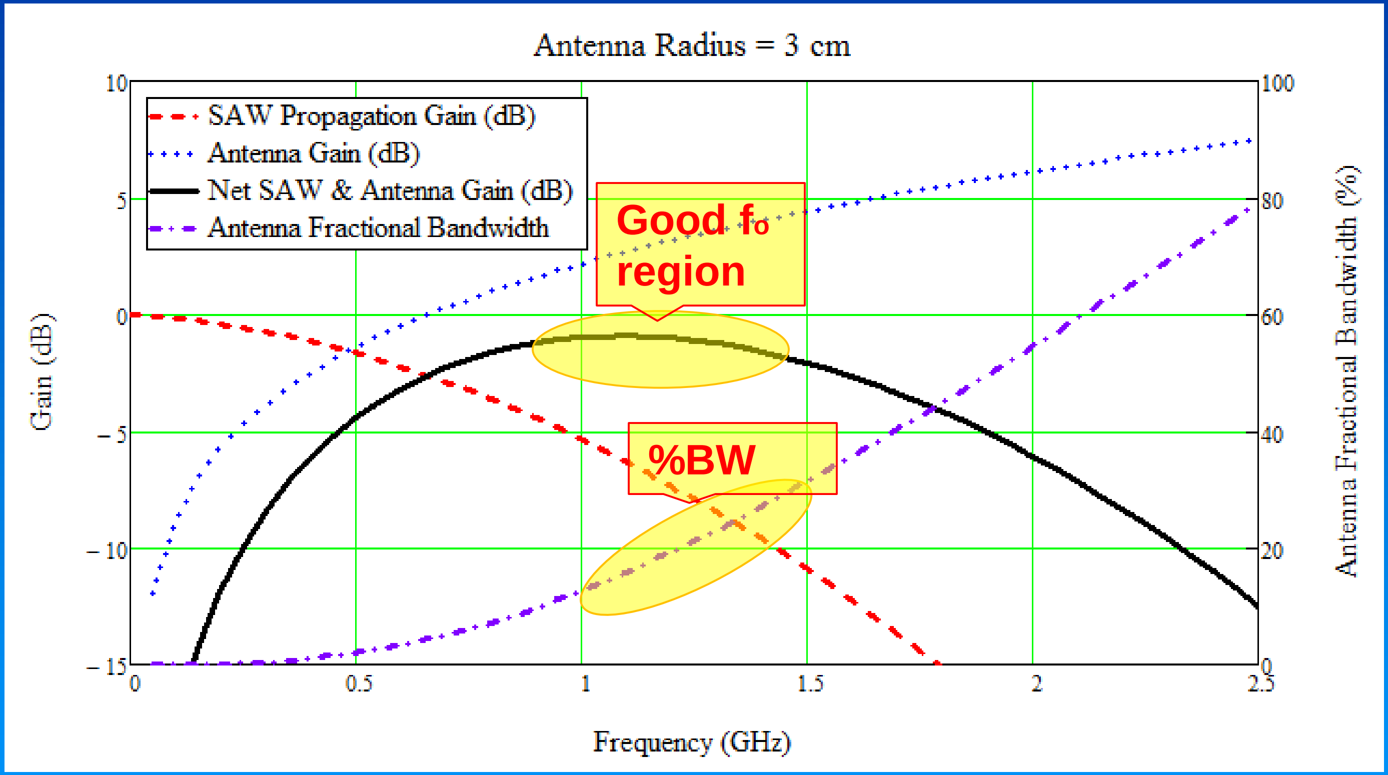
Large dinner plate design met fractional bandwidth, but hardly miniature compared to SAW sensor size

Target Gain vs. Frequency

Analysis points to ~1 GHz

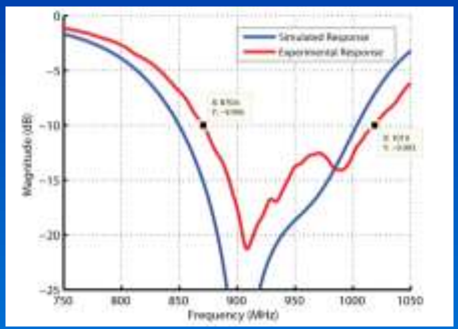
$$\alpha_{SAW} = (.19f + .88f^{1.9})\ {}^{dB}/_{\mu sec}$$

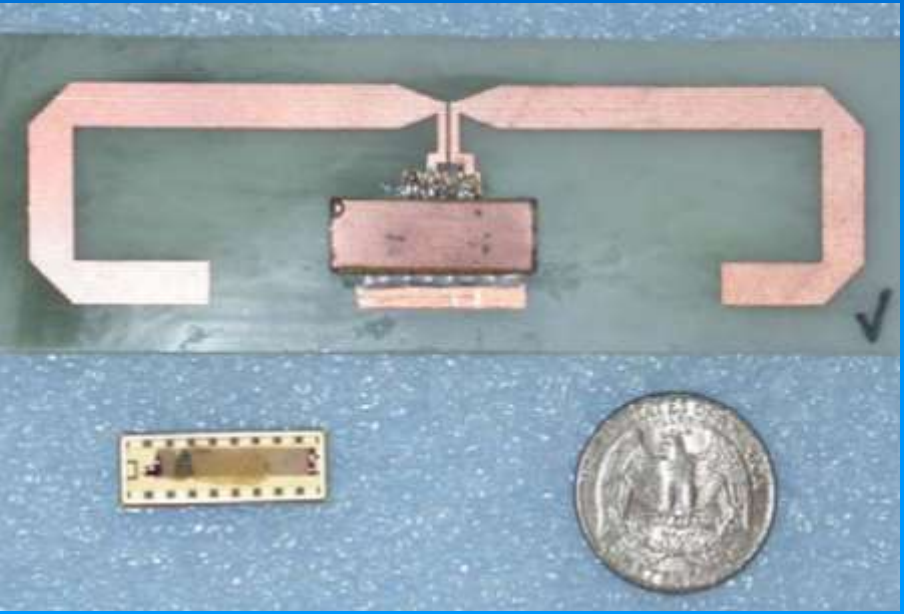
where *f* is in GHz



SAW, antenna and net gain in dB, and fractional bandwidth, versus frequency for a **3cm radius ESA**. Assumes a SAW propagation length of **5 usec**.

915 MHz Wideband Folded Dipole Antenna





Miniature 915MHz Integrated OFC SAW-Patch Antenna

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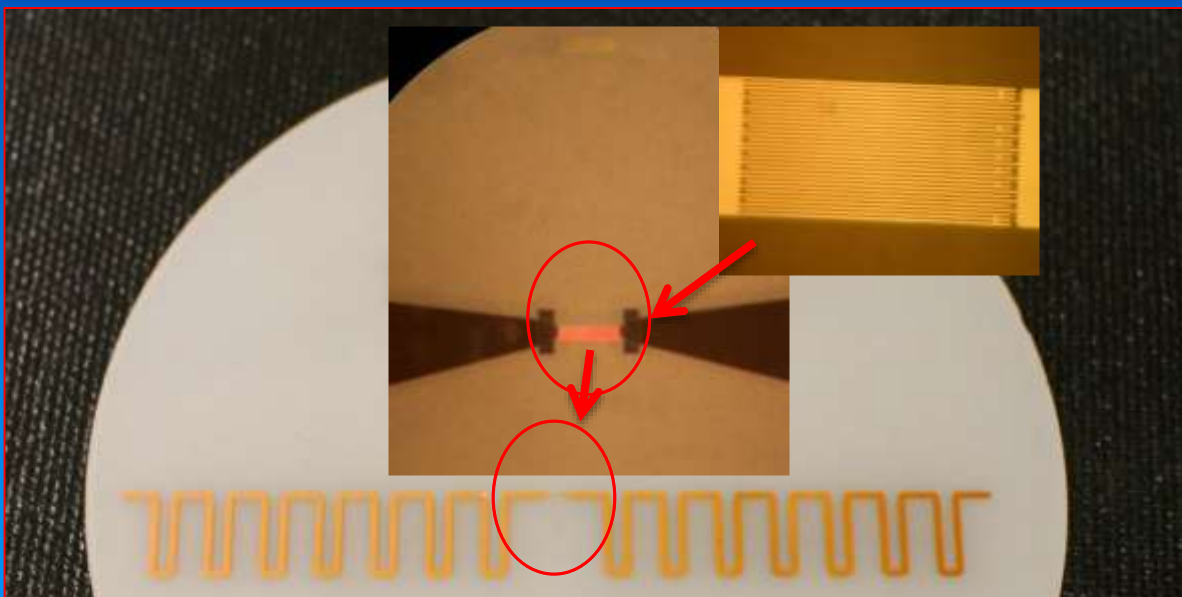
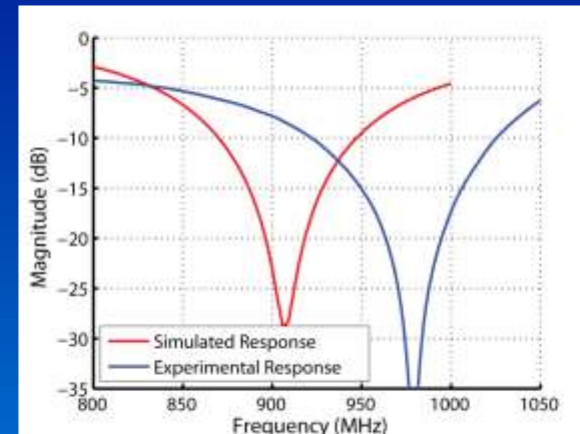
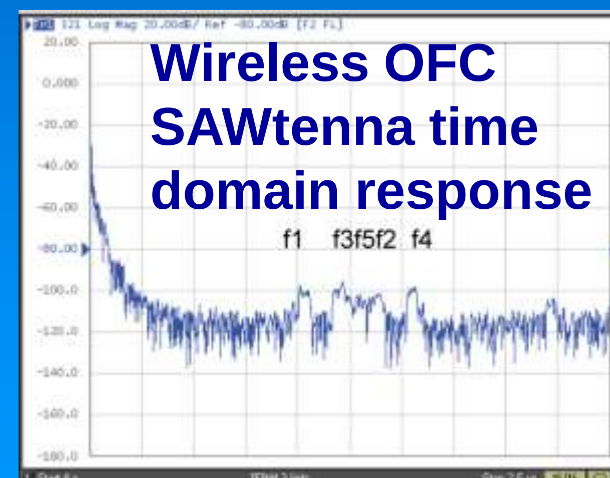
SAWtenna @ 915 MHz

Fully integrated on-wafer SAW OFC sensor and antenna





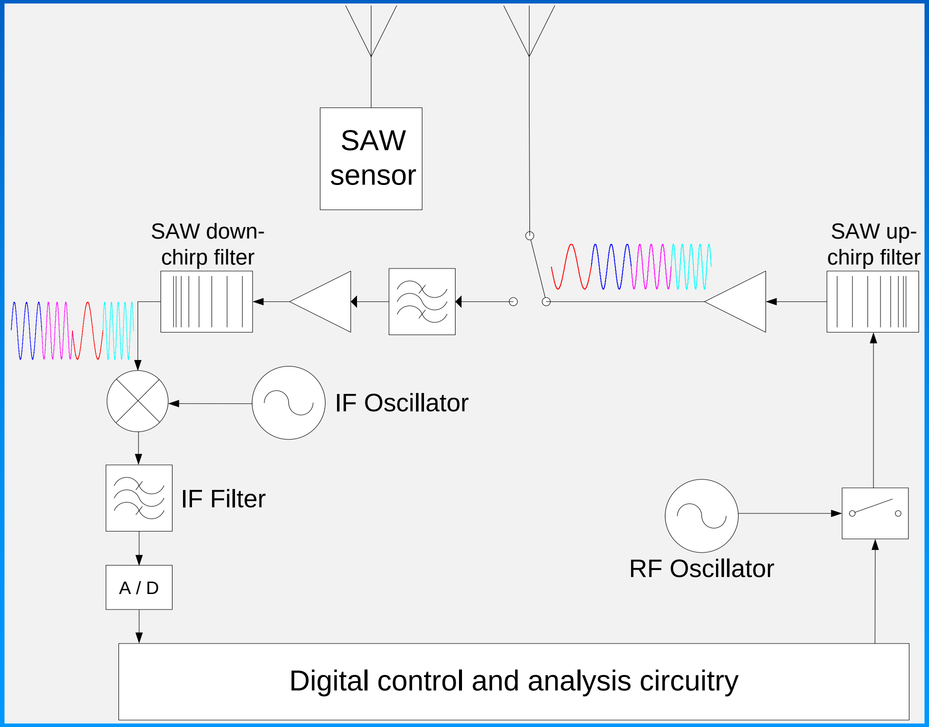
Test wafer-level SAW & antenna integration



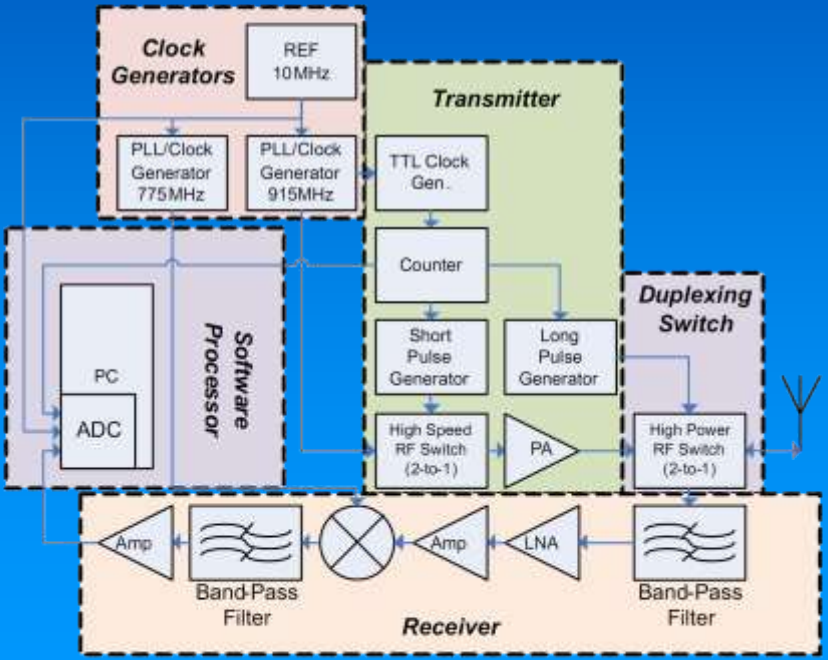
Synchronous Correlator Transceiver

Synchronous Transceiver - Software Radio

- Pulse Interrogation: Chirp or RF burst
- Correlator Receiver Synchronous
- Software Radio Based



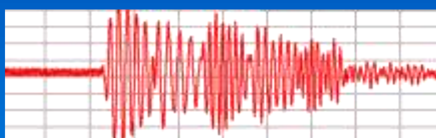
915 MHz Pulsed RF Transceiver Block Diagram

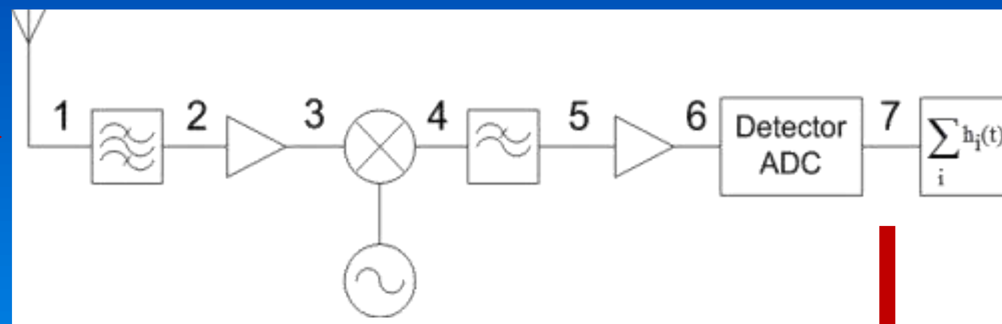


Synchronous Correlator Receiver

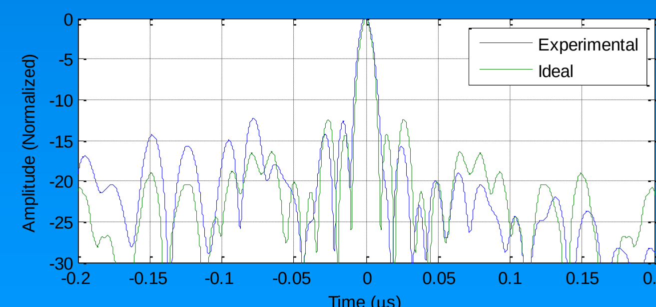
Block diagram of a correlator receiver using ADC

OFC Single Sensor Signal

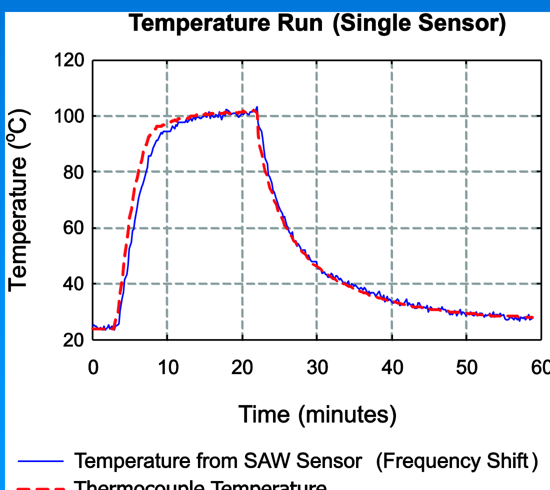




Output



Temperature Extraction



MNI Transceiver Design

- 915 MHz Pulsed RF Chirp Correlator Receiver
  - Synchronous operation
  - Integration of multiple “pings”
  - OFC processing gain

- Adaptive filter temperature extraction
- Software radio based approach for versatility

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Current Sensor System Results

- 915 MHz synchronous transceiver developed by Mnemonics, Inc. (MNI), Melbourne, Fl
- OFC SAW temperature sensors developed by UCF
  - 5 chip OFC delay line sensor
  - 0.8 um electrodes
- Correlator software developed at UCF and enhanced at MNI

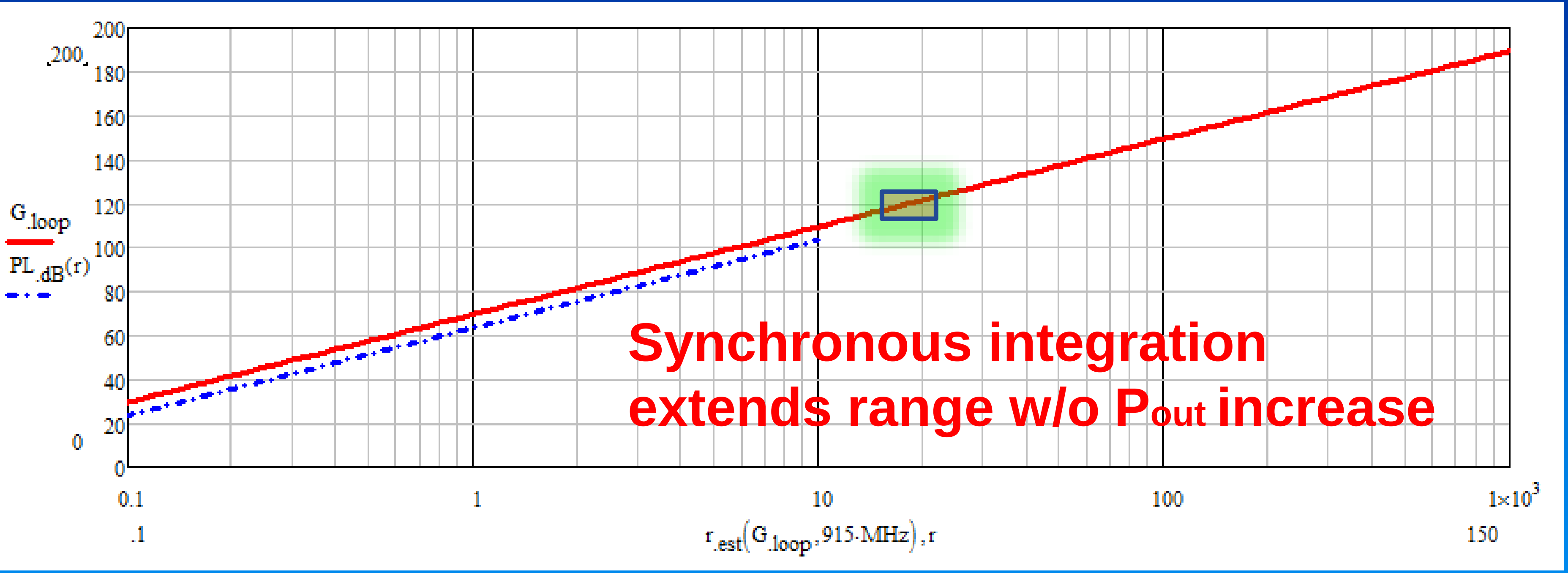
Critical Transceiver Operational Parameters

- EM Path Loss Considerations
- Electrically Small Antennas (ESA)
- SAW Device Propagation Loss
- Target Gain versus Center Frequency
- Integrated SAW and Antenna

RF Chirp Transceiver Parameters

- Chirp pulse= 700ns, 20V_{pp}
- System Bandwidth ~ 74MHz
- Receiver Gain = 45dB
- NF = 15dB
- Chirp PG= 49 = 17 dB
- SAW PG = 25 = 14 dB

Range Prediction for MNI Receiver for RFID Detection (not sensor)



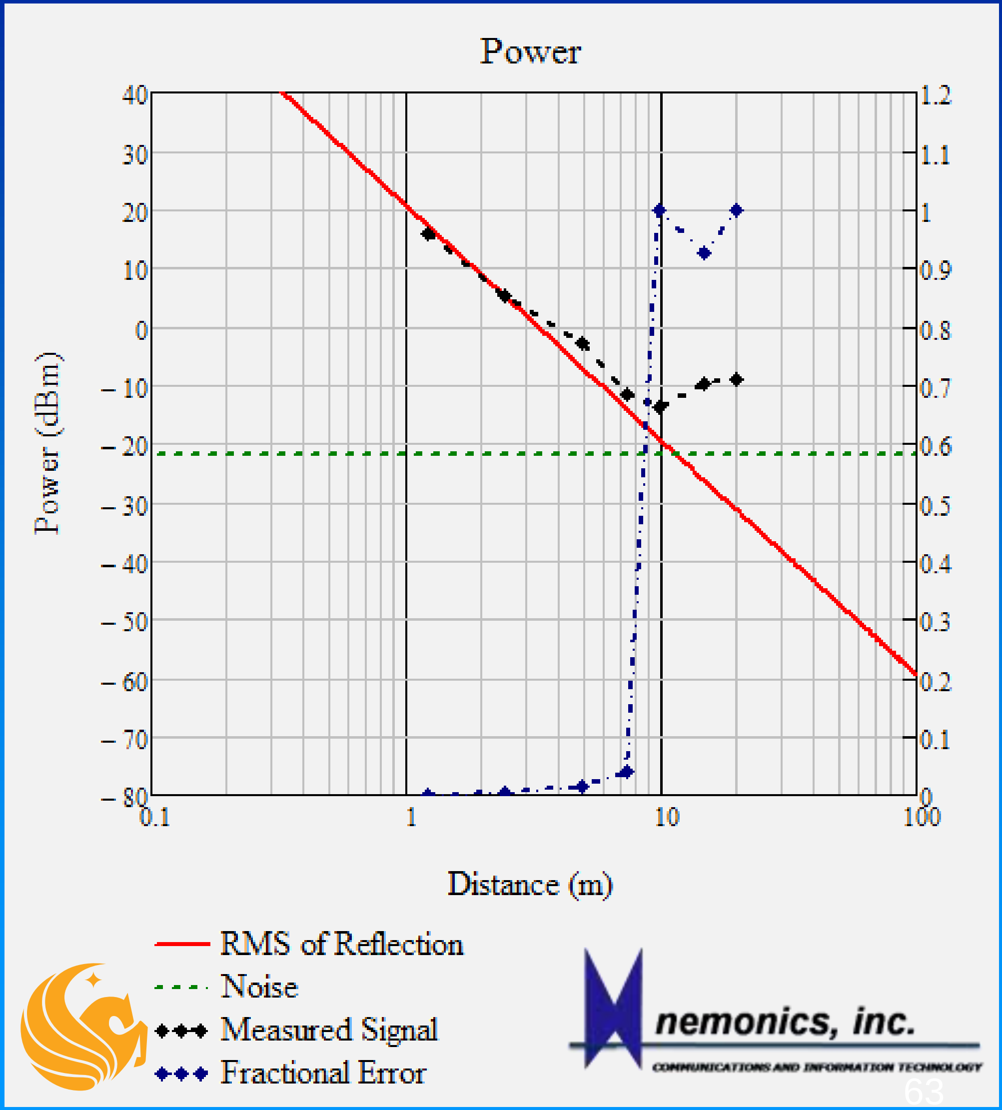
- Range is a function of the complete system loop gain, shown in solid line (red). Loop gain is dependent on the transmit power, noise and gain in the system. Typical loop gains are realistically achievable between 100 to 180 dB. The box shows the predicted loop gain for the MNI/UCF system, which is very close to measurements obtained.

Chirp Transceiver: SAW OFC Sensor Range Experiment

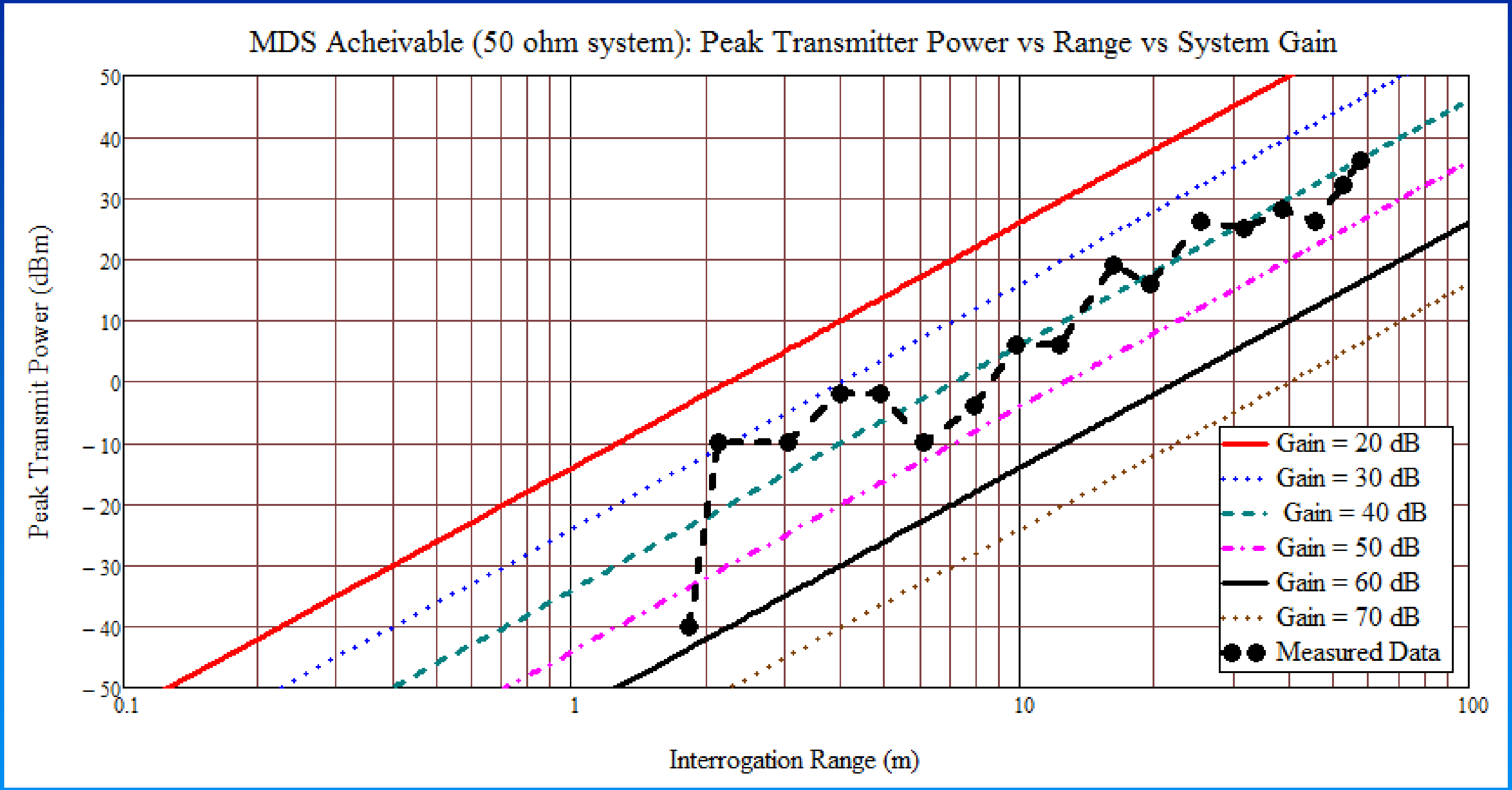
- ***<u>Single sensor only; no signal integration</u>***

- Multiple distances from 1.2m to 20m
- 0 to 20dB additional attenuation at each step
- 128 readings taken per distance per attenuation

- Longest distance of successful interrogation 7m
- Reading error .07 corresponds to 60% of all data points within 5°C (3.5%)



915 MHz OFC Temperature Sensor System Measured Device Data in a Hallway



Data is measured in a hallway approximately 2.1 meters wide. Antennas: transmit is a wideband 1 dB dipole; receive is a 9 dB Yagi. The system loop gain is calculated at ~40 dB (+/-3 dB). Transmit signal is a single, 700 nsec, 915 MHz chirp pulse. The OFC SAW device uses 5 chips, each with an approximate 15 MHz bandwidth. SAW device processing gain is 25. Slope of the fit measured data is -38.7 dB/decade; close to the 40 dB/decade expected for isotropic radiation path loss. The hallway is probably producing a waveguiding effect and external noise was low during testing. Test shows that some environments can produce long ranges.

UCF Sensor Development

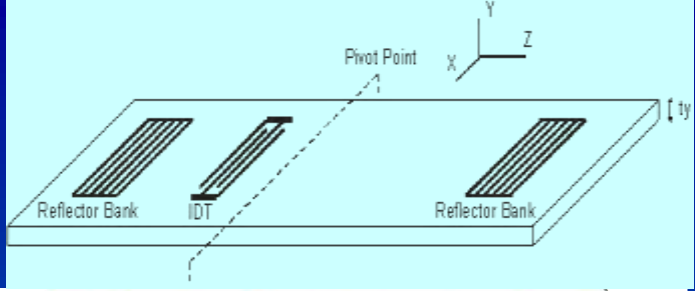
- Wired SAW sensing has quite an extensive body of knowledge and research continues

- Wireless SAW sensing has been most successfully demonstrated for single, or very few devices and in limited environments

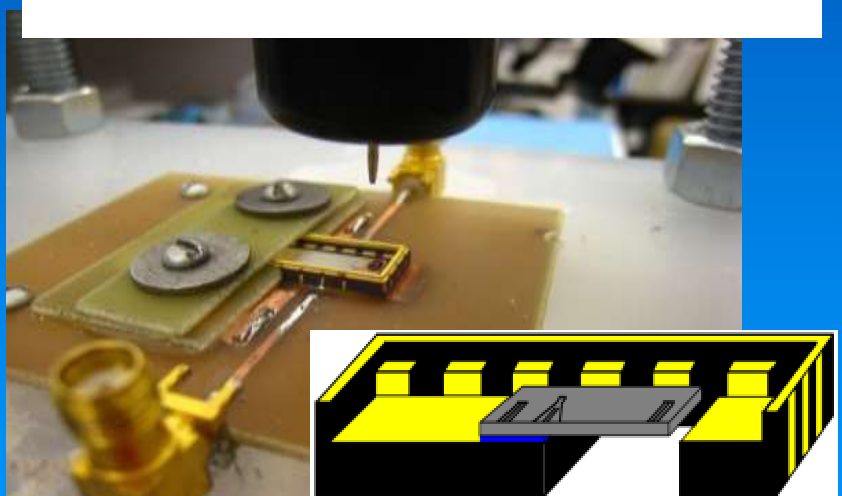
UCF OFC Sensor Successful Demonstrations

- Temperature sensing
  - Cryogenic: liquid nitrogen
  - Room temperature to 250°C
  - Currently working on sensor for operation to 750°C
- Cryogenic liquid level sensor: liquid nitrogen
- Pressure/Strain sensor
- Hydrogen gas sensor
- Closure sensor with temperature

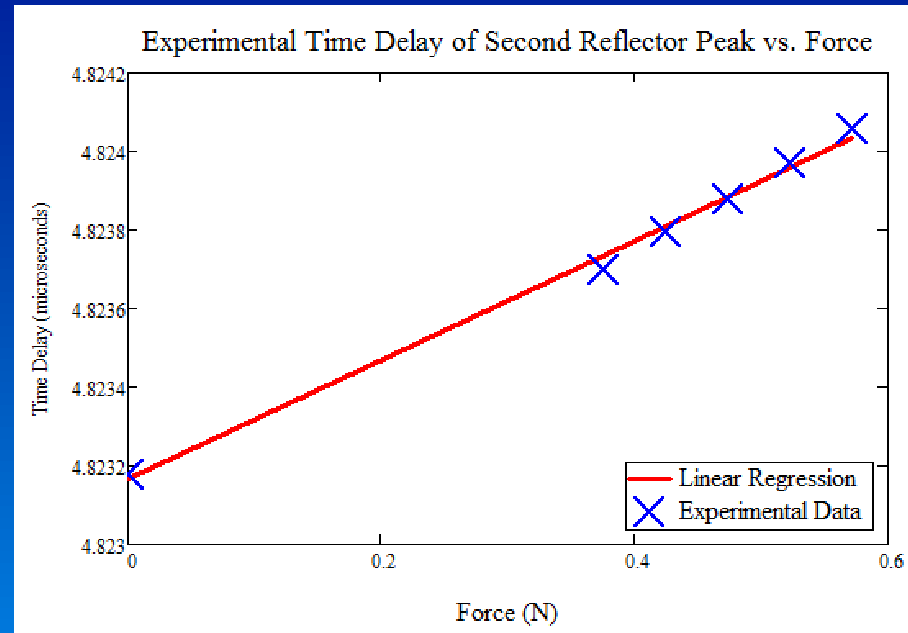
OFC Cantilever Strain Sensor

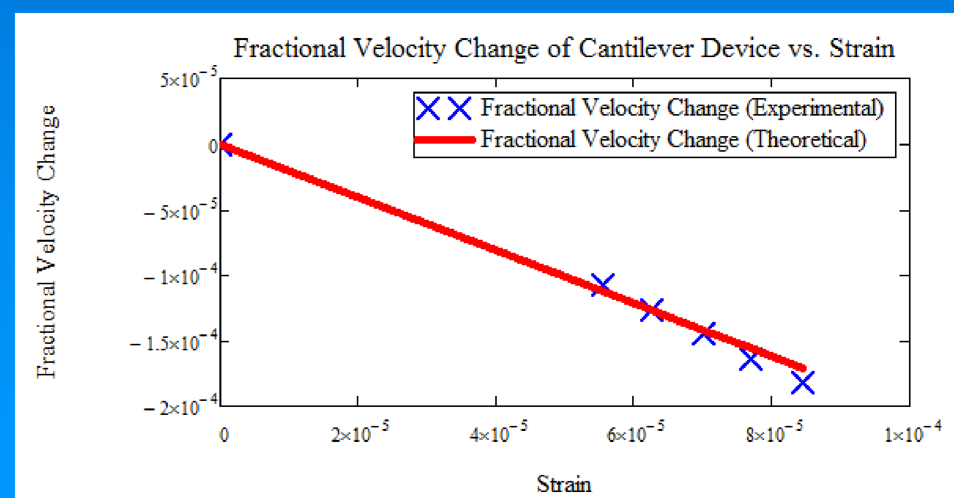


Plot generated by ANSYS demonstrating the strain distribution along the z-axis of the crystal.



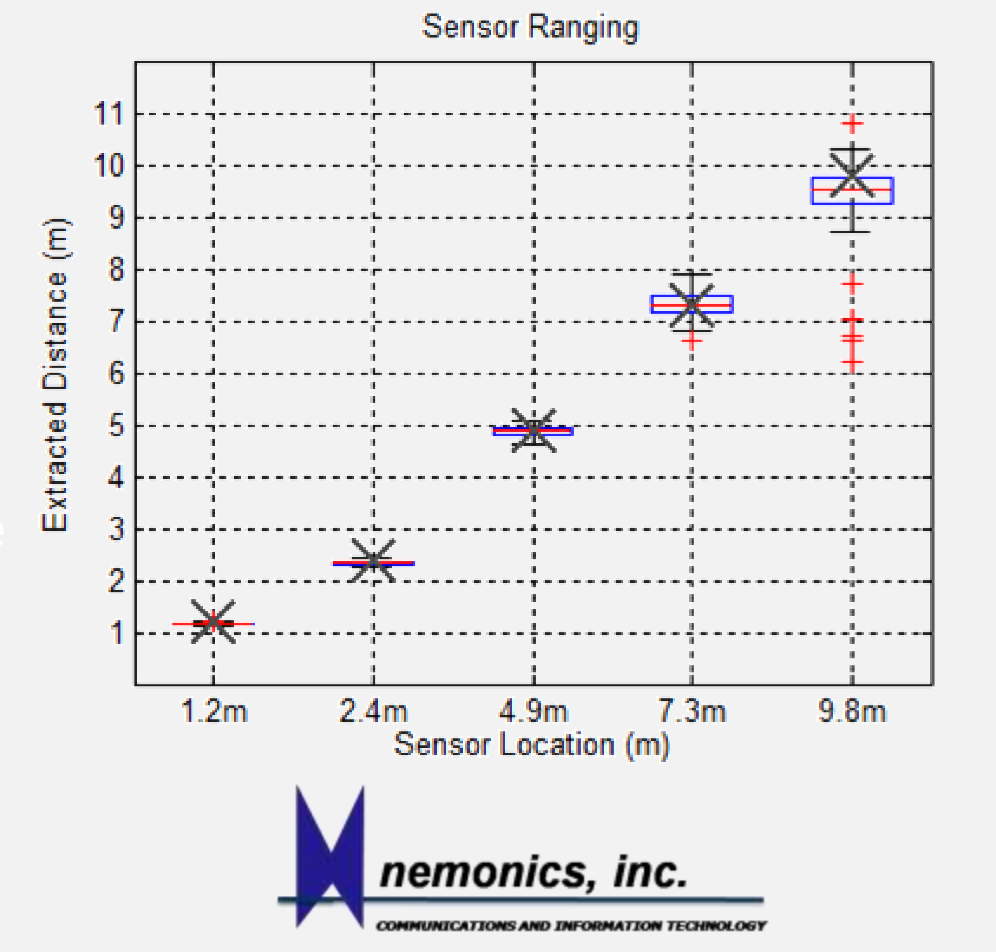
Test fixture, this shows the surface mount package, which contains the cantilever device, securely clamped down onto a PC board which is connected to a Network Analyzer.



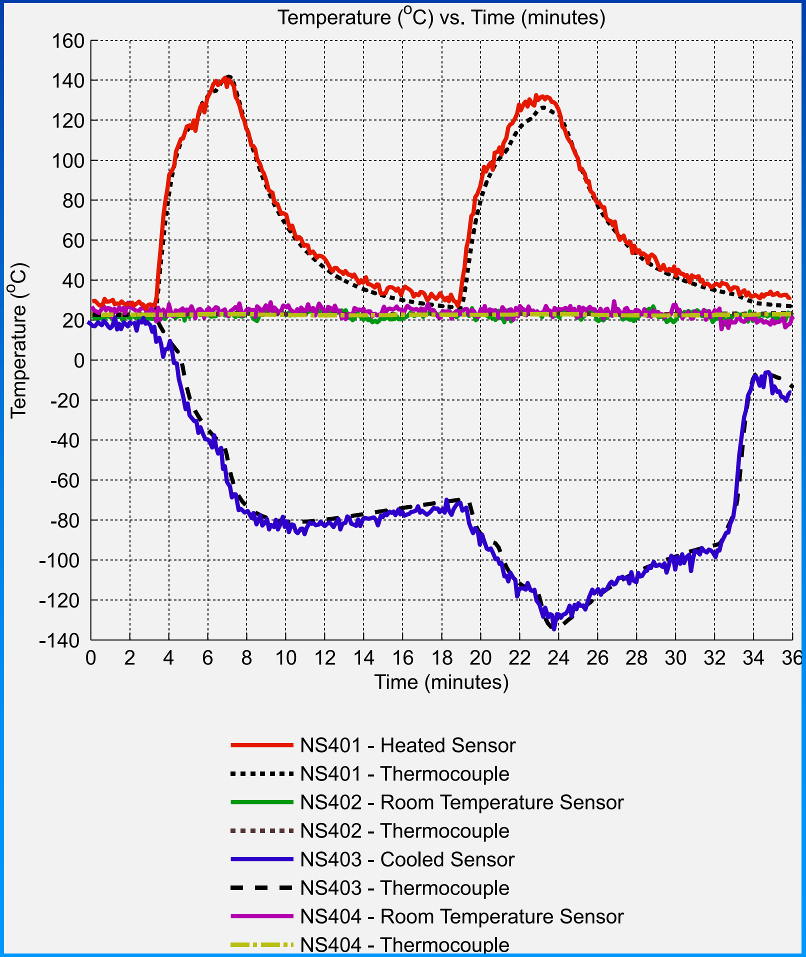


OFC SAW Correlator Receiver Tag Ranging

- Distance from interrogator to the sensor can be extracted based on EM delay (8m per chip length – 54ns)
- X-axis indicates various distances at which sensor was placed away from interrogator
- Cross-marks indicate distance from interrogator on y-axis
- 128 Measurements were made for each step
- Blue box indicates spread of a half of all data
- Black boundaries indicate spread of 99.3% of all data
- Red pluses indicate outliers



Four-sensor operation



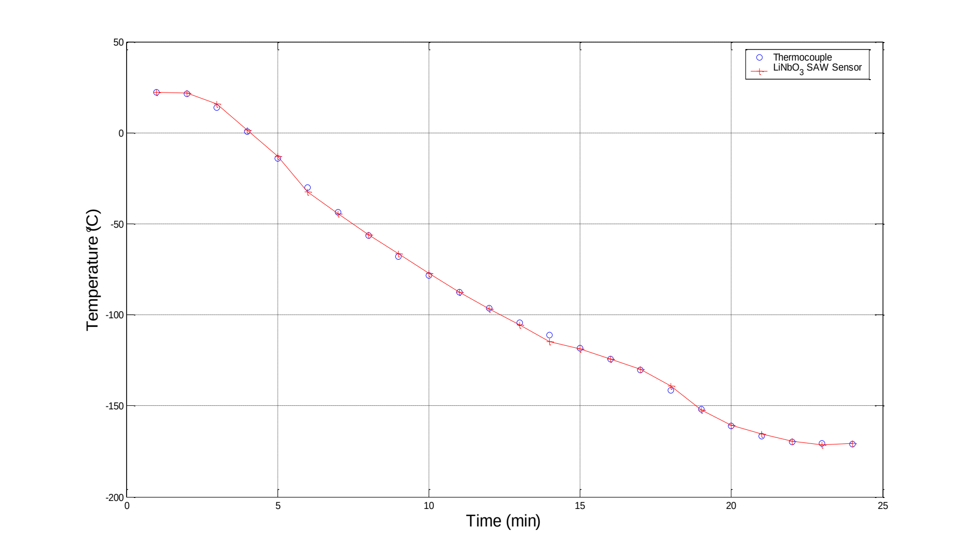
- Four OFC SAW sensors are co-located in close range to each other at a distance of 0.8m to 1.2m
- Sensors NS402 and NS404 remained at room temperature
- Sensor NS401 heated to 140°C
- Sensor NS403 cooled to -130°C
- Data was taken simultaneously from all four sensors and then temperature extracted in the correlator receiver software
- Error is within ±5°C (±3.5% for given dynamic range)

OFC Cryogenic Sensor Results

Scale

Vertical: +50 to -200 ºC

Horizontal: Relative time (min)



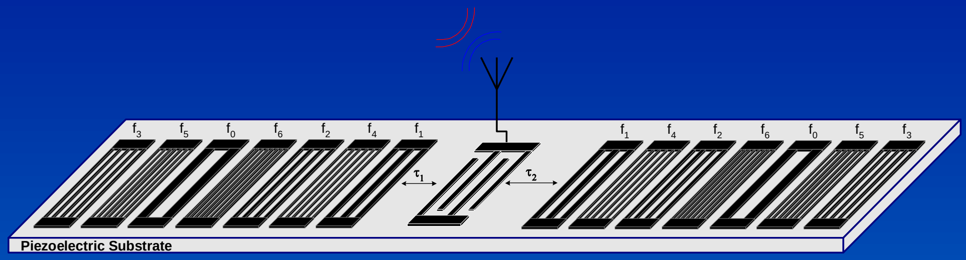
OFC SAW temperature sensor results and comparison with thermocouple measurements at cryogenic temperatures. Temperature scale is between +50 to -200 ºC and horizontal scale is relative time in minutes.

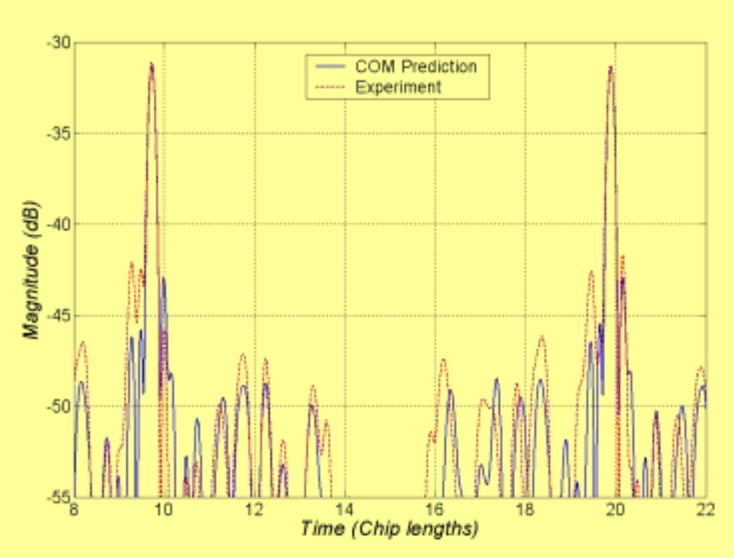
Measurement system with liquid nitrogen Dewar and vacuum chamber for DUT

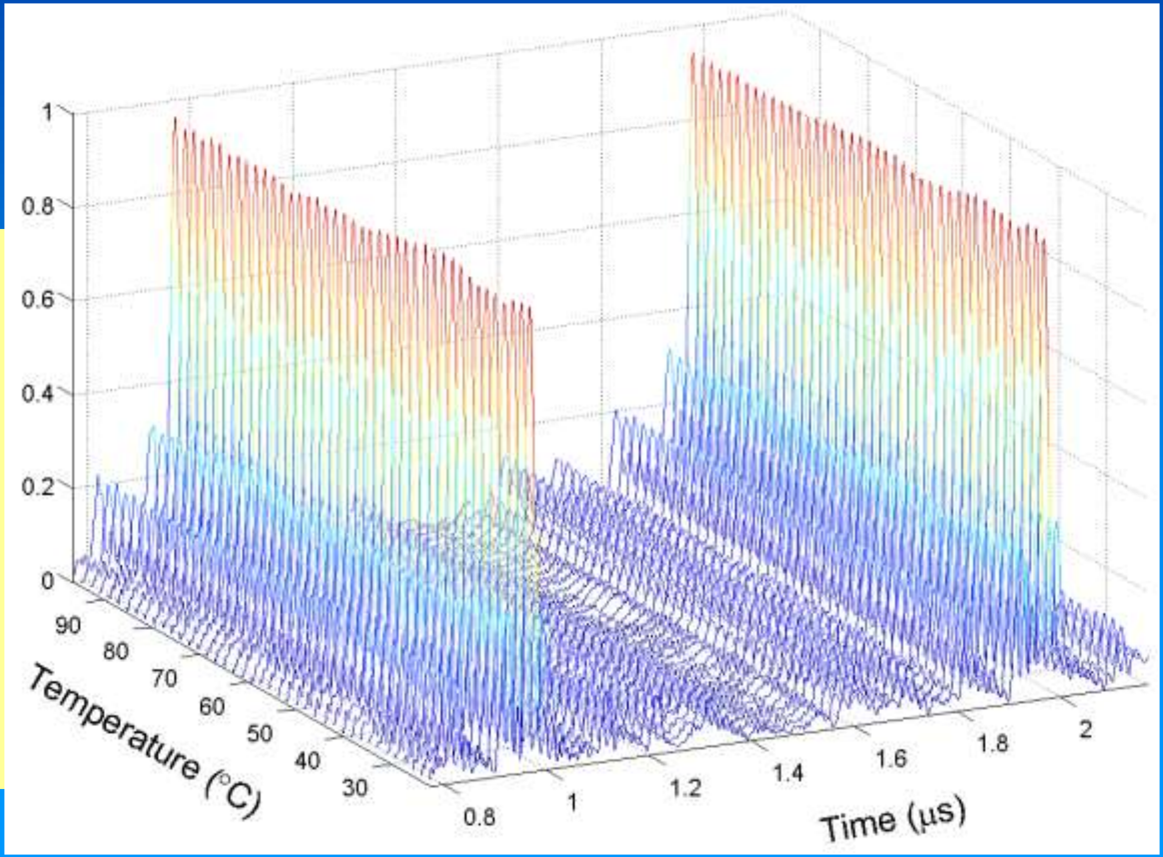
Differential Delay Correlator Embodiment

Temperature Sensor Example

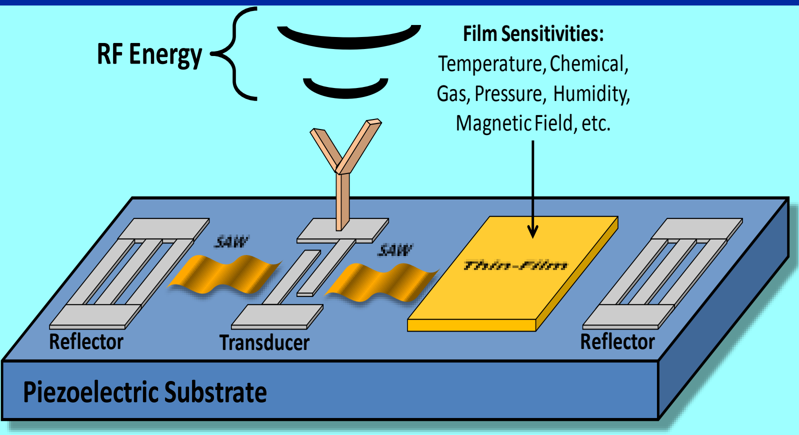
250 MHz $LiNbO_3$, 7 chip reflector, OFC SAW sensor tested using temperature controlled RF probe station



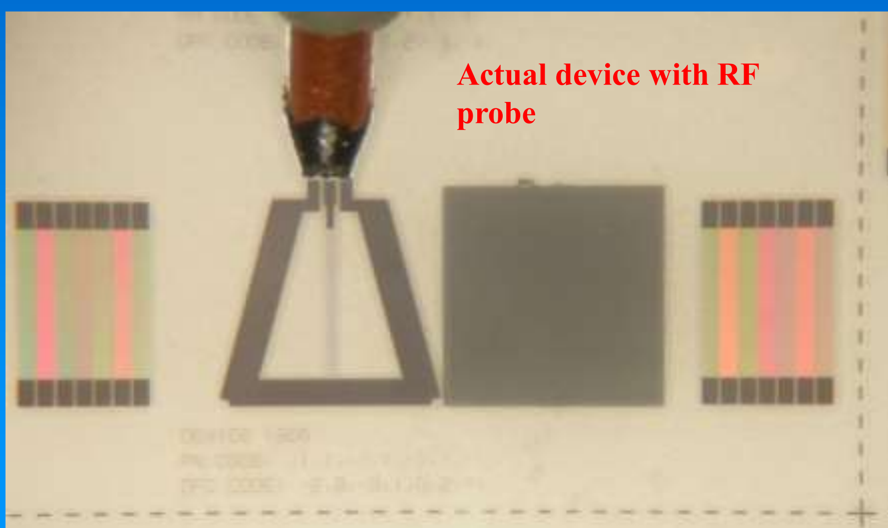


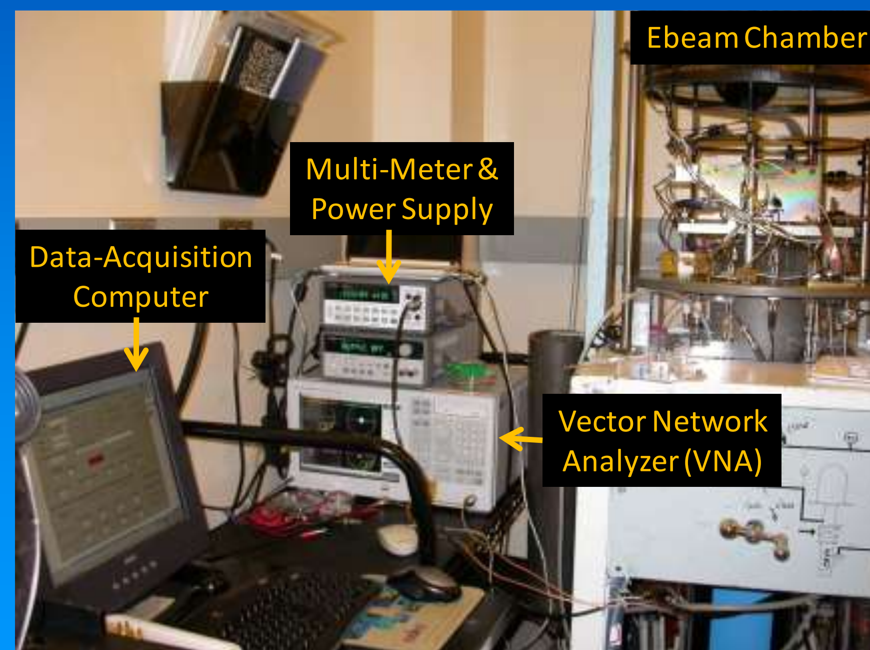


Schematic and Actual OFC Gas Sensor



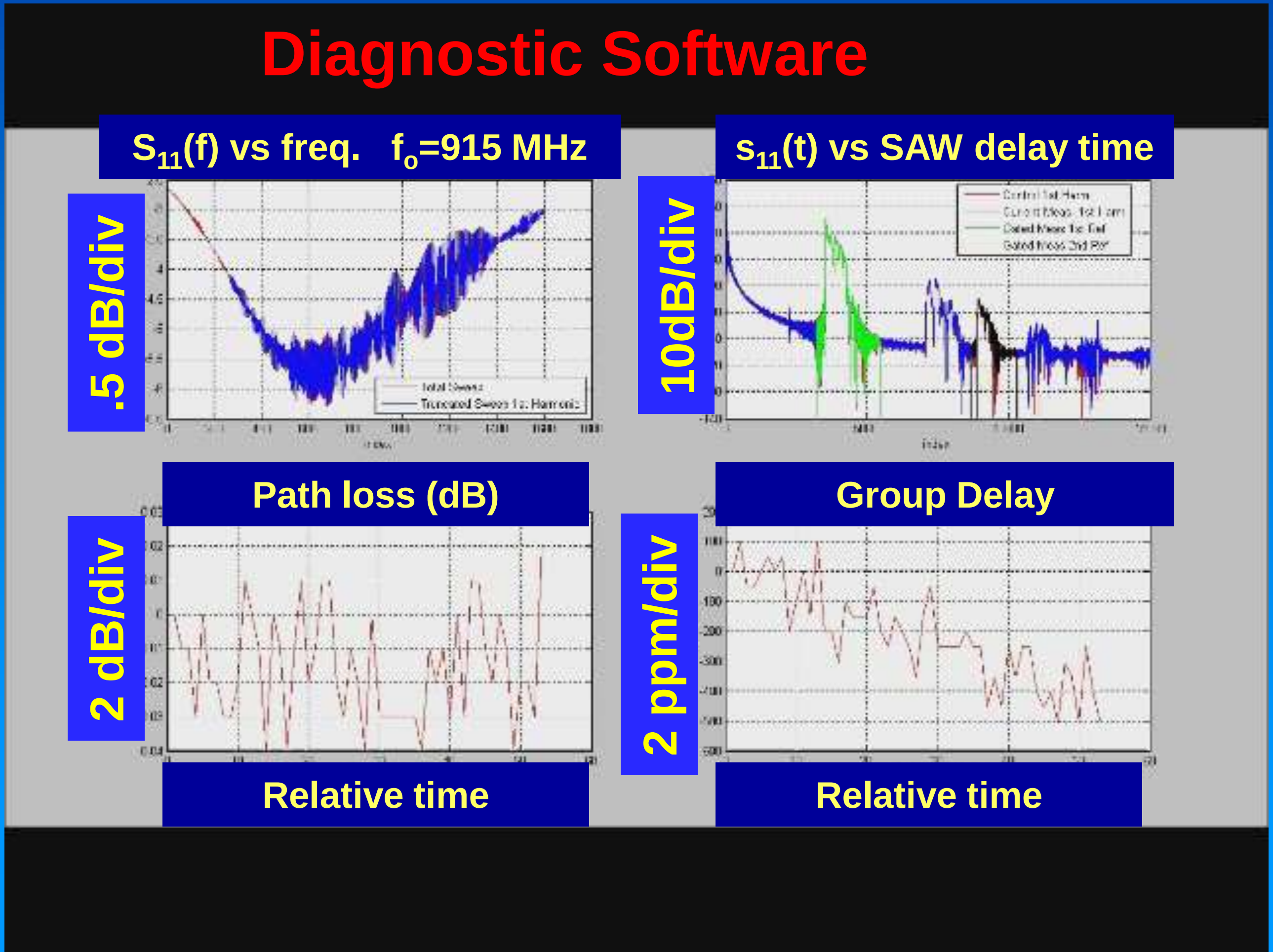
Differential Mode OFC Sensor Schematic





Wireless Passive Room Temperature Reversible Hydrogen Sensor

Sequence time is approximately 16 minutes; T=25 ^{o}C
f_o=900 MHz, Gas: 2%H_2 in N_2



UCF/MNI Current Sensor & System Investigations

<u>Wireless Sensor Activity</u>

- Hydrogen Sensor
- Corrosion Sensor
- Liquid Level Sensor
- Strain/Pressure Sensor
- Humidity Sensor
- High Temperature Sensor
- Closure

- <u>RF Radio TxRx &DSP</u>
- 2nd Generation Receiver
- Advanced DSP for faster acquisition and display
- Wireless Backhaul
- SAW device & TxRx optimization

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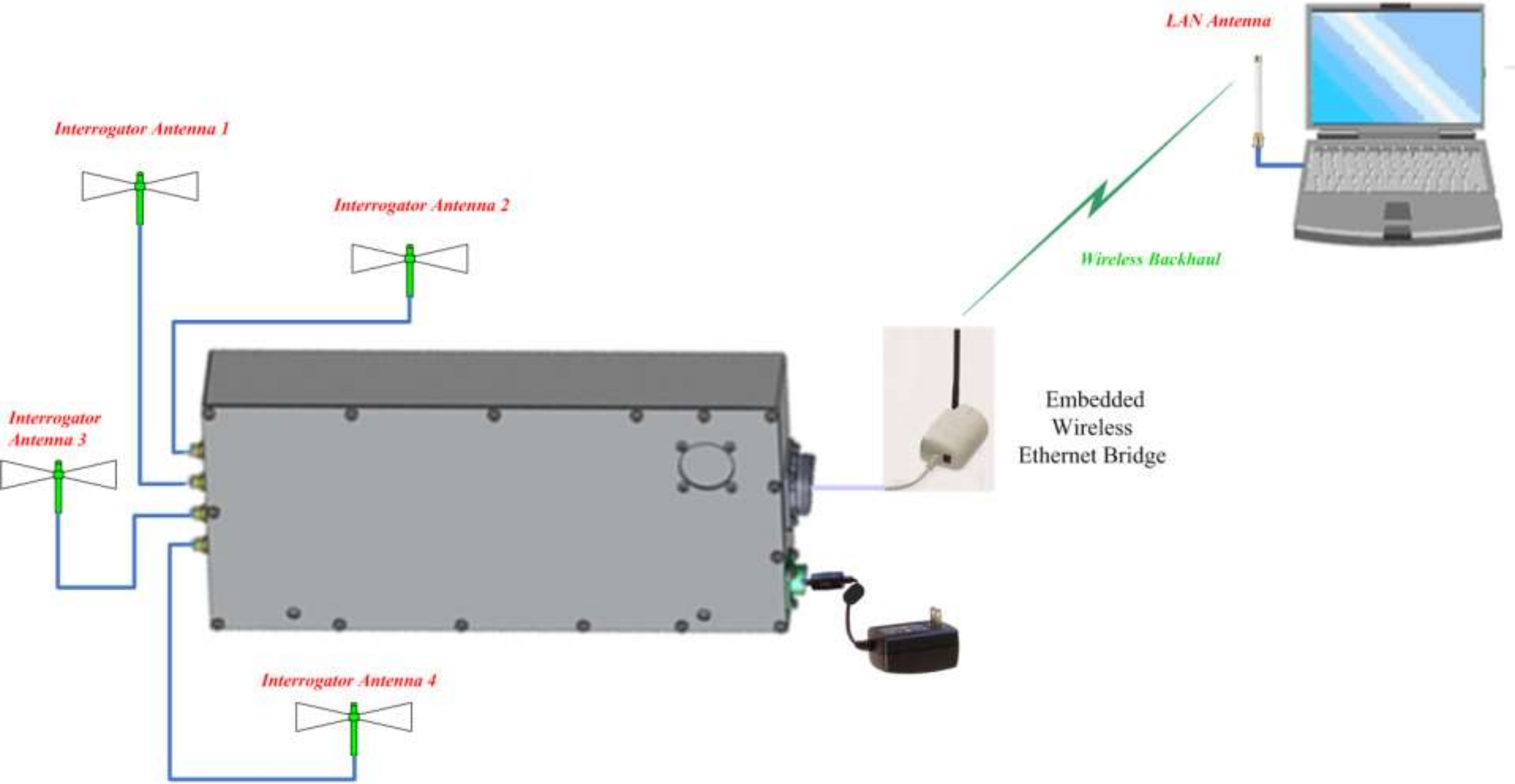
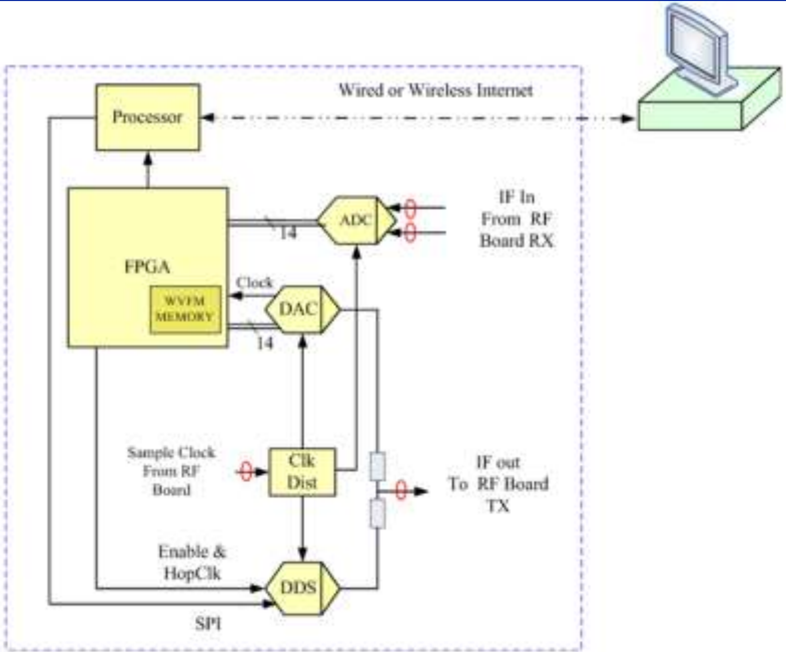
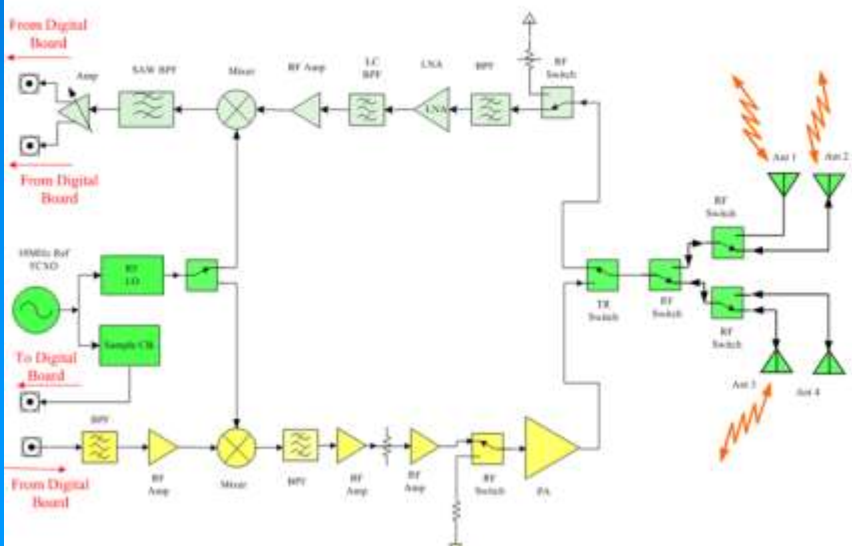
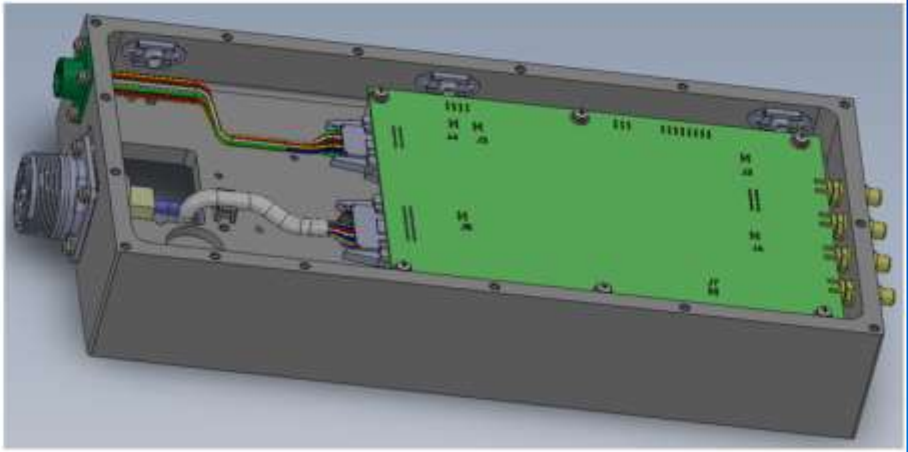
Wireless RF SAW Interrogator- 2nd Generation With Wireless Backhaul Option

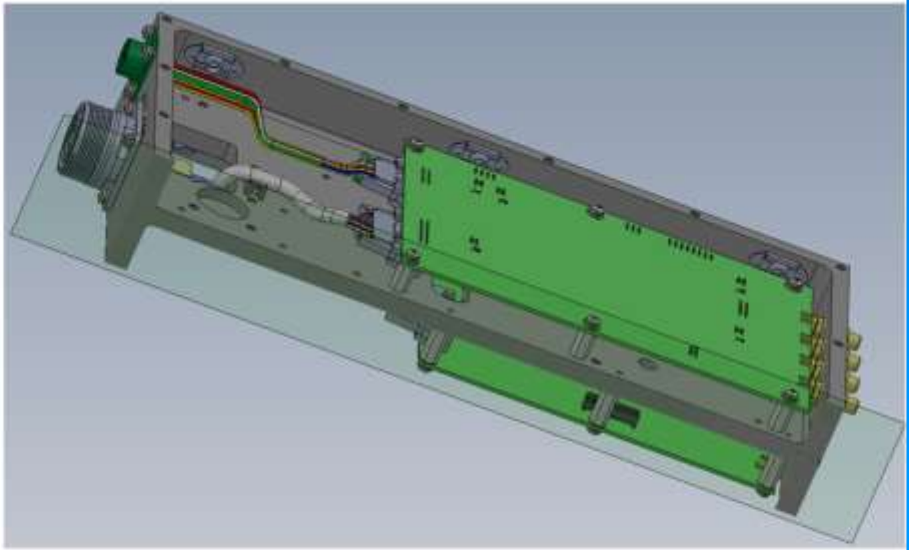


Wireless RF SAW Interrogator- 2nd Generation

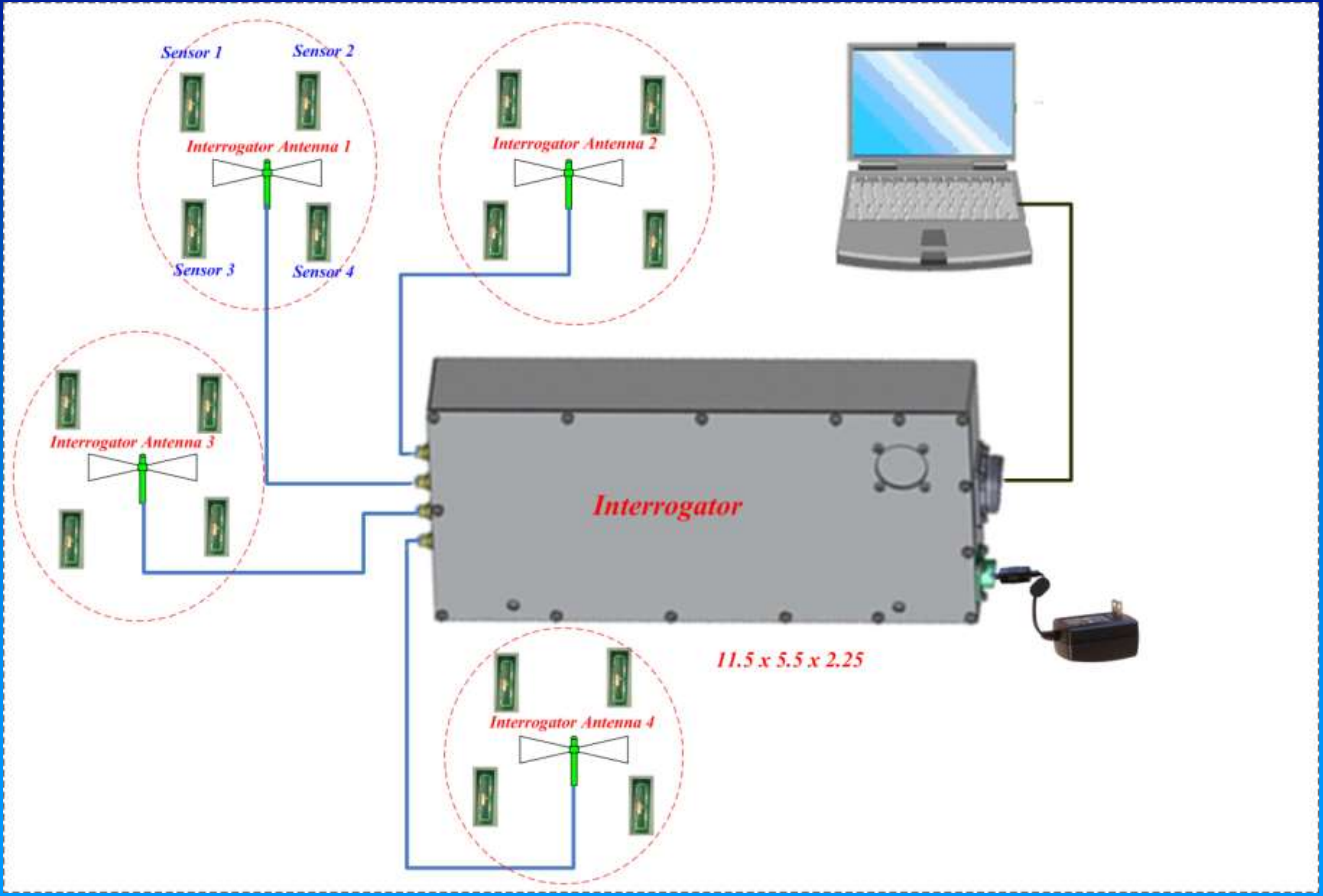








Wireless RF SAW Interrogator- 2nd Generation



Observations

- SAW passive wireless sensor technology is beyond feasibility
- SAW technology can be adapted to application specific systems
- Passive multi-sensor systems achieved
- A host of sensor platforms are possible
- Teaming and partnerships will advance the technology
- Regulatory issues need to evolve with sensor technology