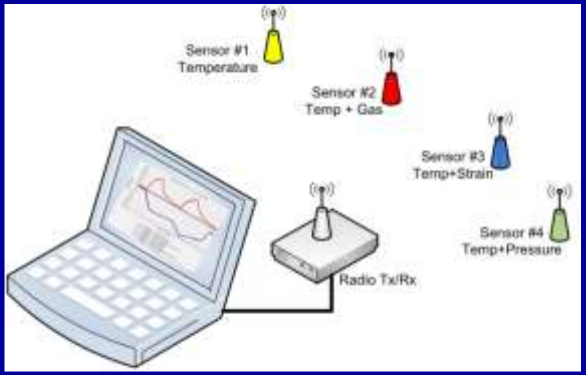
915 MHz SAW Multi-Sensor System



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Timeline of OFC Wireless Results

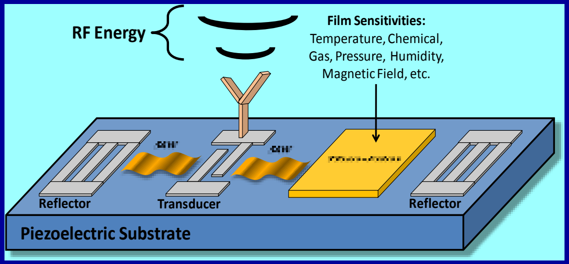
Year	Hardware	# Sensors	2 dBi antenna Isotropic Range (meters)	Data Transfer Rate (sec)	Post Processing Rate (msec)/sensor	Plotting and Overhead (sec)
2008	UCF	1-2	< 1	5	>1000	2
2009	UCF	1-2	1-3	2	>1000	2
2010	UCF & MNI	1-4	1-4	0.5	500	2
2011	MNI	1-6	1-5	0.5	100	2
2012	MNI	1-8	1-7	0.5	10	2
2013	MNI and ?	1-16	1-10	0.5	5	?
2014	MNI and ?	1-32	1-50	0.001	1	?

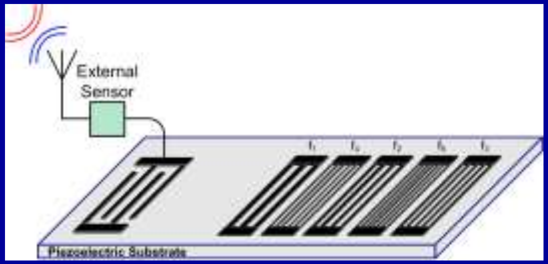
UCF Wireless Demonstrations:

- **Sensors: temperature, range, strain, hydrogen, magnetic, liquid, and cryogenic.**
- **Environments: isotropic, hallways (60m), faraday cage (.5x.5 m), anechoic**

Confluence of Technology

- **SAW design, analysis and simulation**
- RF receiver technology – fast & cheaper
- Post-processing – fast & cheaper
- Hardware – design, cost, performance, etc.
- SAW sensor embodiments
  - On-board sensors
  - Off-board sensors





Why OFC SAW Sensors?

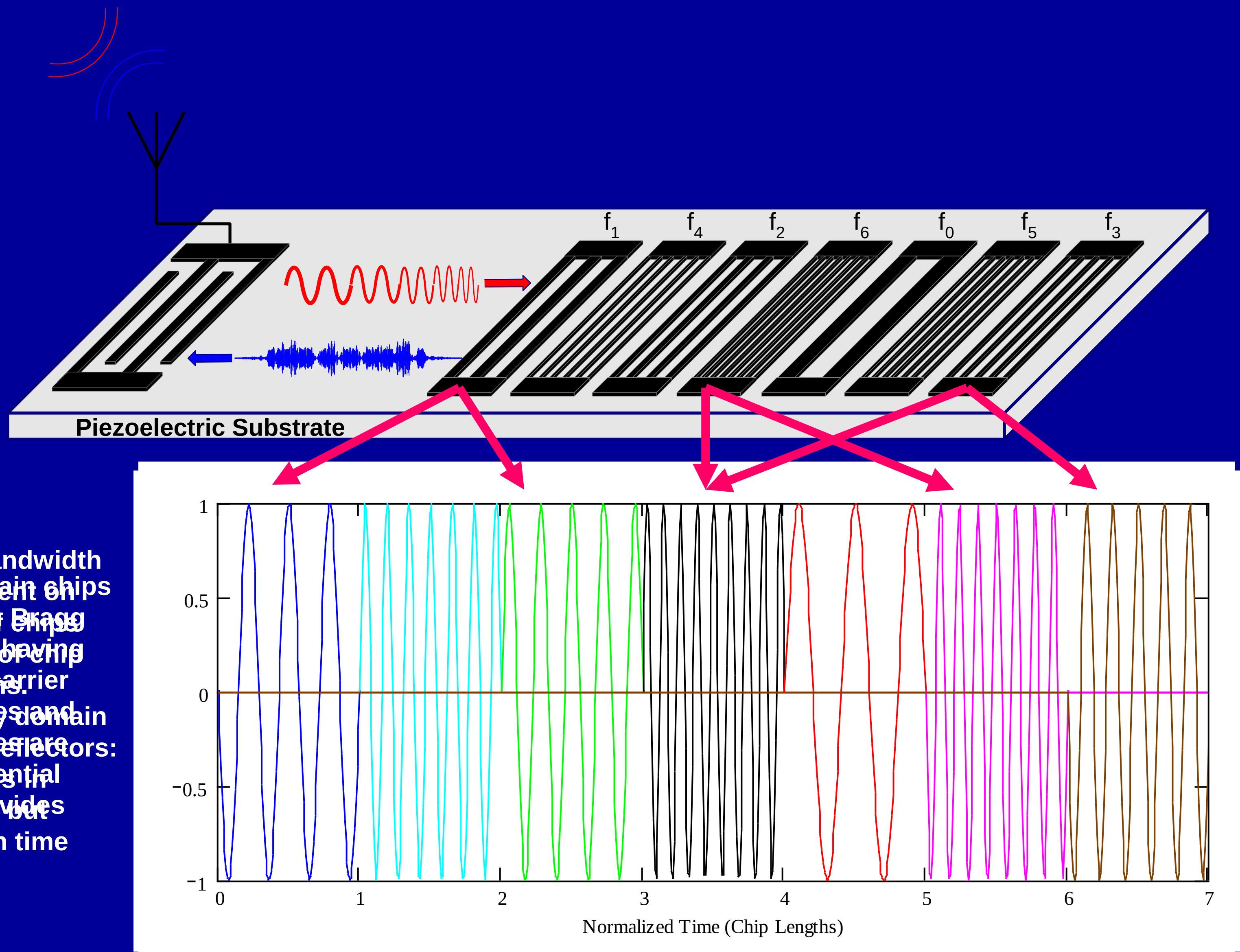
Advantageous

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

1st Demonstrated

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

Schematic of OFC SAW ID Tag



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

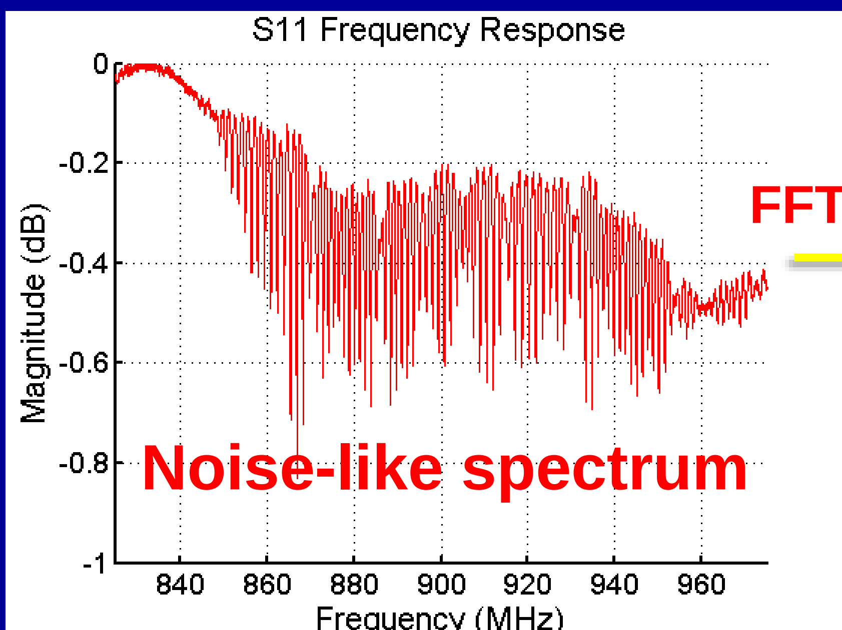
Time domain chips realized in Bragg reflectors having differing carrier frequencies and frequencies are non-sequential which provides coding

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

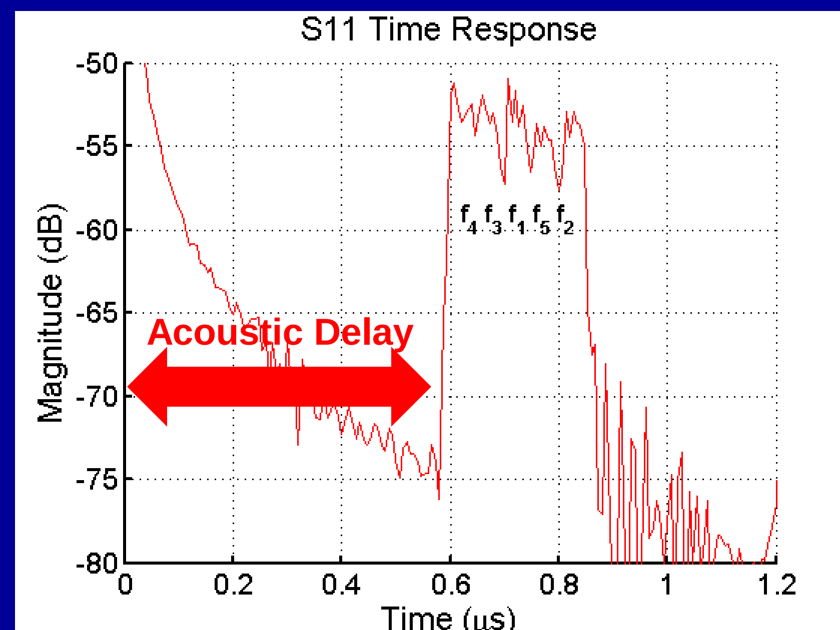
Example 915 MHz SAW OFC Sensor

Photo Micrograph

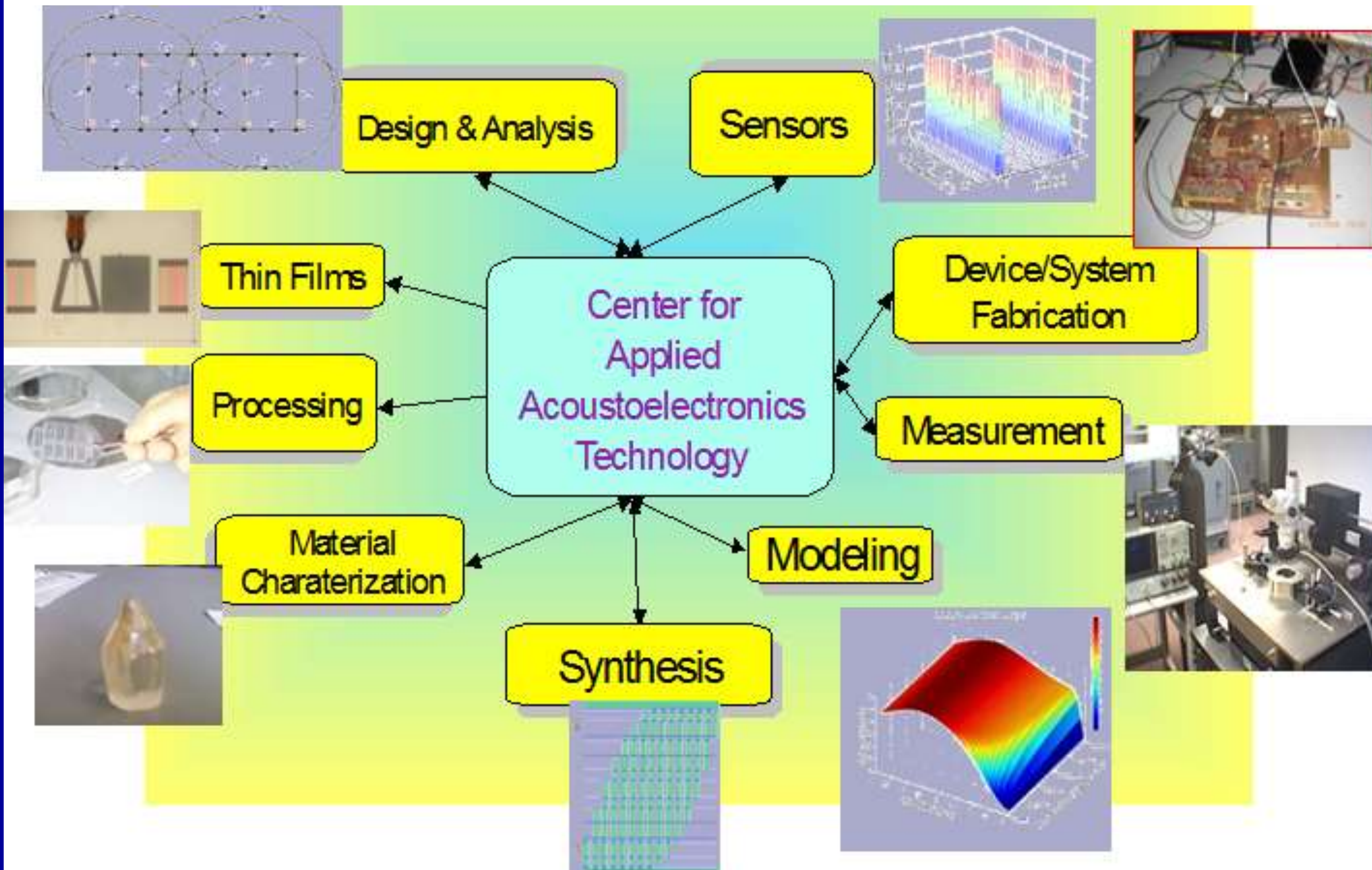
f4 f3 f1 f5 f2



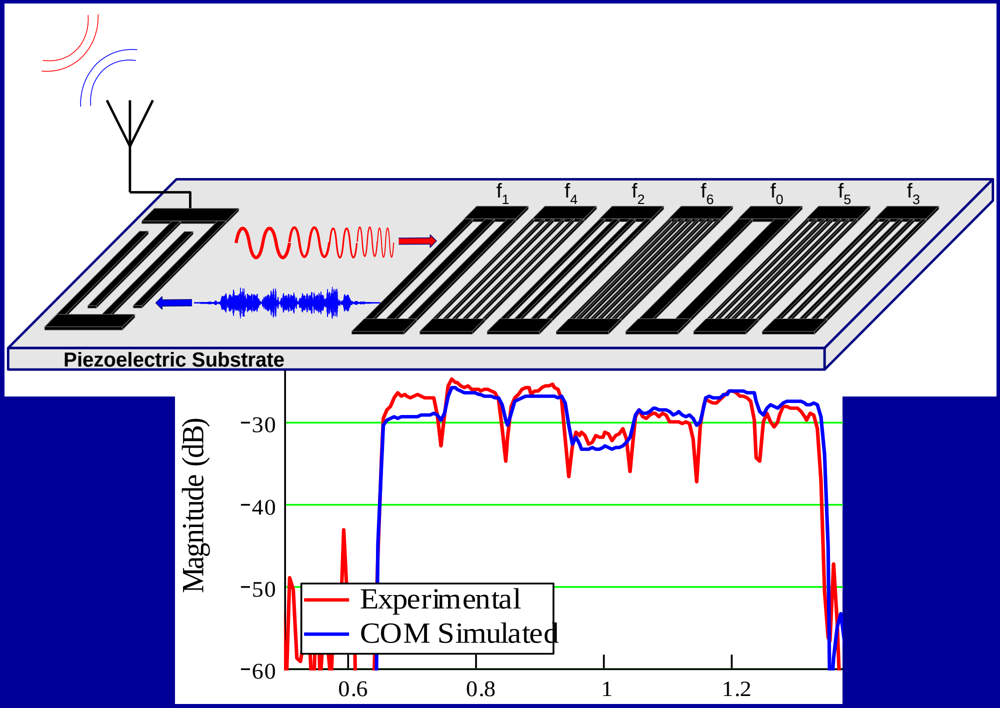
FFT

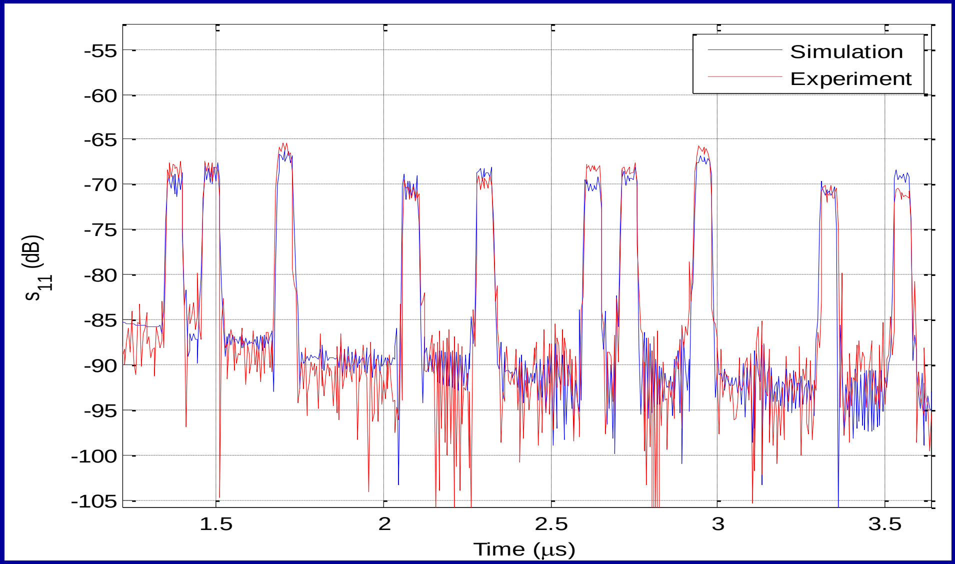


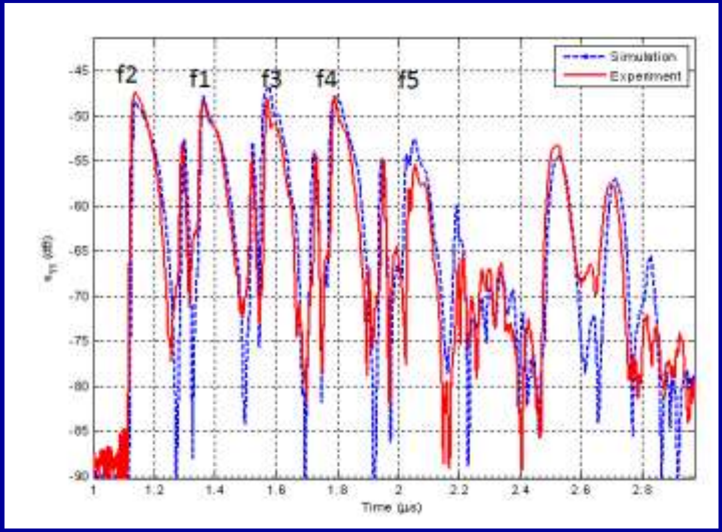
UCF Fast Prototyping
Mask (0.8 um resolution) to System
<1 week from idea to device prototype



Complex SAW Coupling-of-Modes Analysis, Modeling, Synthesis & Data Extraction







Confluence of Technology

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- **RF receiver technology – fast & cheaper**
- Post-processing – fast & cheaper
- Hardware – design, cost, performance, etc.
- SAW sensor embodiments
  - On-board sensors
  - Off-board sensors

RF Component Advances

- RF components cost a few cents and ADC's are rapidly lowering cost for broad bandwidth signal processing
- Texas Instruments, Linear Technology, RFMD, Triquint, Maxim and many others, offer RF components, transceivers and ADC on a chip
- Transceiver systems can now be custom built in the 433 to 2400 MHz bands at reasonable development and production costs
- Huge number of applications
- ASIC development as volumes increase

Confluence of Technology

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COHERENT CORRELATOR DISCUSSION

It's all about S/N Ratio

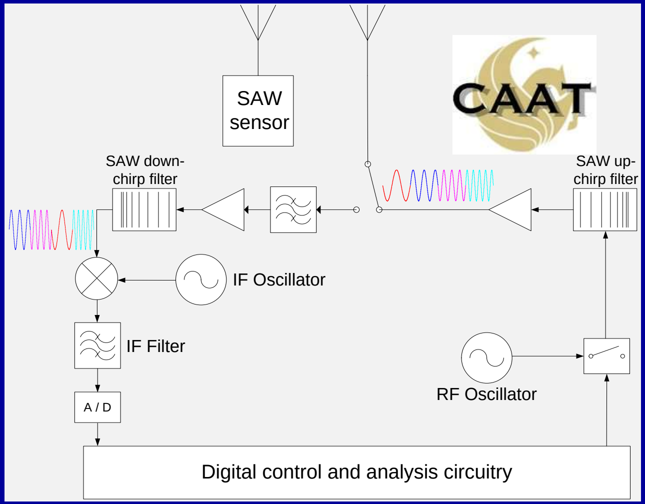
- Transceiver: time duplexed mode, opposing on-off state.
- Transceiver: synchronous mode for switching and integration.
- Interrogation signal: wideband, time-pulse (optimized for device code)
- Transceiver output: windowed time domain (or frequency domain sweep) to a post-processor.

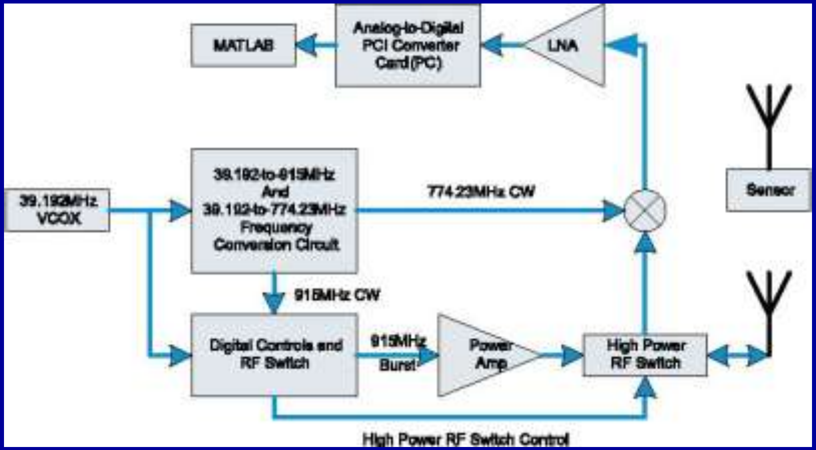
UCF Synchronous Transceiver-Software Radio (2004-2010)

- **Pulse Interrogation: Chirp or RF burst**

- **Correlator Synchronous Receiver**
  - **Integration of multiple "pings"**
  - **OFC processing gain**

- **Software Radio Based**
- **Reconfigurable**
  - **application specific**



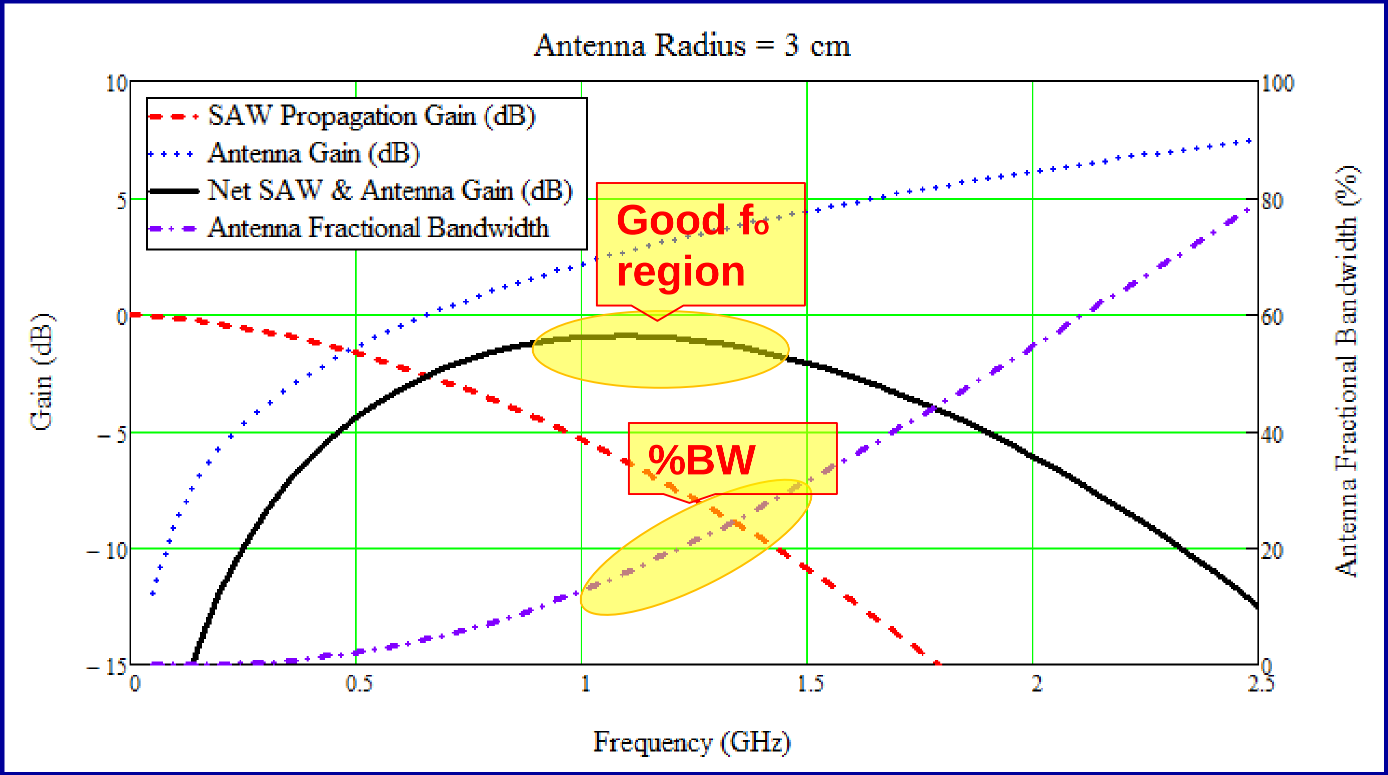


Target Gain vs. Frequency

Analysis points to ~1 GHz

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

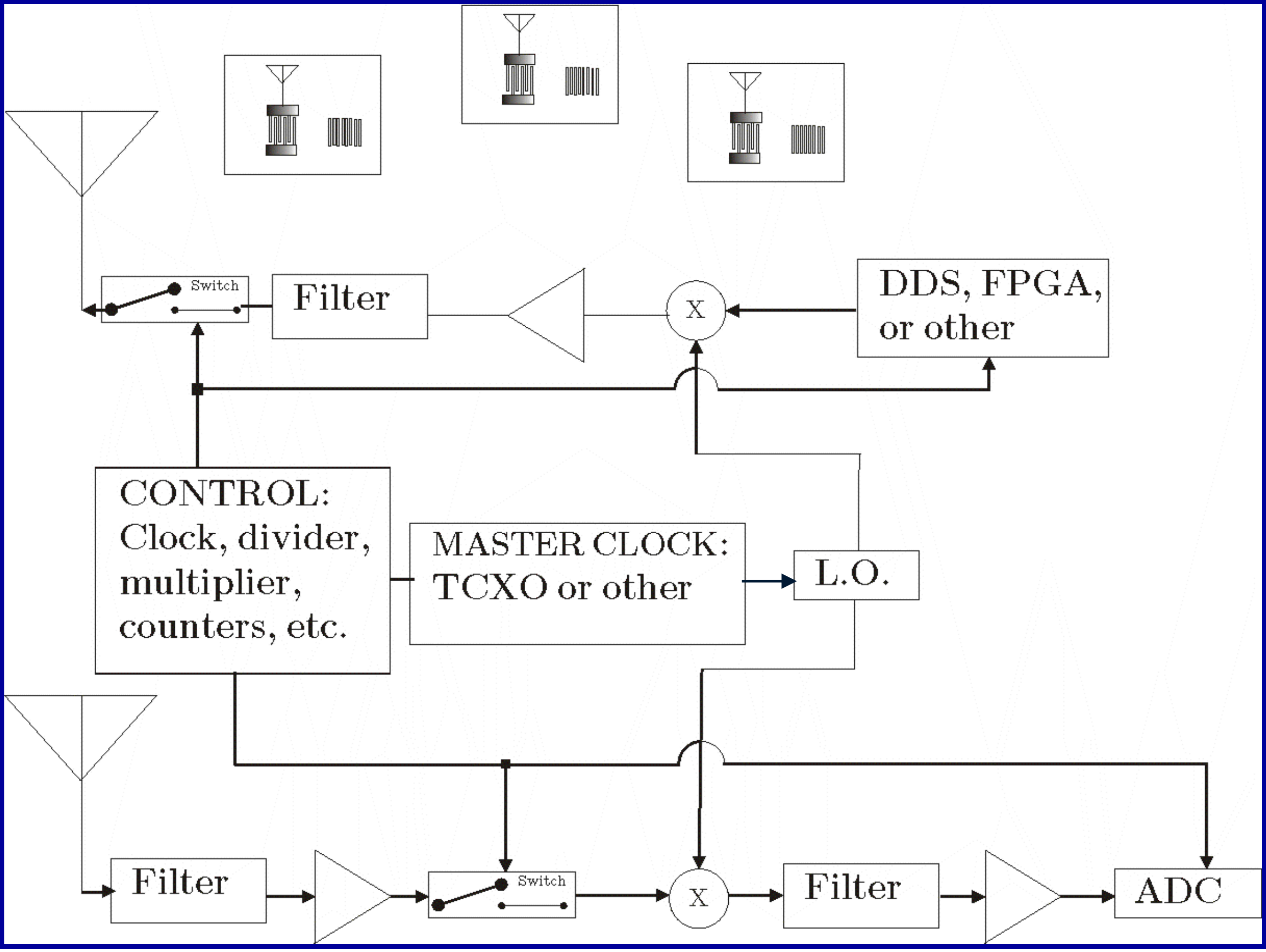
where *f* is in GHz



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**.

Example:

Hardware Synchronous TDM Pulsed Transceiver



A heterodyne coherent correlator transceiver block diagram for use in a multi-sensor SAW system with 3 SAW sensors within the antenna range. The system assumes a wide-band pulsed transmit signal, and time duplexed between transmit and receive cycles. The output from the ADC is input to a post processor that is typically a software based signal-processor.

System Demonstration

- OFC SAW sensors developed by UCF
  - 5 chip OFC delay line sensor
  - 0.8 um electrodes
- Correlator software developed by UCF for demonstrations
- 915 MHz synchronous transceiver developed by Mnemonics, Inc. and delivered on NASA STTR contract

Wireless OFC Demonstration Temperature & Range

Confluence of Technology

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- RF receiver technology – fast & cheaper
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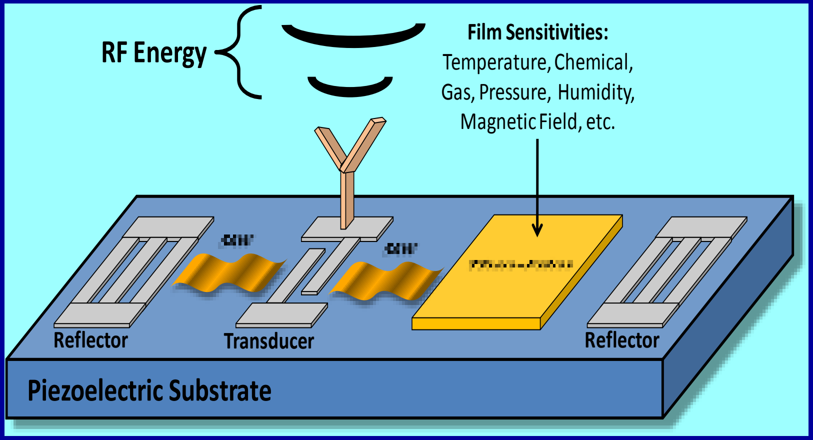
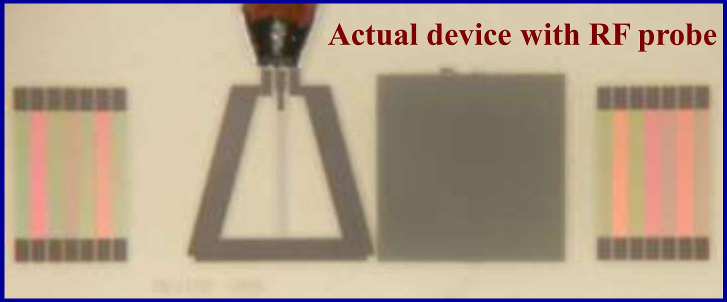
Example of Problem: Dual-Track OFC Gas Sensor



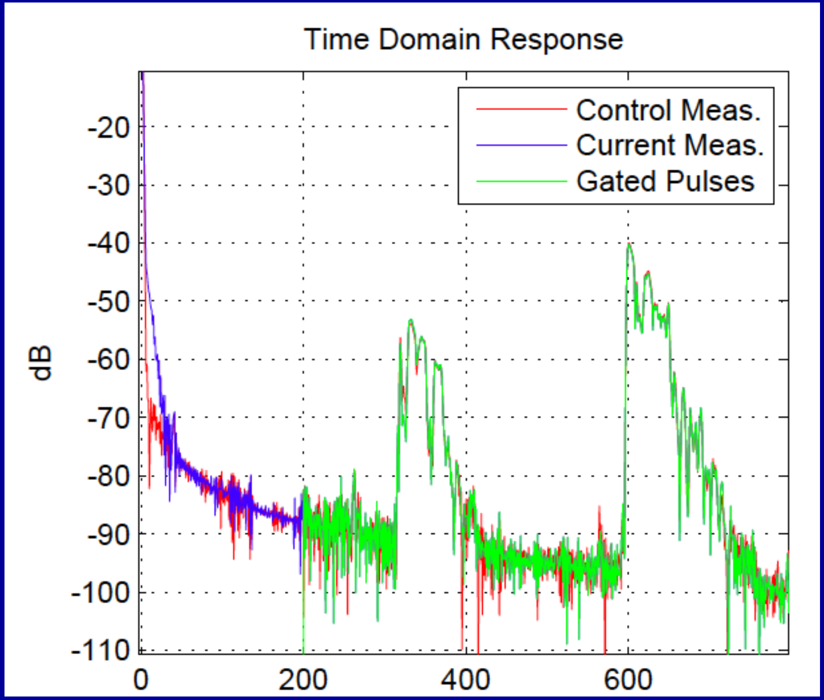


Differential Mode OFC Sensor Schematic

Ultra-thin, nano-clusters

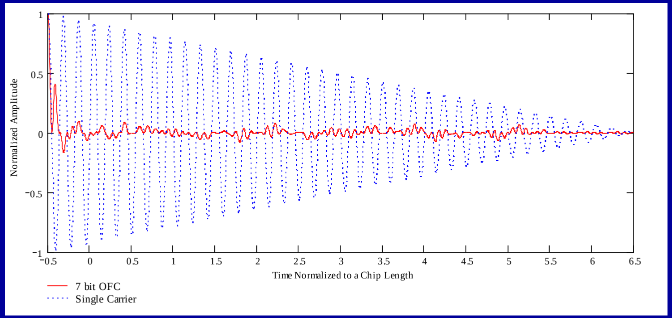
Film thickness: 10-50 Ang.

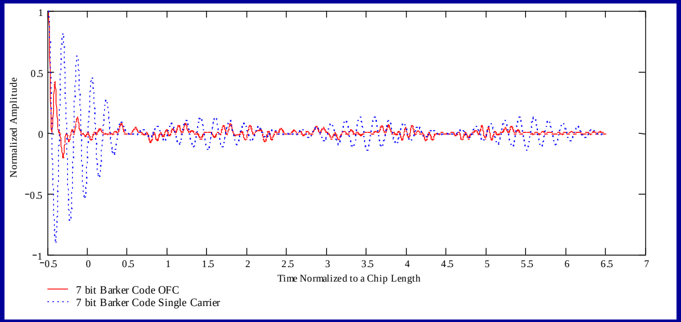
- ❑ **Dual track device: track#1 as reference and track#2 for thin film sensor**
- ❑ **Coded dispersive pulses**



Matched Filter Properties

- A symmetric time domain pulse compression, regardless of the nature of the signal.
- Compressed peak time pulse is well defined and detectable.





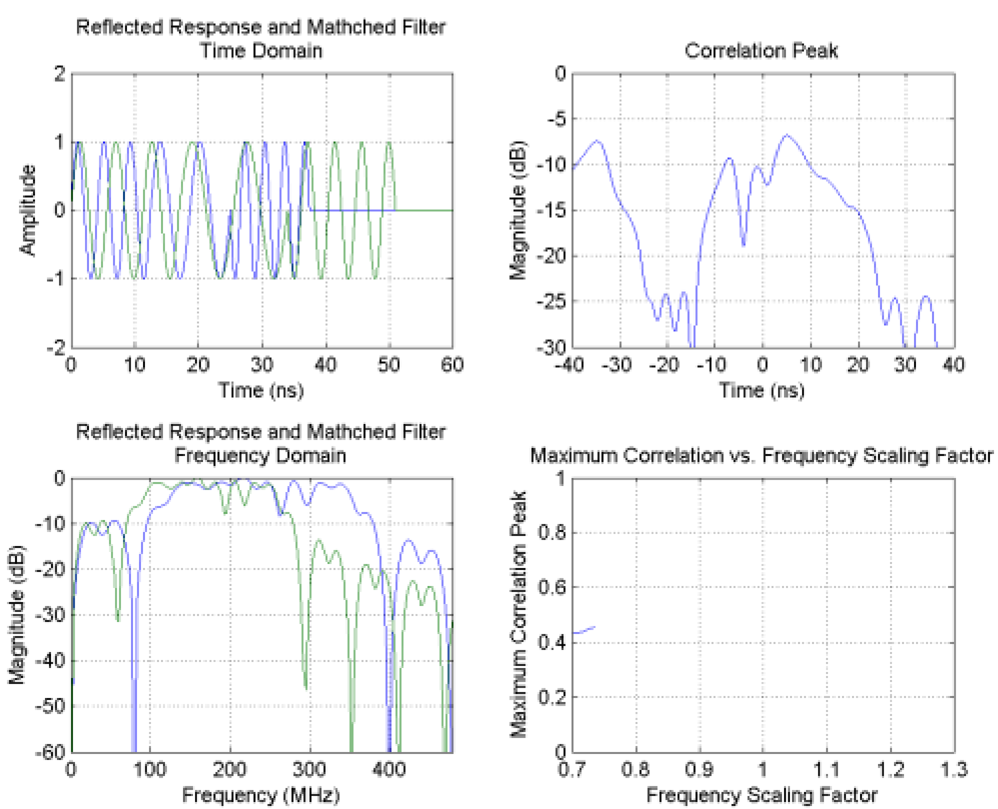
- Non-dispersive, linear phase, band-limited frequency response.
- MF is purely real in both domains
- Quadrature noise may be eliminated, increasing the effective S/N by 3 dB.

Correlator Time Delay Extraction (CTDE)

Approach

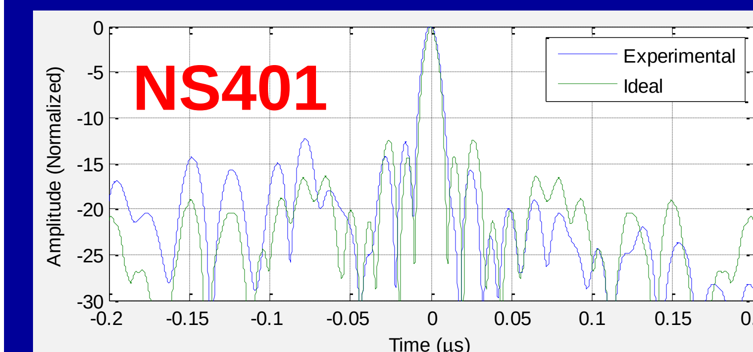
- Received signal: $H_R(f)$ = sum of all sensors in range + noise + other
- MF each received sensor coded signal
  - Process magnitude
  - Process phase
- Eliminate imaginary term for coherent integration by removing signal delay
- Maximize S/N ratio in delay extraction

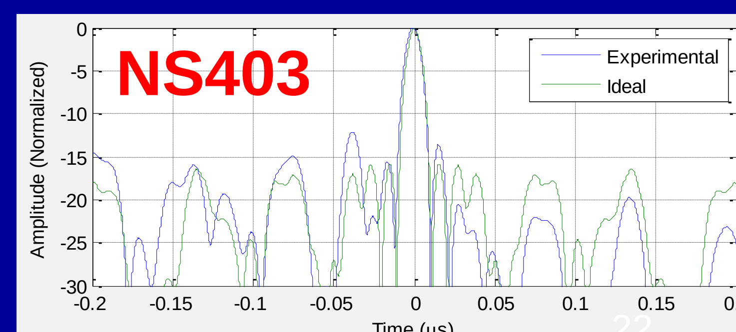
Adaptive Temperature Correlator



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

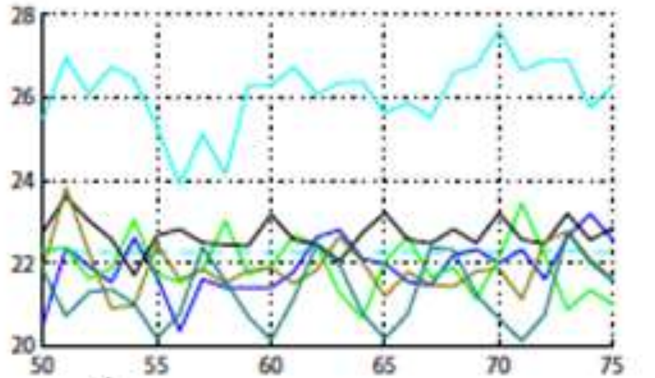
Normalized amplitude (dB) versus time

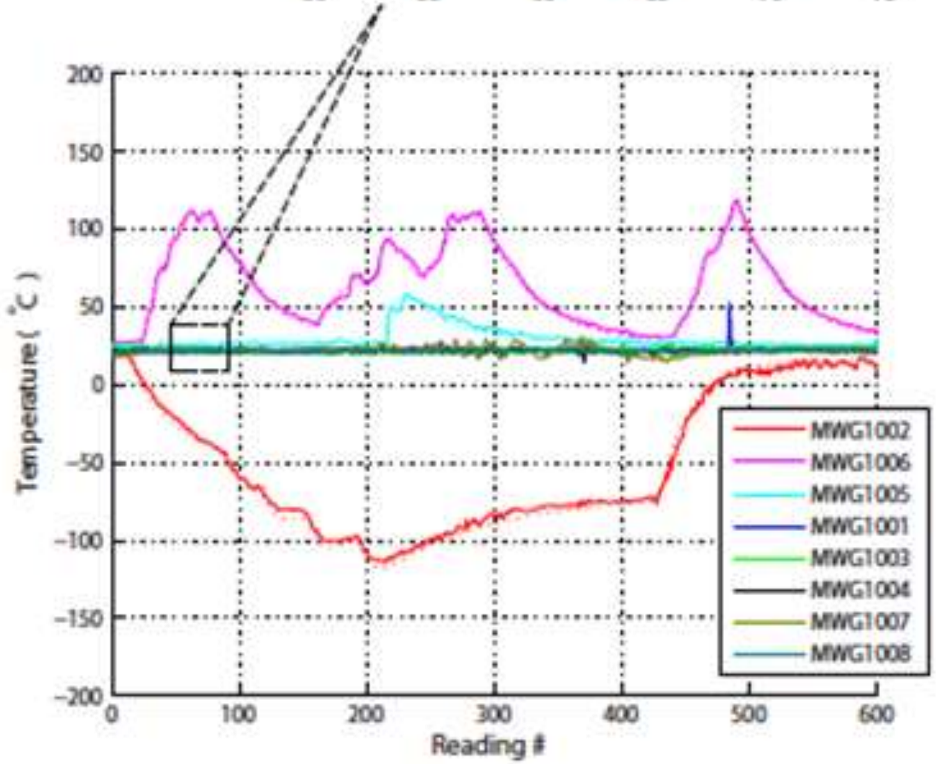




Stationary plots represent idealized received SAW sensor RFID signal at ADC. Adaptive filter matches sensor RFID temperature at the point when maximum correlation occurs.

<u>Sensor Range</u>:
Random from 1-4 meter radius



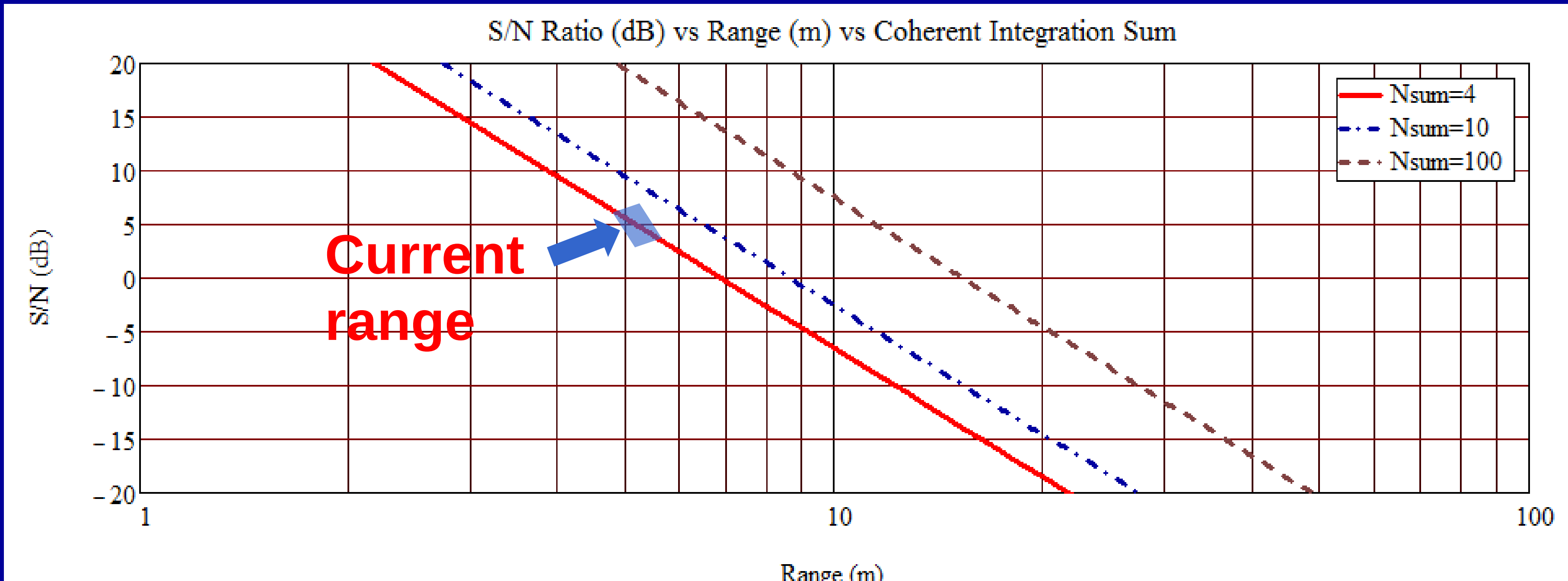


<u>Device Measurements</u>

- **MNI Transceiver**
- **915 MHz, Δf=72 MHz**
- **5-chip OFC**
- **700 nsec chirp, P_{pp_out}=28dBm, E=1μJ**
- **12-bit ADC**
- **NF~14 dB**
- **2 dBi folded dipole**
- **N_{sum}=4**
- **5 μsec time window**
- **ΔT=±150C, *dT*=±2C**

OFC 8-sensor detection system results in an open-atrium from approximately 4 meters in range. Synchronous integration of 4 sweeps per sample.

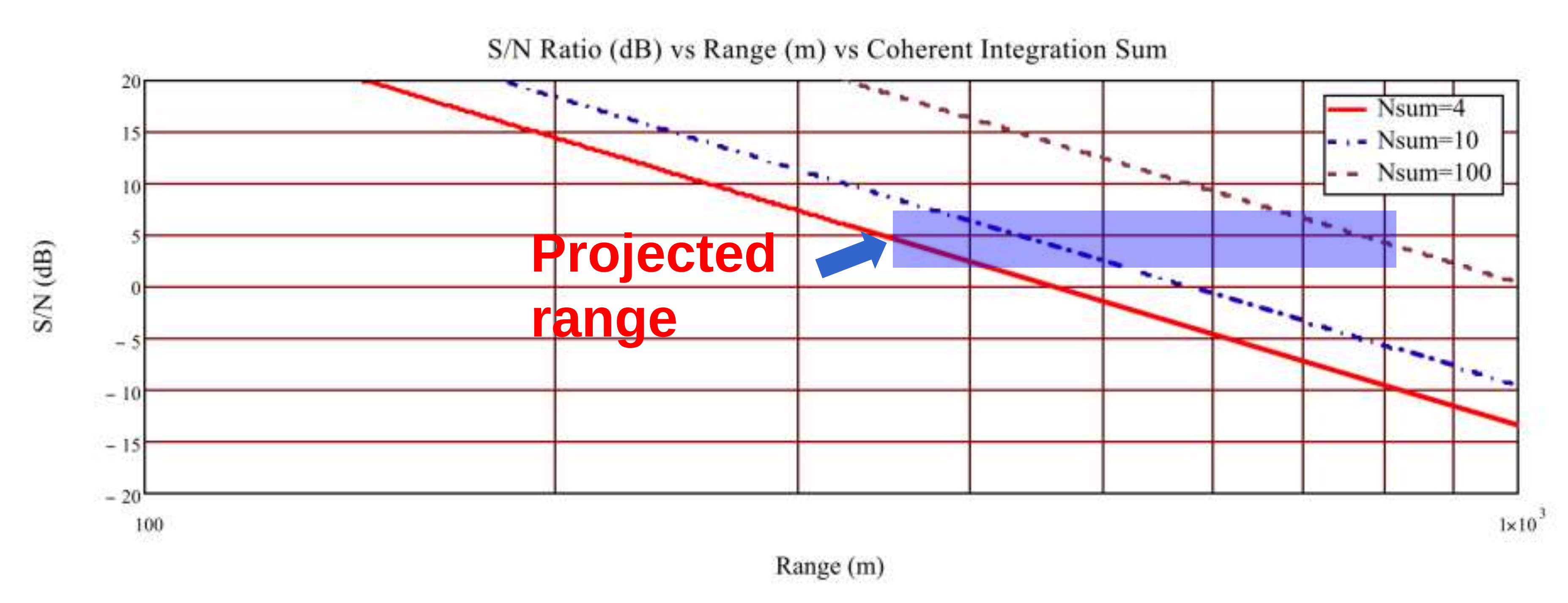
Current System



A 12-bit ADC, P_o=28dBm, $TxRx_{antenna}$=2 dBi, NF= 14 dB, and SAW sensor loss = 10dB

Isotropic propagation prediction of S/N versus range for synchronous interrogations (NSUM) = 4, 10, and 100, for a 915 MHz Mnemonics- transceiver using a 5-chip OFC SAW sensor. The S/N determines the precision and accuracy of the extracted sensor information.

FUTURE FOR SAW SENSOR SYSTEMS



A 16-bit ADC, P_o=30dBm, $TxRx_{antenna}$=20 dBi, NF= 6 dB, and SAW sensor loss = 4dB

Isotropic propagation prediction of S/N versus range for synchronous interrogations (NSUM) = 4, 10, and 100, for a 915 MHz transceiver using a 5-chip OFC SAW sensor. The S/N determines the precision and accuracy of the extracted sensor information.

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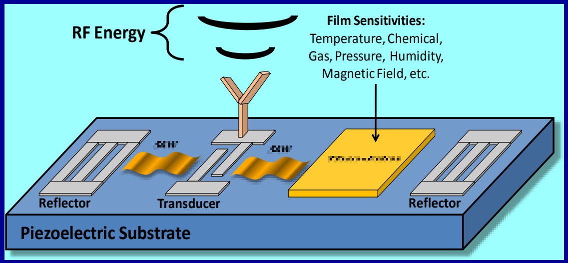
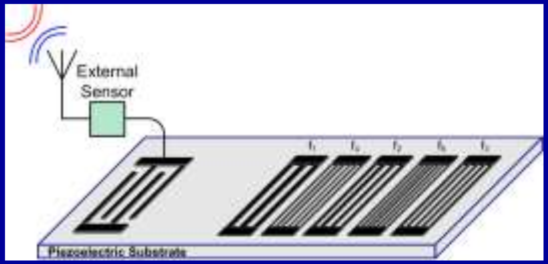
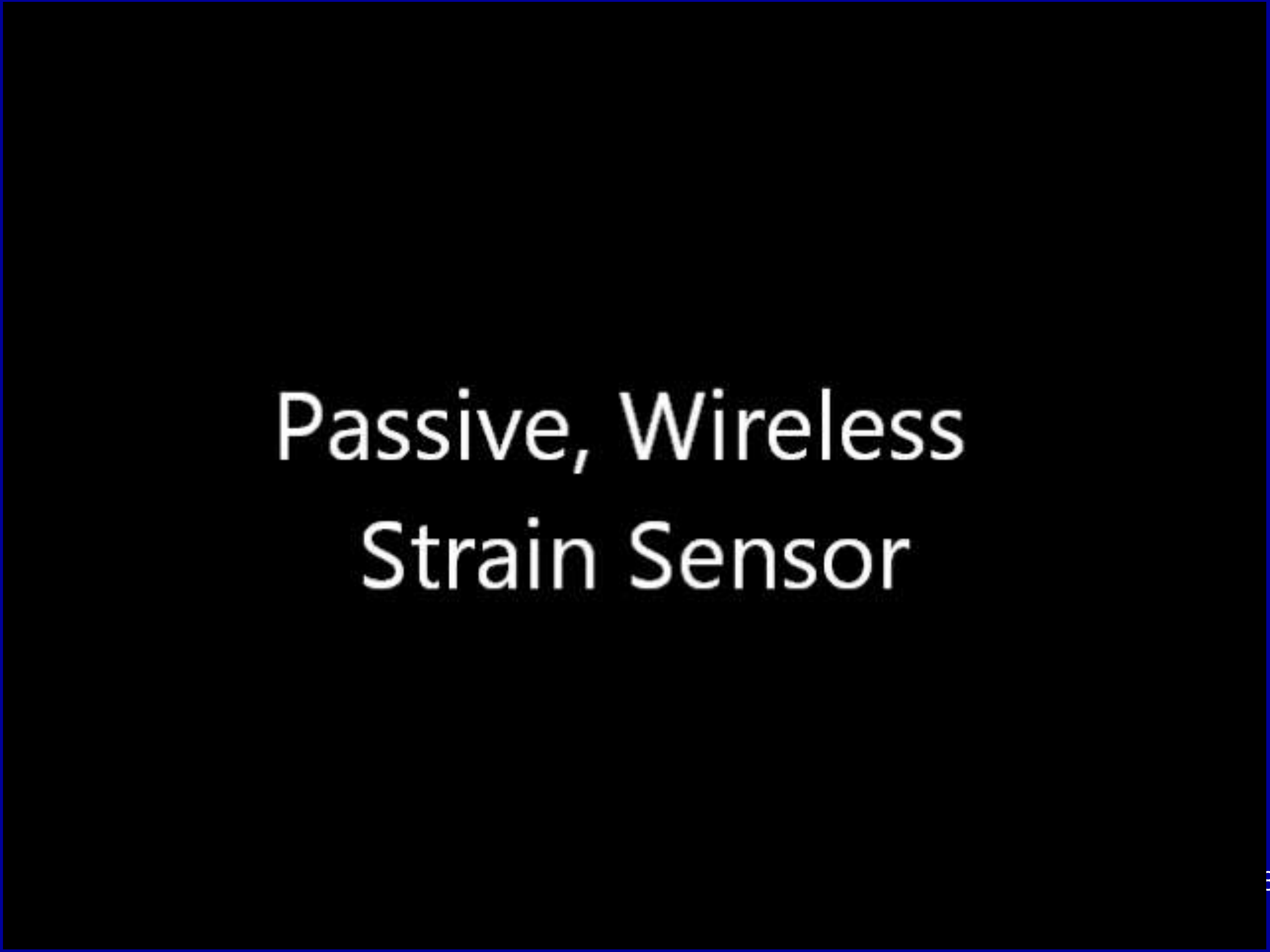


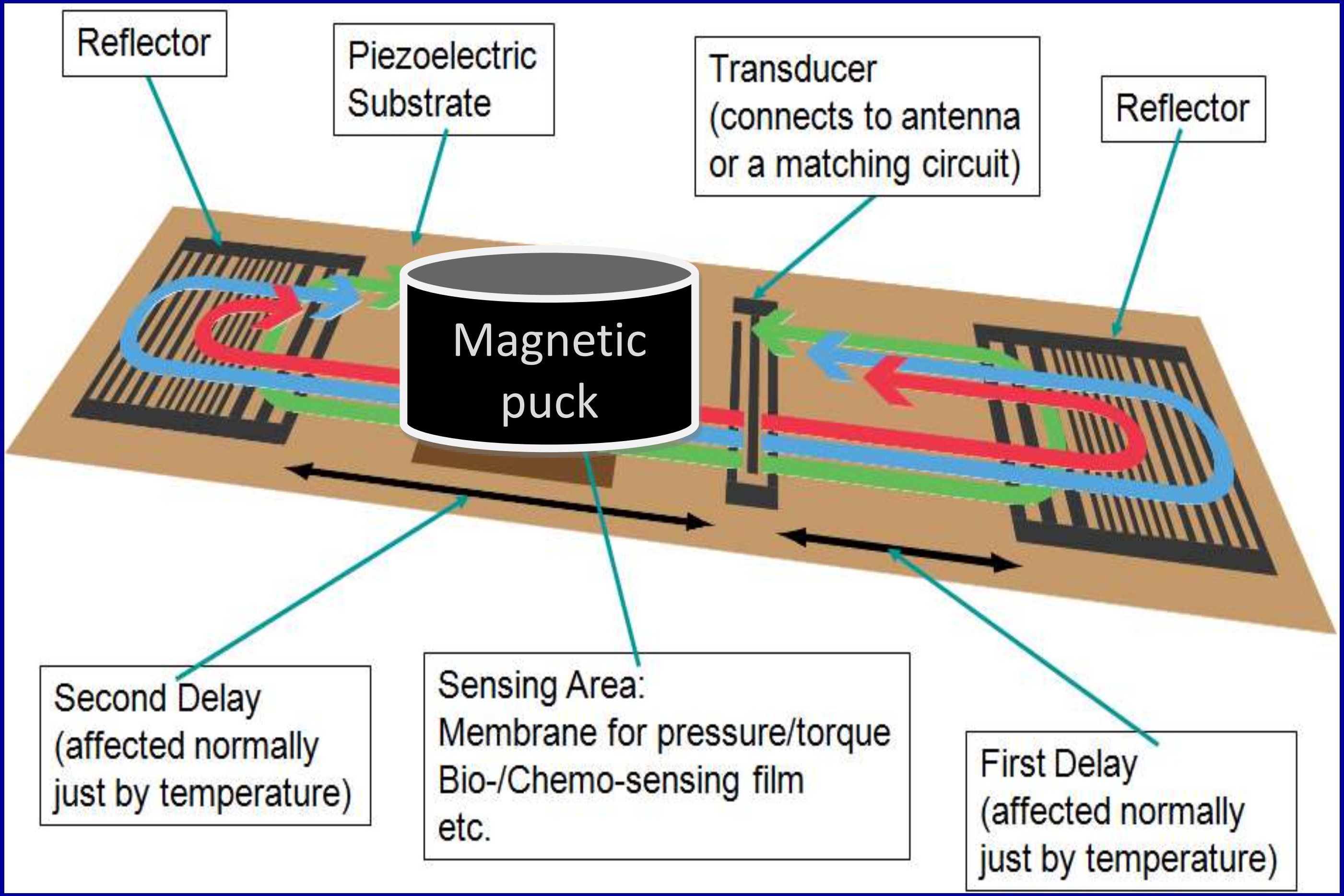


Wireless OFC Gas Sensor

Wireless OFC Demonstration



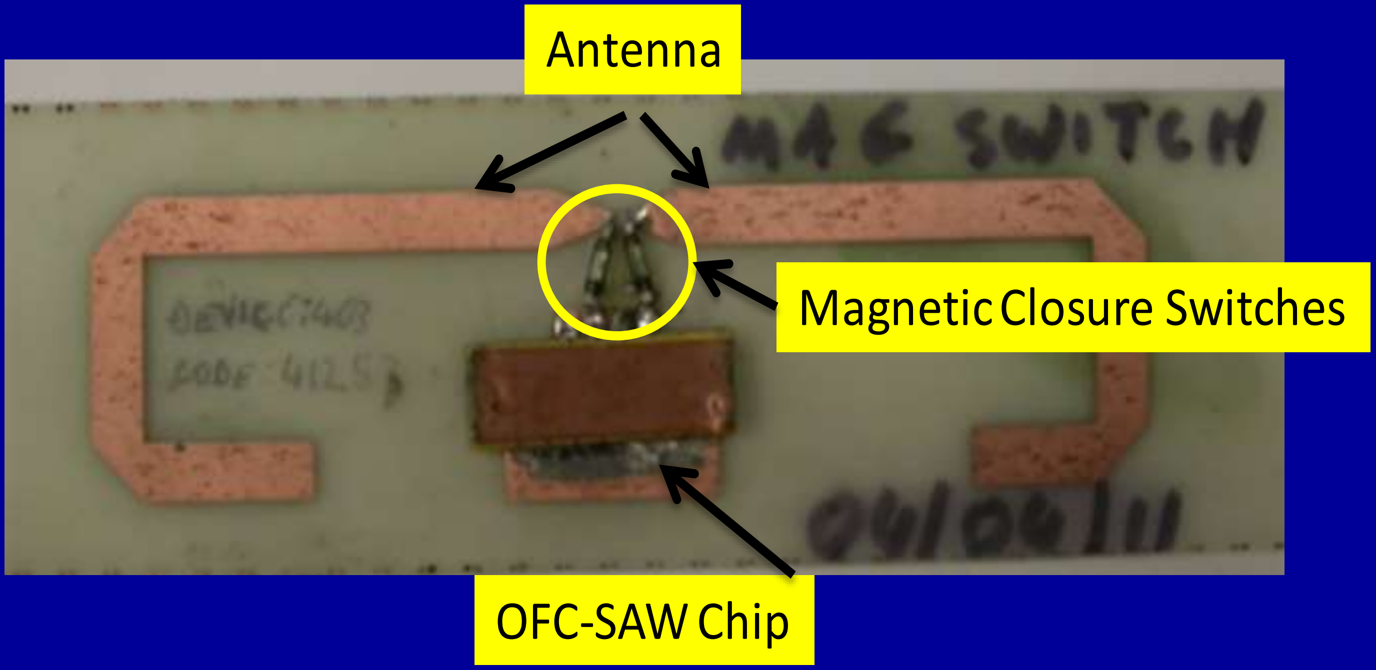
#1 On-Board Integrated Closure Sensor



#2 External sensor; the OFC SAW is the RFID and sensor used to modulate

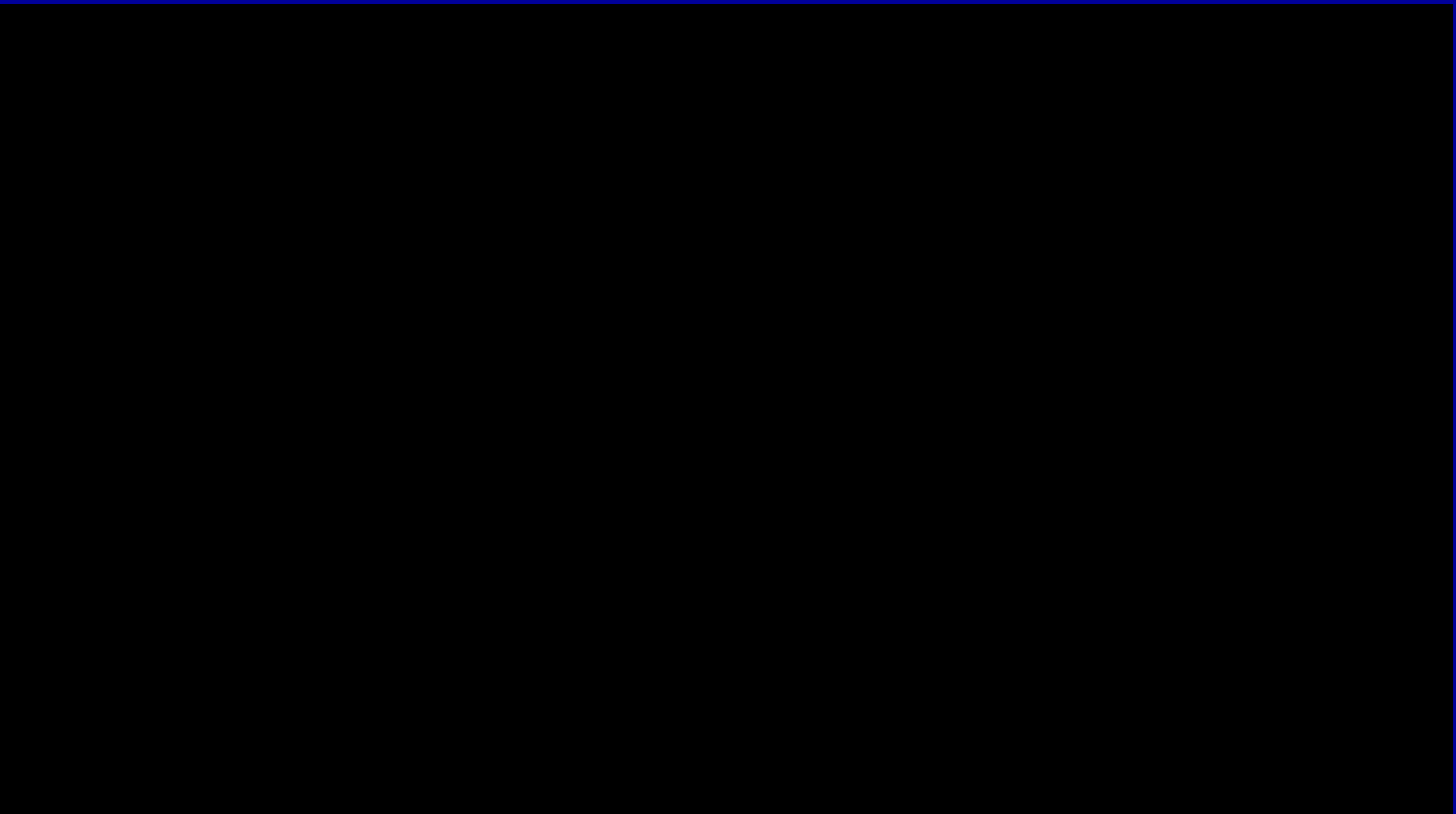
#2: 915MHz OFC-SAW-tag and antenna closure sensor

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



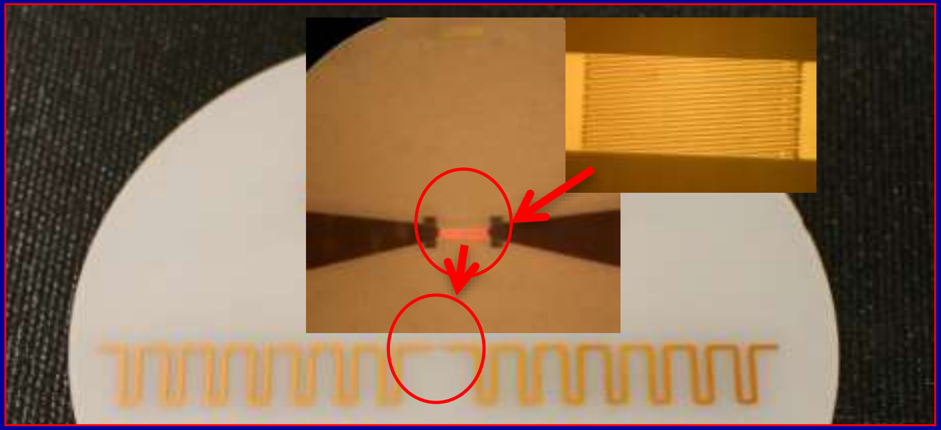
- **on-off ratio >30dB**
- **Multi-track**

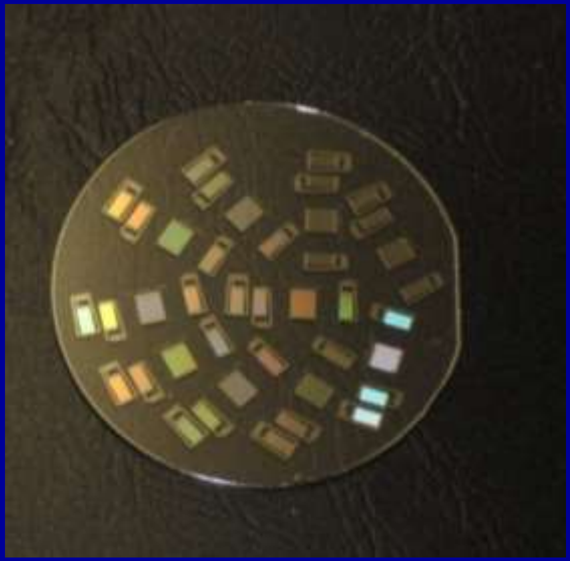
Wireless OFC Off-board Closure Sensor



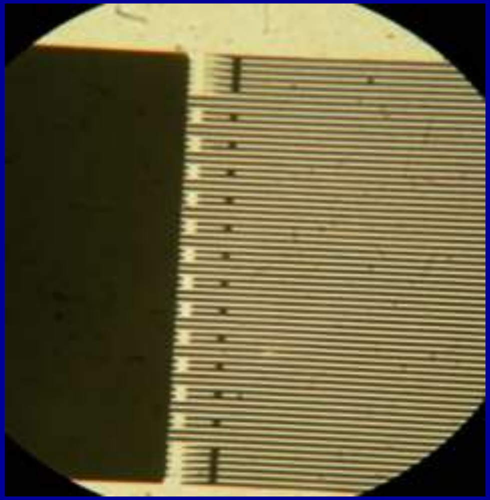
High Temperature Sensors

- 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 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: narrow-, wide-, ultra wide–, band have all been demonstrated

Thank You!

ACKNOWLEDGMENTS

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- This work was partially supported by grants from the Florida High Tech Corridor Council and the Florida Space Institute.
- MNI for transceiver development