Approximately 4-5 billion SAW devices are produced each year.

If you have a cell phone, you own multiple solid state acoustic devices.

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 (~4000 m/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
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
UCF CAAT Sensor Research since 2004

**Major Student Fellowships:**
- 5- GRA Research Program Fellows: = $410K
- 2- McKnight: = $160K
- 1- NSF:= $65K
- 2-FSGC: = ~$40K

**18 Contracts:**
- 9 - STTR/SBIR Phase I = $410K
- 7- STTR/SBIR Phase II = $1.92M
- 2 – DoD = $1.13M
  
Other = $750K

7 – UCF Patents on SAW based sensors and systems & several pending
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) cannot 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: $1 < \text{range} < 1000$ meters
• # of devices: 2 – 100’s - coded and distinguishable at TxRx
• Single platform and TxRx for differing sensor combinations
• Can operate over a wide temperature range.

Jim Nichols – KSC/NASA Licensing Manager
NASA Techbriefs Webinar
Sept 19, 2013
Why SAW Passive Sensors?

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• 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

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

\[ \frac{\lambda f}{\nu} = \lambda \text{ vs } f \]

| \( \lambda_{\text{SAW}} \) | 300 \( \mu \text{m} \) | 3 \( \mu \text{m} \) |
| \( \lambda_{\text{EM}} \) | 30 \text{m} | .3 \text{m} |

FOR \( \tau_D = 20 \mu \text{sec} \)

\[ L_{\text{SAW}} \approx 6 \text{cm} = 2.4'' \]

\[ L_{\text{COAX}} \approx 6000 \text{m} = 3.75 \text{mi} \]

SAW RF Mobile Phone Filter
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 = \( \lambda / T \)

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

Center frequency = \( f_{\text{SAW}} = \frac{\nu_{\text{SAW}}}{L} \)
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

With \( \frac{3}{4} \) 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 Prototyping and Test

Wireless Multi-Sensor Concept

915 MHz Systems

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

Wireless H₂ Gas
• < 50 ppm
• RT reversible
• Response <1s

Wireless Temperature
• <.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 $\sim 10^2$-$10^3$ MHz
- Monolithic structure fabricated with current IC photolithography techniques
Example of a Multi-reflective Passive SAW Code Device
Wireless OFC Demonstration
Schematic of a typical OFC SAW ID Tag

RF\textsubscript{in} \sim 1\text{GHz}

RF\textsubscript{out} \sim \text{encoded at } 1\text{GHz}

SAW velocity \sim 4000 \text{ m/sec}

Sensor bandwidth

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

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.
Bit, PN, OFC Signal Comparison

- Normalized Frequency
  - Normalized to Peak of Single Carrier (dB)
  - 7 chips/bit PN-OFC
  - 7 chips/bit PN Single Carrier
  - BPSK

- Normalized Amplitude
  - 7 chips/bit PN-OFC
  - 7 chips/bit PN Single Carrier
  - BPSK

- Time Normalized to a Chip Length
SAW OFC RFID signal – Target reflection as seen by antenna

SAW absorber

S₁₁ w/o absorber and w/ reflectors

OFC Sensor Response

Coded SAW chips are bound in frequency and received sequentially in time
Example 915 MHz SAW OFC Sensor

SAW Sensor

US Quarter

Light Micrograph

SAW OFC Reflector Chip Code

FFT

S11 Frequency Response

Magnitude (dB)

Frequency (MHz)

S11 Time Response

Magnitude (dB)

Time (μs)
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
It’s all about S/N Ratio for any sensor system

- Interrogation signal:
  - Time windowed, all sensors 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

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

or

\[
\frac{S}{N} = G_{\text{TR}} \cdot G_{P} \cdot G_{E} \quad (2)
\]

where \( G_{\text{TR}} = \left[ \frac{V_r^2 \cdot N_{Sum}}{V_{MDS}^2} \right] \), \( G_{P} = \left[ G_{\text{Sensor}} \cdot G_{\text{Tx-ant}} \cdot G_{\text{Rx-ant}} \right] \) and \( G_{E} = \text{PL}^{-1} \).

\( V_r \) is the transmit voltage level and \( V_{MDS} \) is the voltage level detectable at the ADC, \( \text{PL} = \text{Path Loss} = \left[ \frac{\nu_{EM}}{(4 \cdot \pi \cdot R \cdot f_o)^4} \right], R=\text{range} \)
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

Experimental
Ideal

Temperature Run (Single Sensor)

Temperature from SAW Sensor (Frequency Shift)
Thermocouple Temperature
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**
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 ~250°C to 0.1 Kelvin
Hydrogen Gas Sensor using Acoustoelectric Effect (AE)

Motivation

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
NASA-KSC Wireless Test: Hydrogen Gas Sensor
0.2\% max H_2 0.02\% concentration steps
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
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
  – Luis Rodriguez
  – Jose Figueroa
  – Roman Grigarov
  – Scott Smith
  – Chris Carmichael
  – Marc Lamothe
  – Art Weeks

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Thanks for your attention!