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SAW Sensor Development at 4.3 GHz for the Wireless Avionics Intra-Communications Band

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***Abstract*—This paper discusses 4.3 GHz passive wireless surface acoustic wave (SAW) temperature sensors and system. Wireless, passive, SAW sensors, which can operate in a multi-sensor environment, have been successfully demonstrated at various frequencies by many and varied research and commercial groups. The current research extends the SAW sensor operational frequency with an initial demonstration of temperature sensing. A key motivation is the allocation of the wireless avionics intra-communications (WAIC) band. WAIC provides communications between two or more points within a single aircraft. Possible SAW wireless applications include cabin pressure, door sensors, proximity temperature, humidity, corrosion, and many aspects of structural health monitoring (SHM), including engine SHM. System implementation considerations using wideband SAW sensors are outlined. Recent design and experimental results on 4.3 GHz SAW delay line sensors are presented.**

Keywords— Surface acoustic wave, SAW, WAIC, sensor

I. Introduction

This paper discusses recent developments of 4.3 GHz passive wireless SAW sensors and system. Wireless, passive, SAW sensors, which can operate in a multi-sensor environment, have been successfully demonstrated at various frequencies by many and varied research and commercial groups. Past sensor work produced SAW sensors and systems using orthogonal frequency coded (OFC) delay line RFID sensors at frequencies up to 1 GHz [1][2]. The current research significantly extends the SAW sensor operational frequency and bandwidth with an initial demonstration of temperature sensing. A key motivation of this work is the recent allocation of the wireless avionics intra-communications (WAIC) band at 4.3 GHz with 200 MHz bandwidth [3]. Design, simulations and experimental results on 4.3 GHz SAW delay line sensors using transducer and reflector harmonic operation are shown. WAIC scenarios, applications, opportunities and challenges are discussed. The WAIC approach provides many important benefits for next generation aircraft, including safety, reduced wiring and overall weight, increased reliability, increased sensing data, lower maintenance, fuel economy, and system networking. Challenges include inter- and intra- sensor interference, interference with other systems, and sensor accuracy and reliability. The WAIC system presented herein is shown in Fig. 1. This work is conducted in collaboration with the University of Central Florida (UCF) and the SAW devices were fabricated and measured at UCF.

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II. Background

A. WAIC

The WAIC band provides communication between two or more points on a single aircraft, with the majority of applications within the aircraft cabin and fuselage. The spectrum is allocated for installation of integrated wireless components and sensors within the aircraft, which would become essential elements within the aircraft’s internal network. The systems can only be used for safety related applications and cannot be used for off-board air-to-ground, air-to-satellite, air-to-air service or for passenger or inflight entertainment services. The WAIC uses short range radio technology (< 100m) and a relatively low maximum transmit power of 10 mW for low data rates and 50 mW for high data rates.

1) WAIC Goals:

- Provide increased sensor data
- Improve operational efficiencies
- Reduce weight
- Increase system safety
- Improve reliability via wireless connectivity
- Maintain and increase system redundancy
- Increase dissimilar system redundancy
- Ease in reconfigurability
- Reduce installation and operational costs

2) WAIC Impact:

Approximately 1/3 of electrical wires could be converted to wireless connectivity. The impact can be enormous since there can be 10’s – 100’s thousands wires, with total lengths of 100’s kilometers and weight of 1000’s kilograms.

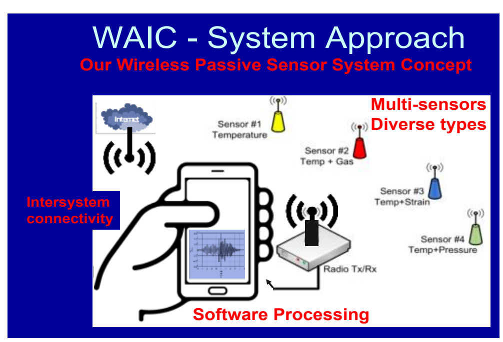

Fig.1. Wireless sensor system concept.

Wireless sensors can be placed on rotating and moving parts and systems, such as brakes, turbines, and landing gear

3) WAIC Requirements and Issues:

- Network integration and compatibility
- Cost
- Reliability
- Must not interfere with radio-altimeter [4]
    - During inflight, landing, takeoff & ground
        - Between aircraft
        - Within aircraft

B. SAW sensors

This new WAIC band and application space offers many opportunities as well as challenges for SAW sensor technology. High volume SAW device production is currently manufactured for GHz communication applications but have been limited to approximately the 2.4 GHz range. SAW filters and resonators offer advantages of solid-state, small size, high performance, power handling, low loss and low cost. Despite all the advantages, SAW devices have their inherent limits. Photolithographic line resolution determines one limit and is in the range of 0.2 microns. The second limitation is the competing technologies that offer better system performance, especially for RF frontends that require low insertion loss. In general, the choice of a chosen technology is a parameter-matrix of cost versus performance versus size.

The WAIC sensor technology choices have similar tradeoffs, but the parameter-matrix is different. New SAW sensors will need development for passive wireless WAIC applications and need to find their unique application space. Passive SAW sensors have all the inherent attributes of the high-volume SAW RF and IF devices. Additional consideration is that SAW sensors can operate in harsh environments, over fairly wide temperature ranges, can be RFID encoded, and multi-sensor operations can be achieved with relatively small modifications in embodiment. This translates into a common SAW platform with small embodiment changes, independent of the sensor's parameter extracted, with operation within a single transceiver interrogation system.

C. SAW Sensor Device Goals:

- RFID encoded
- Initially temperature and stress-pressure sensors
- Minimize device losses
- Antenna integration
- Low cost

1) SAW Sensor Challenges

- 4.3 GHz SAW currently unachievable with fundamental frequency operation
- 200 MHz is small fractional bandwidth (4.7%) at fundamental but challenging at harmonics
- Acoustic substrate propagation losses are high with increased delay and device structures
- Reduce SAW sensor losses for increased range
- Develop low cost sensors with integrated antenna

2) SAW Sensor System Challenges:

- Low cost transceiver system at 4.3 GHz
- 200 MHz acquisition bandwidth desired
- Acoustic substrate propagation losses are high with increased delay and device structures
- Simultaneous interrogation of multiple sensors, differing measurands, and diverse passive sensor technologies
- Achieve required signal to noise ratio within fuselage and cabin for measurand extraction
- Networking capability

D. Transceiver at 4.3GHz

Fig. 1 shows the conceptualization of a WAIC system approach for wireless passive sensors. A large number of transceivers have been built over a period of 7-8 years at UCF for interrogation of SAW sensors [5]. The last several years have focused on the development of the universal software radio peripheral (USRP) software defined radio (SDR). The previous approaches were focused at 915 MHz that was a good test vehicle for development at an ISM band. The USRP SDR had proven to be versatile, the size and cost are acceptable, and the move to the 4.3 GHz band seemed feasible. The Ettus USRPs B200 and B200mini had been previously used and both have similar specifications. The USRP can operate to 6 GHz; covering the 4.3 GHz WAIC band. The USRP is limited to 56 MHz while the WAIC maximum bandwidth is 200 MHz. Other USRP systems were researched with wider bandwidth, but had other compromising parameters, such cost, size, availability, etc. The decision was to continue with the B200mini development and use frequency hopping between contiguous bands, as necessary, to cover the entire bandwidth, at the expense of increased data acquisition time.

1) Identified transceiver challenges

- Interfacing between hardware and software
- Software control of important hardware parameters, such as frequency, bandwidth, etc.
- Agile frequency hopping while changing bandwidths
- Data acquisition speed
    - Data transfer and handling
- GUI speed
- Embedded processor acquisition and processing speed

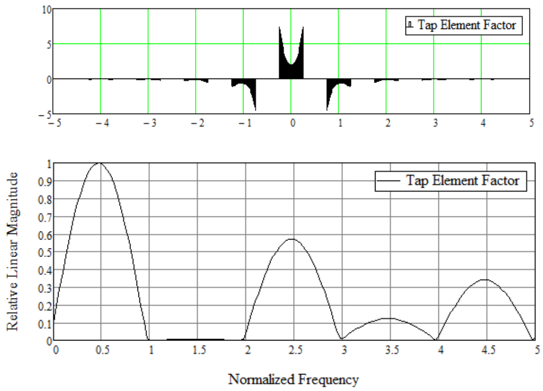

Fig.2. Normalized SAW tap element factor charge distribution and frequency predictions for 2 electrodes per IDT period with electrode duty factor of 50%.

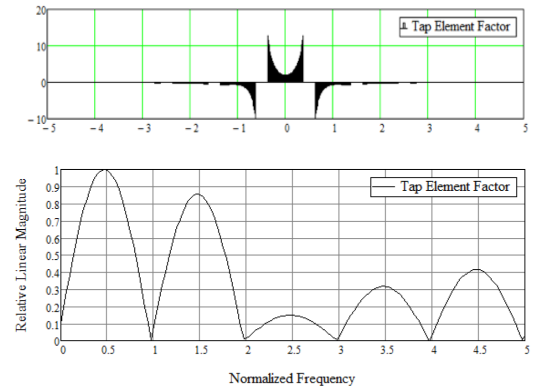

Fig.3. Normalized SAW tap element factor charge distribution and frequency predictions for 2 electrodes per IDT period with electrode duty factor of 75%.

III. SAW 4.3 GHz Sensor Implementation Approach

The strongest IDT electroacoustic coupling occurs when there is one active element per acoustic wavelength. This occurs when the IDT electrode period is ½ the acoustic wavelength; this is physically represented with 2 electrodes per wavelength yielding an electrode separation of ½ wavelength. For a 3rd and 5th harmonically operated IDT, the effective coupling is reduced by 3 and 5, respectively, compared to fundamental operation. This translates to less power radiated by a factor of 9 and 25, respectively but does not directly mean more loss. Indirectly, the IDT Q is higher at harmonics than at fundamental, and the associated electrical load effects can affect bandwidth and parasitic losses. Therefore, when possible, it is advantageous to operate the IDT at the lowest harmonic possible.

For a 3rd harmonic device, the line resolution is approximately 0.6 µm and a 5th harmonic device is approximately 1 µm. Commercial masks can be obtained at 0.6µm line resolution and 3rd or 5th harmonically operated devices can be manufactured with contact or stepper printing.

The harmonic coupling can be derived from the fundamental device physics. It has been shown that the SAW response is proportional to the electrostatic charge on the electrodes. The approach is to find the coupling of a single-element, uniformly periodic, IDT that consists of a single electrode at 1V and surrounded by an infinite number of grounded electrodes and to calculate the time and frequency domain charge characteristic. This structure is referred to as the tap element factor and defines the frequency dependent coupling factor for a single electrode as a function of frequency. Rather than infinite number of electrodes, as few as 6-10 ground electrodes are used in simulations providing adequate electric field decay. If the voltage sequence (also called the array factor) is then convolved in time with the element factor, or conversely multiplied by the element factor in frequency, the complete time and frequency response for any arbitrary IDT is obtained. Fig. 2 and 3 are examples used for comparison of the line width to period ratio (duty factor) effects. As seen in Fig.2, a 50% duty factor has a strong 5th and no 3rd harmonic; with weak 7th, and 9th. In contrast, Fig.3 with a duty factor of 75% shows a strong 3rd, 7th, and 9th and a smaller 5th harmonic coupling. The SAW sensor approach will be to use the lowest harmonic that is available for a particular fabrication facility, and optimize harmonic coupling.

Initial devices were designed and fabricated at the University of Central Florida (UCF) to show feasibility. UCF's in-house mask fabrication is limited to about 0.8 µm line resolution, therefore, the initial test devices were designed for 5th harmonic operation. Results of a first demonstrated 5th harmonic 4.3 GHz delay line and a simple reflective delay line are shown in Fig.4. The 2-port delay line device has approximately 32 dB insertion loss and the 1-port reflective delay line shows a 0.45 µsec delay and a good pulse reflection amplitude.

The higher operating frequency allows considerable decrease of the antenna size. Fig. 5 compares a UCF 915 MHz folded dipole PCB antenna as compared to a similar 4.3 GHz antenna with required bandwidth. If the device and antenna are integrated onto the same substrate, further reduction of size and cost would be realized.

IV. Transceiver Implementation Approach

The heart of the system is a National Instruments (NI) USRP B200 or B200 mini hardware, shown in Fig. 6. The B200 mini is chosen since it is readily available, relatively low cost, and has a credit card size. The system is augmented with a custom designed RF frontend to add additional amplifiers, switches, filters. This provides additional gain for Tx power output and increased sensitivity at the Rx to meet specifications and optimize signal to noise ratio at the output ADC. The entire system uses commercially available RF components. The system can operate from approximately 100 to 6000 MHz and is controlled via software. The ADC has a 56 MHz bandwidth that limits the bandwidth of a single interrogation signal. This

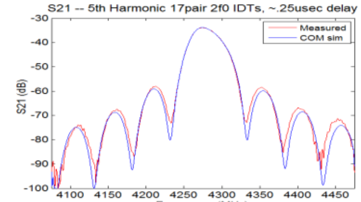

Fig.4. SAW 4.3 GHz, 5th harmonic measured time and frequency responses.

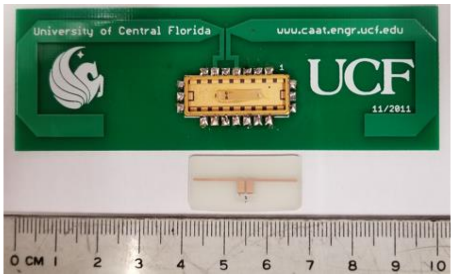

Fig.5. A 915 MHz SAW wireless sensor with PCB folded dipole antenna(top) compared to a 4.3 GHz SAW device with a suitable PCB antenna (bottom).

bandwidth can be expanded by using multiple pings and software control of center frequency, at the expense of lower acquisition speeds.

The transceiver is operated in a time division multiplex (TDM), synchronous, coherent mode. The Tx signal is currently either a chirp or a noise-like PN sequence generated at base-band within the FPGA. The signal is up converted to the desired center frequency and sent to the RF board. On the Rx side, multiple sensor signals are received in each interrogation cycle and are integrated to obtain the required SNR. The number of ADC samples are 512 over the desired frequency window and establishes the time window, approximately 10 µsec or greater. This time window is normally adequate for the SAW based systems.

The ADC data samples are sent to the processor, which can be a computer or embedded processor, for post processing and sensor data extraction. If 100 cycles are integrated, then an approximately 10 dB increase in SNR is expected and the 5120 data points yields a single measurand sample. For WAIC systems, the final extracted information is very small which can be transmitted wirelessly, or otherwise, to the system network backbone. The network can then integrate the information into existing displays, or command and control hardware.

The SDR approach provides great flexibility in setting important system parameters and control functions. Center frequency, bandwidth, RF power, and other functions can be set in a user-friendly GUI environment. All sensor's signals received at the Rx that are in the correct RF band are simultaneously obtained in a given interrogation cycle. The post processing software is configured to recognize the sensor, based on the RFID code, and to post process the data. Given passive sensor embodiments, the sensor type (physical, gas, liquid or other) can be post processed in the transceiver SDR system based on sensor specifications and the extracted shift in delay or frequency of the received signal. The USRP SDR approach has

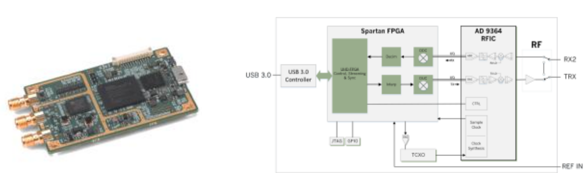

Fig.6. NI Ettus USRP B200mini (left) and its block diagram (right) from Ettus WEB page

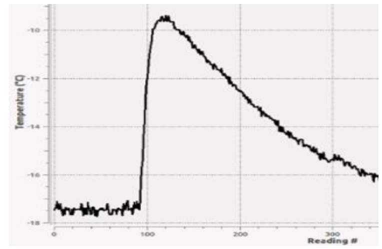

Fig.7. Proof-of-concept experiment to demonstrate a 4.3 GHz transceiver system with an uncalibrated prototype SAW device in wired mode. Temperature was changed with a heat gun, increasing temperature, turning heat gun off.

previously been used to extract SAW wireless temperature and strain, simultaneously. In addition, a SAW OFC and resonator temperature sensor data has been extracted simultaneously by changes in software postprocessing extraction techniques. An example of a wired 4.3 GHz SAW temperature sensor, using a modified 915 MHz system operating at 4.3 GHz, is shown in Fig. 7.

V. Discussion and Conclusions

This paper introduces a new and promising application-space for passive SAW sensor systems in the WAIC band. The WAIC concept has been outlined for SAW sensor applications at 4.3 GHz. The use of wideband communication system concepts is described. Finally, 4.3 GHz SAW delay line device results, using harmonic operation, are demonstrated for use as SAW sensors. Temperature measurement using a 4.3 GHz sensor system is demonstrated in wired operation as proof of concept.

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