Wireless IDT Ice Sensor

K.A. Jose, G. Sunil, V.K. Varadan and V.V. Varadan

Center for the Engineering of Electronics and Acoustic Materials and Devices
Pennsylvania State University, University Park, PA 16802.

Abstract: **This paper presents the design and performance evaluation of a Wireless IDT Ice Sensor for sensing the phase change from water to ice and hence to detect and monitor the ice formation at a remote location. The sensor is based on the principle of shear horizontal waves and its un-damped nature in the presence of a liquid. The frequency shift due to the phase change of water to ice is measured wirelessly and it is observed that, the sensor has potential applications for ice detection in airplane wings.**

I. Introduction

Accurate and repeatable detection of formation of ice on aircrafts experiences detrimental efforts because of its operation on wide variation of temperature and pressure. Accretion of ice on fixed and rotary wing aircrafts leads to loss of flight control and stability due to extra weight and change of airfoil profiles. Current aircraft ice removal system uses a lot of power for the heating up the outer skins of the aircraft, because of the lack of reliable ice detection mechanisms that could predict the formation of the ice from the first mono-layer upwards. An accurate and repeatable sensor to detect the onset of ice formation, regardless of the temperature or pressure during formation would eliminate most or all of the difficulties, because an early detection of ice would be helpful in turning on the de-icing circuits to melt the ice. Hence there is a strong need to develop a new ice sensor which permits accurate detection and monitor the formation of ice so that the deicing circuits can be triggered to melt the ice before it accretes.

Because of the difficulties associated with the detection and monitoring the formation of ice on a moving platform, only few papers are only published in literature. Conventional ice sensor has the disadvantage of handling and packaging problems because these macro-scale sensors may affect the aerodynamics during its operation [1-4]. A miniature ice detection systems using microfabricated diaphragms as sensing elements with a capacitance detection circuitry [3], microwave ice detection based on the amplitude of the reflected signal [4] are some of the techniques previously adopted.

Recently there has been of great interest of using Surface Acoustic Wave (SAW) devices as both physical and chemical sensors. The SAW devices offer a simple and inexpensive technique for sensing applications, because any form of interaction between characteristics like mass density, dielectric properties and elastic stiffness with the acoustic wave leads to a change in its propagation characteristics in the form of either a frequency shift or a phase change. Since the acoustic energy is confined to a thin near-surface region of the substrate, SAW based sensors are highly sensitive to surface perturbations while it is propagating. SAW devices are good candidates for such a requirement since they are amenable to wireless interrogation and can be fabricated for conformal applications such as deploying sensors on 'structural skins' like aircraft wingtip and fuselage.

It is already established that surface acoustic waves are very sensitive to the environments surrounding to it. When SAW is exposed to such surroundings like temperature, pressure, humidity it shows change in velocity. Also it is well known that, properly designed Love wave acoustic sensors are very promising for sensing the gaseous and liquid environments [5-6], humidity sensors [7-8] and ice detection system [9-10]. Most of these sensor are based on measuring the change in velocity or phase of the propagating waves as established in passive remote SAW temperature measurement system [11] and wireless SAW humidity sensor system [8]. The electromagnetic wave is transmitted by the antenna system and is picked up by a small antenna connected to the SAW device, which is subsequently converts this EM wave to acoustic waves and retransmits back to the reading system. Recently, Gangadharan et.al. [12] presented a design of a Love wave based acoustic sensor for sensing the ice formations. Rayleigh wave is a traveling surface wave with horizontal displacement and motion of a point in the medium is an ellipse. Love wave is considered as a standing wave formed by spherical normal modes, which has no vertical displacement. Love wave modes can propagate inside a waveguide with a thickness of fraction of a wavelength. Love waves are essentially SH polarized guided waves. The concentration of the wave energy in the thin guiding layer make the Love mode more sensitive to changes in propagation characteristics than compared to equivalent modes like

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SH-APM or pure SH. This paper presents the wireless implementation of conformal ice sensor for detecting the onset of ice formation using SAW devices. The SAW devices can also fabricated for conformal applications on the leading edge of aircraft wings. Batteries are lengthy wires are often required to power the sensors. This makes it difficult to retrofit aircraft with sensors and requires design changes for new systems. Miniature and wirelessly interrogable sensors are ideal for aerospace applications.

II. PRINCIPLE

Figure 1 shows the schematic diagram of the SAW ice sensor. SAW device is fabricated on ST-cut quartz substrate and SiO_2 is deposited on to it by RF sputtering. This structure supports Love waves that are SH waves, confined to the superficial layer of an elastic half space, with the layer having a different set of properties from the rest of the half space. The Love wave propagates in a wave guide made of a layer of material M_1 deposited on a substrate of another material M_2 with different acoustic properties and infinite thickness compared to the guiding layer. These waves are transverse and they bring only shear stresses into action.

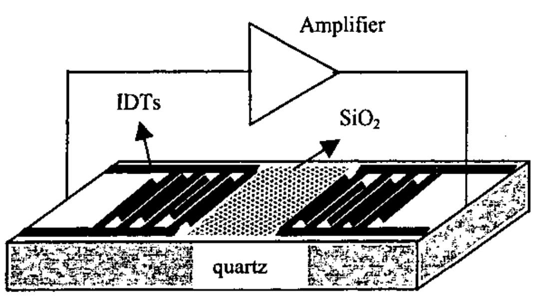

Figure 1. Schematic diagram of the ice sensor

Since the sensing of the onset of ice formation is essentially carried out in a liquid environment, longitudinal bulk wave modes cannot be used efficiently because they leak into the liquid. Lamb waves and Rayleigh waves also rapidly attenuate at a liquid interface. SH polarized wave modes are preferred since they do not couple elastically to an ideal liquid. For an increased sensitivity, SH polarized guided waves may be used since all the wave energy can be confined to a thin guiding layer. This is the advantage of the Love wave modes over the SH- Acoustic Plate Modes (SH-APM). Another advantage is that the generating and receiving inter digital transducers (IDTs) would be effectively shielded under the guiding layer.

III. ICE SENSOR FABRICATION AND TESTING

The ice sensors were fabricated on Y rotated ST cut quartz substrates, with propagation perpendicular to the crystallographic X-axis. The transmit and receive IDTs consists of 75 finger pairs with 10.54 micron width of electrode and 10.54 micron separation. The IDT centre-to-centre separation was 6 mm. Silicon dioxide guiding layer was deposited using sputtering technique. SiO_2 satisfies the condition for overlay material with good elastic properties and low thermal coefficient of expansion. The schematic diagram of the experimental setup for the wireless ice sensor configuration is shown in figure 2. The ice sensor is incorporated as a feedback element in an RF oscillator circuit. The surface perturbations due to the change of water to ice are measured as a frequency shift of the RF oscillator. The RF output from the coupler is fed to the transmitting antenna. A frequency counter and spectrum analyzer are connected to a receiving antenna and the frequency as well as power level was measured. At this time only quasi-wireless operation was possible because of the design of the current ice sensor.

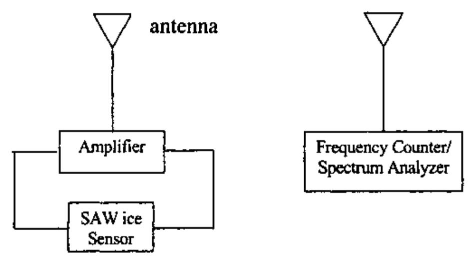

Figure 2 Schematic diagram of the wireless Ice sensor setup

Measured quantities of distilled water were pipetted onto the sensor and was permitted to cool to form ice. Frequency of the oscillator was measured at different temperatures while water is permitted to cooled to form

Oscillation Frequencies, MHz		Sensor I	Sensor II
1	Water	227.5	114.27
2	Ice	234.2	120.78
3	Air	234	120.47

Table I: Measured frequencies for two different Ice sensors

ice. The injected water film usually took about 100 to 120 seconds to freeze to ice. The transition point of the shift from water to ice was clearly marked because of a frequency shift in the range of 6-7 MHz. Measurements were taken while the water is permitted to cool down to form ice and also when the ice melt to form water at room temperature. By spraying a thicker film of water, it was noticed that though there was a different frequency shift, it was apparent that the top layer of the water deposited did not form ice as yet, suggesting that the frequency change was initiated by the formation of a critical quantity of ice layer thickness.

IV. RESULTS AND DISCUSSIONS

The sensor is kept inside the environmental chamber and water is permitted to cool from room temperature to form ice. Two types of measurements were made for different sensors. Ice sensor (234 MHz) connected directly to the HP 8510C Network Analyzer to determine the attenuation characteristics of the device when subject to water and ice mass loading. Measured quantities of water is pippeted into the bare sensor and the transmission characteristics (S_{21}) were measured with change in temperature of the water. Figure 3 presents the measured S_{21} for a bare ice sensor, sensor with water and the senor with water is cooled to form ice. It is observed that the peak of S_{21} is changed due to change in temperature of the water and when ice is formed, the peak is coming back to that same as the bare sensor. The change in frequency measured due to water for this device is about 7 MHz and the frequency shifts back to the original frequency due to the formation of ice.

Measurements were made for ice sensor using a feedback amplifier and monitoring the frequency of the oscillation using a remote frequency counter. The output from the feedback loop is connected to a transmitting

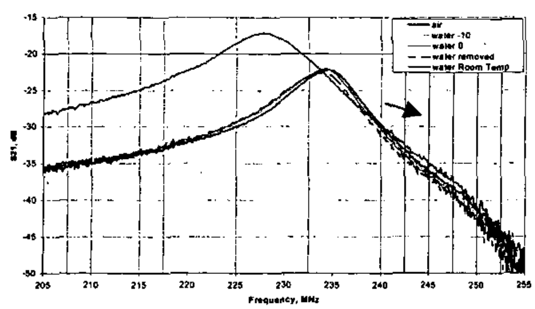

Figure 3. Measured S_{21} response of the IS-I using the network Analyzer for air, water and ice.

antenna through a directional coupler with proper impedance matching. Another antenna is connected to the frequency counter and the change in frequency due to change to temperature of the water is remotely measured as shown in figure 2. Figure 4 presents the measured change in frequency due to the change in temperature of the water. It is seen that, the Rayleigh surface wave that would typically be excited without the presence of the guiding layer of SiO_2 is not present and the operating frequency of the device is depending on the thickness of the SiO_2 layer. Thus the surface wave is efficiently coupled into the elastic guiding layer of SiO_2. Measured quantities of water are placed on the device.

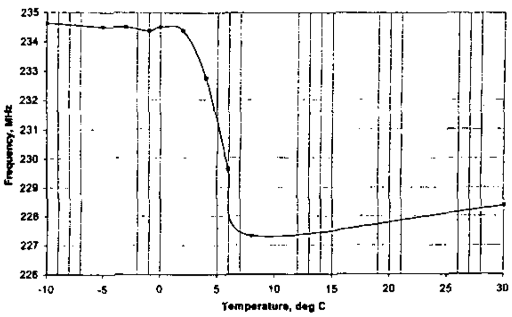

Figure 4. Measured change in frequency due to the formation of ice using HP 8501 C Network Analyzer for Sensor I

It can be seen that due to the formation of ice, the oscillator frequency has changed about 6 MHz and the oscillator frequency was same as that of a bare ice sensor. The frequency shift is immediate and can be observed as soon as the interface water freezes and does not wait for the entire water to form ice. Also there is no significant reduction in amplitude of the signal, but the frequency peak shifts back to values close to that for the bare device. No frequency shift could be measured due to small changes in viscosity of the water as the water temperature decreased to freezing. This has lead us to conclude that, the variable that determines the resonant frequency change was related to the parameters of the ice like the relative permittivity (3.8 for ice compared to 80.1 for water), density and shear modulus (0 for water relative to 10^9 Pa for ice). This change in frequency could be attributed mainly to the acousto-electric effect due to the high permittivity and conductivity of water relative to SiO2 and a smaller part to the mass loading effect. This effect can be linked to that observed by the loading of different chemical sensors. It can be considered the ice layer on top of the propagation path of the Love wave sensor to approximate an elastic film in welded contact with the SiO_2 coating that support the shear effects. It was noticed that the effect of the electrical perturbation also depends upon the ratio of the area of coverage of water film to the area between IDTs.

It is also noted that as the area of coverage of the liquid on top of the device increases, the resonant frequency decreases. For practical applications, it would be useful to define a measurement area where readings against different types of devices could be calibrated. It is suggested that, an area of 5mm x 5mm about the center point of the device could be used as a standard for measuring the relative performances between different types of loading. Measured frequency shifts for different water droplet areas are presented in figure 5. For each sample, the temperature is lowered and water is allowed to freeze while monitoring the frequency. For each sample it is observed that while forming ice, the frequency shifts to very nearly the same value and when the ice is removed, the frequency shifts back to the original frequency. A slight increase in the frequency for different areas of ice can be noticed. However this increase is small compared to the change in frequency with water.

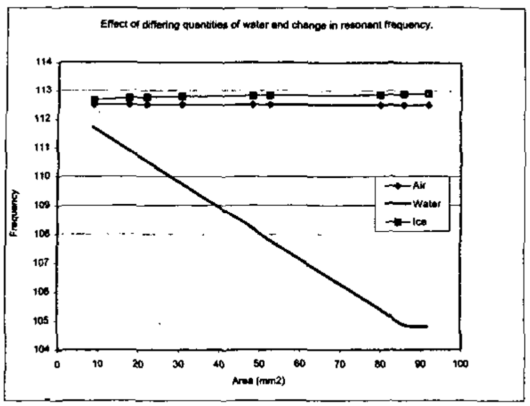

Figure 5. Measured frequency shift for ice and water of different volume.

V. CONCLUSION:

A wireless Love wave acoustic sensor for the sensing the formation of ice has been fabricated and characterized. Changes in frequency of 6-7 MHz have been observed on all the devices fabricated. It is observed that there is a definite frequency of oscillation for air, water and ice and that could effectively utilized to distinguish between water and ice. It is inferred that the change in frequency would primarily be due to effect differences between ice (relative permittivity 3.8) and water (relative permittivity 80.1). The potential applications for such a sensor is ranging from detection of sub-millimeter layers of ice on slippery roads to monitoring the buildup of ice on aircraft fuselage for triggering de-icing circuits to remove the accumulated ice. The amenability of SAW sensors to wireless transmission and interrogation automatically means that monitoring of ice formation could be performed at remote locations.

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