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Electroacoustic Ice Detection Using Surface Acoustic Wave Devices

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Summary:

Icing of infrastructure or vehicles can lead to structural failure due to increased loads. In particular aerodynamic structures like wind turbine rotor blades demand for a small, thin, retrofittable and wirelessly working ice detection sensor. This paper shows that surface acoustic wave (SAW) devices, made from piezoelectric single crystals 64° YX- and 128° YX-lithium niobate, allow to directly detect ice loaded surfaces by analysing the acoustic- and capacitive-dominated admittance behaviour of an ice-loaded interdigital transducer.

Keywords: surface acoustic wave sensor, ice detection, lithium niobate, admittance, interdigital transducer

Introduction

Surface acoustic waves (SAW) allow the development of small, lightweight and retrofittable SAW sensors which, as passive components, can be operated and interrogated by radio signal via antennas. A remotely installed interrogation unit transmits an electromagnetic signal, which is received by the sensor's antenna and converted into an acoustic wave in the interdigital transducer (IDT) via interdigitated comb electrodes. This conversion is based on the converse piezoelectric effect. The acoustic wave is reflected or sent back to the interrogation unit as an electromagnetic wave. The analysis of the output and input signal thus allows a statement about ambient conditions like surface loads. While [1] and [2] show the ability to determine liquid wetting and phase transitions from water to ice of a loaded delay line (DL), by changing propagation characteristics of the acoustic wave, this paper focuses on changes in admittance due to a water loaded IDT. A related approach considering water toxicity sensing is shown in [3].

Materials

The SAW devices considered are two-port delay lines (DL) made of piezoelectric substrates 128° YX- and 64° YX-lithium niobate ($LiNbO_3$) respectively with a thickness of 500 µm. In the following, these will be abbreviated as 128LN and 64LN. The IDT's aluminium metallisation and the passivation layer of silicon dioxide (SiO_2) have a thickness of 300 nm and 500 nm. Input and output transducers each consist of 31 finger pairs with a finger width of 30 µm. The aperture is 2 mm and the delay line has a length of 10 mm (see Fig. 1). All measurements are carried out in a temperature test chamber (Voetsch VT4002).

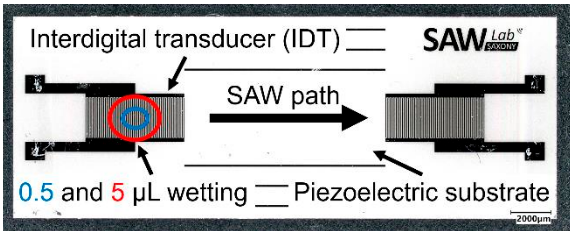

Fig. 1: SAW two-port delay line

The SAW device to be measured is located on a carrier and is connected to a vector network analyser (Agilent E5070B, short: VNA) with two spring contacts per IDT via a printed circuit board matched to 50 Ohm characteristic impedance and SMA connection. The IDT's admittance Y_{11} over frequency is calculated from S-parameters retrieved by VNA.

Measurements

First, the devices are measured at room temperature (20 °C) in dry condition. Then drops of water are placed in the centre of one IDT in 0.5 µL steps using a pipette. Slight deviations of volume due to evaporation are neglected because of a short measuring time. The maximum drop volume for this measurement is 5 µL. Subsequently, these measurements are repeated at -20 °C in the temperature test chamber.

Results

Surface loading on the IDT shows a significant influence on the admittance behaviour for 128LN and 64LN devices. Figures 2 and 3 describe the normalised conductance and susceptance over frequency. Each curve can be zoned in an acoustically (0.95 < f/f$_s$ < 1.05) and capacitively (0.95 > f/f$_s$ > 1.05) dominated frequency range (f$_s$: synchronous frequency, where acoustic wavelength and transducer period match for maximal SAW excitation).

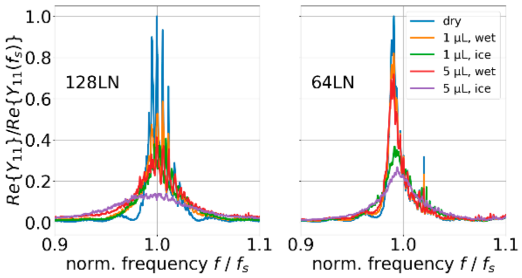

Fig. 2: Normalized conductance over frequency for 128LN (left) and 64LN (right)

IDT loading by liquid and frozen water on 128LN leads to a high decrease in conductance with a further decrease by increasing drop volume (see Fig. 2, left). 64LN device shows a significantly lower decrease in wet state but a higher decrease in conductance for frozen water. An increasing drop volume slightly decreases conductance (see Fig. 2, right). This behaviour can be explained by the different polarisation of the SAWs propagating in 128LN and 64LN. 128 LN's Rayleigh waves with a dominant surface-normal amplitude radiate bulk acoustic waves into the drop and get damped. 64LN's shear-horizontal polarised SAW does not couple at the substrate-fluid-interface due to water's low viscosity but gets damped by increasing viscosity due to freezing.

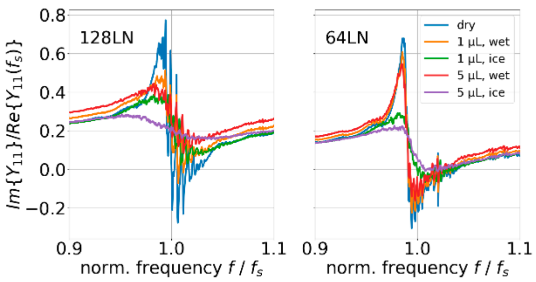

Fig. 3: Normalized susceptance over frequency for 128LN (left) and 64LN (right)

The 128LN device shows a higher susceptance compared to the 64LN device and a more significant capacitive influence in the wet state. In both cases the susceptance increases with frequency (see Fig. 3). The difference in susceptance despite of identical IDTs is caused by 128LN's higher effective dielectric constant ε_{eff}. The more significant capacitive influence in wet state and the linear increase of susceptance with frequency can be explained by the dependence to frequency and the IDT's static transducer capacitance. The susceptance increases with an increase in total effective dielectric constant of the load and frequency.

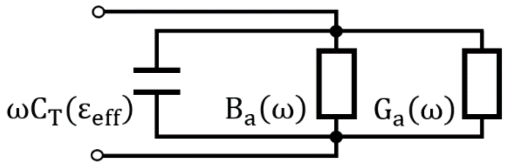

Fig. 4: Equivalent circuit regarding crossed-field model

These relations are described by the crossed-field model [4] which applies due to a parallel order of wave vector and substrate's crystallographic rotation axis [5]. The equations for conductance (1) and susceptance (2) can be derived by using an equivalent circuit (see Fig. 4):

$$G = Re\{Y\} = G_a(\omega) \quad (1)$$

$$B = Im\{Y\} = B_a(\omega) + \omega C_T(\varepsilon_{eff}) \quad (2)$$

with $\omega = 2\pi f$ and the static transducer capacity $C_T(\varepsilon_{eff})$ as well as acoustic-related G_a and B_a.

Conclusion

Both, 128LN and 64LN, devices show capabilities to gain information about a water drop's phase by analysing the loaded IDT's admittance. In the acoustically dominant region 64LN's admittance behaviour allows a differentiation between liquid and frozen water drops in the measuring range. In the frequency range where the capacitive behaviour dominates 128LN's admittance allows for the same differentiation.

References

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