SAW SENSORS FOR DIRECT AND REMOTE MEASUREMENT

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***Abstract* – SAW devices have been proofed to be suitable not only for signal processing but also for sensor aims. Beginning with the early seventies of the last century, SAW sensors are under discussion for several decades. The physical effect of a change of the elastic constants of the substrate material or a change in the mass loading under the influence of changing conditions in the environment lead to a change in the phase velocity of the surface acoustic wave and commonly to a frequency shift in SAW devices. Numerous solutions for sensors and sensor systems are based on this effect. However, there is not to see a mass application of SAW sensors up to now. On the other hand SAW sensors have some features that allows to create unique sensor systems for measurements which are not possible otherwise.**

The paper will discuss some aspect of the today's status from the point of view of practical application.

I. INTRODUCTION

Electronic elements working with surface acoustic waves (SAW) have been successfully used in electronic circuitries for several decades. Such elements as filters and resonators have to be stable in their properties under changing environmental conditions. But it is well known that SAW elements react on the change in operation conditions (such as temperature, mass loading or mechanical stress) by changing both the amplitude and the frequency. Producers of SAW devices for signal processing try to fight against this behaviour. However, while investigating the physical properties came up the idea for using SAW devices as sensors already in the seventies of the last century /1/, /2/, /3/. Even though there is a lot of research done (and corresponding to that numerous publications as well), one can not observe a high volume production and a mass application. Because of the simplicity in production (only one photolithography) SAW sensors would be dedicated for mass production. But there is no broad application. At the present time the development in the sensor market is mainly driven by the automotive field, the medicine technology and the environment protection. SAW sensors can contribute in this regions. Beside the capability for a high volume production they have unique possibilities for sensor solution which are not achievable by using conventional concepts.

SAW sensors have some special features which distinguish them from other kinds of sensors. They are very small in size with a minimal volume of substrate. So they can react very fast on changes in the environmental conditions. The small dimensions make it possible get a signal even when only a very small amount of the material under investigation is available.

Most SAW sensors have a frequency shift as the output signal. This makes the accuracy of the senor signal independent on stochastic variations in the amplitude. Furthermore the frequency can be resolved over several order of magnitudes and this results in a high sensitivity and a high accuracy. The sensor signal can often be directly transmitted to a computer because of its quasi digital character. Moreover the SAW will be not influenced by magnetic fields. This makes them suitable for measurements near conductors for high currents or fast alternating currents where other methods fail.

A big advantage is that SAW sensors are operating at high frequencies. This makes the electronic circuitry relatively easy and allows to transfer the signal over short distances by using capacitive or inductive connectors. The most important aspect of the high frequency mode of operation is the possibility of using a radio transmission over several meters and to make the sensor itself passive.

II. SURFACE ACOUSTIC WAVES AND DEVICES

The mostly used type of surface acoustic waves is the Rayleigh mode wave with an elliptical displacement of the particles in the plane perpendicular to the surface in propagation direction. This type is also used in SAW devices for signal processing. In the sensor field the Rayleigh mode is suitable for gas sensors but not for liquids. In liquids occurs a radiation of energy into the liquid and thus a strong attenuation of the wave. In this case are waves used with a horizontal polarisation with a particle displacement perpendicular to the propagation direction. This concerns skimming bulk waves, leaky waves shear horizontal polarized acoustic plate modes and Love modes/4//5/.

Even the detection of ice is possible by using Love mode waves/6/.

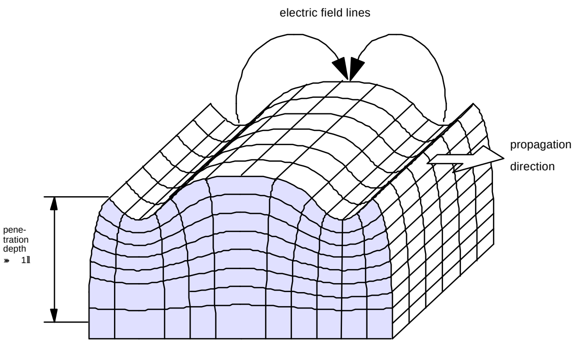

Figure 1: Rayleigh mode wave

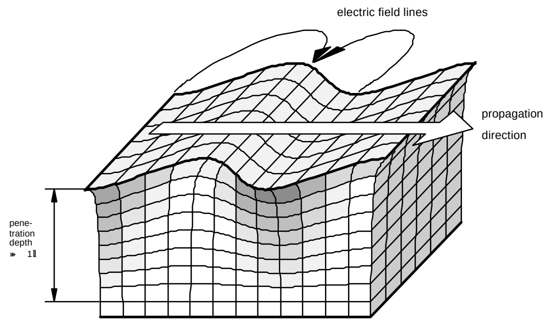

Figure 2: Shear mode wave

In any case interdigital transducers are used for excitation of the wave and for receiving it. Interdigital transducers are overlapping metallic finger structures which are performed by a photolithographic process. There are two main types of devices which are used as signal processing devices and as sensors as well.

A delay line (figure 3) consist of two interdigital transducers and a space in between. In many types of sensors this space is covered by a special coating that react with the material to be measured. The other type is a resonator (figure 4). One or two interdigital transducers are placed between two reflectors forming a standing wave which leads to a resonant behaviour. Such devices are used as sensors when the whole substrate takes part in the operation of the sensor (temperature sensor, pressure sensor) or when the surface is influenced by using a coating material and a mass loading occurs because of the adsorption or absorption of the material to be measured.

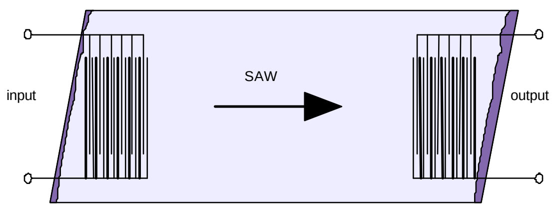

Figure 3: Delay line

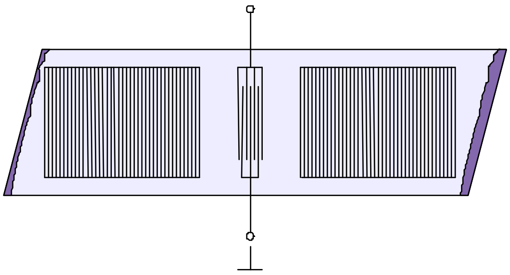

Figure 4: One port resonator

Whatever the influence on the SAW device is it turns out in a change of the phase velocity and consequently in a shift of the frequency the device is working at (figure 5).

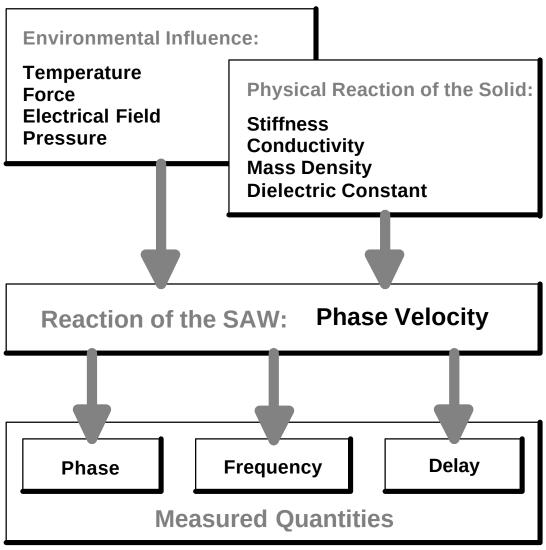

Figure 5: Influence on SAW sensors

III DIRECT COUPLING INTO THE CIRCUIT

More than by other sensor concepts, the electronic circuitry for a readout is at least as important as the sensor itself. In the simplest case, the sensor is connected to the electronic circuitry by wires.

In the beginning of the eighties of the last century such systems were first used for gas sensing /7/.

An example for that is the commercial available gas sensing system SAGAS or GASYS respectively developed by the Forschungszentrum Karlsruhe and produced by the company Bürkert /8//9/. This system consist of 8 sensors with different polymer coatings and one reference device. It is dedicated to probe the concentration of numerous toxic and non-toxic gases. Figure 6 shows the principle of operation.

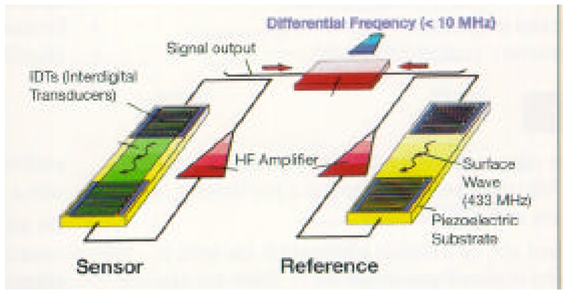

Figure 6: Principle of operation (courtesy of Bürkert)

As today's electronics commonly consist of a hardware part and the software the final result will be calculated from this 8 different sensors outputs. Figure 7 shows the sensor head with the 8 SAW sensors and the reference element (with lid).

Figure 7: Sensing head (courtesy of Bürkert)

In the particular case of SAGAS the electronic circuitry uses oscillators with SAW resonators being the frequency determining part of the oscillators. The whole circuitry operates in a multiplex regime. The producer declare that the time of service is 0,5-1 year (depending on the coating) and the limits of detection are a few ppm of organic gas concentration.

It is also possible to use the anisotropic behaviour of crystalline quartz and a Pd film as sensing membrane. In this case one can measure gas concentrations of different organic gases in a mixture and the humidity by using delay lines/10/.

IV CAPACITIVE COUPLING

One of the exceptional advantages of the SAW sensor concept is the operation at high frequencies. This allows a wireless coupling of the sensor signal which is important especially for measurements on rotating ore moving parts. One example for the usage of capacitive coupling is a torque sensor developed and produced by the company Transense Technologies /11//12/. The basic construction is a metallic shaft on which are two resonators fixed. They are in a rectangular position to each other and so the strain will be measured in two directions. The difference signal contents the actual strain to be determined. The coupling to the interrogation unit is performed by a capacitive coupling element (figure 8).

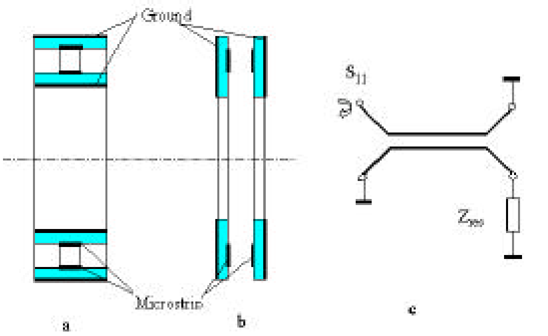

Figure: 8 Cross-sections of the cylindrical (a) and planar (b) rotational couplers and their equivalent circuit (c) at zero angle of rotation (courtesy of Transense)

Such types of sensors are dedicated to measure torque on driveshafts and crankshafts of engines in order to control the power transmission and engine operation. Furthermore torque sensors are also needed for electrical power assisted steering systems. Figure 9 shows a prototype of a torque sensor for the determination of the steering angel.

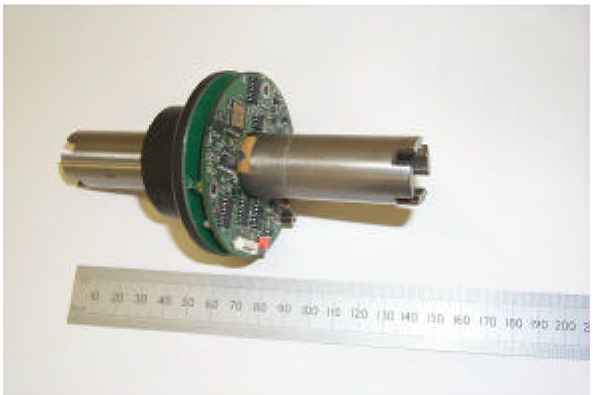

Figure: 9 A prototype of the torque sensor for a steering system (courtesy of Transense)

A second example is a temperature measurement system developed by the company senTec Elektronik Ilmenau. This system is dedicated to measure the temperature in a very fast rotating axis (36000 rotations per minute). In order to avoid too high centrifugal forces only the very small and light SAW resonator is places inside the axis and the electrical connection to the outside electronic circuitry is performed by using a capacitive coupling element (Figure 10). As our experiments showed, the resonator is not influenced by the very high rotational speed.

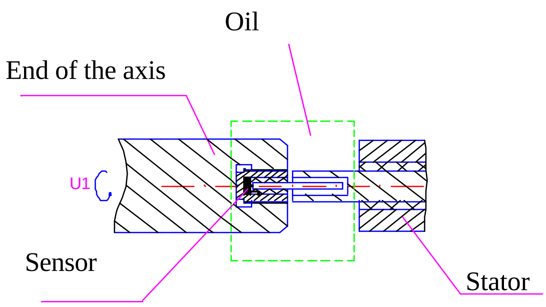

Figure 10: Capacitive coupling of a SAW temperature sensor

Not only a capacity can serve as a connecting element but also an inductor is suitable for that. However, our experiment showed that a capacitive coupling is easier to perform.

V Remote Measurement

Due to the high operational frequency (today’s SAW elements are working in a frequency range from 10 MHz up to 2.5 GHz) and the high dynamic range for the excitation of surface acoustic waves it is possible to transfer energy to a SAW devices by using an RF signal. A SAW device connected to an antenna can operate even the energy received is very small. Moreover, the device can respond to the received signal by transferring a very low but anyway well detectable signal. While propagating along the surface the SAW is exposed to the influence of the environ-ment and hence the responded signal contains information about the environ-ment of the sensor. The main advantage of such a wireless sensor system is that it is completely passive without the necessity of a power supply for the sensor itself. So the sensor can be placed at bad accessible places, at moving or rotating parts or at places were it is not possible to measure otherwise (e. g. under high temperature conditions, vacuum etc.).

There are two main principles of operating. One of the possibilities is to use a device with one interdigital transducer and reflectors /13/. The interdigital transducer is connected to an antenna and can receive the interrogation signal (pulse). The SAW excited by the interdigital transducer propagates along the surface of the piezoelectric substrate (e. g. quartz) and is reflected by the reflectors travelling back to the interdigital transducer. The reflected signal is reconverted in an electrical signal by the interdigital transducer and transferred back to the interrogation unit. The delay time between the transferred and the received interrogation signal contains the information about the physical quantity to be measured.

The other principle of operating is the usage of SAW resonators instead of the reflecting delay line/14//15/. Resonators have lower losses while be interrogated and therefore a longer distance of operating. Furthermore they allow an interrogation method which is based on a frequency measurement and not on the amplitude which avoid some sources of error.

When the interdigital transducer of a resonator (see fig.4) is connected to an antenna a burst signal can excite the resonator to oscillations. The frequency inside the burst has to be close to the resonance frequency of the resonator. The resonator will oscillate in a attenuated oscillation after the interrogation signal is switched off. Figure 11 illustrates the situation.

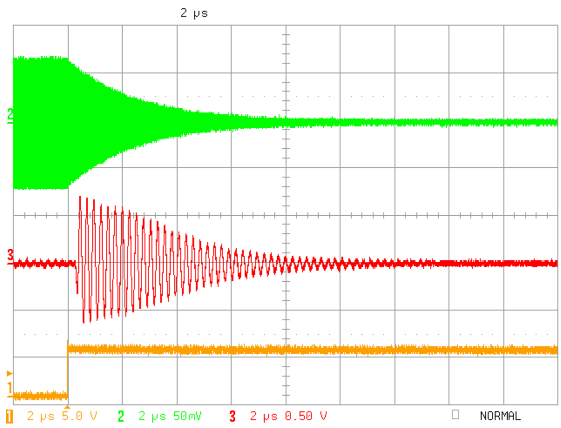

Figure: 11 Interrogation signal and attenuated oscillation (at the top), mixed signal (beneath), switching signal (bottom)

The operational principle is based on the storage behaviour of a resonator. The resonator store the energy during the attenuated oscillation after excitement and gives it as oscillation back to the interrogation unit via the antenna. In this time the resonator oscillate on the actual own resonance frequency (eigenfrequency) which is influenced by the environment and thus containing an information about the quantity to be measured.

In order to avoid the problems we saw in the case of determining the resonance frequency by using a method with stepping through the expected frequency range and measuring the maximum amplitude we now use a new approach. The RF response signal is mixed with a signal from a local oscillator and converted in a frequency scale by using a Fourier transformation.

The mixed signal is shown in figure 11 in the middle. The calculation of the result as well as the controlling of the whole interrogation unit is performed by a micro controller. Figure 12 shows a rough block diagram of the electronic circuitry (which is rather complicated).

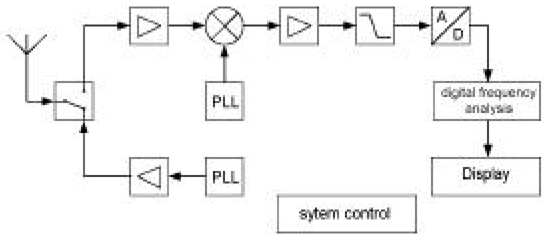

Figure 12: Interrogation unit (block diagram)

Experimental measurements with a single SAW resonator in a telemetry system showed a high radio channel influence on the resonance frequency in this network. To minimize this unwanted influence a difference measurement method with two connected SAW resonators has been chosen (see figure 14).

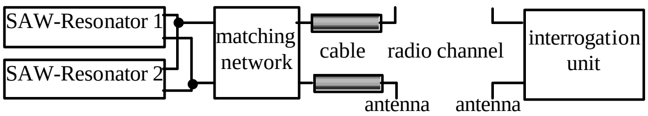

Figure 14 : Double resonator sensor

The main advantage of this equipment is a stable RF link with almost no influence of the distance between the two antennas. The difference frequency can better serve as sensor signal as in a single resonator sensor. This is in particular important for measurements on moving parts.

Figure 15 shows the centre frequency and attenuation behaviour of the S_{11}-parameter for a double SAW resonator system (with the both resonator centre frequencies f_{01} = 432.7 MHz and f_{02} = 434.1 MHz) for two different antenna distances (10 cm, 15 cm).

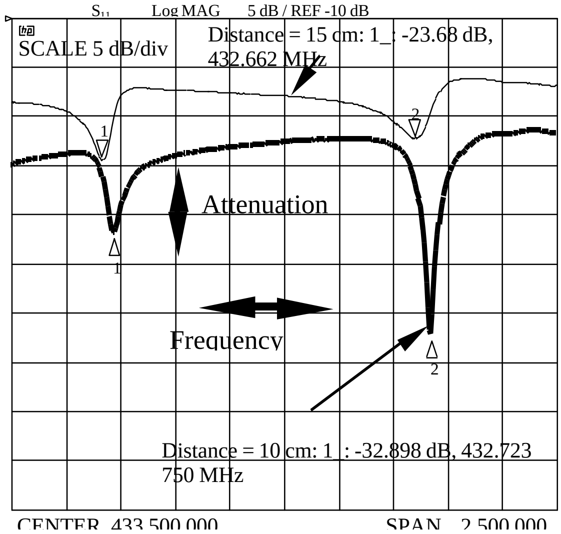

Figure 14: Centre frequency and attenuation of the S_{11}-parameter for a double SAWR for two antenna distances (10 cm, 15 cm).

An example for the practical application of such a system is temperature measurement equipment for rotational moulding of plastics. The method of rotational moulding is performed in huge furnaces and by using big metallic moulds with an completely irregular movement in the furnace. Figure 15 shows a metallic mould for manufacturing plastic parts in dimensions of meters. Figure 16 shows a mould with the senor on it.

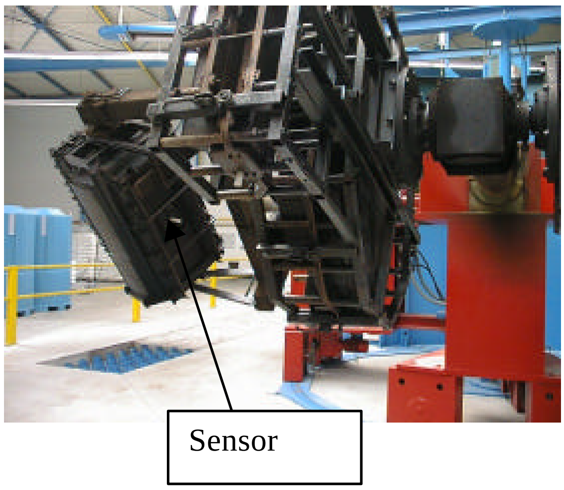

Figure 16: Machine for rotational moulding outside the furnace

The RF link was performed through the hole for the axis in furnace (figure 17).

Figure 17: The antenna can "see" the sensor inside the furnace

We could show that a temperature measurement is possible with a sufficient accuracy (about 1%).

VI Hybrid Sensors

During our measurements we were forced to match our sensors to the antenna by using a matching network that consists of a capacity and an inductor. This is necessary in order to minimize lost of energy caused by reflections at mismatched parts while interrogated. However, the matching network itself influences the output frequency of the sensor system. This experience ended up with the idea to use the double resonator sensor only as a transponder for the signal derived from capacitive or inductive sensors /16/. In this way the resonators can be produced in a conventional manner with a well protecting housing and the sensing element can ideal adapted to the special measurement task.
Concerning the separation of transmitter and sensing element both of them can be optimised separately. Once again, two SAW resonators are used in order to reduce several external disturbing influences on the radio channel.
Figure 18 shows the simple circuitry used as matching network. The matching network should be as minimal as possible.

This condition meets the so called 'L-Matching Network'. The principle circuitry of the complete sensor is shown in figure18.

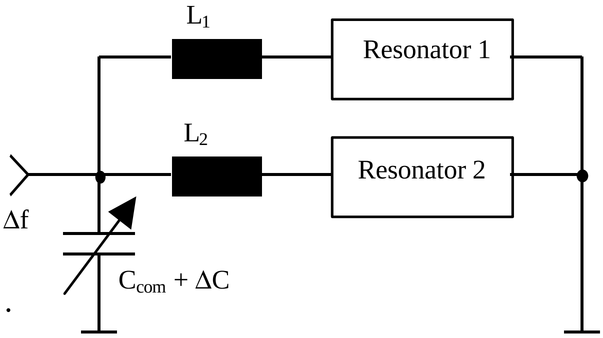

Figure 18: Principle circuitry of the sensor

The capacity ΔC represents a capacitive sensor which shift the frequency of the whole equipment (figure 19).

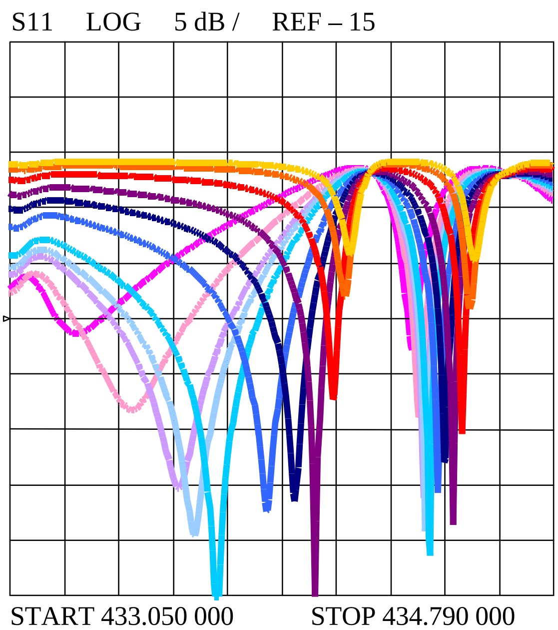

Figure 19: Measured frequency shift by varying the capacitance ΔC

In the same way as in the case of the double resonator arrangement before mentioned, the difference frequency contains the information given by the sensor.
The hybrid concept is the key for opening possibilities to place sensors for remote interrogation under conditions which do

not allow a remote sensing by using conventional active transponder systems(e. g. under high temperature conditions).

VII Summary and Conclusions

SAW based sensors has been proofed to be dedicated as well for direct measurement of physical quantities (temperature, pressure, mechanical strain, gas concentrations, properties of liquids etc.) as for remote sensing.

The high frequency operation together with the energy storing in SAW devices led to concepts for using them as passive sensors with the ability to be interrogated by RF signals. Researcher and user in the industry show an increasing interest in this field.

In general, new piezoelectric crystals with a high thermal stability up to over 1000°C as Langasite or Galliumorthophosphate make the SAW sensor concept to a favorite solution for many tasks where other solutions fail.

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