Optimized Design and Fabrication of a Wireless Pressure and Temperature Sensor Unit Based on SAW Transponder Technology

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***Abstract* — The optimized design and fabrication of a passive pressure and temperature sensor unit based on SAW transponder technology fully meeting the restrictions of the European Industrial, Scientific and Medical (ISM) RF band at 433.92 MHz is presented. The sensor unit consists of a reflective SAW delay line which is used as temperature sensor and transponder, and a capacitive pressure sensor. With a special arrangement of the impedance loaded splitfinger interdigital transducer (IDT) and the reference reflectors on the SAW substrate a temperature corrected evaluation of the pressure signal is enabled. Due to the small dimensions and cost-effective design of the sensor unit the utilization as tire pressure sensor is proposed. A prototype of the SAW delay line and the micromachined pressure sensor is demonstrated.**

I. Introduction

Temperature and pressure represent not only basic physical parameters but also the two most important process parameters in many industrial sectors. Especially in the field of automotive applications wireless monitoring of temperature and pressure inside car and truck tires is becoming increasingly important. Up to now, only pressure monitoring systems consisting of an active, battery powered sensor unit inside each wheel [1],[2] are available on the market. One problem of these systems is the required lithium battery which makes a large part of the weight, limits the lifetime of the sensor unit and leads to problems regarding waste management.

A new and promising approach based on passive surface acoustic wave (SAW) transponders inside each tire has been presented in [3]. Each sensor unit obtains its energy from the electromagnetic RF field of the transceiver unit. Consequently, even a high inquiry rate does not decrease the lifetime of a sensor unit and enables the detection of a sudden tire pressure decrease. The lightweight sensor unit itself consists of an antenna, a reflective SAW delay line and a capacitive pressure sensor electrically connected to one of the delay line's reflectors, as shown in Fig. 1.

This paper describes a new and optimized design of the key elements of the sensor system, namely the reflective SAW delay line and the high-Q capacitive pressure sensor. Due to a drastic miniaturization of the pressure sensor most of the requirements of the automotive industry – low cost, high reliability, small dimensions and weight - are fulfilled. A detailed view is given on the design of the SAW transponder. After a characterization of the measurement system and a detailed description of the realized SAW transponder and pressure sensor, measurement results are discussed.

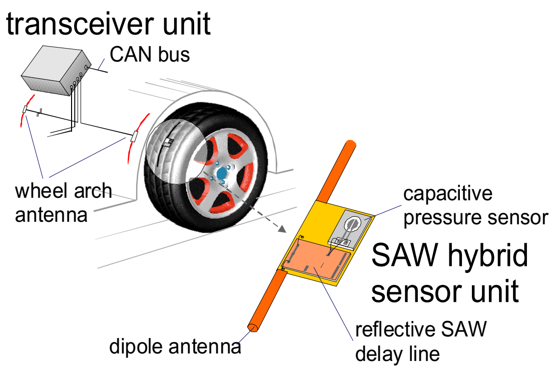

Fig. 1. SAW sensor system applied to wireless tire pressure and temperature monitoring.

II. SAW Sensor System

A. Principle of Operation

The functional principle of the wireless SAW sensor system as shown in Fig. 1 has already been described in [3]. The pressure and temperature measurement cycle is initiated by a high frequency electromagnetic burst signal emitted from the wheel arch antenna of the central transceiver unit. This signal is received by the antenna of the SAW transponder unit mounted on the rim. The interdigital transducer (IDT) connected to the antenna transforms the received signal into a SAW wave. All of the acoustic reflectors placed within the acoustic path of the SAW reflect parts of the incoming wave. Two reflectors are used for time-delay based temperature measurement and reference, another is electrically connected to the capacitive pressure sensor. In the IDT the microacoustic waves which include the pressure and temperature information are reconverted into an electromagnetic pulse train. Finally, they are retransmitted to the wheelarch antenna connected with the central transceiver unit. In the transceiver unit the received sensor signal is analyzed and provided to automotive safety and stability systems.

B. Time Domain Based Analysis of the Sensor Signal

Compared to the frequency domain based sensor signal analysis, as it is done in SAW sensor systems based on two SAW resonators detuned by capacitive sensors [4], the time domain analysis in the present system is more expendable. Nevertheless, using a SAW delay line as transponder enables a high sensitivity at high inquiry rates even when operating in narrow frequency bands [5]. Additionally, a simple wheel identification can be established if the transponder is used as identification tag as well. In Fig. 2 the received sensor signal of a realized sensor unit described in the following sections is shown. It demonstrates that using enough space between the acoustic reflectors on the substrate, the individual echoes can easily be separated even at narrow bandwidth, e.g. 2.5 MHz. Due to the long time delay between the decaying inquiry pulse and the echo of the first reflector of the delay line multipath distortion is easily controlled. Since a single measurement cycle takes only about 20 µs even high speeds pose no problem to the sensor system.

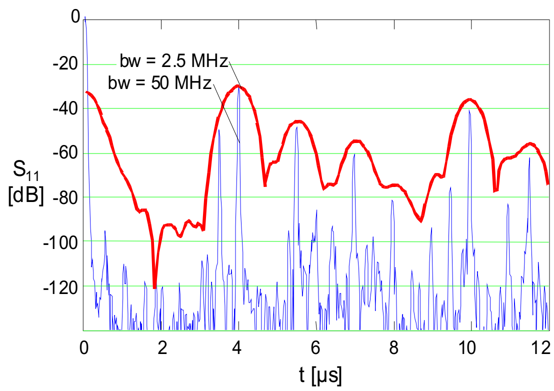

Fig. 2. Sensor response of a capacitively loaded SAW delay line on two burst signals with different bandwidths.

III. Impedance Loaded SAW Delay Line

In former SAW pressure sensor designs [5], the reflective SAW delay line was both used as transponder and sensor, resulting in rather big sensor dimensions not suited for tire pressure measurement. A solution was found in combining the SAW delay line with an "external" pressure sensor as shown in Fig. 1 resulting in a SAW chip with very small dimensions.

A. Principle of Operation

A simplified scheme of the delay line is shown in Fig. 3. The three acoustic reflectors - one impedance loaded reflector and two reference reflectors used for temperature measurement - are implemented as splitfinger IDTs and distributed to two tracks. The principle of an impedance loaded splitfinger IDT is that of an RLC resonance circuit in which the measurand dependent sensor impedance modulates the reflected echo both in magnitude and phase [6].

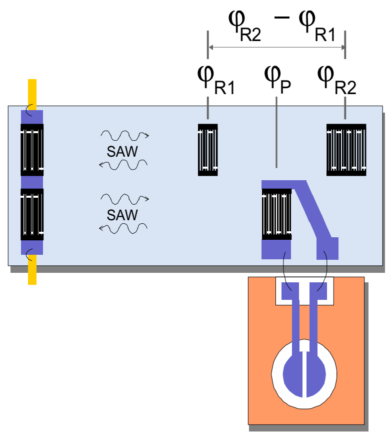

Fig. 3. Reflective SAW delay line combined with a high-Q capacitive pressure sensor.

Although both magnitude and phase can be used for extracting the pressure information from the received sensor signal in the time domain, a phase based signal evaluation is advantageous [3]. Following this new approach, the sensor impedance is adapted to the impedance of the splitfinger IDT in the way that phase modulation is maximized and a high and almost sensor signal independent signal-to-noise ratio is obtained.

B. Temperature Measurement and Compensation

For tire pressure measurement also the monitoring of the temperature inside the tire is necessary for interpretation of the measured pressure data. In the case of the SAW delay line the phase shift caused by thermal variation (-40°C to +130°C) is superimposed on the phase shift due to the varying impedance load of the pressure sensor. Despite this fact, the temperature can be determined independently from the pressure measurement by measuring the time delay between the two reflected pulses of the reference reflectors [3]. A change in temperature $\Delta\vartheta$ results in a variation of the acoustic path length Δl and a variation of the SAW phase velocity Δv. The resulting change of propagation time $\Delta\tau$ along the acoustic path of the reflective SAW delay line also leads to a phase change:

$$\frac{\Delta\tau}{\tau} = \left(\frac{\Delta l}{l\,\Delta\vartheta} - \frac{\Delta v}{v\,\Delta\vartheta} \right) \Delta\vartheta = TCD_1\,\Delta\vartheta \tag{1}$$

$$\Delta\varphi = 2\pi f_0\,\Delta\tau \tag{2}$$

In (1) TCD_1 represents the first order temperature coefficient of delay. In the case of the used YZ-Lithiumniobate ($LiNbO_3$) substrate, the temperature coefficient of delay is 94 ppm/K [7].

The temperature correction of the pressure signal is achieved by arranging the electrically loaded reflector equidistantly between two reference reflectors in a second track (Fig. 3). The sensor information is then calculated from the phase difference between the measured phase of the loaded reflector and the average value of the phase values of the reference pulses:

$$\Delta\varphi_{T0} = \varphi_P - \varphi_{R1} - \frac{\varphi_{R2} - \varphi_{R1}}{2} \tag{3}$$

Assuming a constant temperature of the $LiNbO_3$ substrate the temperature dependent phase shifts due to varying time delays are eliminated.

C. Design Parameters and Fabrication of the Delay Line

Important design parameters of the reflective SAW delay line shown in Fig. 3 are related to the two IDTs connected to the antenna and the splitfinger IDTs operating as reflectors. Realizing the two in-/out coupling IDTs as Single Phase Unidirectional Transducers (SPUDTs) significantly reduces the losses of the transponder. Since the electrical behavior of a splitfinger IDT is that of an RLC resonance circuit [8], a matching with the impedance of the pressure sensor has to be done [3]. Basic design parameters regarding the splitfinger IDTs are the metallization height and width of the transducer fingers, the aperture and the number of fingers.

Additional track changing reflective multistrip couplers (MSC) reduce the chip length [8]. A structured resist [9] and solderable pads enable a cost-effective attachment onto the antenna substrate without housing. Both transponder and sensor are finally covered with a thin protective silicone layer.

IV. High-Q Capacitive Pressure Sensor

Due to the resonance circuit like behavior of the impedance loaded IDT, the application possibilities of an capacitive pressure sensor as load for the splitfinger IDT depends on the Q-factor of the impedance. Silicon based micromachined capacitive pressure sensors found on the market showed a very low Q-factor. Therefore, a high-Q capacitive pressure sensor made of quartz with the dimensions of 20 x 20 mm² was developed [3]. In order to meet the requirements of a small and cheap sensor unit a second sensor design shown in Fig. 4 and 5 was done using a Finite Element Method (FEM) program.

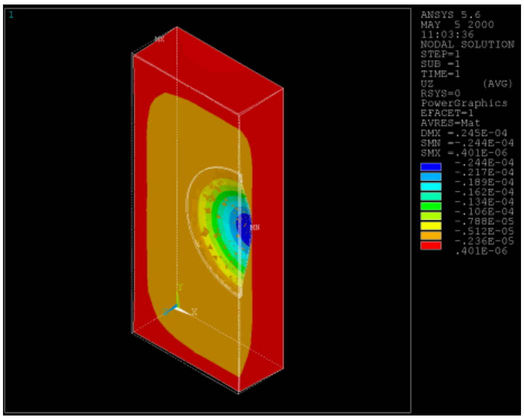

Fig. 4. FEM simulations of a micromachined capacitive pressure sensor made of two glass layers.

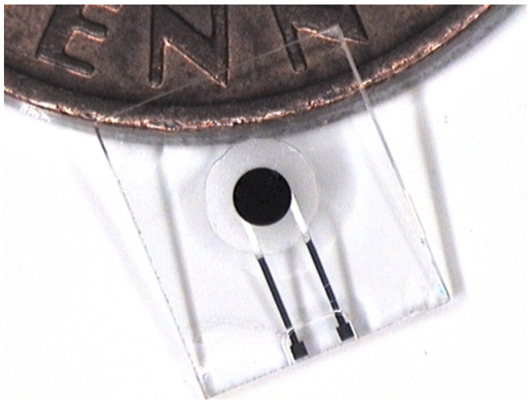

Fig. 5. Prototype of a high-Q micromachined pressure sensor.

A. Pressure Sensor Design and Measurement Results

The new sensor has dimensions of 5 x 5.7 x 1mm³ and consists of two layers of structured borosilicate glass joined with a one component epoxy adhesive at atmospheric pressure forming a hermetically sealed, circular cavity. A high layer thickness of the electrodes and the low resistivity of aluminum result in a measured series resistance of about 3 Ohms only. The high Q-factor and the low stray capacities enable an operation up to microwave frequencies as it is shown in Fig. 6. The principle of the fabricated pressure sensor is that of a capacitive reference pressure sensor operating in the touch mode [10]. Thus, a very high but nonlinear pressure sensitivity shown in Fig. 6 is attained. As it is shown in [3] the low sensitivity at low pressures can be compensated with an appropriate matching and the nonlinear sensitivity of the impedance loaded splitfinger IDT. A maximum of sensitivity within the most important pressure interval between 200 and 300 kPa is also enabled. In combination with the SAW delay line prototype a minimum accuracy of ±10 kPa could be achieved within the pressure interval of 100 kPa to 400 kPa. The attained excess pressure of the sensor is higher than 1500 kPa, the heat stability is 130°C.

B. Fabrication Samples

Instead of the etching processes used for silicon micromachining the blindhole in the base substrate forming the cavity of the pressure sensor was structured using the powder blasting technology. Due to the oxidation process of the aluminum on air there is no short circuit when the top electrode sputtered on the diaphragm touches the electrode on the base glass. As basic design parameters the diameter and thickness of the diaphragm, the cavity height and the diameter of the electrode were varied to confirm the FEM simulations and to find an optimum sensor design. Additionally, some of the process steps were varied in order to find the cheapest and most reliable fabrication process resulting in a high yield and low sample variation.

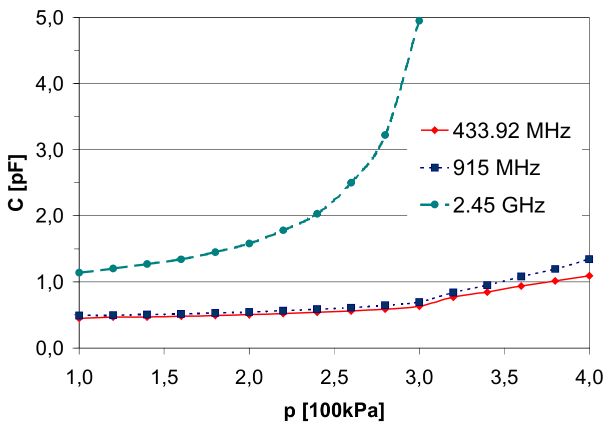

Fig. 6. Pressure dependent capacitance of the fabricated high-Q pressure sensor measured at several frequencies.

V. CONCLUSION

A wirelessly requestable, passive pressure and temperature sensor unit based on the combination of SAW transponder technology with a high-Q capacitive pressure sensor was presented. Due to the low weight, the small dimensions and therefore the cost-effective design of the sensor, it is highly suitable for tire pressure measurement. An optimum design of the SAW transponder enabling an accurate, temperature corrected pressure measurement has been demonstrated. The structure of the micromachined pressure sensor enables an operation up to microwave frequencies.

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