TIRE PRESSURE MEASUREMENT USING A SAW HYBRID SENSOR

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Abstract: A tire pressure measuring system based on surface acoustic wave (SAW) sensors is presented. Since SAW sensors are powered by the energy of the RF field no battery is required, which is a major drawback of conventional systems. A successful combination of a SAW reflective delay line with a capacitive pressure sensor is shown. With a new way of matching the sensor impedance to the SAW reflector impedance both a high signal-to-noise ratio and a high signal dynamic are achieved which supports accurate signal evaluation. A prototype of a tire pressure sensor unit is presented.

Keywords: SAW, tire pressure sensor, wireless remote sensing

1   INTRODUCTION

The development of an "intelligent tire", capable of continuously transmitting information about its actual state, is a technical challenge for automotive research groups world-wide. Especially monitoring the pressure and temperature inside car and truck tires is becoming increasingly important. The aim is both to prevent accidents caused by a tire puncture and to provide an economical advantage through a decrease of fuel consumption an a longer tire lifetime. In the past several systems consisting of a battery powered sensor unit inside each wheel, a central receiver unit and a display on the dashboard have been realized [1],[2]. The major problem of such microcontroller based systems is the required lithium battery which limits the lifetime of the sensor unit.

In this paper a different approach based on surface acoustic wave (SAW) sensors is presented. Wireless passive SAW sensors for several physical quantities were developed in the last decade [3],[4]. Compared with conventional telemetry systems the main features of SAW based sensor systems are a large readout distance of several meters and an energy supply of the sensor only by the electromagnetic RF field of the central transceiver unit. Consequently, a high inquiry rate does not decrease the lifetime of the sensor unit and enables the detection of a sudden pressure decrease inside the tire.

Requirements defined by the automotive industry are also fulfilled: low costs and high reliability, a long system lifetime, resistance to harsh environment and a small sensor unit size and mass.

This paper deals with the concept and implementation of a tire pressure measurement system based on passive SAW transponders. After a short description of the measurement system, the sensor unit and its components a prototype of the tire pressure sensor unit is presented. Measurement results are reported and discussed. A brief conclusion summarizes the content of the paper.

2   SAW SENSOR SYSTEM

In figure 1 a schematic drawing of the tire pressure measurement system as an example of a wireless SAW hybrid sensor system is shown. A measurement cycle is initiated by a high frequency electromagnetic burst (RF interrogation signal) emitted from a central transceiver unit. This wave 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 surface acoustic wave according to the inverse piezoelectric effect.

In figure 1 three acoustic reflectors are placed in the acoustic path of the SAW. The first and the third are used as reference, whereas the second one is electrically connected to a pressure sensor. All of them reflect parts of the incoming wave. In the IDT the reflected acoustic waves are reconverted into an electromagnetic pulse train and are retransmitted from the sensor unit to the central transceiver unit, where the received signal is amplified and down converted to the baseband. Via a controller area network (CAN) interface automotive safety and stability systems are provided with the sensor data.
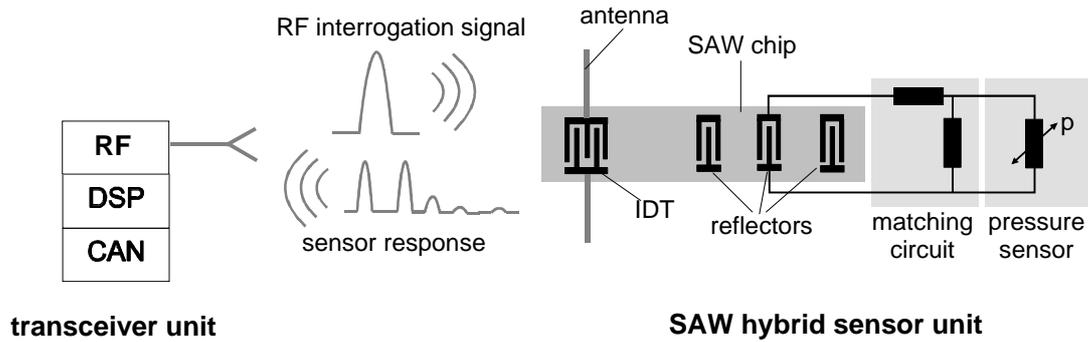
Figure 1. Schematic drawing of a SAW sensor system applied to tire pressure monitoring

The raw sensor data include both information on the propagation characteristic of the SAW and the reflection properties of the acoustic reflectors. As the velocity of the SAW depends on temperature the tire temperature can be determined by measuring the time delay between the two reflected pulses of the reference reflectors in figure 1.

The low propagation velocity of the SAW allows a long delay time between the RF interrogation signal and the sensor response leading to a small chip area. Additionally, in the case of a reflective delay line, the acoustic path on the piezoelectric substrate (e.g. Lithiumniobate) is used twice, also resulting in very small SAW chips. Particular attention has to be paid to the transmission path between the central transceiver unit and the sensor unit. Due to the fact that the RF interrogation signal has to cover twice the distance between transceiver and sensor unit without amplification along the way the attenuation is doubled compared to conventional battery powered sensor systems. Thus, the signal amplitude received by the transceiver unit is several orders lower than the amplitude of the emitted interrogation signal.

Nevertheless, using the ISM frequency band at 433.92 MHz interrogation distances of 1 to 2.5 meters are feasible which enables the implementation as tire pressure sensor system [5]. Since a single interrogation cycle takes only about 30 µs, even sensor units mounted on fast moving or rotating parts can read out successfully.

3   IMPEDANCE LOADED REFLECTIVE DELAY LINE

In former SAW pressure sensor designs [6],[7] the reflective delay line was both used as transponder and sensor. The SAW delay line was embedded into a piezoelectric diaphragm with a hermetically closed cavity beneath. Bending under the applied pressure some of the diaphragm sections were compressed some were stretched. The phase velocity of the SAW is slower in stretched sections, whereas it is faster in compressed sections. Thus, the pressure sensor information was included in the time delay between the pulses generated by the acoustic reflectors of the delay line.

With reference to the demands of the automotive industry a smaller pressure sensor unit at lower costs was desired. A solution was found in the application of a reflective delay line of which one acoustic reflector is electrically loaded with the impedance of an "external" pressure sensor [8]. In figure 1 the three acoustic reflectors are implemented as splitfinger IDT. The second IDT is terminated with a matching circuit, e.g. a parallel or serial coil, and the sensor impedance (Z_{Sensor}) which varies with the measurand. In (1) the reflectivity of an impedance loaded reflector as a function of the variable sensor impedance is represented by the complex scattering parameter S_{11}, where the P-matrix elements [9] describe the electroacoustic behavior of the reflector:

$$S_{11}(Z_{sensor}) = \frac{2 \cdot P_{13}{}^2}{P_{33} + \dfrac{1}{Z_{sensor} + Z_{match}}} \tag{1}$$

In (1) the denominator consists of the electrical reflectivity P_{33} and the admittance of the load and the matching circuit. As the sensor impedance modulates the reflected pulse both in amplitude and phase, there are two ways of calculating the sensor information in the time domain.

One strategy also reported in [8] is to match the sensor impedance to the electrical impedance of the reflector in the way that the amplitude modulation is maximized. This is outlined in figure 2 where the amplitude of the reflected pulse as a function of the load impedance is shown as a contour plot.

The simulation is based on the scattering parameters of a realized reflective SAW delay line measured by a network analyzer. The sensor impedance is assumed as series arrangement of a varying capacity and a constant resistance of 5 Ohms, a typical value of realized sensors. The sensor impedance is matched to the impedance of the splitfinger IDT with the help of a lossless series coil.
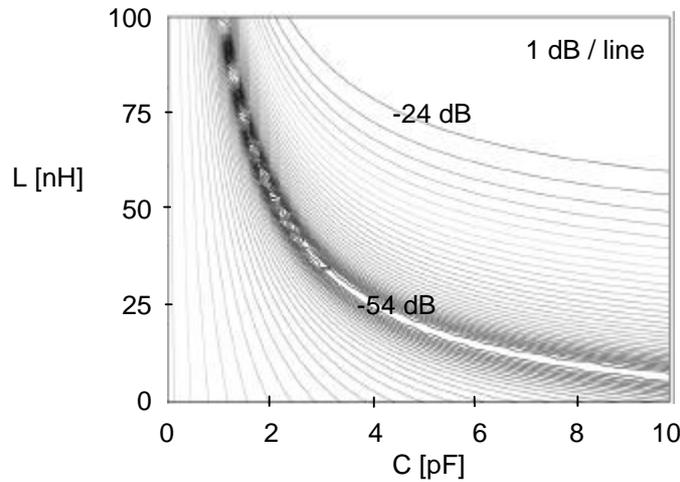

Figure 2. The magnitude of the scattering parameter S_{11} representing the reflectivity of an impedance loaded reflective delay line as a function of the variable sensor capacity and serial inductance of a matching coil. Points of constant reflectivity are connected.

As can be seen in figure 2, a very high capacity range in connection with the appropriate series inductance is needed to modulate the magnitude of S_{11} between –24 dB and –54 dB. Neither losses of the antenna nor transmission losses are included so far. Although a change of more than 20 dB in the reflectivity could be achieved with realized sensors there is one big drawback in deriving the sensor information from the amplitude of the reflected pulses. As the achievable amplitude resolution depends on the actual signal-to-noise ratio, the useable dynamic range is limited.

To overcome this limitation we present a new way of matching, which is first shown in this paper. Following this, the sensor impedance is adapted to the acoustic reflector in the way that a maximum of phase modulation is achieved. In figure 3 the phase difference $\Delta\varphi_{S11}$ between the reflected pulses of the electrically loaded reflector and one reference reflector is shown as a function of the load impedance.
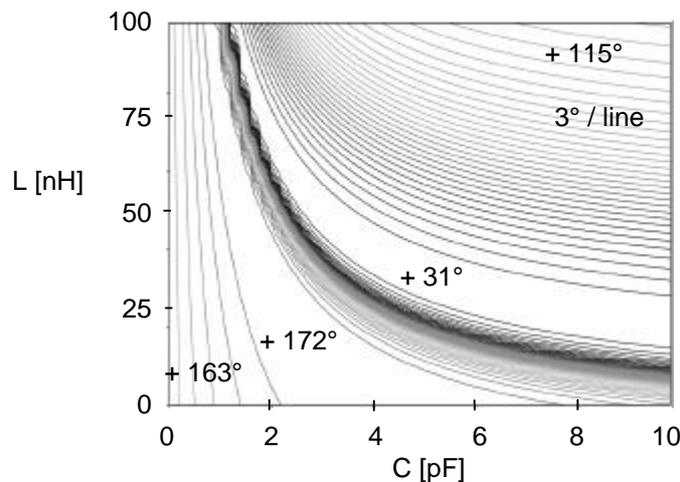

Figure 3. The phase difference $\Delta\varphi_{S11}$ between two reflected pulses of a delay line as a function of the variable sensor capacity and serial inductance of a matching coil connected to one acoustic reflector. Points of constant reflectivity are connected.

The similarity between the contour plots in figure 2 and figure 3 is founded on the fact, that phase and amplitude are linked by the Hilbert transformation [10]. As both a high signal-to-noise ratio and a

high modulation factor is desirable the appropriate matching can be found by comparing figure 2 to figure 3.

The same diagrams can also be used for sensors with a measurand dependent inductance. In that case the sensor impedance has to be matched to the impedance of the connected acoustic reflector with the help of an appropriate capacity. Simulations of a parallel inductance matching or a matching based on combinations of several inductances lead to similar diagrams as figure 2 and 3. Basically, the applicability of an impedance sensor as load for a SAW delay line depends on the Q-factor of the impedance. A bad Q-factor reduces both the achievable magnitude and phase modulation dramatically. Nevertheless, with limitations also resistive impedance sensors with a very high resistance span can be applied as impedance load [8]. The successful implementation of the new way of matching leading to a maximum of phase modulation is shown in section 5.

4   HIGH-Q CAPACITIVE PRESSURE SENSOR

Although it is generally possible to adapt both inductive and capacitive sensors to the reflector of the SAW delay line, using capacitive sensors is more advantageous because a low series resistance and temperature coefficient and a good reproducibility at low price can be achieved.

Surface and bulk micromachined capacitive pressure sensors found on the market were investigated. Measurements showed poor suitability for the application as electrical load of SAW delay lines due to their low Q-factor. The measured low quality factor can be explained by the fact that the electrodes of micromachined capacitive pressure sensors based on silicon technology are usually structured by doping the silicon instead of a metalization which results in a rather high serial resistance (about 20 to 50 Ohms). An ultrahigh doping of the silicon membrane leading to higher Q-factors would worsen the mechanical properties of the diaphragm.

Therefore, a new sensor with metalized electrodes was designed. A prototype of the sensor and its components is shown in figure 4 (left picture) as well as the attachment of the sensor unit including a prototype antenna on the rim (right picture).
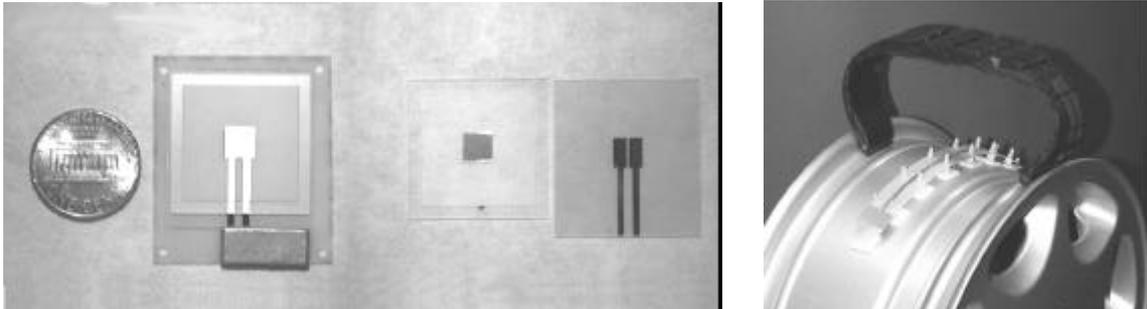

Figure 4. Capacitive gage pressure prototype and its components (left picture), attachment of the tire pressure sensor unit including an antenna prototype on the rim (right picture).

The gage pressure sensor was composed of two quartz structures which are expected to have minimal thermal stress and a low temperature coefficient [6]. In the quartz cover plate a quadratic blind hole was structured with the help of a sandblast apparatus. On the resulting diaphragm a common electrode with an electrically isolating cover layer was deposed. On the second quartz plate two electrodes with a layer thickness of 1 μm aluminium leading to the bond pads were structured. Both parts were joined with a one component epoxy adhesive at atmospheric pressure forming a hermetically sealed off cavity. The geometry of the sensor was determined by the use of a Finite Element Method (FEM) program.

The sensor was designed for a pressure range of 100 kPa up to 400 kPa, an excess pressure stability of 600 kPa and a heat stability up to 130°C. In figure 5 the measured capacity as a function of the applied pressure is shown. Comparing the sensor capacity curve to the diagram in figure 3 the appropriate series inductance was determined as 100 nH. Additional measurements showed that the membrane electrode of the sensor touches the bottom electrodes above the regular pressure range. As the membrane electrode is coated with an isolation layer this "touch-down" range can also be utilized for measurements. The relative high layer thickness of the electrodes and the low resistivity of aluminium results in a measured series resistance of only about 3 Ohms.
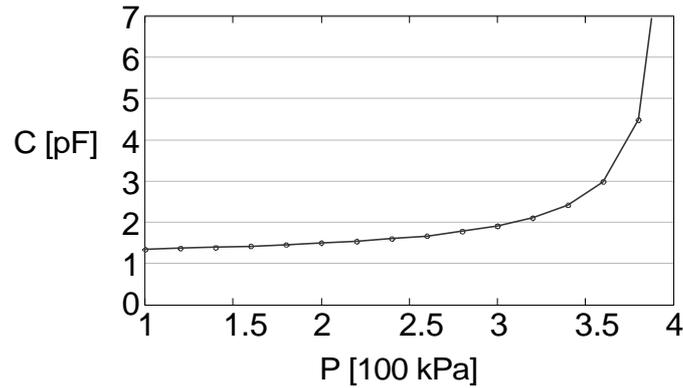
Figure 5. Measured capacity of the gage pressure sensor prototype as a function of the applied pressure.

5   MEASUREMENT RESULTS

In figure 6 the measured phase difference signal $\Delta\varphi_{S11}$ (left diagram) and the signal insertion loss $|S_{11}|$ (right diagram) of the pressure sensor unit are shown as functions of the tire pressure. As it can be seen in the diagrams a phase modulation of 110 degrees at a negligible signal level dependency on the varying pressure was obtained. Compared to conventional pressure sensors it is remarkable that the pressure resolution is not constant within the whole pressure range. With a respective choice of the matching circuit elements the curve progression can be varied within narrow limits. In combination with a conventional transceiver unit a typical accuracy of about ±15 kPa within the pressure range of 100 to 400 kPa is achievable.
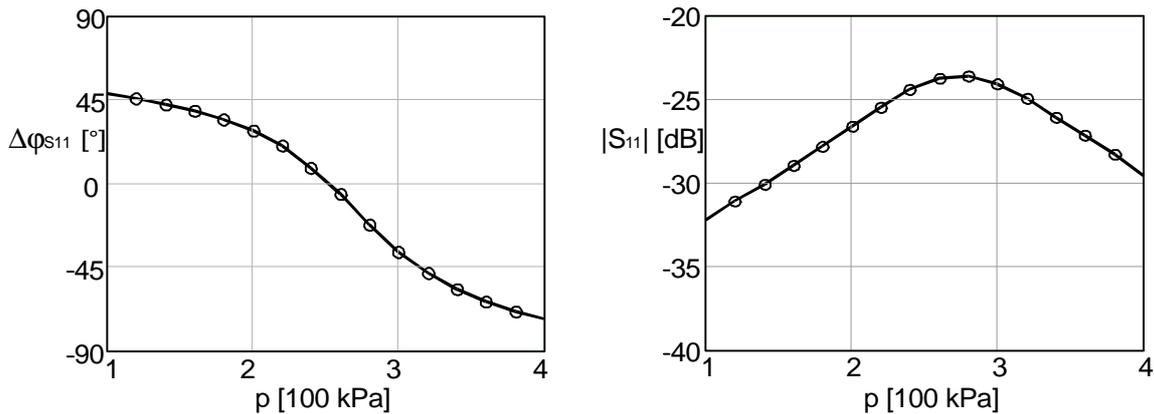

Figure 6. Left picture: measured phase difference signal $\ddot{A}\ddot{o}_{S11}$ generated by a pressure sensor unit prototype as a function of tire pressure. Right picture: pressure dependent magnitude of the measured scattering parameter S_{11} representing the insertion loss of the pressure sensor unit.

As can be seen from the right diagram of figure 6 both the maximum insertion loss of –32 dB and the insertion loss variation of 8 dB are very low compared to conventional hybrid SAW sensors optimized with respect to amplitude modulation. This means a significant improvement in accurate evaluation of the sensor signal and thus sensitivity of the sensor system.

As a second step the transmission path between sensor unit and transceiver unit has to be optimized. A preferred position of the sensor unit on the rim has to be found. An optimization of the antenna has to be done. As a further step a miniaturization of the capacitive pressure sensor to 5 x 6 x 1 mm is planned.

6   CONCLUSION

The principle and design of a tire pressure measurement system based on the combination of SAW transponder tags with high-Q capacitive pressure sensors to "SAW hybrid sensors" was shown. A sensor unit prototype with a typical accuracy of ±15 kPa within a pressure range of 100 to 400 kPa, an excess pressure stability of 600 kPa and a heat stability up to 130°C was presented.

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A new way of matching the sensor impedance with the reflective SAW delay line leading to both a high signal-to-noise ratio and a high modulation factor was introduced.

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