Hybrid Wireless SAW Sensor for Pressure and Temperature Measurement

Rukhlenko@bluewin.ch

www.intraSAW.com

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Outline

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Basic Wireless Monitoring Techniques

- Radio transmission with an active sensor unit
- RF carrier signal power supply (AC/DC conversion)
- Inductive coupling (short-distance)
- RF signal reflection (passive transponder)

Active (Battery Powered) Sensors

- Limited lithium battery lifetime
- Battery replacement inside the tire
- Battery waste management problem
Wireless Surface Acoustic Wave (SAW) Sensors

- Wireless interrogation (energy supply via the electromagnetic RF field of the transceiver unit)
- Large readout distance (2-3 m, ~mW)
- Temperature stability
- No battery required
- No aging
- Low mass and size
- Low cost
- Batch (group-type) mass production
**Hybrid SAW + MEMS Pressure Sensor**

**Construction:**

Hybrid SAW sensor = SAW reflective delay line + high-Q capacitive micromachined pressure sensor as the electrical load.

**Micromachined Capacitive Pressure Sensor Functions:**

1) Measure pressure (direct function)
2) Load electrically (capacitive high-Q load) the SAW sensor

**SAW Sensor Functions:**

1) Measuring the temperature
2) Compensation temperature in the pressure measurement
3) Wireless transmission of the measurand data (pressure, temperature)

**Simultaneous monitoring of the tire pressure and temperature becomes possible.**

The measurement cycle is initiated by a RF burst signal emitted from the wheel arch antenna of the central transceiver unit. This signal is received by the antenna of a SAW transponder unit mounted on the rim. The interdigital transducer (IDT) connected to the antenna transforms the received signal into a surface acoustic wave (SAW). All of the three acoustic reflectors are placed within the acoustic paths of the SAW transponder. The first and third reflector are used as reference, whereas the second one is electrically connected to (impedance loaded by) a pressure sensor. In the IDT the reflected acoustic waves which contain the sensor information are reconverted into an electromagnetic pulse train to be retransmitted back to the central transceiver unit, where the received signal is amplified, down converted and analyzed.
Equivalent Hybrid Sensor Circuit

\[ \text{L}_{\text{Match}} \]

\[ \text{R}_{\text{Sensor}} \]

\[ \text{C}_{\text{Sensor}} \]

This is virtually a pulse radar scheme.

The transmitted burst signal is created by switching an IF continuous-wave signal, where the switch is triggered by a microcontroller. The generated 10.7 MHz burst signal is filtered and mixed with the 423.22 MHz signal. The resulting amplified burst meets the specifications of the 433.92 MHz industrial-scientific-medical (ISM) channel. After having transmitted the interrogation burst signal, the transceiver is switched into receiving mode. The incoming sensor signal is amplified by a low-noise amplifier (LNA), down converted to the intermediate frequency and filtered. Finally, it is demodulated in the quadrature demodulator unit. The digitized I and Q signals are processed by a microcontroller connected to the controller area network (CAN) interface which is responsible for the calculation of the sensor data and providing it to automotive safety and stability systems.
A new capacitive differential pressure sensor featuring metallized electrodes with a series resistance of $R_s = 3 \, \Omega$ was developed. It consists of three layers of structured borosilicate glass forming a hermetically sealed cavity. A pressure sensor prototype has the dimensions 5 x 5.7 x 1mm.


Surface and bulk micromachined capacitive pressure sensors have low Q-factor as typically the electrodes based on the silicon technology are manufactured by doping the silicon that results in high serial resistance (20-50 \, \Omega).
The patch antenna with the integrated sensor board is mounted on the rim with a stress ribbon. The antenna is the capacitively shortened $\lambda/2$ dipole etched out of the copper layer on the 0.5 mm FR-4 substrate. Antenna gain is about –2.1 dB.

SAW Sensor Modeling

1, 2 – acoustic ports, 3 – electric port

Fig. 3. Mixed three-port representation of a SAW transducer
Mixed Scattering Matrix of a SAW Transducer

An ideal SAW transducer is a reciprocal and lossless three-port acoustoelectric network with two acoustic and one electric ports.

Mixed scattering matrix of a SAW transducer

\[
\begin{bmatrix}
  b_1 \\
  b_2 \\
  I
\end{bmatrix} =
\begin{bmatrix}
  m_{11} & m_{12} & m_{13} \\
  m_{21} & m_{22} & m_{23} \\
  m_{31} & m_{32} & m_{33}
\end{bmatrix}
\begin{bmatrix}
  a_1 \\
  a_2 \\
  V
\end{bmatrix}
\]  

(1)

where

- \( a_1, a_2 \) - incident waves at the acoustic ports 1,2
- \( b_1, b_2 \) - reflected waves at the acoustic ports
- \( I \) - terminal current at the electric port 3
- \( V \) - voltage applied to the transducer bus-bars
According to the power conservation law, all the electrical power delivered to the transducer is radiated acoustically in both directions.
### SAW Transducer Wave Scattering Matrix

Wave scattering matrix of a SAW transducer

\[
S = \begin{bmatrix}
  \frac{m_{11} - m_{13}m_{31}}{Y_0 + Y} & m_{12} - m_{13}m_{32} \frac{2\sqrt{Y_0m_{13}}}{Y_0 + Y} \\
  m_{21} \frac{2\sqrt{Y_0m_{23}}}{Y_0 + Y} & m_{22} - m_{23}m_{32} \frac{2\sqrt{Y_0m_{23}}}{Y_0 + Y} \\
  \frac{\sqrt{Y_0m_{31}}}{Y_0 + Y} & -\frac{\sqrt{Y_0m_{32}}}{Y_0 + Y} & Y_0 - \frac{Y}{Y_0 + Y}
\end{bmatrix}
\]  

(4)

where \( Y_0 = \frac{1}{Z_0} \) - characteristic admittance (source/load) at the electric port.

**Assumption:** \( m_{11} = m_{22} = 0 \) mechanical (mass-electrical loading) reflections are negligible.

**Validity:** \( f_0 \neq \frac{v}{2p} \) where \( f_0 \) – central frequency, \( v \) – SAW velocity, \( p \) – IDT period.

- **Short-circuit:** \( Y_0 = \infty \rightarrow s_{11} = 0 \)
- **Open-circuit:** \( Y_0 = 0 \rightarrow s_{11} = -1 \)
- **Matched:** \( Y = Y_0^* \rightarrow s_{11} = -1/2 \)
- **Impedance loaded:** \( Y_0 > Y \rightarrow s_{11} = -m_{13}m_{31}Z_0, Z_0 \) – matched load impedance
Temperature Measurement

1. Monitoring the temperature inside the tire is desirable.
2. The phase shift caused by the thermal variation is superimposed on the phase shift due to the variable impedance load.

The temperature can be determined by measuring the time delay \( \tau = \frac{L}{v} \) between the two reference reflectors.

Time delay method provides worse accuracy than the phase measurement. However, this accuracy is sufficient for monitoring purpose.

\[
\Delta \frac{\tau}{\tau} = (\alpha_t - \alpha_r) \Delta T = \Delta \tau, \quad \tau = \frac{L}{v}, \quad \Delta \varphi = 2\pi f_0 \Delta \tau \tag{5}
\]

where \( \alpha_t = \alpha_r - \alpha_v \) - temperature coefficient of delay (TCD).

\[
\alpha_t = \frac{1}{L} \frac{dL}{dT} - \text{temperature coefficient of expansion (TCE)}.
\]

\[
\alpha_v = \frac{1}{v} \frac{dv}{dT} - \text{temperature coefficient of velocity (TCV)}.
\]

Temperature Compensation

Temperature range: from -30°C to +130°C \(\Delta T=160°C\)
Substrate material: YZ LiNbO_3, \(\alpha_r=94\)ppm/ºC.
Central frequency: \(f_0=432\) MHz (ISM)
Time delay: 4, 7, 10 \(\mu\)s.
\[
\frac{\Delta \tau}{\tau} = \alpha_r, \quad \Delta T = 94 \times 160 \times 10^{-6} \approx 0.015 \quad (6)
\]
The phase shift caused by the thermal variation:
\[
\Delta \varphi = 2\pi f_0 \Delta \tau = 2\pi \times 434 \times 4 \times 0.015 \approx 163.6 \text{ rads} \quad (7)
\]
Temperature compensation must be done!
\[
\Delta \varphi = \varphi_p - \varphi_T = \\
= \varphi_p - \frac{\varphi_{R_1} + \varphi_{R_2}}{2} = \varphi_p - \varphi_{R_1} - \frac{\varphi_{R_2} - \varphi_{R_1}}{2} = \Delta \varphi_{PR} - \frac{\Delta \varphi_R}{2}
\]
Prototype Hybrid SAW Sensor Parameters

1. Phase modulation range is about 110º (pressure range 100-400 kPa).
2. Amplitude modulation is about 8 dB (ambiguous and obsolete for this case).
3. The pressure resolution is not constant (non-linear dependence).
4. Maximum sensitivity can be controlled by tuning the matching circuit.
5. Signal-to-noise ratio 20 dB
6. Pressure range 100-400 kPa
7. Pressure accuracy ±15 kPa
8. Temperature range -30ºC to +130ºC
9. Temperature accuracy ±10ºC
10. Interrogation cycle 20 ns


Conclusions

The principles and design of the pressure and temperature measurement (monitoring) system based on a hybrid of the reflective surface acoustic wave (SAW) delay line (SAW transponder) with the high-Q micromachined capacitive pressure sensor are presented.

The hybrid sensor unit integrated with antenna does not require power supply (electrical battery) and serves for simultaneous measurement of the pressure and temperature.

With a new approach to matching the capacitive sensor impedance to the SAW transponder impedance both a high signal-to-noise ratio and a wide signal dynamic range can be achieved.

The prototype tire pressure sensor (Siemens AG, Germany) is discussed.
References


The End

Thanks for your attention.

Questions?