

High Precision Wireless Measurement of Temperature by Using Surface Acoustic Waves Sensors

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Abstract—Surface acoustic wave devices can be used as wireless sensor elements (SAW transponders) for measuring physical quantities such as temperature, that do not need any power supply and may be accessed wirelessly. The complete wireless sensor system consists of such a SAW transponder and a local radar transceiver. An RF burst in the VHF/UHF region transmitted by the radar transceiver is received by the antenna of the SAW transponder. The passive transponder responds with an RF signal - like a radar echo - which can be received by the front-end of the local transceiver. The amplitude and phase of this RF response signal carry information on the positioning Surface acoustic wave (SAW) devices can be used as sensor elements that do not need any power supply and may be read out wirelessly. The reader unit performs a radar measurement of the impulse response of the SAW transponder via a high-frequency electromagnetic radio link. A temperature variation changes the SAW velocity and thereby the response pattern of the SAW device. By analyzing the time delay between backscattered pulses with different time delays we get a coarse estimation of the temperature of the SAW transponder. By using this information the ambiguity of $\pm 2\pi$ in the phase differences between the pulses can be eliminated, which enables to an overall temperature resolution of $\pm 0.2^\circ\text{C}$.

Index terms— Temperature sensor, passive sensors, surface acoustic waves, transponder, radio waves

I. INTRODUCTION

Surface acoustic wave (SAW) devices are special micro acoustic components consisting of a piezoelectric substrate with metallic structures such as interdigital transducers (IDTs) and reflection or coupling gratings deposited on its plain-polished surface. Due to the piezoelectric effect an RF input signal will stimulate a microacoustic wave propagating on the surface of the substrate. Figure 1 shows a SEM photo of two SAW pulses, which were emitted by an IDT. Vice versa, a SAW wave generates an electrical charge distribution at the receiving IDT and therefore an electrical RF output signal occurs [1]. SAW technology has been exploited for electronic analog signal processing over the past 30 years, with the development of a tremendous amount of devices and systems for consumer, commercial and military applications running now at some billion dollar annual rate.

Many piezoelectric single crystal substrates, like LiNbO_3 or LiTaO_3 show a non-vanishing temperature coefficient of delay. Hereby, a temperature variation strains the SAW chip and also changes the SAW velocity by influencing the elastic constants of the crystal substrate. Thus, by carefully analyzing the impulse response of a given SAW device on these materials, one can determine the temperature of the SAW chip. By using a SAW identification (ID) tag [2], [3] this SAW based sensor technique can be implemented with sensor elements (transponders) that do not need any power supply and which are connected to their reader unit solely by a wireless radio link [4]-[6].

Figure 2 shows the operating principle of such sensor systems: A local radar transceiver (TRx) used as reader unit sends out a radio frequency (RF) electromagnetic read-out signal in the UHF/VHF range. This

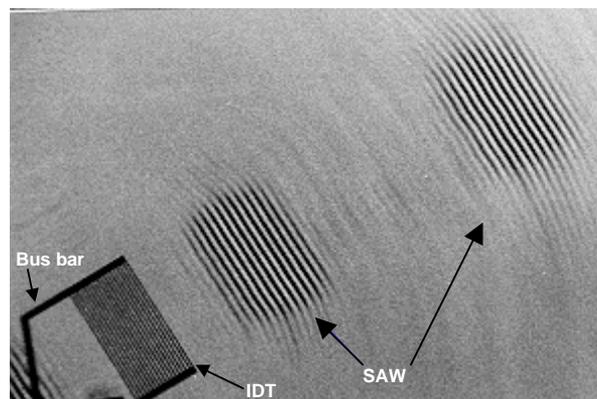


Fig. 1 SEM-photo of an interdigital transducer and two SAW pulses. (Photo by Siemens AG)

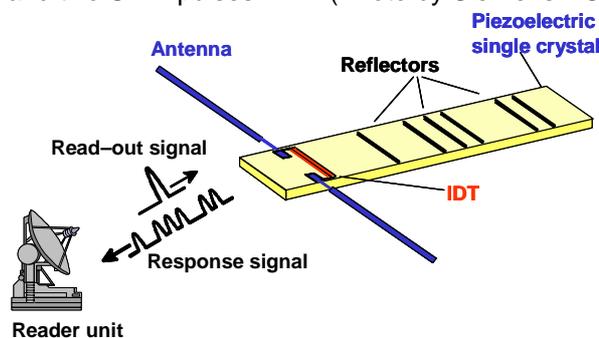


Fig. 2 Schematic of the operating principle of a SAW-based radio-link temperature measurement system.

read-out signal is picked up by the antenna of the passive SAW transponder and conducted to an interdigital transducer (IDT). The IDT converts the received signal into a SAW signal by the converse piezoelectric effect. The SAW propagates towards several reflectors distributed in a characteristic pattern. A small part of the wave is reflected at each reflector. The micro acoustic wave packets now returning to the IDT are re-converted into electrical signals by the IDT and re-transmitted to the radar TRx unit by the transponder antenna (see figure 3).

The velocity of the micro acoustic wave and thereby also the time distances of the RF transponder response is affected by the temperature. The evaluation of this response signal in the radar unit thus allows the determination of the environmental temperature of the passive SAW transponder. Since such sensors need neither wiring nor batteries they can be placed advantageously on moving or rotating parts and in hazardous environments such as contaminated areas or high voltage plants, chemical or vacuum process chambers, under concrete, etc. On the other hand, SAW transponders cannot be addressed individually. Using time division techniques typically 5 to 10 different SAW sensors, each with 3-4 reflectors, can be build up.

In the following contribution we will discuss in chapter II the local radar TRx and in chapter III the investigated SAW transponder. The used measurement set up will be explained in chapter IV, and in chapter V we will discuss the achieved measurement results. A short conclusion will end this contribution.

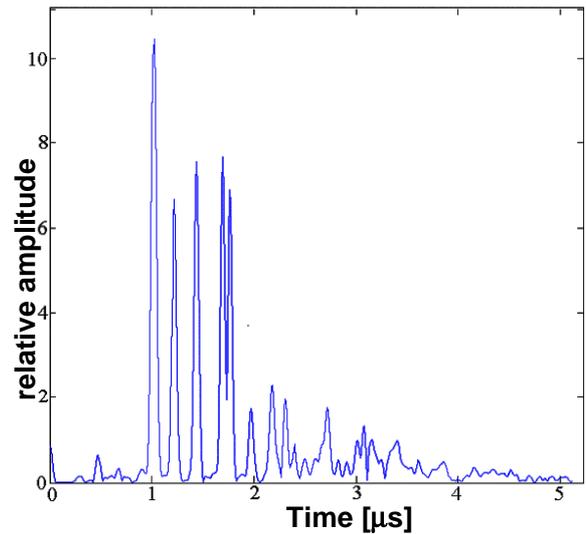


Fig. 3 Time domain impulse response of the investigated SAW tag with five reflectors.

II. READER UNIT

The read out units of wireless SAW sensor systems resemble those used in traditional radar systems [7]. In Europe, only two frequency bands suitable for SAW devices are allocated to unlicensed low power devices (LPDs) such as industrial, scientific, or medical (ISM) apparatus: 433.07...434.77 MHz and 2.4...2.483 GHz. The allowed equivalent isotropically radiated power (EIRP) in these bands is $P_0 = 10$ mW.

For the investigation presented here, we used a commercial reader unit for SAW ID tags from Baumer Ident (see figure 4). The sweep bandwidth B of 40 MHz of the transmitter Tx can be chosen between 2402-2470 MHz with a time resolution of 25 ns corresponding to the inverse of the used bandwidth. The system uses a frequency modulated continuous wave (FMCW)-principle with a sweep time of 16 ms. Thus, the applied beat frequency is given by 2,5 Hz/ns. The radiated output power (EIRP) can be chosen between 0,01 and 10 mW according standards FCC part 15 / I-ETS 300440. The system obtains a read out distance of up to 6 m depending on the tag type and the reader antenna. Two serial interfaces (RS 232 and RS 422) allow data transmission to an external PC or host system. In its normal mode the reader gives out the ID number of every tag, which passes the beam of the reader antenna. The reader, however,

can also be operated in a service mode, in which it delivers the sampled real base band data of each measurement cycle. Applying a Fourier transformation to this data and scaling the result with the beat frequency of the FMCW system gives the impulse response of the received signal.



Fig 4 2.45 GHz SAW reader unit by Baumer Ident.

III. SAW TRANSPONDER

For wireless SAW transponders we used commercial ID-tags from Baumer Ident. They use a pulse positioning coding scheme with five reflectors. Figure 5 shows the working principle of such a pulse position coded SAW tag. The local position of each individual reflector and thus the corresponding time position of the reflected signal can be chosen out of several slots. The tag we used utilizes 10 allowed slots for each reflector, which gives a code range of 10^4 with four code reflectors and one calibration reflector. Similar types are currently

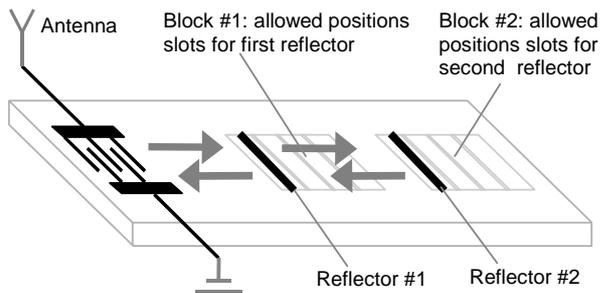


Fig. 5 Pulse position coding scheme for SAW tags.

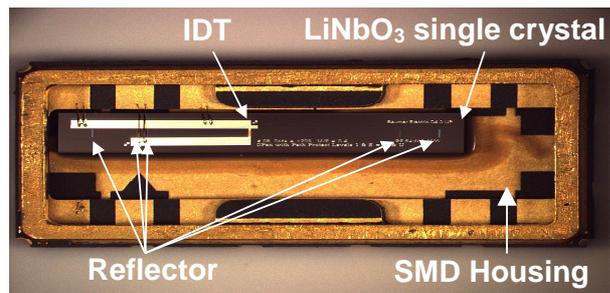


Fig. 6 Photo of an assembled SAW tag by Baumer Ident.

developed which offer a code range of 20 to 64 Bits [8]. The initial delay between the IDT and the first reflector is $1.2 \mu\text{s}$, the coding time slots are 25 ns spaced. Figure 6 shows the mounted SAW chip in a SMD package. The Material of the piezoelectric single crystal is black Lithiumniobat, LiNbO_3 ; the propagation direction is rot 128° . The corresponding propagation velocity v of the SAW is 3960 m/s, which gives for 2.45 GHz a wavelength λ of $0.8 \mu\text{m}$. The metallization is Aluminium, Al. The bi-directional IDT is placed near the centre of the chip with three reflectors to the left and two to the right. The two bright lines parallel to the acoustic path are bus bars for the electrical wiring of the IDT to the pins of the SMD package. The package will be hermetically sealed to protect the surface of the chip and then connected to an antenna to finish the SAW transponder.

IV. MEASUREMENT SET UP

For the temperature measurements we connected the Baumer reader unit to a RF antenna. The SAW tag was placed in the beam of the antenna inside of a temperature controlled oven. The electromagnetic waves passed through a small glass window of the oven. For temperature control an additional NiCr-Ni-thermocouple in good thermal contact to the SAW tag was used. The reader unit was connected to a computer for a detailed signal analysis using the RS 232 interface. Thereby the computer program could read out the sampled real base band data of each read out cycle and could also control all settings of the reader unit.

For signal analysis we used the numerical tool MATLAB. The interface to the reader unit was established by the use of the MEX file option of MATLAB, which allows the call of specifically developed C routines [9]. Figure 3 gives the time domain response signal of the investigated SAW tag. The first and largest response starts at $1.2 \mu\text{s}$. Then there are two well separated impulses followed by two interfering signals. Finally we get several smaller spurious signals due to multi reflections between the coding structures and reflections by the chip edge.

In the first step we optimised the frequency range of the reader system to ensure a perfect base band adjustment of the mixed down Rx signals of the SAW tag. This is performed if the transfer function of the antenna and the SAW reflective delay line is symmetrically to the centre of the frequency band of the Tx read out signal. In this case the mixed down SAW signal will be arranged symmetrically to zero frequency. The frequency adjustment can be done most easily by evaluating the time domain response in a polar diagram. Any shift in frequency with respect to zero frequency will result in a phase modulation within the peaks, which broadens the spikes. Figure 8 shows the obtained time domain data by using a read-out frequency range starting with 2.402 GHz, which corresponds to a centre frequency

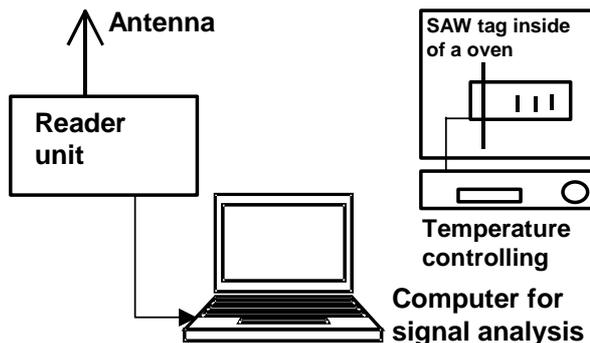


Fig. 7 Used set up for the wireless temperature measurement.

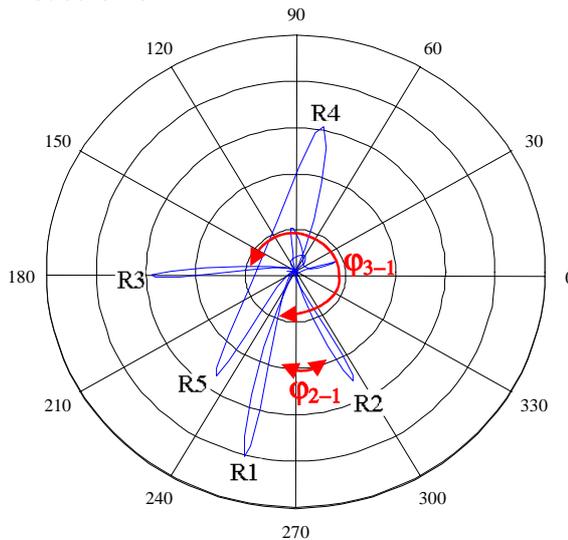


Fig. 8 Polar map of the SAW response signal in the base band measured with a FMCW signal starting with 2402 MHz.

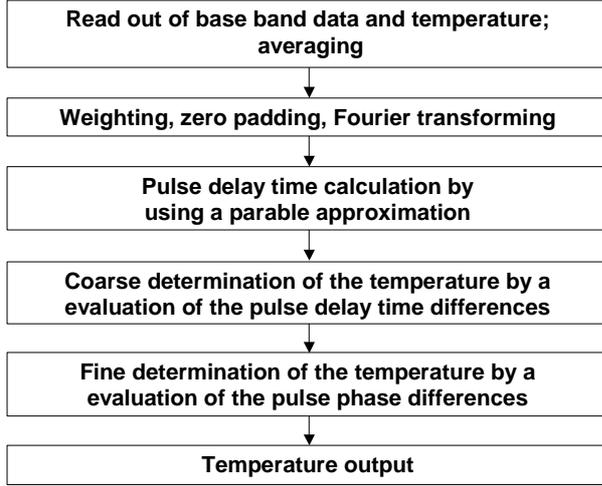


Fig. 9 Flow chart of the data analysis of a wireless passive SAW temperature sensor

$f_0=2.422$ GHz. For all further investigations this latter frequency range was used, because this setting resulted in the smallest spikes. There remained an intersymbol interference between the signals from reflector 4 and 5.

V. MEASUREMENT RESULTS

Figure 9 gives a flow chart of the used data analysis. The sampled 512 real base band data of each measurement cycle of the Baumer reader unit were read out via the RS 232 interface and transferred to Matlab using the MEX file. The ambient temperature of the SAW tag was noted und controlled. For improving the signal to noise ratio an averaging over several reading cycles could be performed.

Previous to the Fourier transformation we applied a weighting function to the data to minimize the spurious level in time domain. Due to its excellent side lobe level performance we used a Blackman-Harris weighting function, but this led to a huge pulse spreading of $w=1.9$ if compared to unweighted. Maybe the intersymbol interference between the signals from reflector 4 and 5 could have been avoided by using a weighting function with a smaller spreading, e.g. a Hamming function. To improve the resolution we applied a zero padding scheme with additional 512 points before performing the Fourier transformation. The resulting point spacing after the Fourier transformation Δt_{FFT} then results in:

$$\Delta t_{FFT} = \frac{1}{2 \cdot B}$$

To calculate the exact time position of each impulse we constructed a parable approximation through the local maximum of the amplitude and both adjacent points. The locus of the maximum of this parable was taken for the exact time position of this impulse. Using this technique we got an enhancement in resolution of the peak position of about a factor of 10, which results in an accuracy of 1 ns. Because the distance between the reader unit and the SAW tag is unknown or may vary and thereby the time delay to the first response impulse may be unknown or may vary too, we evaluated only the time difference between two pulses, e.g. $\tau_{2-1}=\tau_2-\tau_1$, as a function of the temperature. The linear term of a Taylor series expansion usually describes the situation well enough:

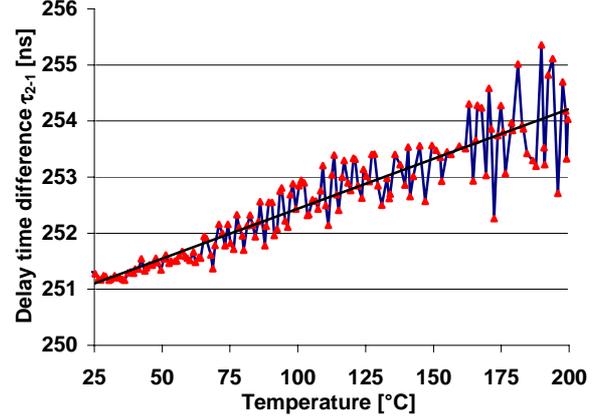


Fig. 10 Variation of the delay time difference $\Delta\tau_{2-1}$ between the first and second response as a function of temperature.

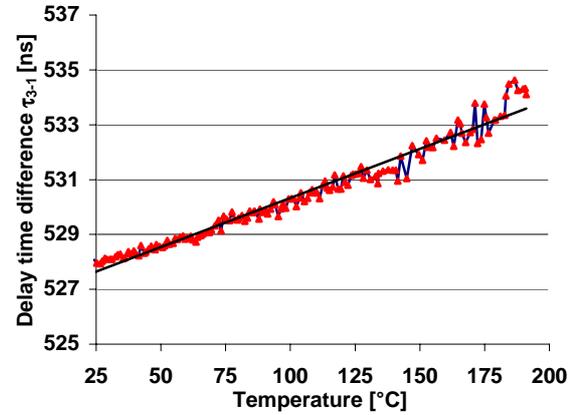


Fig. 11 Variation of the delay time difference $\Delta\tau_{3-1}$ between the first and third response as a function of temperature

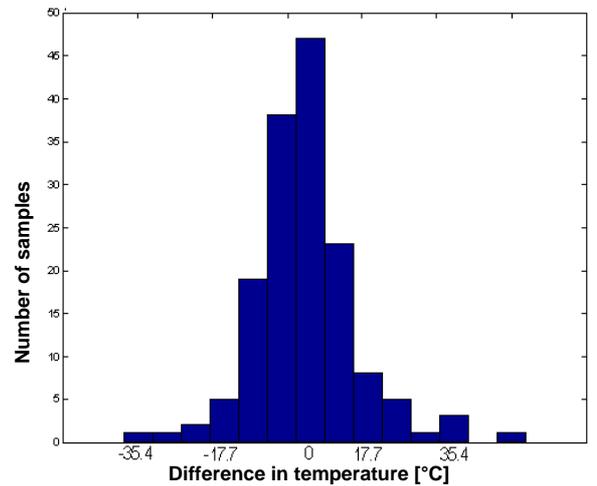


Fig. 12 Resulting error if the temperature is calculated solely by the delay time differences.

$$\tau_{2-1}(\vartheta) - \tau_{2-1}(\vartheta_{ref}) = TCD_{\tau} \cdot (\vartheta - \vartheta_{ref}), \quad (1)$$

where TCD_{τ} is the well-known linear temperature coefficient of delay:

$$TCD_{\tau} = \frac{1}{\tau} \cdot \frac{\partial \tau}{\partial \vartheta}$$

Figure 10 and 11 show the measured variation of the delay time differences $\Delta\tau_{2-1}$ and $\Delta\tau_{3-1}$ between the first and second, and the first and third impulse as a function of temperature. The gradient of the lines of best fit are with 70,8 and 70,0 ppm/°C in excellent agreement with the values from literature.

In both figures a periodical variation in the delay time differences occurs, which can be affected by varying the tag position inside the oven. Therefore, these variations are likely caused by multipath reflections inside the metallic chamber of the oven and the signal to noise ratio of the Rx data. Figure 12 shows the resulting inaccuracy when we try to calculate the temperature solely with the help of the delay time difference. We get an accuracy for the temperature of $\sigma=10^{\circ}\text{C}$ by evaluating $\Delta\tau_{3-1}$.

The resolution can be increased significantly by evaluating the phase differences precisely:

$$\Delta\varphi_{2-1} = 2\pi f_0 \Delta\tau_{2-1}. \quad (2)$$

Again the temperature dependence is given by:

$$\Delta\varphi_{2-1}(\vartheta) - \Delta\varphi_{2-1}(\vartheta_{ref}) = TCD_{\varphi} \cdot (\vartheta - \vartheta_{ref}), \quad (3)$$

where TCD_{φ} is now the slightly different the linear temperature coefficient of phase.

The evaluation of the phase differences, however, induces an ambiguity when the phase shift exceeds 360° . Figure 13 shows the variation of the phase difference $\Delta\varphi_{2-1}$ between the first and second response as a function of temperature. We use the coarse estimation of the temperature resulting from the evaluation of $\Delta\tau_{2-1}$ and $\Delta\tau_{3-1}$ to overcome this equivocation of the phase evaluation. To determine the absolute phase φ_{2-1} within 2π the accuracy $\Delta\tau_{2-1}$ of the delay time τ_{2-1} must be:

$$\frac{\Delta\varphi_{2-1}}{\varphi_{2-1}} = \frac{2\pi f_0 \Delta\tau_{2-1}}{2\pi f_0 \tau_{2-1}} = \frac{\Delta\tau_{2-1}}{\tau_{2-1}} \quad (4)$$

By demanding $\Delta\varphi_{2-1} < 2\pi$ we get:

$$\Delta\tau_{2-1} < \frac{1}{f_0} \quad (5)$$

Situation becomes a little bit easier if we use a long delay time difference τ_{3-1} (with a small relative error) for the coarse determination of the temperature and a short delay time difference τ_{2-1} (with a large unambiguity) for the first phase evaluation. This leads to a finer determination of the temperature, which allows the phase evaluation of longer delay time differences. The required accuracy $\Delta\tau_{3-1}$ then becomes to:

$$\Delta\tau_{3-1} < \frac{\tau_{3-1}}{\tau_{2-1}} \cdot \frac{1}{f_0} \quad (6)$$

The relative accuracy in terms of the point spacing after the Fourier transformation Δt_{FFT} (including the doubling of the points due to the zero padding) then is given by:

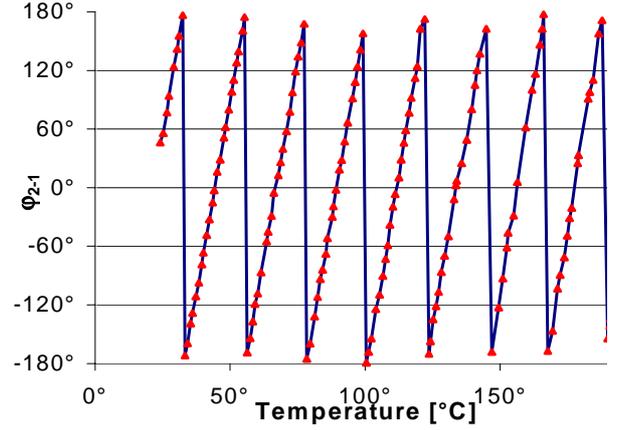


Fig. 13 Variation of the phase difference $\Delta\varphi_{2-1}$ between the first and second response as a function of temperature.

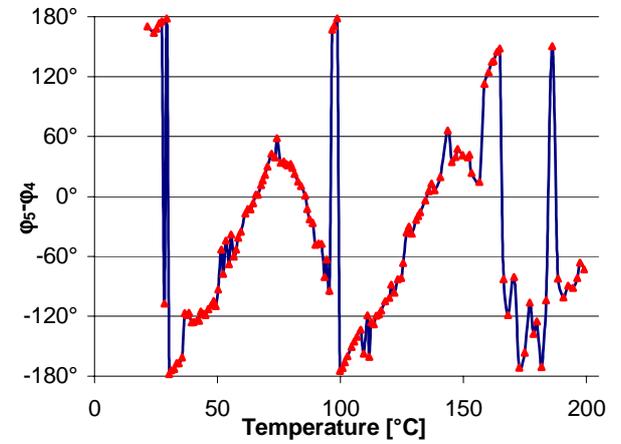


Fig. 14 Variation of the phase difference $\Delta\varphi_{5-4}$ between the fifth and fourth response as a function of temperature.

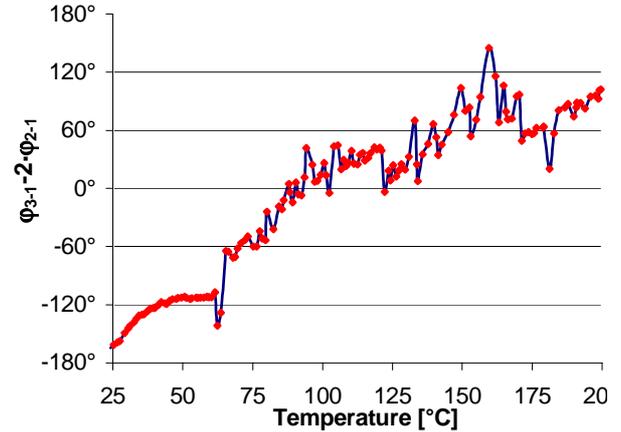


Fig. 15 Variation of the weighted difference of two phase differences $\Delta\varphi_{3-1} - 2 \cdot \Delta\varphi_{2-1}$ as a function of temperature.

$$\frac{\Delta\tau_{3-1}}{\Delta t_{FFT}} < \frac{\tau_{3-1}}{\tau_{2-1}} \cdot \frac{2 \cdot B}{f_0} \quad (7)$$

If we assume an accuracy of $\Delta\tau_{3-1} = \Delta t_{FFT} / 5$ by using the parable approximation of the maximum, we get:

$$\frac{\tau_{3-1}}{\tau_{2-1}} < \frac{\Delta\tau_{3-1}}{\Delta t_{FFT}} \cdot \frac{f_0}{2 \cdot B} \approx \frac{f_0}{10 \cdot B} \quad (8)$$

If we insert the data of the Baumer SAW reader system, we get a minimum ratio between the longer and the shorter delay time difference of 6. Therefore a very short delay time difference would be advantageous.

On the other hand we do need a minimum spacing to avoid intersymbol interference. Figure 14 shows the corresponding variation of the phase difference between the pulses #5 and #4 of the RF response as a function of temperature. The intersymbol interference between these two signals destroys the monotonic relation between temperature and phase difference. A temperature determination using this phase difference is therefore no more possible.

However, we can construct mathematically a very short delay time difference by analysing $\varphi_{3-1} - 2 \cdot \varphi_{2-1}$. Since the delay time difference between signal #2 and #1 is 250ns and between signal #3 and #1 is 525 ns, we get one single time slot for the weighted difference: $\varphi_{3-1} - 2 \cdot \varphi_{2-1} = 25\text{ns}$

Figure 15 gives the temperature characteristics for this very short time difference. The temperature range of unambiguity is more than 200°C. Adding this temperature information to the coarse estimated value from the delay difference information we can eliminate one after the other the ambiguity in phase differences of φ_{2-1} and φ_{3-1} . Using this technique we get the continuous phase difference $\Delta\varphi_{3-1}$ between the first and third response (see figure 16), which allows us to determine the temperature with a resolution of $\pm 0.2^\circ\text{C}$. Figure 17 gives the resulting temperature error by using the continuous phase difference $\Delta\varphi_{3-1}$.

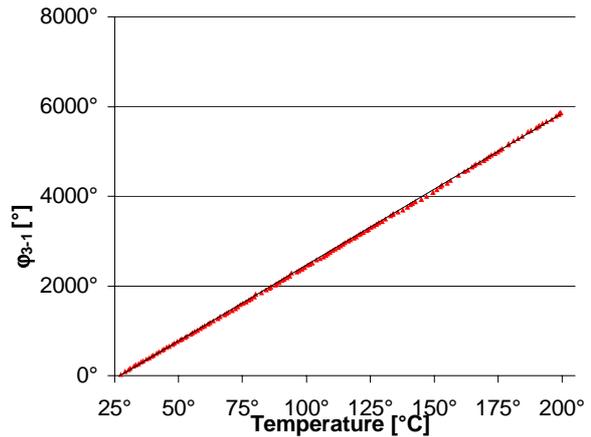


Fig. 16 Variation of the continuous phase difference $\Delta\varphi_{3-1}$ between the first and third response as a function of temperature.

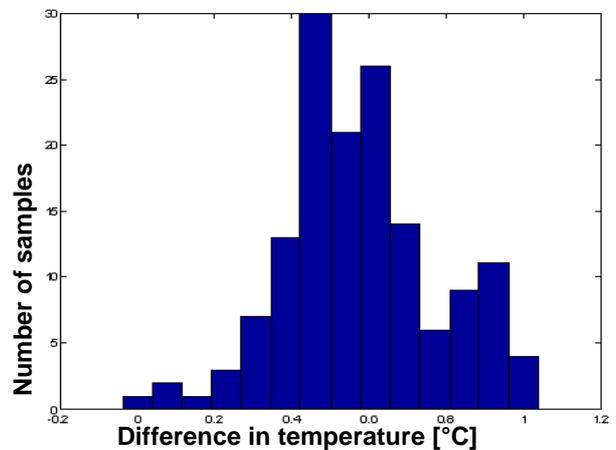


Fig. 17 Resulting error if the temperature is calculated using the continuous phase differences between the pulses.

IV CONCLUSION

By combining the principles of conventionally wired SAW sensors with the radio-request technique, known from SAW ID tags, passive sensors read out solely by a radio-frequency link can be developed. Based on a commercial read out system developed for identification applications and the corresponding SAW transponder, we build up a wireless measurement system for temperature. Using a precise evaluation of the delay time differences between the responded signals we could overcome the limited temperature range of the phase evaluation. The over all measurement accuracy is in the order of 0.2°C within a temperature range of more than 200°C . The read out distance is up to 6 m.

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