2.45 GHz Passive Wireless Temperature Monitoring System Featuring Parallel Sensor Interrogation and Resolution Evaluation

J. H. Kuypers*, S. Tanaka, M. Esashi
Department of Nanomechanics
Tohoku University
Sendai, Japan
*jan@mems.mech.tohoku.ac.jp

D. A. Eisele, L. M. Reindl
Laboratory for Electrical Instrumentation
IMTEK, University of Freiburg
Freiburg, Germany

***Abstract*—We report on the development of a TDMA (time division multiple access) based wireless sensor system for temperature monitoring. The transponders consisting of passive surface acoustic wave delay line sensors were designed for operation in the ISM band at 2.45 GHz and for a temperature range from -20 °C to 180 °C. A multi-step evaluation scheme using a combined delay and phase analysis, is introduced. A temperature resolution of 0.19 K (6σ) was achieved at a transmission power of +2 dBm (1.59 mW), when the distance between the transceiver and sensors was about 140 cm. We also report the importance of mounting the sensors during packaging based on experimental results.**

I. INTRODUCTION

Wireless sensor technology possesses a large potential concerning measurement flexibility, monitoring of moving objects, and measurement in hazardous environments. This technology is a key for an emerging ubiquitous computing society, in which tiny wireless sensors will be embedded in virtually all items around us. The application of surface acoustic wave (SAW) based sensors [1][2] has the advantage of being passive and thus free from the replacement of batteries, featuring a long lifetime and high reliability. In addition, the wireless interrogation of these passive sensors is possible with read-out ranges of up to 5 m, which is considerably larger than inductively powered sensors using 13.56 MHz.

In previous studies [1][3], SAW based sensors were applied to wireless temperature measurement, and the possibility of time division multiple access (TDMA) scheme was suggested. However, the TDMA of SAW based sensors has not been demonstrated. In this study, we developed a SAW passive wireless temperature monitoring system based on the TDMA scheme. The developed system is compliant with the frequency regulations for short range devices operated in the 2.45 GHz ISM band. This paper discusses the design of the temperature sensors, and reports the first experimental results of the parallel operation of 4 sensors.

This work was supported in part by the Strategic Information and Communications R&D Promotion Programme (SCOPE) from the Ministry of Internal Affairs and Communications (062302002).

II. SENSING PRINCIPLE

The principle of the temperature sensor is based on the temperature dependence of the propagation velocity of the SAW. The typical layout of the SAW sensor together with its simulated time response is shown in Fig. 1. A radio wave emitted from a transceiver is received by an antenna, and SAWs are generated by an interdigital transducer (IDT) connected to the antenna. The surface wave propagates along the piezoelectric substrate, reflects at reflectors, and then returns to the IDT. The returned SAW is reconverted to a radio wave, which is transmitted to the transceiver. Any mechanical deformation of the substrate or change in the propagation velocity occurring between the IDT and the reflectors results in a change of the delay time of the returned signal.

In this study, chemically reduced (black) 128°YX $LiNbO_3$ was used as the piezoelectric substrate material. $LiNbO_3$ is often used for SAW devices as it features large piezoelectric coupling, which is important for low-loss and wide-band SAW transducers, negligible excitation of bulk waves, and a moderate temperature dependence of the SAW velocity. The chemical reduction of $LiNbO_3$ is effective to reduce pyroelectric effects, causing charge-up problems during fabrication.

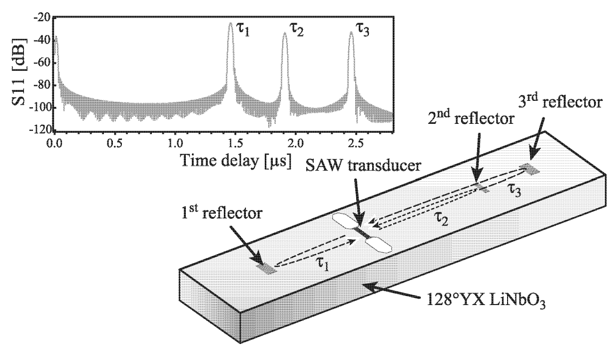

Figure 1. Typical structure of a one port SAW delay line sensor.

A. *Temperature Sensitivity*

The temperature coefficient of delay (TCD), which is the rate of change in time delay of a SAW caused by a temperature variation, is defined as

$$\mathrm{TCD} = \frac{1}{\tau}\frac{\partial \tau}{\partial T} = \frac{1}{l}\frac{\partial l}{\partial T} - \frac{1}{v_0}\frac{\partial v_0}{\partial T} = \alpha - \frac{1}{v_0}\frac{\partial v_0}{\partial T}. \quad (1)$$

The first term in (1) corresponds to the thermal expansion coefficient of the substrate along the SAW propagation direction, which is found as 15.4 ppm/K [4]. The latter term corresponds to the change in the SAW velocity which is computed as -55.8 ppm/K based on a temperature-dependent implementation of the method given by [5] using material data from [4][6]. The resulting TCD for 128°YX $LiNbO_3$ is 71.2 ppm/K.

B. *Time Delay Dependence*

The temperature dependent formulation of a time delay τ is represented by

$$\tau(\Delta T) = \tau_0(1 + \mathrm{TCD} \cdot \Delta T), \quad (2)$$

where τ_0 refers to the initial time delay, and ΔT to the temperature variation. The sensitivity for a given time delay is thus

$$S_\tau = \frac{\partial \tau}{\partial T} = \tau_0 \mathrm{TCD}, \quad (3)$$

suggesting that the temperature sensitivity for a typical time delay of $\tau_0 = 1$ µs is approximately 0.07 ns/K. Increasing the sensitivity requires either a material with larger TCD or larger time delay. For 128°YX $LiNbO_3$ 1 µs of time delay corresponds to a chip length of approximately 2 mm. Larger time delays are obtained using a longer chip, however the propagation loss at 2.45 GHz increases at 5~6 dB/µs.

C. *Phase Dependence*

Higher sensitivity is achieved by evaluating the phase of the complex time response for a given reflector delay. The phase is related to the time delay as

$$\varphi = 2\pi f \tau, \quad (4)$$

where the frequency f corresponds to the center frequency of 2446 MHz. From (3) the temperature sensitivity of the phase is represented as

$$S_\varphi = \frac{\partial \varphi}{\partial T} = 2\pi f \tau_0 \mathrm{TCD}. \quad (5)$$

The temperature sensitivity for a typical time delay of $\tau_0 = 1$ µs is approximately 63°/K, suggesting that high sensitivity is achieved even by a low-accuracy phase measurement. However, one phase value corresponds to many temperatures at intervals of 5.7 (360°/63°) K, and a unique temperature cannot be determined just by evaluating the phase. Hereafter, this is referred to as "phase ambiguity".

III. MULTI-STEP EVALUATION SCHEME

A multi-step evaluation scheme, which uses both time delay and phase, is adopted to achieve both high resolution and wide range in temperature measurement. The multi-step evaluation scheme is illustrated in Fig. 2. At first, the largest and thus most sensitive relative time delay (e.g. $\tau_{31} = \tau_3 - \tau_1$ in Fig. 1) is chosen for the first rough temperature estimation. Because the time delay and phase depend on the distance of the free space propagation between the sensor and interrogation unit, antenna phase, the length of cables etc., only relative time delays and phases are employed. The temperature resolution for this first evaluation is low judging from the achievable resolution of time delay measurement and the sensitivity determined by (2). Therefore, the following resolution refinement is performed using a relative phase. At this time, the temperature range corresponding to a phase change of 2π ($360°/S_\varphi$) must be smaller than the uncertainty of temperature determined using the time delay to escape from the phase ambiguity problem. Otherwise, one phase might correspond to two or more temperatures in an uncertainty of the first temperature evaluation. Therefore, a sufficiently small time delay is required for this second temperature evaluation (see (2)(5)). The required time delay is thus created as a delay difference using three reflectors, as

$$\tau_{3221} = \tau_{32} - \tau_{21} = (\tau_3 - \tau_2) - (\tau_2 - \tau_1). \quad (6)$$

Evaluating the phase φ_{3221} of this delay leads to an increased resolution of the sought-after temperature. Further resolution refinement is performed using a more sensitive phase, which corresponds to a longer time delay. Again, the temperature range corresponding to a phase of 2π must be smaller than the uncertainty of the temperature determined using φ_{3221}. In our design, the most sensitive phase φ_{31} can be used for this second resolution refinement.

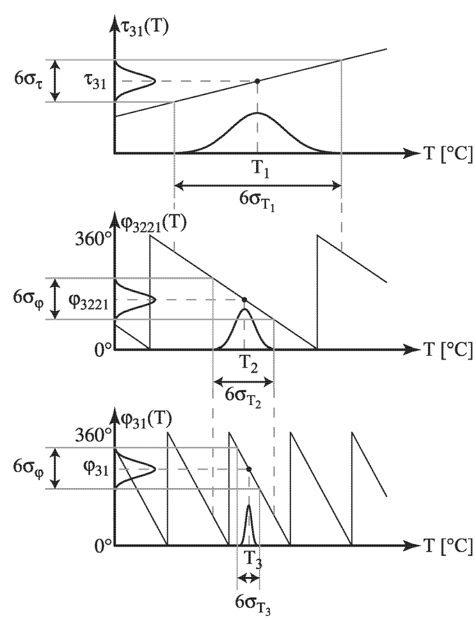

Figure 2. Principle of the three-step combined delay and phase evaluation scheme for temperature measurement.

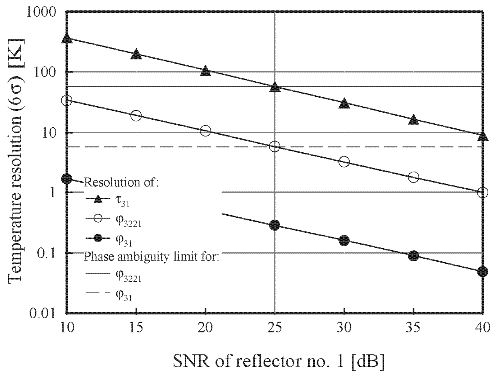

Figure 3. Resolution limitations of the fabricated sensors relative to the SNR of the first reflector.

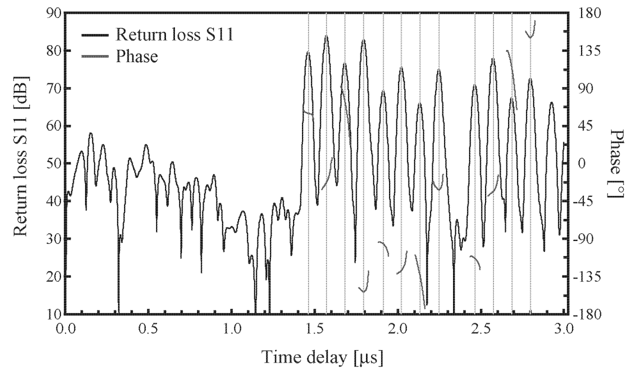

Figure 4. Time domain data of four fabricated TDMA sensors interrogated in parallel.

A. *Limiting Considerations*

The accuracy of the sensor can be increased by designing the time delays to be large, which will possibly require the use of more than three reflectors to employ the multi-step evaluation scheme. For practical devices there are limitations in time delay concerning the sensors signal strength due to increased loss and the chip size due to available packages and wafer cost. Besides, the interference of parallel sensors must be considered in the TDMA scheme. The reflectors must be designed to prevent return-signals of the parallel sensors from overlapping with each other. Therefore, it is not possible to maximize both achievable resolution and number of parallel sensors for a given temperature range at the same time. For optimal design in these limitations, a higher order SAW simulation based on the K-model [7] is carried out to design the reflectors, interdigital transducer and the exact reflector positions [8].

B. *Design Considerations based on SNR Relations*

To implement the multi-step evaluation scheme, the achievable resolutions in the measurement of the time delay and phase are needed to be estimated for the design. This issue is addressed in [8] based on experimental data for the wireless interrogation of delay-line sensors with a bandwidth of 75 MHz and a center frequency of 2446 MHz. Fig. 3 shows the estimated temperature resolution related to the SNR of the first reflector for the fabricated TDMA sensors with the relative time delays τ_{31} = 1 μs and τ_{3221} = 0.1 μs. Based on (5), the phase ambiguities are computed for φ_{3221} and φ_{31}, and it is found that phase ambiguity occurs if the temperature range exceeds 57.4 K and 5.74 K, respectively. Fig. 3 confirms that an SNR larger than 25 dB in the measurement of τ_{31} is sufficient to prevent the phase ambiguity of φ_{3221}. Similarly, the temperature resolution for φ_{3221} at 25 dB is high enough to avoid the phase ambiguity of φ_{31}.

This SNR relationship is not only of importance during the design phase, but is also used during the actual sensor evaluation. By monitoring the background noise level and computing the SNR for individual sensors, the temperature resolution is determined for each measurement.

IV. Results and Discussion

For the interrogation of the fabricated 4 temperature sensors (referred to as A, B, C, and D), a 2.45 GHz SAW reader (Siemens SOFIS Module) with a bandwidth of 75 MHz, a center frequency of 2446 MHz, a sweep time of 1 ms, a transmitting power of +2 dBm (1.59 mW), and 1024 sampling points was used. The operating principle is identical to a Frequency Modulated Continuous Wave (FMCW) radar [9]. The time domain data is retrieved by applying windowing, zero-padding, and performing FFT. Fig. 4 shows the return loss together with the reflector phase for the four sensors interrogated in parallel. The sensors were characterized in an oven with a glass window, which was placed about 30 cm from the reader antenna. A Pt100 sensor was used as a temperature reference. In order to minimize temperature differences between the sensors under test and the reference, the data was acquired during the cool-down of the oven, preventing temperature fluctuations resulting from the on/off control of the heater.

The extracted delay and phase data of τ_{31}, φ_{3221} and φ_{31} for the sensor D are shown in Fig. 5. The exact delay time is found by fitting a spline function to three points closest to the peaks [3] shown in Fig. 4. For the phase evaluation the real and imaginary part of the return loss are separately interpolated by spline functions, evaluated at the previously determined delay time, and normalized.

Computed TCDs for each relative time delay TCD_{31}, TCD_{32}, TCD_{21}, and TCD_{3221} are 64.3, 87.2, 36.4, and 319.8 ppm/K, respectively. However, they, especially TCD_{21} and TCD_{3221}, are considerably different from the theoretical value of 71.2 ppm/K. The theoretical value is calculated under the assumption that the TCD is uniform over the whole sensor chip. The sensors were mounted in ceramic SAW packages with two-component high temperature epoxy. As the thermal expansion coefficient of the used package is 7.1 ppm/K and thus significantly smaller than the value of 15.4 ppm/K for 128°YX $LiNbO_3$, the above assumption is not valid for the real sensors. In addition, it is doubtful that the thickness and composition of the epoxy are uniform. Thus, now we assume that the sensor substrate has different TCDs on either side of the IDT, TCD_1 and TCD_2 corresponding to

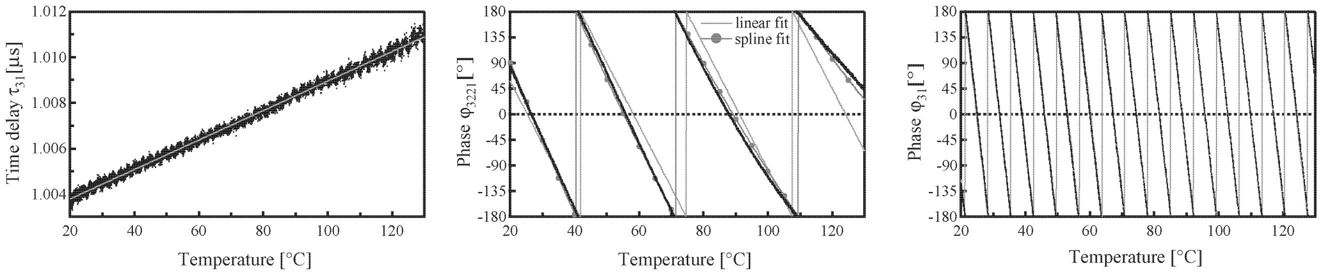

Figure 5. Measured temperature characteristics of the delay and phase differences for the three step evaluation scheme.

that on the right and left side, respectively. The rigorous expression for the time delay τ_{21} is then found as

$$\begin{aligned}\tau_{21}(\Delta T) &= \tau_{2,0}(1+\mathrm{TCD}_2\cdot\Delta T)-\tau_{1,0}(1+\mathrm{TCD}_1\cdot\Delta T)\\ &= \tau_{21,0}(1+\mathrm{TCD}_2\cdot\Delta T)+\tau_{1,0}(\mathrm{TCD}_2-\mathrm{TCD}_1)\cdot\Delta T,\end{aligned} \tag{7}$$

where the first term corresponds to the initially assumed time delay for a uniform material with TCD_2. Using (3), the TCD for τ_{21} is represented as

$$\begin{aligned}\mathrm{TCD}_{21,eff} &= \frac{1}{\tau_{21,0}}\frac{\partial\tau_{21}(\Delta T)}{\partial\Delta T}\\ &= \mathrm{TCD}_2+\frac{\tau_{1,0}}{\tau_{21,0}}(\mathrm{TCD}_2-\mathrm{TCD}_1).\end{aligned} \tag{8}$$

Performing the same analysis for τ_{3221}, we find

$$\mathrm{TCD}_{3221,eff} = \mathrm{TCD}_2-\frac{\tau_{1,0}}{\tau_{3221,0}}(\mathrm{TCD}_2-\mathrm{TCD}_1). \tag{9}$$

In case of the relative time delay $\tau_{32} = \tau_3 - \tau_2$ the subtracted part, which is equal to τ_2, corresponds to the identical acoustic track covered by the SAW. Therefore, the TCD of the time delay τ_{32} corresponds to the physical TCD between the two reflectors 2 and 3. We will assume here that the TCD to the right, TCD_1, is uniform and thus identical to TCD_{32}. By substituting measured TCD_{32} for TCD_1 in (8) and measured TCD_{21} for $\mathrm{TCD}_{21,eff}$, TCD_2 = 100 ppm/K is obtained. Using TCD_1 and TCD_2 in (9) yields $\mathrm{TCD}_{3221,eff}$ = 318.4 ppm/K, which is close to the found value of 319.8 ppm/K. The mounting issue is particularly important for the use of small delay differences, as e.g. for TCD_{3221} the discrepancy in TCDs is amplified by the delay ratio $\tau_{1,0}/\tau_{3221,0}$, which corresponds to a factor of ca. 18 for the sensor D.

The TCD obtained from the phase evaluation of φ_{3221} and φ_{31} based on (5) is 127.2 ppm/K and 57.5 ppm/K, yielding phase ambiguity intervals of 32.1 K and 7.1 K, respectively. Due to the reduced ambiguity interval of φ_{3221} a SNR larger than 30.5 dB is required for reflector 1 to prevent phase ambiguity. The temperature resolution at 30.5 dB and 35.5 dB is 0.19 K and 0.1 K (6σ), corresponding to a read-out distance of 140 cm and 130 cm, respectively.

New sensors were fabricated mounted only at the chip edge, that is, outside of the acoustic track region to confirm the above discussion. For this case, the results agree well with the assumption of a uniform TCD, and phase ambiguity is prevented for an SNR larger than 25 dB, as designed.

V. Conclusion

A wireless temperature sensor system operating in the 2.45 GHz ISM band and featuring parallel sensor interrogation was demonstrated. A fundamental design concept for a multi-step evaluation scheme based on the relationship between the SNR and temperature resolution was proposed. This relationship was also used as the basis to determine the accuracy of each sensor measurement. In this first demonstration of TDMA (time division multiple access) sensors, the temperature resolution of 0.19 K (6σ) was achieved at a transmission power of +2 dBm (1.59 mW), when the distance between the transceiver and sensors was about 140 cm. Finally, the importance of mounting the sensors during packaging was identified.

Acknowledgment

J. H. K. would like to thank C. Seisenberger with the SIEMENS AG for the continuous support concerning the Siemens SOFIS Module used in this study.

References

[1] X. Q. Bao, W. Burghard, V. V. Varadan, and K. V. Varadan, “SAW temperature sensor and remote reading system”, Proc. IEEE Ultrason. Symp. 1987, pp. 583-585

[2] L. Reindl, G. Scholl, T. Ostertag, H. Scherr, U. Wolff, F. Schmidt, “Theory and application of passive SAW transponders as sensors”, IEEE Trans. Ultra. Ferro. Freq. Cont., vol. 45, no. 5, 1998, pp. 1281-1292

[3] L. M. Reindl, I. M. Shrena, “Wireless measurement of temperature using surface acoustic waves sensors“, IEEE Trans. Ultra. Ferro. Freq. Cont., vol. 51, no. 11, 2004, pp. 1457-1463

[4] R. T. Smith, and F. S. Welsh, “Temperature dependence of the elastic, piezoelectric, and dielectric constants of Lithium Tantalate and Lithium Niobate”, J. Appl. Phys., vol. 42, no. 6, 1971, pp. 2219-2230

[5] J. J. Campbell, W. R. Jones, “A method for estimating optimal crystal cuts and propagation directions for surface waves”, IEEE Trans. Sonics Ultrason., vol. SU-15, no. 4, 1968, pp. 209-217

[6] G. Kovacs, M. Anhorn, H. E. Engan, G. Visintini, and C. C. W. Ruppel, “Improved material constants for $LiNbO_3$ and $LiTaO_3$”, Proc. IEEE Ultrasonics Symp. 1990, pp. 435-438

[7] J. H. Kuypers, D. A. Eisele, L. M. Reindl, “The K-model - Green's Function based analysis of surface acoustic wave devices”, Proc. IEEE Ultrasonics Symp. 2005, pp. 1550-1555

[8] J. H. Kuypers, S. Tanaka, D. A. Eisele, L. M. Reindl, M. Esashi, “Passive 2.45 GHz TDMA based multi-sensor wireless temperature monitoring system: results and considerations”, Proc. IEEE Ultrason. Symp. 2006, in press

[9] M. I. Skolnik, “Introduction to radar systems“, 3rd ed., Mc Graw Hill, pp. 193-197