HIGH TEMPERATURE STABLE SAW BASED TAGGING SYSTEM FOR IDENTIFYING A PRESSURE SENSOR

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Abstract - **Driven by the need for identifying an AVL pressure sensor inside of a combustion engine, various methods for this purpose have been examined. The solution found has to be compatible with the constraints placed by both the harsh environmental conditions acting on a sensor mounted close to the combustion chamber and the reading technique employed to monitor the data. Thus the final solution, preferably mounted inside of the pressure sensor, has to withstand shock, vibrations, high temperatures and temperature gradients, to provide a high isolation resistance and to fit into small size bore. Furthermore, the solution has to cope with additional demands such as low-costs or minor modifications of the sensor only**

Keywords - **identification tag, harsh environment, SAW transponder, rf reader unit**

I. INTRODUCTION

During the past years cylinder-pressure measurement at combustion engines has established from an occasionally applied experts tool to a standard instrument in engine research and development as well as in production quality assurance (Figure 1. displays such a standard pressure sensor to be mounted close to the combustion chamber).

According to this, a lot of engines are equipped with pressure transducers and transducers are installed many times a day to different engines. Due to this sensors can be mixed-up resulting in wrong measurements because of differences in sensitivity and so precious test bed time is lost due to troubleshooting.

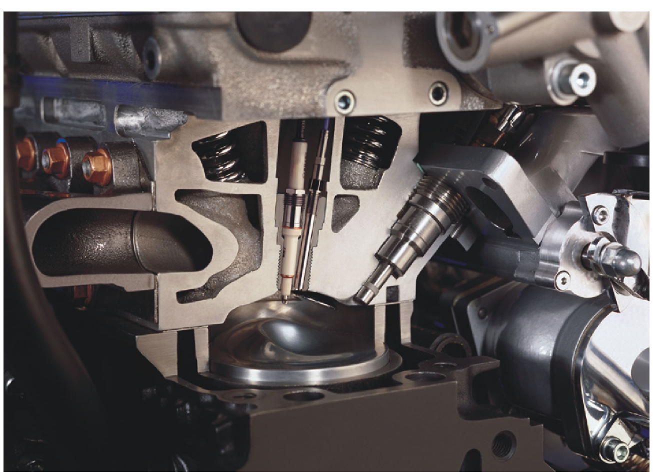

Fig. 1: Cross section showing part of the combustion chamber of an engine with a standard pressure sensor of AVL next to the spark plug.

The goal of the development described in the further contribution is the possibility for identification of a mounted sensor. This should not just avoid mistakes but should lead to a significant facilitation of work due to integration of this functionality in the overall system namely the "indicating measuring chain" – compromising sensor, amplifier, indicating system, indicating software.

The system developed detects the installed sensor and makes the complete setup of the amplifier knowing the sensitivity of this sensor. Further functions of the sensor identification in the compound "indicating measuring chain" are possible.

The demands on the identification element installed in the transducer are determined on one hand by the rough environment and on the other hand by already existing sensor products. In the area of the mounting position temperatures up to 400°C and accelerations up to 2000 g can appear.

The identification element has to be small enough so that it can be mounted in existing sensors. The application of the existing piezo cable and the exchange of the cable by the customer in case of damage are significant requirements with regards to stock keeping and sensor availability. Furthermore, the solution should be mechanically compatible with existing sensors and must not add substantial costs. A high-temperature stable SAW identification tag (surface acoustic wave) with an interrogation unit operating in the microwave range turned out to be the solution of choice, which can fulfill all above. For this purpose a surface acoustic wave device has been used for tagging. An RF burst in the VHF/UHF region via the common signal line is received by the antenna placed on. The passive transponder responses with an RF signal - like an radar echo - which can be received by the front-end of the local transceiver. The delay in the RF response signal carry information concerning the ID of the pressure sensor.

II. APPROACH TO THE SOLUTION

A SAW device compromises metallic structures (interdigital transducers, IDTs) placed onto the plain-polished surface of a piezoelectric substrate [1]. Owing to the piezoelectric effect an electric signal at the IDT will stimulate a SAW on the surface. Vice versa a SAW causes an electric charge distribution at the receiving IDT and hence an electric signal. Conventional SAW devices are commonly employed for delay lines, resonators, filters and oscillators to be used in television receivers and mobile communication sets etc.

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In case of a one port SAW device only one IDT is connected electrically and all others are reflective. If such an IDT is connected to an antenna, the element can be employed as a passive wirelessly interrogable system [2-5]. Such an SAW-based ID-tag is used for remote sensing of an identification (ID) code and is implemented in a road pricing system in Oslo, Norway [6] and for train identification at the subway in Munich, Germany [7].

Figure 2 points out the structure of such an ID SAW device. The incoming electromagnetic RF interrogation signal becomes converted into a respective SAW pulse, which is partially reflected by the arranged reflectors with a delay corresponding to the SAW propagation parameters and the reflector positions. External parameters such as the temperature, the mechanical stress or bending to the sensor may cause e.g. a change of the delay of the retransmitted signal or a shift of resonance frequency for resonators, respectively.

In particular, many piezoelectric single crystal substrates, like $LiNbO_3$ or $LiTaO_3$ show a non-vanishing temperature coefficient of delay [8,9]. Hereby, a temperature variation strains the SAW chip and also changes the SAW velocity by influencing the elastic constants of the crystal substrate. Thus if one considers to employ one of this substrates for design of an ID-Tag to be used in harsh environment, the temperature dependent change in the delay of the retransmitted signal has to be taken into account. Furthermore, these two materials are known to exhibit pyroelectricity. This places additional constraints on the choice of the proper substrate when to be used in environments where pronounced temperature gradients are present, such as near to the combustion chamber of an engine. Alternatively one may look for Langasit or $GaPO_4$, as these substrates are stable up to least 900°C [10-12]. However both materials are less common and less studied.

For a first choice $LiNbO_3$ was chosen because of the reasonable coupling constant describing the conversion of an electric wave into a mechanical one and vice versa and good availability. To account for pyroelectricity both black and white $LiNbO_3$ have been examined. Alternatively first tests on $GaPO_4$ are under way.

Owing to the inherent temperature variation of the elastic constants one may think to exploit this spurious side effect when extracting an ID out of the response of the SAW device. In order to account for the unknown distance between the reader unit and the SAW tag only the time difference between two pulses is evaluated, e.g.

$$\Delta\tau_{2\text{-}1} = \tau_2 - \tau_1 \tag{1}$$

as a function of temperature. The linear term of a Taylor series expansion usually describes the situation well enough:

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

where TCD_τ is the well known linear temperature coefficient of delay:

$$TCD_\tau = \frac{1}{\tau} \cdot \frac{\partial \tau}{\partial \vartheta}. \tag{3}$$

Referring to literature a resolution in temperature of about 10°C is possible by simply analyzing the respective variation of the pulses compromising the ID.

III. System Concept

The concept of the presented identification system and the integration in existing sensor systems is sketched in Figure 3 below. In the given example an AVL pressure sensor operating under extreme environmental conditions (pressure, temperature, vibration, shock) is connected to a sensor-evaluation unit. The identification system may only use the existing shielded connection without direct ohmic connection, not destroying the high isolation resistance necessary for correct charge amplifier operation.

Thus the standard sensor cable remains unaffected. The RF-interrogation unit is coupled to the signal line. Inside of the pressure sensor the SAW-ID tag is coupled via an antenna to the signal line to preserve high resistance. The interrogation unit identifies any sensor connected to the evaluation unit and can provide additional sensor information like calibration data or duration of life-time.

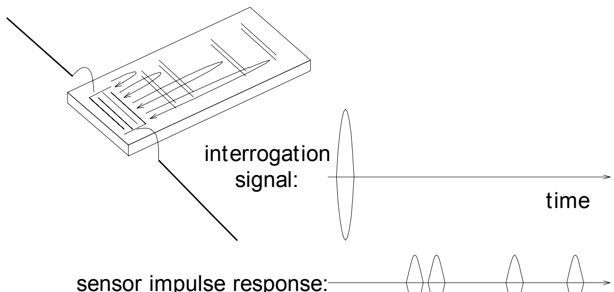

Fig. 2: ID-tag type SAW device

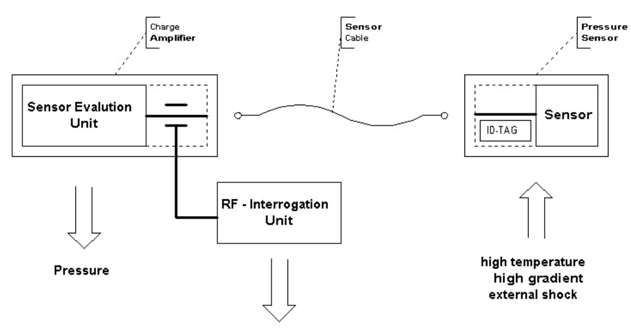

Fig. 3: Block diagram of the set-up for identifying sensors under harsh environmental conditions without influencing the sensor signal.

IV. THE SAW TAG

The identification information itself is coded on a SAW-ID tag, which is fabricated on a temperature stable substrate. The identification itself is realized with a pulse position coding scheme employing an ON-OFF coding by respective placement. Five separated codeblocks with ten digit positions each are employed to allow for 10^5 different codes as desired. The positions within one block are separated by about 20 ns, while themselves are placed 80 ns apart. Additional start and stop references permit to correct for the shift in the delay owing to temperature variation. The initial delay separating initial transducer and start reference in time was chosen thus to allow the spurious signals owing to reflections in between the respective digits of the code block to decay.

Two types of coding have been investigated: The first one is based on both input and output IDT´s while for the other one reflectors are used for the code block (see Figures 4 and 5.) Usually the IDT´s show a higher coupling but additional spurious signals occur resulting in the need for a long initial delay. On the other hand the reflector design allows to reduce this initial delay but brings about the problem of multiple reflections in between the code block positions which have to be taken into account.

A crucial point is the high temperature resistivity of substrate and metalization. Therefore the high temperature stability of the SAW ID-tags has been investigated. The experimental set-up (see Figure 6) includes a high temperature chamber kiln, a RF network analyzer and a host computer for controlling and data analysis. Each assay has been placed in the chamber wired to the socket of a special RF 50 Ohms feed through.

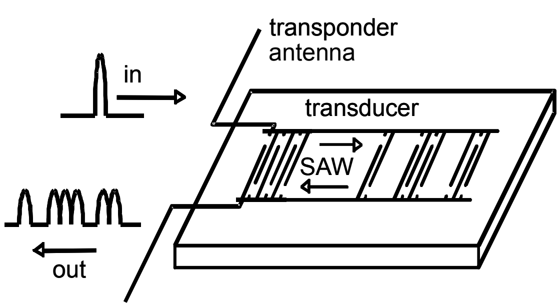

Fig. 4: Coding based on transducers

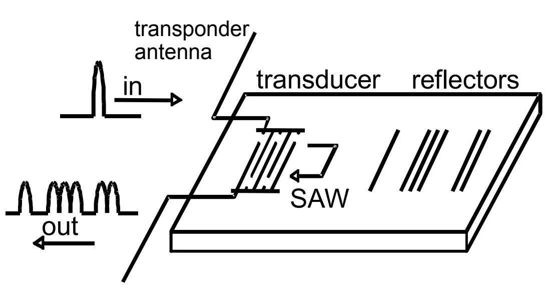

Fig. 5: Coding based on reflectors

The temperature cycles have been performed under atmospheric pressure and with ambient air. After heating up to the nominal value the attenuation in the response signal has been evaluated and logged as a function of time. The measurements include both, short-time thermal resistance and long-run aging. Two different crystal types of $LiNbO_3$, a "black" and a "white" form, were investigated for the application. Figure 7 shows the acoustic attenuation loss of "black" and "white" $LiNbO_3$. The attenuation of "black" $LiNbO_3$ rises fast with temperatures above 300°C and leaves the range ability of the interrogation unit. Hence the further analysis on this material was dropped regarding to the application. SAW devices on "white" $LiNbO_3$ showed a short-time stability up to 500°C. The thermal limitation seems not to be caused by a change in the crystal lattice, because a demolition of the metalization always determines the breakdown (see Figure 8). Two mechanisms of thermal damage characterize the disordered metalized surface. On the one hand the metal concentrates to small droplets [3], on the other hand the fingers of the transducers are interrupted.

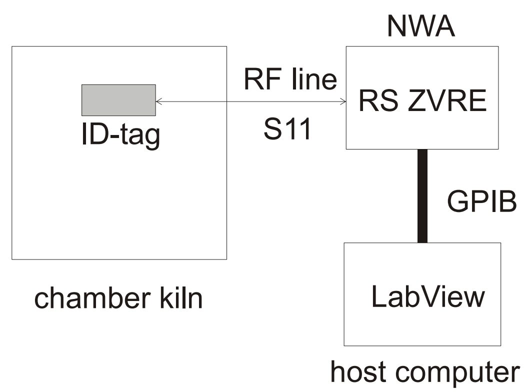

Figure 6: Schematic assembly of the test bench

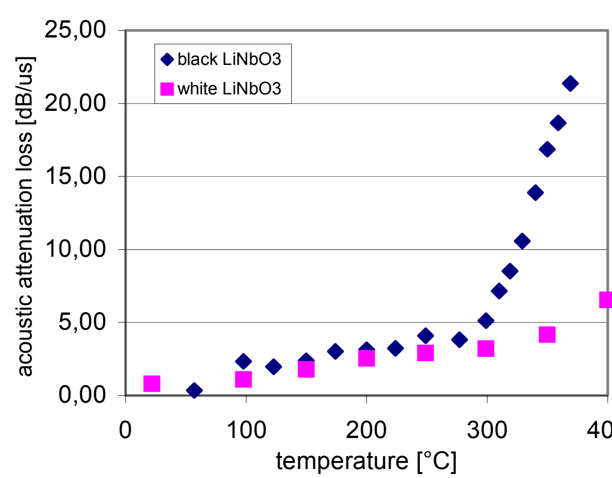

Fig. 7: Acoustic attenuation loss of „white" and „black" $LiNbO_3$ SAW ID-tags.

Beneath the melting alike process the deteriorations of fingers maybe explainable by spark formation of the pyroelectric effect and high electric field force. These damaging affects stepwise a change of the signal amplitude (see Figure 9). The occourance of this damage is statistical and limits the stability of the investigated SAW devices in the temperature range between 450°C and 500°C. Those stepwise changes of the attenuation detach to lower temperatures, which allows predictions on the long-run stability of $LiNbO_3$.

Below 450°C the aging of $LiNbO_3$ shows a continuous decrease in the response signal (see Figure 10), maybe caused by a decomposition over the congruent melting above 300°C [1,5]. The gradient of this increasing attenuation can characterize the economic life-time of each temperature level.

The long-run test series show an exponential correlation between the temperature and the aging of $LiNbO_3$, comparable to many other aging processes known. A prognosis to lower temperatures down to 300°C based on ARHENIUS equation for economic life-time has been performed on this results indicating that the SAW-ID tag will survive several year under this conditions (Figure 11).

The small SAW-ID tag is mounted inside the hermetically closed pressure sensor. An antennal-like structure on the substrate allows for non-ohmic coupling thus preserving the high isolation resistance.

In Figure 12 the arrangement of the tag inside the sensor is shown. The stability of the shock mount manufactured out of a high-temperature resistant plastic was tested up to 3500 g for the whole arrangement, i.e. including a SAW device.

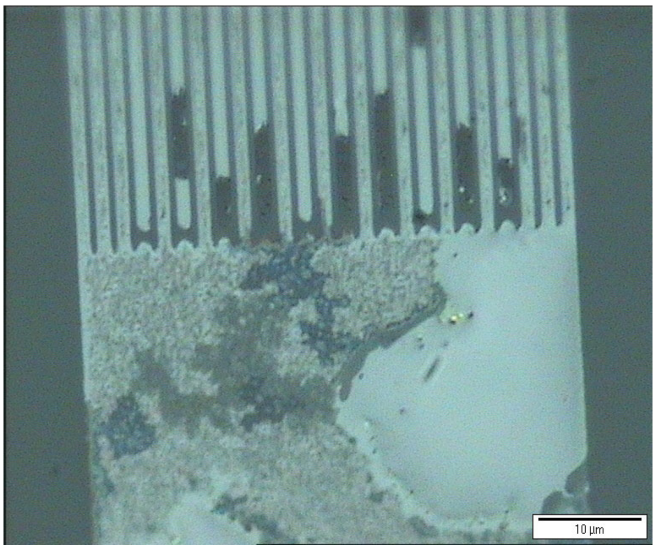

Fig. 8: LM-micrograph of a damaged transducer after use at 500°C

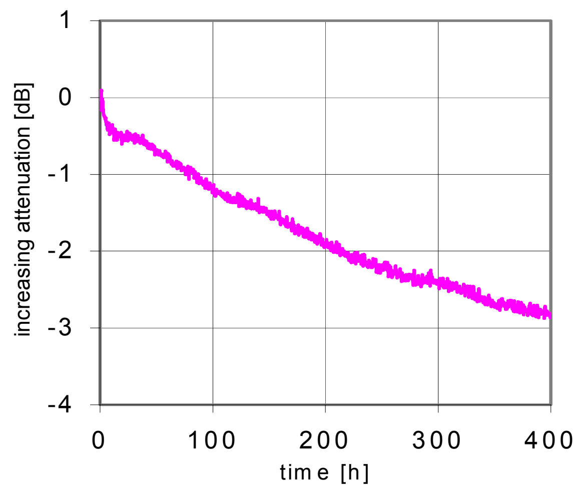

Fig. 10: Long time ageing of the investigated ID-tag at 400°C.

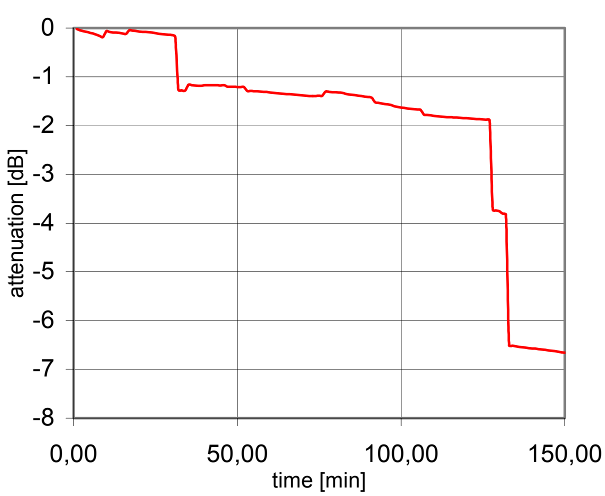

Fig. 9: Aging of a SAW device at 450°C with several fast transitions between an ordinary decay.

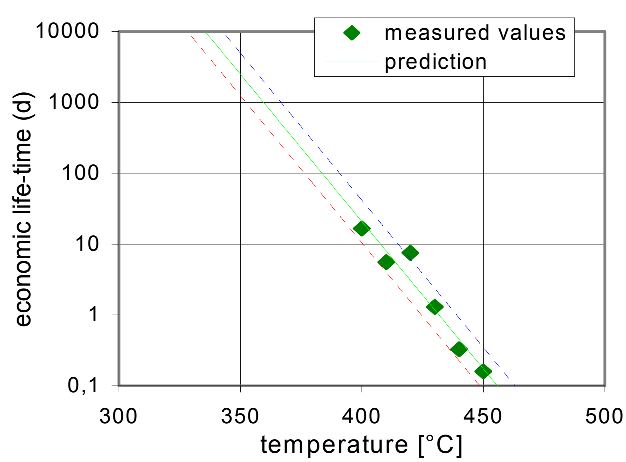

Fig. 11: Measurements of the long-time thermal stability of $LiNbO_3$ SAW devices. Additionally an ARHENIUS graph with the confidence interval is fitted to the data.

Also further rigid tests referring to the temperature stability up to 400°C and temperature gradients up to 70°C along the length of the SAW ID-tag, to account for the effect of pyroelectricity, were successfully completed. At least up to 400°C no trace for the impact of pyroelectricity on the metalization was observed. Finally a SAW ID-tag was mounted inside of a conventional AVL-pressure sensor. This sensor was installed a test combustion engine at AVL and full functionality was proven, i.e. both the pressure signal and the ID were successfully read out.

V. RF Interrogation Unit

The interrogation unit has to generate and transmit a response signal to the ID tag and to determine the ID by evaluating the reflected receive-signal. The frequency of operation is not restricted to ISM band limits due to the limitation of free space propagation to regions, which are completely shielded.

In general there are two basic principles to interrogate a SAW device, either in time-domain or in frequency-domain. A request in time-domain needs a pulse generator delivering short RF-bursts and a fast sampling stage, whereas in frequency domain sampling a continuous wave (CW) signal is used with a moderate sampling rate. For this – not time critical – application a CW principle with frequency stepping (FS) as modulation scheme is used. A block diagram is shown in Fig. 13. [13, 14].

Signal generation is performed using a phase locked loop (PLL) stabilized oscillator, which is capable of delivering exact frequency points for highly linear stepped ramps.

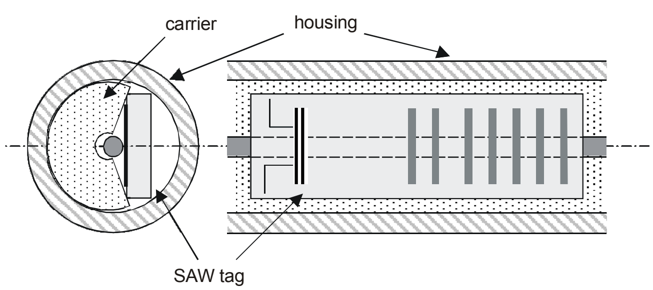

Fig. 12: Schematic arrangement of the SAW-ID-tag mounted inside of the sealed pressure sensor.

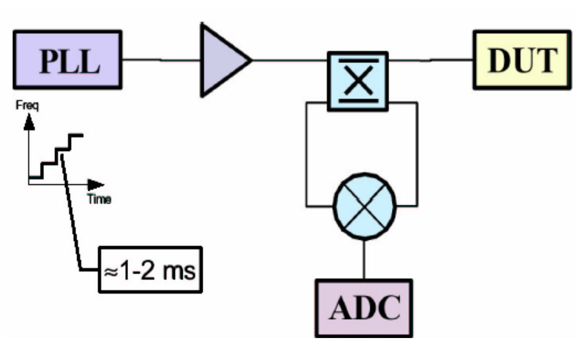

Fig. 13: Block diagram of the low-cost reader unit.

Transmit- and receive-signal are separated by a quadrature hybrid with sufficient isolation. The device under test (DUT) accounts for the ID tag including coupling and transmission loss. After mixing the receive- with the transmit-signal (homodyne principle), the filtered mixer output is sampled and digitized. The micro controller (µC) controls the frequency ramp and performs signal processing.

Using an inverse fast Fourier transformation (IFFT) the pre-processed frequency-domain data is converted to a time-domain signal, where the pulses caused by each digit position is clearly recognizable and can be evaluated to extract the correct ID information.

Measurement Results

A typical time-domain signal, obtained with an IFFT of the frequency domain-data is plotted in Figure 14. The signal consists of the code block, which is marked by the box, and dominant spurious responses before. These signals are caused by inner reflections in between the individual digits. With a proper design the spurious signals are decayed enough in the code block section, thus a correct identification is possible by simply determining the digits' positions with high resolution.

Fig. 15 displays the temperature dependent shift of the peaks compromising the code block up to 450°C. This data show that up to this temperature the ID can be read out underlining the stability of the approach followed.

Conclusions

A low-cost sensor identification technique for the application under harsh environmental conditions compatible with existing AVL pressure sensors was introduced. Neither the shape of the pressure sensor nor the cable have to be modified. The solution proposed was found to be stable up to at least 400°C for an long period in time, resistant against high temperature gradients and external shocks.

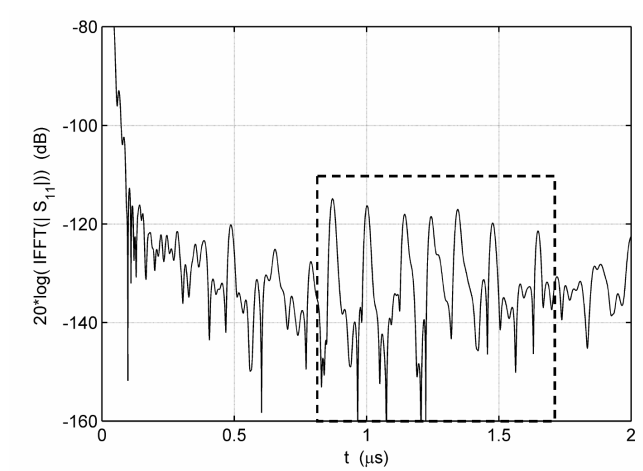

Fig. 14: A typical read-out signal of an SAW-ID-tag. The marked box indicates the code block

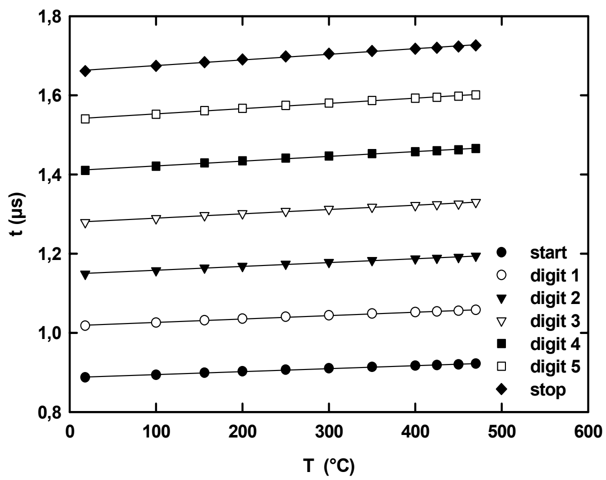

Fig. 15: Temperature dependent variation of the code block as defined in Fig. 14.

Up to 10^5 different sensors are addressable on such a small-sized SAW ID-tag providing every pressure sensor with an individual number. The main goal of providing the full functionality in the overall system namely the “indicating measuring chain” could be achieved.

In a next step Studies on $GaPO_4$ will be undertaken in order to extend the upper limit in temperature.

Finally, considering the small size of the tags, its stability under harsh conditions, this approach may be suitable for many identification tasks in industrial environments.

Acknowledgement

Many of the results reported in this contribution were obtained by a common effort of all colleagues and students working on this current topic. In particular the authors would like to thank Gerald Glanzer, Thomas Pürstinger and Gernot Knoll at CTR, Stefan Scheiblhofer and Stefan Schuster at ICIE, and Josef Glaser, Robert Strmsek and Klaus Leitmeier at AVL for their continuous contribution in this project.

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