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SAW Transponder – RFID for Extreme Conditions

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1. Introduction

Harsh or hazardous environments, e.g. continuous furnaces, process chambers, rotating or moving objects, require a robust wireless passive transponder technology for sensor and RFID applications. The transponders' operating temperature often exceeds 200°C in these applications and is way above the thermal limit of CMOS devices. Surface acoustic wave (SAW) devices are excellent candidates for high temperature applications as their operation has been shown at temperatures of 1000°C (Hornsteiner, 1997). With the use of an RF (radio frequency) antenna SAW devices can be interrogated passively and wirelessly.
The main advantage of surface acoustic wave sensors is their outstanding thermal stability specially compared to semiconductors. The sensors utilize the piezo-effect that creates so-called surface acoustic waves by means of a transducer structure on the surface of the sensor. Metallization gratings, so called reflectors are used to supply the device with a unique identification code (ID), achieved by pulse position coding (Reindl, 1998). This allows using the device as a high temperature stable RFID transponder (radio frequency identification). Depending on temperature or mechanical strain the surface acoustic waves are also affected. These changes on the surface acoustic waves can be used to implement an additional sensor functionality. In this way pressure sensors in combination with temperature sensing have been demonstrated [Pohl,1997; Kalinin, 2004].
In ideal application fields of SAW based RFID systems environmental conditions like high temperature or high doses of γ-radiation exist. Successful application examples are the automatic identification of pressure sensors, vehicle identification in paint shops and several tagging tasks in the steel industry. Often the temperature information contained in the response signal gives valuable additional process information of the tagged goods.
This chapter gives an overview of SAW based RFID transponders made for extreme conditions like temperatures up to 400°C or cryogenic temperatures down to –196°C. Their function principle and system performance is explained and pertinent application examples are given.

2. Principle of operation

A wireless surface acoustic wave based RFID system essentially comprises a reader unit emitting and receiving radio waves and a SAW reflective delay line attached to an antenna, building the transponder (Figure 1). For data acquisition, the impulse response of the SAW

transponder is analysed by a digital signal processor. The response signal contains a pattern of reflectors, which resembles for instance a binary, decimal or hexadecimal code. Utilizing the natural sensitivity of the piezoelectric substrate crystal, e.g. on temperature or strain, the SAW tag can operate as a sensor.

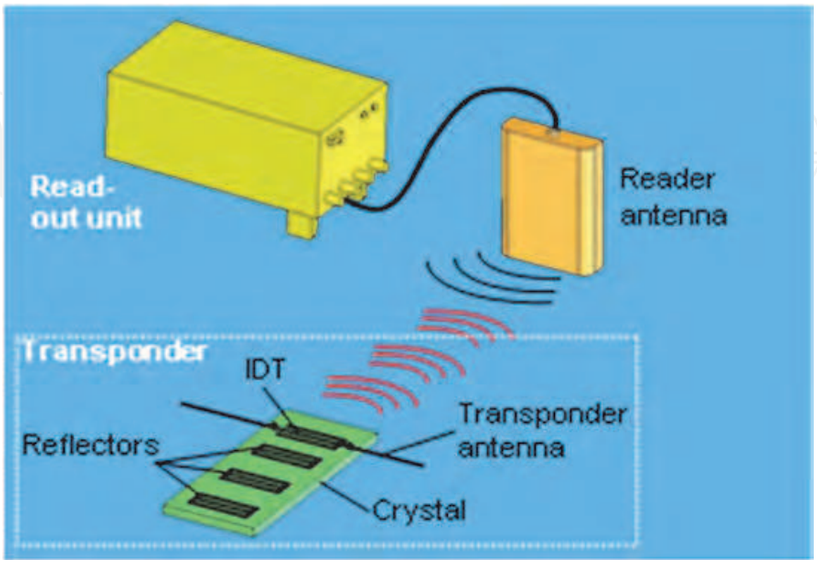


Fig. 1. SAW transponder interrogation setup.

The SAW RFID system is suited for high operating temperatures as it is purely based on piezoelectricity and therefore fully passive. It makes use of the piezoelectric-substrate lithium niobate. The operating principle of the system is as follows:
A high-frequency electromagnetic (EM) interrogation signal is picked up by the antenna of the passive SAW device and conducted to a transducer. The interdigital transducer (IDT) converts the received signal into a surface acoustic wave (SAW) by the converse piezoelectric effect. The SAW propagates towards reflectors distributed in a characteristic barcode-like pattern and is partially reflected at each reflector. The acoustic wave packets returning to the IDT are reconverted into electrical signals by the IDT and sent back to the request unit by the antenna. This response contains information about the number and location of reflectors as well as the propagation and reflection properties of the SAW. It is evaluated by the interrogation unit to extract the desired information.
In a particular design example eight reflectors are used to supply the SAW device with the unique identification code (ID) and a temperature sensing functionality. The first response pulse should have an adequate time delay towards the interrogation pulse to avoid environmental electromagnetic reflections and echoes corrupting an early sensor response. A practicable value for this delay time is 1.0 µs. In Figure 2, a typical impulse response of the designed SAW tag is shown. The SAW's edge reflection (at 0.4 µs) and crosstalk signal rests can be seen in the time between 0 and 1 µs. Then, the tag's eight response pulses rise clearly out of the surrounding noise level (about 1 µs up to 2.25 µs). The first and last pulse take the function of start- and stop-bit and are used for compensation of temperature changes, the second pulse is additionally taken for temperature measurement. Via pulse position coding, (Reindl, 1998) the other pulses are used to encode a unique ID comparable to an ID stored in a microprocessor's ROM.

While wireless interrogation can be achieved at any readout frequency, there is only a distinct number of radio frequency (RF) bands which are free for industrial-scientific-medical (ISM) applications. Here, the ISM band from 2.4 GHz to 2.4835 GHz proved to be most suitable as it has an adequate bandwidth (83.5 MHz) and an almost worldwide geographical licence. At the same time it allows a read out at a distance of several meters. At this frequency, the RF wavelength is about 13.5 cm, thus permitting the usage of simple and small antennas, e.g. dipoles, slot- or patch antennas, favorably for the transponder part.

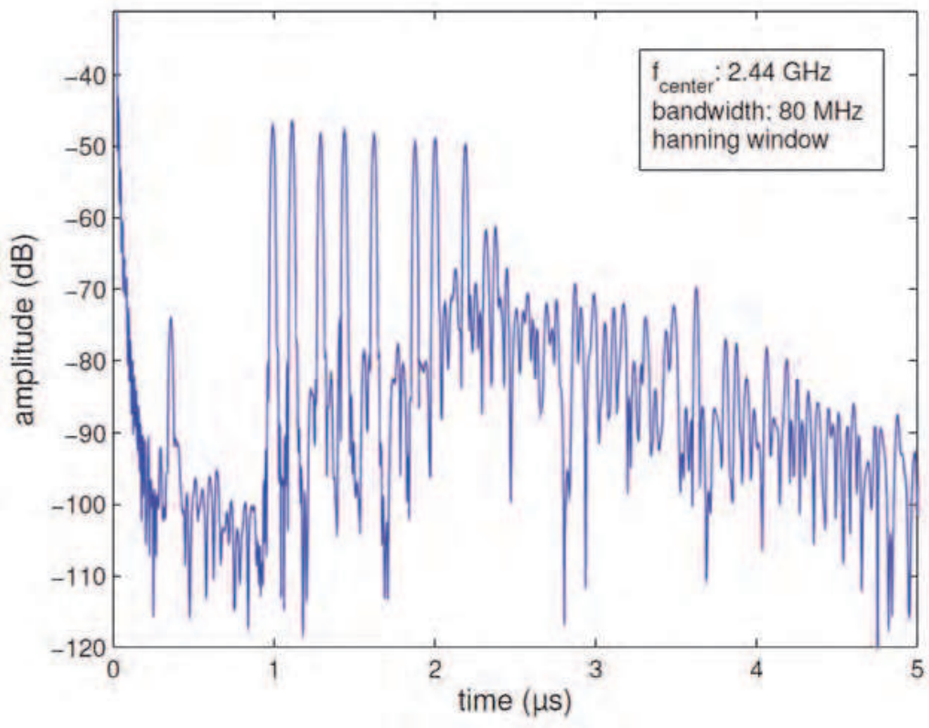


Fig. 2. Impulse response of a SAW transponder with eight reflectors.

2.1 Reader systems for SAW transponder

Reader systems for SAW transponders usually utilize the continuous wave radar principles. Impulse radars could be considered but are inferior in cost and are not efficient in terms of feeding the electromagnetic energy in the transponder. A set of three radar types are investigated: First, a frequency modulated continuous wave (FMCW), second, a frequency stepped (FSCW) and third, a switched frequency stepped (S-FSCW) radar. All three realized types generate a RF ramp within the ISM band at 2.4 GHz. The FMCW radar is equipped with a fast direct digital synthesis (DDS) based frequency synthesizer that provides fast frequency sweeps of 100 µs duration (Figure 3). The DDS works with a frequency pre-distortion to combat non-linear frequency chirps as reported in (Scheiblhofer, 2006). The Tx and Rx paths have separate antennas to achieve better signal isolation. The front-end collects during one frequency sweep 1024 data points. Data averaging is performed by repeated frequency sweeps over the whole bandwidth.

The FSCW radar generates the frequency ramp with a phase locked loop (PLL) based synthesizer (Figure 4). The synthesizer is significantly slower than the DDS providing sweep

durations of 100 ms. During one frequency sweep the radar collects 636 data points. Contrary to the FMCW the measurements are taken on discrete frequency steps.
The S-FSCW radar front-end is additionally equipped with Tx- and TRx switches (Figure 5). The switches are accurately synchronized to the signal response of the SAW delay line (Figure 2). The method yields in a significant reduction of environmental echoes and noise (Stelzer, 2004). The radar collects 636 data points during one sweep. The FSCW and the S-FSCW radar can average data either on a single frequency step or alike the FMCW over the whole sweep.

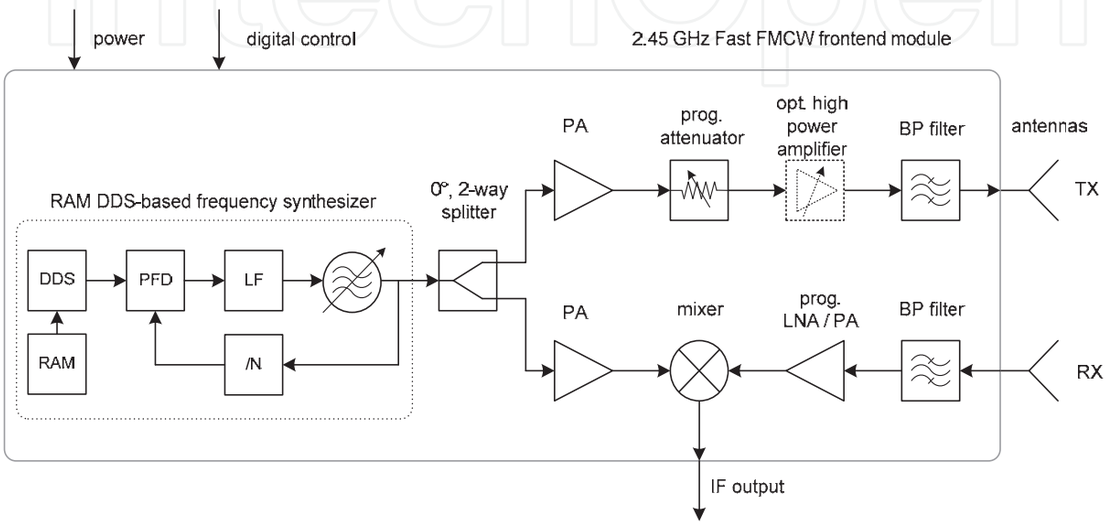


Fig. 3. Block diagram of a FMCW radar front end.

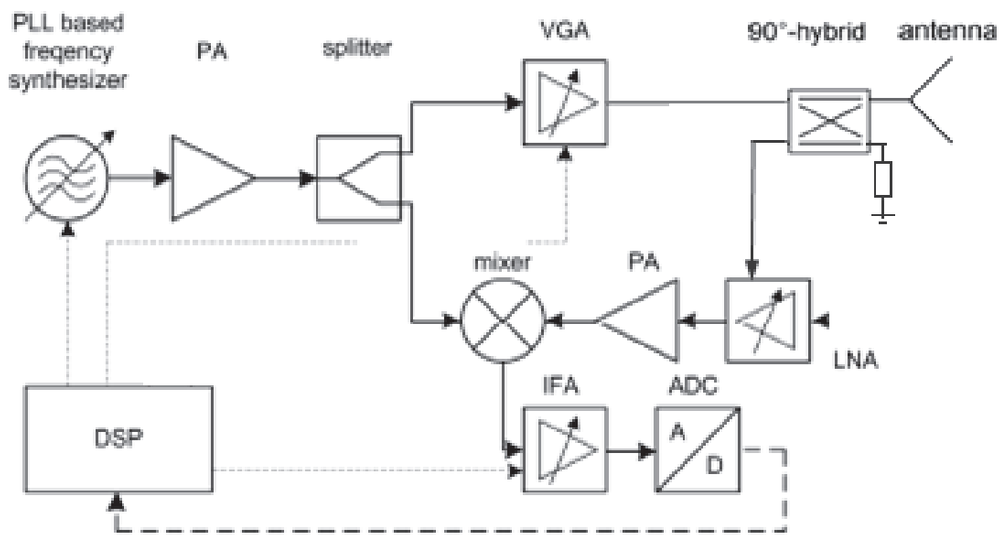


Fig. 4. Block diagram of a FSCW radar front end.

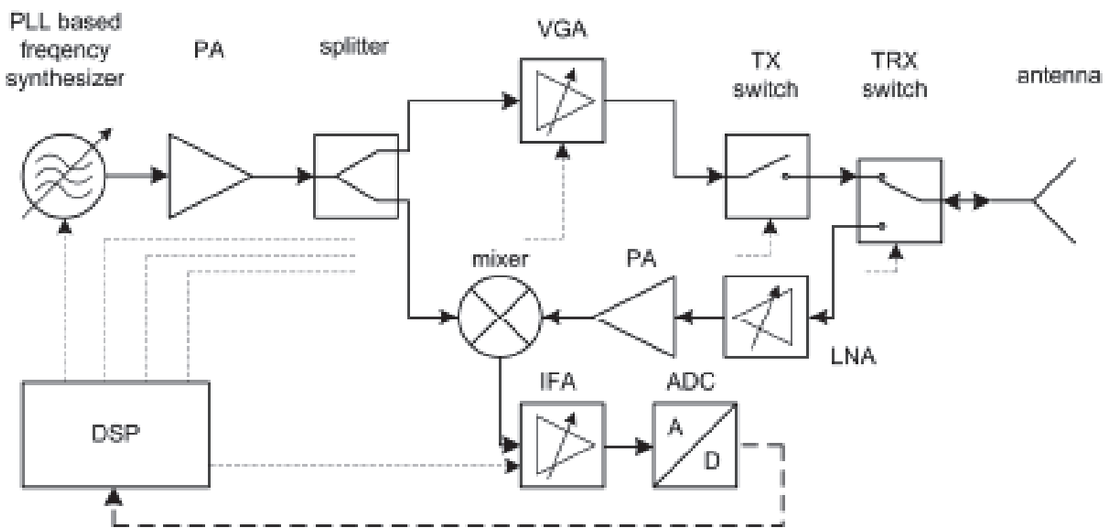


Fig. 5. Block diagram of an S-FSCW radar front end.

2.2 Package for SAW transponder

An important aspect for the transponder is the development of an appropriate packaging, which is functional at high temperatures (HT). A metallic housing with glass feed-throughs, withstanding temperatures up to 400°C is shown in Figure 6. The sensor tags' fixation inside the housing is done by a polyimide glue and its electrical interconnection by wire bonds. It is essential that the packaging is hermetically sealed. This is best done by resistance welding the lid to the socket. The weld is robust against high temperature and high temperature gradients. A complete transponder tag, using a monopole antenna welded to the pins is the simplest form of tag-antenna integration. This monopole tag is fully functional and does not need any additional hardware or any power supply. It can be injection molded into various plastics or ceramics depending on target applications. For optimized read range the connector pins can be welded to a stainless steel slot antenna. The interconnection between tag housing and antenna is done by laser welding, making this RFID transponder system HT resistant well beyond 400°C. It can easily be screwed on metallic objects via the integrated assembly units. By the design of this transponder, a metallic surface acts as a

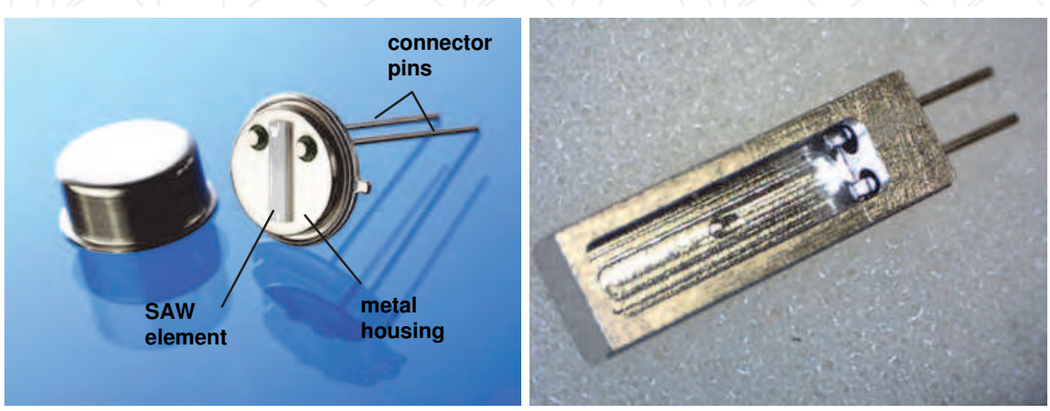


Fig. 6. Transponder housing TO39 (left) and custom KOVAR® housing (right).

reflector, increasing the antenna gain. This in turn doubles the operable readout range. An alternative package is shown in Figure 6 (right). This KOVAR® package is optimized for thermal conductivity to the sensing SAW element, thus increasing the temperature dynamics by a factor 5.

3. System performance

The robustness of SAW transponder technology was proven with various temperature tests. SAW transponders are not only stable at high temperatures; they even can be read out operationally. In case the transponder is read out at high temperature a reduced read-out distance has to be taken into account in the system design.

3.1 Durability

The durability of the packaged SAW devices has been tested by thermal aging (Fachberger, 2008). Several tags of each type of metallization were stored in an oven at temperatures of 300°C and 350°C. Measurements were made in an air-conditioned cabinet at 22°C. The devices were placed in a test jig equipped with lateral interfering spring pins and measured with a network analyzer (NWA). In some cases the contact pins were oxidized on the surface; these pins had to be cleaned with a blade to achieve a good electrical contact to the spring pins. For each measured device the weakest peak amplitude was recorded. The rejection criterion was defined to be a decrease of more than 3 dB in the peak amplitude (measured from the initial level). That is the failed devices were still operating but were significantly degraded.

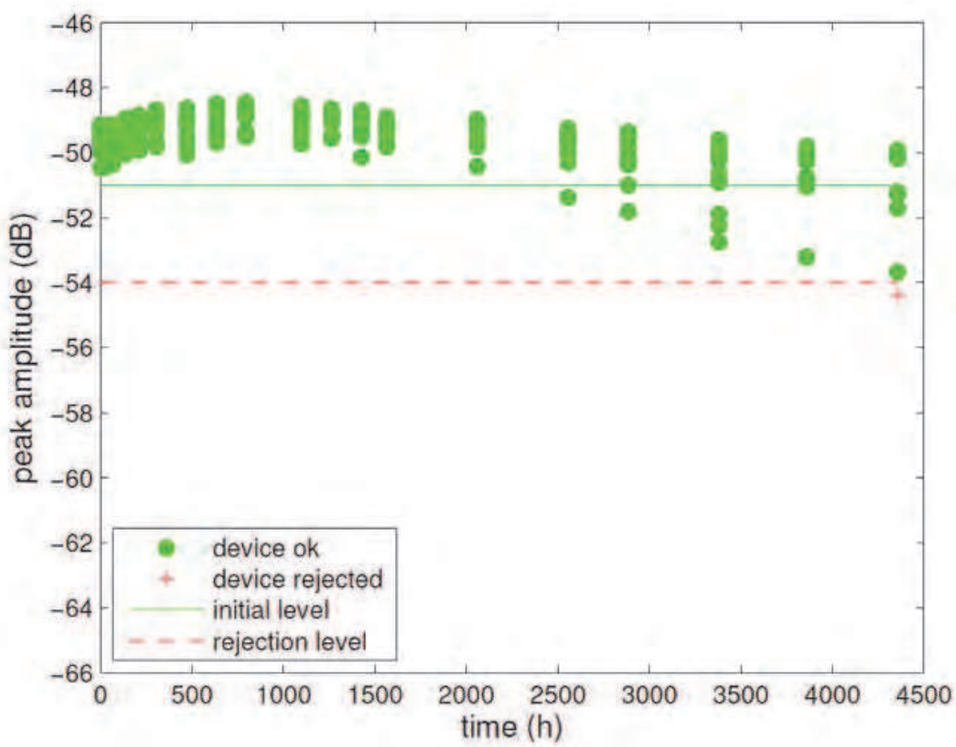


Fig. 7. Annealing at 300°C. Peak amplitudes over annealing time

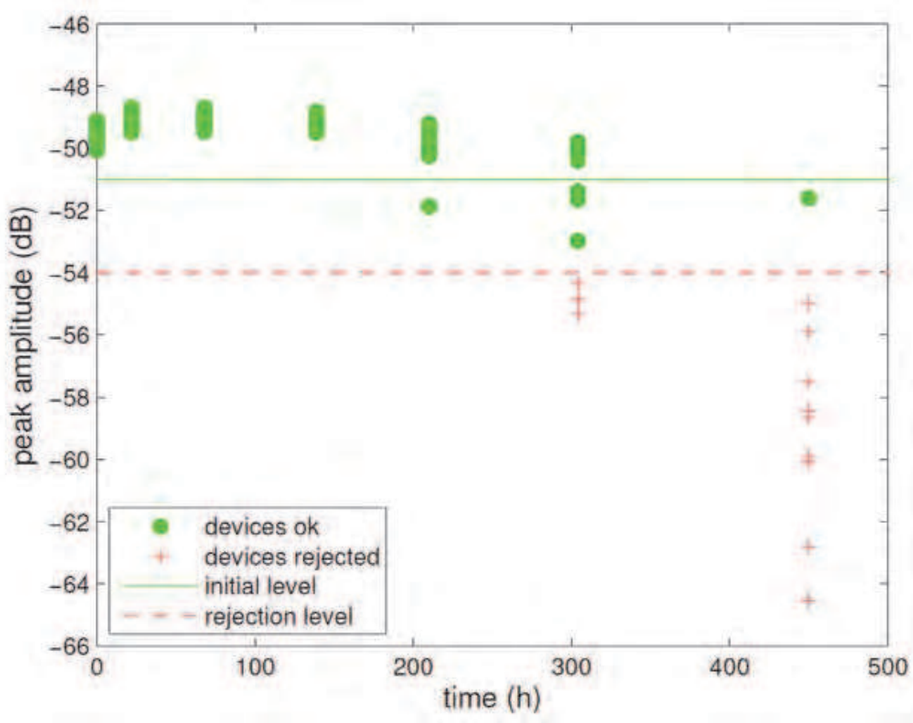


Fig. 8. Annealing at 350°C. Peak amplitudes over annealing time

First tests using a standard Al/Ti metallization showed very poor behavior at 300°C annealing. Some of the devices showed a run-in effect, where the peak amplitude dropped below the rejection limit in the first 20 h at 300°C and recovered after further heating. After aging for 450 h at 300°C all devices were rejected. Subsequently an Al/Ti sandwich metallization was developed.

The Al/Ti sandwich devices also showed a run-in effect for the first 1000 hours at 300°C during which the signal level actually increased. Figure 7 shows the amplitude over time at 300°C. The rejection criterion was exceeded after 4350 hours (more than 6 months) for one of ten devices. Aging at 350°C produces a similar behavior; run-in with increasing signal level is observed within the first 50 hours (Figure 8). After 300 hours three of ten devices dropped below the rejection limit. Interpolating the overall trend, we estimate a lifetime of 4000 hours at 300°C and 250 hours at 350°C. According to the Arrhenius equation, a lifetime of 15 hours can be estimated at a temperature load of 400°C (assuming that no further reactions are activated).

To check the effect of temperature changes, cycling tests were carried out. A batch of 15 packaged Al/Ti sandwich devices was placed in a preheated oven at 240°C. Every 15 minutes air cooling was turned on or off. Cycles between 30°C and 230°C were achieved in this way. The devices were measured according to the procedure described in the previous section.

Even after 5600 cycles none of the device exceeded the 3 dB rejection level (Figure 9). Some deviations in the peak amplitude are present, however, as no trend can be observed, these are presumably artifacts of the measurement (e.g. variations of the electrical contact resistance between spring pins and contact pins due to oxidation of the contacts' metal surface).

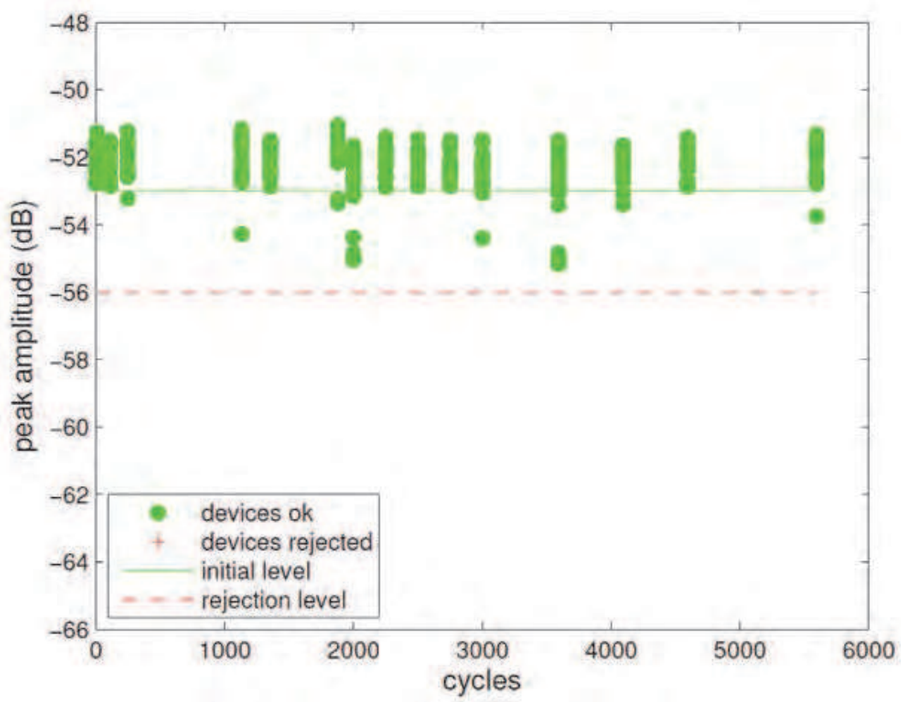


Fig. 9. Cycling between 30°C and 230°C. Peak amplitudes over cycles.

3.2 Read out range

The read out range can be a compulsory system specification especially in harsh environment where antennas cannot be placed arbitrarily. The achievable range of typical SAW transponders was measured in various benchmark configurations. Depending on antenna gain, output power and noise reduction via averaging the read range results in 5 m and above. All measurements were carried out with a FSCW (frequency stepped continuous wave) reader and a SAW transponder with a slot antenna at 25°C and a radiated power of 10mW EIRP. The antenna gain, the antenna configuration and the averaging settings were varied.

The results of the distance measurements are summarized in Figure 10. The readout distance is defined as the distance where the signal power sinks below 80 % of the reference signal, where 1x 9 dBi or 1x 18 dBi means that one reader antenna per channel with an antenna gain of 9 dBi or 18 dBi is used, 2x 9 dBi or 2x 18 dBi means double antenna per channel mode. In addition, some measurements have been performed using the averaging ability of the system. This facility increases the readout range but at the cost of readout speed. With a two antenna system using 18 dBi each and an averaging factor of 8 (8x av.), a maximum readout range of about 6.5 m has been achieved.

Figure 11 shows the readout range between RT and 300°C using a 9 dBi antenna in single channel mode, for a single shot measurement. The measured read out range at RT was taken as reference distance. At 300°C, the readout range decreases to 30 % of the original range at RT. Due to physical effects, the attenuation of the transponder signal increases with operating temperature. In the temperature range between RT and 300°C, the loss is almost linearly 0.05 dB/µs °C. Roughly half of this value, 0.02 dB/µs°C [13], can be ascribed to the change of the acoustic propagation attenuation of the crystals with

temperature. The other half of the attenuation can be referred to the temperature dependent frequency shift of the transducers and the transfer function of the transponder antenna relative to the fixed ISM band.

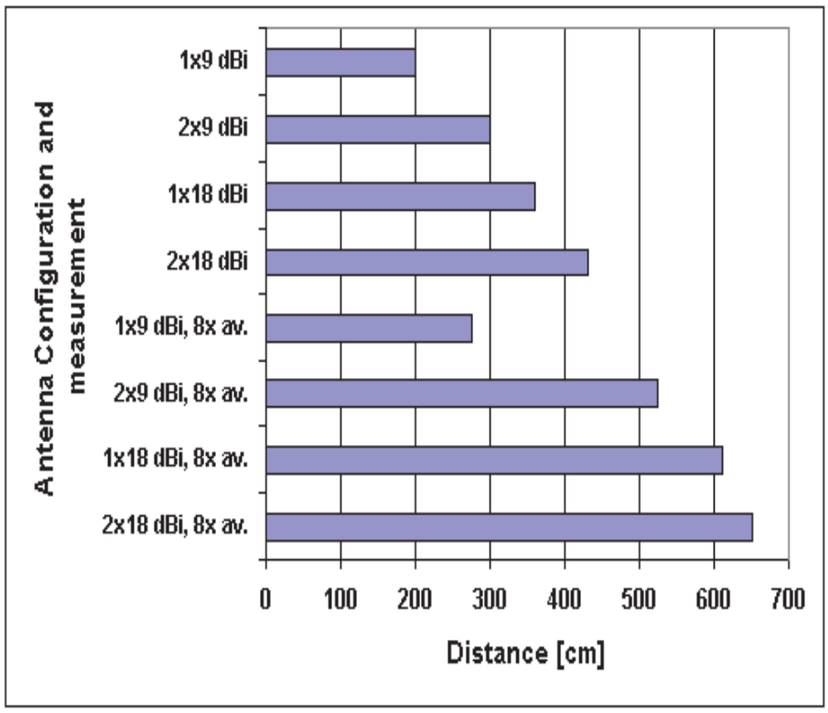


Fig. 10. Read range for various antenna configurations and averaging factors.

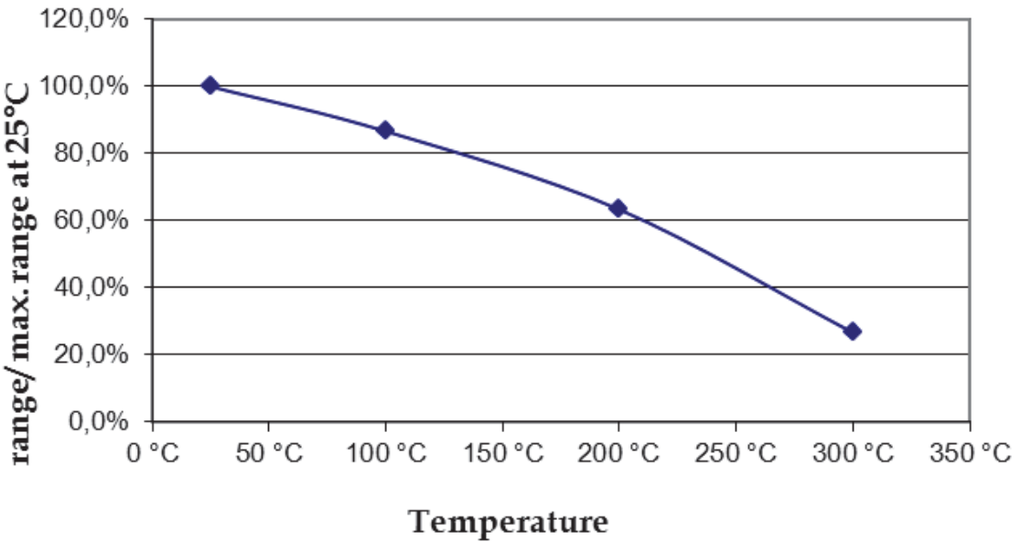


Fig. 11. Read range depending on transponder temperature.

The described tags work also as temperature sensors. It is possible to measure temperature with at least 0.6°C of accuracy, depending on calibration sets and evaluation algorithm. This theme is discussed in detail in (Fachberger, 2006) and is omitted here because this chapter focuses on the RFID-applications of the tags.

3.3 Exposition to gamma radiation

To examine the robustness of the tags further, the devices where exposed to strong gamma ray doses to investigate their behavior in sterilization chambers e.g. those for food or medicine sterilization. The dose started with 6 kGy (Gray, 1 Gray = 1 Joule per kg mass of absorbed radiation) and was increased up to 100 kGy so that every tested tag had to withstand a summarized radiation of more than 500 kGy. Table 3 lists some ranges for specified radiation doses. During that test, no degradation was observed. The tags can be used in environments with high doses of gamma radiation, e.g. food or medical sterilization chambers.

Radiation dose	Application / Effect
0.1 mGy	Flight in stratosphere
1.2 – 2 mGy	Natural Radioactivity
4.5 – 5 Gy	Human lethal dose
40 – 70 Gy	Tumor treatment
Up to 10 kGy	Sterilization of food
Up to 50 kGy	Sterilization of medicals and surgery instruments

Table 1. Table of radiation dose and specific applications

4. Application examples

In practice the application SAW transponders comes in discussion literally when alternative technologies fail, i.e. do not survive the process conditions. SAW transponders do not offer memory and work with proprietary reader systems and above all they are in the price range of active tags. Still the cost-benefit analysis works out for certain processes. The key factors are: cost of tagged investments, cost of lost tracks or lost assignment of assets, follow-up costs of safety hazards and cost savings through process optimization using RFID.

4.1 Automotive paint shop

Modern automotive paint lines are fully automated. However, the automatic assignment of the car body to the process parameters (shape, paint color) is rather difficult as heating cycles with maximum temperatures of up to 250°C are involved. Conventional RFID-tags, and even conventional SAW-tags cannot stand these conditions for long term. Through the optimization of the SAW-metallization and a customized metal antenna it was possible to reach the required lifetime of the tag. In combination with a solder free packaging and

assembly technique a very robust and stable SAW-transponder was achieved. The cycling test showed, that after 3000 cycles from room temperature to 220°C and back, with a hold time of 30 min for each temperature level, the drop out quote was well below 10%. The drop out was defined as a degradation of the signal amplitude of 3 dB compared to the initial amplitude values, the same definition used for the durability tests described in chapter 3.1. In this case a different SAW metallization based on Al and Cu was used. In this way a higher readout range could be achieved, however the temperature stability of these tags is slightly lower than of those presented in chapter 3.1.

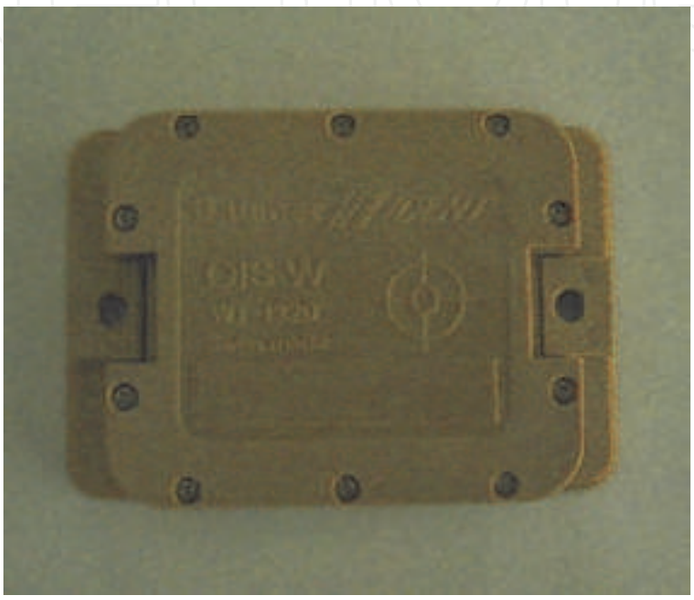


Fig. 12. SAW transponder used in automotive paint shops (Source: Baumer Ident).

4.2 Identification of slag vessels

SAW transponders are increasingly investigated by steel producing companies. Due to the high temperatures of handling assets like steel and slag vessels the advantage of SAW transponders comes in place. The cost ration of tagged item per tag remains small and the revenues through a well-documented track process are high. The example shows the tagging of slag vessels from tapping to the heap.

Recycling processes of slag coming from the converter and stored in special slag ladles strongly depends on the slag composition. A correlation of the casting process and the slag ladle is recommended for high quality post-processing of the slag. For an automatic transport logistics a SAW transponder for identification was placed directly on the ladle. The transponder had to withstand temperatures of up to 350°C and heavy mechanical shocks during emptying of the ladle. An exemplary system configuration is shown in Figure 13a. In spite of the metallic surrounding and coexisting WLAN, a readout distance of 4 m had been achieved. The tags were mounted inside the transport ears to have more protection against slag splashes and collisions with the transport hook (Figure 13b). Figure 13c and 13d show the rough environment around the slag tapping and the emptying of ladles on the heap. Slag vessels have also been tagged while being transported on the crane as shown in figure 14.

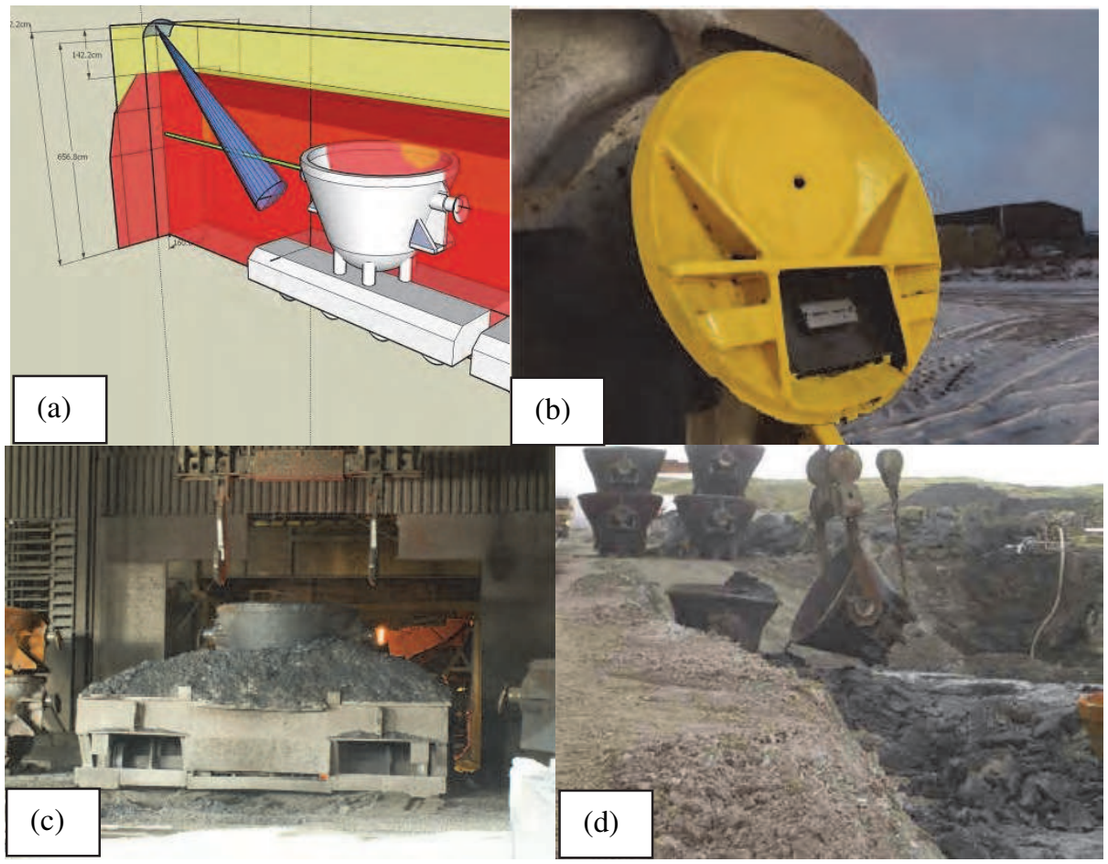


Fig. 13. (a) System setup for interrogation, (b) mounting of the tag, (c) area of slag tapping, (d) slag vessel emptying on the heap



Fig. 14. Slag vessel on the transport crane.

4.3 Identification of slide gate plates

Another example from the steel industry shows the application of SAW transponders for tagging of slide gate plates and monitoring their temperature behavior during the cast. A RFID sensor system to track slide gate plates and furthermore to continuously monitor the temperature during steel casting was developed. The sensor system should help to optimize the casting process and as a consequence reduce costs by improving slide gate plate logistics, maximizing individual plate usage, and minimize unscheduled casting interruptions.

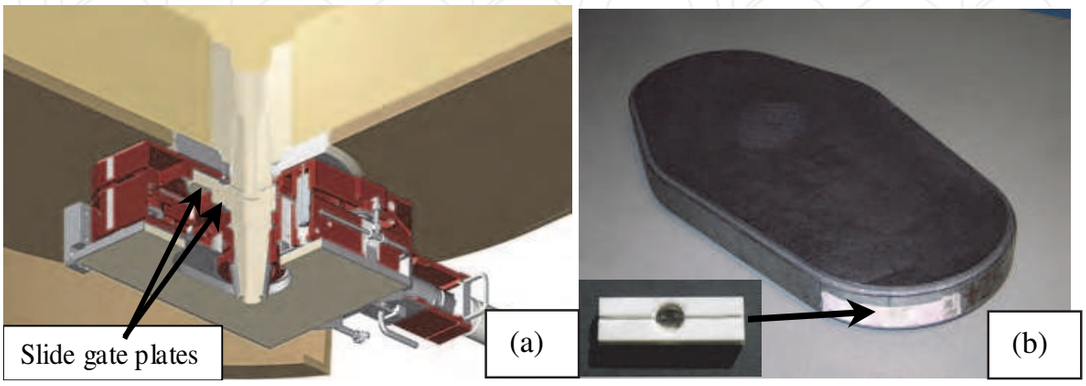


Fig. 15. (a) Slide gate mechanics, (b) implementation of a SAW transponder in the plate

Slide gates, as shown in Figure 15a, are large valves, which are used to regulate the flow of liquid steel (Fachberger, 2010). The flow is controlled via the overlap of two holes, one in each of the two refractory plates. During casting these ceramic plates are exposed to high temperatures of more than 1500°C, high mechanical loads of several tons of liquid steel, and chemical attack by e.g. alloys. Depending on the steel grade, the throttling, and the casting time the plates have to be replaced before a critical degree of wear is reached. SAW transponders are mounted on the outer radius to limit the heat exposure (Figure 15b).

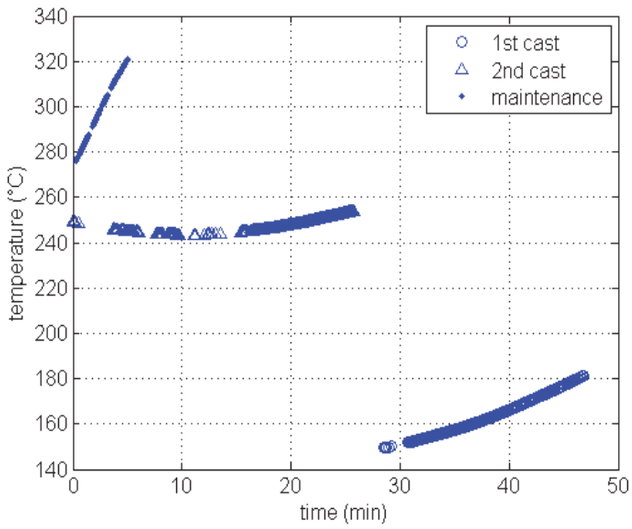


Fig. 16. Temperature monitoring of slide gate plates during casts and maintenance; the usage of plates (casting time, replacement frequency) is monitored throughout the casts via antennae inside the slide gate mechanics and further data transfer to the control stand.

4.4 Identification of automotive pressure sensors

Identifying individual sensors is often desired, in particular when sensors are frequently replaced or recalibrated, as e.g. in test blocks for combustion engines. Here a commercially available pressure sensor from AVL, which is typically mounted close to the combustion chamber of an engine, has to be identified, and therefore, was equipped with an identification tag (Figure 17). The aim of the identification (ID) is to automatically assign correct calibration data. With an ID-tag placed inside the pressure sensor housing instead of a standard RFID tag being attached to the end of the sensor cable, as in existing solutions, cables can be disconnected to reduce set-up time without the need of carefully reconnecting sensors to assigned connectors. This reduces set-up time as well as prevents from incorrect measurements caused by wiring errors and the use of incorrect calibration data (Bruckner, 2003).

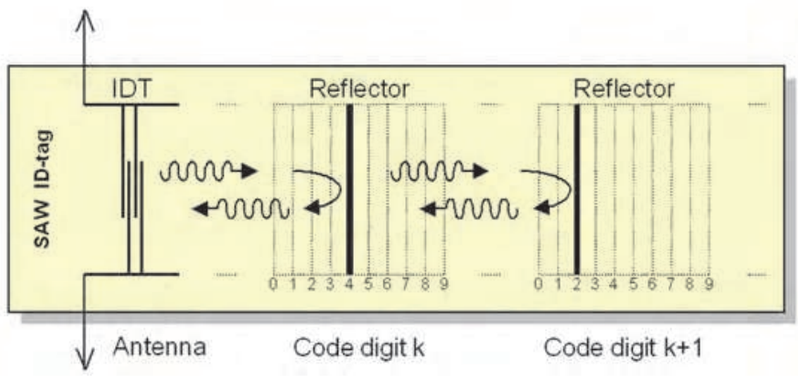


Fig. 17. Principle of the RFID coding using pulse position coding with a decimal basis.

The concept of the presented identification system and the integration in existing sensor systems is sketched in Figure 18 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

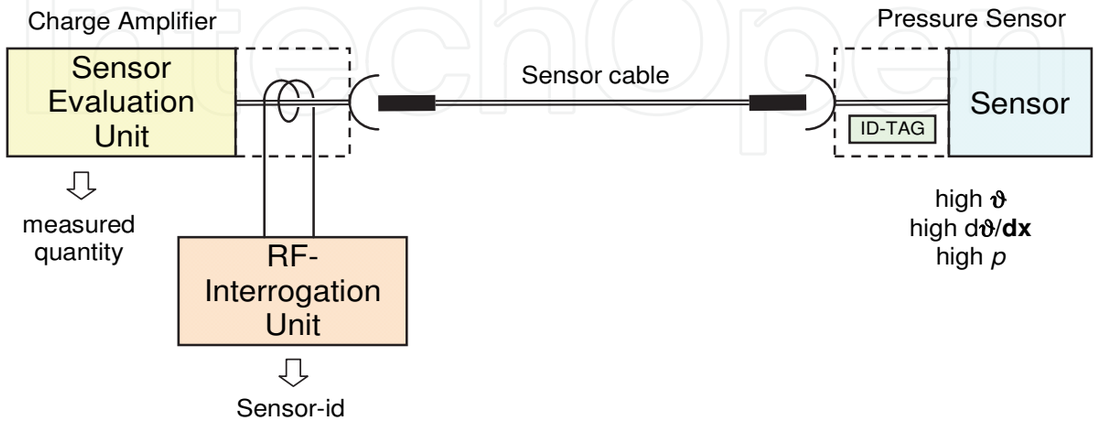


Fig. 18. Principle of the SAW transponder integration and readout in the sensor.

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 structure directly on chip 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 sensor age from the database.
The stability of the assembly shown in figure 19 was tested up to 3500 g. 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 were performed. At least up to 400°C no trace for the impact of pyroelectricity on the metallization was observed.

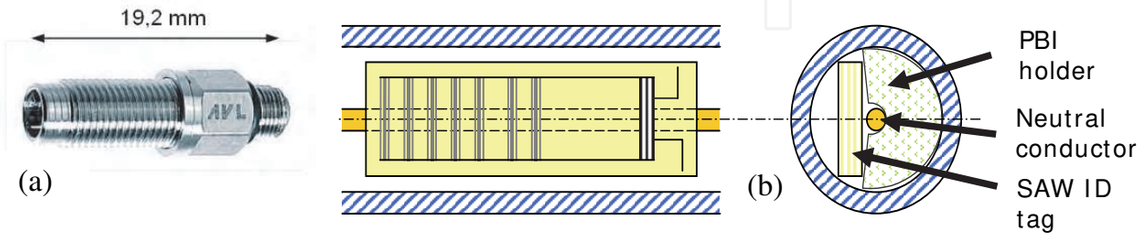


Fig. 19. A standard pressure sensor of AVL Type GM12D (M5*0,5) (a) and schematic arrangement of the SAW ID-tag mounted inside of the sealed pressure sensor (b).

5. Conclusion

In this chapter the operation principle of SAW transponders was discussed for RFID applications. The SAW transponder systems are to be considered for harsh environment processes. This has been demonstrated for various applications in steel and automotive industries.
Future work in research and development deals with the increase of temperature stability of transponders. This includes the stabilization of metallization films, substrate and packaging technology. A unique RFID code on sensors has its advantage for automatic calibration of individual sensors. Thus SAW based pressure and strain sensors are under development for wireless high temperature applications.

6. Acknowledgment

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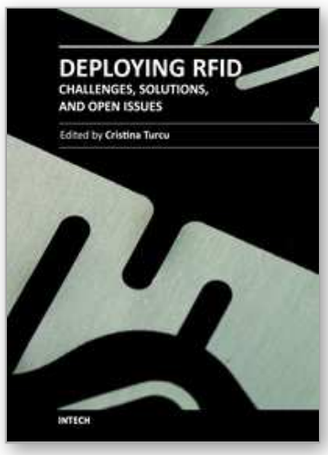
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Radio frequency identification (RFID) is a technology that is rapidly gaining popularity due to its several benefits in a wide area of applications like inventory tracking, supply chain management, automated manufacturing, healthcare, etc. The benefits of implementing RFID technologies can be seen in terms of efficiency (increased speed in production, reduced shrinkage, lower error rates, improved asset tracking etc.) or effectiveness (services that companies provide to the customers). Leading to considerable operational and strategic benefits, RFID technology continues to bring new levels of intelligence and information, strengthening the experience of all participants in this research domain, and serving as a valuable authentication technology. We hope this book will be useful for engineers, researchers and industry personnel, and provide them with some new ideas to address current and future issues they might be facing.

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