Wireless and Passive Sensors for High Temperature Measurements

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***Abstract*—Surface acoustic waves have been studied for more than 50 years and are mainly used as passive components (resonators, frequency filters, sensors, etc.) for signal processing, and more specifically. As demonstrated by Bao et al, surface acoustic wave devices can operate without onboard power supply using a dedicated interrogation unit. Using appropriate design considerations, these devices are sensitive to external conditions including temperature, pressure, strain or chemical/biological mass loading. Therefore, the unique characteristics of such devices allows for an effective implementation providing new opportunities for remote control of physical and chemical parameters.**

***Keywords*-Surface acoustic wave; high temperature; sensor; langasite; quartz; aging; radiofrequency; reader; passive.**

I. Introduction

The work presented in this paper has been achieved within the SAWHOT European project frame [1], devoted to the development of sensor and interrogation system for an unprecedented temperature range (from cryogenic conditions to temperature in excess of 650^{o}C). In the following, the development of temperature sensors operating from room to high temperature is described, the application concerning high temperature furnace monitoring, turbine operation control. Two different types of substrate have been used for the fabrication of SAW (Surface Acoustic Wave) sensors to assess first the possibility for accurate measurements using a differential structure, second to reach temperatures in excess of 700^{o}C using a single resonator sensor to demonstrate the capability of these devices to withstand such operation conditions. Quartz [2] and Langasite-based [3] solutions have been respectively implemented in that purpose [4].

The first part of the paper briefly recalls the principle of wireless SAW sensors. Design rules are subsequently reported considering the specific problem of temperature robustness. Particularly, the specific problem of packaging and antenna assembly is discussed. The final sections are devoted to effective temperature measurements in the above-mentioned ranges. As a conclusion, the capability of LGS-based sensors to reach temperature in excess of 700^{o}C is discussed.

II. Wireless SAW sensor interrogation principle

SAW sensors are based either on delay lines on Lithium Niobate operating in the Industrial-Scientific-Medical (ISM) 2.45 GHz band or on resonators working at lower frequencies, i.e. ISM bands centered in 434, 868 or 915 MHz. For the later case, the basic principle of the interrogation strategy is a combination of a frequency-sweep network analyzer used to identify the resonance frequencies of the device, and a monostatic pulse-mode RADAR strategy [5] for improving the isolation between emission and reception stages. The whole interrogation system is usually called reader as it actually reads the resonance frequencies. A radio-frequency pulse gates a carrier at variable frequencies within the ISM band. If the emitted pulse spectrum overlaps the bandpass of one resonator, the acoustic device stores the energy. Once the antenna of the interrogation unit switched from the emission to the reception stages of the reader, the resonator restores the loaded energy at its own resonance frequency, shifting with the variation of the physical parameter measured by the resonator [6]. This pulse is received by the interrogation unit using a wideband power detector. The returned power vs frequency curves allows for the identification of the resonance frequency [7].

III. SAW sensor design for high temperature measurements

An important knowledge has been developed for 20 years based on work devoted to the simulation and computation of surface acoustic wave devices (SAW), [8]. The two mainly exploited methods are FEM (Finite Element Method) [9] and BEM (Boundary Element method) [10], both combined to accurately represent effective SAW boundary conditions. FEM is used to account for the inhomogeneous part of the transducer whereas of BEM is used to represent the contribution of the substrate. This later function is achieved

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using Green's function of any layered substrates (Fig. 1) assuming flat interface between each layer of the stack. These computations are used to derive mixed-matrix or Coupling-Of-Mode (COM) parameters necessary to simulate the electrical response of actual devices.

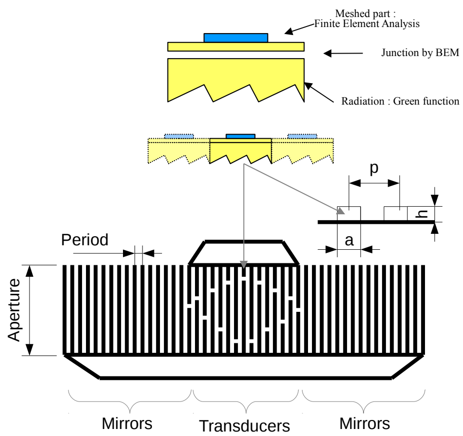

Figure 1. FEM/BEM synoptic.

Two high temperature ranges are targeted, below and over 500^{o}C. For "low temperature", sensors based on Quartz are used with aluminum-copper electrodes allowing for high quality factor resonances ($\geq$ 10000) [11]. Regarding the Curie temperature of Quartz, this material can not be used at temperature higher than 573^{o}C (limited to 540^{o}C in practice); therefore Langasite (lanthanum gallium silicate) substrate [12] has been chosen for temperature measurement over 500^{o}C [13], [14].

Quartz sensors used for first tests are TSEAS10 (5x5 mm^2, Fig. 2) from SENSeOR (Mougins, France), this device uses two resonators for differential measurements reducing the influence of correlated noise and aging effect on the response. SAW devices based on Quartz with Al-Cu electrodes provide high Q factor as required for wireless interrogation considering the capability of the sensor to store energy from the RF wave, and to restore it at its own frequency depending of environmental physical parameters [15].

Fig. 2 shows a quasi-perfect match between the simulation and the experiment for this type of sensor (association of quartz substrate with aluminum for interdigital transducers, IDT).

IV. Packaging of SAW devices for high temperature

Packaging is one key-point of the project. The device must be mounted on a carrier to avoid applying any stress on the device. Therefore, package and substrate materials require coefficients of thermal expansion as close one another as possible. The whole package is composed of a standard SMD ceramic case with tungsten/molybdenum pads (Kyocera 7.1*9.1 mm^2 A440), connected to device by gold wire-bonding (Fig. 3).

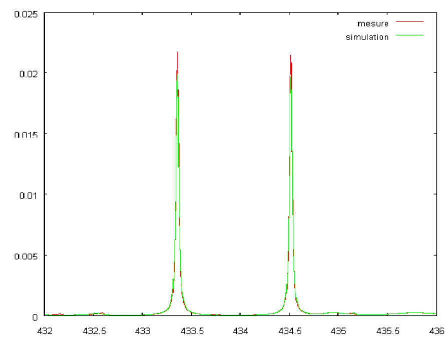

Figure 2. Comparison between computation and measurement of the TSEAS10 double resonators sensor.

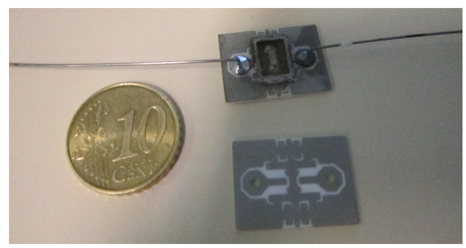

Figure 3. The different stages of the packaging process.

At the moment, devices are sealed using another upside-down package as lid. The case is connected to an alumina plate with patterned connection, this footprint is realized in AgPb alloy to avoid the migration of the solder, stainless steel antennas and case are connected to the pattern thanks to tin solder.

An additional conditioning is required to preserve the device integrity when exposed to high temperature. The corresponding process is currently under patent application process and will be described when presented at the conference.

V. Temperature measurements with SAW sensors based on quartz

The first experiment helps us to understand what happens to Quartz-based sensor between 25 ^{o}C and 250 ^{o}C.

The interrogator includes adapted SAW filters yielding operating in the 434MHz-centered ISM frequency band (434 MHz$\pm$0.85MHz). The algorithm used by the reader is based on the separation of the above 1.7MHz band in two equilibrated frequency sub-bands. Each resonance of the differential sensor is located in one of the band for the whole temperature excursion. The problem in our case is that the sensor is used out of its specifications (room temperature to 250^{o}C instead of -15^{o}C to 165^{o}C); therefore

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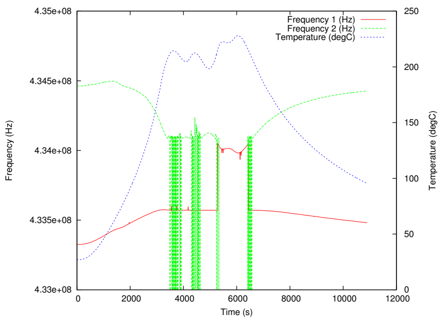

Figure 4. Behavior of resonator at intermediate temperatures, exhibiting the crossing of the higher frequency resonance (starting as the green curve) into the low-frequency band between dates 500 and 600, for temperatures above 180^{o}C.

the resonance frequencies are overlapping over 180^{o}C. With this algorithm, the first band begins at 433.05MHz and finishes at 433.89MHz, while the second band starts at 433.89MHz and stops at 434.83MHz. Each band is used to measure only one frequency. if two resonance frequencies arise in the same band, the measured signal is the one with the largest amplitude. On Fig. 4, the first frequency (green curve) is leaving the upper band to penetrates the second one (>434 MHz), the power received by the reader corresponding to this resonance is larger than for the other one (red curve).

The second experiment aims at using Quartz sensor at temperature up to 450^{o}C without frequency band program of the reader (the contrary of the last experiment), providing the flexibility needed to measure SAW sensors out of their specifications.

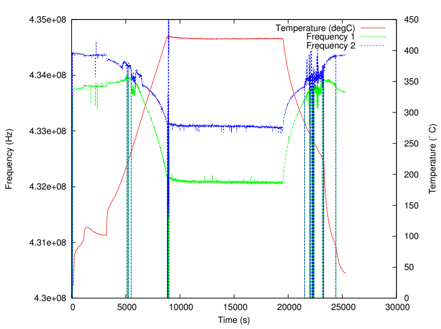

Figure 5. Behavior of resonator at intermediate temperature (around 450^{o}C).

The sensor is based on differential measurements, but the two corresponding resonators do not exhibit the same behavior versus temperature. The 434 MHz frequency (blue between 0 and 5000s) is the reference mode exhibiting less frequency variation than the sensor mode (433 MHz) corresponding to the sensor mode. The turnover of the reference mode is situated in the temperature range from room temperature to 200^{o}C, then, the frequency is dramaticaly decreasing as shown from 5000s to 10000s. The turnover of the other mode is situated at higher temperature, therefore the frequency shift of this mode versus temperature is less important than for the reference mode. The higher frequency is crossing the other resonance between 5000s and 7500s, then both frequencies have changed their places in the frequency band when the oven stoped to heat up at 22500s. With this later algorithm, the reader is able to measure frequencies, which are separated from at least 200 kHz (depending of the averages number performed and the frequency band measured,considering 150 steps in a 4 MHz wideband, each “valid” measure separated by 7 steps). More experiments have been led on Quartz-based sensors to evaluate if a solution with this substrate can be an alternative to high temperature substrate at intermediate temperatures (room temperature to 500^{o}C). As shown on Fig. 6, this resonator suffered 50h at 450^{o}C without visible damages.

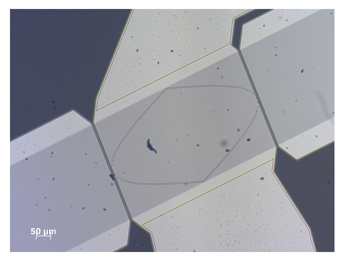

Figure 6. Picture of the IDT of TSEAS10 sensor used during 50 hours at 450^{o}C while measured by wireless interrogator. IDT are polluted after the opening of the ceramic package using milling tools.

VI. AGING AND TEMPERATURE MEASUREMENTS WITH SAW SENSORS BASED ON LANGASITE

The first steps of the experiments are focusing on the evaluation of the efficiency of the wireless sensor at intermediate (Fig. 8), and then at high temperature (Fig. 13). Moreover, the frequency measurements of the devices will help understanding and evaluating the frequency variations of the resonators. The necessity of a “preaging” process for Langasite sensors then will be emphasized.

For the first experiment, the resonator was placed in a ceramic oven (able to warm up up to 1200^{o}C, Fig7).

The resonator has been submitted at a temperature of 500^{o}C during 50h. Meanwhile, its resonance frequency has been wirelessly monitored with a refreashing rate of about one measurement per second.

As expected, the temperature cycle applied to the resonator did operate as an aging process and the frequency of the resonator has evolved. As shown on Fig. 8, a difference of 300 kHz is observed at room temperature before and after the 50h-500^{o}C cycle (at dates 50000s and 320000s). The frequency is shifting along time (during the 500^{o}C heating process), showing a difference of 50 kHz between the dates

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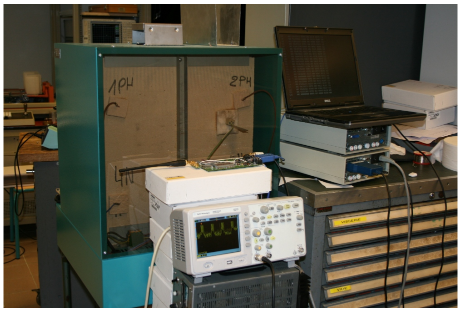

Figure 7. High temperature bench : ceramic oven with non-metallic back for RF wireless measurement associated with oscilloscope for debugging signal issue from reader unit, another temperature probe is used to measure temperature as close as possible of the device.

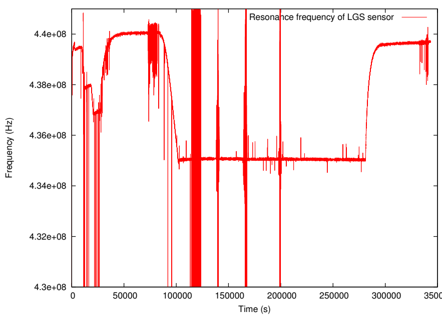

Figure 8. Wireless measurement of the sensor at 500^{o}C during 50h. Between 0s and 50000s, the sensor is packaged (Fig3) and placed in the oven for a first preliminary cycle (100^{o}C for 2h, 270^{o}C for 2h and 360^{o}C for 2h). Between 80000s and 280000s, the sensor withstands a temperature of 500^{o}C.

100000s and 280000s. The observed variance at short term of the measured frequency is 10 kHz.

The resonator then is used at 700^{o}C to push ahead the experiment (Fig. 9) and to continue to estimate the observed shift of the frequency.

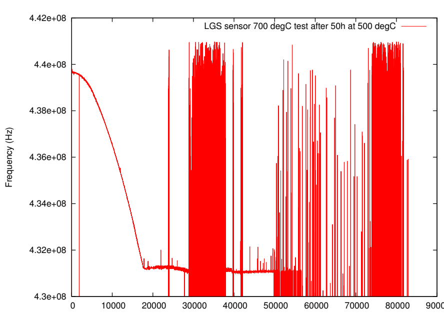

Figure 9. Wireless measurement of the sensor at 700^{o}C. Between 0s and 18000s, the oven is warming up. The sensor is then operating at 700^{o}C during 36000s (from 18000s to 54000s), then the sensor does not operate anymore.

After 10h of measurements, the interrogator does not measure any response. In order to determine the origin of the failure, the package has been opened and it was identified a break of the wire-bonding induced by the deformation of the metallization used for the connection pad of the case. Concerning data acquired during these 10h of operation, the signal is too noisy to determine the frequency shift. As a conclusion, this resonator was able to operate during 50h at 500^{o}C and then 10h more at 700^{o}C. The noise measured during both experiments (Fig. 8 and Fig. 9) is related to the laboratory activities. Note that the resonator was still operating when probed with tips.

In parallel, another resonator was used for stabilizing a temperature controlled oscillator based on a Collpits-like structure. The device was placed in the oscillation loop once dicing process performed without any preaging. This resonator (Fig. 10) showed a Q factor of 5000 with a coupling factor of 0.04%. The temperature of the system was locked at 50^{o}C. This test was performed to estimate aging effects of LGS resonators used at room temperature to corroborate the need for pre-aging process application in general.

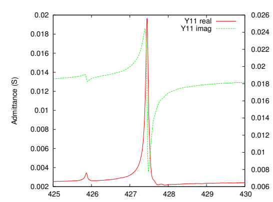

Figure 10. Reponse of the resonator used in the oscillator loop.

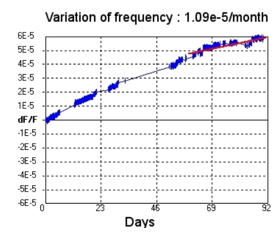

Figure 11. Variation of frequency of the oscillator over time (1.09^{-5} for LGS versus 1^{-7})

Regarding the frequency variation curve (Fig. 11) and the frequency variation at intermediate temperature (Fig. 8), the langasite based devices would need the development of a “preaging” process to reduce as much as possible the frequency shift of the sensor in harsh environments.

For the second experiment, a different resonator is used for life time tests, regarding the low (10-20 cm) range induced by its “low” coupling coefficient (0.19%, low compared to the other devices issued of the same wafer) and its low Q factor (<500), it is not possible to use this sensor for wireless measurement. The resonator is placed in the oven with another case up and down as hood, this package will protect the resonator against a direct contact with high temperature environment (as it will be in packaged device for wireless measurements).

The sensor is measured using tip-prober between each successive cycle to evaluate the impact of the temperature on the response of the device. The temperature cycle used in this experiment is composed of a 5h warming from room temperature to 700^{o}C, and then keeping the temperature constant during 10h.

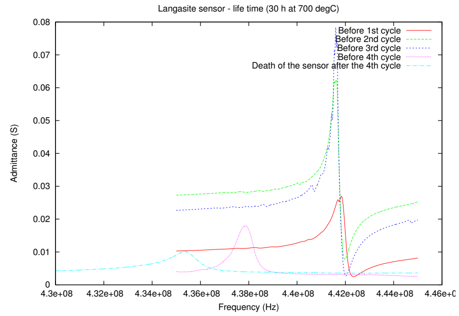

Figure 12. Life time test: temperature cycles are performed from room temperature to 700^{o}C during 10h, showing a life time of 30 hours.

As shown on Fig. 12, the dynamics of the resonator admittance is changing along cycles . The coupling coefficient of the device remains constant despite successive cycle application. However, after 4 cycles, no more response is measured.

The third experiment aims at using langasite sensors in high temperature environment (>500 ^{o}C). The goal of this experiment is to observe the evolution of the resonance frequency at 700^{o}C (Fig13) and to evaluate the effect of operating in harsh environment on the response of the device.

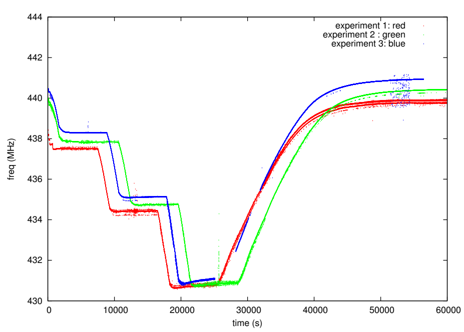

Figure 13. Behavior of a langasite sensor. The experiment cycle is divided in 3 steps, 300 ^{o}C, 500 ^{o}C and 700 ^{o}C for 2h at each temperature.

Considering the used resonator, the frequency band of the reader had to be adapted and a wide band interrogator was used (440 MHz $\pm$ 10 MHz instead of classical configuration 434 MHz $\pm$ 0.85 MHz). As expected, the frequency band needed to measure the behavior of the Langasite sensor was around 10 MHz (441 MHz at room temperature versus 430.5 MHz at 700^{o}C).The frequency of the resonator decreases by 300 kHz after each step at 700^{o}C, as shown in Fig. 13, the frequency is only shifting at "low" temperature (room, 300^{o}C, 500^{o}C), the evolution of the frequency at 700^{o}C after each process is less significant (50 kHz). After this last experiment, the sensor was not able to operate anymore. The package has been opened to analyzed what happened to the device (Fig. 14 and Fig. 15). It appears that the fail is coming from the destruction of the IDT induced by a too long exposure at high temperature [16], [17], [18].

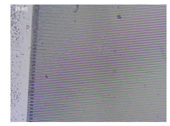

Figure 14. State of langasite resonator : picture of the IDT.

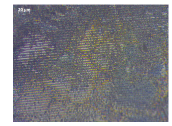

Figure 15. State of langasite resonator : picture of the mirrors.

VII. Conclusion and future work

In the frame of the SAWHOT project, SAW devices for wireless passive high temperature measurements have been developed. Two main operating range have been identified, from room temperature to 500^{o}C and beyond 500^{o}C. For both ranges of temperature, sensors have been developed, starting from basic design opertaion (using FEM/BEM and mixed-matrix-based tools) to characterization in oven using wireless measurements. Simulated results did match with devices behavior when measured via tip-probing. Quartz-based sensors were found suitable for intermadiate temperature measurements (<500^{o}C). This type of sensor shows that this range of temperature can be measured using Al-Cu electrode on SAW Quartz resonators, withy numerous degree-of-freedom for optimizing specifications such as sensitivity, frequency range and the number of resonators (differential measurements or not). The algorithm for resonance frequency tracking prevents the overlapping of both measured resonators. For high temperature (>500^{o}C), Langasite-based sensors were found to operate up to 700^{o}C. The firsts experiments have been done using a wideband reader, according to the frequency/temperature range. The results show that the sensors can be actually measured at 700^{o}C using SENSeOR's interrogator with a 30 cm range interrogation distance (across the oven back). The resonance frequency of the sensor is evolving at high temperature, showing a decrease of 300 kHz of the frequency after each cycle at room temperature, 300^{o}C, 500^{o}C. At 700^{o}C, the shift of frequency is reduced and is around 50 kHz. Moreover, the langasite device has been able to operate at this temperature for 30h, during this period, the dynamic admittance is increasing, while the coupling coefficient remains constant.

Further works are currently performed, focusing on the upgrading of the sensor parameters (Q factor, coupling coefficient), the life time of sensor at high temperature and the aging process for the devices.

Acknowledgment

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