Novel narrowband acoustic sensors for sub-GHz wireless measurements

D. Rabus, T. Baron, É. Lebrasseur, S. Alzuaga, G. Martin, S. Ballandras
FEMTO-ST Time & frequency department, UMR 6174 CNRS
32, avenue de l'Observatoire, 25044 Besançon, France
Email: {david.rabus,ballandr}@femto-st.fr

J.-M. Friedt
SENSeOR SAS
18 rue A. Savary, Besançon, France
Email: jmfriedt@femto-st.fr

***Abstract*— High-overtone Bulk Acoustic Resonator is an acoustic transducer based on an excitation of a bulk acoustic wave by a thin piezoelectric film bonded to a thick low acoustic loss substrate. This combination of materials aims at providing on the one hand a high frequency transducer as defined by the thickness of the thin piezoelectric layer, and on the other hand the robustness of a thick substrate while keeping the acoustic properties of single crystal piezoelectric materials. More specifically, this architecture provides high quality factors using bulk acoustic wave at frequencies only accessible to surface acoustic wave (SAW) devices with interdigitated transducer generation. The multimode spectrum is well suited for an openloop, wireless interrogation strategy in which the frequency of the incoming electromagnetic wave defines the operating point. We here demonstrate the use of a frequency sweep RADAR-like network analyzer for probing through a wireless link HBARs with different temperature coefficients in order to perform temperature measurements insensitive to other correlated noise sources (capacitive frequency pulling, electrode aging, stress).**

I. Introduction

Acoustic transducers have been known to suit well the purpose of acting as passive sensors interrogated through a wireless link. While historically bulk acoustic-wave resonators have been restricted to about 50 MHz fundamental mode – limited by mechanical robustness as the membrane is thinned to increase the resonance frequency until the current state of the art thin-Film Bulk Acoustic Resonator (FBAR) devices are manufactured – Surface Acoustic Wave (SAW) devices have been the standard mean of reaching frequencies above the 100 MHz range. Increasing the frequency at which passive acoustic sensors work is targetted for several reasons, including higher efficiency of the antenna associated with the transducer (from 70 cm wavelength for the unlicensed European 434 MHz Industrial, Scientific and Medical (ISM) band to 12 cm for the 2450 MHz international ISM band), smaller transducer dimensions and wider relative allocated bandwidth when complying with radiofrequency emission regulations. Narrowband (resonator) and wideband (delay line) SAW transducers [1] have been extensively used as temperature [2], stress [3], [4], pressure [5] and chemical sensors [6] interrogated using electronic systems similar to RADARs [7]–[16].

In the following discussion, we focus on a novel bulk-acoustic wave sensor configuration in which a thin piezoelectric layer (for high frequency working conditions) is bonded to a thick low-acoustic loss substrate providing the ruggedness needed for practical applications [17]. We will demonstrate how these devices provide, with respect to SAW transducers, improved resonator quality factor, improved coupling, both factors contributing to an increased interrogation distance when probed through a wireless radiofrequency link. The practical demonstration we will focus on is the demonstration of a differential temperature sensor using two HBAR transducers, one exhibiting a large temperature coefficient of frequency (TCF) and the other one a turnover within the measurement range. Beyond the demonstration of narrowband interrogation strategies of a single mode in one of the allocated ISM bands, a wideband pulse generation RADAR is used to probe multiple adjacent modes in a delay line-reminiscent strategy.

II. HBAR design and improved quality factor advantage

HBAR manufacturing either uses a classical cleanroom process of thin film depositions on a thick, low acoustic loss substrate, or a novel approach we promote here with [18] the assembly of two single-crystal piezoelectric substrates through a room-temperature, high pressure Au/Au bonding. The advantage of using single-crystal substrates is the wide degrees of freedom in selecting the appropriate cut and relative orientations for the assembled setup to provide the required characteristics, either in terms of coupling or temperature sensitivity [19] (large frequency drift with temperature for a sensor, negligible frequency dependence with temperature in the case of a reference transducer, generation of a shear wave rather than longitudinal wave). Since a sensor is subject to a wide range of environmental parameters, preliminary design of the behavior of the transducer for various temperatures and stress conditions is of utmost importance for a successful design: the required material constants are only available for commonly used single-crystal materials such as quartz, lithium niobate (LNO) and lithium tantalate.

The manufacturing process has been detailed previously [20], and basically requires a first preliminary bonding of the two substrates by depositing under cleanroom conditions a thin gold layer on both substrates and applying the necessary pressure for the two substrates to hold together. This gold layer will also later act as a buried electrode. Having performed this preliminary bonding step, a stronger bond is obtained under high pressure and room temperature, before a lapping and polishing process reduces the thickness of the piezoelectric layer to the required sub-20 μm thickness. Finally, a last cleanroom step is required to pattern and deposit the top electrode for polarizing the piezoelectric layer. The final device typically exhibits (for a 350 μm-thick substrate and a 15 μm-active piezoelectric layer) modes separated by a few megahertz – the thinner the propagation substrate the wider apart the modes – whose coupling is modulated by an envelope defined by the thin piezoelectric substrate thickness. For a 15 μm thick quartz layer, the typical envelope will provide maximum coupling efficiency in the 130 MHz range (fundamental frequency of the thin layer) and a third overtone in the 400 MHz, close to the unlicensed European Industrial, Scientific and Medical (ISM) band we target for a wireless interrogation.

III. Narrowband interrogation strategy

Our wireless interrogation strategy is based on the principles of a frequency-sweep network analyzer, with a microcontroller-programmed direct digital synthesizer (DDS) generating a 34±1 MHz signal mixed and band pass filtered with a fixed 400 MHz to generate a programmable frequency in the 434±1 MHz range. Since all interactions in probing a piezoelectric transducer are linear, the detection only requires integrating the power returned in the ISM band by the transducer: if the emitted signal is located within the bandpass of one of the resonator modes, energy is stored in the transducer. Similar to a RADAR principle, this emission is stopped after a duration computed so that the emitted pulse bandwidth is narrower than the transducer width at half height, and the stored energy is released during the listening step. This returned energy is integrated using a logarithmic power detector, digitized for further processing, and the microcontroller programs the DDS with the next frequency to be probed. The whole 2 MHz-wide ISM band is probed using 128-measured frequencies, with the 15.6 kHz step small enough to make sure that at least three probe signal lie within the 55 kHz-wide bandpass of the resonator exhibiting a quality factor $Q = 8000$ around a central working frequency $f_0 = 434$ MHz (Fig. 1) as classically observed for Rayleigh mode SAW transducers. HBARs exhibit quality factor 3 to 4 times larger [18], hence requiring increased interrogation durations and more closer interrogation frequencies, without significant change to the basic circuit other than software configuration with appropriate parameters.

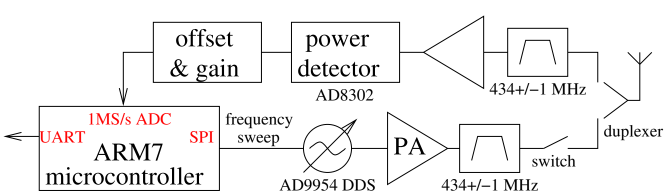

Fig. 1. General principle of the frequency-sweep, RADAR-like, network analyzer for probing through a wireless link resonators. Although focusing on the 434±1 MHz range, this design is flexible enough to be compatible with any frequency range in the 400 to 530 MHz range.

The requirement for a high quality factor is mandatory to distinguish the amount of power returned by the sensor from the surrounding clutter: a single measurement a few microseconds after the RADAR duplexer switches from emission to reception provides a representative measurement of the returned power from the transducer. Since a transducer time constant is Q/π periods, the above-mentioned parameters yield typical time constants in the 6 μs range. Increasing the quality factor improves the signal to noise ratio when sampling long after the switching step, when clutter has faded out. The second useful parameter is coupling, strongly improved with respect to SAW transducers by the use of the bulk wave generated by a strongly coupled material such as LNO, and the use of large electrodes not limited in dimension by the working frequency as is the case for SAW devices.

IV. HBAR sensor characteristics

Since we focus on openloop measurement of these multimode devices, the piezoelectric and propagation substrate thickness are defined by the central working frequency and, if a single device is to provide both reference and measurement modes, the spacing between these two modes. The coarse envelope of the transfer function is defined by electrical boundary conditions on the buried and surface active electrodes. Hence, only the odd harmonics are excited. On the other hand, the passive substrate only requires complying with mechanical boundary conditions, and all harmonics are supported. In order for two adjacent modes to be separated by less than the available bandwidth of 2 MHz, the most significant conditions lies with the substrate thickness (Fig. 2).

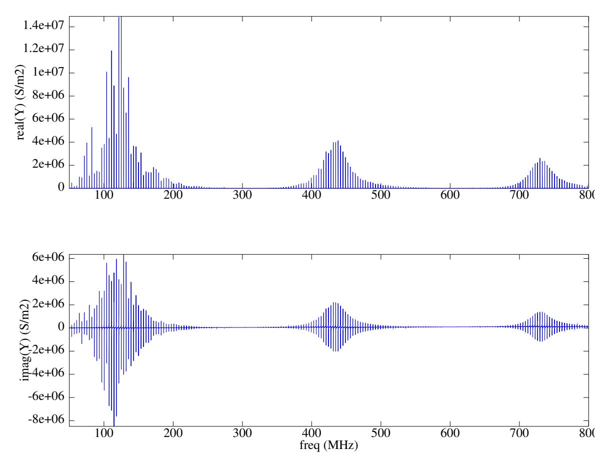

Fig. 2. Left: mixed matrix simulation of a stack of 30 μm thick $LiNbO_3$ and 200 μm Quartz, exhibiting the frequency domain response as a series of sharp resonances modulated by an envelope whose shape is defined by the thin piezoelectric layer thickness.

Although HBARs act as coupled resonators with the thin piezoelectric layer and the thick substrate both contributing to the transfer function, a first approximation for computing the thick substrate dimension is to consider the confinement of acoustic half-wavelengths in this layer of thickness t. In this case, assuming an acoustic velocity v, the spacing between two modes is $\Delta f = v/(2 \times t)$. In the case of the shear bulk wave propagating in quartz ($c \simeq 3300$ m/s), the thickness t so that $\Delta f \leq 2$ MHz is $t \geq 825$ μm. Hence, the challenge of manufacturing HBAR working in the 434 MHz or 2450 MHz unlicensed ISM band lies more in the thin piezoelectric film lapping and polishing process than thick substrate handling. The same calculation in the thin film demonstrates that a fundamental mode of 434 MHz requires a 4 μm thick thin film or, lowering the requirement on the thin film thickness by assuming that the third overtone is used to reach 434 MHz, 12 μm.

Using an HBAR as opposed to a SAW resonator not only improves the quality factor of the probed mode for separating the acoustic returned power from the background electromagnetic clutter, but also improves the coupling coefficient and hence the ability of the acoustic transducer to efficiently convert the incoming electromagnetic energy into the a mechanical wave stored in the resonator. When using the HBAR fundamental mode of the thin piezoelectric layer, the coupling coefficient is significantly improved with respect to the Rayleigh surface wave coupling on quartz whatever the single-rotation cut angle (Fig. 3). As such, improved interrogations ranges are expected when probing HBAR using a wireless link with respect to SAW.

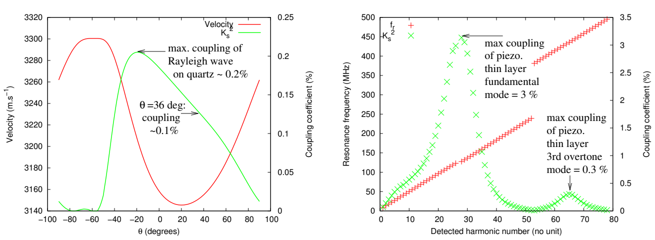

Fig. 3. Comparison of the coupling coefficient of a SAW Rayleigh mode as a function of quartz rotation (left), and for an HBAR made of a thin lithium niobate active layer on top of a quartz substrate (right). The lack of electromechanical coupling around mode 50 yields a discontinuity in the automated harmonic number detection.

V. HBAR AS PASSIVE SENSORS FOR WIRELESS MEASUREMENT

A RADAR-like wireless measurement requires a differential strategy to get rid of capacitive frequency pulling and communication channel influence on the measured resonance frequency. One approach is to use successive modes of a single HBAR: although the behavior of various modes of an HBAR can significantly differ, adjacent modes exhibit too close behaviors to be suitable for a differential measurement strategy. An alternative strategy is to use a single substrate propagating two modes, such as SC-cut quartz, but the two velocities should differ by no more than 0.5 % for the two modes to remain within the 434 MHz band. Finally, the solution demonstrated here uses two different HBAR, one exhibiting a strong temperature coefficient of frequency (TCF), and the other one a turnover within the measurement range, the difference between the two designs being the relative orientation of the thin ($LiNbO_3$ (YXl)/163^o) piezoelectric layer and the thick (AT-cut quartz) substrate.

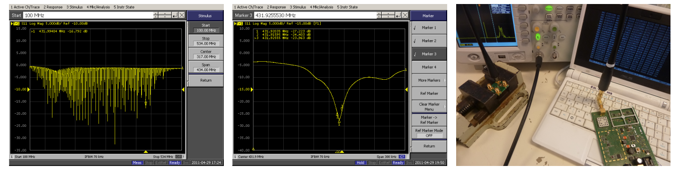

Fig. 4. Experimental wireless measurement of an HBAR with a mode at 431.92495 MHz (network analyzer characterization). Left and middle: from wideband characterization of the transducer to the response of the single mode selected for wireless interrogation. Right: experimental setup, with a practical interrogation range of 0.5 m.

Demonstration of temperature measurement is achieved using our radar-mode interrogation unit (Figs. 4 for the experimental setup and 5). In this experiment, two HBAR transducers were designed with large and low temperature coefficient of frequency: when probing both devices sequentially, with the two HBARs packaged in the same environment and subject to the same radiofrequency propagation channel, the common effects (stress, capacitive pulling, electrode aging) are reduced and the temperature becomes the dominant effect measured as the frequency difference. So far we have focused on the frequency domain characterization of one particular mode of the HBAR, but this transducer also acts as a delay line with a mechanical pulse generated by the piezoelectric layer when subject to a short radiofrequency pulse, and the mechanical pulse bouncing multiple times inside the thick substrate. Hence, a time-domain, wideband characterization approach also appears suitable to the use of HBARs as sensors.

One dedicated application is the use of HBARs as passive buried sensors for long term monitoring of mechanical properties of buildings (temperature, stress) or as identifiers of buried structures including victims of avalanches. Indeed, the time domain characteristics of HBARs acting as a comb of reflected pulses excited over a wide range of nearly one decade (from 100 to 1000 GHz) makes this device an ideal transducer to be interrogated in the time domain using pulse-mode bistatic GPR (Fig. 6).

As opposed to the classical surface acoustic wave delay line which is only compatible with a single antenna set defining the central frequency of the probe pulse (defined by the dimensions of the antennas), the wide frequency range at which HBARs operate yields a compatibility with a wide set of GPRs working from 100 MHz (for probing deep structures with low spatial resolution) to 1000 GHz (subsurface sensors located in concrete for building monitoring). Furthermore, as opposed to resonators which provide long responses inappropriate for GPR measurements (which only last a few tens of microseconds for typical structures buried up to a few hundred meters deep) since the frequency identification is challenging on such short samples, HBARs provide a time domain pulse comb compatible with the classical delay line analysis of

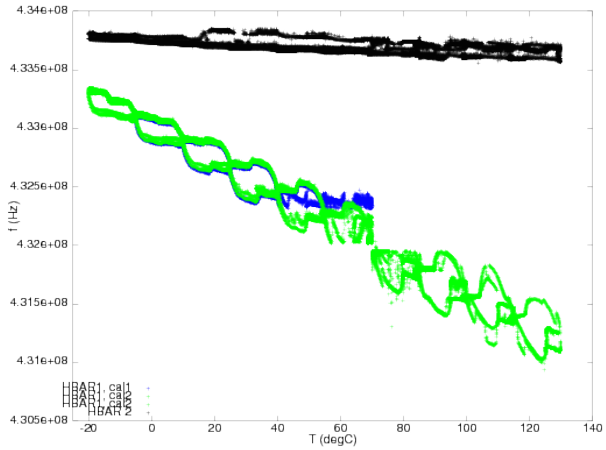

Fig. 5. Wireless temperature measurement an HBAR located in a temperature controlled chamber. The HBAR frequency and Pt100-temperature probe measurements are continuous, while both sensors exhibit different thermal capacitance, hence the time delay between the responses as each temperature step is programmed.

differential phase measurement to recover the acoustic velocity and hence the associated physical quantity under investigation.

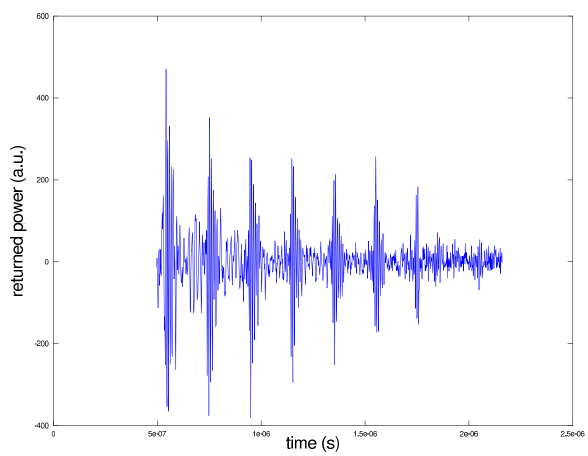

Fig. 6. Left: Ground Penetrating RADAR interrogation of an HBAR. The used antenna generates a pulse centered around 100±30 MHz (Malå RAMAC unit).

VI. Conclusion

We have demonstrated the manufacturing and use of High-overtone Bulk Acoustic Resonators (HBAR) as passive transducers interrogated through a wireless radiofrequency link for temperature sensing applications. Both narrowband and wideband interrogation techniques are applicable to these sensors exhibiting multiple modes over a order of magnitude, from 100 to 1000 MHz. Detailed modelling allows for the selection of the single-crystal substrates in order to tune the frequency behviour as a function of the physical quantity under investigation.

References

[1] D. Puccio, D. Malocha, D. Gallagher, and J. Hines, "SAW sensors using orthogonal frequency coding," in *IEEE International Frequency Control Symposium and Exposition*, 2004, pp. 307–310.

[2] J. H. Kuypers, M. Esashi, D. A. Eisele, and L. M. Reindl, "2.45 GHz passive wireless temperature monitoring system featuring parallel sensor interrogation and resolution evaluation," in *IEEE Ultrasonics Symposium*, 2006, pp. 1453–1458.

[3] J. Beckley, V. Kalinin, M. Lee, and K. Voliansky, "Non-contact torque senseor based on SAW resonators," in *IEEE International Frequency Control Symposium and PDA Exhibition*, 2002, pp. 202–213.

[4] A. Pohl, R. Steindl, and L. Reindl, "The "intelligent tire" utilizing passive SAW sensors – mesurement of tire friction," *IEEE transactions on instrumentation and measurement*, vol. 48, no. 6, pp. 1041–1046, december 1999.

[5] H. Scherr, G. Scholl, F. Seifert, and R. Weige, "Quartz pressure sensor based on SAW reflective delay line," in *IEEE Ultrasonics Symposium*, 1996, pp. 347–350.

[6] Y. Dong, W. Cheng, S. Wang, Y. Li, and G. Feng, "A multi-resolution passive SAW chemical sensor," *Sensors and Actuators B*, vol. 76, pp. 130–133, 2001.

[7] W. Buff, F. Plath, . Schmeckebier, M. Rusko, T. Vandahl, H. Luck, F. Möller, and D. Malocha, "Remote sensor system using passive SAW sensors," in *IEEE Ultrasonics Symposium*, 1994, pp. 585–588.

[8] A. Pohl, G. Ostermayer, L. Reindl, and F. Seifert, "Spread spectrum techniques for wirelessly interrogable passive SAW sensors," *IEEE Fourth International Symposium on Spread Spectrum Techniques and Applications*, pp. 730–735, 1996.

[9] F. Seifert, A. Pohl, R. Steindl, L. Reindl, M. Vellekoop, and B. Jakoby, "Wirelessly interrogable acoustic sensors," *Joint Meeting EFTF-IEEE IFCS*, pp. 1013–1018, 1999.

[10] W. Bulst, G. Fischerauer, and L. Reindl, "State of the art in wireless sensing with surface acoustic waves," *IEEE Transactions on Industrial Electronics*, vol. 48, no. 2, pp. 265–271, April 2001.

[11] I. Avramov, "The RF-powered surface wave sensor oscillator – a successful alternative to passive wireless sensing," in *IEEE International Frequency Control Symposium and PDA Exhibition Jointly with fhe 17 European Frequency and Time Forum*, 2003, pp. 911–917.

[12] T. Nomura, A. Saitoh, and H. Tokuyama, "Wireless sensor using surface acoustic wave," in *WCU*, 2003, pp. 935–938.

[13] A. Stelzer, S. Schuster, and S. Scheiblhofer, "Readout unit for wireless SAW sensors and ID-tags," in *International Workshop on SiP/SoC Integration of MEMS and Passive Components with RF-ICs*, 2004.

[14] L. Reindl, "Wireless passive SAW identification marks and sensors," *2nd Int. Symp. Acoustic Wave Devices for Future Mobile Communication Systems*, pp. 1–15, march 2004.

[15] M. Hamsch, R. Hoffmann, W. Buff, M. Binhack, and S. Klett, "An interrogation unit for passive wireless SAW sensors based on Fourier transform," *IEEE transactions on ultrasonics, ferroelectrics, and frequency control*, vol. 51, no. 11, pp. 1449–1456, november 2004.

[16] P. Pursula, J. Marjonen, H. Ronkainen, and K. Jaakkola, "Wirelessly powered sensor transponder for UHF RFID," in *Transducers & Eurosensors'07*, June 2007, pp. 73–76.

[17] M. Pijolat, A. Reinhardt, E. Defay, C. Deguet, D. Mercier, M. Aid, J. Moulet, B. Ghyselen, D. Gachon, and S. Ballandras, "Large Qxf product for HBAR using smart cut transfer of LiNbO3 thin layers onto LiNbO3 substrate," in *IEEE Ultrasonics Symposium*, 2008, pp. 201–204.

[18] D. Gachon, E. Courjon, G. Martin, L. Gauthier-Manuel, J.-C. Jeannot, W. Daniau, and S. Ballandras, "Fabrication of high frequency bulk acoustic wave resonator using thinned single-crystal lithium niobate layers," *Ferroelectrics*, vol. 362, no. 1, pp. 30–40, 2010. [Online]. Available: http://www.tandfonline.com/doi/abs/10.1080/00150190801997872

[19] T. Baron, D. Gachon, G. Martin, S. Alzuaga, D. Hermelin, J.-P. Romand, and S. Ballandras, "Temperature compensated radio-frequency harmonic bulk acoustic resonators," in *Proceedings of IEEE International Frequency Control Symposium*, 2010, pp. 652–655.

[20] T. Baron, J. Masson, J.-P. Romand, S. Alzuaga, L. Catherinot, M. Chatras, and S. Ballandras, "BAW pressure sensor on LiNbO3 membrane lapping," in *Proceedings of EFTF*, 2010.