Novel narrowband acoustic sensors for sub-GHz ISM compliant wireless measurements

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High-overtone Bulk Acoustic Resonator (HBAR): basics

Objective: robust structure for high frequency/high Q resonators

Mechanical structure: stack of single-crystal piezoelectric layer + low acoustic loss substrate ⇒ robust structure ($\gg$ FBAR) while reaching high frequency (thin piezo layer)

Issues:

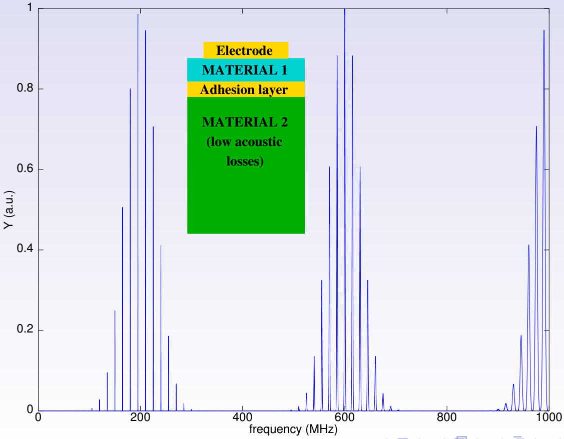
- thin single-crystal piezoelectric layer [1]
- wafer scale assembly, [2]
- low acoustic loss adhesion strategy,
- reaching the buried electrode

[1] T. Baron, D. Gachon, G. Martin, S. Alzuaga, D. Hermelin, J.-P. Romand, S. Ballandras, *Temperature Compensated Radio-Frequency Harmonic Bulk Acoustic Resonators*, Proceedings of IEEE International Frequency Control Symposium (2010)

[2] T. Baron, D. Gachon, J.-P. Romand, S. Alzuaga, S. Ballandras, J. Masson, L. Catherinot, M. Chatras, *A Pressure Sensor Based on a HBAR Micromachined Structure*, Proceedings of IEEE International Frequency Control Symposium (2010)

High-overtone Bulk Acoustic Resonator (HBAR): expected response

Coupled resonators between the thin piezoelectric film and low acoustic loss (thick) substrate



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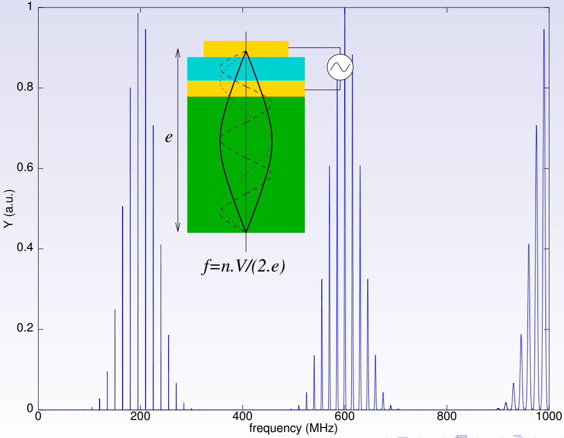
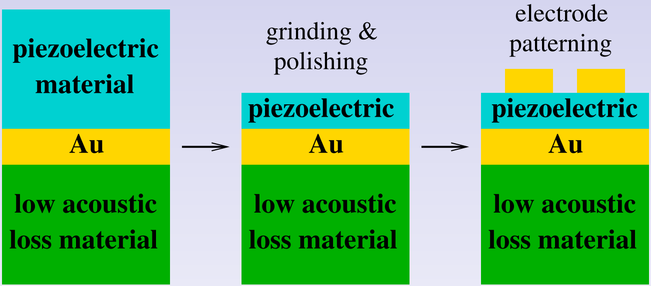


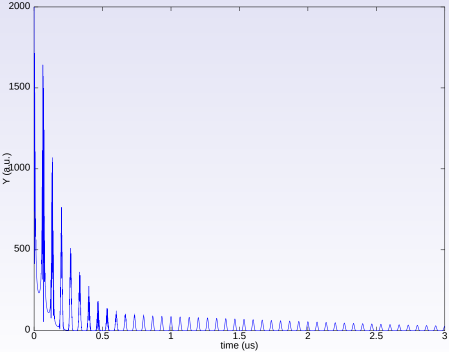
Manufacturing flowchart



1. 4" wafer scale process
2. room temperature gold-eutectic bonding (high pressure)
3. if no access to buried electrode, coupled resonators
4. small resulting dimension ($<$1 mm$\times$1 mm)
5. **bulk** electrode $\Rightarrow$ reduced aging and influence of environment (w.r.t IDTs)

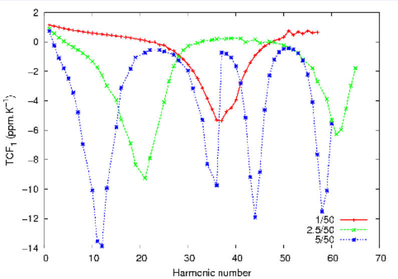
Interrogation strategies

- Closed loop (oscillator) is challenging due to the multimode response
- Open-loop interrogation strategy suitable for this multimode transducer
- Fourier transform of a frequency comb is a series of time-domain pulses $\Rightarrow$ can be used either as a narrowband transducer (frequency domain) or a wideband, multimode device (time domain)



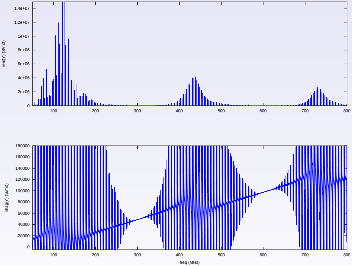
Frequency v.s physical quantity (sensor)

- Stack of single-crystal materials $\Rightarrow$ accurate simulation of thermal behaviour (expansion coefficients)
  $\Rightarrow$ design of either temperature compensated device or temperature sensor (mixed matrix simulation)
- Interrogation range limited by resonator Q (energy storage) and receiver detection limit (LNA & power detector noise)



temperature dependence as a function of overtone number

(varying LNO (YXl/163^o)/quartz thickness ratios)



static capacitance

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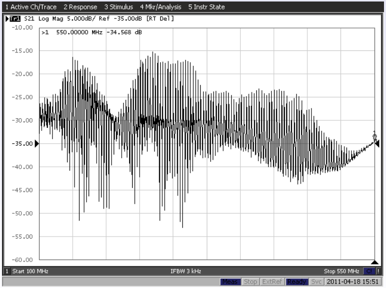
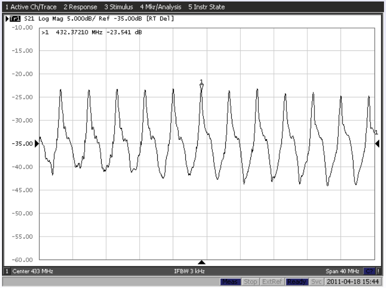
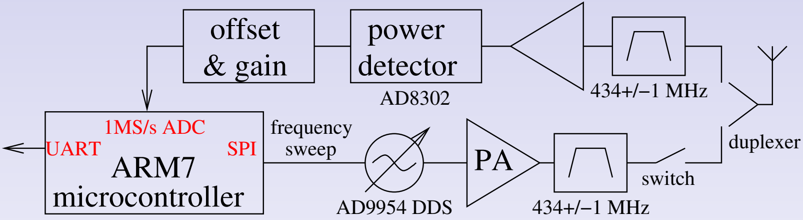




Wireless measurement (frequency)

Measurement strategy: frequency sweep-monostatic RADAR interrogation



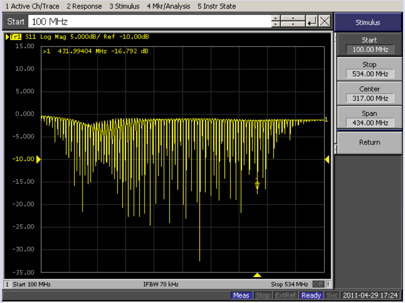
1. program frequency synthesizer (AD9954) at frequency f
2. send RF pulse for a duration longer than $Q/(\pi f)$ s (resonator load)
3. switch antenna from emission (synthesizer + power amplifier) to reception (low noise amplifier + power detector)
4. record magnitude of returned signal (wideband power detector) within the frequency interrogation range after a duration $\ll Q/(\pi f)$ (resonator energy release)
5. $f \rightarrow f + \Delta f$ & repeat for all values of f in interrogation band [3] [4]

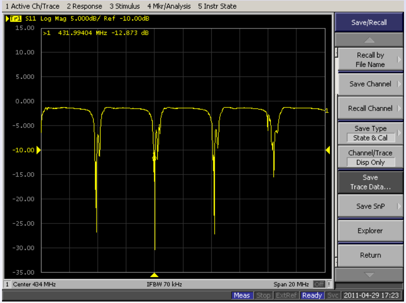
[3] J.-M Friedt, C. Droit, G. Martin & S. Ballandras, *A wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement*, Rev. Sci. Instrum. **81**, 014701 (2010)

[4] C. Droit, G. Martin, S. Ballandras & J.-M Friedt, *A frequency modulated wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement*, Rev. Sci Instrum. **81** (5), 056103 (2010)

Wireless measurement (frequency)

Experimental setup: SENSeOR interrogation unit programmed to probe 432-434 MHz range (128 frequency steps), 16 averages ($\simeq$ 120 ms/measurement)





wideband narrowband

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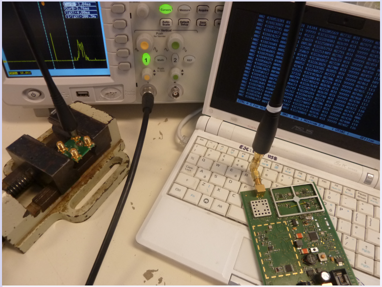
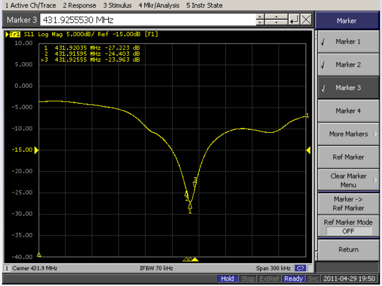


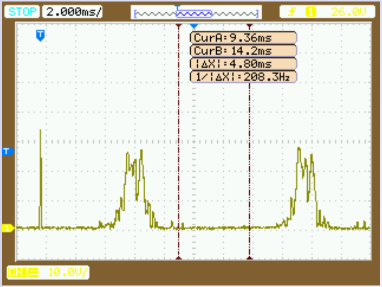


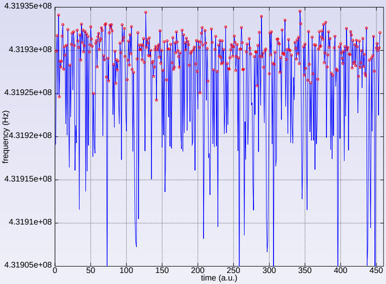
Experimental setup

selected resonance at 431.92495 MHz

Wireless measurement (frequency)

⇒ resulting signal is a curve of returned power as a function of frequency f, with maxima close to each resonance frequency



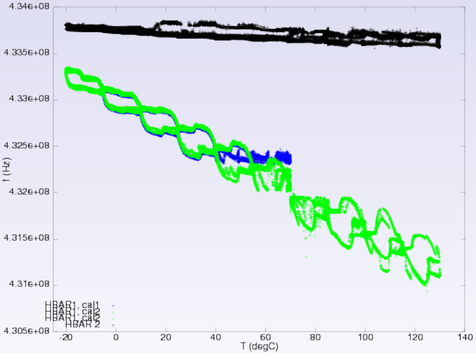


⇒ after removing measurements with excessive standard deviation amongst the 16 measurements (28% of the dataset, red): $\sigma_f = 1800$ Hz

(if 1.7 MHz bandwidth allows for 170 K temperature span, 10 kHz/K and $\sigma_f = 1800$ Hz$\sim \sigma_T = 0.2$ K)

Wireless measurement example

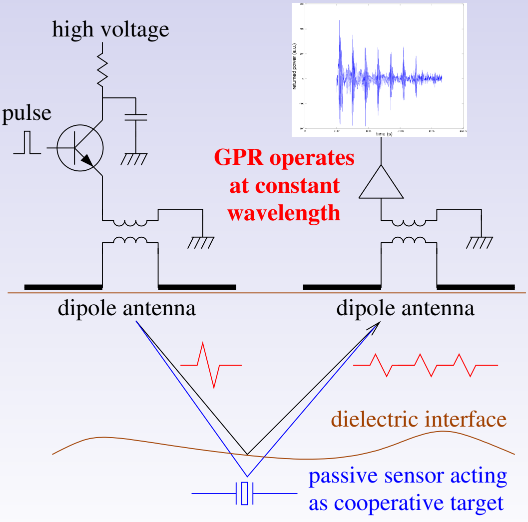
Measurement example: one resonance frequency as a function of temperature, for one temperature compensated HBAR (black) and one temperature sensivite HBAR (sensor: green & blue): wireless, $f \in [431 - 343]$ MHz.



$\Rightarrow$ differential frequency measurement strategy available (reduces sensor and local oscillator aging drift + correlated noise sources)

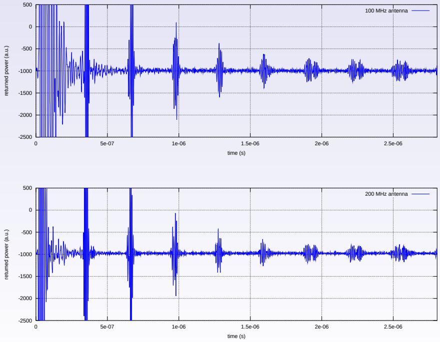
Wireless measurement (time)

- Wideband RF pulse illuminates dielectric interfaces & the HBAR sensor,
- bistatic configuration,
- baseband measurement ⇒ amplitude *and phase* informations,
- demonstration using unmodified commercial Ground Penetrating RADAR (GPR) : Malå RAMAC



Wireless measurement (time)

- Resonance over a wide frequency range ⇒ the **same HBAR** is compatible with multiple RADAR frequencies (in GPR: defined by antenna dimensions)
- here all reflections are from the same acoustic mode: a sensor will require different modes exhibiting different sensitivities with respect to the physical quantity under investigation



Left: the same HBAR probed with a GPR equipped with 100 (top) and 200 MHz (bottom) antennas

Conclusion

- Wafer scale manufacturing process of high Q multimode resonators,
- used as passive sensors compatible with time domain (wideband) & frequency domain (narrowband) wireless interrogation,
- demonstrated interrogation range of $\simeq$ 1 m using a frequency sweep monostatic switched RADAR strategy, or 100 & 200 MHz commercially available Ground Penetrating RADAR
- single crystal materials $\Rightarrow$ detailed modelling (mixed matrix), including thermal behaviour,
- ability to select materials and cuts in order to achieve temperature turnover within the measurement range (reference device) or high temperature drift (sensor),
- tiny dimensions ($<$1 mm$\times$1 mm)

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SENSeOR

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