Piezoelectric acoustic transducers as narrowband passive sensors for wireless measurement in the European ISM band (434 MHz): application to the measurement of the temperature of buried structures

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slides & references available at http://jmfriedt.free.fr

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Outline of the presentation

Objective:

solution for buried/embedded sensors for structural health monitoring

Requirements for embedded sensors:

- Problem of local energy source: how to replace battery when the sensor is buried or in concrete ? (WSN[1,2])
- External energy source: excessive time lapse needed to charge circuit
- RFID will not provide measurement + short range
- Solution: passive sensors interrogated through a wireless link

Outline:

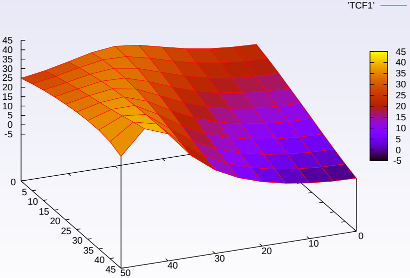
1. Acoustic sensor basics and properties
2. Application to wireless measurement of passive transducers using custom reader electronics
3. Ground Penetrating RADAR (GPR) for SAW delay lines
4. Extension to HBAR

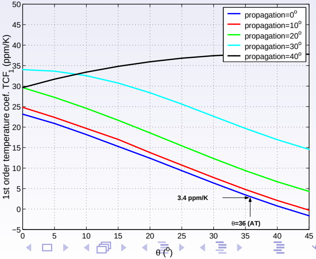
[1] K.M. Farinholt, G. Park, C.R. Farrar, *RF energy transmission for low-power wireless impedance sensor node*, IEEE Sensors Journal **9** (7), 2009 793-900

[2] S.G. Taylor, K.M Farinholt, G. Park, C.R. Farrar, *Energy harvesting and wireless energy transmission for powering SHM Sensor Nodes*, Los Alamos report (2010) available at permalink.lanl.gov/object/tr?what=info:lanl-repo/lareport/LA-UR-09-07854

Embedded sensor requirements

- Sensors = dielectric or piezoelectric substrate.
- Piezoelectric is the most compact way of converting incoming radiofrequency (RF) energy to a mechanical wave acting as physical quantity probe
- Rich field thanks to the anisotopic property of piezoelectric materials (sensitive or insensitive to given physical effects)
- Competitive: RF filter & resonator industry (Murata, Taisaw, Rakon, EPCOS, Triquint, ...) ← cost-effective mass production of the considered technology (single patterned metallic layer step)





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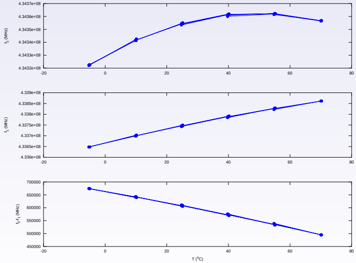
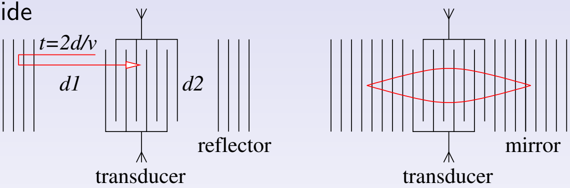


Basics

A **piezoelectric** substrate converts incoming RF signal to a mechanical wave: two approaches

- store energy and release it during the listening step: resonator (narrowband, frequency output)
- impulse response: delay line approach (wideband, time delay output)

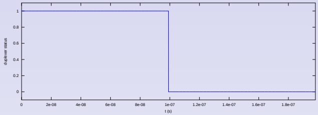
Both approaches provide positive aspects and drawbacks (radio-frequency emission compliance)

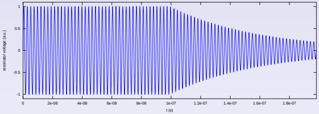


Lower frequency in order to improve penetration depth of RF signal in dielectrics, within acceptable antenna dimension limits and RF emission compliance (315 & 426 MHz in Japan, 434 MHz in Europe)

Linear process: whatever incoming energy reaches the sensor, some signal will be returned (no threshold), but can only be detected if above the receiving stage noise level.

Frequency domain approach (resonators)

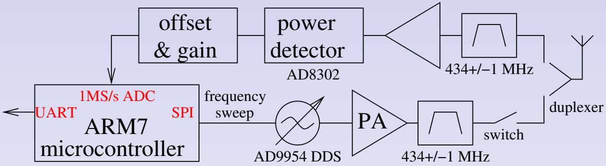




- Low loss device (most incoming energy is stored and released during the listening step)
- Dedicated electronics: frequency-sweep, monostatic pulse mode RADAR
- Fewer Intellectual Properties issues
- Time constant: $Q/(\pi f)$ for a resonator operation at $f \simeq 434$ MHz and $Q \simeq$10000: 6 μs
- Typical interrogation duration: 128 points over 2 MHz wide ISM band, 60 μs/sample = 8 ms
- Compatible with intermittently visible sensors (rotating & moving part)

Wireless measurement (frequency)

Measurement strategy: frequency sweep-monostatic RADAR interrogation



1. program frequency synthesizer 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 $< Q/(\pi f)$ (resonator energy release)
5. $f \rightarrow f + \Delta f$ & repeat for all values of f in interrogation band [3] [4]

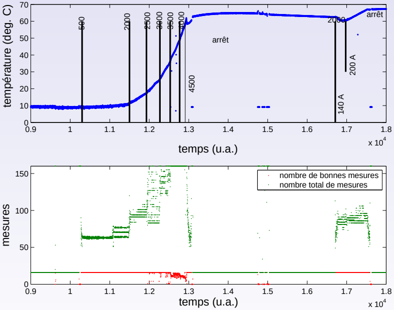
[3] J.-M Friedt, C. Droit, G. Martin & S. Ballandras, *A wireless interrogation system exploiting narrowband acoustic resonator for remote physical quantity measurement*, Rev. Sci. Instrum. **81**, 014701 (2010)

[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)

Frequency domain approach (resonators)

Moving objects: main parameter is angular coverage of the rotating (sensor) antenna and static (interrogation unit) antenna.

5000 RPM electric motor



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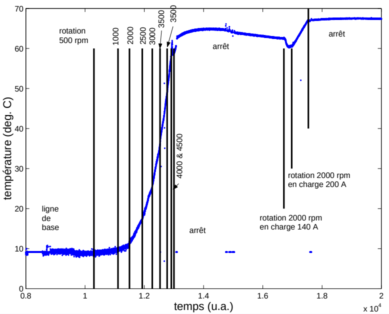

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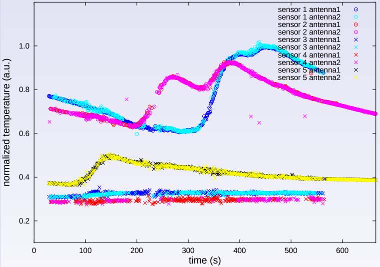
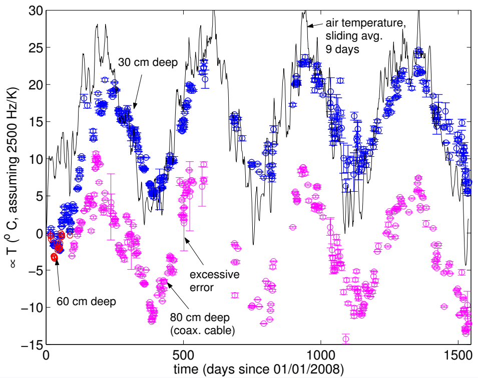
up to 280 km/h motorbike tire



5 sensors located around a wheel, frequency multiplexing, data cleaned using a standard deviation criterion

Frequency domain approach (resonators)

Long term monitoring of temperature sensors buried 30, 60 (dead) and 80 cm deep
Robust solution: no cable, resistant to lawn mowing, no visible drift, measurements consistent with reference data (`www.meteociel.fr`) [5]



[5] J.-M Friedt, T. Rétornaz, S. Alzuaga, T. Baron, G. Martin, T. Laroche, S. Ballandras, M. Griselin, J.-P. Simonnet, *Surface Acoustic Wave Devices as Passive Buried Sensors*, Journal of Applied Physics **109** (3), p.034905 (2011)

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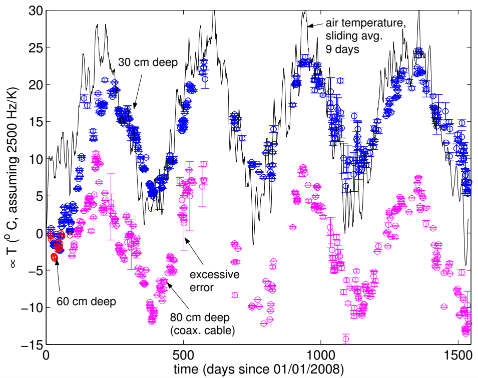

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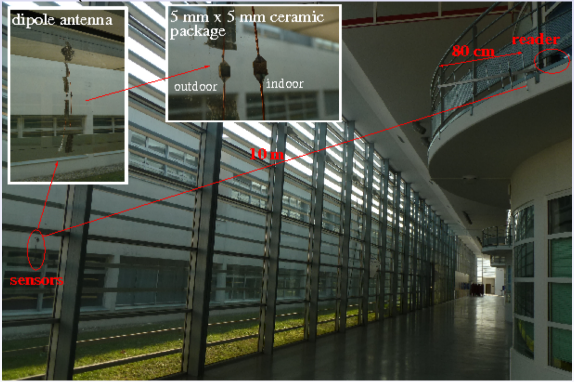
Double glazing window insulation

- Two temperature sensors, one indoor and one outdoor (dipole),
- 5 second measurements every 5 minutes,
- Bluetooth link between interrogation unit and laptop connected to the internet (`http://sequanux.org/jmfriedt/t/resultat.html`)



10 m interrogation range using a 5-element Yagi-Uda antenna, no correction to the original calibration data obtained in climatic chamber

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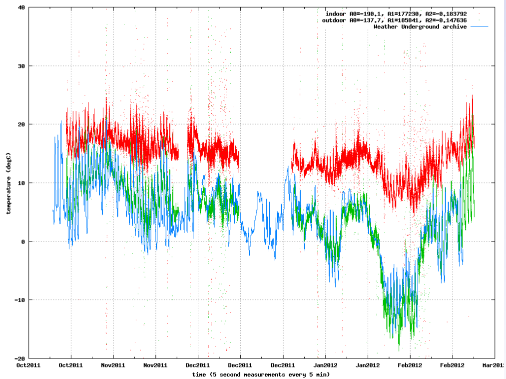
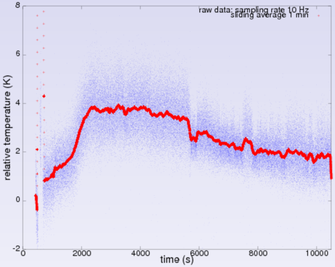


Reference curve: `http://www.wunderground.com/weatherstation/WXDailyHistory.asp?ID=IFRANCHE6`, 12 km away

Application to civil engineering structure health monitoring

Sensor buried ≃3 cm deep in wet concrete (accelerated hardening)



- Objective: assess concrete curing condition.
- Passive sensor ⇒ no battery leakage, *but* requires antenna (beware of reinforced concrete)
- Applicable to stress sensor

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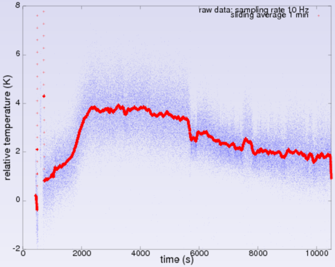

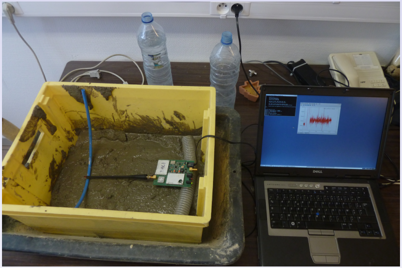

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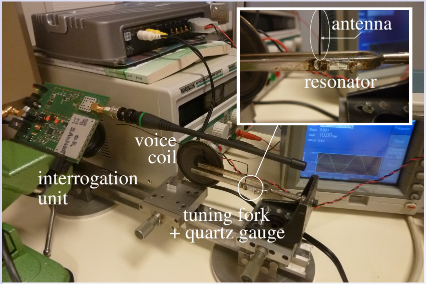
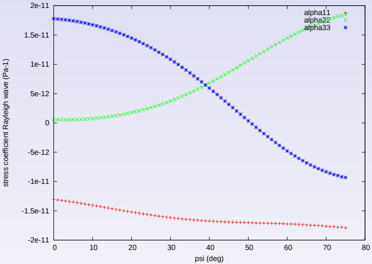
Detected quantities

- **Temperature**: easiest (sensor mechanically isolated from environment),
- **stress** – no identifiable dependence of strain coefficient wrt temperature[6] $\Rightarrow$ **pressure** (strain gauge on a membrane)





- Resulting sensitivity: $\Delta f/f \in [-20..+20]$ ppm/MPa, max stress (quartz) <250 MPa, *i.e.* $\Delta f \leq 2$ MHz at 434 MHz
- Challenge: linking stiff strain gauge (quartz) to stiff substrate (steel)

[6] S. Alzuaga, É. Michoulier, J. Masson, J.-M Friedt, G. Martin, P. Berthelot, V. Pétrini & S. Ballandras, *Characterization of the thermal dependance of SAW stress sensitivity*, CFA 2010, available at http://cfa.sfa.asso.fr/cd1/data/articles/000218.pdf

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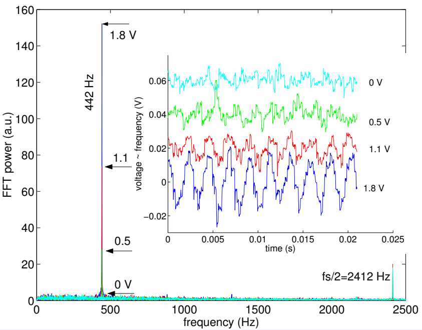

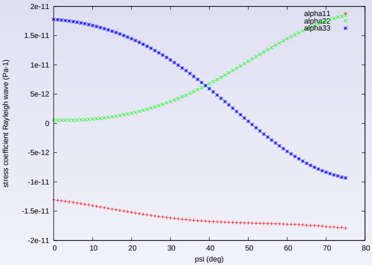

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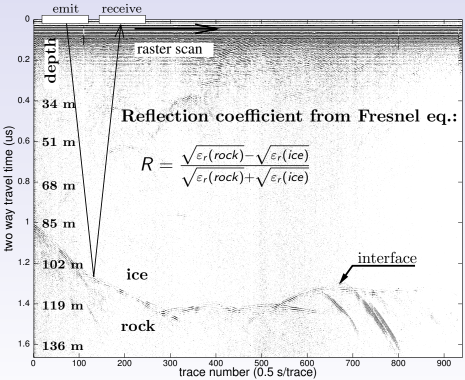
- Interrogation strategy for probing the sensor at 4.8 kHz

[6] S. Alzuaga, É. Michoulier, J. Masson, J.-M Friedt, G. Martin, P. Berthelot, V. Pétrini & S. Ballandras, *Characterization of the thermal dependance of SAW stress sensitivity*, CFA 2010, available at http://cfa.sfa.asso.fr/cd1/data/articles/000218.pdf

Time-domain approach

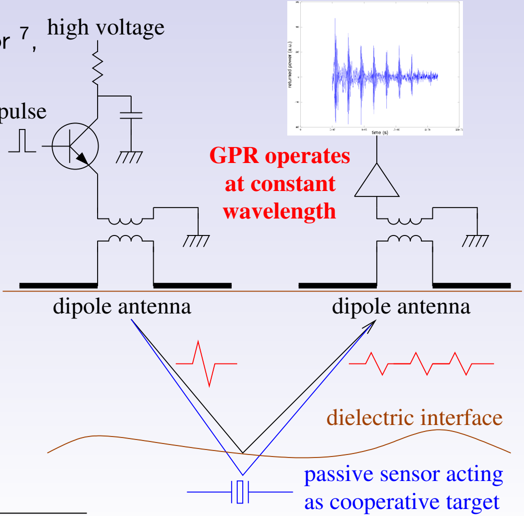
- Fancy interrogation strategies exist, but the most simple approach aims at recording the impulse response
- Probe delay line sensor with a single RF pulse, and time difference between returned pulses is a function of measurement quantity
- High losses in this simple approach, but *compatible with existing equipment*
- Acoustic delay line provide measurement capability to Ground Penetrating RADAR (GPR) classically used for structure health monitoring and road condition assesment



Most simple use: identification. But efficient signal processing for retrieving physical quantity.

Wireless measurement (time)

- Wideband RF pulse illuminates dielectric interfaces & the sensor [7],
- bistatic configuration,
- baseband measurement ⇒ amplitude *and phase* informations,
- demonstration using unmodified commercial Ground Penetrating RADAR (GPR) : Malå RAMAC



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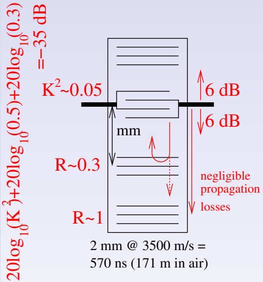
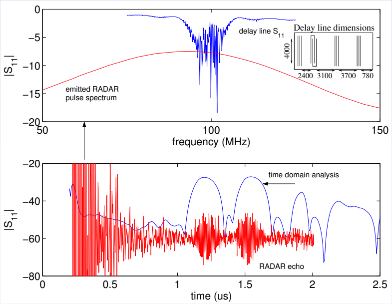
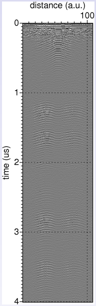
Measurement example: delay line probed with GPR

Method: record on a long enough duration to observe all reflected pulses from delay line (typically ≤ 5 μs, *i.e.* 425 m-deep reflectors in ice)





100 MHz



200 MHz

Post-processing: the hyperbola curvature of the acoustic sensor is inconsistent with the assumed depth of a dielectric reflector $\Rightarrow$ easy identification of the acoustic response after migration

Curvature of the hyperbola $\leftrightarrow$ depth of the sensor.

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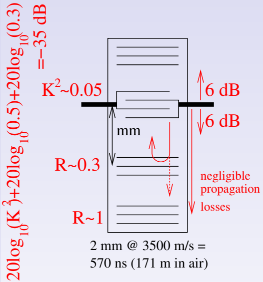

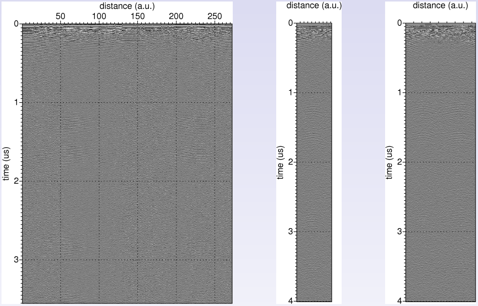

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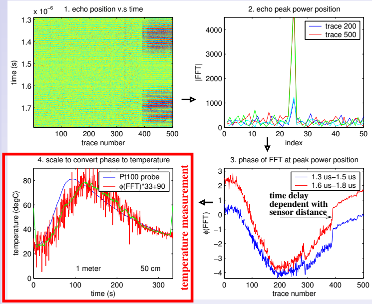
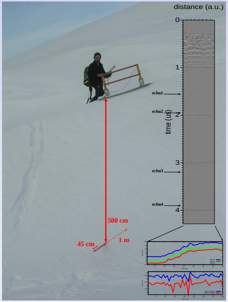




- Distance between reflected pulses provides the physical quantity.
- Phase of the Fourier transform for accurate delay estimate (rather than magnitude of the time domain signal). Alternative: cross correlation.
- Only data post-processing, no modification on the original hardware.
- But piezoelectric conversion efficiency (K^2) $\Rightarrow$ losses: typical insertion losses in the 35 dB range. Hence the interrogation range estimate:

$$d_{SAW} = d_{ice-rock} \times 10^{(IL_{ice-rock} - IL_{SAW})/40}$$

High-overtone Bulk Acoustic Resonator (HBAR)

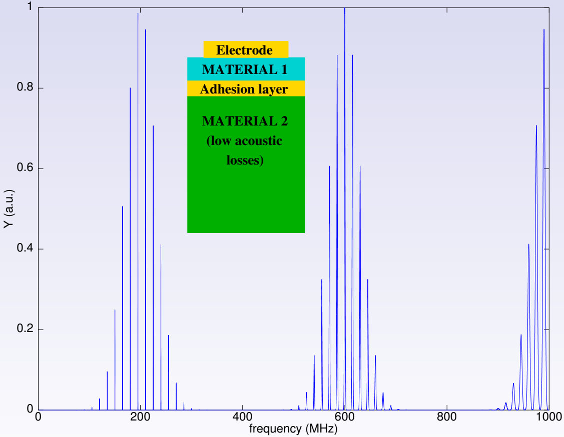
- Latest research activity: a single sensor compatible with multiple GPR operating frequencies,
- mix between delay line and frequency domain approach (frequency comb is also a time-domain pulse comb),
- if neighbouring responses exhibit different sensitivity to measured quantity: differential sensor.
- thin single-crystal piezoelectric layer [8]
- wafer scale assembly, [9]

[8] 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)

[9] 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)

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



Stack of single-crystal materials ⇒ accurate simulation of thermal behaviour (expansion coefficients)

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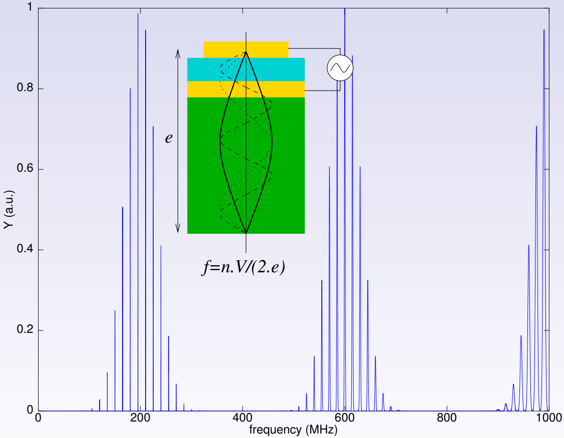

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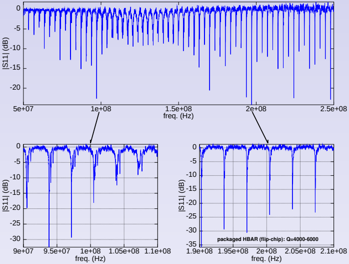
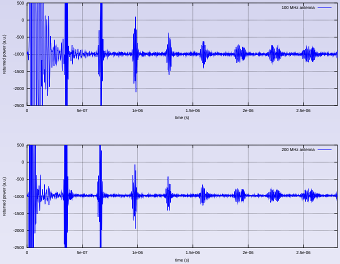
Interrogation strategies

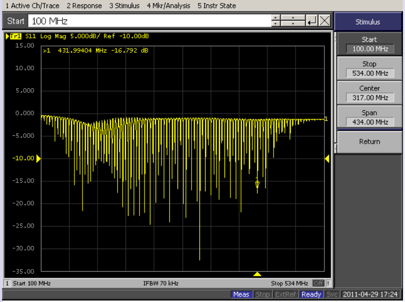


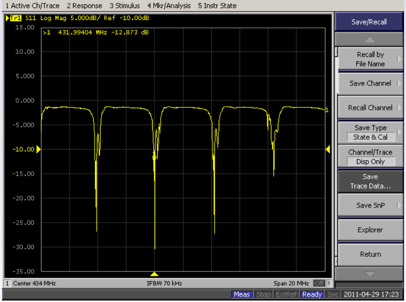


- Closed loop (oscillator) is challenging due to the multimode response
- Open-loop interrogation strategy suitable for this multimode transducer
- Fourier transform of a frequency comb is a series of time-domain pulses ⇒ can be used either as a narrowband transducer (frequency domain) or a wideband,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

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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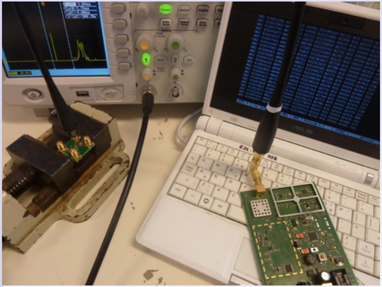

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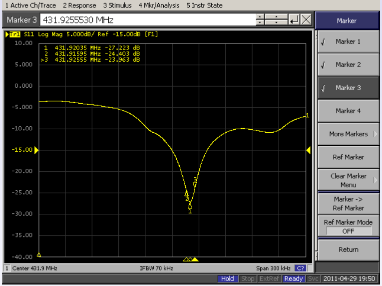
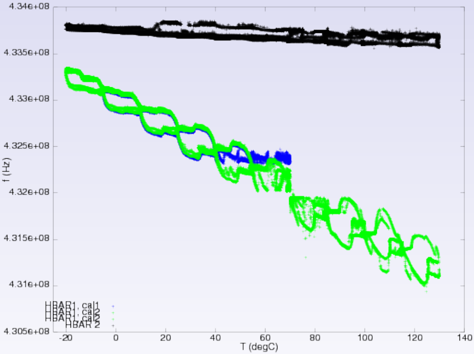


selected resonance at 431.92495 MHz

Wireless measurement example

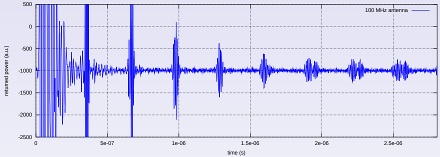
Measurement example: one resonance frequency as a function of temperature, for one temperature compensated HBAR (black) and one temperature sensivite HBAR (sensor: green & blue): wireless, $f \in [431 - 343]$ MHz.

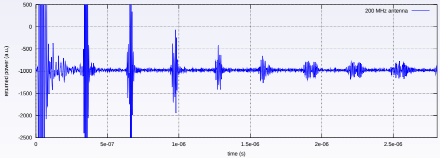


$\Rightarrow$ differential frequency measurement strategy available (reduces sensor and local oscillator aging drift + correlated noise sources)

Wireless measurement (time)

- Resonance over a wide frequency range ⇒ the **same HBAR** is compatible with **multiple RADAR frequencies** [10] (in Ground Penetrating RADAR: 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 Malå RAMAC GPR equipped with 100 (top) and 200 MHz (bottom) antennas

[10] T. Rétornaz, J.-M Friedt, S. Alzuaga, T. Baron, É. Lebrasseur, G. Martin, T. Laroche, S. Ballandras, M. Griselin, J.-P. Simonnet, *Piezoelectric radiofrequency transducers as passive buried sensors*, Nondestructive Testing and Evaluation (accepted 2012)

Conclusion

- demonstrated solution for buried/isolated/mobile sensors interrogated through a wireless link, no local energy source
- robust solution (temperature>160°C), linear interrogation process ⇒ extended interrogation range, up to 12 m using directive antenna,
- frequency based (narrowband) and time based (wideband) interrogation strategies,
- use of commercially available Ground Penerating RADAR equipment, requiring only post-processing (no hw modification),
- 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×1 mm) for the sensor, **BUT** huge antenna ⇒ how to extend a horizontal dipole buried in ice ?
- single crystal materials ⇒ efficient modelling,
- commercially available solution for immediate use.
- in all experiments, the sink (PC + network) is the weak link ⇒ complement data transmission with *non-volatile mass storage*

Perspectives

Work in progress aimed at getting rid of the dedicated interrogation electronics:

- use commercially available RF transcievers (UHF/SHF radiomodem with analog outputs) to probe SAW sensors
- find ways of using UHF SAW sensors ($f \leq 2.4$ GHz) with widely available microwave RADARs (frequency conversion)
- merge SAW sensor measurement capability and WSN functionnalities (porting interrogator embedded sofware to TinyOS to take advantage of its MAC layer)

$\Rightarrow$ no/minor hardware modification to existing RADARs + software processing for using **acoustic sensors as cooperative targets**

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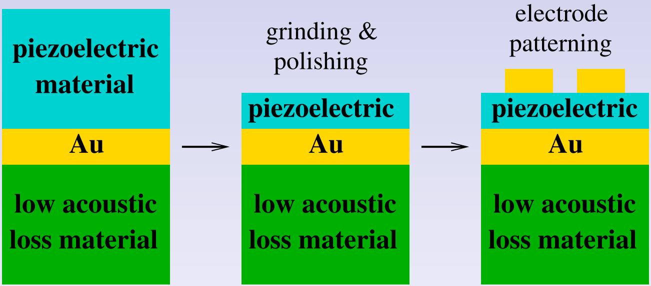
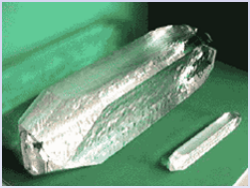
HBAR manufacturing flowchart



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×1 mm)
5. **bulk** electrode ⇒ reduced aging and influence of environment (w.r.t IDTs)

Generating acoustic waves

- Acoustic waves in solids: mechanical, thermal expansion, piezoelectric generation
- An RF voltage applied to an interdigitated transducer generates an acoustic wave[11]
- Surface, bulk waves, shear/longitudinal/Rayleigh/ guided (Love mode)
- Delay line (single path) or resonator (reflectors define a cavity)



material	wave	(m/s)	TCF	comment
$LiNbO_3$	shear	4700	-90 ppm/K	ferro. & pyroelectric, $T_C > 1200^o C$
$LiTaO_3$	shear	4100	-36 ppm/K	$525 < T_C < 700^o$C
$KNbO_3$	Rayleigh	2800	< 1 ppm/K	huge coupling, $T_C \simeq 430^o$C
	shear	3500	?	
LiB_4O_7	Rayleigh	3500	-300 ppb/K^2	water soluble
langasite	Rayleigh	2900	-70 ppb/K^2	no Curie temperature, > 1000^{o}C
Quartz	Rayleigh	3150	-40 ppb/K^2	most used
	shear	5100	-60 ppb/K^2	less coupled

[11] R.M. White & F.W. Voltmer, *Direct piezoelectric coupling to surface acoustic waves*, Appl. Phys. Letters **7** (12), 1965, 314-316