High-overtone Bulk Acoustic Resonator (HBAR) as passive sensor: towards microwave wireless interrogation

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Introduction

Context: acoustic wave transducers used as passive, wireless sensors

Objective: use of commercially available RADAR for probing cooperative target acting as sensor

- Alternative strategy to energy harvesting: no energy at all !
- Passive transducer acts as sensor remotely characterized
- The sensor itself is tiny ($<5\times5$ mm^2) but the antenna is huge
- Analog transducer does not provide identification or anticollision capability

$\Rightarrow$ increase operating range to the microwave range for **reduced antenna size** and **spatial multiplexing** thanks to directive beams with modest antenna dimensions on the reader.

Basics of RADAR

- bistatic (physically separated emitter and receiver) or monostatic configurations: isolation defines rage
- pulsed (electromagnetic pulse) $\overset{FFT}{\Leftrightarrow}$ frequency sweep (FMCW)
- echos due to electromagnetic impedance variations (permittivity ε_r and conductivity σ)

$$v = \frac{c}{\sqrt{\frac{\varepsilon_r}{2}\left(\sqrt{1+\frac{\sigma^2}{\varepsilon^2\omega^2}}+1\right)}}$$

- provides both magnitude *and phase* informations on the returned pulse
- typical frequency range: 50 MHz-50 GHz [a]

[a] H. Stockman, *Communication by means of reflected power*, Proc. I.R.E **36** pp.1196-1204 (1948)

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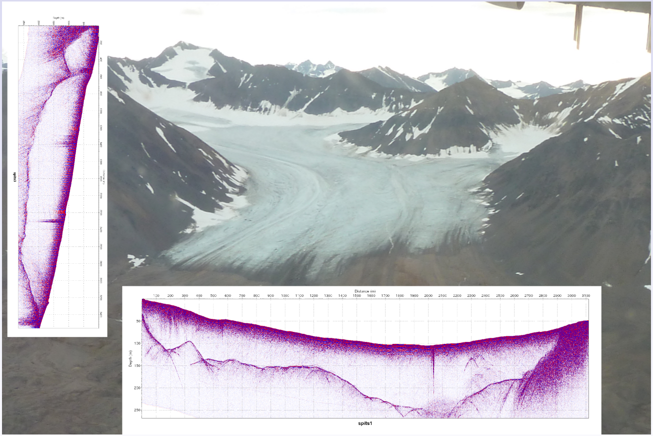
RADAR example (2)

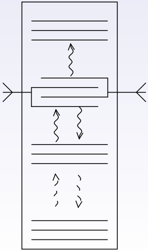
HF-VHF RADAR is long range (even over the horizon), but requires excessive antenna dimensions for industrial applications ($\lambda_m = 300/f_{MHz} \Rightarrow \lambda/4 = 1$ m at 75 MHz).



Objective: electromagnetic scanvengers, here called **cooperative target**

Basics of Surface Acoustic Wave (SAW) delay lines

- acoustic = propagation of a mechanical wave on a substrate
- most efficient way of converting electromagnetic (EM) to mechanical: piezoelectric substrate + interdigitated transducers
- identification + sensor
- physical quantity measurement function of acoustic velocity
- incoming EM pulse generates mechanical pulse which returns as EM with a **time delay** function of physical quantity (temperature, stress, pressure ...)

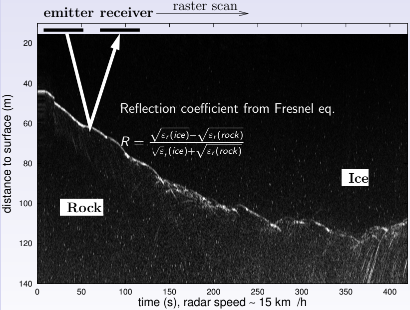


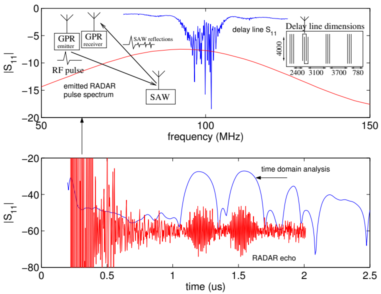
- high electromechanical coupling coefficient (LNO)
- mirror = patterned electrodes
- time delay between incoming pulse and reflection = measurement
- typical velocity: 1500-5000 m/s for most materials
- typical delays: 1-5 μs (3 μs at 3000 m/s $\Rightarrow$ 4.5 mm path)

SAW delay line as RADAR cooperative target

Acoustic transducer as RADAR cooperative target:

- complement the passive interface monitoring with sensor interrogation
- linear conversion process from EM to mechanical: no threshold voltage (cf diodes in Si based RFID)





Challenge: at 5000 m/s, a sensor operating at 5 GHz would require 250 nm lithography (with $\ll \lambda$ resolution)

Link budget for delay lines

- RADAR illumination of point-like target: decay as $1/d^4$
- Free Space Propagation Loss (FSPL)

$$10 \times \log_{10}\left(\frac{\lambda^2}{4\pi} \times \frac{\lambda^2}{4\pi} \times \frac{1}{(4\pi d^2)^2}\right) = 10\log_{10}\left(\frac{\lambda^4}{(4\pi)^4 d^4}\right)$$

- Considering we know the range at ice-rock interface and reflection coeffient

$$\left(\frac{\varepsilon_{ice} - \varepsilon_{rock}}{\varepsilon_{ice} + \varepsilon_{rock}}\right)^2 \simeq 19 \text{ dB}$$

- $FSPL_{ice-rock} + IL_{ice-rock} = FSPL_{SAW} + IL_{SAW}$

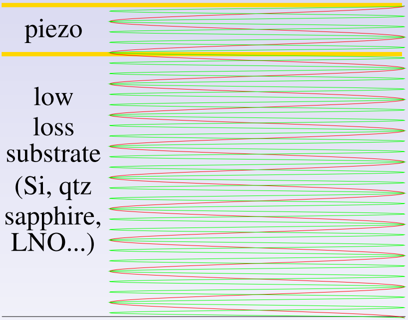
$$\Rightarrow d_{SAW} = d_{ice-rock} \times 10^{(IL_{ice-rock} - IL_{SAW})/40} \simeq 40 \text{ m}$$

assuming $d_{ice-rock} = 100$ m, consistent with SNR of a 5 m deep-measurement [1]

[1] 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* J. Appl. Phys. **109** (3), pp. 034905 (2011)

High-overtone Bulk Acoustic Resonator (HBAR)

1. The acoustic wave no longer propagates at the air-crystal interface but in the bulk of the crystal
2. Operating frequencies are defined by layer thicknesses rather than lithography of electrodes
3. Poly-crystalline active layer (AlN, ZnO) or single-crystal (lithium niobate): high coupling
4. Low loss propagation substrate exhibiting appropriate sensitivity to the measured quantity



Typical dimensions: 5-10 μm thick piezo, 300-500 μm thick substrate, 2×2 mm^2 chip

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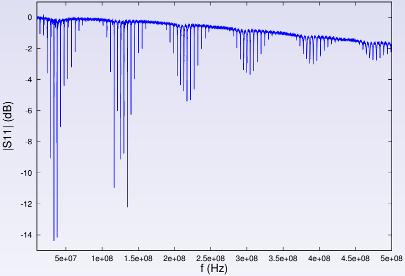

Frequency comb from 50 to 500 MHz

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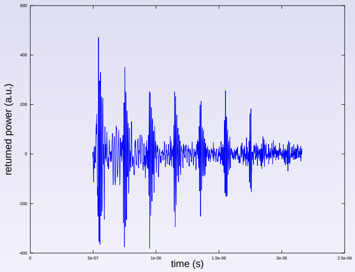


Time domain echos, 0.5-2.2 μs

HBAR measurement strategy

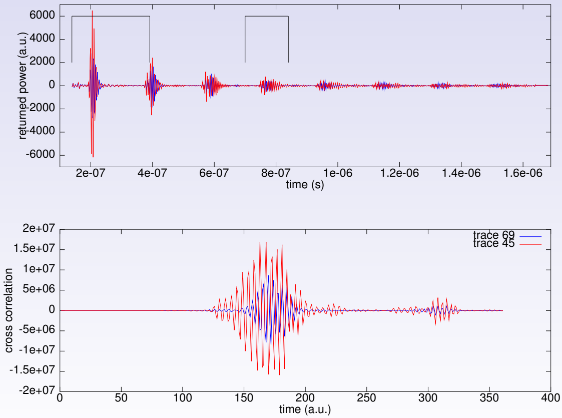
- HBAR spectrum is a comb (in time or frequency domain) of modes
- Frequency domain (resonance identification) or time domain (pulse delay) Digital signal post-processing, *no modification* of RADAR hardware
- Acoustic velocity change with physical property
- **no need to change** RADAR hardware, only signal post-processing step

Frequency domain caracterisation: incompatible with FMCW RADAR (sweep rate $\ll Q/\pi$ periods) and pulse mode (unable to recover an accurate frequency)

$\Rightarrow$ **time domain approach**, search for time delay between returned echos (magnitude & phase)

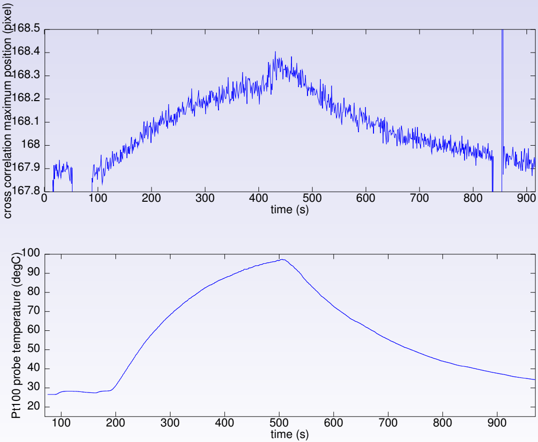
Experimental demonstration (VHF)

Use of cross correlation to accuractely extract the time delay between echos (= acoustic velocity)



Experimental demonstration (VHF)

Temperature measurement



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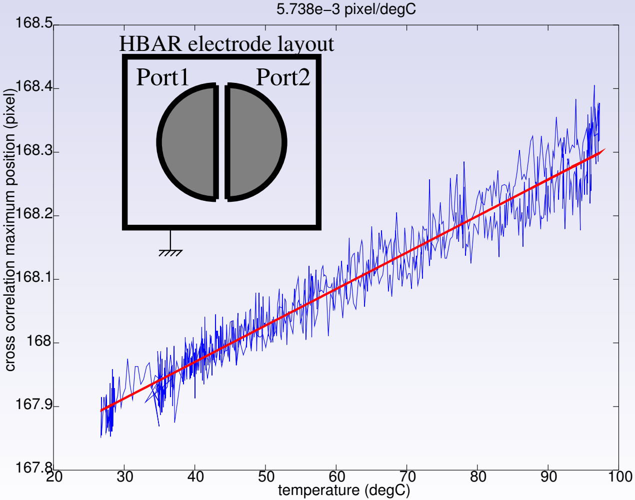
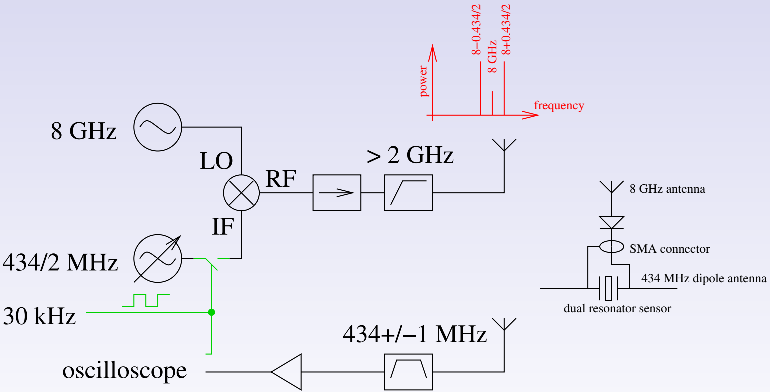


Towards microwaves: mixing

Using a VHF transducer at microwave frequencies: use a diode next to the sensor as AM demodulator



Strategy compatible with **electronic beam steering** on the emission (Space-division multiple access) and omnidirectional receiving antenna

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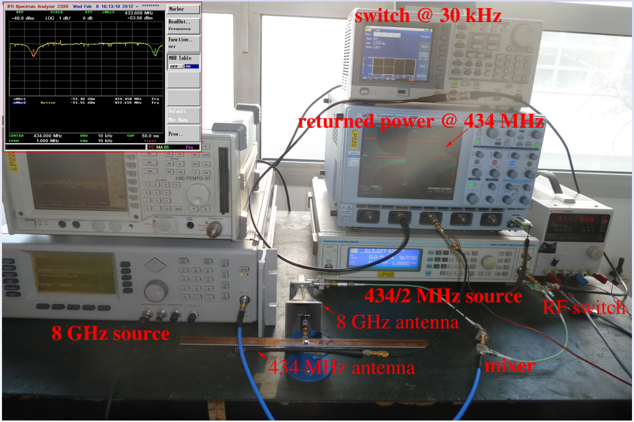

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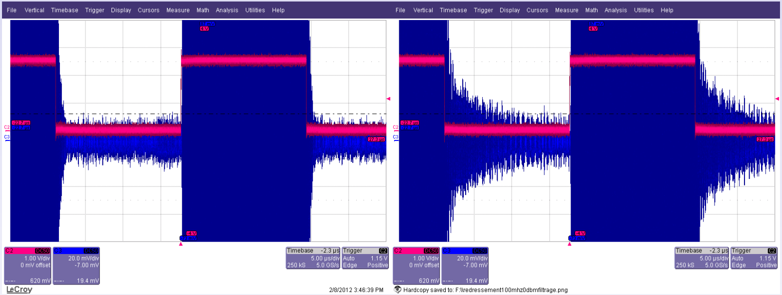
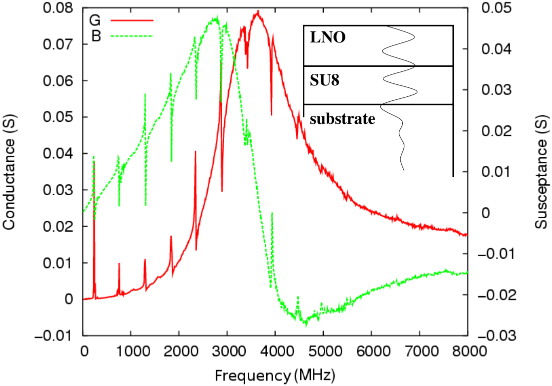


off resonance at resonance

Strategy compatible with **electronic beam steering** on the emission (Space-division multiple access) and omnidirectional receiving antenna

Towards microwaves: baseband

- However, adding a rectifying diode brings back the drawback of RFID
- HBAR can reach the microwave frequency range ... if appropriately designed



In this example, the SU8 assembling glue acts as a strong acoustic reflector and generates modes up to 4 GHz

Conclusion

- use of a widely available tool (RADAR) for probing sensors ("cooperative targets")
- piezoelectric-based (linear) transducers for improved interrogation range
- signal processing for (time-based) delay line: temperature
- $\Rightarrow$ acoustic delay lines for tagging or sensor applications
- $\Rightarrow$ HBAR for multimode (multiple RADAR instrument) & time-domain interrogation

A **passive** sensor solves the issue of **local** energy harvesting, and moves the energy requirement to the interrogating RADAR $\Rightarrow$ best suited in environments where sensor maintenance is impossible once installed (buried in plastic, concrete, soil ...)