A low cost approach to acoustic filters acting as GPR cooperative targets for passive sensing

J.-M Friedt & A. Hugeat
G. Martin, S. Alzuaga, T. Baron, S. Ballandras

FEMTO-ST Time & Frequency, Besançon, France
Contact: jmfriedt@femto-st.fr

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References and slides at http://jmfriedt.free.fr

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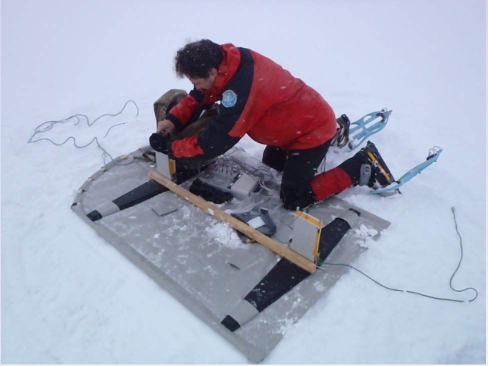
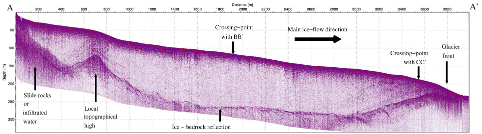
Ground Penetrating RADAR (GPR)





- permittivity and conductivity changes [1]
  $$v = \frac{1}{\sqrt{\frac{\mu\varepsilon}{2}\left(\sqrt{1+\frac{\sigma^2}{\omega^2\varepsilon^2}}+1\right)}^{1/2}}$$
- dielectric interface: Fresnel reflection coef.
  $$R = \left(\frac{\sqrt{\varepsilon_{ice}}-\sqrt{\varepsilon_{rock}}}{\sqrt{\varepsilon_{ice}}+\sqrt{\varepsilon_{rock}}}\right)^2 \simeq -19 \text{ dB}$$
- $v \simeq \frac{c}{\sqrt{\varepsilon_r}}$: 33 (water)-170 (ice) m/μs
- record 200 ns-5 μs
- $\simeq$1000 samples/trace

[1] G. Leucci, *Ground Penetrating Radar: the Electromagnetic Signal Attenuation and Maximum Penetration Depth*, Scholarly Research Exchange **2008**, doi: 10.3841/2008/926091

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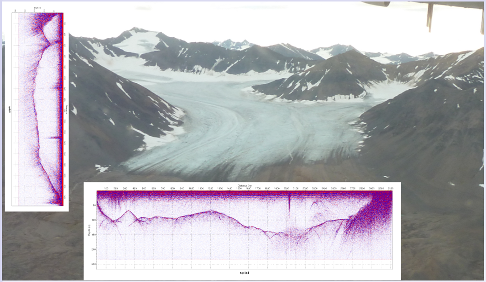

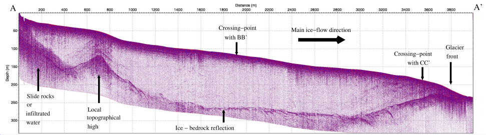

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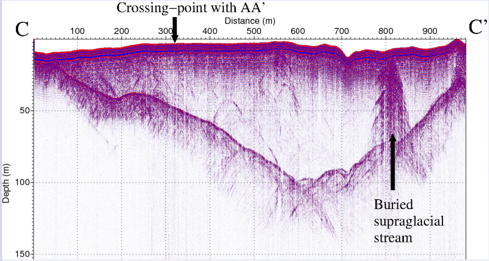

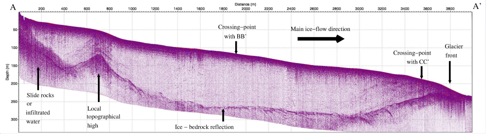

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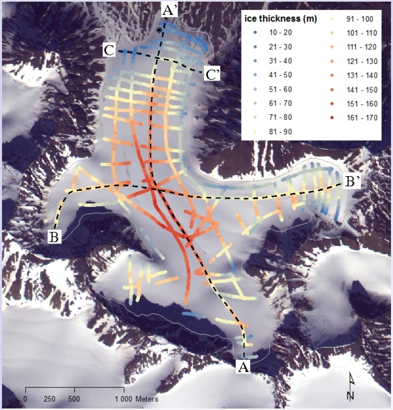
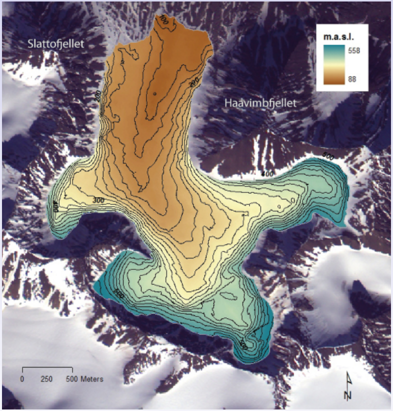
Results

GPR tracks and depth mesurements



interpolated bedrock topography[1]



[1] A. Saintenoy, J.-M. Friedt, & al., *Deriving ice thickness, glacier volume and bedrock morphology of the Austre Lovénbreen (Svalbard) using Ground-penetrating Radar*, Near Surface Geophysics **11** (2), pp.253-261 (2013)

Outline

- What are RADAR cooperative targets ?
- Why GPR cooperative targets ?
- Radiofrequency acoustic transducers as cooperative targets
- Software optimization for dual sub-surface and sensor monitoring
- Low cost demonstration using off-the shelf radiofrequency filters
- Issue of varying operating frequency with soil permittivity, and solution

What are RADAR cooperative targets ?

1. target whose backscattered signal is representative of its state (identification, measurement)
2. active targets: radar beacons (racon), IFF
3. passive targets: buried dielectric reflectors, Lüneberg spheres
4. this work: use of radiofrequency transducers based on surface acoustic wave propagation (RF filters)

H. Stockman, *Communication by means of reflected power* Proc. IRE **36** (Oct. 1948) pp.1196–1204

(picture from http://geogdata.csun.edu/~aether/pdf/volume_05a/rosol.pdf)

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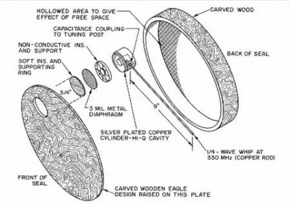

A. Glinsky, *Theremin: Ether Music And Espionage*, University of Illinois Press (2005)
P. Wright & P. Greengrass, *Spycatcher* (1987)

http://madmikesamerica.com/2010/08/the-thing-and-the-curious-life-of-leon-theremin/thing2/

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TOP SECRET//COMINT//REL TO USA, FVEY

CTX4000
ANT Product Data

(TS//SI//REL TO USA,FVEY) The CTX4000 is a portable continuous wave (CW) radar unit. It can be used to illuminate a target system to recover different off net information. Primary uses include VAGRANT and DROPMIRE collection.

8 Jul 2008

(TS//SI//REL TO USA,FVEY) The CTX4000 provides the means to collect signals that otherwise would not be collectable, or would be extremely difficult to collect and process. It provides the following features:

- Frequency Range: 1 - 2 GHz.
- Bandwidth: Up to 45 MHz
- Output Power: User adjustable up to 2 W using the internal amplifier; external amplifiers make it possible to go up to 1 kW.
- Phase adjustment with front panel knob
- User-selectable high- and low-pass filters.

NSA/CSSM 1-52
Dated: 20070108
ify On: 20320108

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LOUDAUTO
ANT Product Data

(TS//SI//REL TO USA,FVEY) Audio-based RF retro-reflector. Provides room audio from targeted space using radar and basic post-processing.

07 Apr 2009

(U) Capabilities
(TS//SI//REL TO USA,FVEY) LOUDAUTO's current design maximizes the gain of the microphone. This makes it extremely useful for picking up room audio. It can pick up speech at a standard, office volume from over 20' away. (NOTE: Concealments may reduce this distance.) It uses very little power (~15 uA at 3.0 VDC), so little, in fact, that battery self-discharge is more of an issue for serviceable lifetime than the power draw from this unit. The simplicity of the design allows the form factor to be tailored for specific operational requirements. All components at COTS and so are non-attributable to NSA.

(U) Concept of Operation
TS//SI//REL TO USA,FVEY) Room audio is picked up by the microphone and converted into an analog electrical signal. This signal is used to pulse position modulate (PPM) a square wave signal running at a pre-set frequency. This square wave is used to turn a FET (field effect transistor) on and off. When the unit is illuminated with a CW signal from a nearby radar unit, the illuminating signal is amplitude-modulated with the PPM square wave. This signal is re-radiated, where it is picked up by the radar, then processed to recover the room audio. Processing is currently performed by COTS equipment with FM demodulation capability (Rohde & Schwarz FSH-series portable spectrum analyzers, etc.) LOUDAUTO is part of the ANGRYNEIGHBOR family of radar retro-reflectors.

Unit Cost: **$30**

Status: End processing still in development

POC: [redacted], S32243, [redacted], [redacted]@nsa.ic.gov

Derived From: NSA/CSSM 1-52
Dated: 20070108
Declassify On: 20320108

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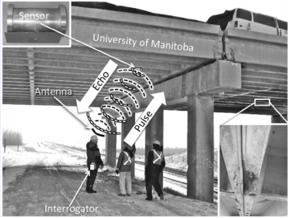
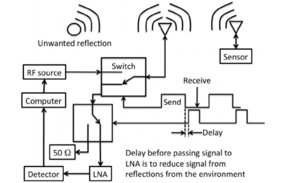


Fig. 1. Passive RFCSs are mounted on or embedded within structures. A sensor with antenna is pictured in the upper left-hand corner. The sensor is approximately 90 mm in length. The sensor is interrogated using a pulse/echo technique. The sensor is passive and does not require any local power, such as a battery.



D. J. Thomson, D. Card, and G. E. Bridges, *RF Cavity Passive Wireless Sensors With Time-Domain Gating-Based Interrogation for SHM of Civil Structures*, IEEE Sensors Journal . **9** (11) (Nov. 2009), pp.1430-1438

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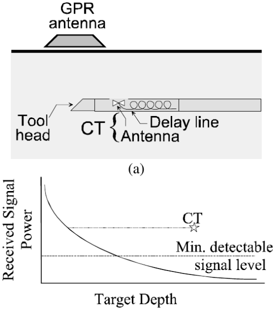
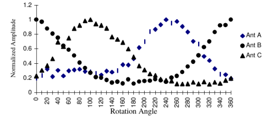
C.T. Allen, S. Kun, R.G Plumb, *The use of ground-penetrating radar with a cooperative target*, IEEE Transactions on Geoscience and Remote Sensing, **36** (5) (Sept. 1998) pp. 1821– 1825





(b)

Figure 3. Normalized response at different rotation angles for (a) the two-CT configuration and (b) the three-CT configuration.

Why GPR cooperative targets ?

- Complement buried structure information with physical quantity measurement
- Accessible quantities: temperature, stress (pressure), identifier (ID)
- Measurement range: depends on RADAR cross section – typical losses in the 30-40 dB range

Passive cooperative target (no local battery source) for extended life expectancy (limited by packaging)

Envisioned applications:

- pipe tagging/stress/temperature
- soil moisture [2]
- concrete temperature [3]

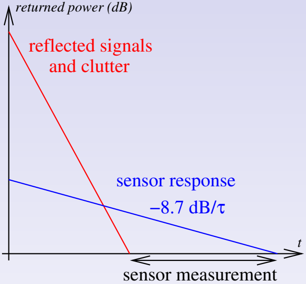
[2] L. Reindl *& al.*, *Radio-requestable passive SAW water-content sensor*, IEEE Trans. Microwave Theory & Techniques, **49** (4), (Apr. 2001), pp. 803–808

[3] J. Kim, R. Luis, M.S. Smith, J.A. Figueroa, D.C. Malocha, B.H. Nam, *Concrete temperature monitoring using passive wireless surface acoustic wave sensor system* Sensors and Actuators A **224** (Febr. 2015), pp.131–139

General strategy

Differentiate the sensor response from clutter (passive interface reflexions)

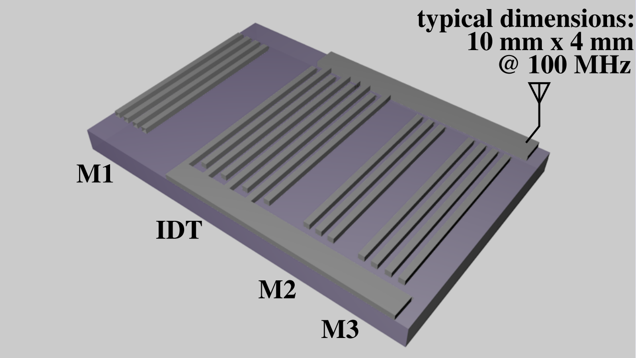
1. load a resonator which slowly releases energy (time constant $Q/(\pi f_0) \gg \tau_{clutter}$): $20 \cdot \log_{10}(e) = 8.7$ but such a strategy is poorly suited to GPR (short pulse unable to load transducer)
2. delay sensor response beyond furthest possible passive reflectors



3. shrink diemensions by converting the electromagnetic wave ($\simeq$ 200 m/μs) to an acoustic wave ($\simeq$ 4000 m/s) confined to the surface of a piezoelectric substrate (*surface acoustic wave* transducers)
4. well known mechanism in radiofrequency signal processing
5. acoustic wave propagation is dependent on substrate properties !

SAW basics

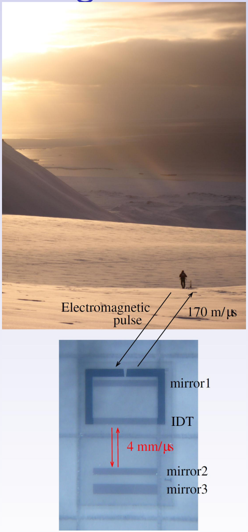
Demonstrated with dedicated readers for Surface Acoustic Wave (SAW) transducers (Transense, CTR, Sengenuity, RSSI, SenSanna, Frec|n|sys, SENSeOR).



- Sensor: $\varphi = 2\pi \cdot D/\lambda = 2\pi D \cdot f/c$ with $dc/c(T,\sigma)$ known
- GPR is wideband pulse generator $\Rightarrow$ delay line architecture.
- This work aims at providing GPR-compatible SAW sensors ...
- ... or divert existing SAW filters for sensing purpose.

Radiofrequency acoustic (SAW) transducers as cooperative targets

- from a user perspective, an electrical dipole
- physics: conversion of incoming RADAR pulse to an acoustic (mechanical) wave through inverse **piezoelectric effect**
- acoustic wave propagates on the surface of the piezoelectric substrate at a speed of **3000-5000 m/s**
- the acoustic wave is reflected by patterned **mirrors**, reaches the transducer and is converted back to an electromagnetic pulse (RADAR echo) ⇒ **tag** or **sensor**
- **design challenge**: match sensor transfer function to incoming pulse spectra



Piezoelectricity is **linear process**: returned power is a fraction of incoming power, no threshold

Unlike RFID which requires power *while* being operated, SAW transducers are ideally suited for GPR interrogation

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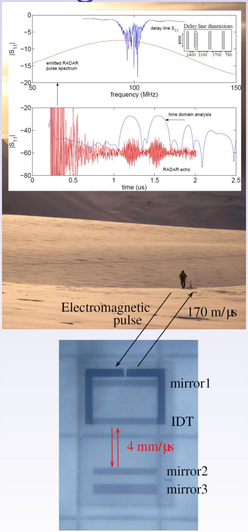

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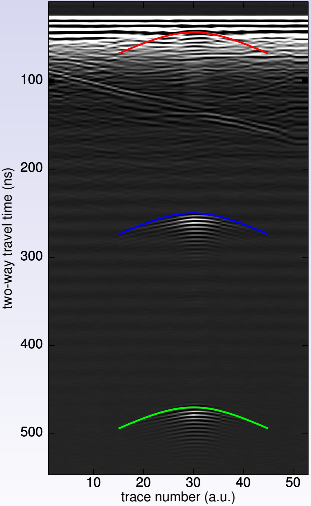
Software optimization for dual sub-surface and sensor monitoring

- Separate sensor response from subsurface reflectors by delaying echo beyond any possible interface reflection (2 μs = 4 mm long sensor at 4000 m/s)
- Short term response = buried structures ("clutter")
- Long term response = buried sensor

Available GPR only allows for a small number of samples (<5000) ⇒ long duration measurement must be at slow sampling rate ⇒ lost resolution in the shallow region [4]



[4] J.-M Friedt *& al.*, *Surface Acoustic Wave Devices as Passive Buried Sensors*, J. Appl. Phys. **109** (3), (02/2011) p.034905

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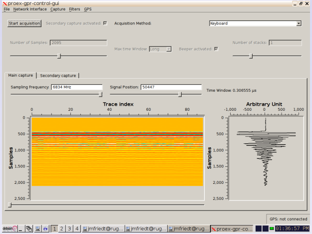
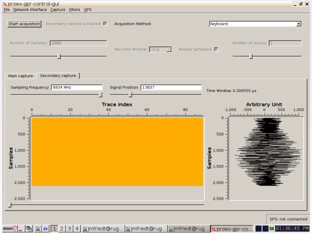
Solution: define two time windows, one focusing on the subsurface structures (e.g. 0-200 ns) and another on the sensor (e.g. 1000-1200 ns)





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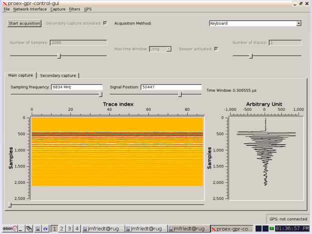
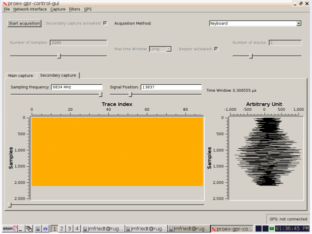
Only **software re-design, hardware remains the same** (reconfigure start delay of the stroboscopic measurement)





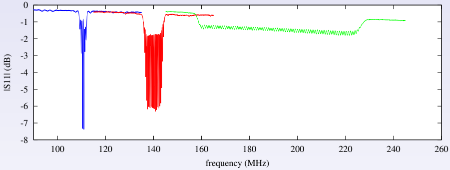
⇒ demonstrated on Malå ProEx GPR
`https://sourceforge.net/projects/proexgprcontrol/`

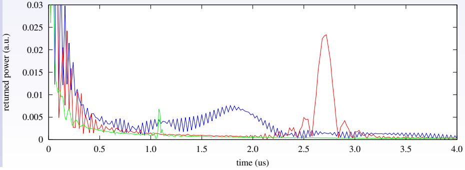
J.-M Friedt & al.
jmfriedt@femto-st.fr

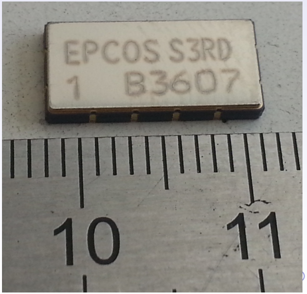
Low cost demonstration using off-the shelf radiofrequency filters

- Dedicated transducers require cleanroom fabrication capability able to handle piezoelectric substrates
- Design considerations:
  - transducer transfer function must match GPR pulse spectrum
  - delay must be within measurement range of GPR
  - reflective transducer operation (most filters operate in transmission)

Measurement example, using an TDK/Epcos B3607 filter:







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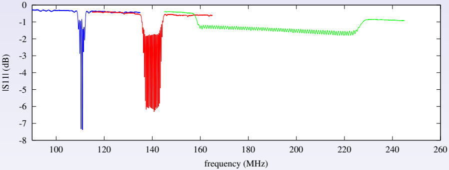
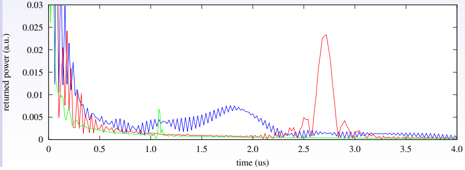
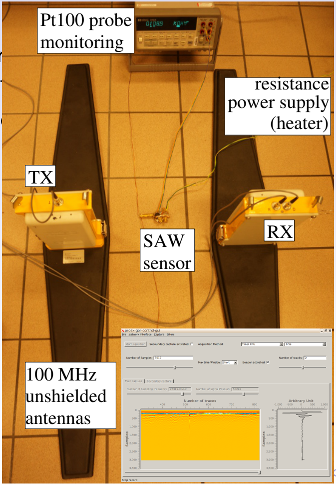
Measurement example, using an TDK/Epc







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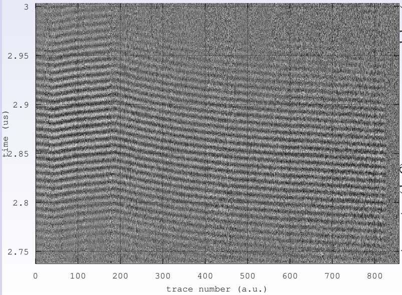
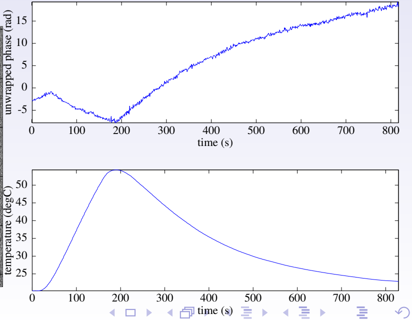
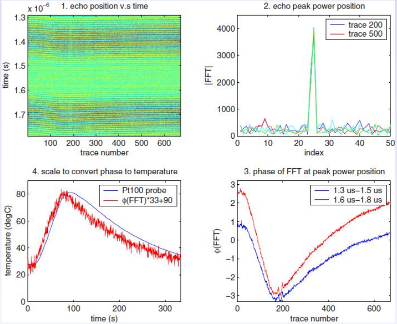




Signal processing steps

Converting the echo delays to a meaningful measurement:

1. multiple echoes from the sensor to get rid of RADAR-target distance dependence
2. phase measurement of each returned echo: **cross-correlation**
3. for single echo (eg SAW filter): phase of the Fourier transform of the main spectrum component (assuming constant RADAR-target distance)
4. SAW delay lines will usually be more narrowband than RADAR pulse ⇒ long echo ⇒ improved SNR
5. sub-sampling period resolution: **polynomial fit** of the cross-correlation maximum
6. danger: multiple nearby cross-correlation peaks ⇒ risk of 2π rotation: $\varphi = 2\pi D/\lambda = 2\pi D \cdot f/c \Rightarrow d\varphi_T = -2\pi Df/c \cdot dc_T/c$ where $dc_T/c(LiNbO_3) = 60$ ppm/K. If $D = 1$ cm, 2π phase rotation on $LiNbO_3$/128 for **35 K** at 100 MHz ($c_{LNO128} \simeq 4000$ m/s).



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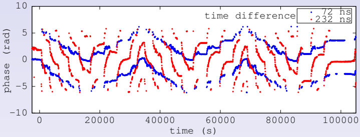
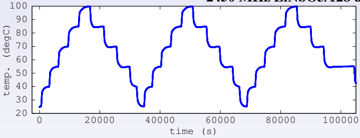
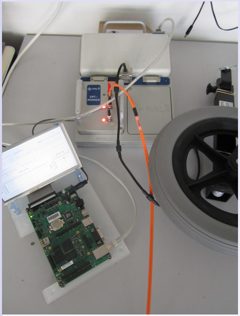


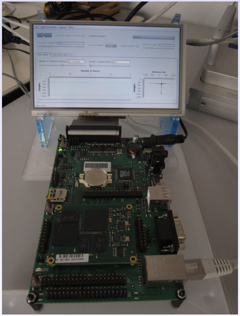
2450 MHz LiNbO3/128 device



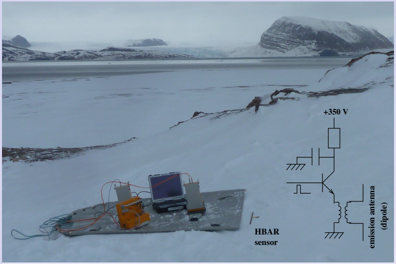
Dedicated software for GPR recording

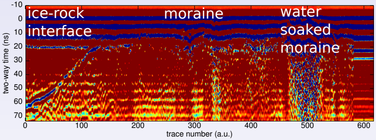


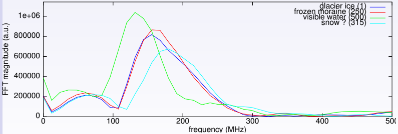
- Run from (low power) embedded board for long term monitoring of a single spot
- Multiple windows separate in time
- Combination with custom hardware (magnetometer, GPS positioning ...) beyond those provided by Malå
- Custom signal processing (GNU/Octave)



RADAR pulse central frequency







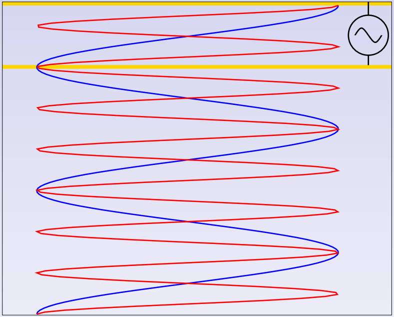
- issue with RADAR pulse generator: central frequency dependent on medium
- in avalanche transistor approach, the capacitor unloads with a time constant given by $\min(S_{11})$.
- $f = \frac{c_0}{2d \times \sqrt{\varepsilon_r(eff)}}$ where $\varepsilon_r(eff) \simeq \frac{\varepsilon_r + 1}{2}$ $(\varepsilon_r \in [3..15])$

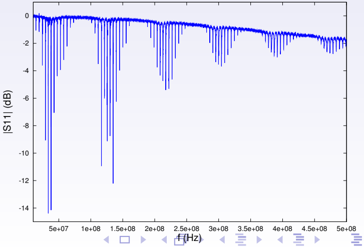
$\Rightarrow$ **f can vary by a factor of 2**

Could we design a transducer operating in all environmental conditions ?

HBAR for sensors compatible with multiple wavelength antennas

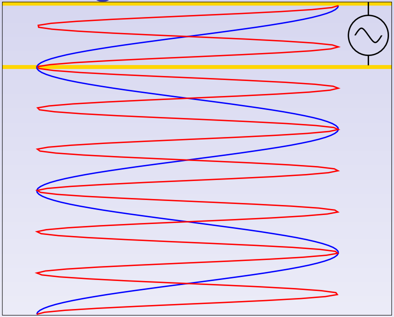
- Stack of an active piezoelectric thin layer over a low acoustic loss substrate
- Mode spacing given by **substrate thickness** t_s: $c_s/(2\times t_s)\times N,\ N\in\mathbb{N}$
- Comb of acoustic modes (BAW) associated with the multiple overtones of the standing wave
- Fourier transform of comb is a time domain comb of echoes
- Broad frequency range (up to one decade) to operate in all GPR environments
- BUT **loss of interrogation range** ?! (35 m → 1.5 m)

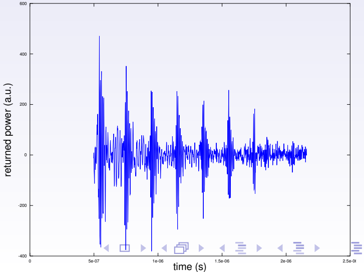




HBAR for sensors compatible with multiple wavelength antennas

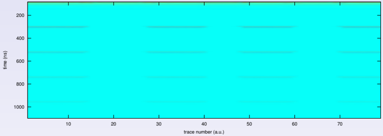
- Stack of an active piezoelectric thin layer over a low acoustic loss substrate
- Envelope given by **piezoelectric layer thickness** t_p: $c_p/(2 \times t_p) \times (2N+1)$
- Comb of acoustic modes (BAW) associated with the multiple overtones of the standing wave
- Fourier transform of comb is a time domain comb of echoes
- Broad frequency range (up to one decade) to operate in all GPR environments
- BUT **loss of interrogation range** ?! (35 m $\to$ 1.5 m)

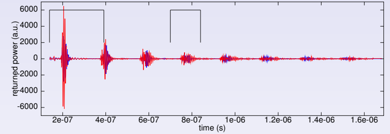


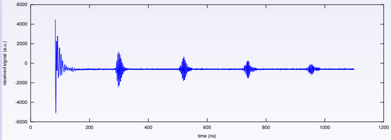


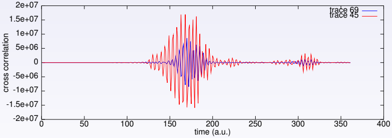
Wireless measurement: time domain approach

1. Radargram, alternatively with & without HBAR
2. Cross-correlate adjacent echoes for precise phase extraction
3. One to one relationship between phase and temperature









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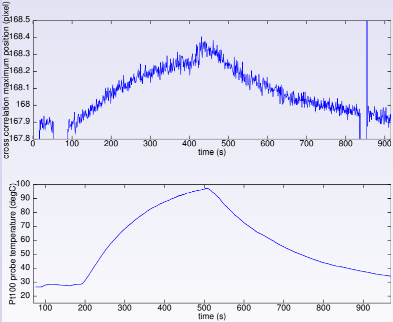

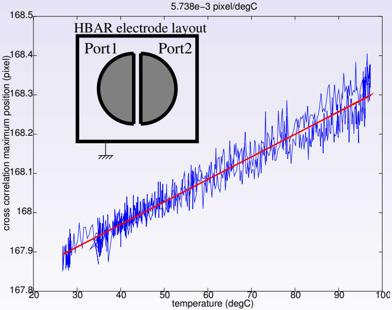

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jmfriedt@femto-st.fr

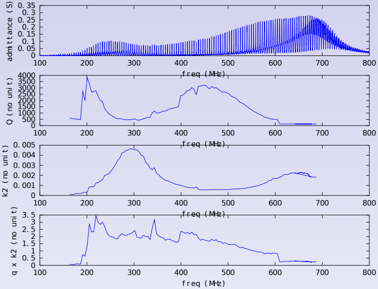
HBAR figure of merit

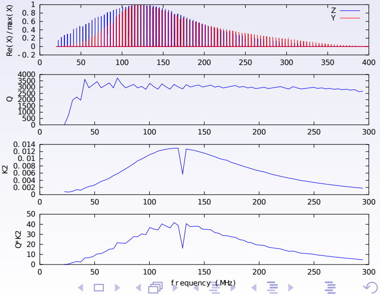
- In the RADAR equation

$$\frac{P_R}{P_E} = \frac{G^2 \cdot \lambda^2 \sigma}{(4\pi)^3 \cdot d^4}$$

the cross section σ is replaced with insertion losses λ^2/IL

- $IL \propto k^2$ so coupling coefficient must be maximized
- **but** $\sum k^2$ of each mode within each piezo layer envelope $=k^2$ of the piezoelectric substrate
- k^2 of piezo layer overtone N decreases as N^2 (cf BAW)
- $\Rightarrow$ tradeoff between maximizing k^2 of each overtone and Q to separate the modes
- figure of merit: $Q \times k^2$





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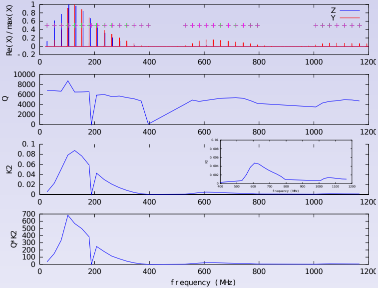
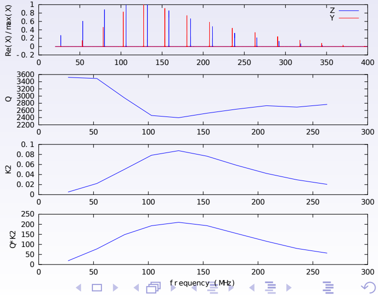
jmfriedt@femto-st.fr

HBAR figure of merit

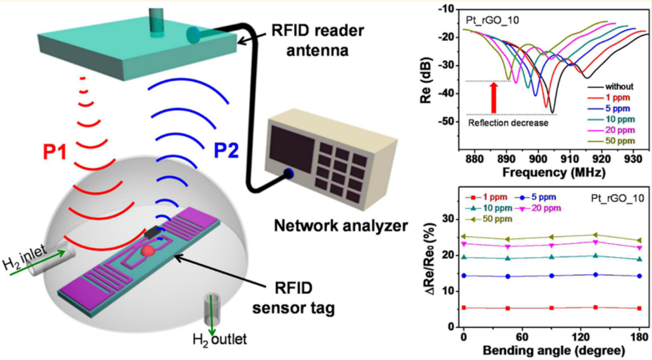
- keeping $Q \times k^2$ large requires operating on the fundamental piezo layer mode $\Rightarrow$ thin piezo film
- few modes within each piezo layer envelope $\Rightarrow$ reduce low loss substrate thickness ...
- **but** keep the multimode aspect so substrate thick enough to provide one mode every 5-10 MHz (0.1-0.2 μs): 500 μm thick sapphire or LNO substrate





How *not* to implement extrinsic load

- Load in parallel to the antenna will kill the resonator contribution
- Measurement range loss in some range of the measurement



- Solution: coupled resonator separates load capability from transduction capability.

Jun Seop Lee *& al.*, *Wireless Hydrogen Smart Sensor Based on Pt/Graphene -Immobilized Radio-Frequency Identfication Tag*, ACS Nano (2015)

Extrinsic load effect on link budget

- One port dedicated to **electro-magnetic transduction**, connected to antenna
- One port dedicated to **load effect** (capacitive, resistive)
- Change load impedance $\Rightarrow$ change phase of returned signal and magnitude
  $\Gamma = \frac{V_R}{V_I} = \frac{Z_L - Z_0}{Z_L + Z_0} \in \mathbb{C}$;
  if $Z_0 \in \mathbb{R}$ and $Z_L \in i\mathbb{R}$, $|\Gamma| = 1$ and
  $\vartheta = \pm\pi - 2\arctan(Z_L/Z_0)$ if $Z_L \gtrless 0$
- Also applicable to the delay line approach by loading one of the mirrors (minor effect) [4]

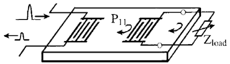


Fig. 2. Schematic drawing of a passive SAW device connected to an external classical sensor.

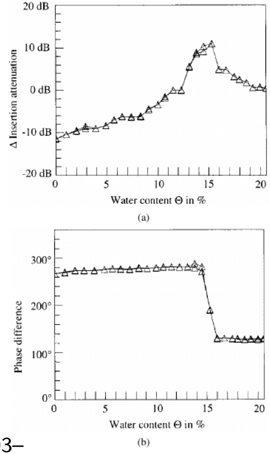
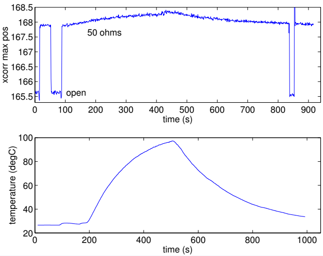


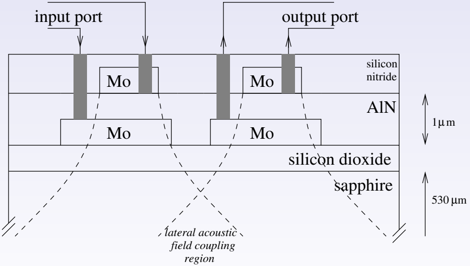
Fig. 13. Difference of the: (a) amplitude and (b) phase difference between reflectors #2 and #1 as a function of the water content of the soil. The Δ s mark

[4] L. Reindl *& al.*, *Radio-Requestable Passive SAW Water-Content Sensor*, IEEE Trans. on Microwave Theory & Techniques *49* (4), 2001, pp.803–

Coupled resonator approach

- By patterning two nearby ($< 10\ \mu$m) electrodes, coupling through acoustic field $\Rightarrow$ 4-port component [5]
- Two ports connected to antenna for wireless communication
- Two port connected to capacitive or resistive load to change coupling (boundary) conditions
- Prevents loading the antenna with sensing load (as done in 2-port devices)





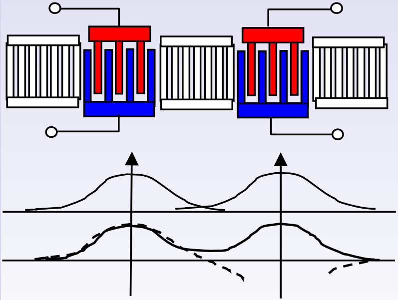
[5] A. Reinhardt *& al.*, *Ultra-high Q.f product laterally-coupled AlN/Silicon and AlN/Sapphire High Overtone Bulk Acoustic Wave Resonators*, 2013 joint EFTF/IFCS

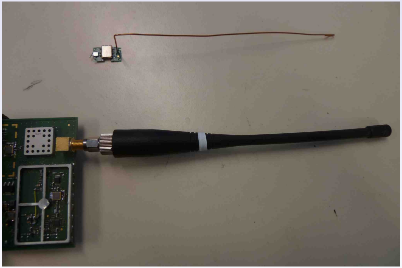
J.-M Friedt & al.
jmfriedt@femto-st.fr

Coupled resonator approach

This strategy is also applicable to resonators [6] :

- one port for wireless communication (antenna)
- the other one for impedance loading
- prevents measurement range loss when load impedance varies
- here demonstrated on an ON/OFF switch





[6] T. Laroche, G. Martin, W. Daniau, S. Ballandras, J.-M. Friedt, J.-F. Leguen, *A Coupled-Mode Filter Structure for Wireless Transceiver-Sensors using Reactive Loads*, Proc. IEEE IFCS (2012)

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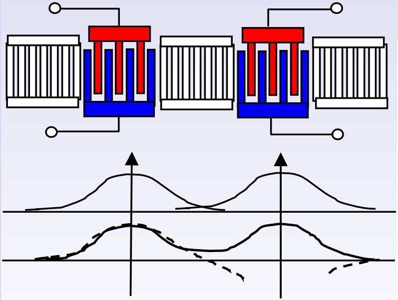

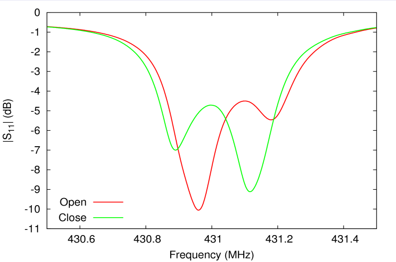

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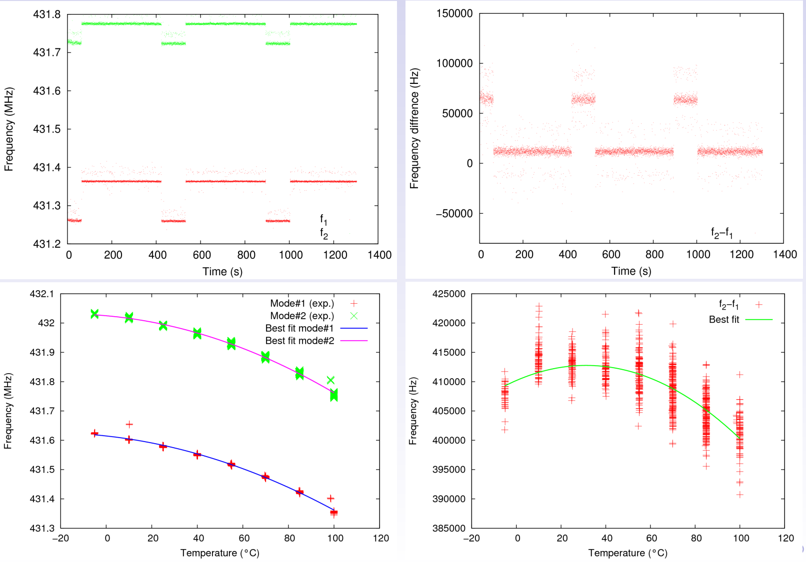
Coupled resonator approach

Differential measurement: both modes exhibit similar temperature sensitivities



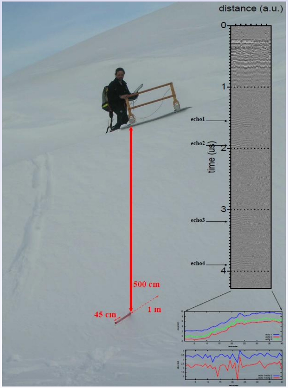
Conclusion and perspectives

- Extend the range of applications of (Ground Penetrating) RADAR by monitoring physical quantities
- Use existing instruments for probing cooperative targets [7]
- Acoustic transducers provide a compact solution ...
- ... ideally suited to GPR interrogation.
- Software enhancement dedicated to sensor monitoring

Perspectives:

- software improvement for **real time display** of the sensor visibility and physical quantity value (calibration)
- beyond physical quantity: **chemical** compound detection (dedicated sensor design): LNO $\rightarrow$ LTO (shear wave)

Acknowledgement: TDK/Epcos kindly provided samples of the B39111B5232H310 and B39191B5087H810 filters, with support of S. Ballandras (Frec|n|sys).



[7] J.-M Friedt, A. Saintenoy *& al*, *High-overtone Bulk Acoustic Resonators as passive Ground Penetrating Radar cooperative targets*, J. Appl. Phys **113** (13), 2013