High-overtone Bulk Acoustic Resonator as passive sensor acting as buried cooperative target interrogated by Ground Penetrating RADAR

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Slides & references: http://jmfriedt.free.fr

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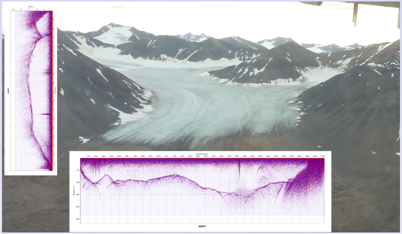
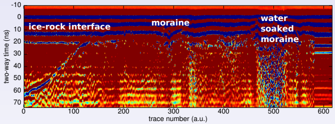
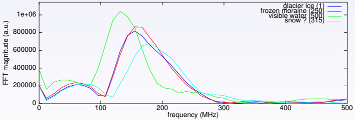
GPR for subsurface interface mapping

- Classical geophysical near-surface (<1000 m) mapping tool
- Pulsed mode RADAR with stroboscopic recording in the commercial implementations (GSSI, Sensors & Software, IDS, Malå)
- Dielectric and conductivity interfaces reflect part of the incoming electromagnetic energy
- electromagnetic velocity is dependent on the medium permittivity: $f = \frac{c_0}{2d\times\sqrt{\varepsilon_r(eff)}}$ with ground permittivity ε_r in $\varepsilon_r(eff) = \frac{(\varepsilon_r+1)}{2}$ ($\varepsilon_r \in [3..15]$) $\Rightarrow$ f **can vary by factor of 2**







GPR for subsurface interface mapping

- Operating frequency range:
  25-250 MHz (geophysics),
  400-800 MHz (civil engineering), up to 1600 MHz (concrete monitoring)
- Basics: load a capacitor with high voltage (350 V), trigger the base of an avalanche transistor, unload in dipole antenna
- **the time constant of the pulse is defined by the antenna min(S_{11})**
- electromagnetic velocity is dependent on the medium permittivity: $f = \frac{c_0}{2d \times \sqrt{\varepsilon_r(eff)}}$
  with ground permittivity ε_r in $\varepsilon_r(eff) = \frac{(\varepsilon_r+1)}{2}$ ($\varepsilon_r \in [3..15]$)
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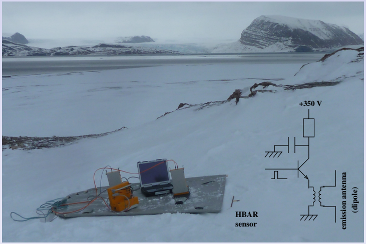
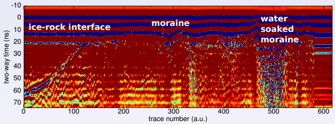
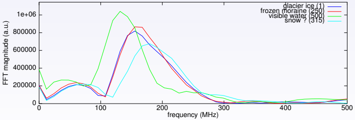
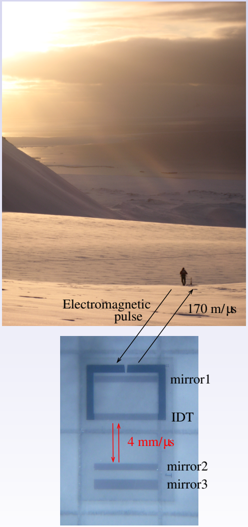






Acoustic sensor compatible with GPR

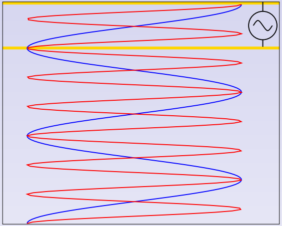
- Incoming electromagnetic pulse is converted to an acoustic wave through (a linear) inverse piezoelectric effect
- Acoustic velocity is dependent on various physical properties (temperature, stress, mass loading=boundary conditions)
- Record time of flight = electromagnetic + acoustic
- Differential measurement to get rid of electromagnetic time of flight
- 10^5 ratio of electromagnetic to acoustic velocity ⇒ microsystems with large antennas

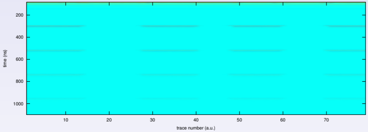


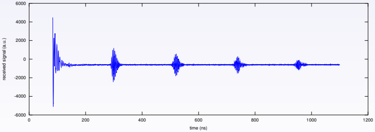
J.-M Friedt *& al*, *Surface Acoustic Wave Devices as Passive Buried Sensors*, J. Appl. Phys. **109** (3), p. 034905 (2011)

HBAR sensor compatible with GPR

- Complement to delay line geometry: High Overtone Bulk Acoustic Resonator (HBAR)
- Stack of an active piezoelectric thin layer over a low acoustic loss substrate
- 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 $\rightarrow$ 1.5 m)







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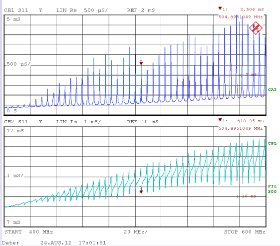
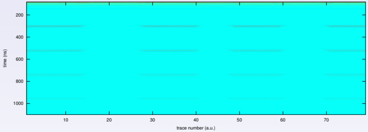
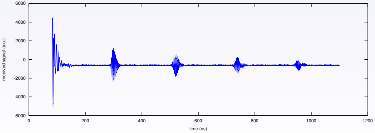
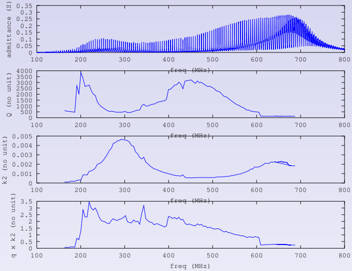


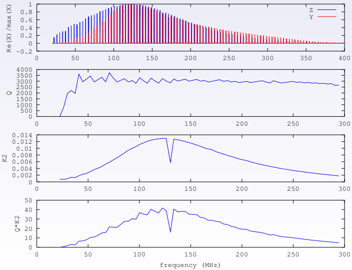




HBAR as time-domain sensors: figure of merit $K^2 \times Q$

- Coupling coefficient is equivalent to the cross-section σ of the RADAR target
$$\frac{P_r}{P_t} = \frac{G_1 G_2 \sigma \lambda^2}{(4\pi)^2 d^4}, \ \sigma \propto K^2\lambda^2$$
- $\sum K^2$ *is equal to the thin piezoelectric film coupling coefficient* (coupled resonator spreads acoustic energy in all overtones of a given envelope)
- Tradeoff: maximize coupling K, keep Q to separate echoes
- Operate on fundamental mode of piezoelectric layer ($K^2 \downarrow N^2$) & few overtones (thin substrate, close echoes)





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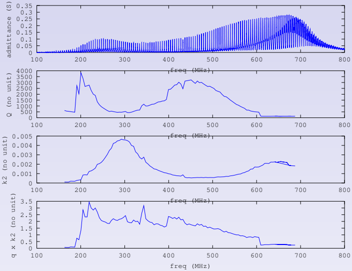

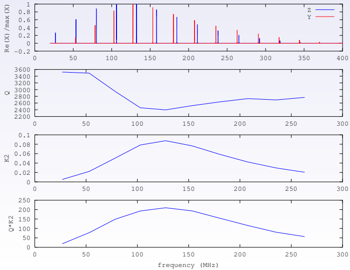

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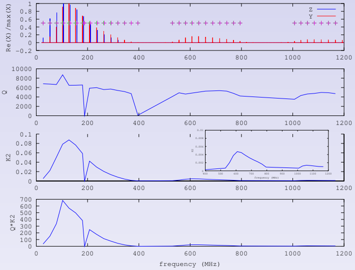
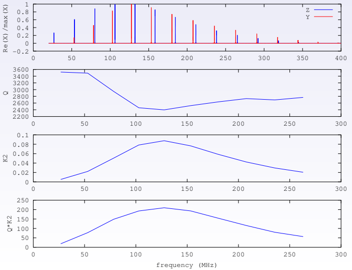
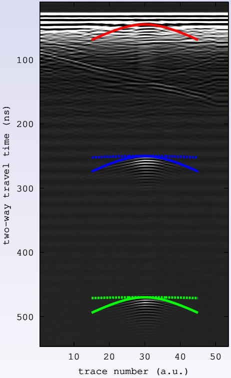




Conclusion

Broadband HBAR[1] is a suitable alternative to acoustic delay line [2] as VHF/UHF RADAR (GPR) cooperative target (passive sensor)
$\Rightarrow$ design rules based on the $K^2 \cdot Q$ figure of merit

- Sensor identification strategy through hyperbola curvature (no convergence in Kirchhoff migration) + repetition of pattern (cross-correlate)
- Loss of interrogation range is due to poor electromechanical coupling in available HBAR
- Select a thin low acoustic loss substrate to minimize number of modes (=closely spaced echoes in time domain)
- Select piezoelectric film thickness to operate on fundamental mode



[1] J.-M Friedt *& al*, *High-overtone Bulk Acoustic Resonator as passive Ground Penetrating RADAR cooperative targets*, J. Appl. Phys. **113** (13), pp. 134904 (2013)
[2] J.-M Friedt *& al*, *Surface Acoustic Wave Devices as Passive Buried Sensors*, J. Appl. Phys. **109** (3), p. 034905 (2011)