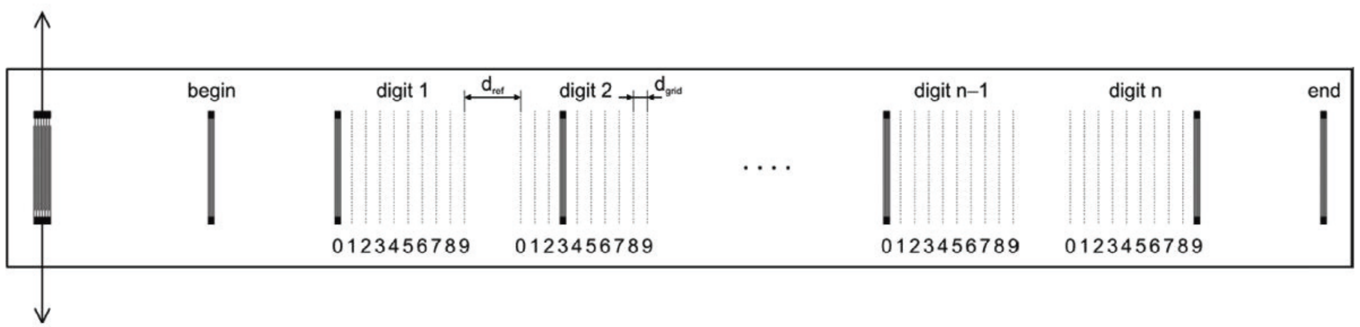
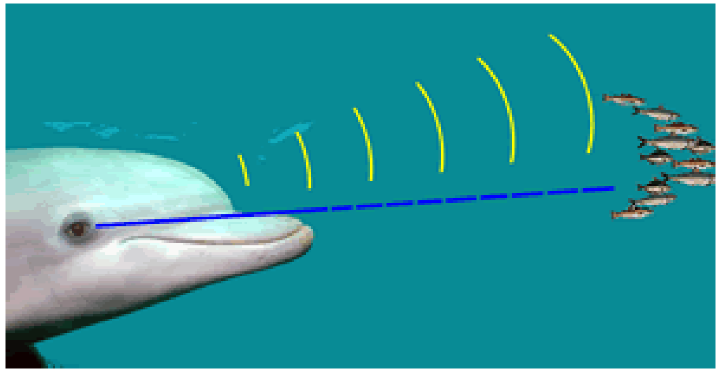
Passive Remotely Controlled SAW (Surface Acoustic Waves) Sensors and SAW RFID tags

(Tutorial II, 15:15 - 17:15)

Victor Plessky, GVR Trade SA, Gorgier, Switzerland





Agenda

Introduction

- History: beginning from Leon Theremin
- Classification of passive sensors; niche for passive sensors and SAW-tags
- SAW resonators vs SAW delay lines
- Examples: Transense sensors; sensors for electric grid
- “Orthogonal frequency coding”
- SAW tags; 6 GHz SAW tag

Recent developments

- Why to use the UWB chirp signals?
- Hyperbolic vs Linear FM; Example of LFM IDT based SAW tag
- Transducer with HFM vs Reflector with HFM
- Design, manufacturing, measurements of reflector HFM sensor
- Passive mic

Conclusions

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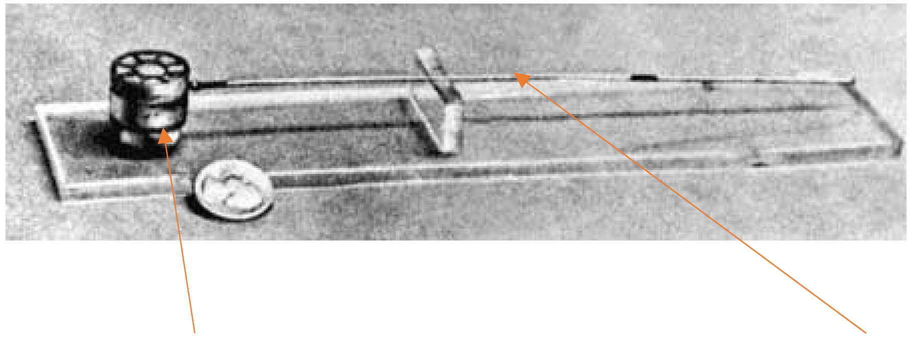
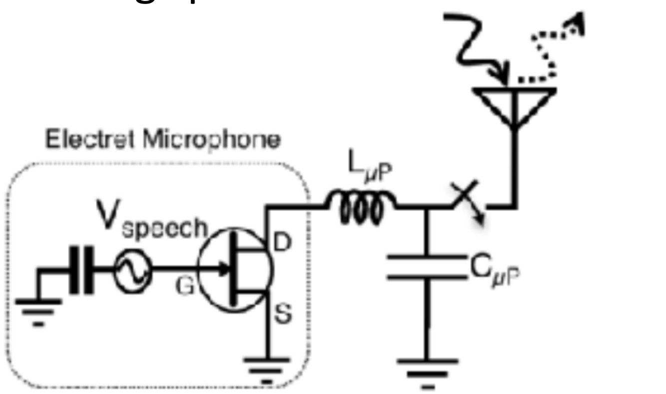
History

- First ever electronic device reflecting back power: 1 bit tag & the voice sensor; year **1945**
- The KGB listened American Ambassador in Moscow for years
- Great invention of Leon Theremin: https://en.wikipedia.org/wiki/The_Thing_(listening_device)



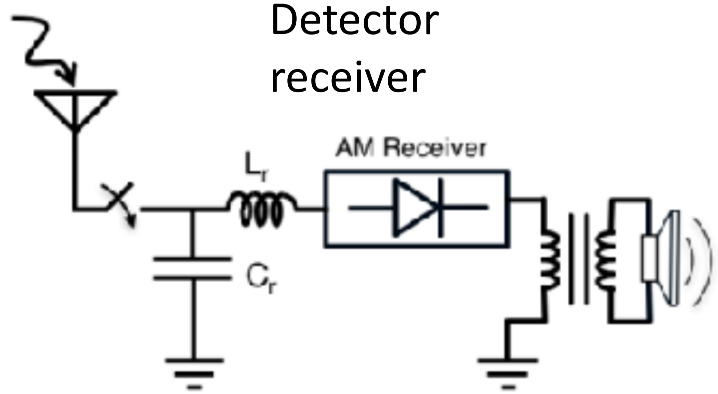
Battery-free phone?

Sending speech

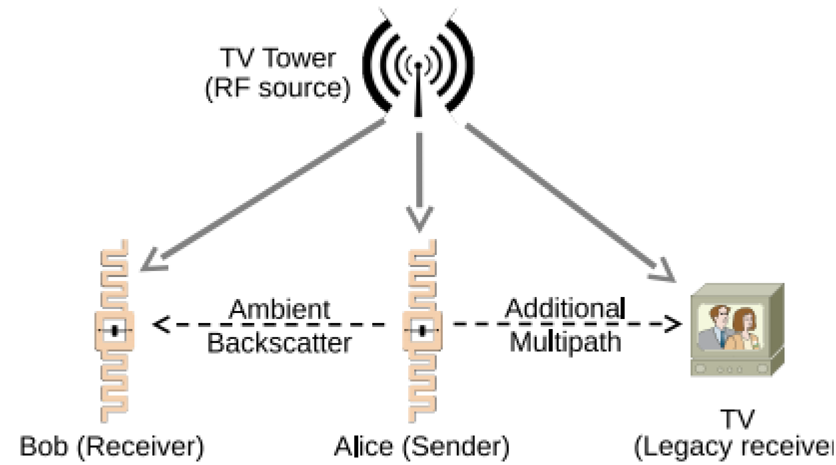


(a) System architecture for transmitting speech at the battery-free phone

Detector receiver



(b) System architecture for receiving speech from the battery-free phone

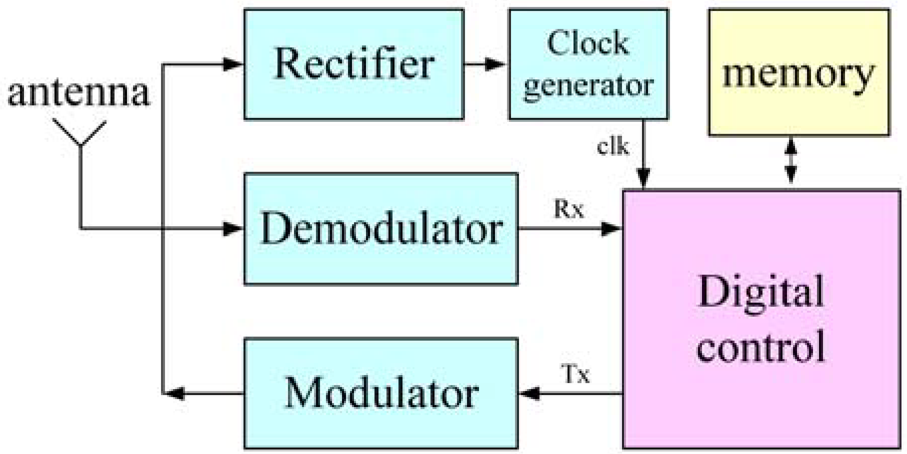


- Communications' using ambient energy
- Passive mic

Joshua R. Smith, (NASA) Passive Wireless Sensor Technology Workshop, WiSEE
Montreal, October, 2017

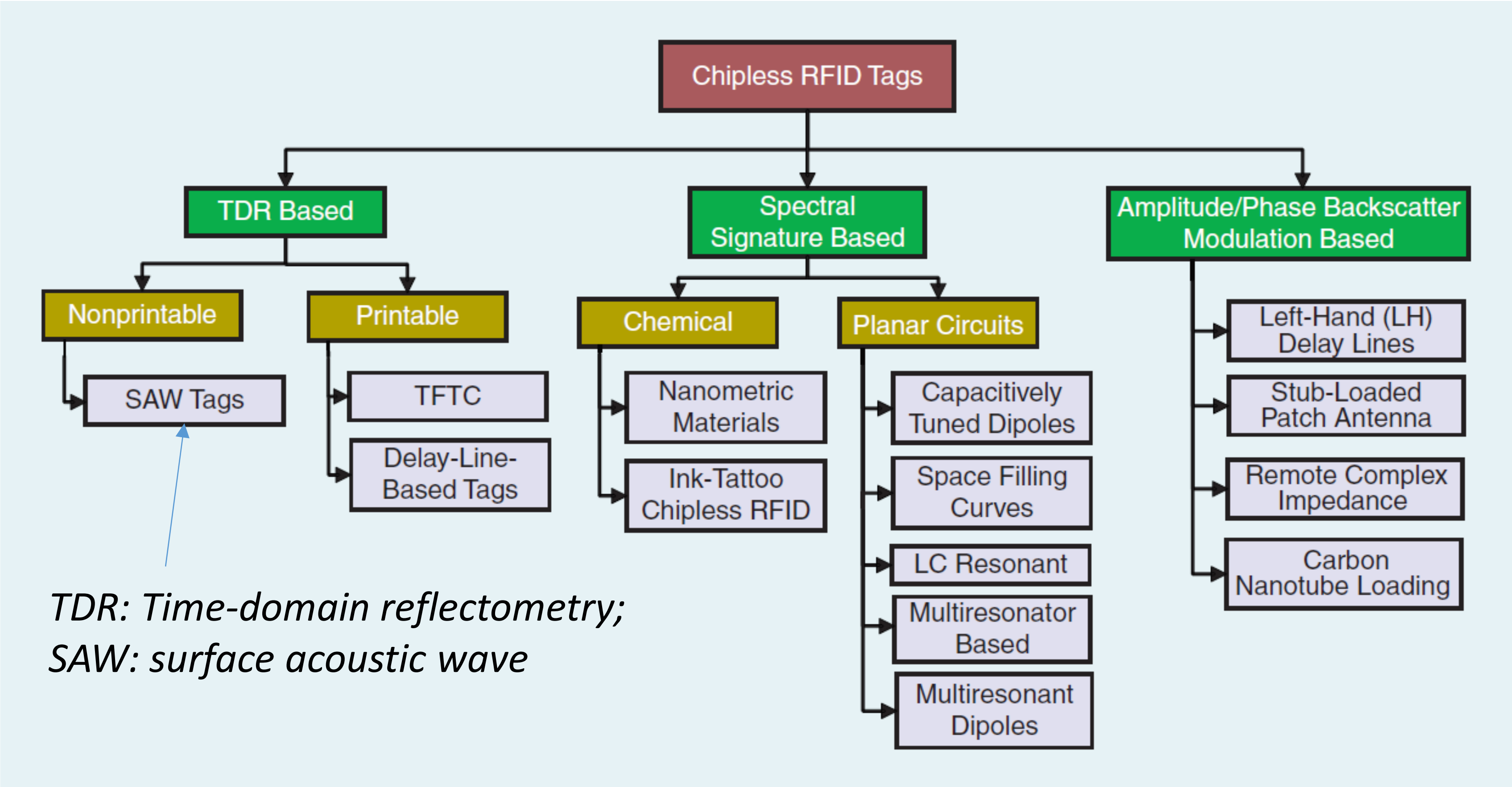
What is wrong with semiconductor RFID tags?

- Easy to read/re-write; unauthorized access
- Sensitive to high temperature
- Sensitive to ionizing radiation
- High EM power demanded for >2 m reading distance
- Privacy issues



Semiconductor chip based passive RFID (and sensors) get power from radio signal, rectifying it and accumulating the energy. For that the RF voltage of about 0.25V must be present on antenna

Passive "chipless" tags and sensors



SAW sensors:

1. SAW/STW resonator based
2. Delay Line based

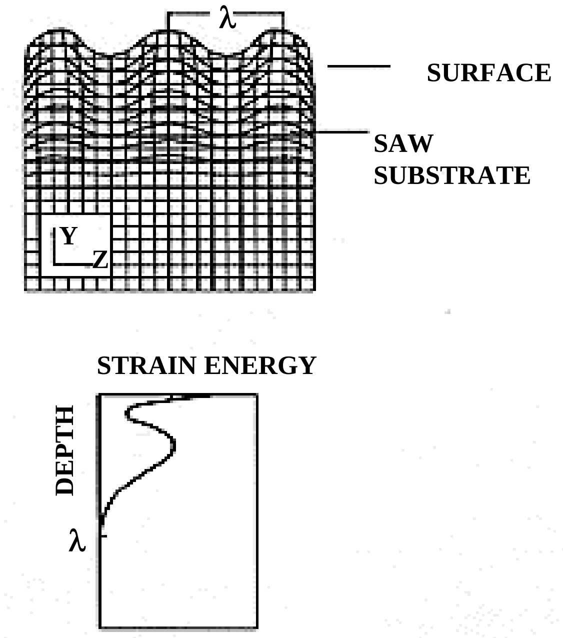
SAW-tags:

1. (Reflective) DL
2. Utra-Wide-Band (UWB), mainly, delay line type

[3] S. Preradovic and N. C. Karmakar, "Chipless RFID: Bar Code of the Future," in *IEEE Microwave Magazine*, vol. 11, no. 7, pp. 87-97, Dec. 2010.

Fundamentals of SAW sensing

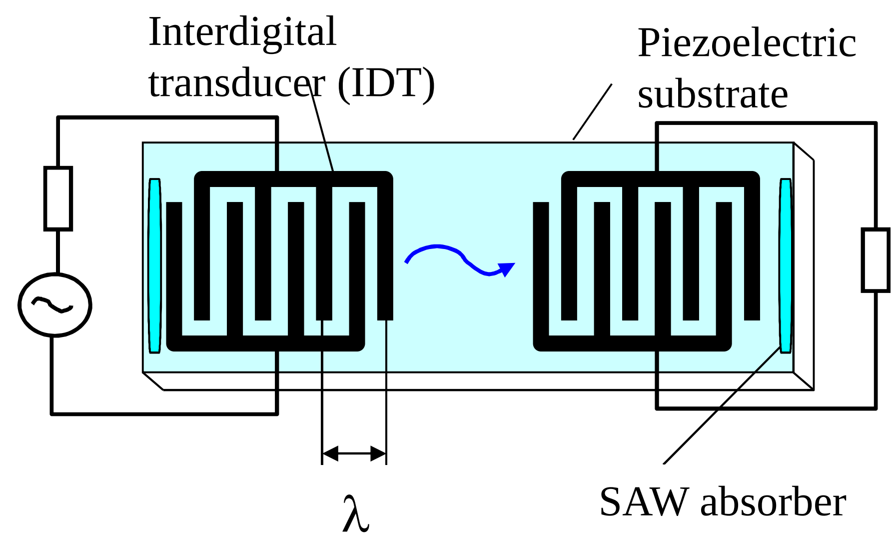
Surface acoustic wave (Rayleigh wave):



Phase velocity for ST-X quartz V_R = 3159 m/s

For f = 433 MHz wavelength λ = 7.3 μm.

Excitation of SAW



Phase delay: $\phi_0 = 2\pi f L/V_R = 2\pi f\tau$

Temperature sensing: $\phi(T) = 2\pi f L(T)/V_R(T) \approx \phi_0 (T - T_0)$ TCD

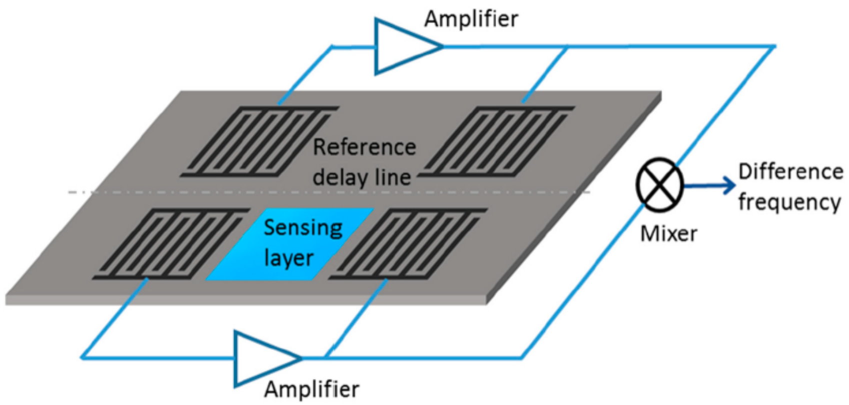
Strain sensing: $\Delta V_R = V_R S_v s$, $\Delta\phi = 2\pi f\tau(1 - S_v)s = 2\pi f\tau S_s s$, S_s = 1.25 ppm/μstrain for ST-X quartz.

Mass load sensing: $\Delta V_R/ V_R = -2\pi f h[c_1(\rho - \mu/ V_R^2) + c_2\rho + c_1(\rho - 4\mu/ V_R^2(\lambda+\mu)/(\lambda+2\mu))]$

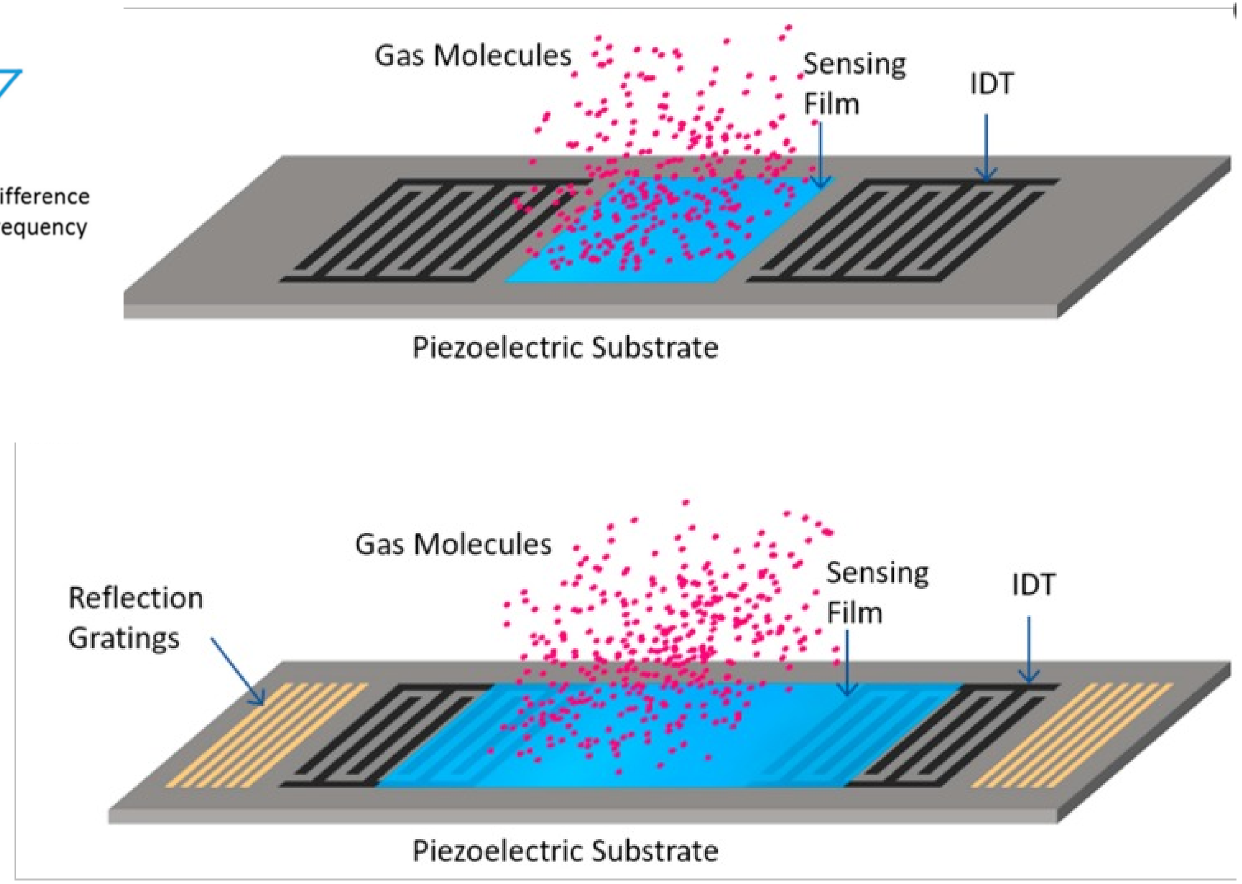
$$\Delta\phi/\phi_0 = -\Delta V_R/ V_R$$

Thanks to V.A. Kalinin

Classic SAW sensors, wired

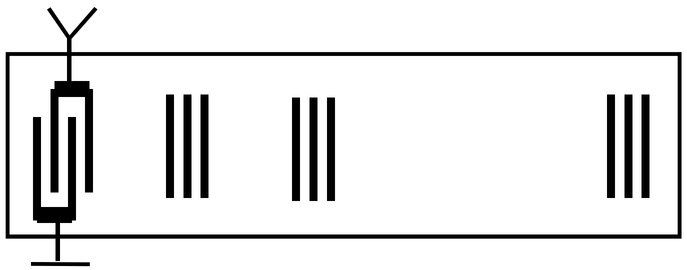


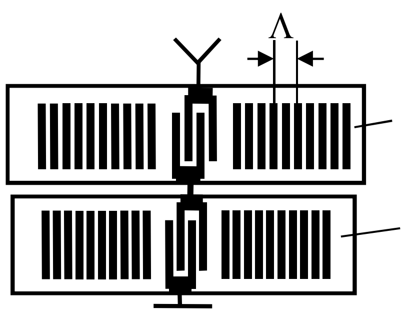
- Direct measurement of mass, $\Delta f \sim f^2$
- Acousto-electric, viscosity, ε
- Stability, aging, calibration
- Selectivity
- cost



Jagannath Devkota, Paul R. Ohodnicki and David W. Greve “SAW Sensors for Chemical Vapors and Gases”, Sensors 2017, 17(4), 801; doi:10.3390/s17040801“

Types of SAW sensing elements for remotely controlled sensors

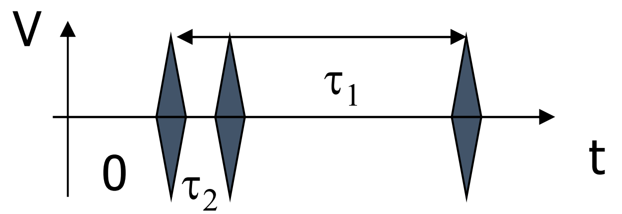




$f_r \approx V_R/\Lambda$

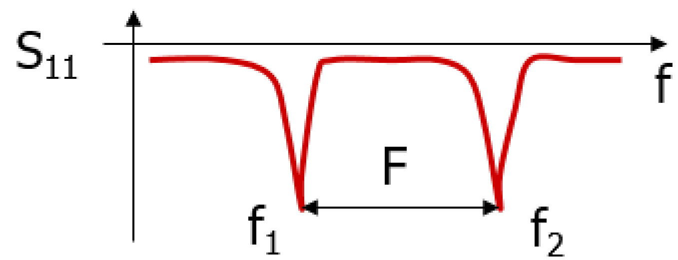
$\Delta f_r / f_r = -\Delta\phi/\phi_0$

- **Reflective delay lines:**



Phase delay measurements: $\Delta\phi_1 = 2\pi f_0 \tau_1 S_s s$

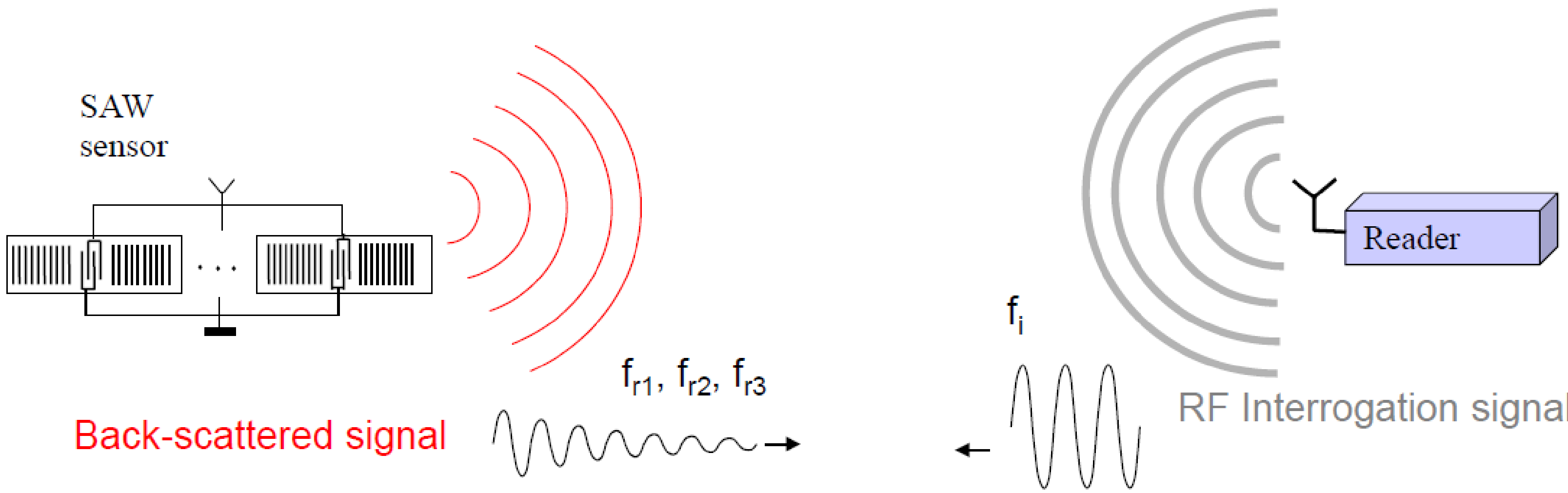
- **One-port resonators:**



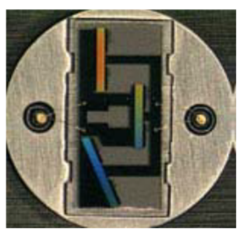
Common mode interference rejection is achieved by means of differential measurements

Thanks to V.A. Kalinin

SAW resonator based sensors



- High Q-factor is demanded, Q>9000
- Often 434MHz ISM band is used
- ST-quartz
- Reference resonator(s) to measure the desired influence and to exclude temperature effects

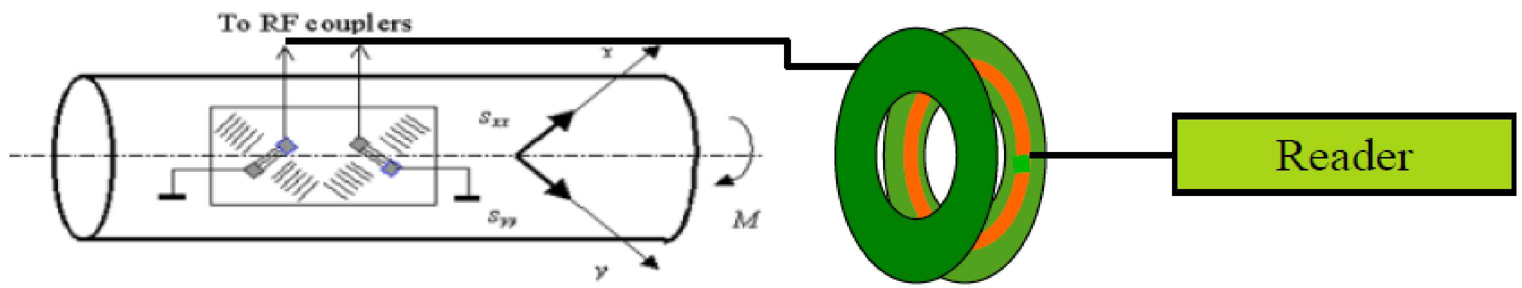


- Shifts due to impedance changes in the radio channel
- Antenna matching

B. Dixon, **V. Kalinin**, J. Beckley and R. Lohr, "A Second Generation In-Car Tire Pressure Monitoring System Based on Wireless Passive SAW Sensors," *2006 IEEE International Frequency Control Symposium and Exposition*, Miami, FL, 2006, pp. 374-380.

Will passive SAW sensors survive?

- High temperatures (>150°C)
- No access to sensor (e.g. inside concrete or rotating parts)
- Very low power of EM radiation demanded
- High radioactivity



Y+34° cut quartz die, 4 × 6 mm,
Sensing element HFSAW:

- M1SAW: $f_1 \cong 437$ MHz,
- M2SAW: $f_2 \cong 435$ MHz,
- TSAW: $f_3 \cong 433$ MHz.

[4] V. Kalinin, "Wireless physical SAW sensors for automotive applications," *2011 IEEE International Ultrasonics Symposium*, Orlando, FL, 2011, pp. 212-221.

Tire pressure and temperature sensor (Transense)

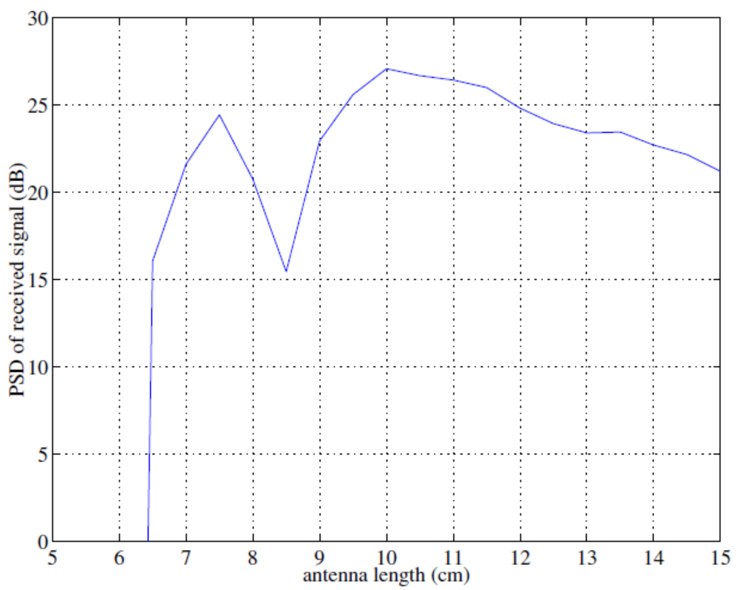


Figure 4. Received signal strength vs. sensor antenna

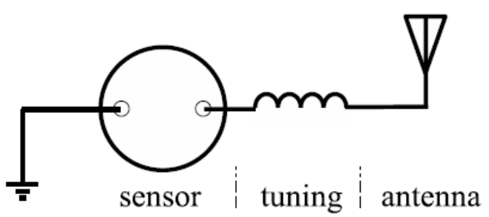
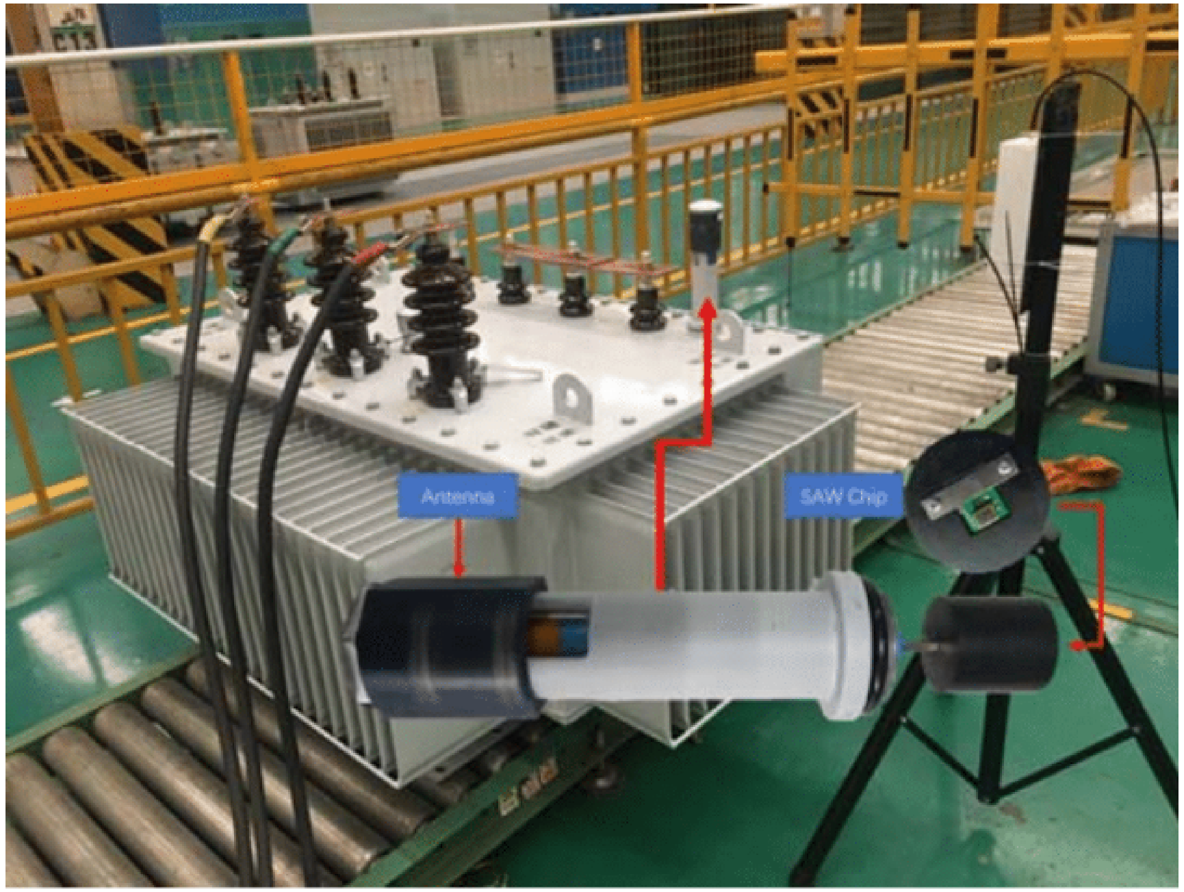


Figure 5. typical antenna tuning configuration

- In order to best measure the frequency of the received signal, a long decaying signal is preferable
- Interrogation of the resonant sensor is performed in the Interrogation of the resonant sensor is performed in the time domain by means of short RF pulses time domain by means of short RF pulses
- each individual SAW is excited several times, and their resulting responses coherently accumulated
- pressure resolution better than 0.4psi, and 0.5°C

Passive and Wireless SAW Sensor in Smart Grid



- Harsh environment: strong electric& magnetic fields, high temperatures are possible
- high operational reliability, low fault rate, long lifetime, and the batteries, no batteries
- low price
- anti-interference performance, low false alarm rate and missing rate

Tao Han, Chenrui Zhang and Yang Yang, "The Last Mile" of Passive and Wireless SAW Sensor in Smart Grid, Seventh International Symposium on Acoustic Wave Devices for Future Mobile Communication Systems, Ciba, Japan, 2018

Very high temperatures

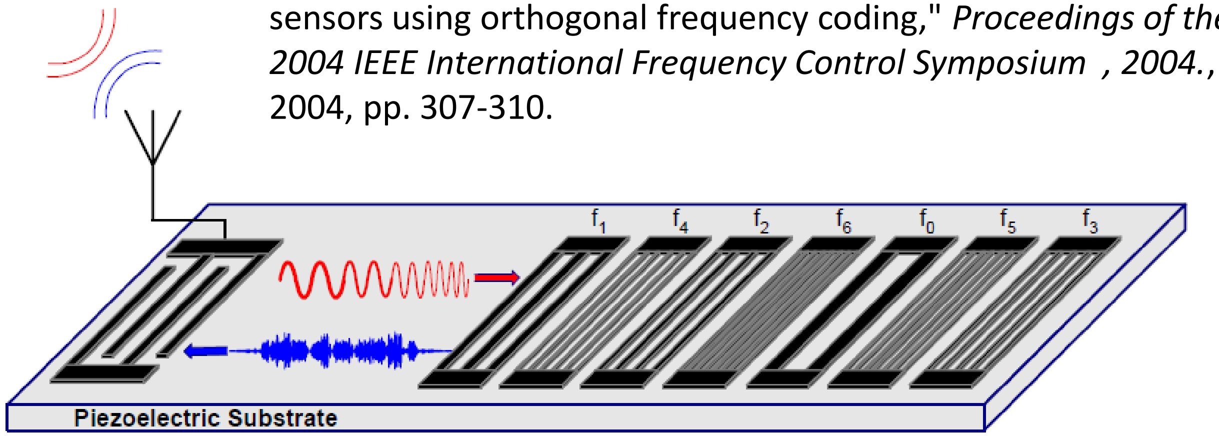
Material	$GaPO_4$	LN	LGS	YCOB	GdCOB
T_{max} (°C) (phase transition or melt)	970	1150	1470	1510	1470
T_{use} (°C) (suggested usage temp) #	700	600	800	~1,250	<1,200
Temperature limited by	Phase transition & attenuation	Resistivity	Resistivity	Resistivity	Resistivity
Mechanical quality factor †	10,000	2,000	15,000	9,000	5,000
Measured temperature (°C)	800	500	600–500	1,000–800	1,000–800
Dielectric loss	0.15	5.5	0.5–0.2	0.3–0.1	0.3–0.2
Dielectric permittivity variation (%)	5	~40	25–15	15–10	10–9
Resistivity (Ω)·cm;	2.3×10^7	6.6×10^5	2×10^6–8×10^6	1×10^7–2×10^8	4×10^6–3×10^7

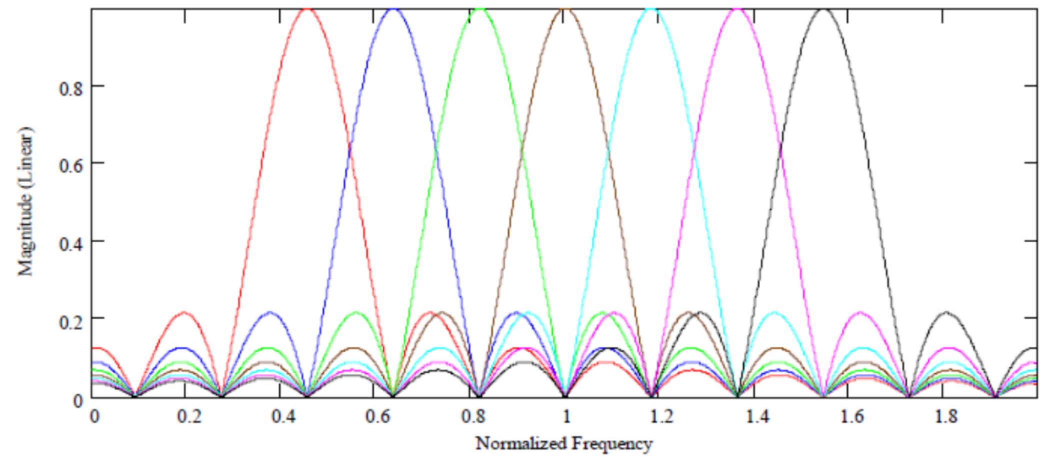
- Great demand in the automotive, aerospace, and energy industries
- Degradation of piezoelectrics
- Degradation of electrodes
- Packaging

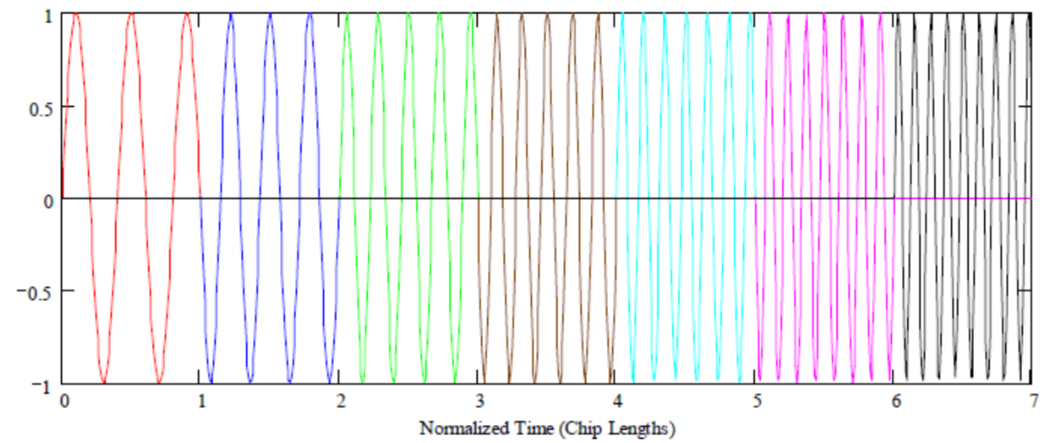
Xiaoning Jiang, Kyungrim Kim, Shujun Zhang, Joseph Johnson and Giovanni Salazar, "High-Temperature Piezoelectric Sensing", *Sensors* **2014**, *14*(1), 144-169;

Malocha's "orthogonal coding" in SAW sensors (I)

D. Puccio, D. C. Malocha, D. Gallagher and J. Hines, "SAW sensors using orthogonal frequency coding," *Proceedings of the 2004 IEEE International Frequency Control Symposium , 2004.*, 2004, pp. 307-310.







- 7 fr. carriers, Fc=250MHz, B/Fc=25%
- T=700ns, B*T $\cong$ 45;
- Processing gain about 16dB

Malocha's "orthogonal coding" in SAW sensors (II)

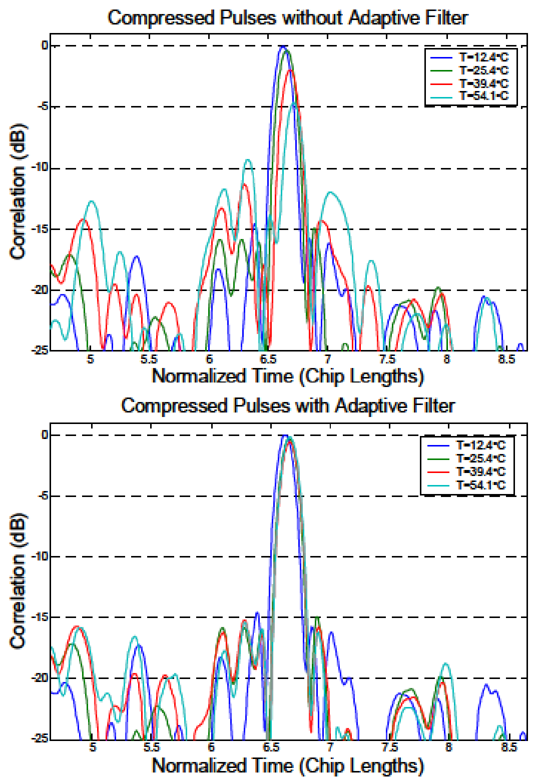


Figure 7. Degradation of compressed pulse response over temperature using static matched filter (upper), and improved compressed pulse response using adaptive matched filter (lower).

- Every SAW unit must be designed individually
- For a given total frequency range the icrease of the number of "carriers" will result in quadratic grows of the device length
- The "reader" must use all IDT combinations for correlation to find correct pulse
- Moreover, the temperature changes destroy the correlation, as on the left side figure

SAW RFID tags

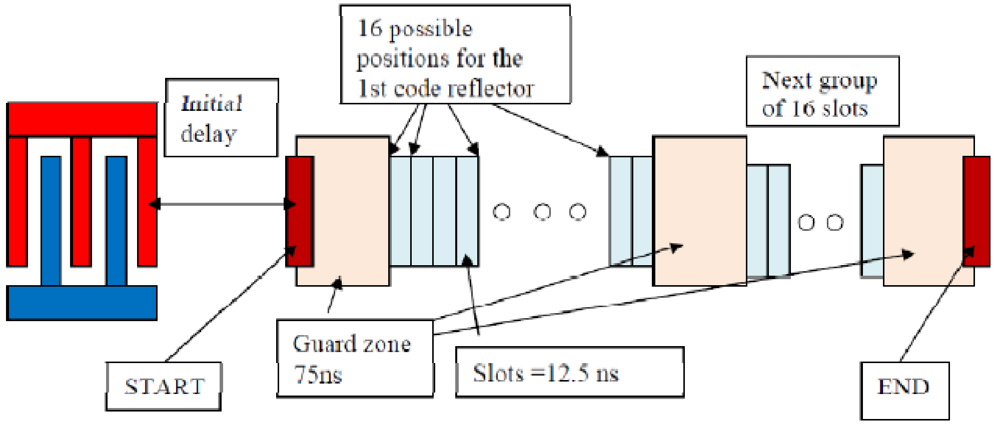


Fig.1 Slots & groups

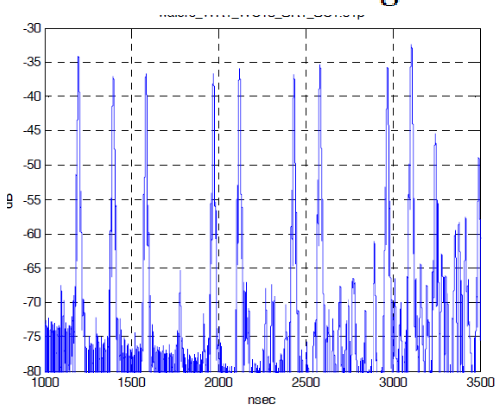
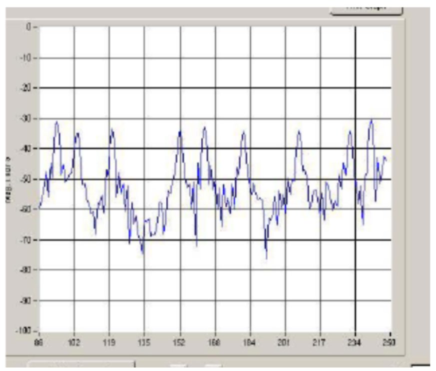


Fig.8 On wafer probed D7 tag, time domain

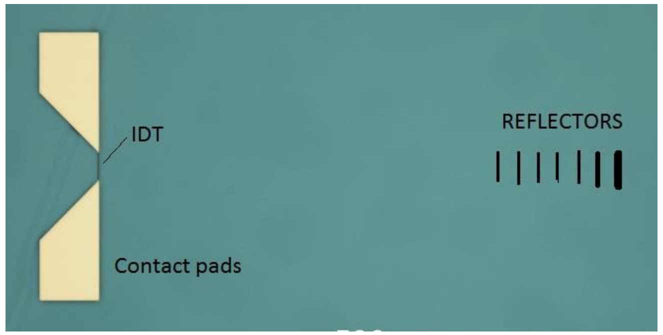


On the reader screen

- ISM frequency band: 2400 MHz –2483.5 MHz
- 24 bits of code (~1.7*10^7)
- The were minimized to a record level of about 37dB for code responses by using a uni-directional transducer (SPUDT, group type) and by decreasing the total number of reflectors
- Reflectors weighted to get uniform pulse amplitudes
- The tag and the reader antennas had directivities of 8dBi and 16.5 dBi respectively. The reading distance of the D7 tag was up to 11m for indoor measurements and **13m** in open space.
- “Collision” Problem

V. Plessky, T. Ostertag, V. Kalinin and B. Lyulin, "SAW-tag system with an increased reading range," *2010 IEEE International Ultrasonics Symposium*, San Diego, CA, 2010, pp. 531-534.

6GHz SAW tags



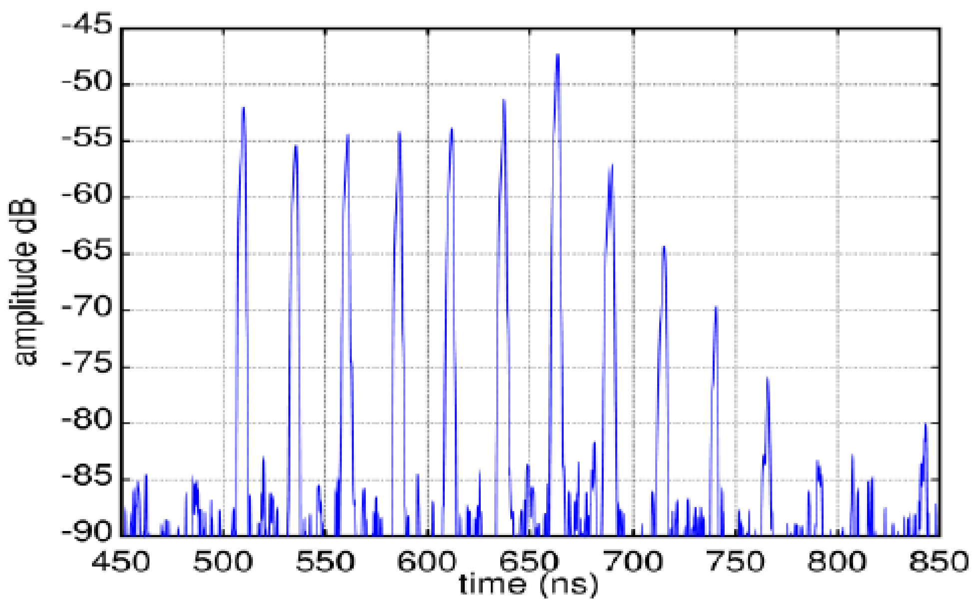
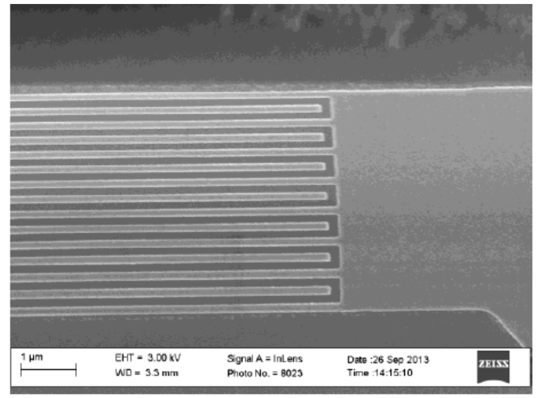
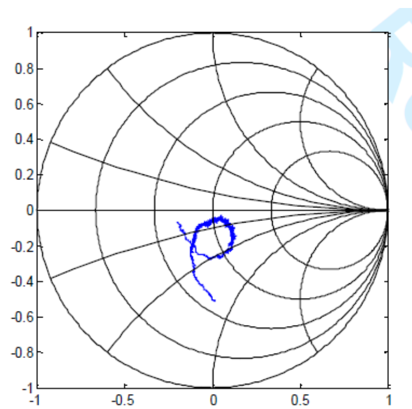


Fig. 6. Measured response in time domain, dB scale



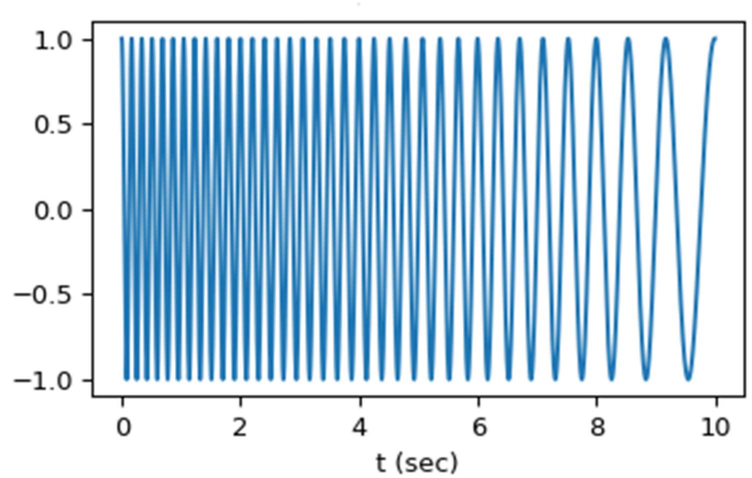


- The tag contains an ordinary IDT consisting of N =15 aluminum electrodes (with metallization coefficient m/p = 0.5 and pitch p = 0.313µm), and 7 weighted reflectors ("Start" reflector + 5 code reflectors + "End" reflector).
- loss level of approximately 55dB
- only 0.5µs of delay (about 1 mm of space) for coding, with B>500MHz we have B*T>250 which provides practically infinite number of codes

V. P. Plessky, M. Lamothe, Z. J. Davis and S. G. Suchkov, "SAW tags for the 6-GHz range," in *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, vol. 61, no. 12, pp. 2149-2152, Dec. 2014.

Recent developments

Why to use the chirp signals in sensors?



Linear Frequency modulation

$$f(t) = f_0 + kt,$$

$$x(t) = \sin\left[\phi_0 + 2\pi\left(f_0 t + \frac{k}{2}t^2\right)\right]$$

- The sensor will give a unique response, different from environmental reflections
- B*T product (B= fr. band, T=duration) is important. Signal can be compressed B*T times, and the duration of compressed pulse is about 1/B.
- The signal-to-noise ratio (S/N) is increased 10*log10(B*T) dB resulting in longer reading distance

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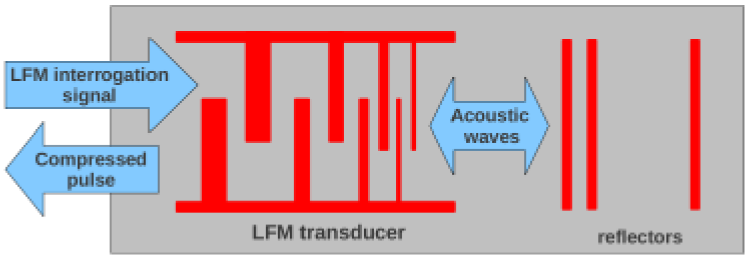
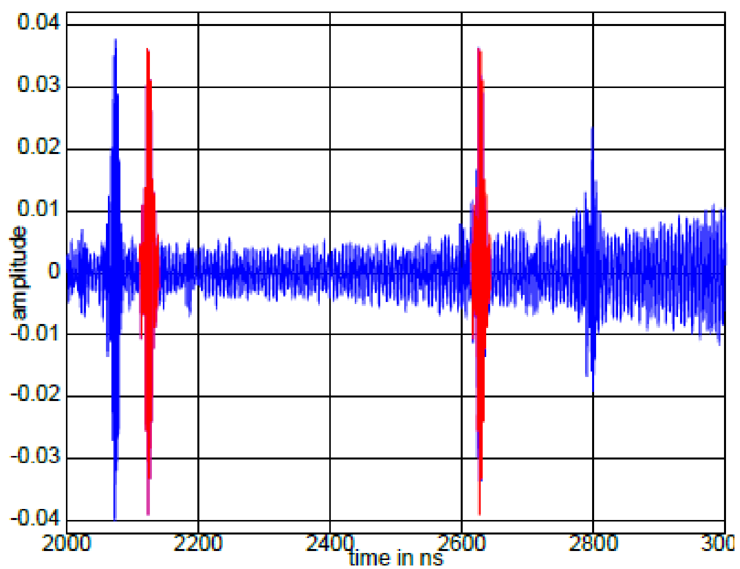
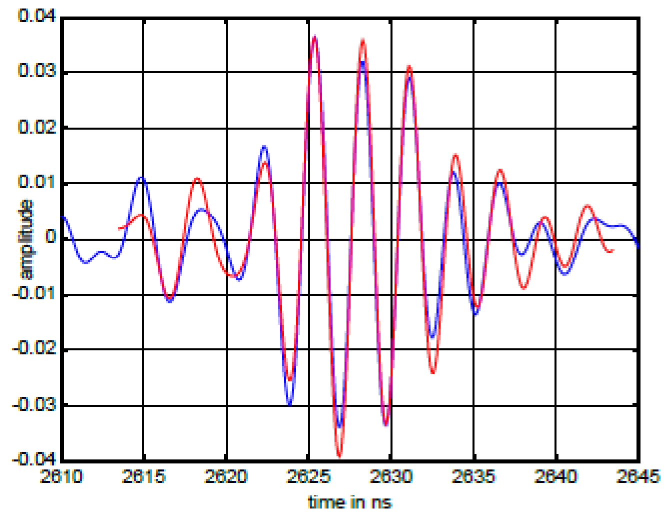
Ultra-Wide frequency Band (UWB) 200MHz -400MHz

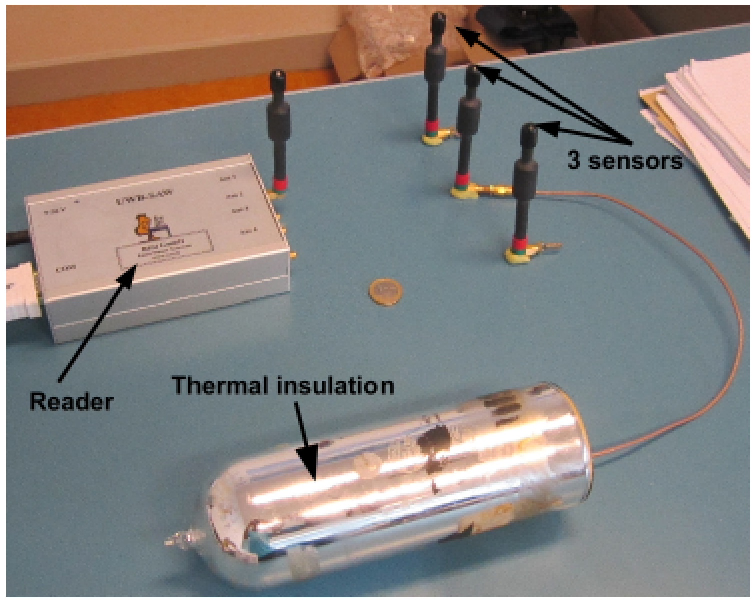


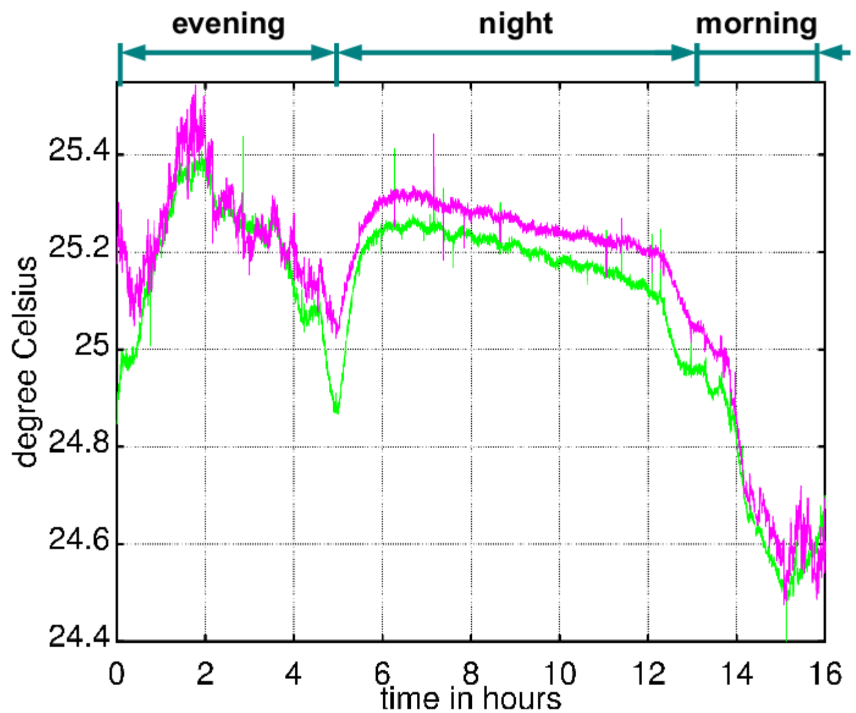




- Band 200 MHz-400 MHz
- T=0.5 us, B*T=100
- LFM signal, negative rate of the fr. change
- Unique shape of compressed pulse = no 2π ambiguity
- Limited BT; strongly corrupted LFM signal
- Not optimized losses
- Demands measured impulse response for compression algorithm

Ultra-Wide frequency Band (UWB) 2.0GHz -2.5 GHz

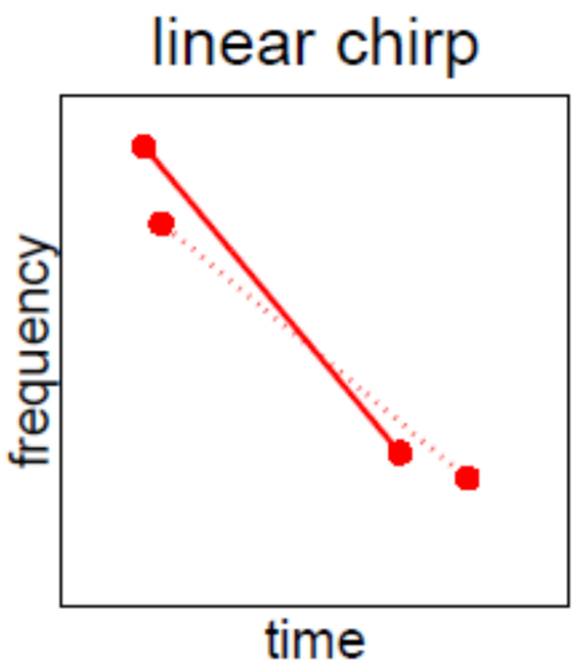




- center frequency 2250 MHz, B = 500 MHz, T =100ns
- Estimated temperature measurement precision is 0.1 °C

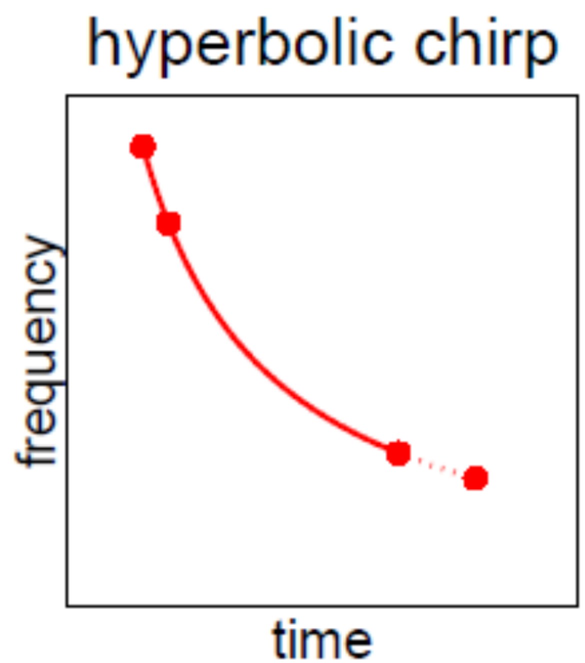
V. Plessky and M. Lamothe, "Ultra-wide-band SAW RFID/sensors," *2014 European Frequency and Time Forum (EFTF)*, Neuchatel, 2014, pp. 16-23.

But do the bats and delphiens use LFM chirps?

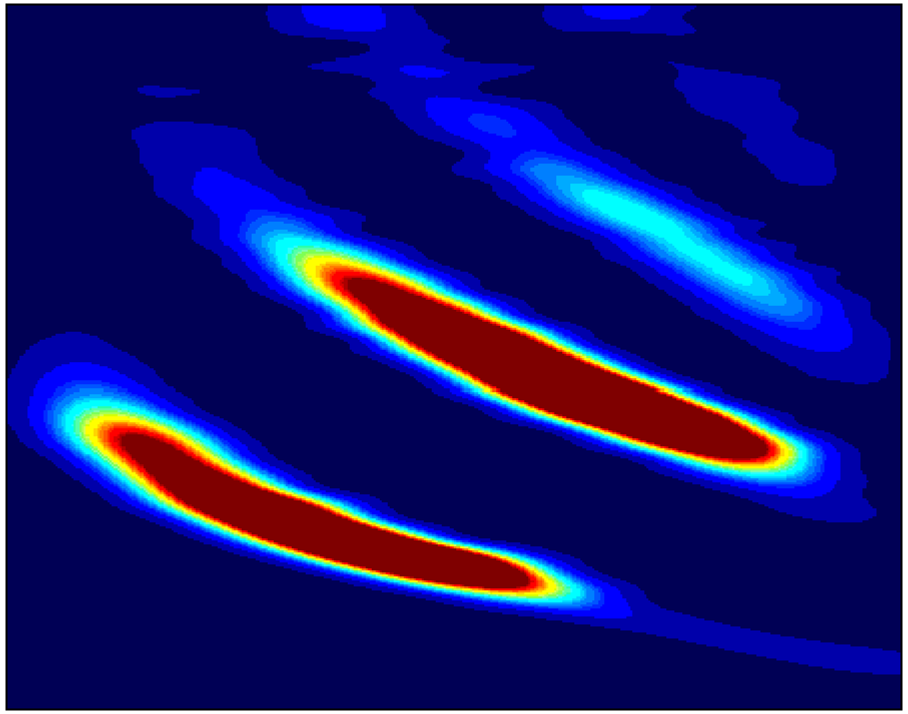


$$B*T*(K-1) > 1$$

(K- scaling factor)
LFM signal compression deteriorates significantly

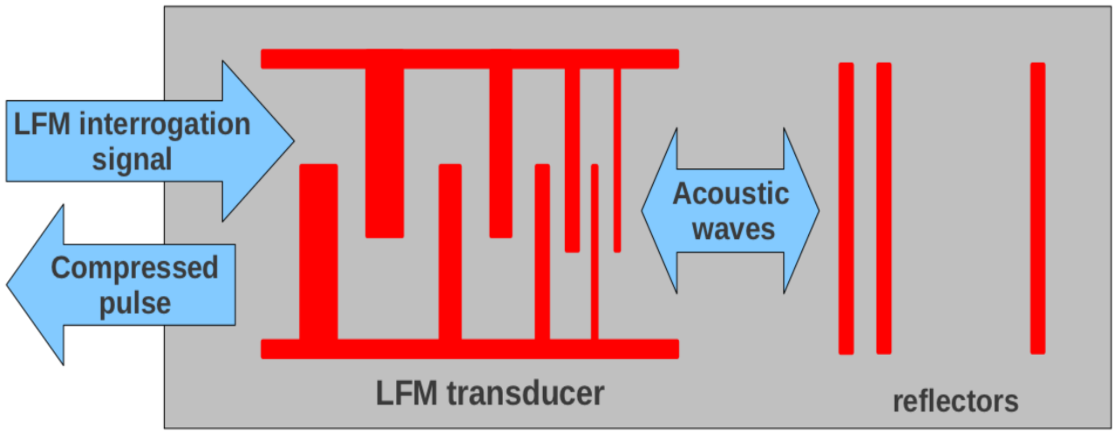


No visible deterioration of compressed pulse



horizontal axis: time (0-2.5ms),
vertical axis: frequency (0-70kHz)

Purely geometric problem: linearly increasing period



$$x_{n+1} - x_n = p_0 + \varepsilon \cdot x_n$$

This formula can be treated as an equation in integer numbers, which has unique solution:

$$x_n = \frac{(1+\varepsilon)^n - 1}{\varepsilon} \cdot p_0$$

If the period of an array increases linearly with coordinate, how can the coordinate x_n of *n-th* element of this array be calculated?
For the geometric structure of electrodes (strips, grooves, etc.) with period linearly changing with coordinate *x* one can write the following relation:

For algebra amateurs (1)

Or, calculating the *n-th* period:

$$\boldsymbol{p_n = x_{n+1} - x_n = (1+\varepsilon)^n \cdot p_0}$$

Two parameters p_0 and ε completely determine the array.

If we fix the first period p_0 and the last period x_{N+1}- x_N =p_{end} we can find that

$$\varepsilon = \left(\frac{p_{end}}{p_0}\right)^{\frac{1}{N}} - 1$$

and re-write the formulas (2) and (3) in the following form:

$$x_n = \frac{\left(\frac{p_{end}}{p_0}\right)^{\frac{n}{N}} - 1}{\left(\frac{p_{end}}{p_0}\right)^{\frac{1}{N}} - 1} \cdot p_0 \quad , \boldsymbol{p_n = \left(\frac{p_{end}}{p_0}\right)^{\frac{n}{N}} \cdot p_0}$$

For algebra amateurs (2)

If the total length $L=x_N$ of the structure is known the number of periods N:

$$\left(\frac{p_{end}}{p_0}\right)^{\frac{1}{N}} = 1 + \frac{p_{end}-p_0}{L}; \quad x_n = L \cdot \frac{p_0}{p_{end}-p_0} \cdot \left\{\left(\frac{p_{end}}{p_0}\right)^{\frac{n}{N}} - 1\right\}$$

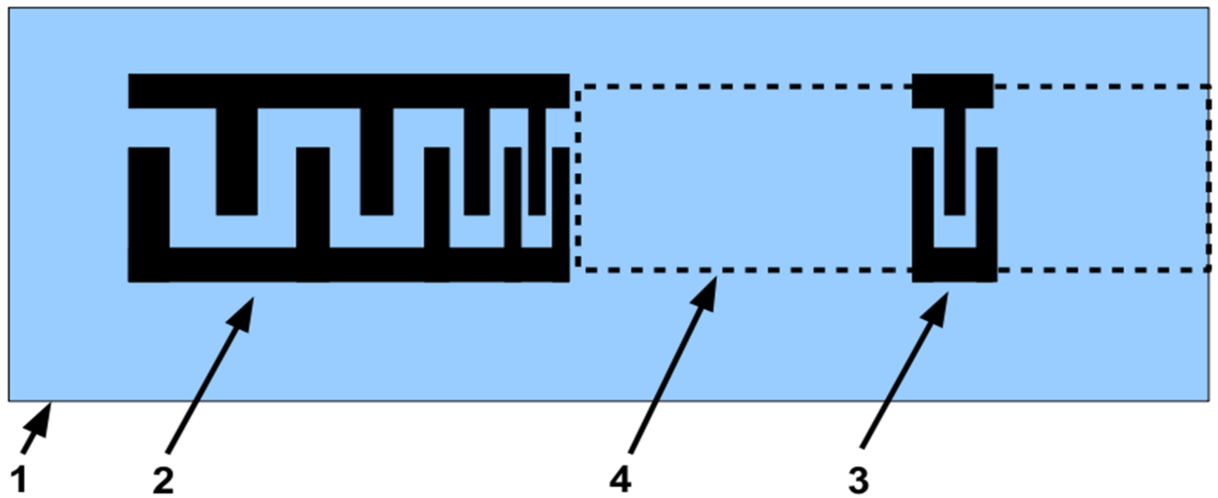
If our structure corresponds to a SAW propagating with velocity *V*, and the periods of the structure are related to frequency as

$$p_0 = \frac{V}{(F_0-\frac{B}{2})}, \quad p_{end} = \frac{V}{(F_0+\frac{B}{2})}$$

(here F_0 is the centre frequency, $|B|$ - the frequency band) , introducing $L= x_N$ – total length, for the case when there is 1 element per period (RACs):

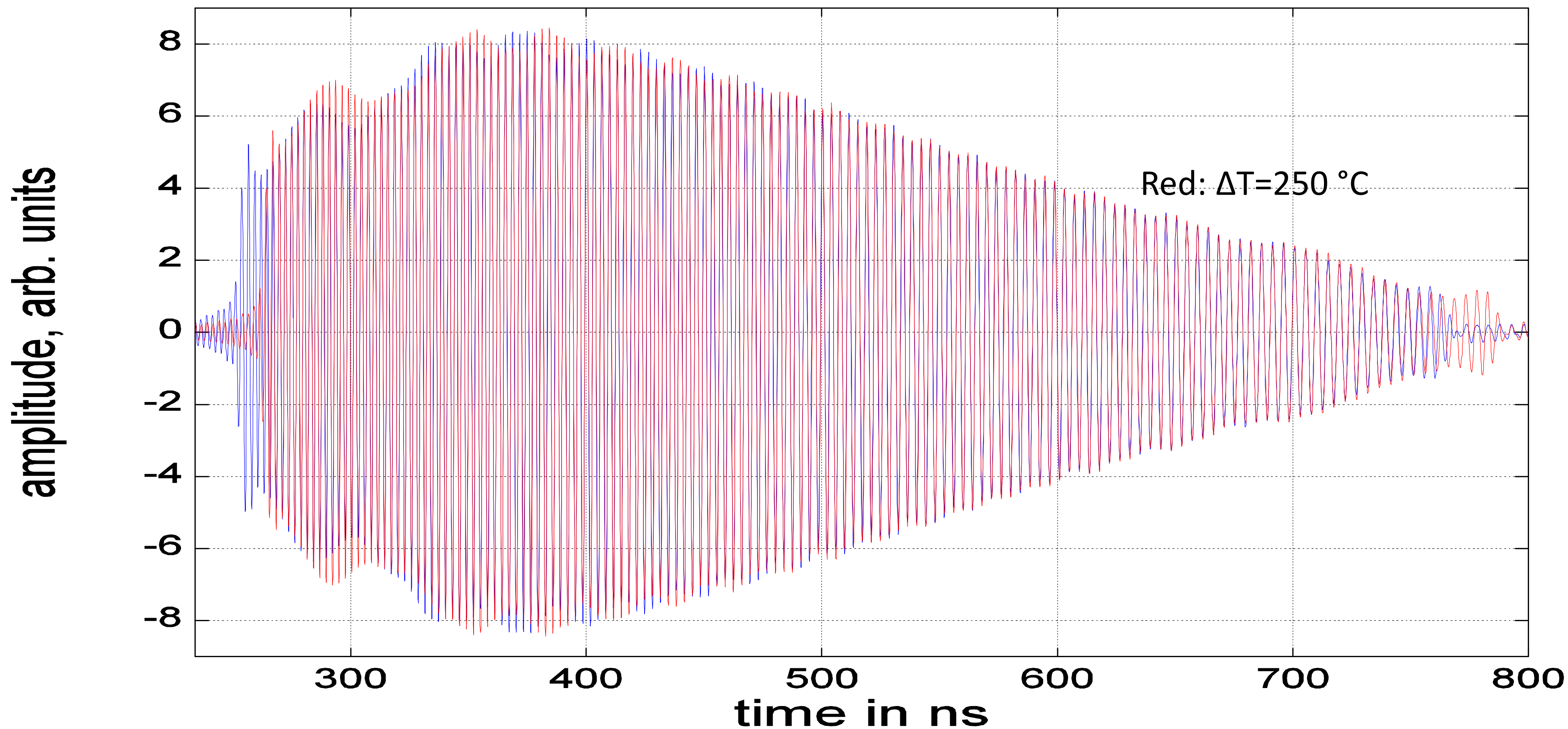
$$x_n = -L \cdot \frac{F_0+B/2}{B} \cdot \left\{\left(1 - \frac{B \cdot V}{L \cdot \left(F_0^2 - \left(\frac{B}{2}\right)^2\right)}\right)^n - 1\right\}$$

Numeric simulations



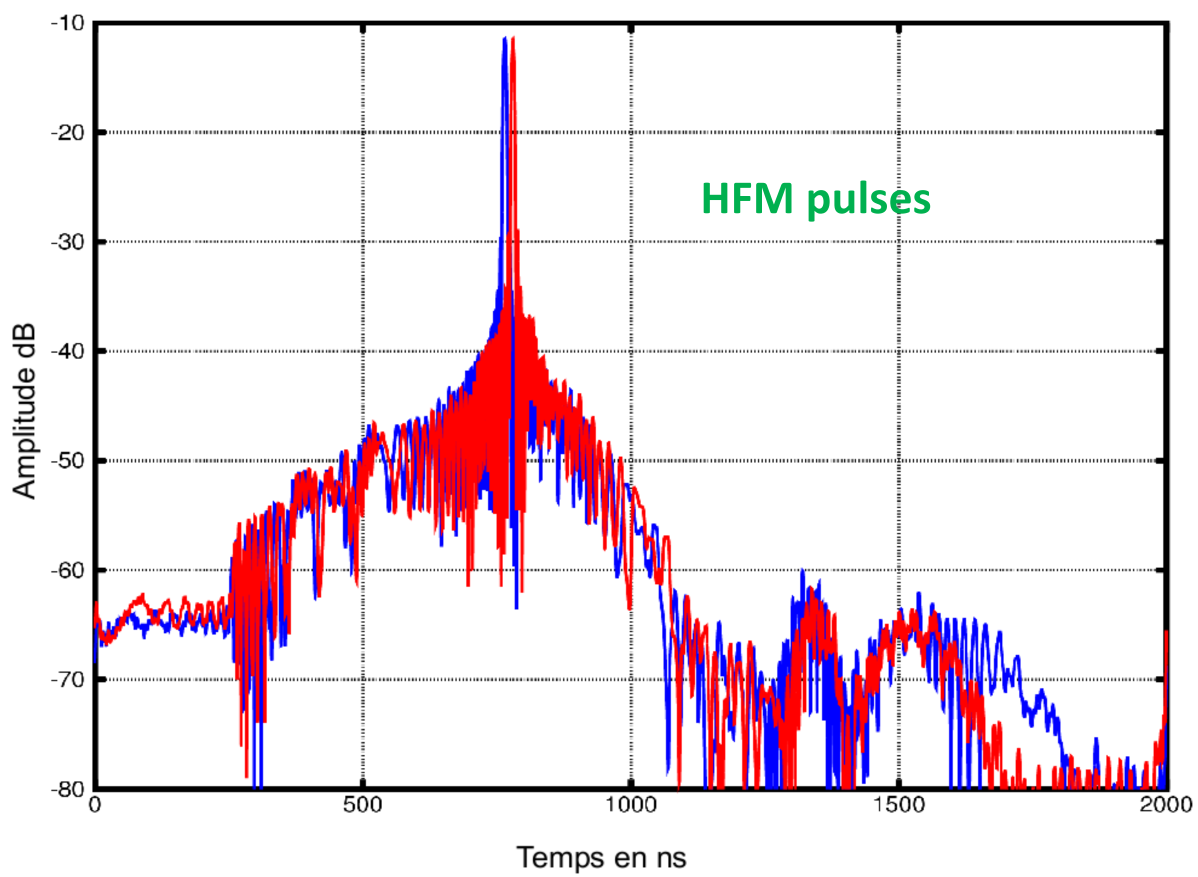
128°-$LiNbO_3$
frequency range 200MHz-400MHz
The dispersive delay time ***T*** is equal to 0.5 µs, B*T product thus being B*T=100
P_0=19.2 µm, p_N=9.6 µm
N=279

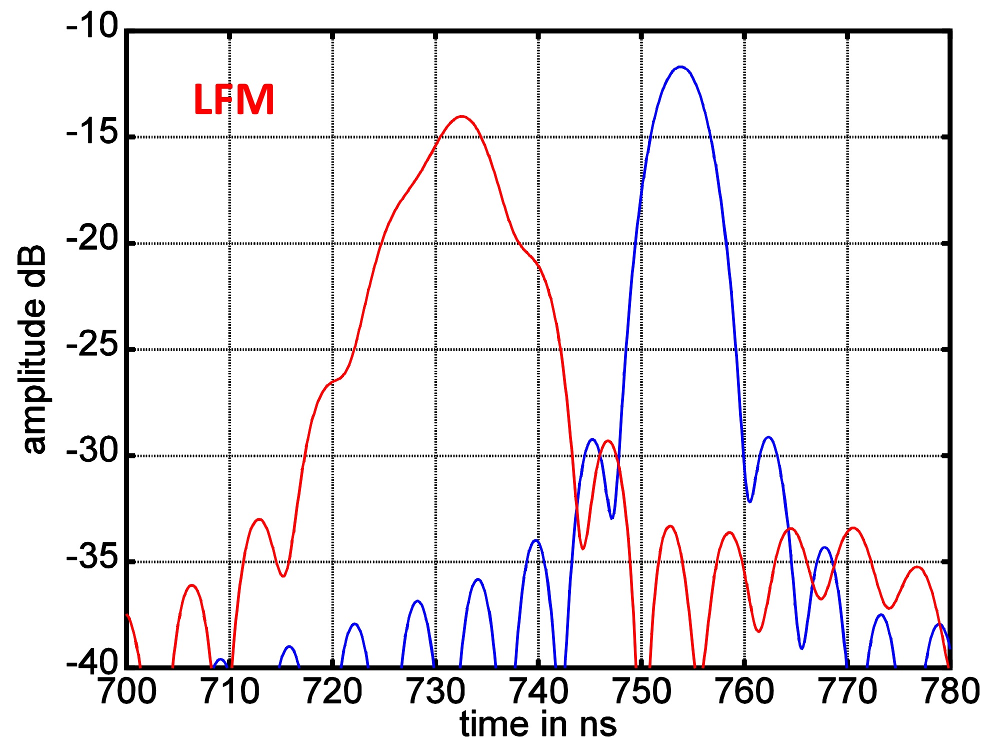
Simulation results



Themain part of this response geometrically is not only similar, but *identical* to the initial response

Compressed peaks





LFM case. Right curve compressed pulse at initial temperature,
left curve – 2% expanded chirp.

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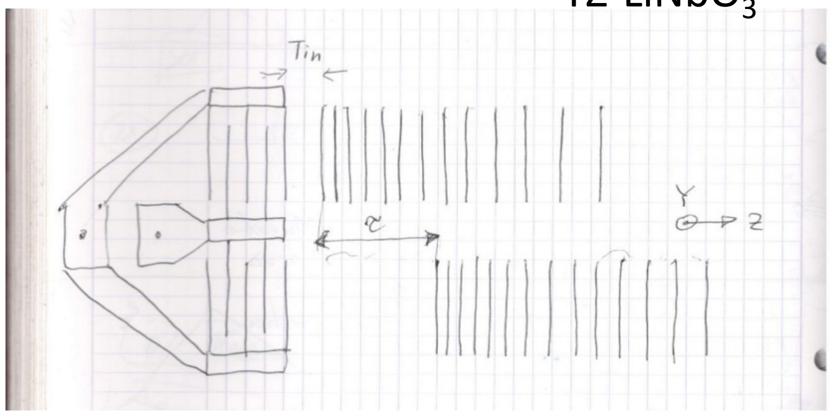
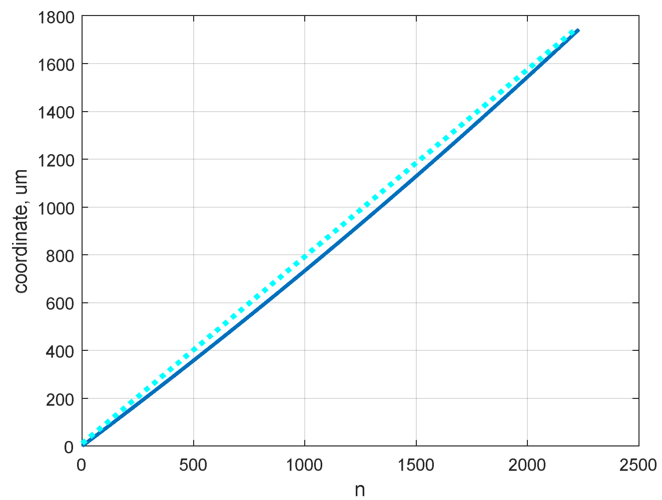
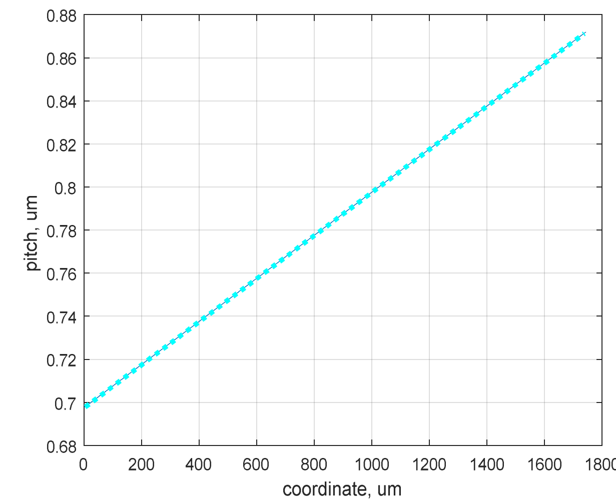
YZ-$LiNbO_3$







F= 2000 MHz to 2500MHz,
p_0=697.6 nm, pN =872.0 nm
N=2231 grooves, for T=1000ns

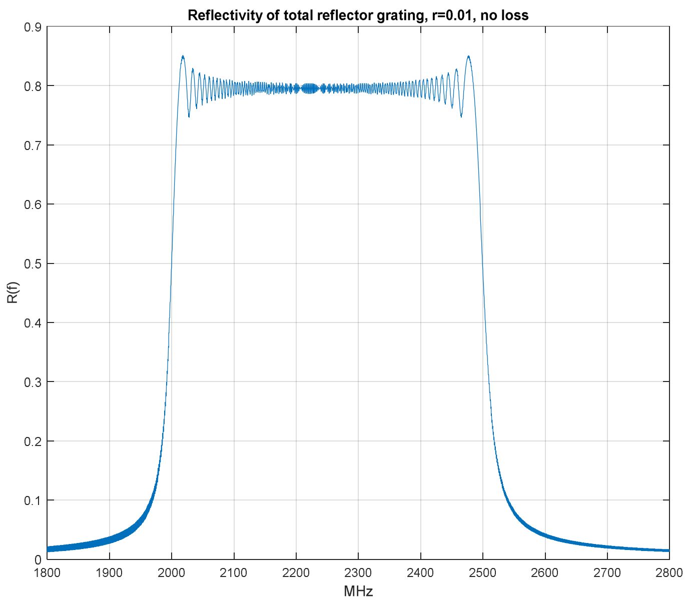
$$L = V * \frac{T}{2} = 1744\ \mu m$$

The coordinate of the grove reflector center
is non-linear but exponential function of its number,
while the pitch of the grating **is** linear function
of the coordinate of reflecting element.

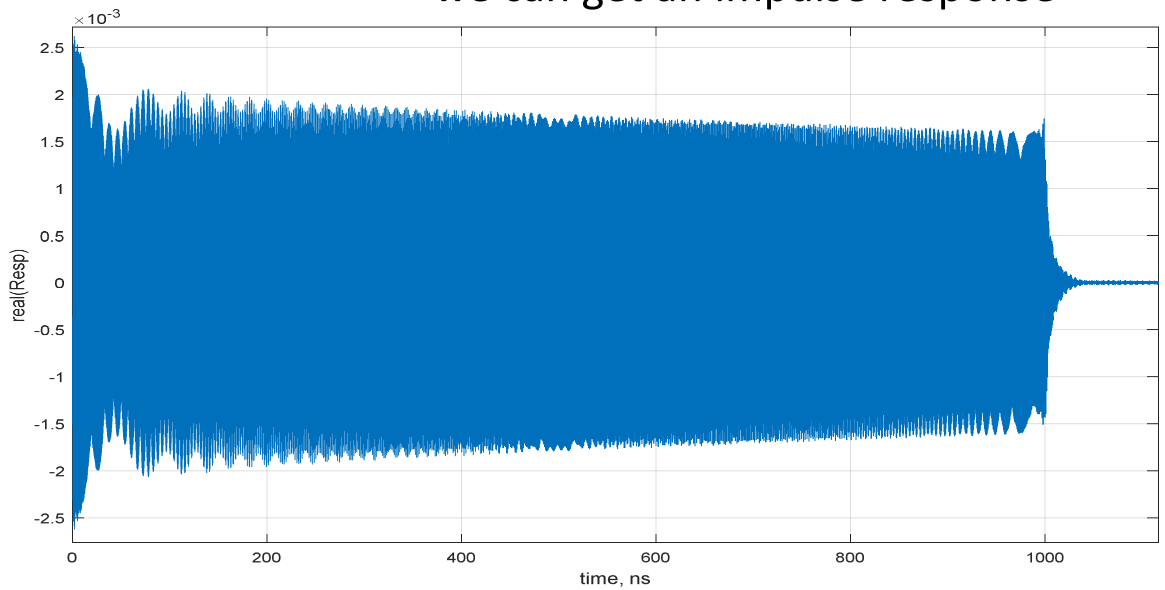
Reflectivity of the chirp grating (no loss included)

For ¦r¦=0.01 – reflection coefficient by a single groove

For *YZ-LN* $r=0.6*(h/\lambda)$; $\lambda \approx 1.55\mu m$, $h \approx 250Å$

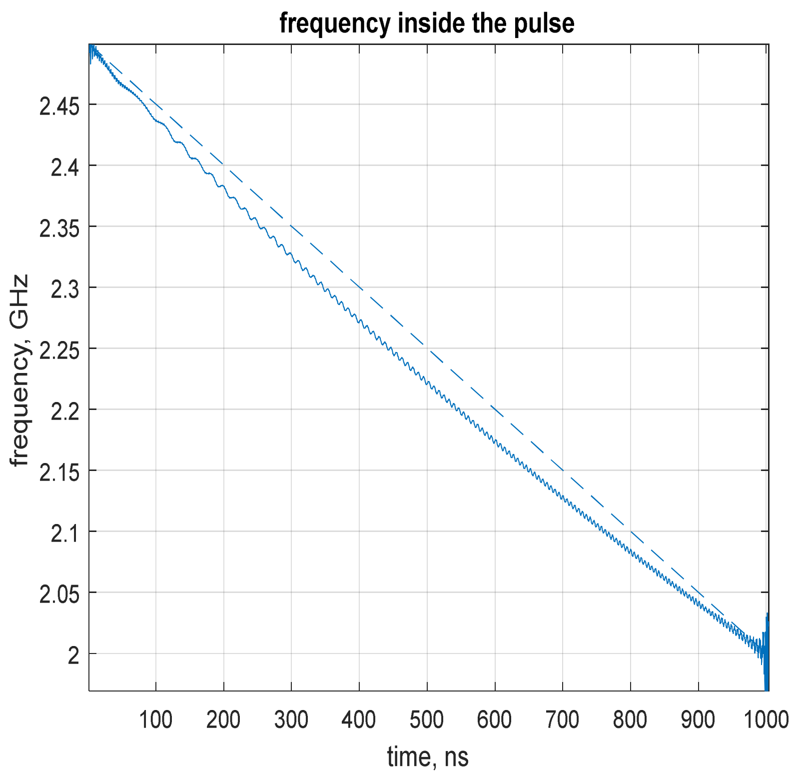


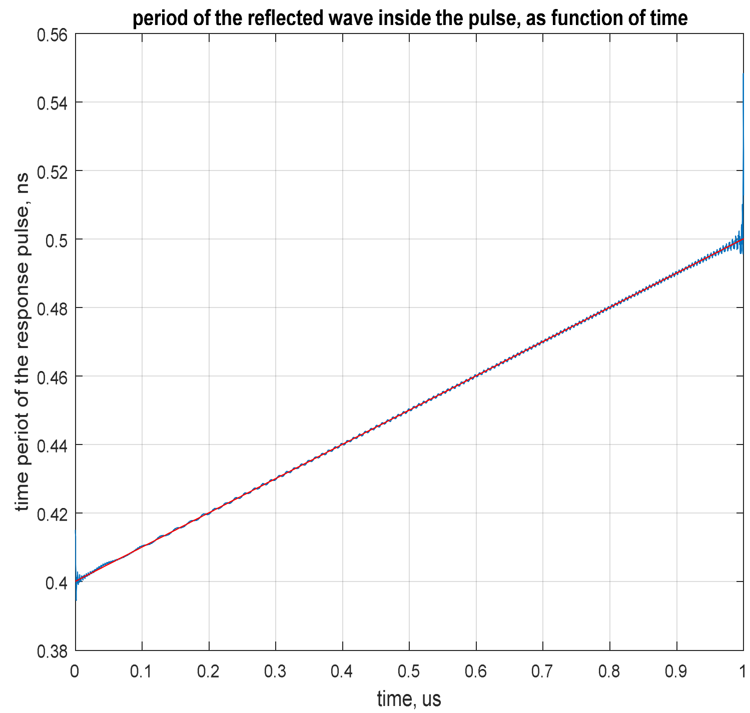
Using Inverse Fast Fourier Transform (IFFT) we can get an impulse response



We have used Nfr=2001 frequency points, fr=[1800:0.5: 2800];

Hyberbolic Frequency Modulation

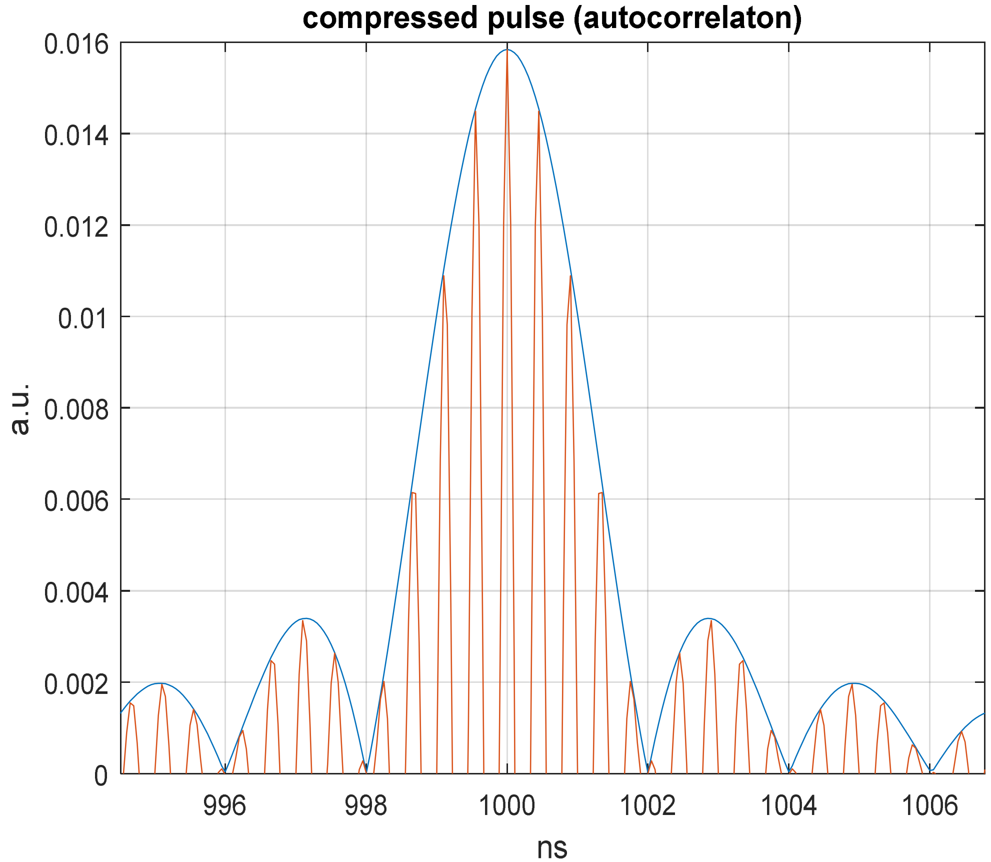




Linear increase of time period (1/f); red line – ideal fitted straight line.
Polynomial fit is
y=0.4001+0.1*t
with the correct beginning period **0.4 ns**= 1/ 2.5 GHz, end period
0.5 ns = 1 /2.0 GHz, and expected rate coefficient (2.5-2.0)/1.0 =0.1.

For comparison:
– dotted straight line

Simulated compressed pulse



The compressed pulse has form close to sinx/x with the width around 1/500MHz = 2 ns. Its form (red line shows *real* part of the signal) is unique, and its position can be determined without uncertainty of phase (2 π). If in a sensor response we will have 2 such pulses, by correlation method we will find the distance between this peaks.

Theoretical (ideal) HFM signal used for compression of sensor response

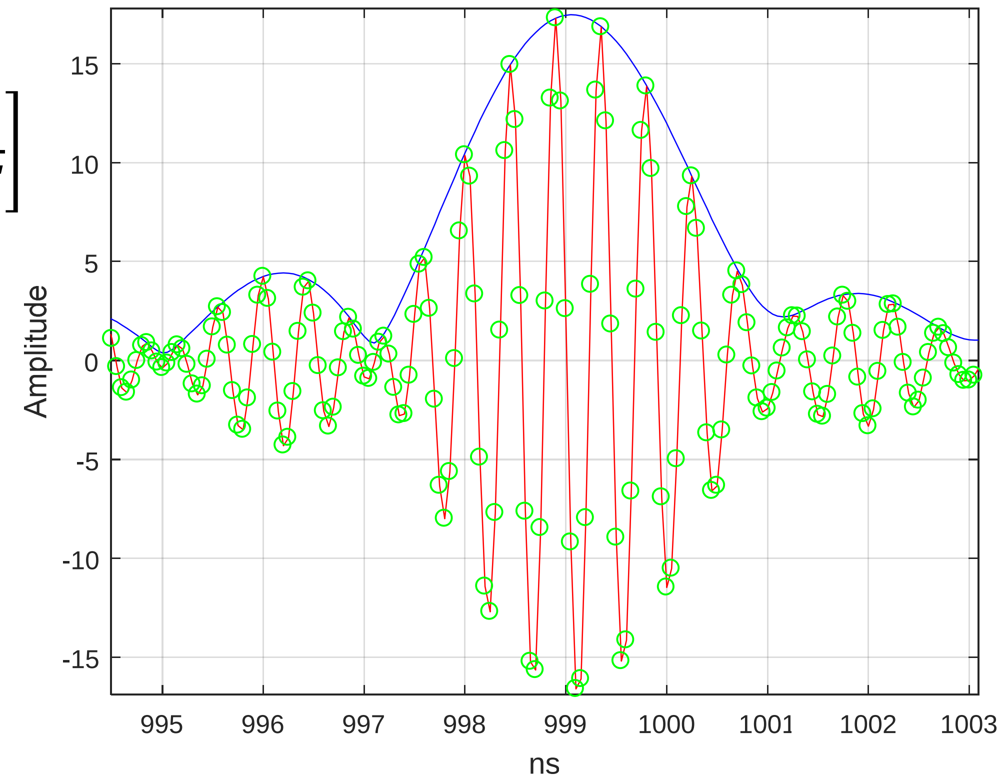
$$T(t) = T_0 + \frac{T_N - T_0}{T} * t$$

Introducing phase

$$\Phi = 2\pi \cdot \int_0^t \frac{dt}{T(t)} = 2\pi \cdot \int_0^t \frac{dt}{T_0 + \frac{\Delta T}{T} \cdot t} = 2\pi \cdot \frac{T}{\Delta T} \cdot ln\left[1 + \frac{\Delta T}{T_0} \cdot \frac{t}{T}\right]$$

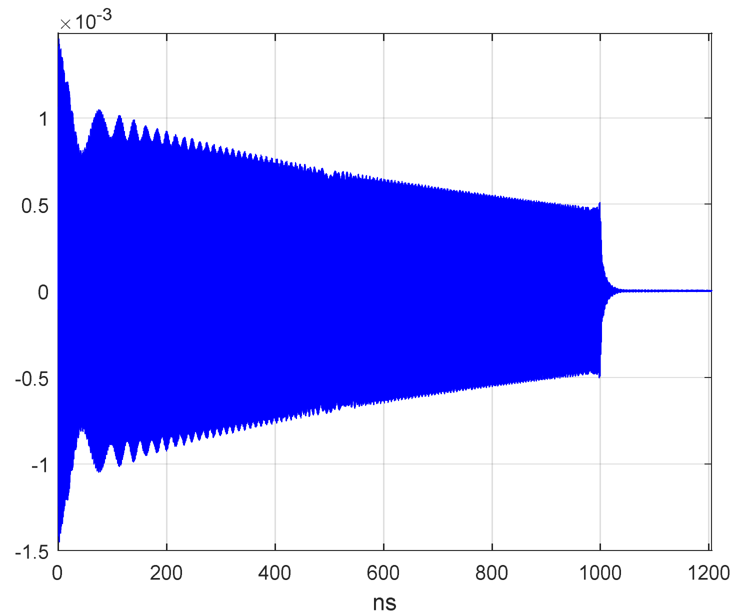
$$\Phi = -2\pi \cdot \frac{T}{B} \cdot (F_0^2 - \left(\frac{B}{2}\right)^2) \cdot \log(1 - \frac{B}{F_0 + B/2} \cdot \frac{t}{T})$$

$$U = 1 \cdot \exp(1i \cdot \Phi)$$

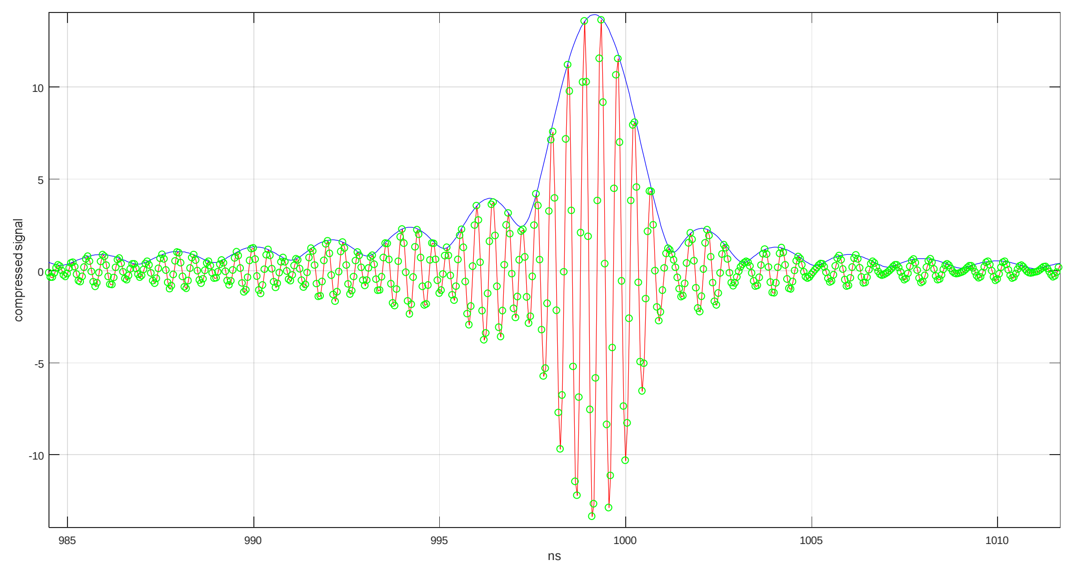


The “compression gain” = 17.5 times, or about 25 dB, which close to ideal value about 10*log10(B*T) = 27 dB

SAW attenuation included



6dB/ µs at 2GHz in LiNbO3



The "compression gain" using ideal HFM signal as refernce is about 14 times, or 23 dB

Experimental results

Profile groove etching

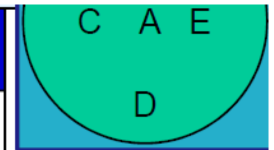
Uniform groove etching

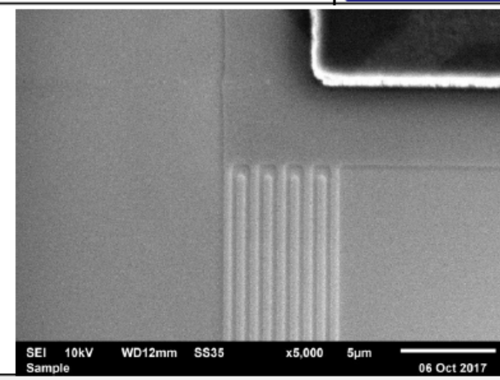
Uniform etching, aperture weighted

Etched grooves

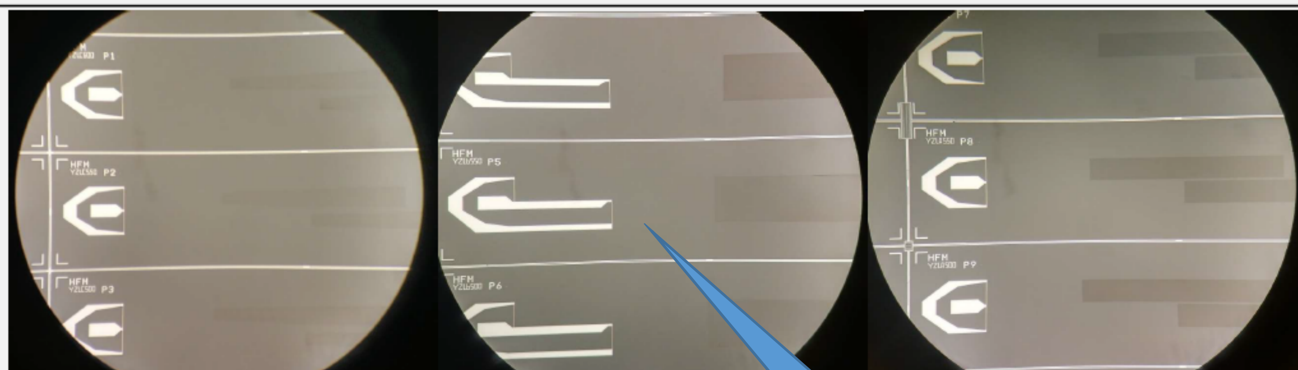
Thickness/C.D. measurement

Metal Thickness (nm)		Metal C.D. By SEM 5000x (um) – P1	
A	72.5	A	0.36
B	71.3	B	0.35
C	72.7	C	0.36
D	73.2	D	0.36
E	71.9	E	0.35





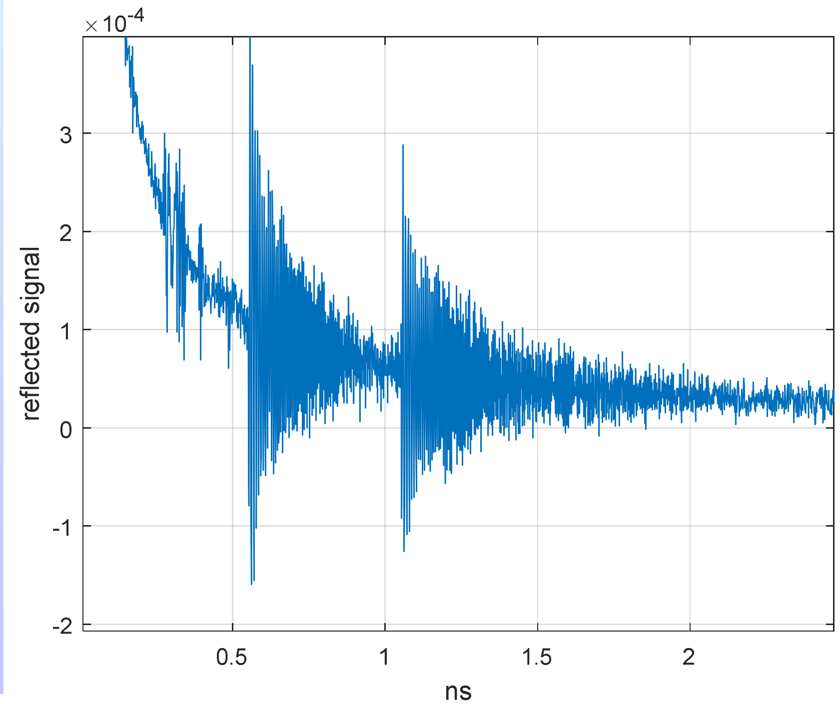
Wafer Picture



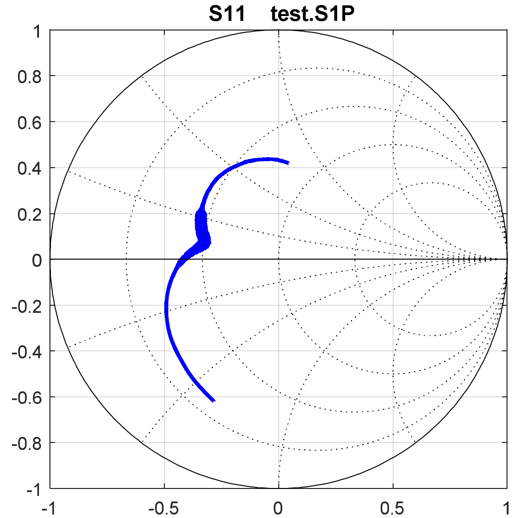
P5

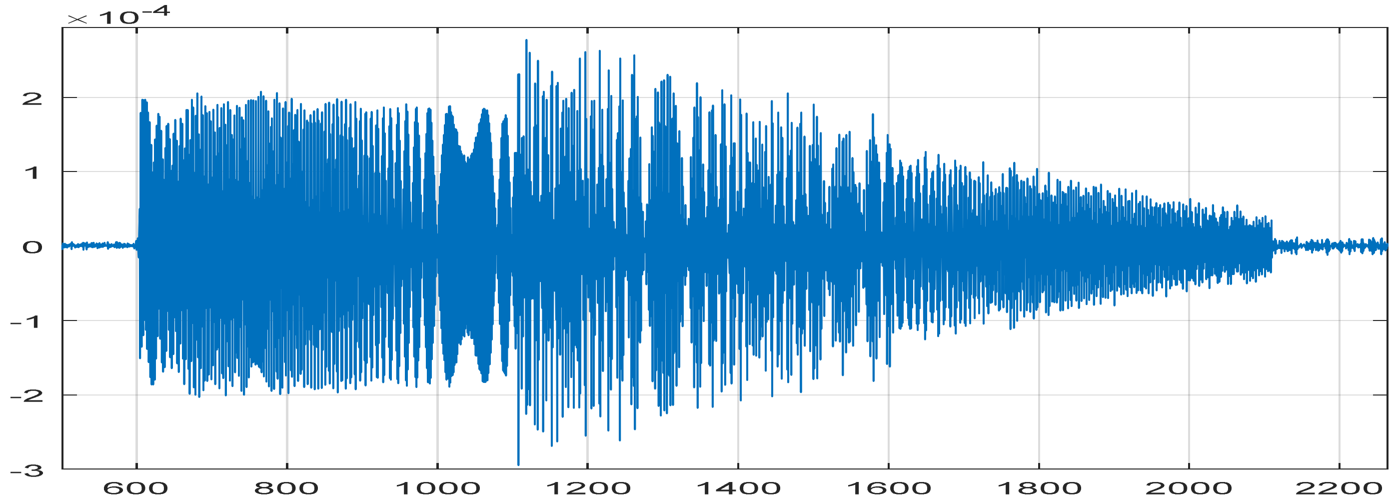
First run samples manufactured
Etching of grooves in LINbO3 crystal – most difficult part of process

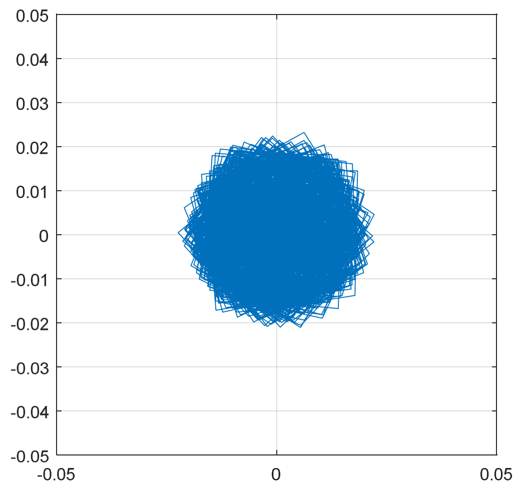
Reflected chirps (sample P5)



Measurements with VNWA (I)

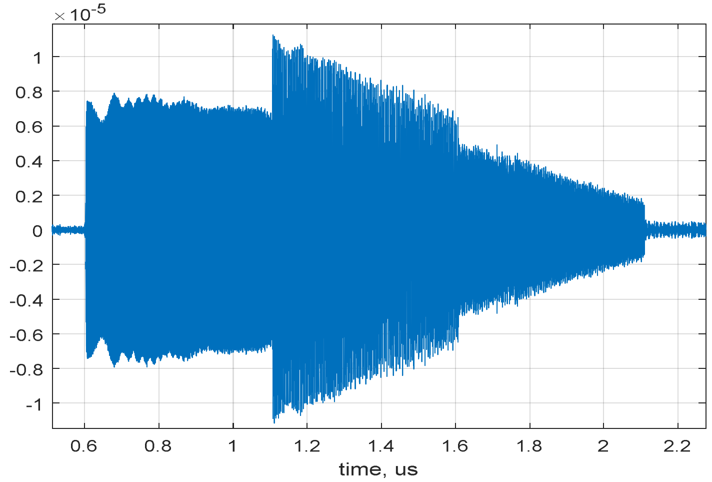


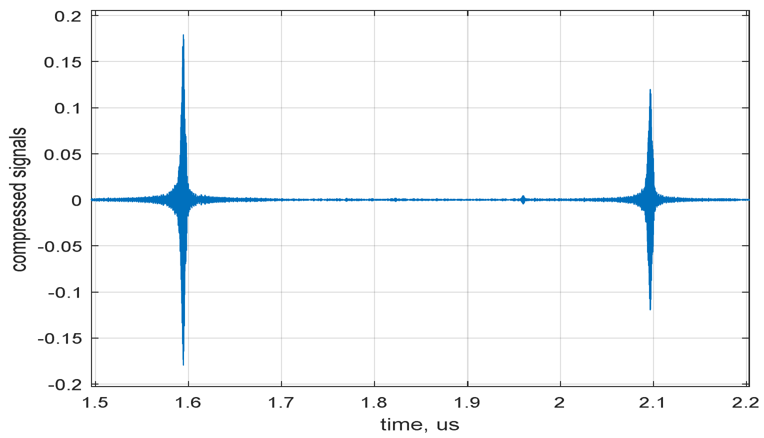


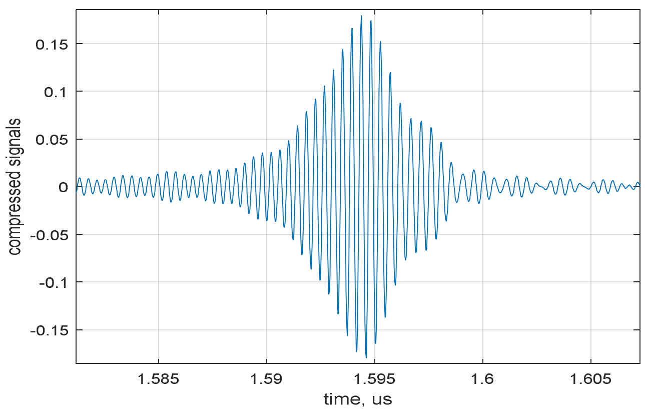


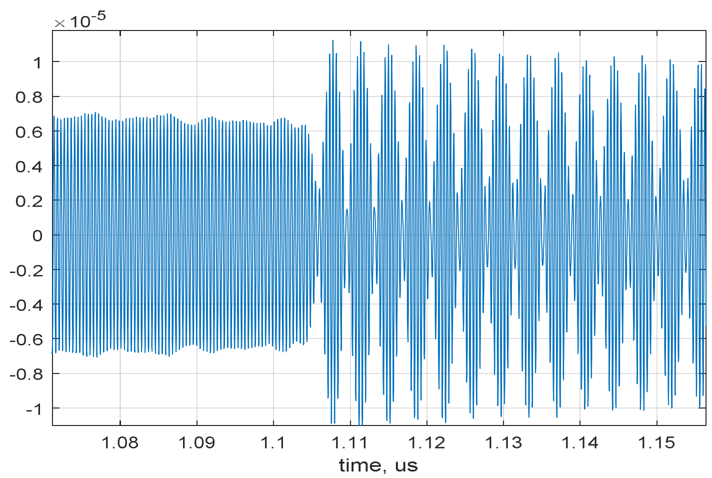
- S11 on Smith chart shows that the transducer is reasonably matched
- But the oscillations with “chaotic” phase have small amplitude, indicating low reflectivity of gratings (about -34dB in total with the IDT loss); Deleting slowly varying part of S11 (reflections from the IDT) helps to see better the signals from reflectors
- Direct IFFT shows then impulse response but its structure is seen not clearly

Measurements with VNWA (II)



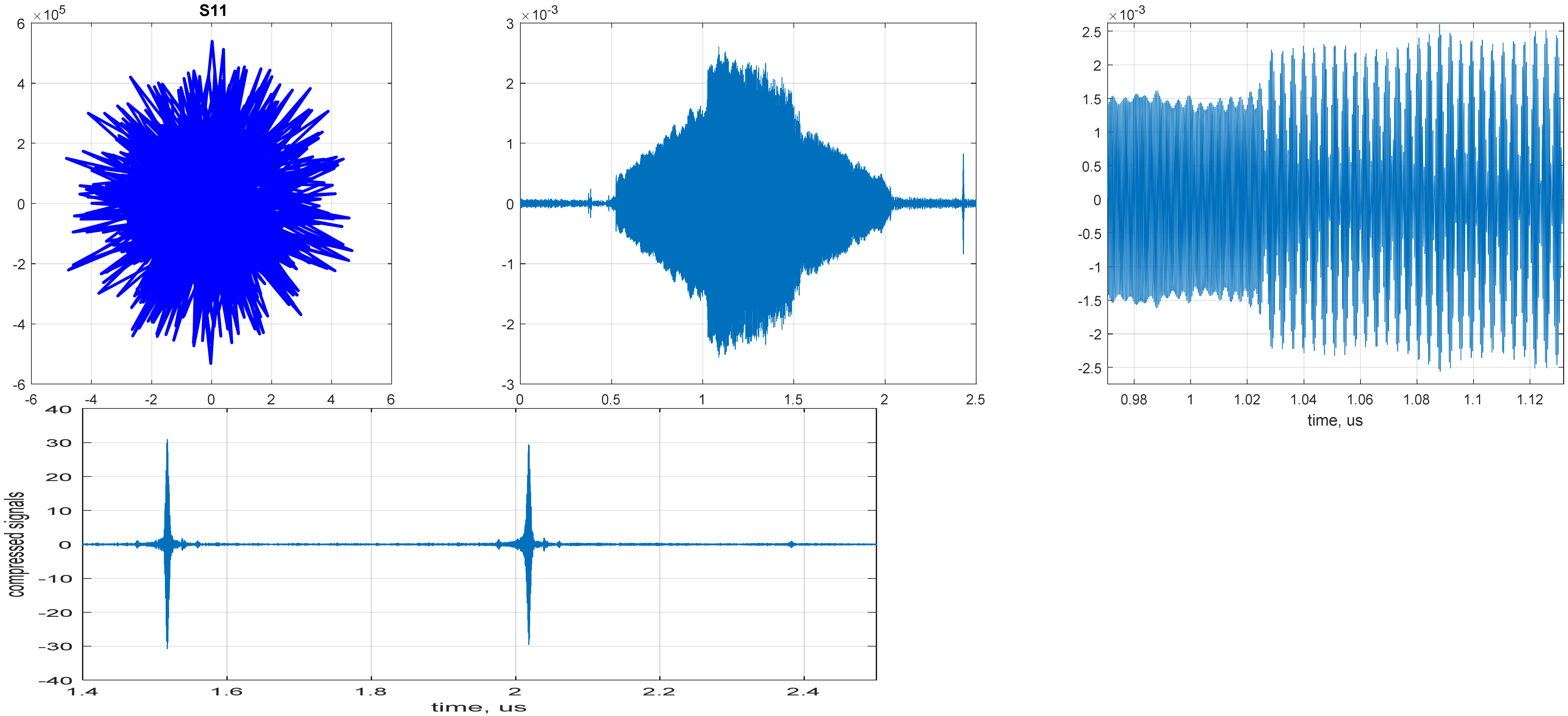




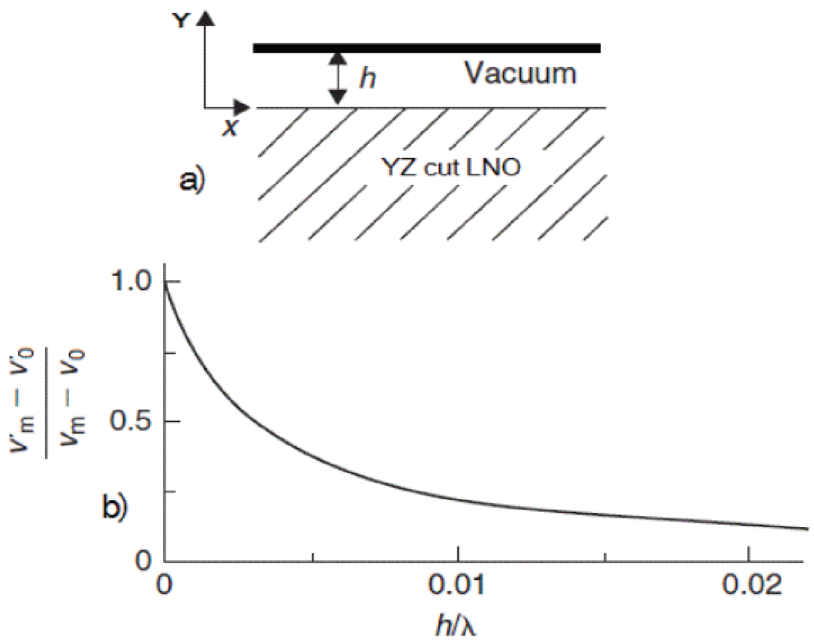


- The “zero-padding” procedure can be used to improve the image of the reflected pulses
- Beginning from about 1.1 us the two pulses overlap
- Compressed pulses have expected (at -3dB level) duration of about 2 ns
- The form of compressed pulses is unique which allows to avoid “2π” uncertainty

Measurements with the “reader”



Crazy ideas:
passive microphone based on SAW



$$\frac{\Delta t}{t} = \frac{3 \cdot P \cdot \left(1-\sigma^2\right)}{16 \cdot \left(\frac{t}{R}\right)^4 \cdot E}$$

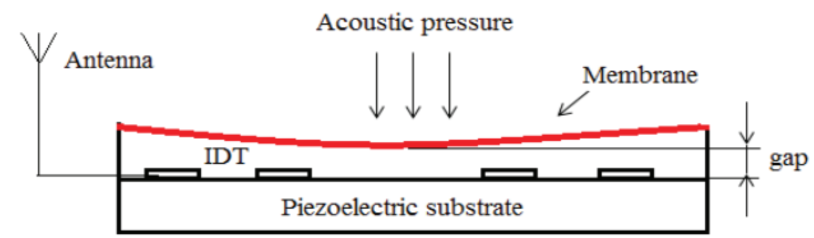


Fig. 2. SAW – MEMS microphone geometry.

- P <1 Pa must be measured, but P/E ~ 10^{-11}
- R/Membrane_thickness ~ 1000 is necessary to get the deflection compared to membrane thickness
- Narrow gap – technology problem
- 10Bln microphones / year;
- no wire, no battery
- Best pressure sensitivity experimentally achieved: 750 Hz shift / Pa, **0.035 ppm/Pa**, J. Meltaus *et al*, Proc. 2014 IUS, p. 388

V. Plessky et al, "Passive wireless SAW - MEMS pressure sensor/microphone," *2014 European Frequency and Time Forum (EFTF)*, Neuchatel, 2014, pp. 147-149.

Acknowledgements

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Thanks!

Conclusions

The **Hyperbolically Frequency Modulated (HFM)** signals and transducers/reflectors are ideally suitable for SAW-sensors and SAW-tags, since compression of such signals, being temperature-invariant, can be achieved with always the same matched-to-signal filter, simplifying significantly the interrogation algorithm.

Thank you!

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