Hyperbolic Frequency Modulation (HFM) in SAW sensors and Passive Wireless Microphone

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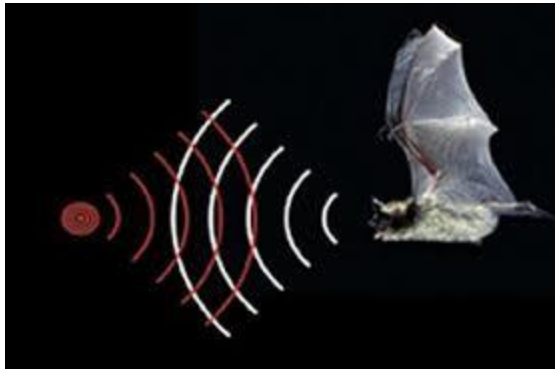
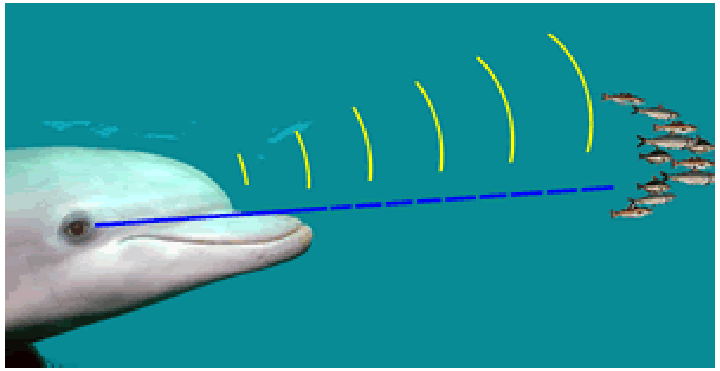




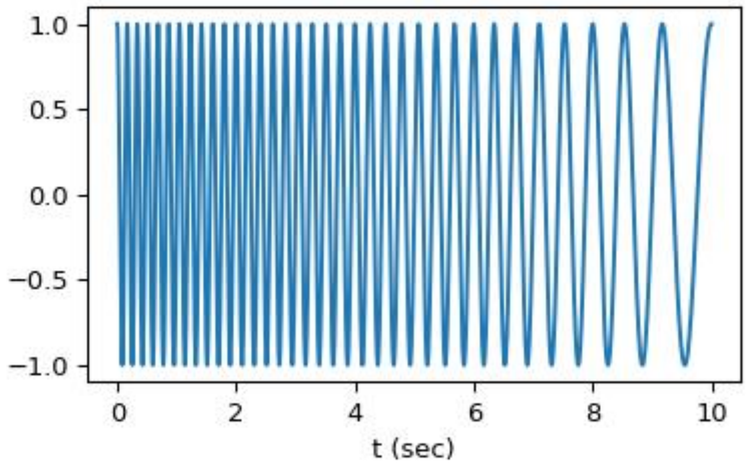
Plan

1. Niche for passive sensors
2. Why chirp signals?
3. Hyperbolic vs Linear FM
4. Reflector with HFM
5. Design, manufacturing, measurements
6. Temperature measurements
7. Passive wireless microphone
8. Conclusions

Will passive SAW sensors survive?

- High temperatures; ***Si*** chip tolerate T < 85°C
- No physical access to sensor needed; long life; no battery to be changed
- Very low power of EM radiation demanded; response is always available – no power threshold
- High radioactivity can be handled
- “Collision” problem – limited number of SAW-tags or sensors can be interrogated simultaneously

Why to use the chirp signals in sensors?



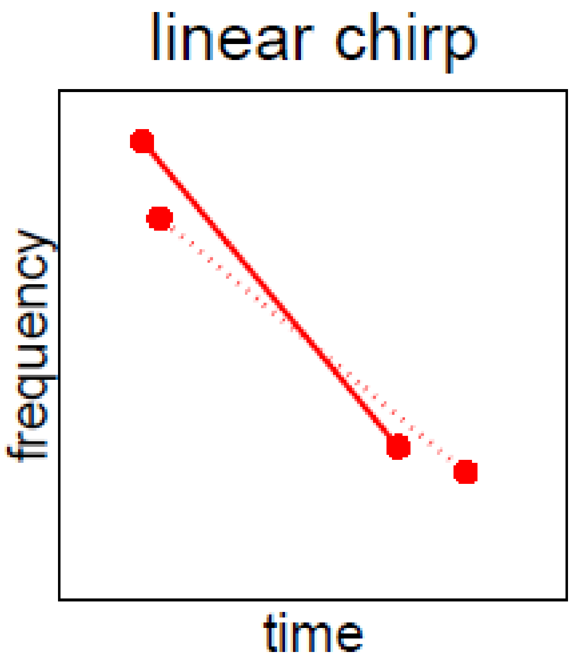
Linear Frequency modulation

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

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

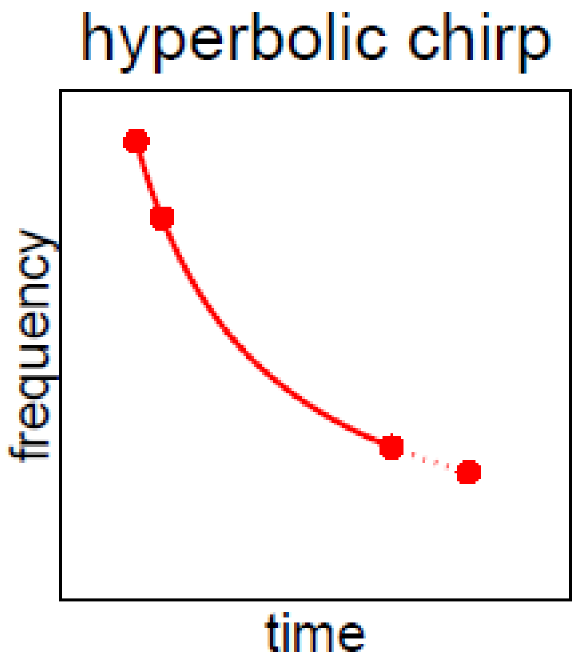
- The sensor will give a unique response, different from environmental reflections
- B*T product (B= fr. band, T=duration) is important. Signal can be compressed B*T times, and the duration of compressed pulse is about 1/B.
- The signal-to-noise ratio (S/N) is increased 10*log10(B*T) dB resulting in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

But do the bats and dolphins use LFM chirps?

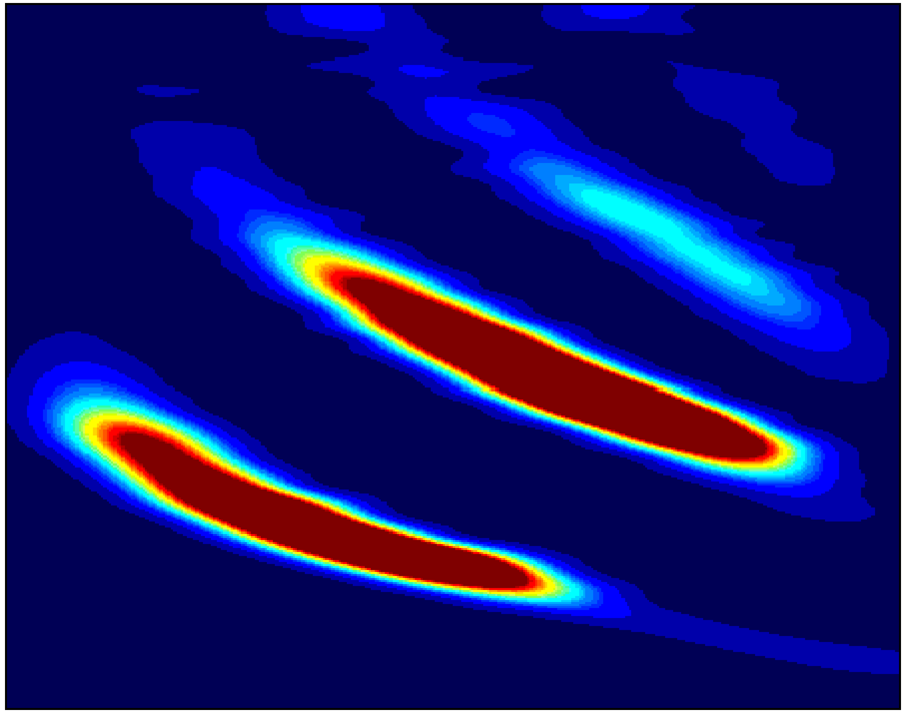


$B*T*(K-1) > 1$

(K- scaling factor)
LFM signal compression deteriorates significantly

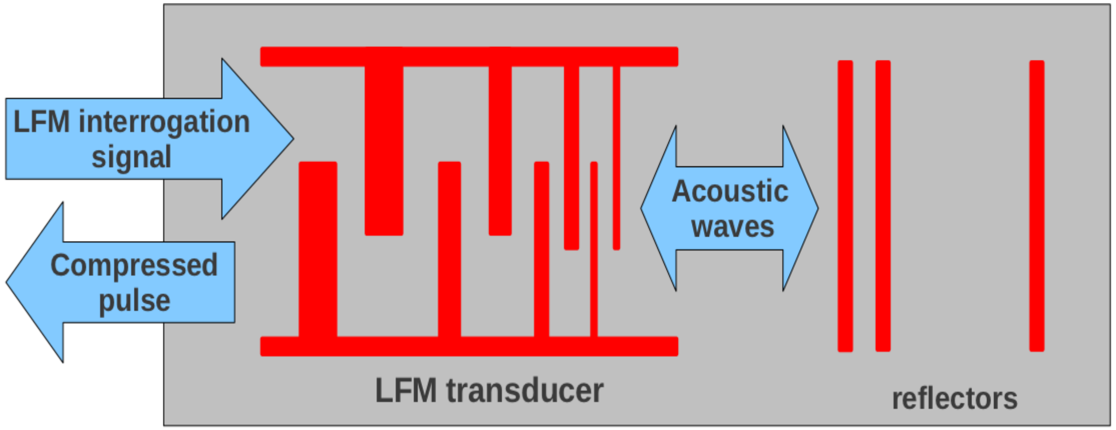


No visible deterioration of compressed pulse



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

Geometrical problem: linearly increasing period



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?

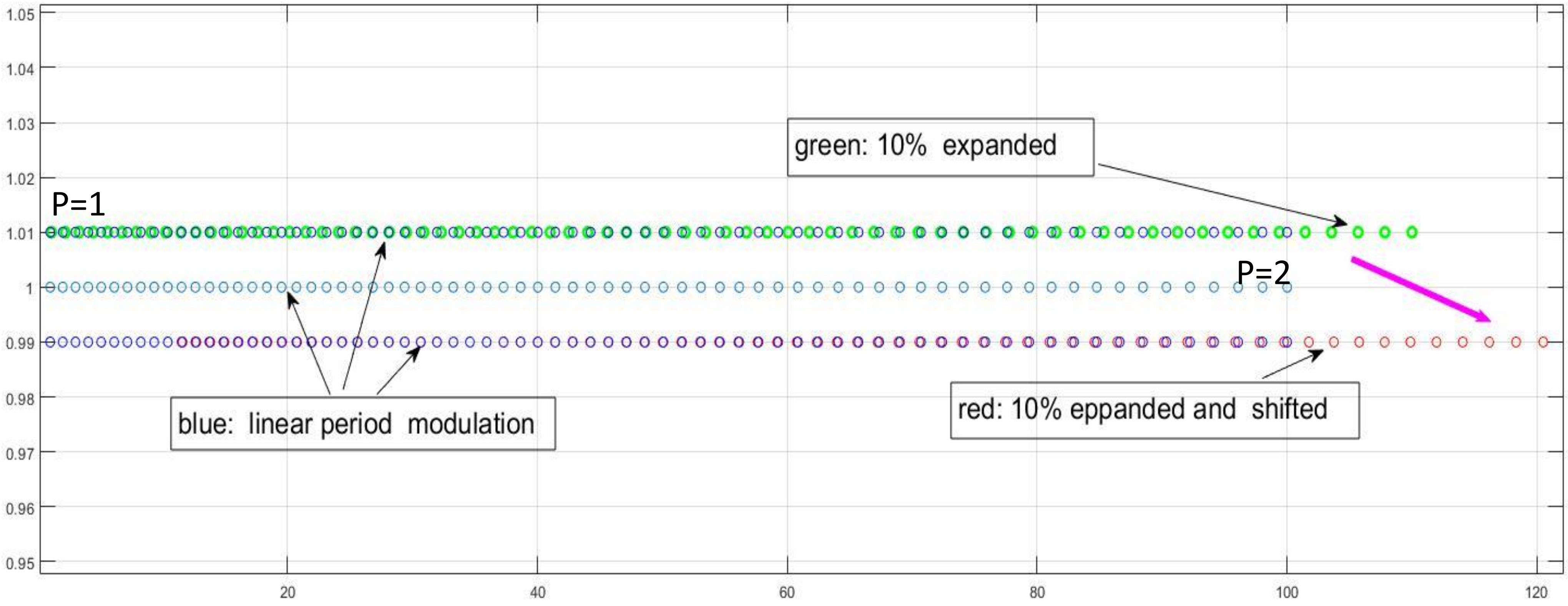
- For the geometric structure of electrodes (strips, grooves, etc.) with period linearly changing with coordinate *x* one can write the following relation:

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

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

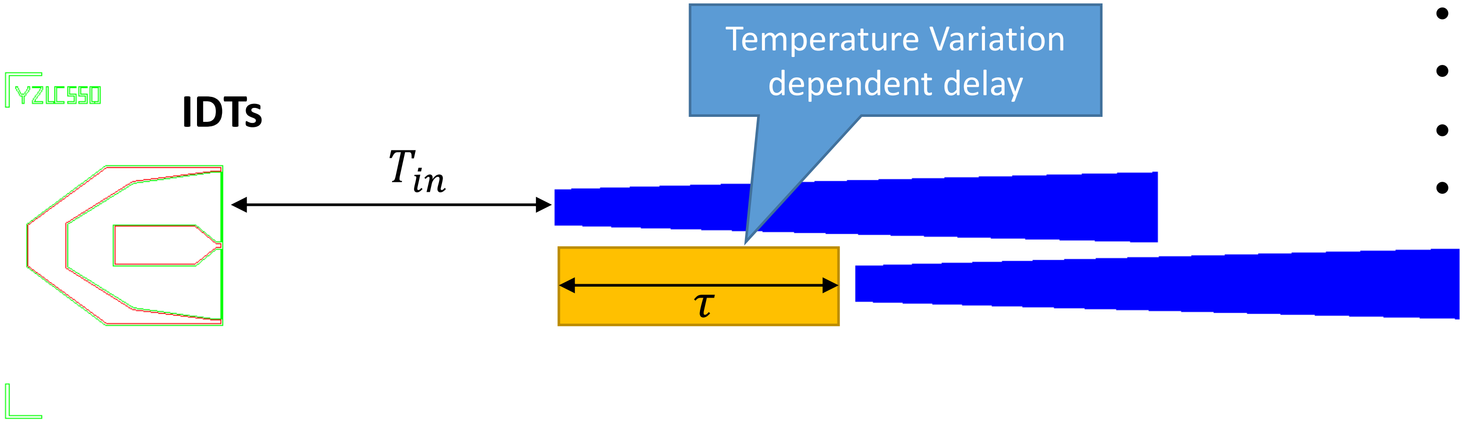
$$x_n = \frac{(1+\varepsilon)^n - 1}{\varepsilon} \cdot p_0$$

An object for which the scaling is equivalent to a shift



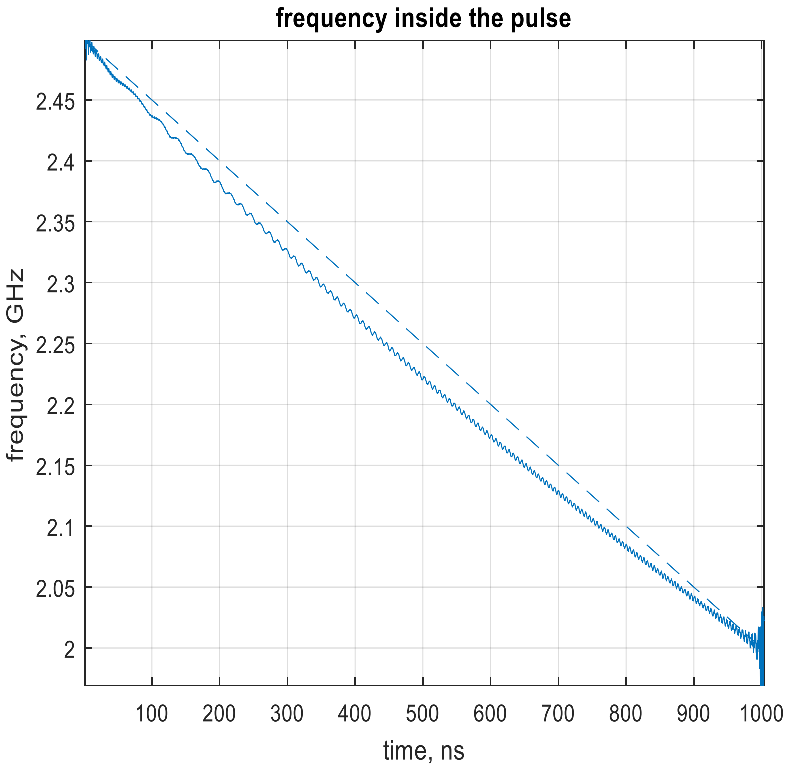
Device Design

- Device operating between 2000-2500MHz using linearly varying pitch in reflectors on YZ-Lithium Niobate
- Linear Variation of pitch in reflectors from 697.6nm to 872nm and 2231 etched groove reflectors for T=1000ns
- HFM pulse impulse response BxT=500

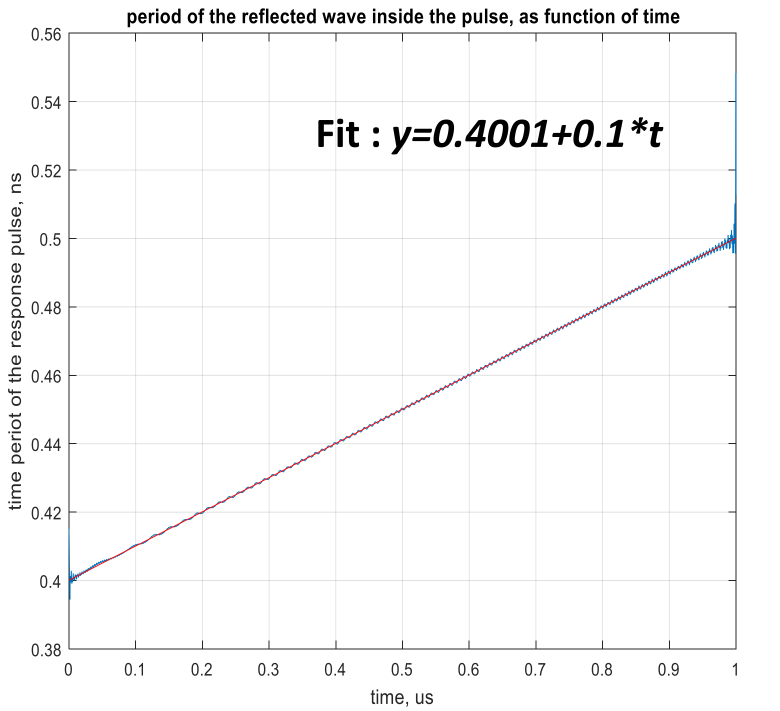


- Initial Delay $\mathrm{T_{in}} = 500 - 600\mathrm{ns}$
- τ = Reflector offset = 500ns
- p_0=697.6 nm, p_N =872.0 nm
- *N=2231 grooves, for T=1000ns*

Hyperbolic Frequency Modulation



For comparison – dotted straight line

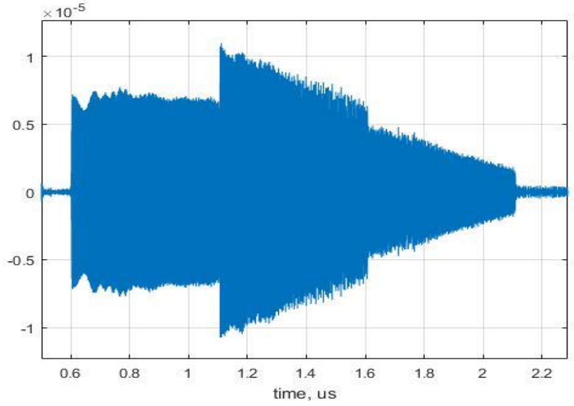


Linear increase of time period (1/f) red line – ideal fitted straight line.

- The beginning period: **0.4 ns** corresponds to 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.

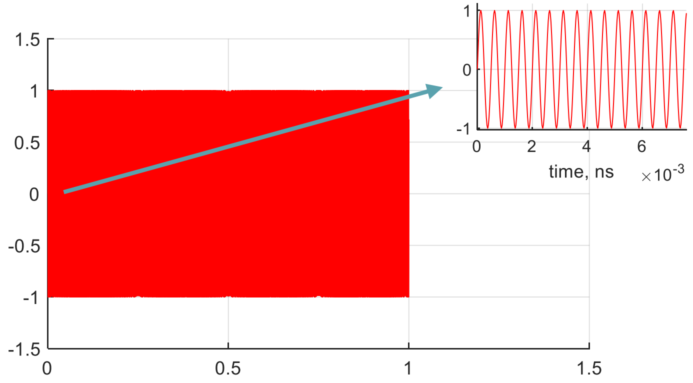
Post-processing

- Convolution of Device Response and unit amplitude signal to give compressed pulses.
- Correlation of response of 1st and second reflector in short time periods (50ns).
- Parabolic approximation of peak to find precise maxima.
- Compiling measured delay results.

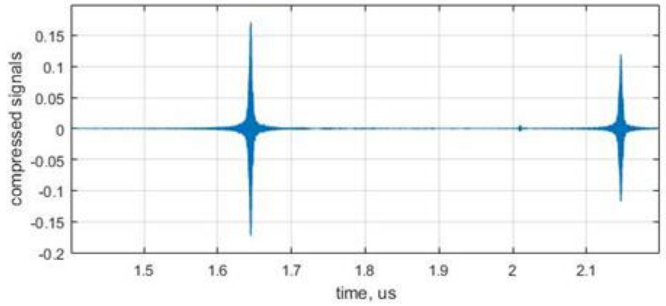


Device Response

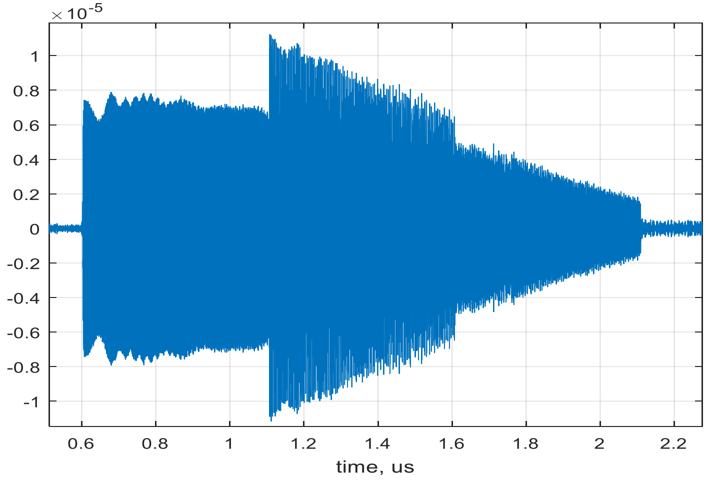
and

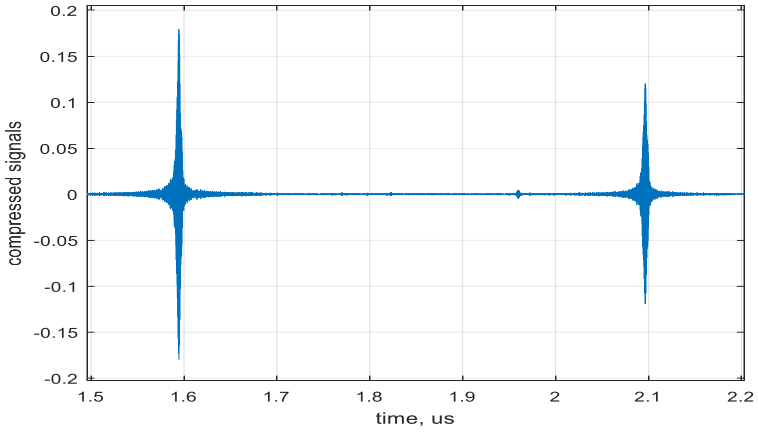


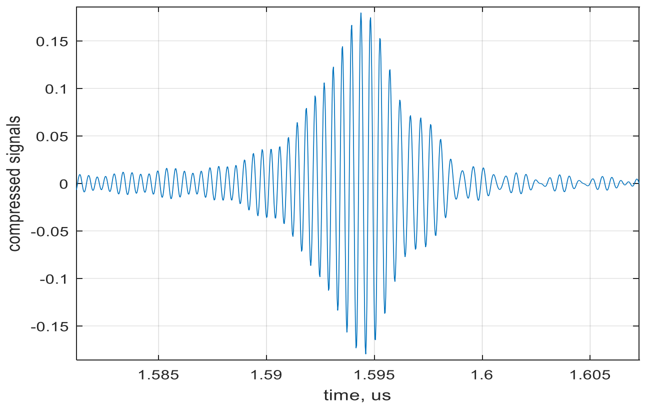
$$\Phi = -2\pi \cdot \frac{T}{B} \cdot (F_0^2 - \left(\frac{B}{2}\right)^2) \cdot \log\left(1 - \frac{B}{F_0 + B/2} \cdot \frac{t}{T}\right)$$

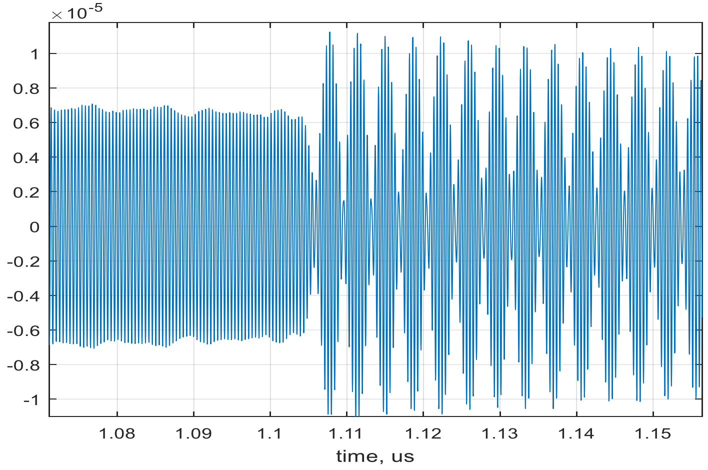


Measurements with VNWA





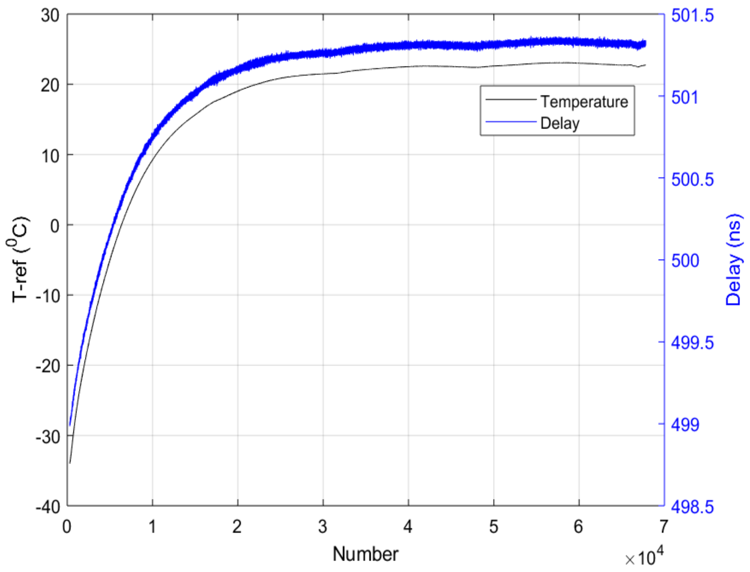


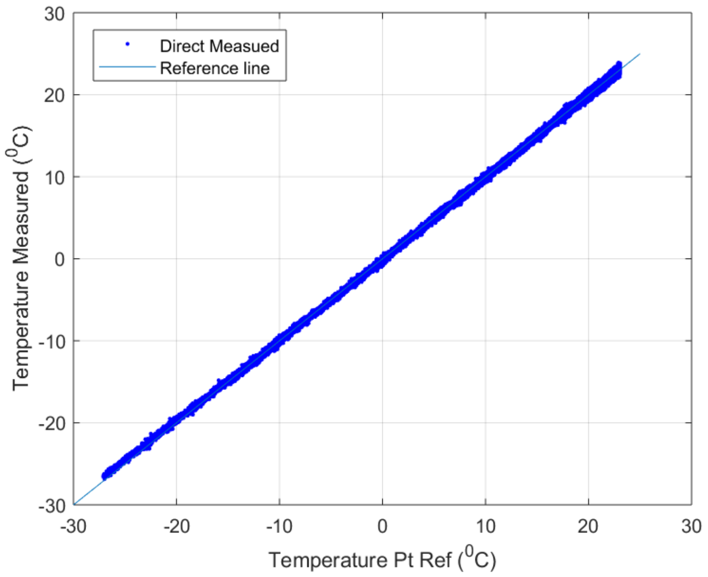


- The “zero-padding” procedure can be used to improve the image of the reflected pulses
- Beginning from about 1.1 us the two pulses overlap
- Compressed pulses, obtained by correlation of measured pulse with theoretical (always the same) pulse, have expected (at -3dB level) duration of about 2.5 ns
- The form of compressed pulses is unique which allows to avoid “2π” uncertainty

Direct Temperature Measurement

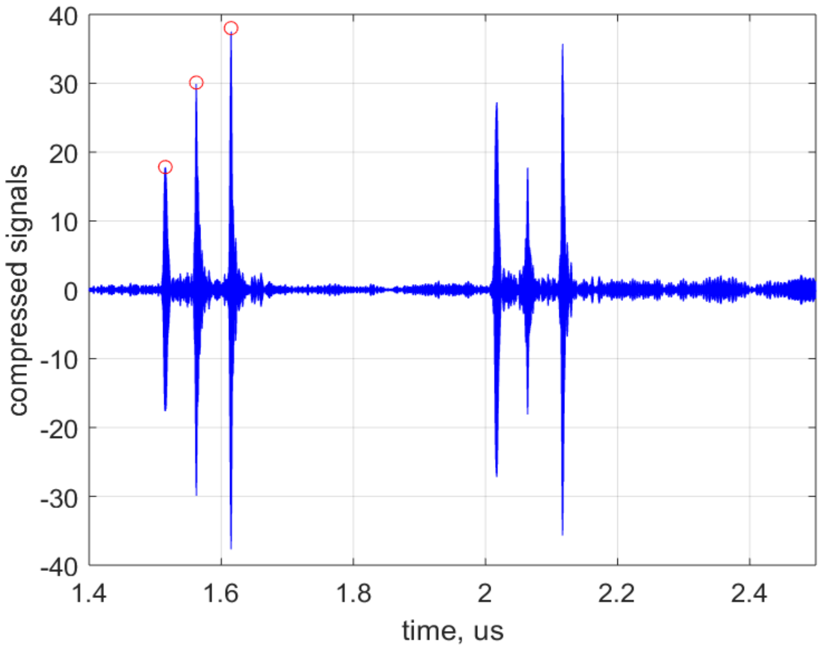
- Fitting Delay and Reference temperature data.
- $\frac{\Delta D_i}{D_1} = \mathrm{TCD}_1(\Delta T_i) + TCD_2(\Delta T_i)^2$
- Temperature Range $= -30^{\circ}\mathrm{C}$ to $23^{\circ}\mathrm{C}$
- 67,000 data points

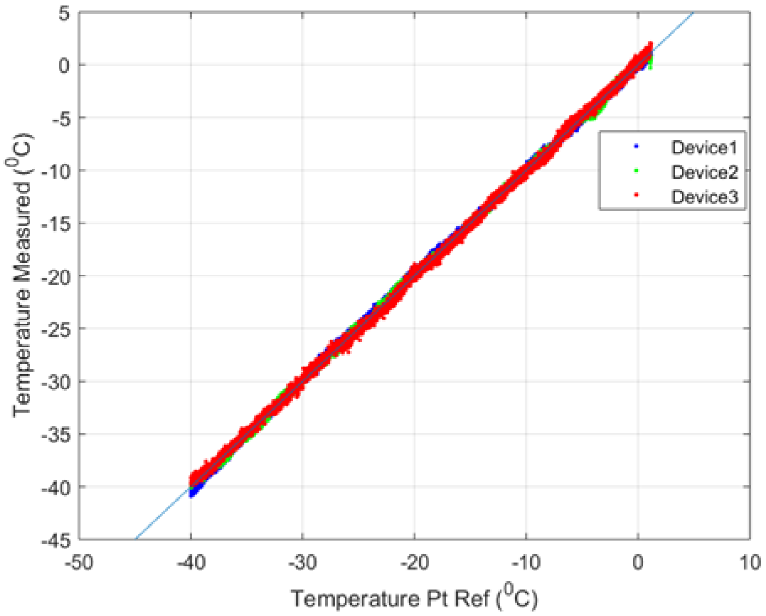




Remote Temperature Measurement

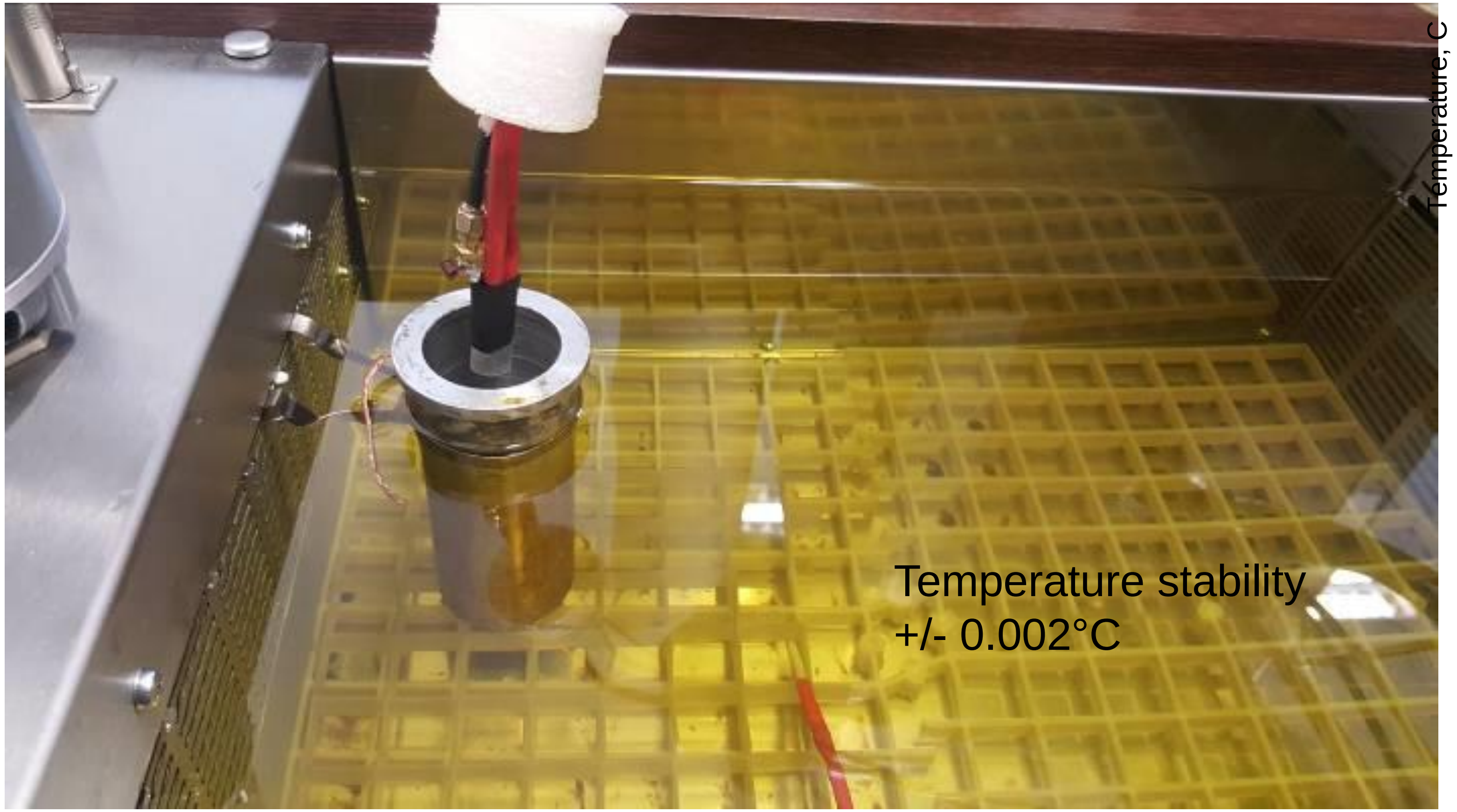
- Simultaneous Remote measurement of 3 sensors
- Distance= 50cm
- Temperature range= $-40^{o}C\ to\ 2^{o}C$
- 9,000 data points

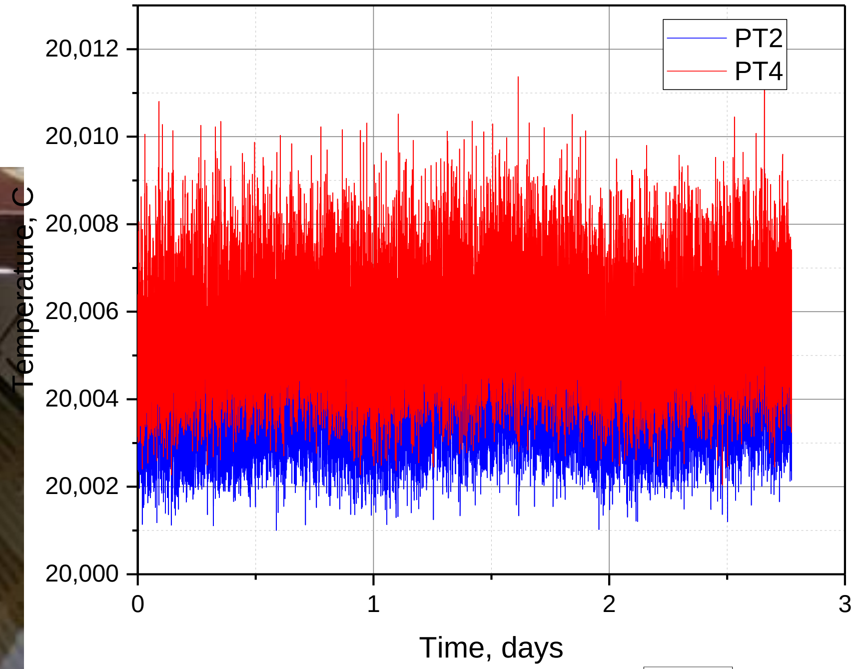


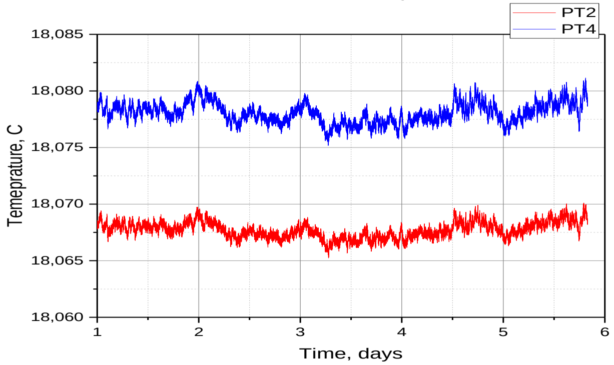


	TCD1(ppm/°C)	*Standard Deviation (°C)*
Device1	87.049	0.2192
Device2	83.199	0.2687
Device3	81.867	0.3243

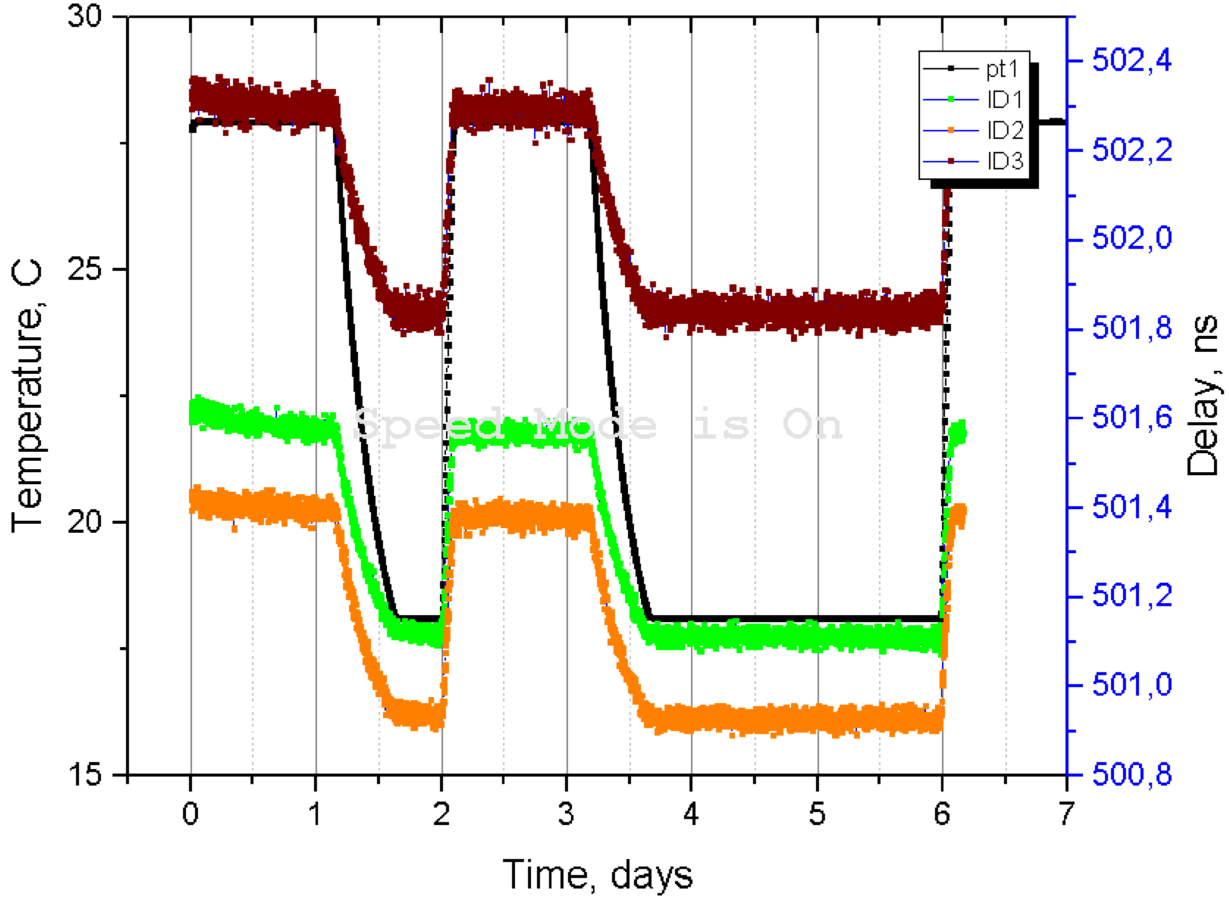
Measurements with the hit chamber

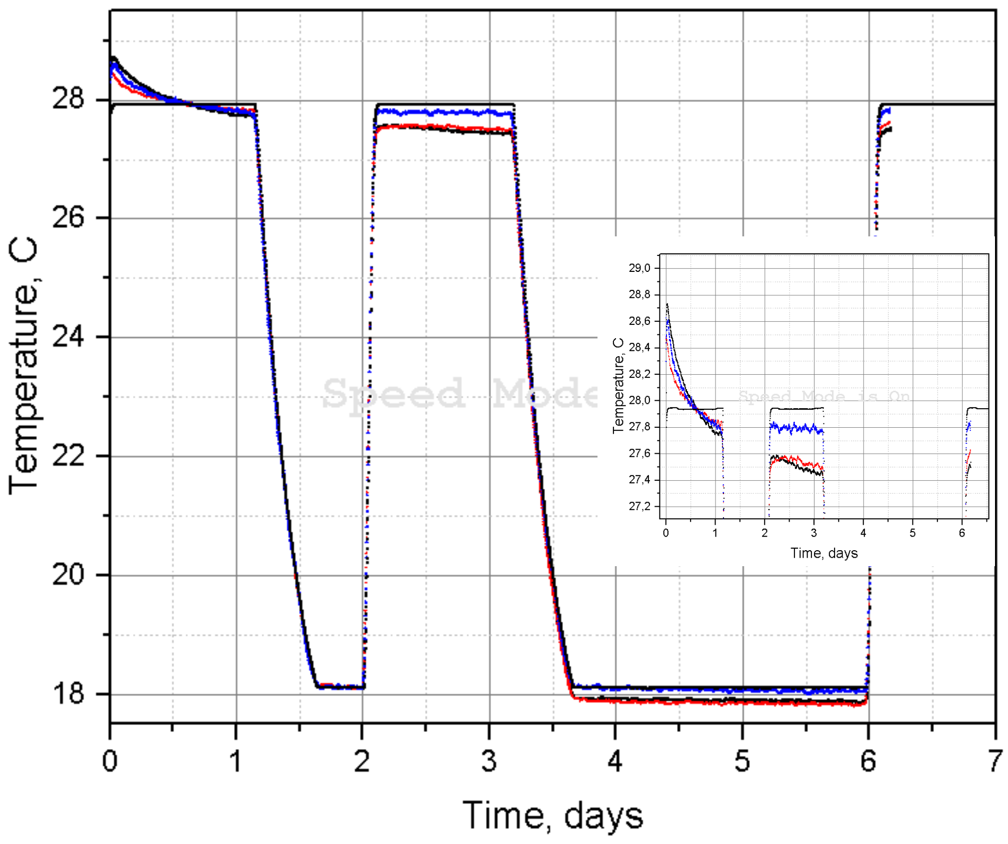




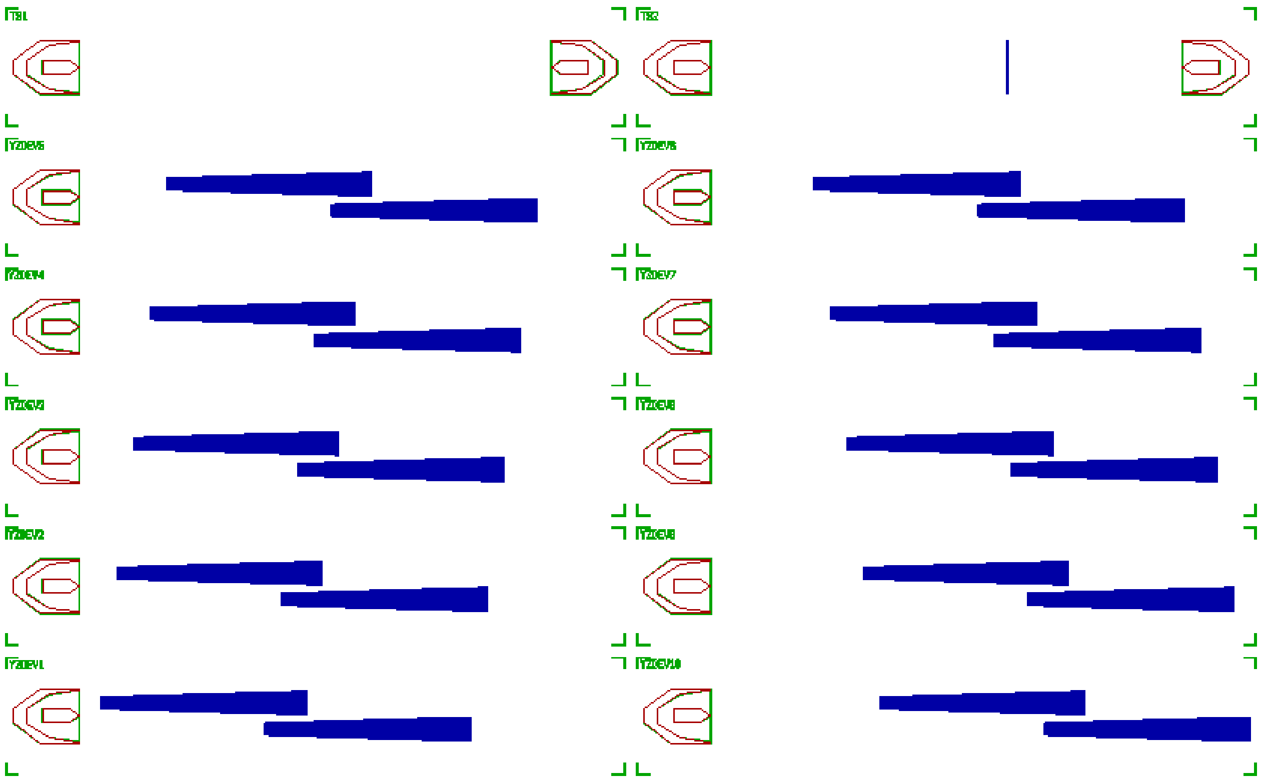


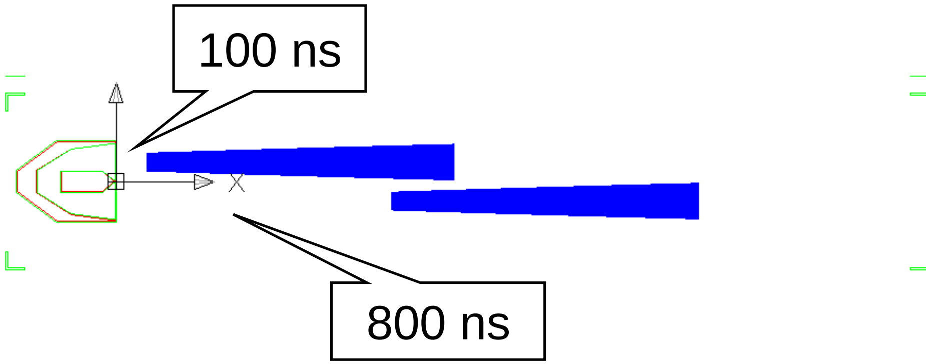
Wired sensors in hit chamber





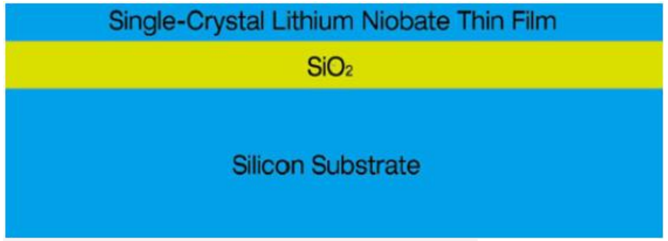
New set of sensors



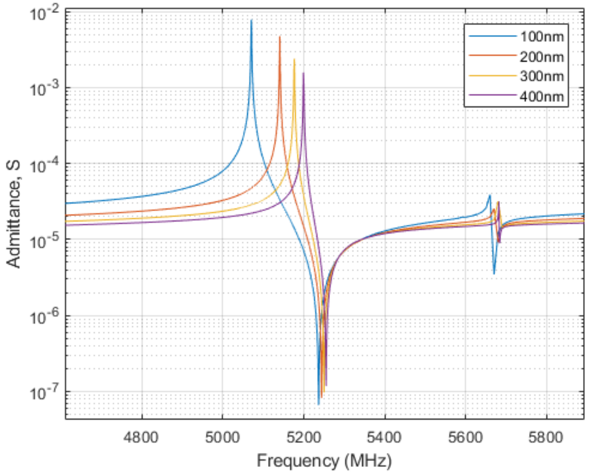


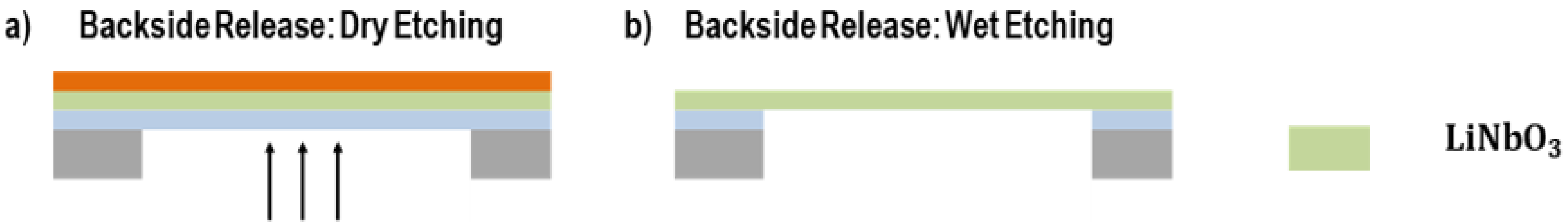
- 10 sensors which Can be interrogated simultaneously
- Increased delay between reflectors
- Smaller initial delay
- Etching if Lithium niobate is not easy

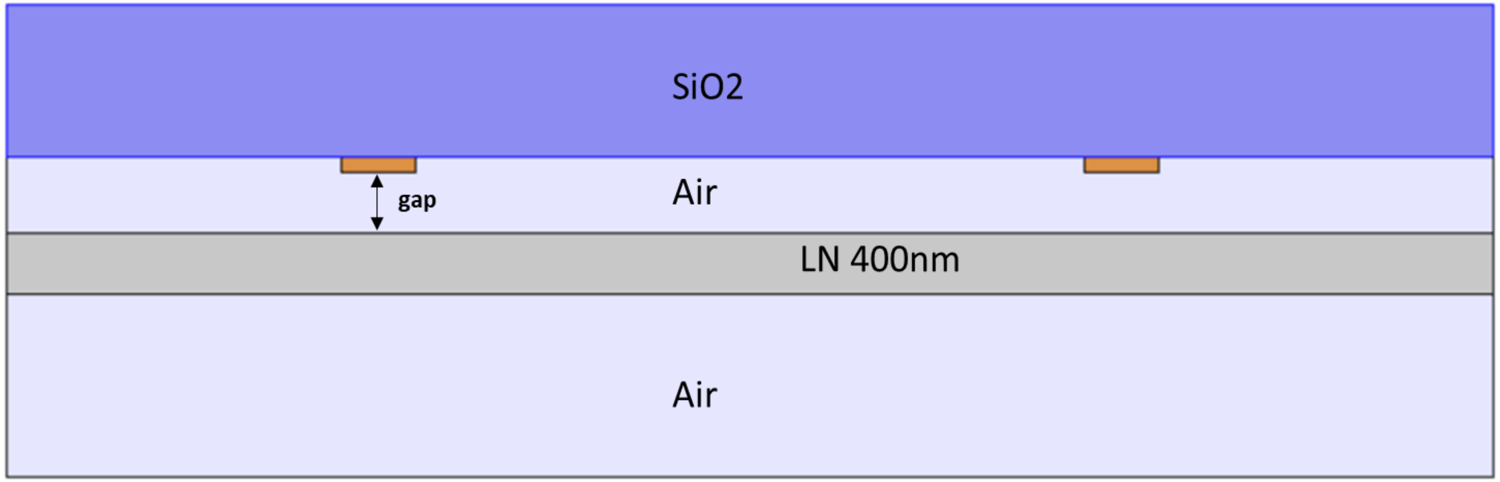
Passive wireless microphone



Size:	3inch
Thickness:	300-700 nm
Orientation:	X cut,Y cut,Z cut







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

R=400µm, t =0.4 µm,

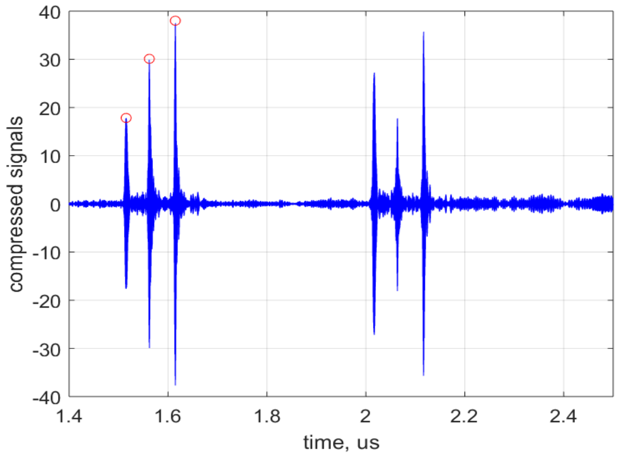
σ=0.3, E=2*10¹¹ Pa

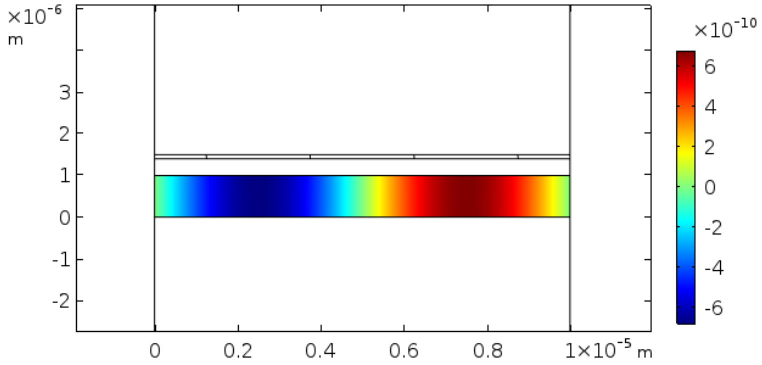
The above formula (1) gives

Δt ≅0.3 (µm) * P/(Pa) =300nm*P(Pa).

Thin LN membrane suspended over electrode system is suitable for very sensitive pressure sensor

3 sensors - Remote compressed responses





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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 always with the same matched-to-signal filter, simplifying significantly the interrogation algorithm.
- Successful demonstration of simultaneous remote HFM SAW temperature sensing with standard deviation of $0.27^0\mathrm{C}$.
- Future work includes fabrication and measurement of new samples.

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Thanks!

Thank you!