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Wireless Passive SAW Identification Marks and Sensors

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Acknowledgement

The research and development project, which is presented in this tutorial, was carried out within the last years in the Corporate Technology Department of Siemens AG, Germany.

The author would like to thank W.-E. Bulst and M. Guntersdorfer for continuously encouraging this work, and C.C.W. Ruppel, W. Ruile, G. Scholl, F. Schmidt, T. Ostertag, and V. Magori for their important contributions as well as J. Hornsteiner, C. Kordon, O. Sczesny, E. Riha, C. Seisenberger, M. Vossiek, and U. Wolff for their valuable contributions. Special thanks to W. Gawlik, U. Knauer, J. Zimmermann, S. Berek, B. Bienert, H. Zottel, T. Sofronijevi´c, and K. Riek for the manufacture of the SAW devices.

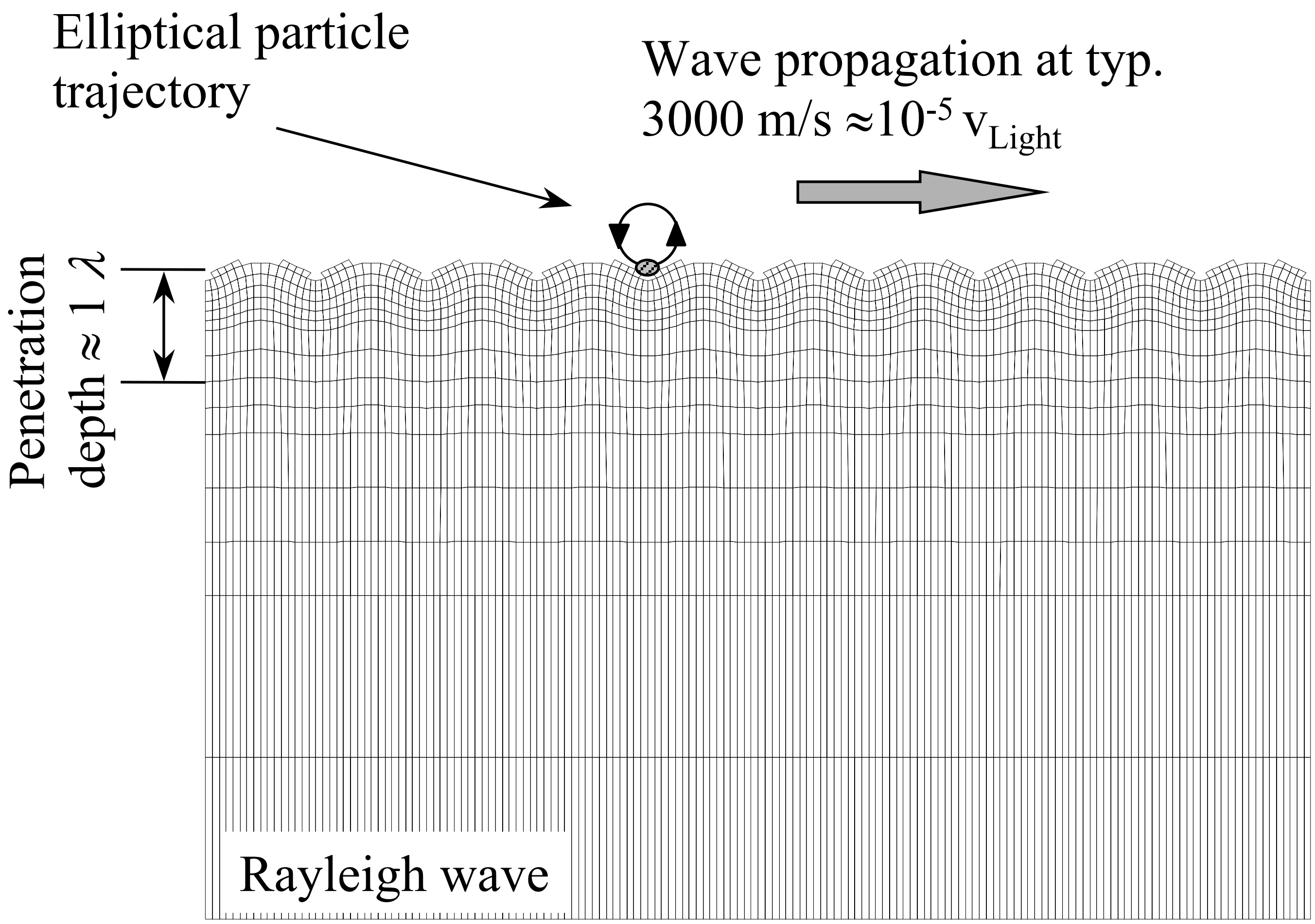
Very important contributions were developed at the Applied Electronics Laboratory of the University of Technology in Vienna, Austria by my teacher F. Seifert, by A. Pohl, R. Steindl, G. Ostermayer, and C. Hausleitner, and the students there, at the Institute for Communications and Information Engineering of the University of Linz, Austria, by R. Weigel, H. Scherr, T. Pankratz, and G. Schimetta, and at the Institute for Measurement Systems and Sensor Technology of the Technical University of Munich, Germany, by E. Schrüfer, and K. Pistor.

Thanks to A. Kirmayr from the University of Applied Sciences, Munich, for his

Outline

- Introduction: Classical SAW Sensors
- SAW Radio Read Out
- SAW Identification Tags
- SAW Radio Readable Sensors
- Application Examples
- Conclusion

Surface Acoustic Waves (SAW's)



At the same frequency, the acoustic wavelength is 10^{-5} times that of electromagnetic waves.

Seismologic surface acoustic wave

San Francisco, City Hall

April 17, 1906

April 18, 1906

History of SAW

1885 Lord Rayleigh characterizes Surface Acoustic Waves (earth quake)

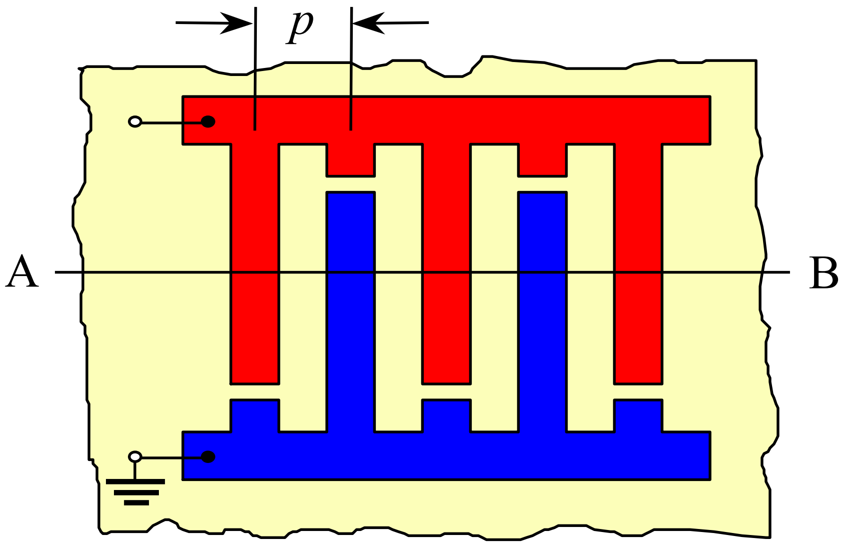
1965 Invention of the Interdigital Transducer (White/Voltmer)

1970 First applications: pulse expansion and compression in radar systems

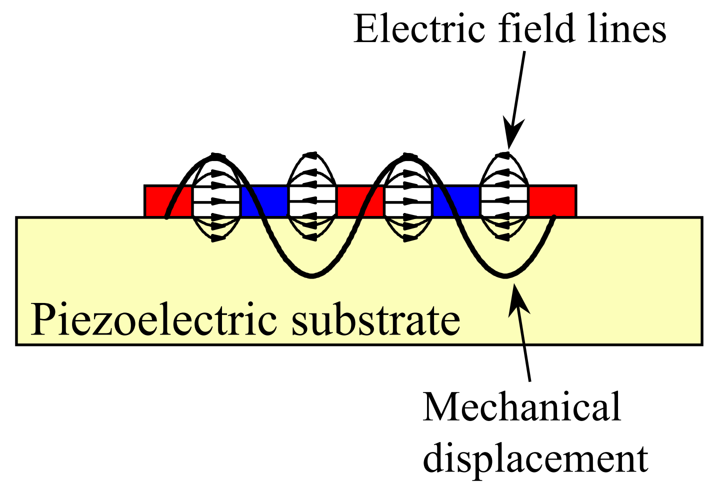
1985 SAW filters replace LC filter in TVs and VCRs

1990 SAW filters allow for miniaturization of mobile phones

Wave Excitation and Detection: IDTs



Top view



Cross sectional view A-B

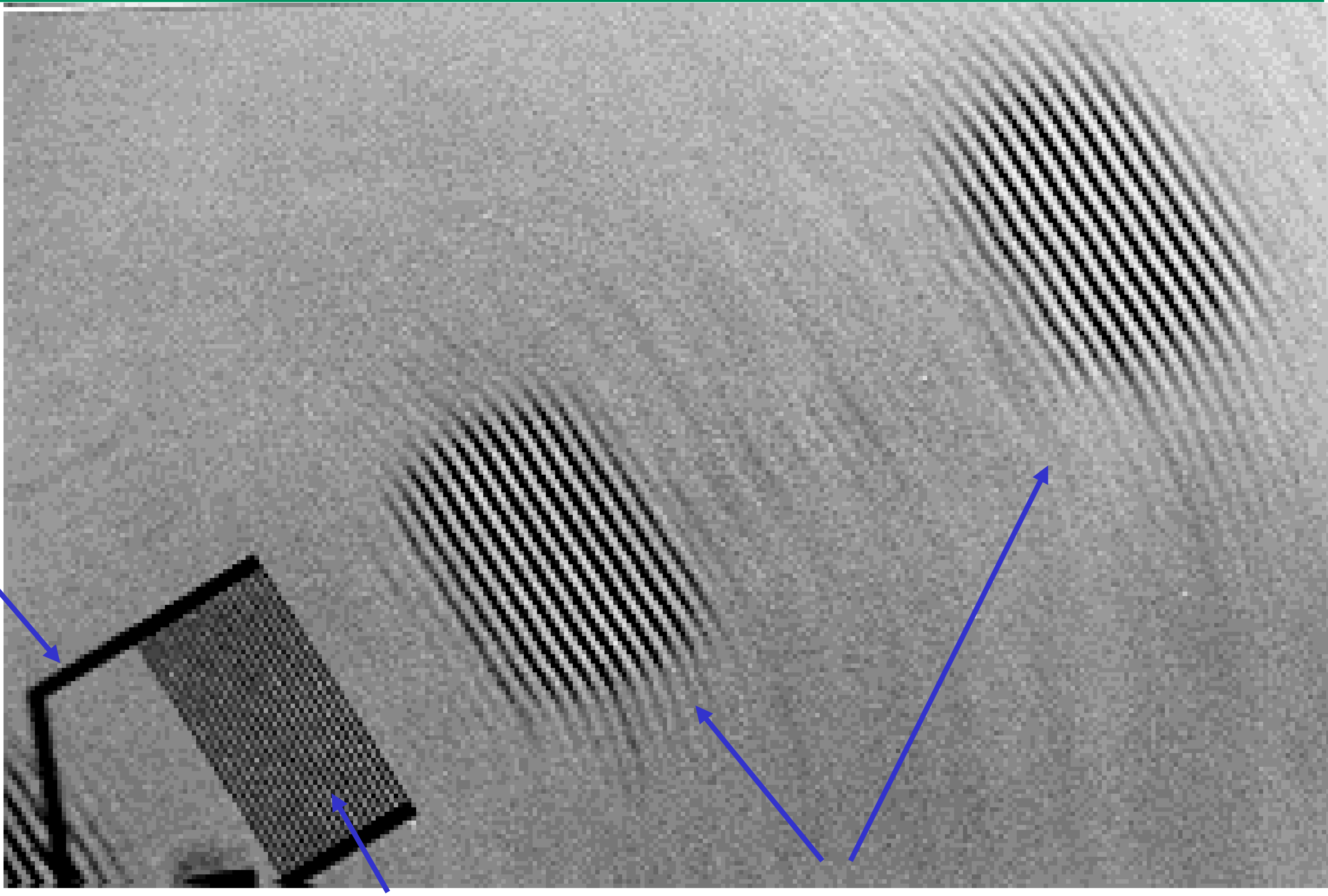
Interdigital Transducer (IDT) as

- transmitter: converse piezoelectric effect ⇒ electric RF field generates SAW
- receiver: piezoelectric effect ⇒ SAW generates electric RF field

In both cases maximum coupling strength for $\lambda_{SAW} = v_{SAW} / f = 2 \cdot p$ (~ 1…10 µm)

SEM-photo of an interdigital transducer and two SAW pulses

Bus Bar



Interdigital Transducer, IDT

Surface Acoustic Wave, SAW

Properties of some commonly used substrata materials

Material	Orientation [1)] Cut	Prop.	Wave type	v_{ph} (m/s)	k^2 (%)	TCD (ppm/°C)	Loss (db/µs) 433 MHz	2.45GHz
Quartz	ST	X	gen. RW	3158	0.1	0	0.75	18.6
	37°rotY	90°rotX	SH wave	5094	≈ 0.1	0	- 3)	-3)
$LiNbO_3$	Y	Z	pure RW	3488	4.1	94	0.25	5.8
	41°rotY	X	leaky SH wave	4750	15.8	69	- 3)	-3)
	128°rotY	X	gen. RW	3980	5.5	75	0.27	5.2
$LiTaO_3$	36°rotY	X	leaky SH wave	4220	≈6.6	30	1.35	20.9
	X	112°rotY	gen. RW	3301	0.88	18	-	-

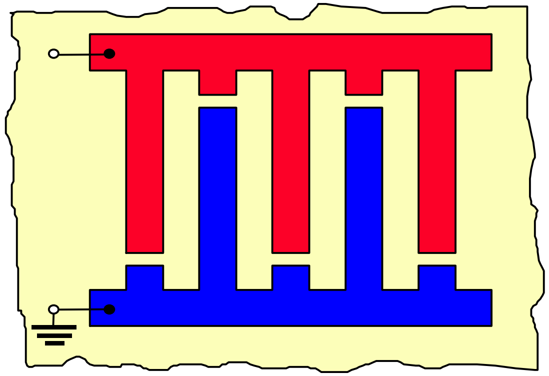
1) Cut = crystalline orientation of the substrate surface normal;
2) Prop. = crystalline orientation of the wave propagation direction.
3) Depends on metallization.

Design of SAW filters

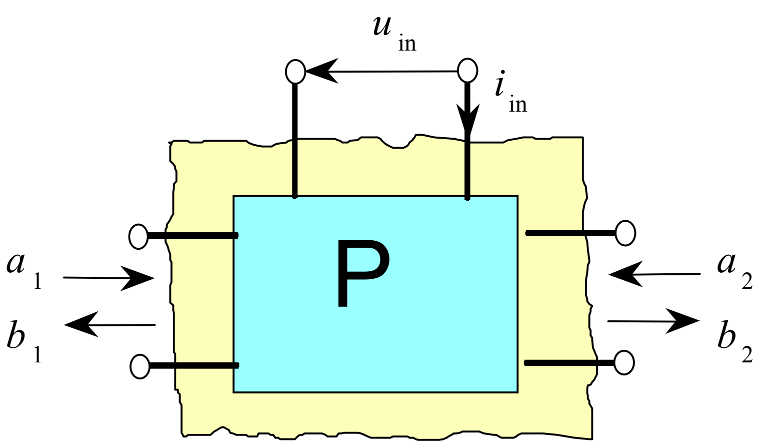
The design of SAW devices is based on

- **signal theory** (e.g. Impulse response modelling)
- **network theory** (e.g. P-Matrix-formalism, coupling of modes, equivalent circuit,angular spectrum of strait-crested waves)
- **field theory** (e.g. FEM)

P-Matrix Formalism



Top view



$$\begin{pmatrix} b_1 \\ b_2 \\ i \end{pmatrix} = \mathbf{P} \begin{pmatrix} a_1 \\ a_2 \\ u \end{pmatrix} = \begin{pmatrix} P_{11} & P_{12} & P_{13} \\ P_{21} & P_{22} & P_{23} \\ P_{31} & P_{32} & P_{33} \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \\ u \end{pmatrix}$$

with

P_{33}: transducer admittance [conductance],

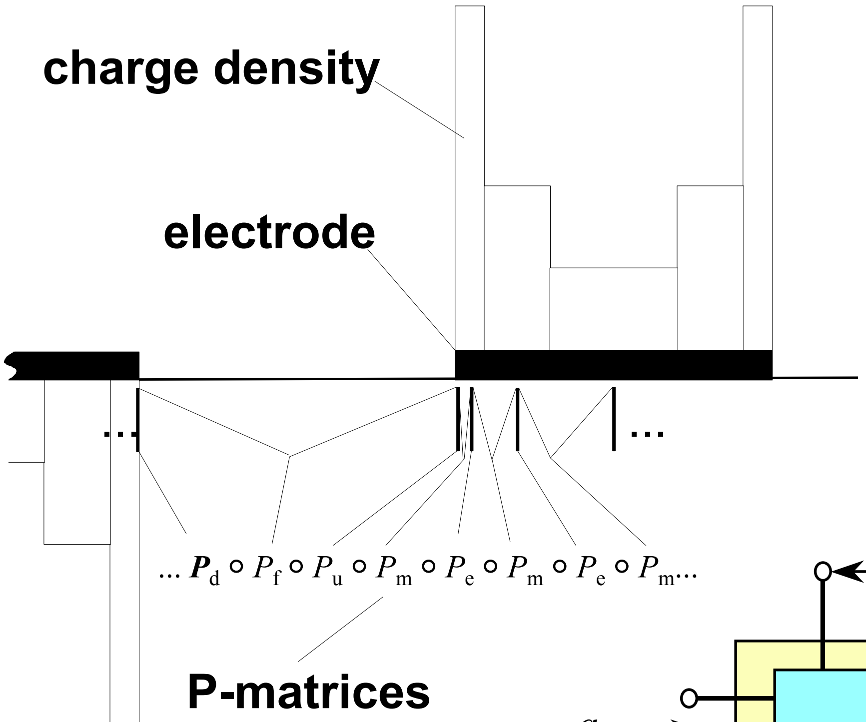
P_{13} and P_{23}: stimulation elements [$\sqrt{\text{conductance}}$],

P_{11} and P_{22}: reflection elements [ ],

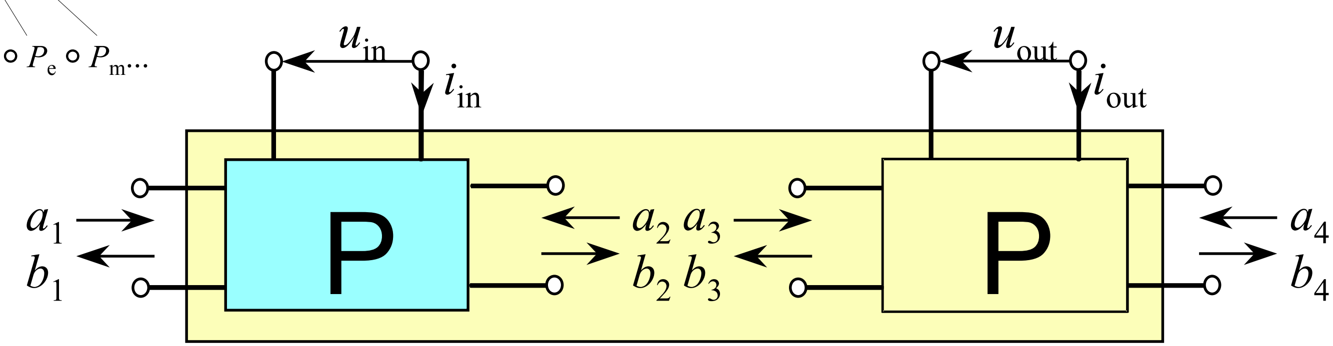
P_{12} and P_{21}: transmission elements [ ].

SAW Device Modelling

Basic cells for the P-matrix model

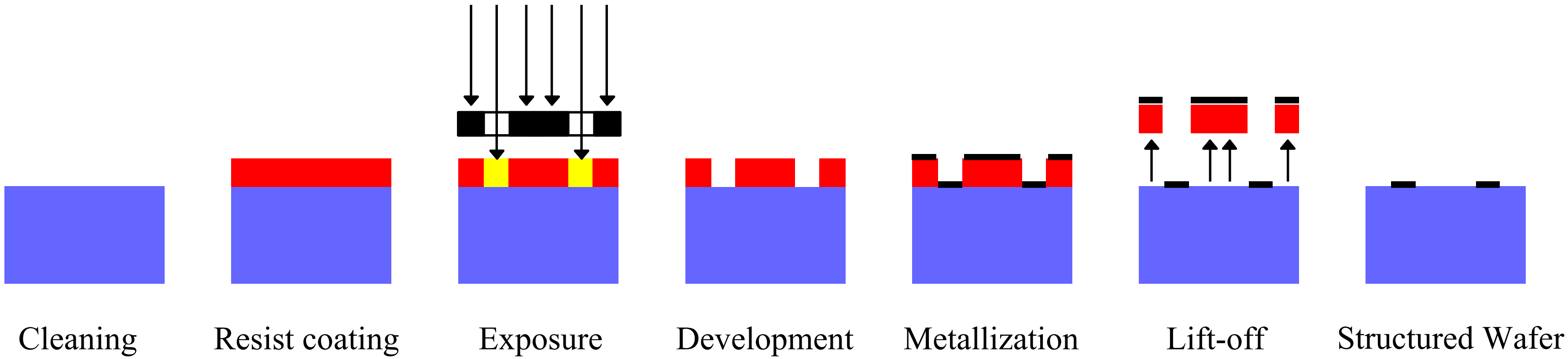


Device Modelling

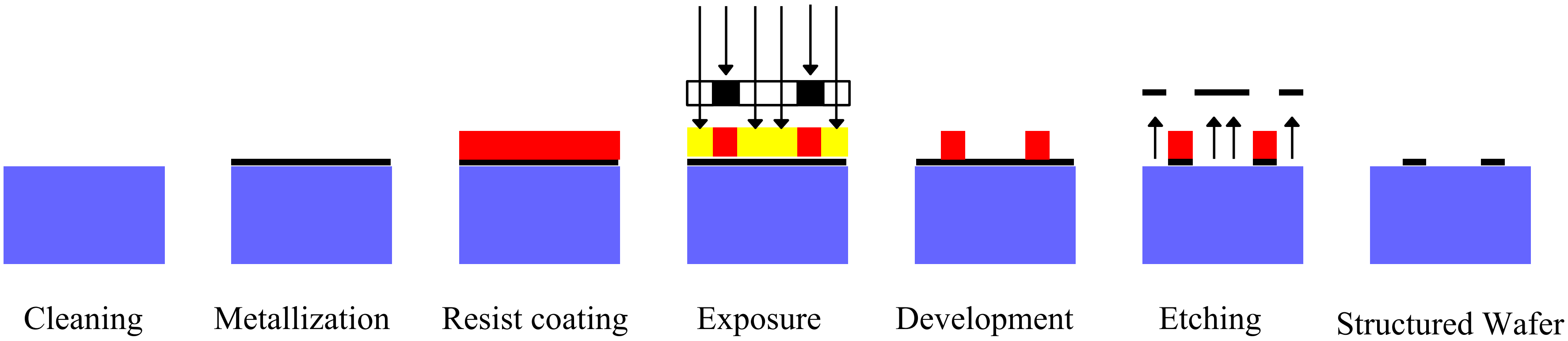


SAW Fabrication

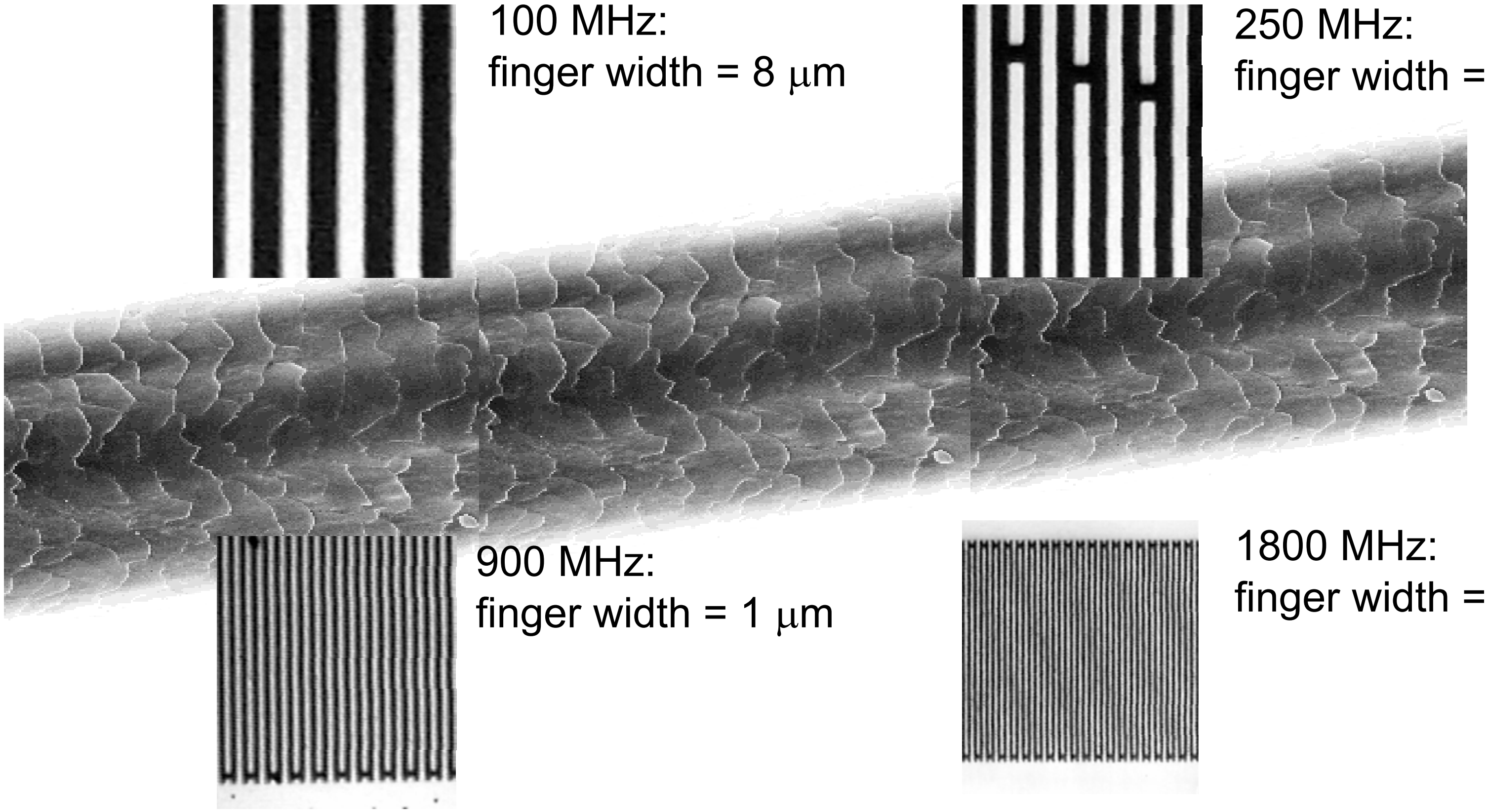
Lift-off Technique



Etching Technique

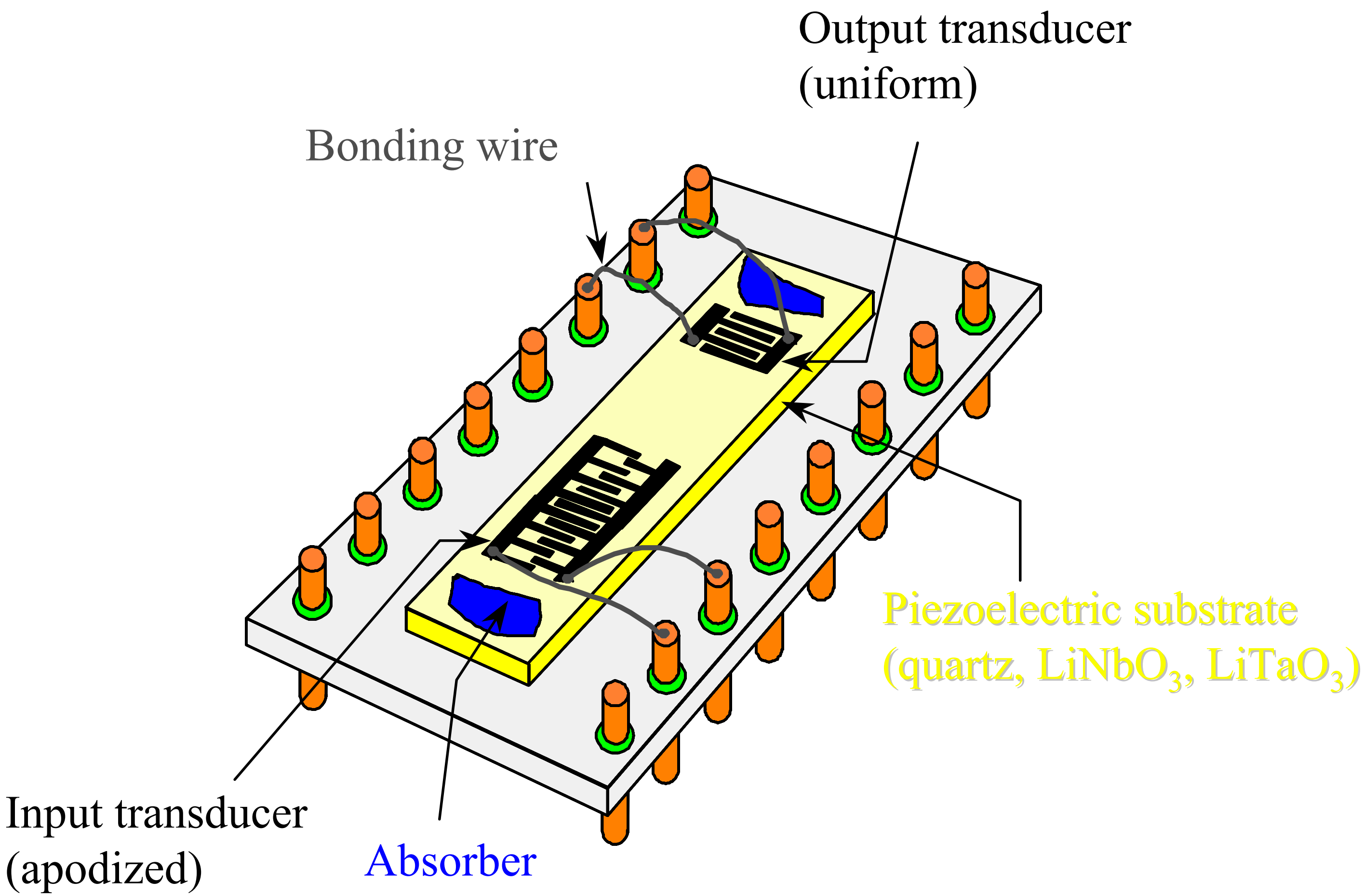


Fabrication - Electrode Widths

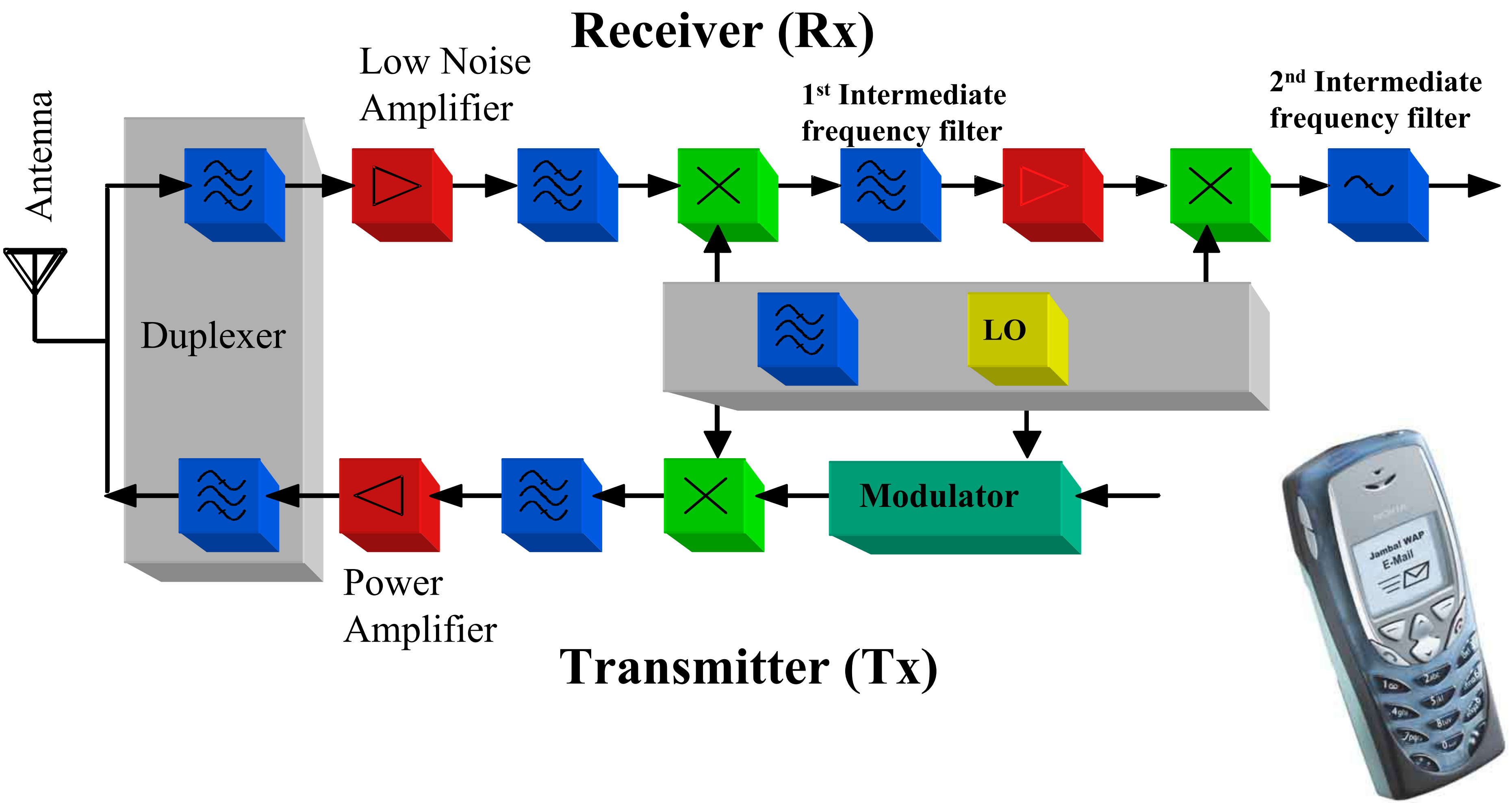


European ISM bands: 434 MHz, 869 MHz, 2.45GHz, 5,8GHz

Classical SAW Band pass Filter



Block Diagram of a Typical Transceiver



Sensitivity

A delay line with centre-to-centre transducer spacing L exhibits a delay time τ of $\tau = \boldsymbol{L}/\mathbf{v}$.

Hence, a small variation Δ in a measurand x, like a variation of the temperature ΔT results in change of the delay time change $\Delta\tau$ of

$$\frac{\Delta \tau}{\tau}(\Delta \vartheta) = \frac{\Delta L}{L}(\Delta \vartheta) - \frac{\Delta v}{v}(\Delta \vartheta)$$

$$= \frac{1}{L} \cdot \frac{\partial L}{\partial \vartheta} \cdot \Delta \vartheta - \frac{1}{v} \cdot \frac{\partial v}{\partial \vartheta} \cdot \Delta \vartheta$$

$$= \left(S_T^L - S_T^v \right) \cdot \Delta \vartheta \equiv S_T^\tau \cdot \Delta \vartheta \equiv TCD \cdot \Delta \vartheta$$

Sensitivity

The sensitivity S_y^x gives the change of the parameter x on the quantity y

$$S_y^x = \frac{1}{x} \cdot \frac{\partial x}{\partial y}$$

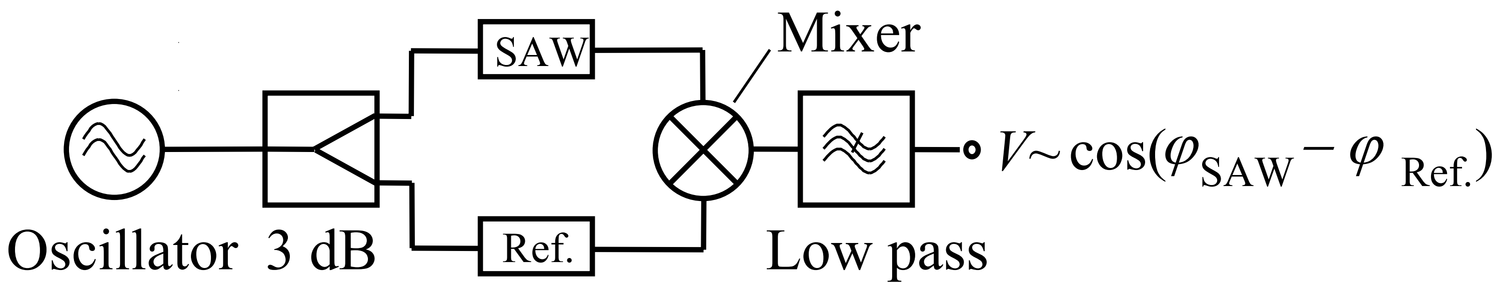
For SAW devices a change of velocity **v** or delay length **L** results in a change of the electrical measurable quantities

delay time τ, $\tau(y_0 + \Delta y) = \tau(y_0) \cdot \left[1 + S_T^\tau \cdot \Delta y\right]$

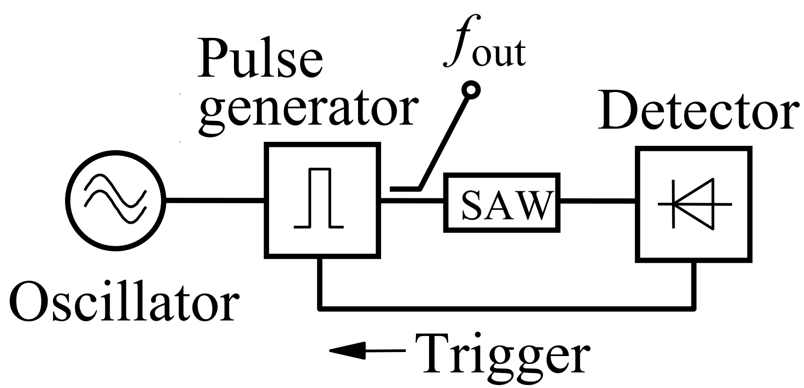
corresponding phase φ, $\varphi(y_0 + \Delta y) = \varphi(y_0) \cdot \left[1 + S_T^\tau \cdot \Delta y\right]$

and the centre frequency ***f*:** $f(y_0 + \Delta y) = f(y_0) \cdot \left[1 - S_T^\tau \cdot \Delta y\right]$

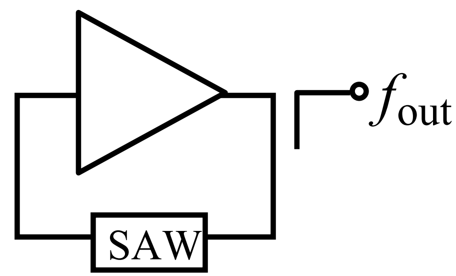
Basic electronic circuitry for **active** SAW sensing



Direct phase measurement



"Sing-around" arrangement



Oscillator

Selected SAW physical sensors from literature

Measurand	Device	Freq. (MHz)	Substrate	Sensitivity Value	Sensitivity Unit
Pressure	DL	105	Quartz	3.8	ppm/kPa
	DL	90	AlN/Si	27	ppm/kPa
Force	DL	8.3	$LiNbO_3$	10.8	ppm/kN
Strain	R	140.2	Quartz	1.28	ppm/10^{-6}
	DL	10.9	PZT	21	ppm/10^{-6}
Position (linear)	DL	8.3	$LiNbO_3$	120.5	ppm/ μm
Position (angular)	R	434	Quartz	2.86	ppm/mrad
Acceleration	DL	251	Quartz	45	ppm/(m/s^2)
	DL	10.9	PZT	8.7	ppm/(m/s^2)
Rotation rate	DL	10.9	PZT	25.7	ppm/s^{-2}
Flow rate (gas)	DL	73	$LiNbO_3$	204	ppm/(cm^3/s)
Flow rate (liquid)	DL	68	$LiNbO_3$	105	ppm/(mm^3/s)
Liquid viscosity	DL	30	$LiNbO_3$	2.7	ppm/cP
Liquid density	DL	6	ZnO /Si_xN_y	30000	ppm/(g/cm^3)
Electric field	DL	900	$LiNbO_3$	141	ppm/(V/ μm)
(normal)	R	85	$Li_2B_4O_7$ on piezoceramic	300	ppm/(V/ μm)
Electric field (transv.)	DL	1000	$LiNbO_3$	120	ppm/(V/ μm)
Voltage	DL	900	$LiNbO_3$	0.93	ppm/V
Liquid conductivity	DL	51	$LiTaO_3$	13400	ppm/(S/m)
Magnetic field	DL	140	Fe-B/ Quartz	0.38	ppm/(A/m)
Temperature	DL	43	$LiNbO_3$	92.13	ppm/°C
Radiation dose	R	199	Quartz	0.48	ppm/$(J/kg)^{0.5}$
Thin film thickness	DL	75	$LiNbO_3$	9.25	ppm/nm

From :
G. Fischerauer, "Surface Acoustic Wave Devices," in: W. Göpel, J. Hesse, J. N. Zemel, H. Meixner, R. Jones (Eds.), *Sensors. A Comprehensive Survey*, Vol. 8. Weinheim: VCH, 1995
(References: see there)

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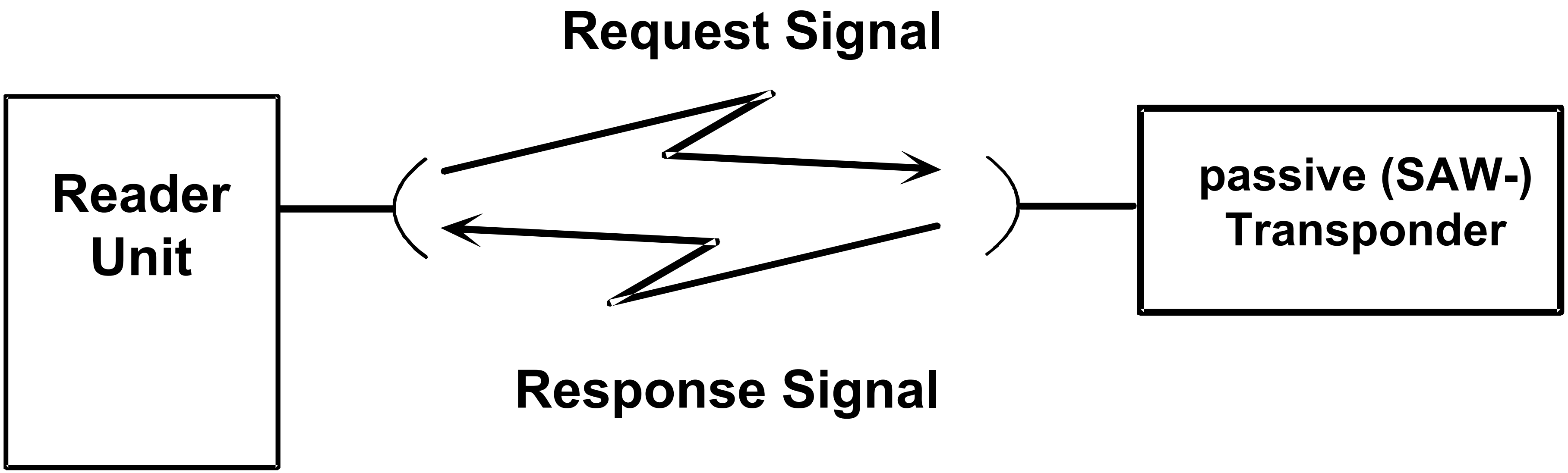
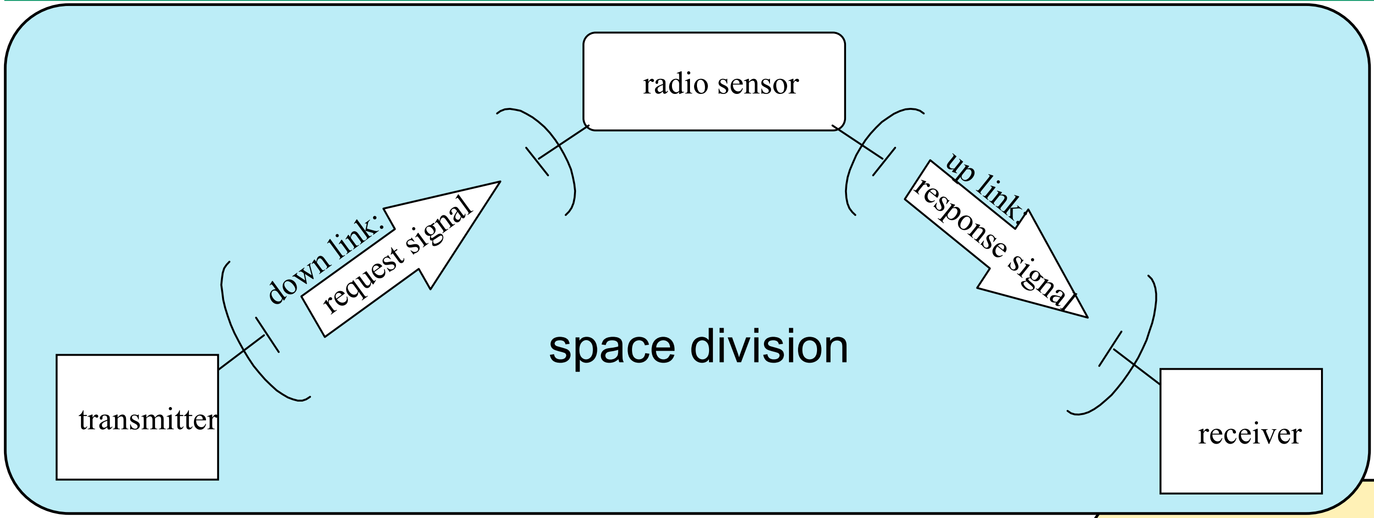
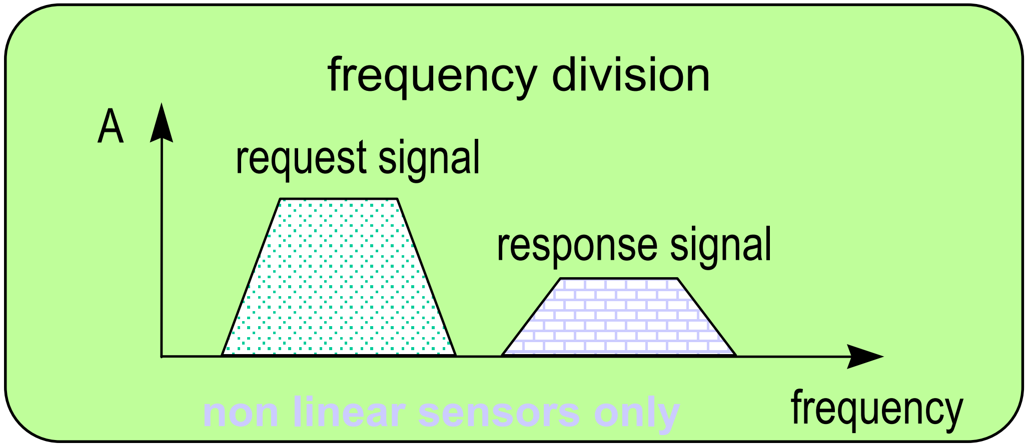
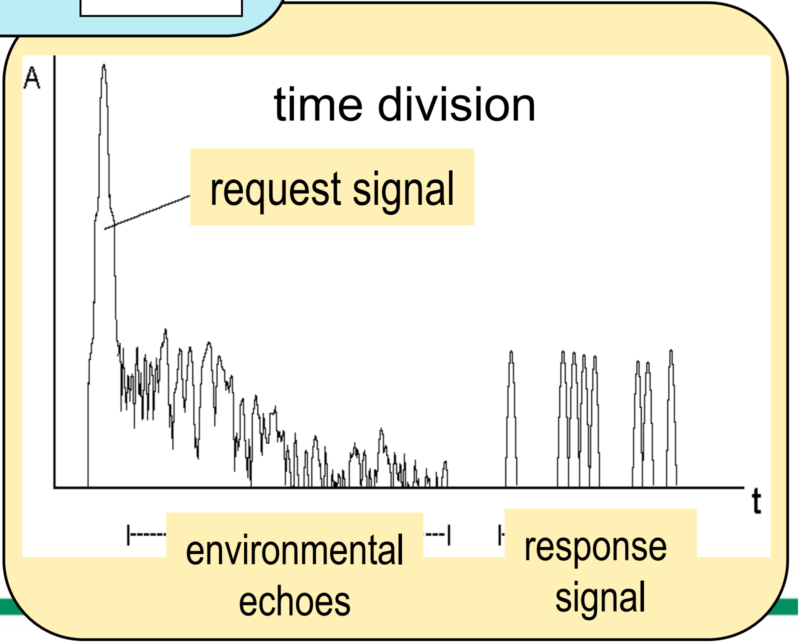
Operating Principle of Wireless Identification or Sensor Systems



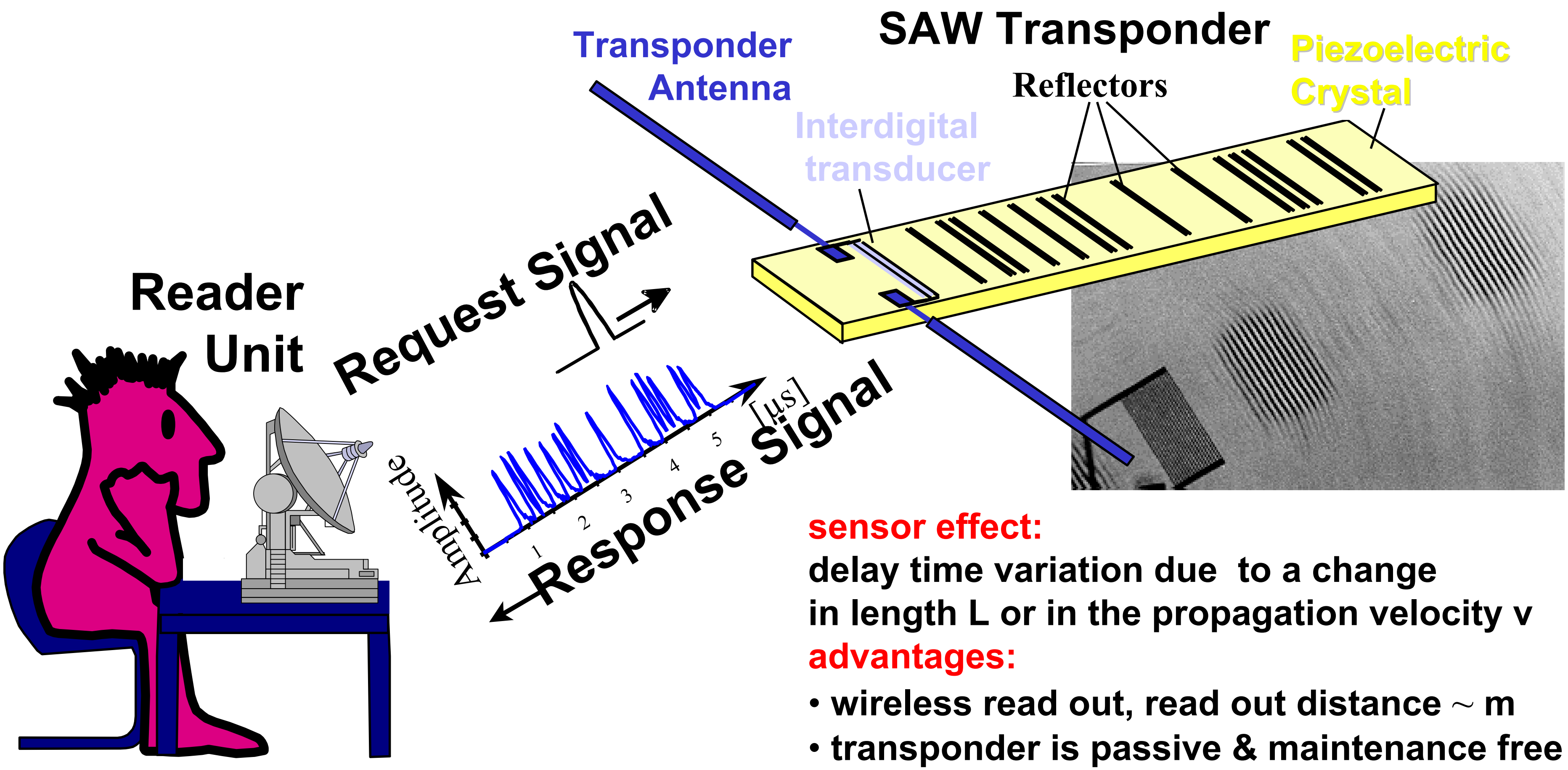
Separation of the sensor response from the request signal







Operating Principle of Wireless SAW - Identification or Sensor Systems

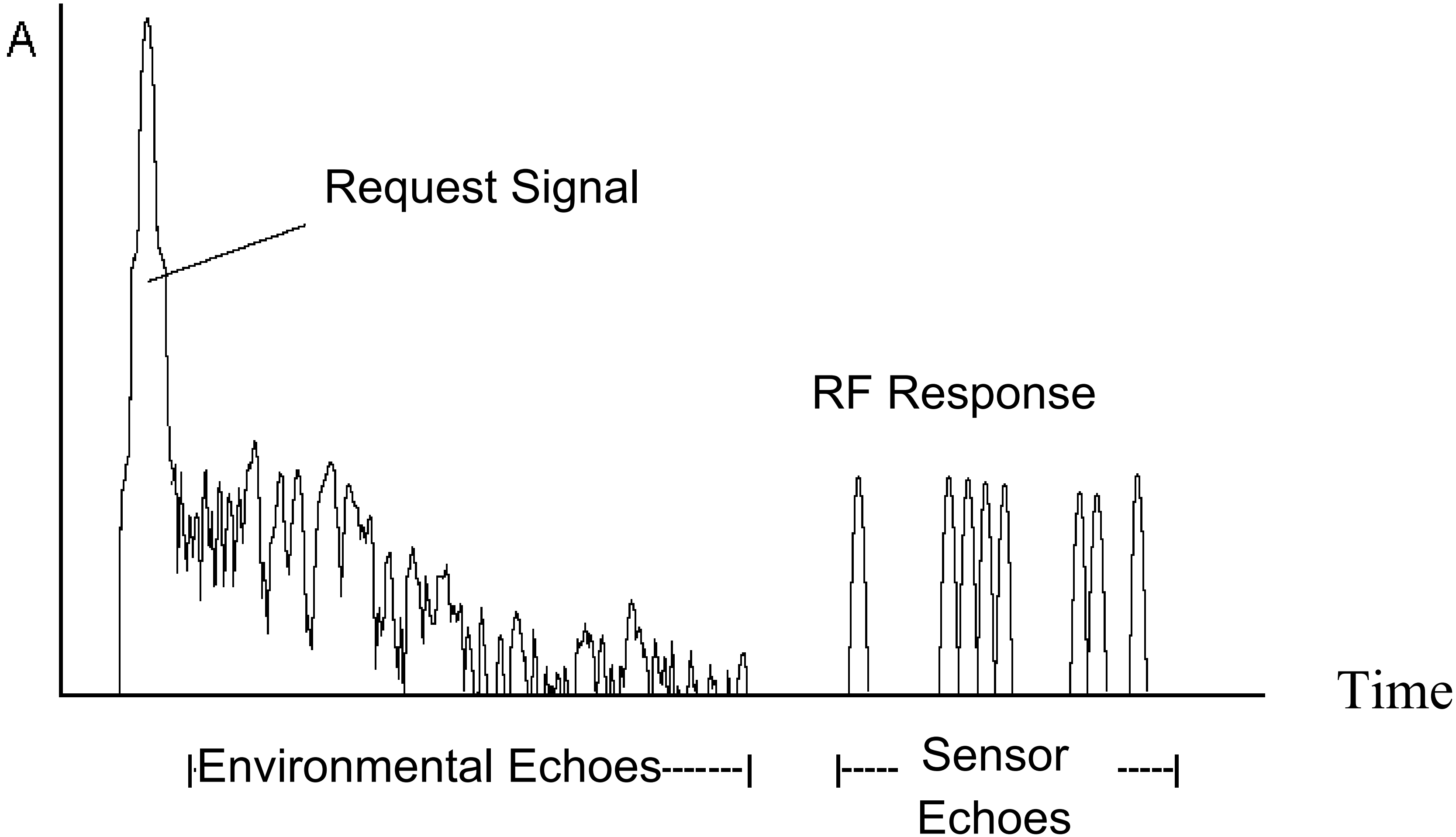


sensor effect:
delay time variation due to a change in length L or in the propagation velocity v

advantages:

- wireless read out, read out distance ~ m
- transponder is passive & maintenance free
- free of ageing ("Quartz-stable")

The time division of the RF response of a SAW transponder



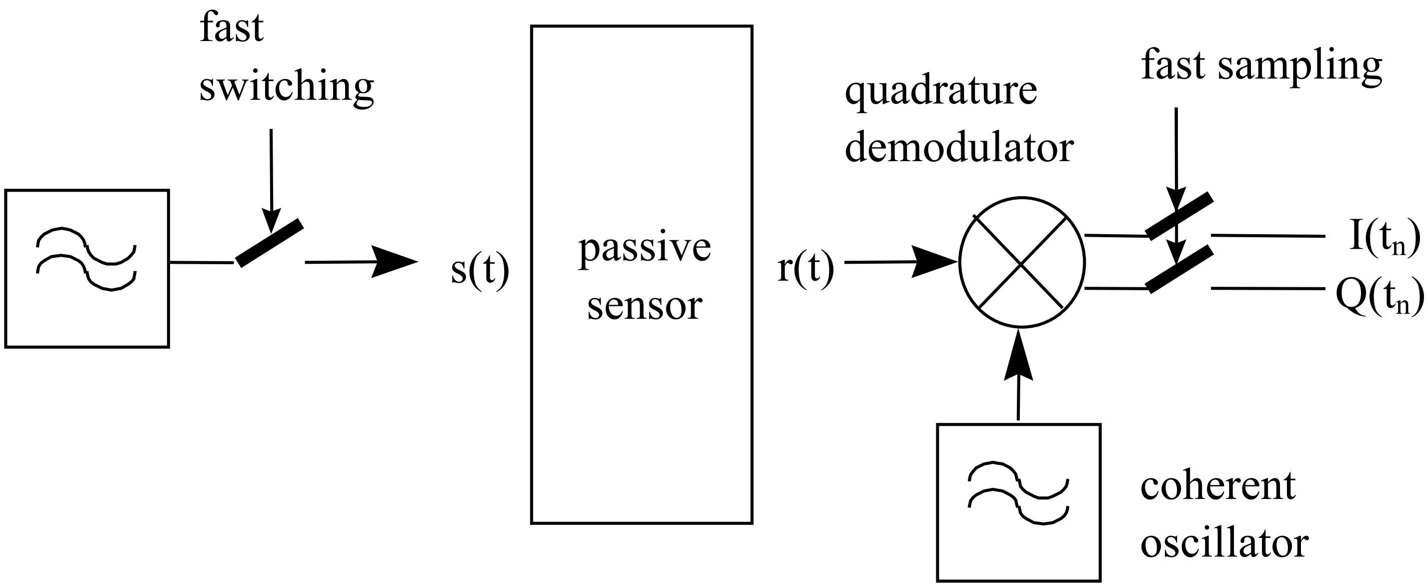
Design of Reader Units

The reader units of wireless SAW identification or sensor systems applications resemble those used in traditional radar, and all designs used in radar technologies can be applied:

- **Time domain sampling using pulse radar**
  - \+ suitable for measuring with a high dynamic resolution of fast changing or moving objects
  - \+ very simple duplexer by using a switching device
  - – expensive due to the necessity of fast sampling and fast signal processing devices
  - – low range due to a low duty cycle
- **Time domain sampling using a chirp radar**
  - \+ same as a pulse radar, but with an increased range, because the TB-product improves the duty cycle
    <u>Restriction:</u> Only medium processing gains are possible: B is restricted by the operating bandwidth of the SAW transponders, and T is restricted by the initial delay of the transponders
- **Frequency domain sampling using a network analyser structure**
  - \+ low cost and low speed standard components
  - \+ lower demand on the signal processing devices
  - \+ high range due to maximum duty cycle
  - – suitable only for measuring low speed changing or moving objects
  - – only a circular device or two separated antennas as duplexer is possible
  - – a high dynamic range of the receiver architectures is necessary
- **Frequency domain sampling using a FMCW design**
  - – same as a network analyser structure, but with a higher dynamic resolution due to the improved measuring speed
    <u>But:</u> A high speed Fourier Transform is needed

Reader units utilizing time domain sampling

High speed, but high cost due to fast components

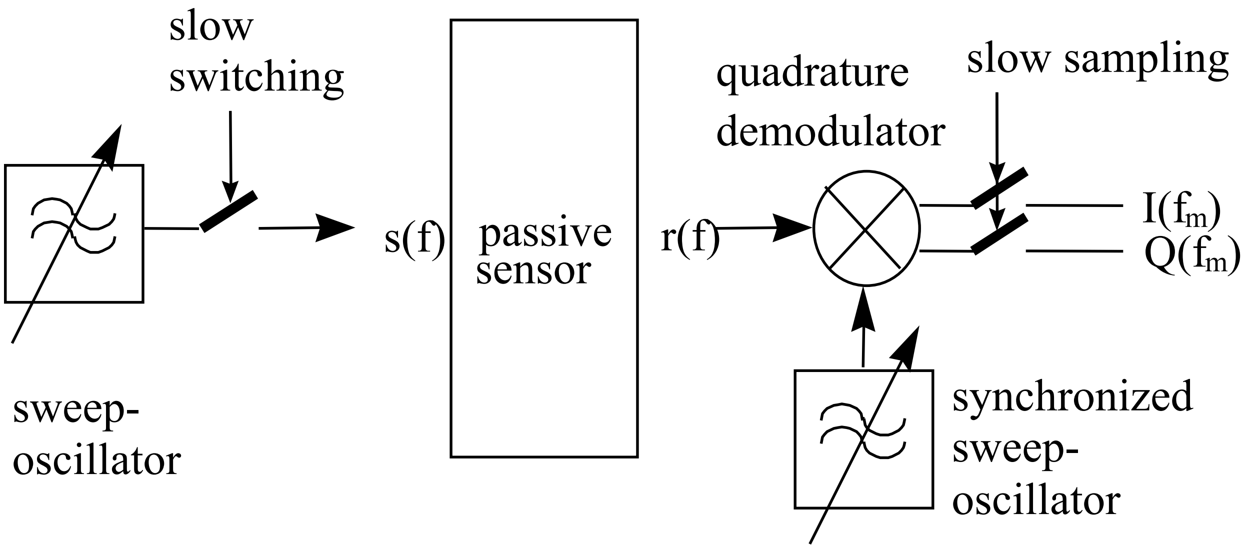


... assuming fast changing measurands:

- the frequency band is transmitted in one burst
- the duty cycle may be enhanced by using chip signals
- need a fast sampling of the response signal

Reader units utilizing frequency domain sampling

very low speed, low cost
standard components

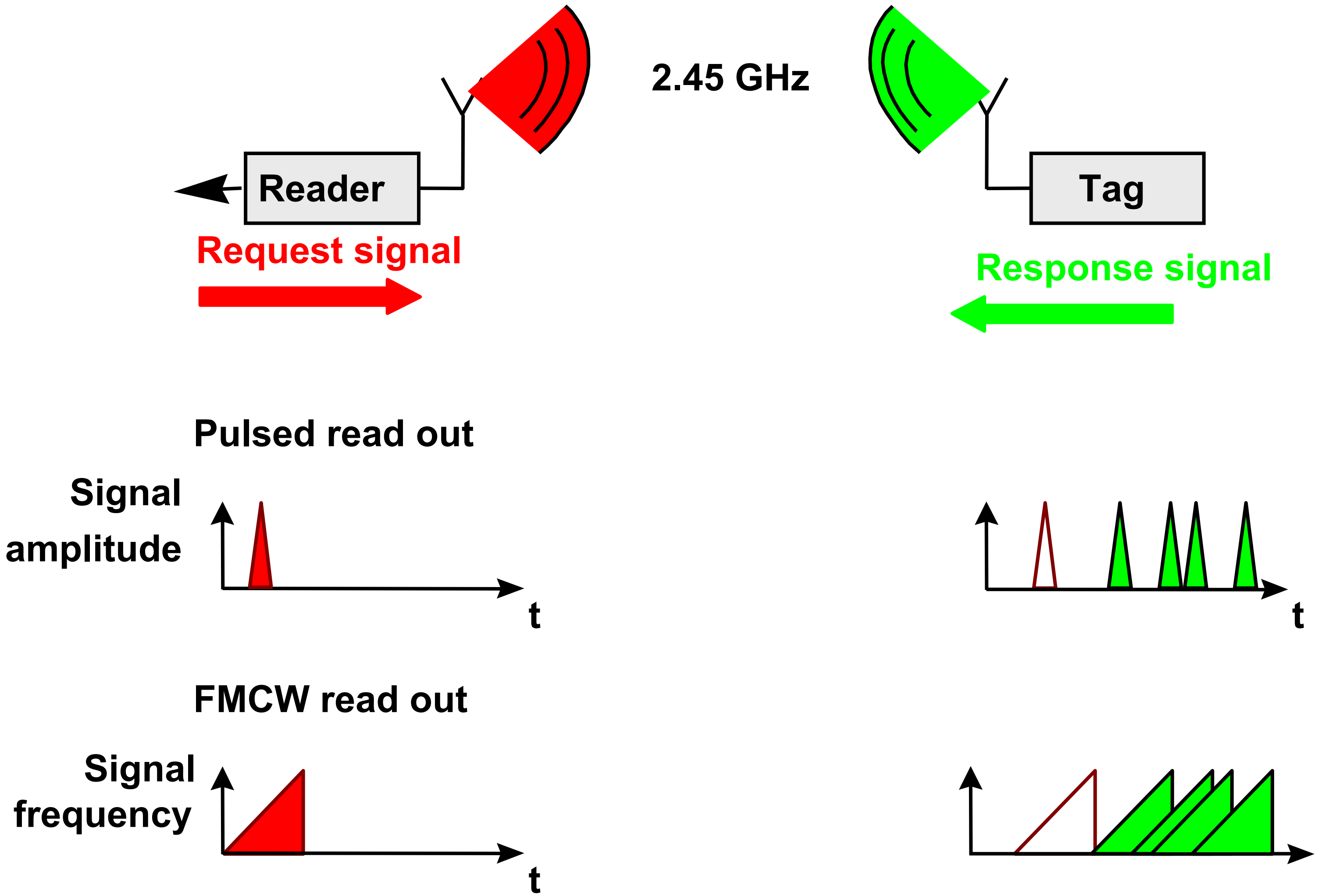


... assuming slowly changing measurands:

- the frequency of the transmitted bursts is varied step by step

Circuitry is like a network analyser

Reader units utilizing a FMCW principle



Modular structure of reader units in a FMCW radar system

DSP Unit

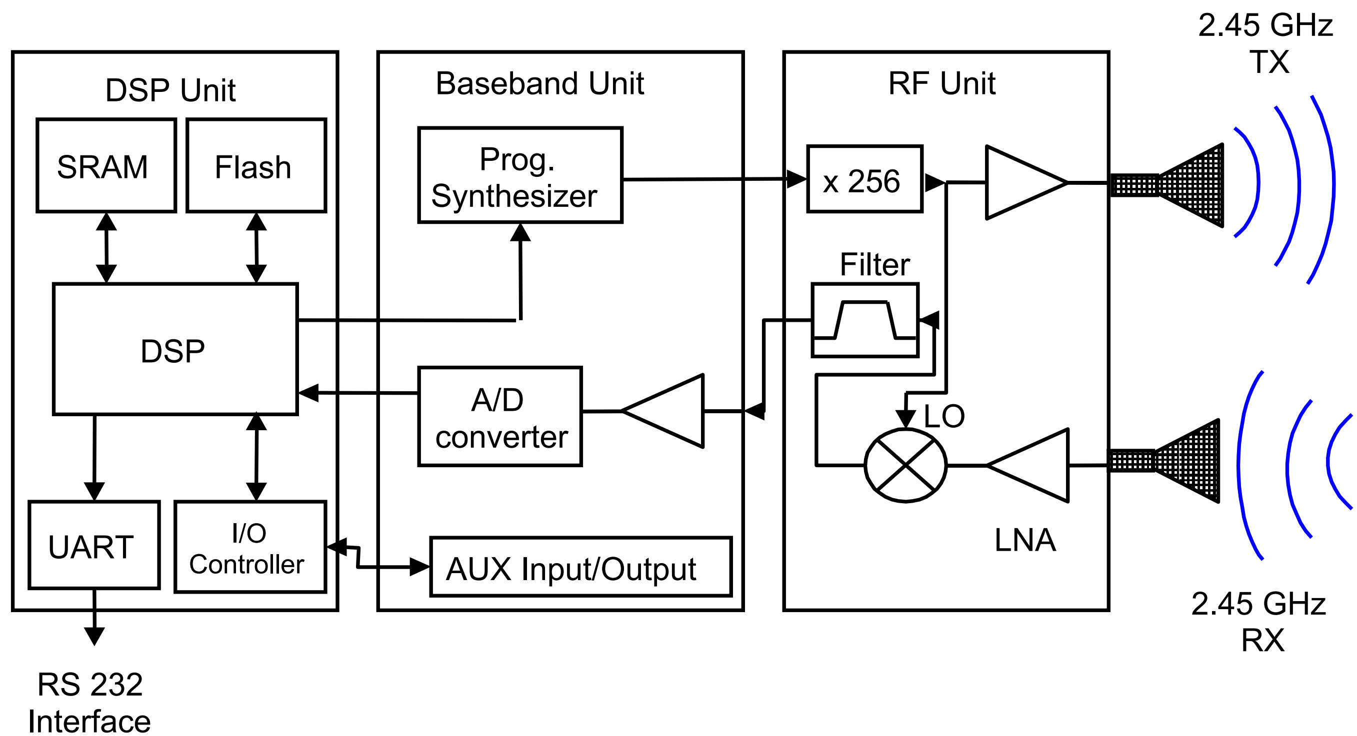
- FFT
- Communication
- System configuration
- FPGA programming

Baseband Unit

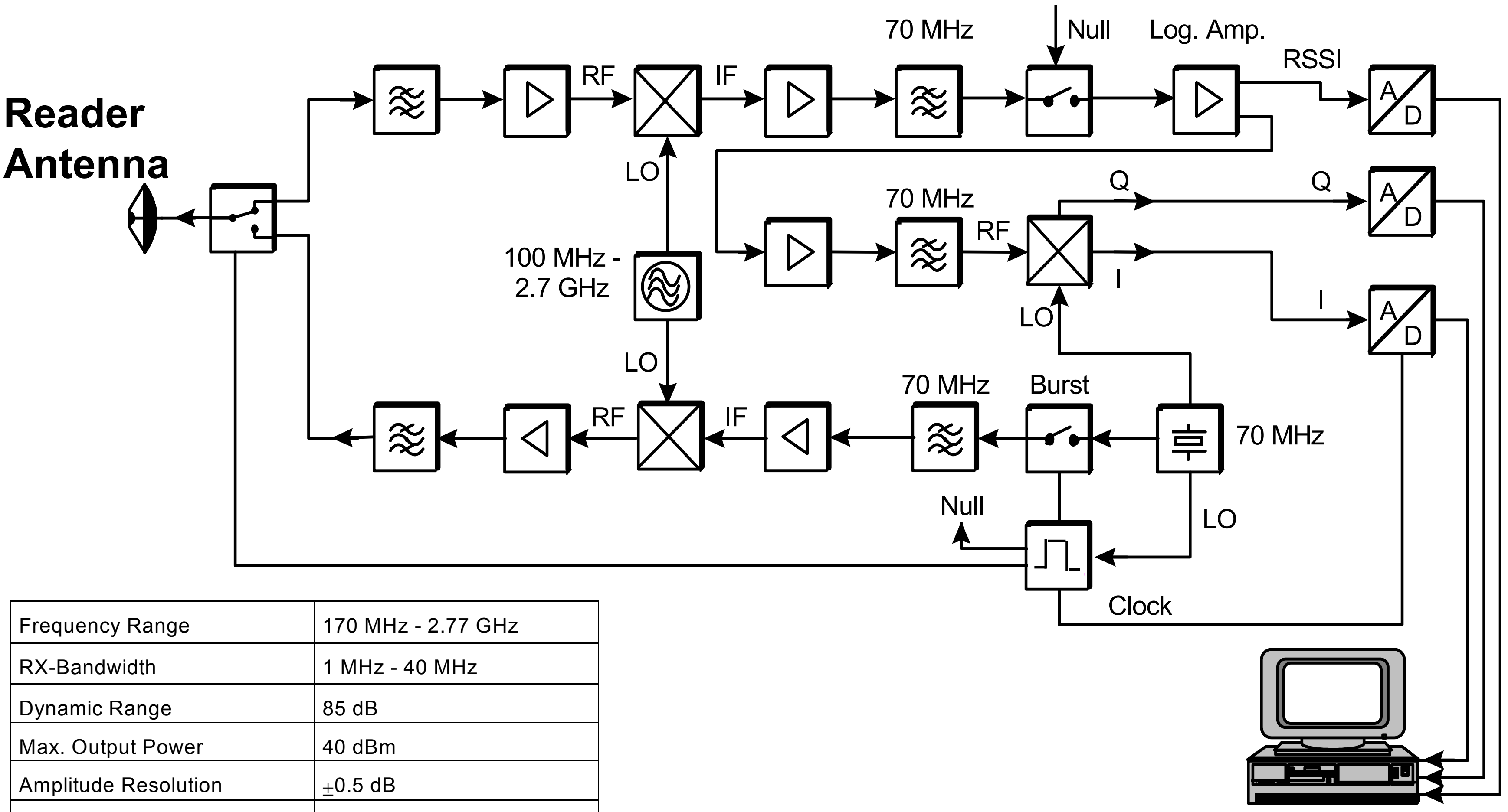
- generates the frequency modulation
- A/D converter of the echo signal (time domain)
- controls Aux I/O

RF Unit

- transmits (Tx) and receives (Rx) in the 2.45 GHz ISM Band
- mixing of Tx / Rx



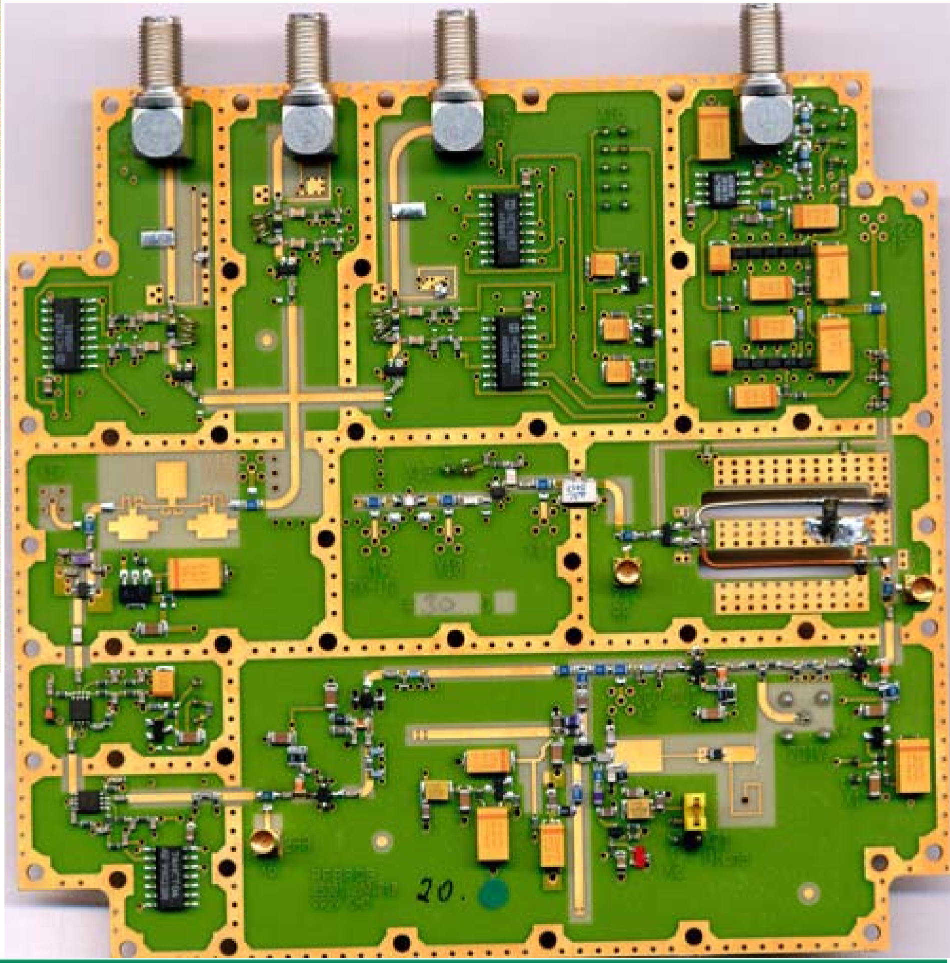
Extended Block diagram of a time domain sampling reader unit

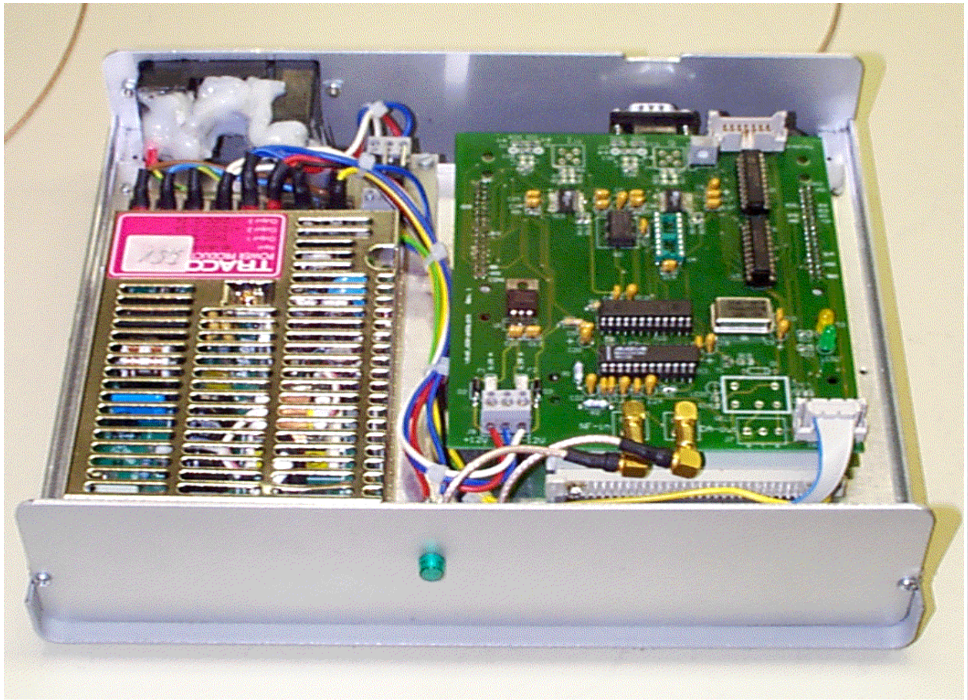


Frequency Range	170 MHz - 2.77 GHz
RX-Bandwidth	1 MHz - 40 MHz
Dynamic Range	85 dB
Max. Output Power	40 dBm
Amplitude Resolution	$\pm$0.5 dB
Phase Resolution	$\pm$ 1°
Noise Figure	5 dB

Reader Unit operating at 2.45GHz, built up using standard ICs.

RF printed circuit board



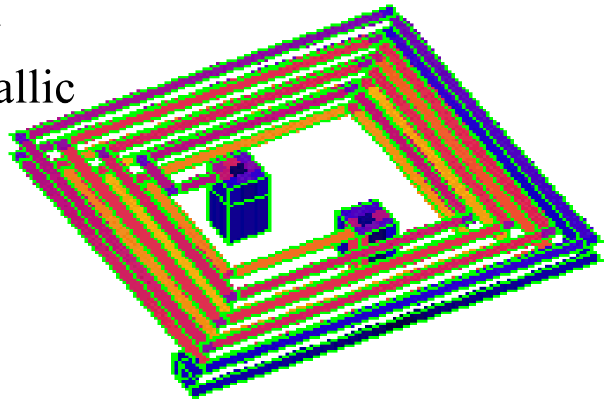


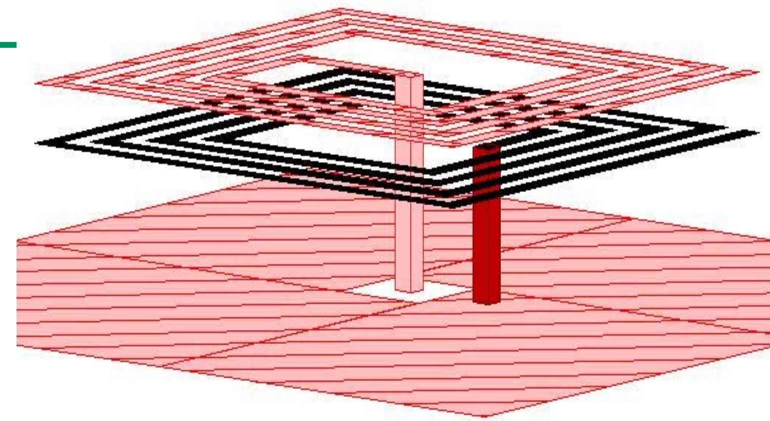
Open card chassis

RF part of a Reader Unit operating at 434MHz

Folded spiral antenna for the 434 MHz band

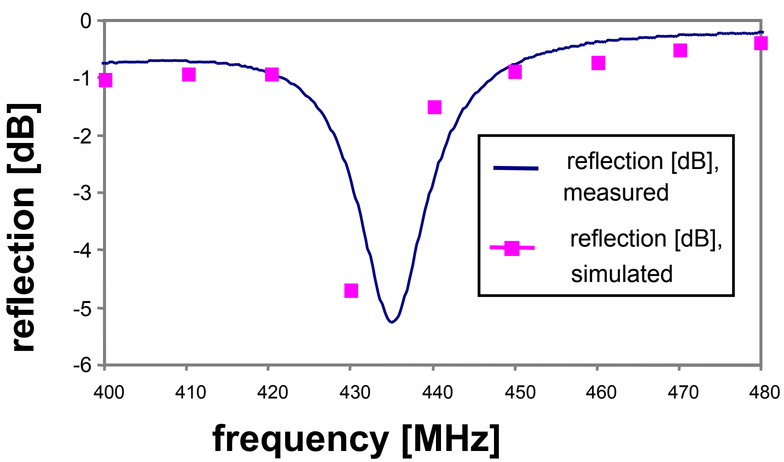
Current density map of the metallic spiral layers





Geometry with ground plane

Reflection Coefficient



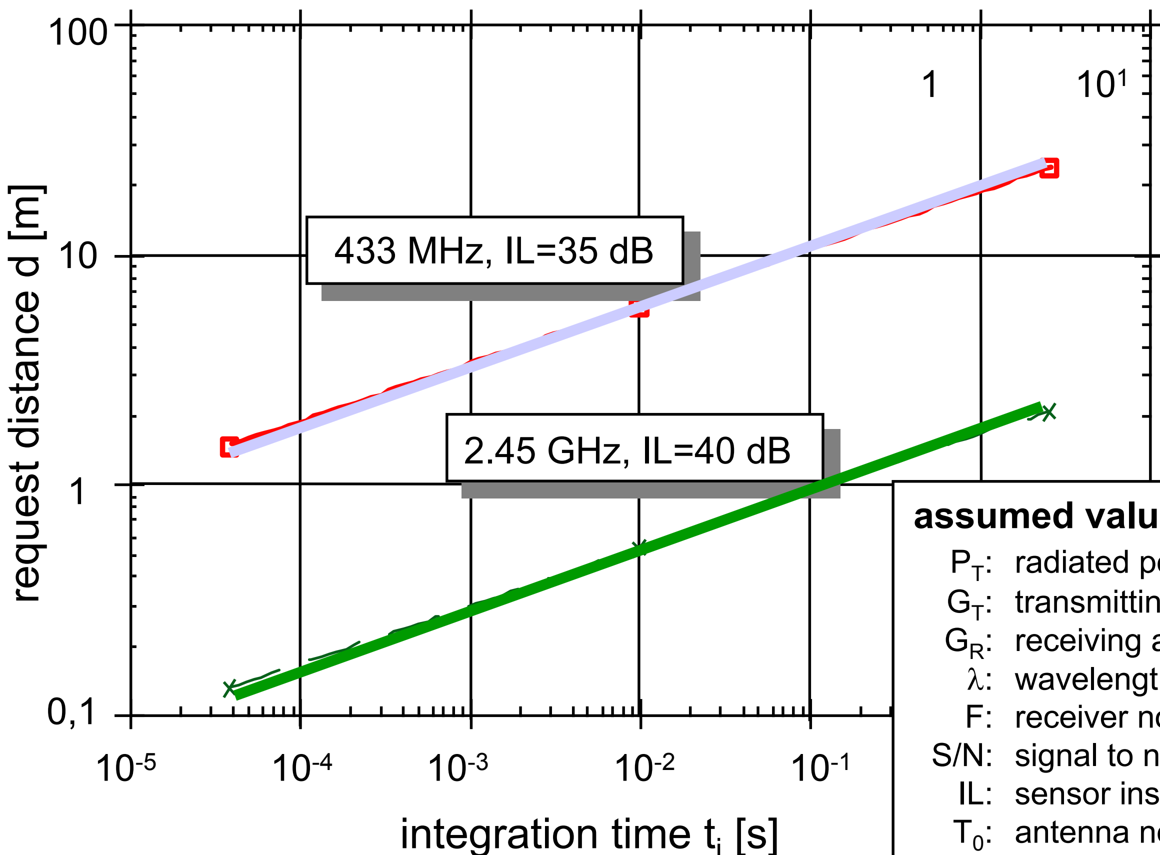
Antenna in a steel package filled with polymer (diameter = 20mm).

ID System OIS-W

Baumer IDENT

A company of the Baumer electric Group

Estimation of the request distance



radar equation

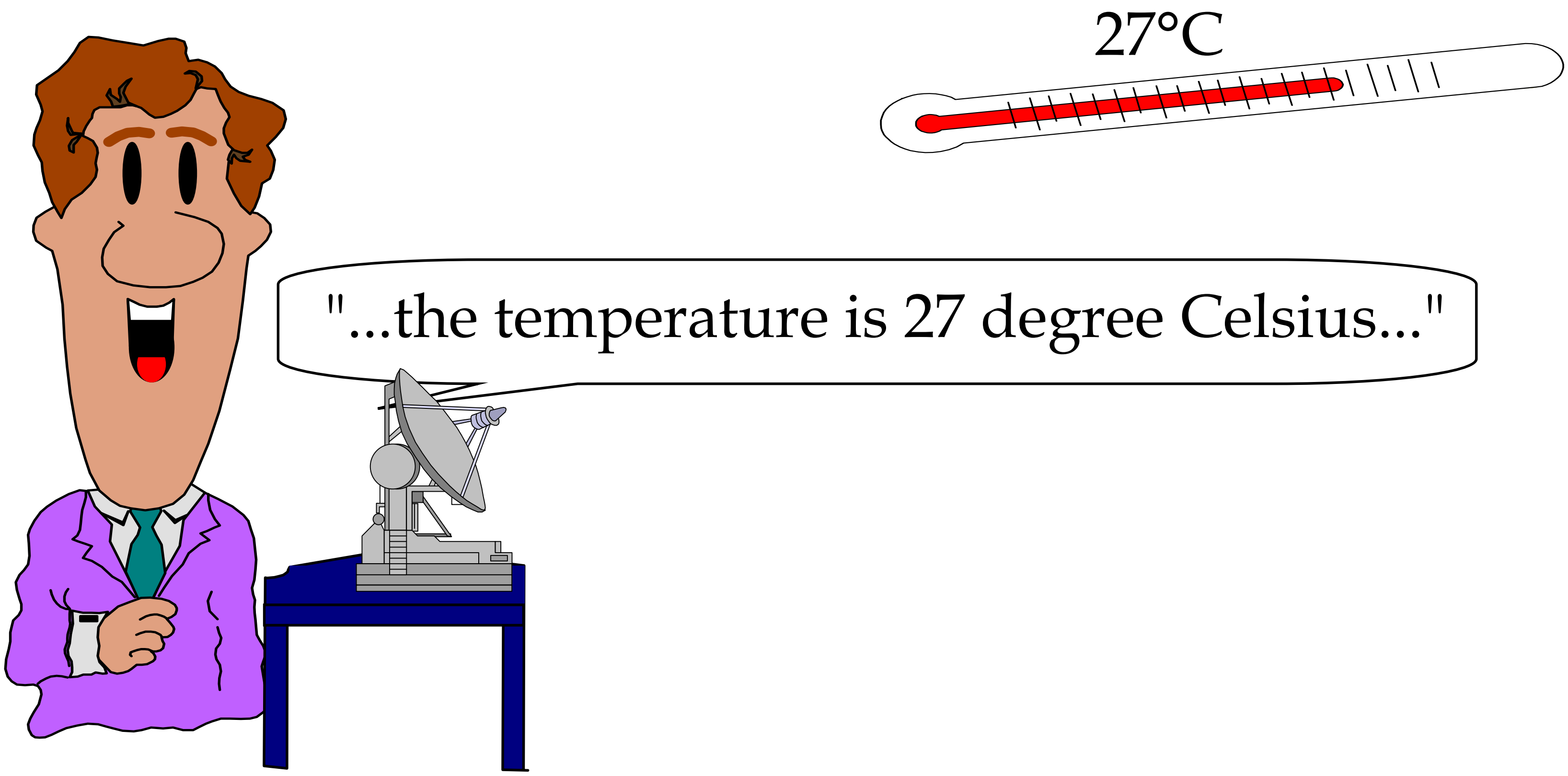
$$d = \sqrt[4]{\frac{P_T \, G_T^2 \, G_R^2 \, \lambda^4 \, t_i}{k \, T_0 \, F \, \frac{S}{N} \, IL}}$$

assumed values for estimations

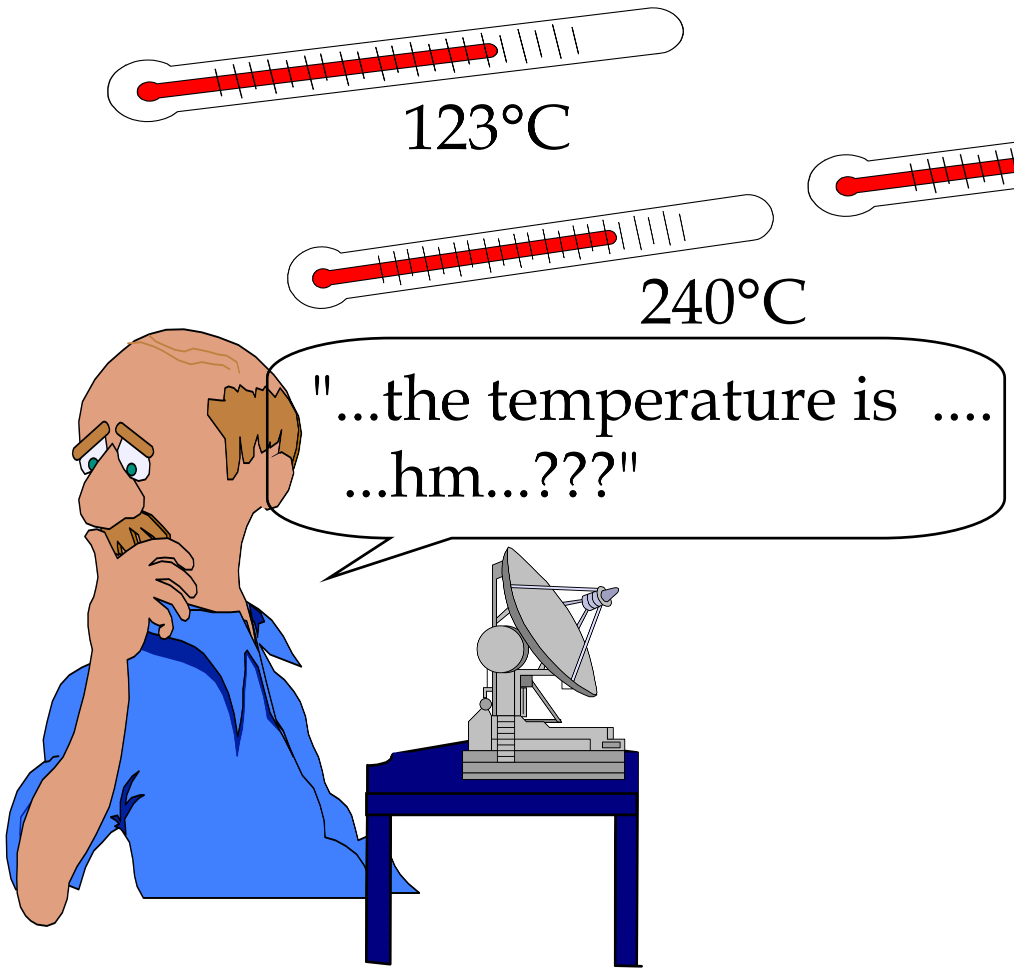
P_T:	radiated power	14 dBm
G_T:	transmitting antenna gain	0 dB
G_R:	receiving antenna gain	-3 dBi / 0 dBi
λ:	wavelength	70 cm / 12 cm
F:	receiver noise figure	12 dB
S/N:	signal to noise ratio for detection	20 dB
IL:	sensor insertion loss	35 dB / 40 dB
T_0:	antenna noise temperature	300 K
t_i :	integration time	

Multiple access of SAW radio sensors

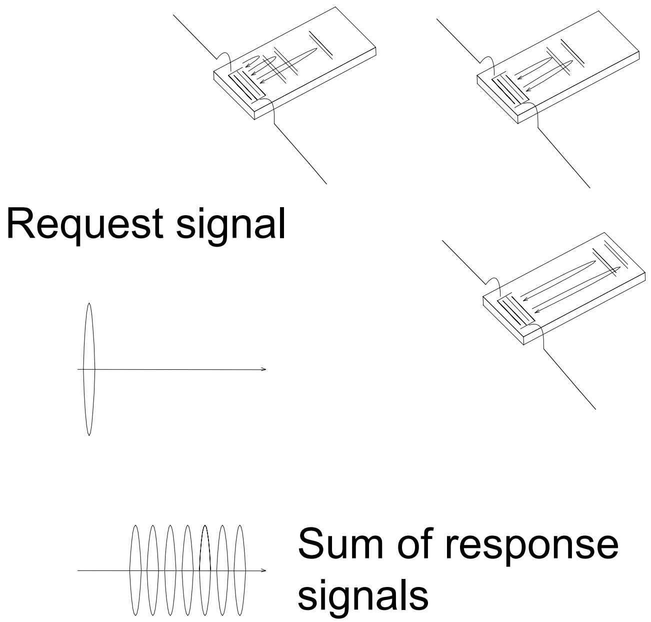
With only one sensor in the beam of the reader unit, everything is fine:



More than one... ???



Example for a TDMA-sample



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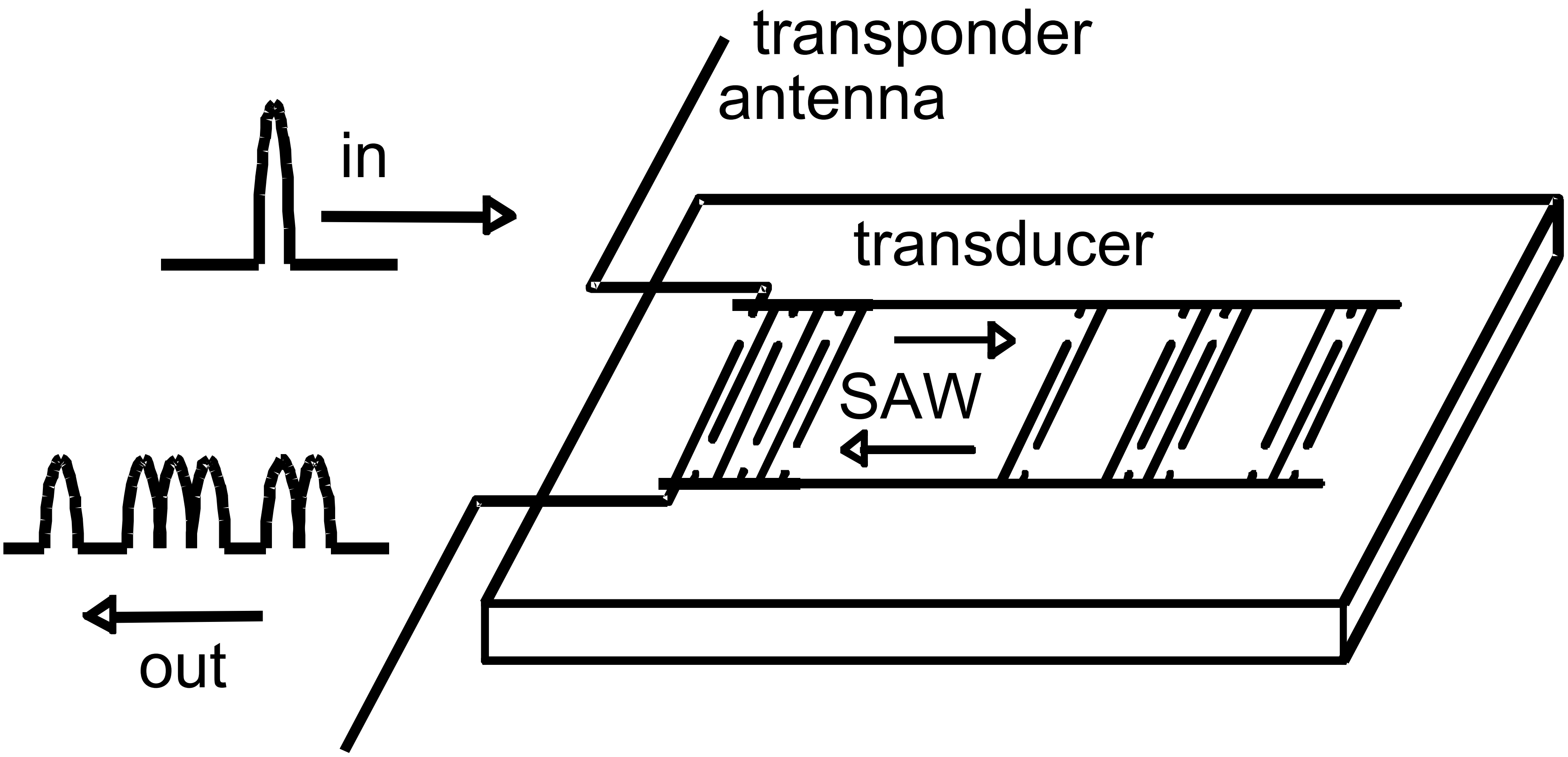
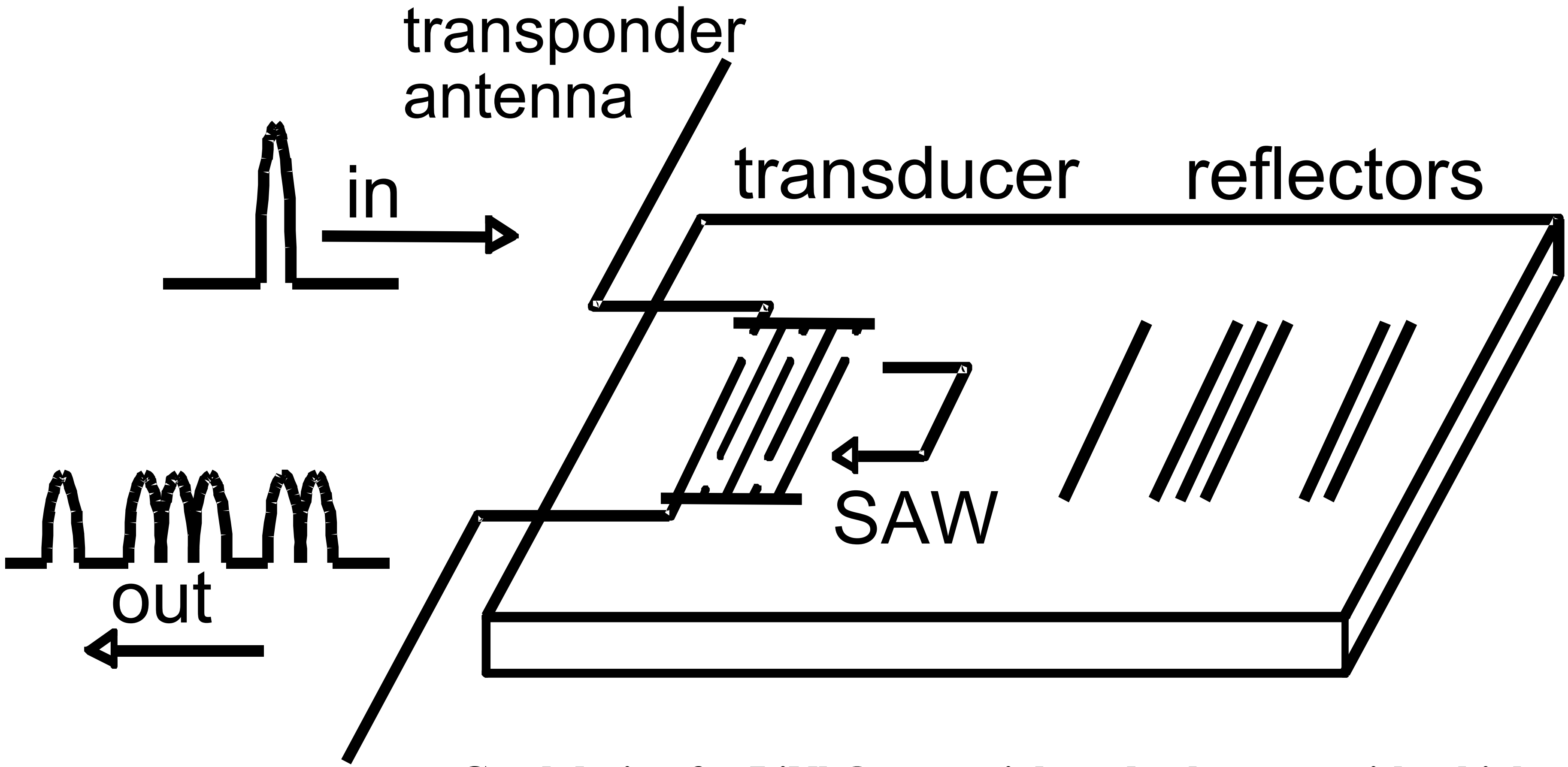
Schematic layout of a SAW ID tag with several transducers wired together to a common bus bar



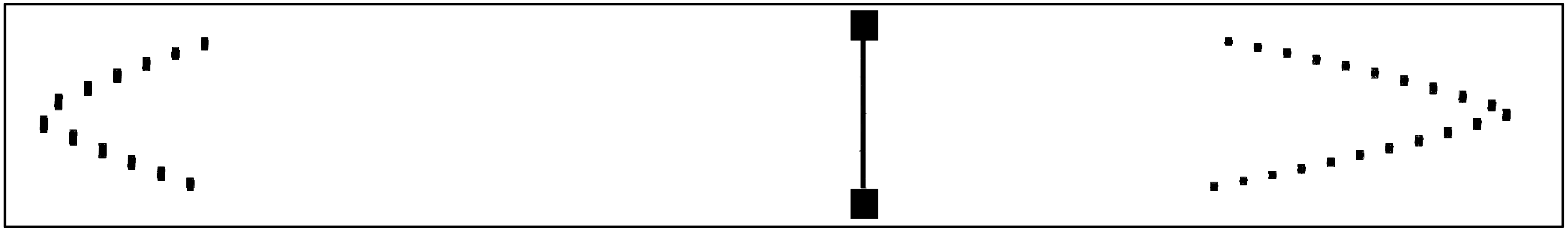
Good design for quartz materials and other substrates with small dielectric and piezoelectric constants

Schematic layout of a reflective SAW tag



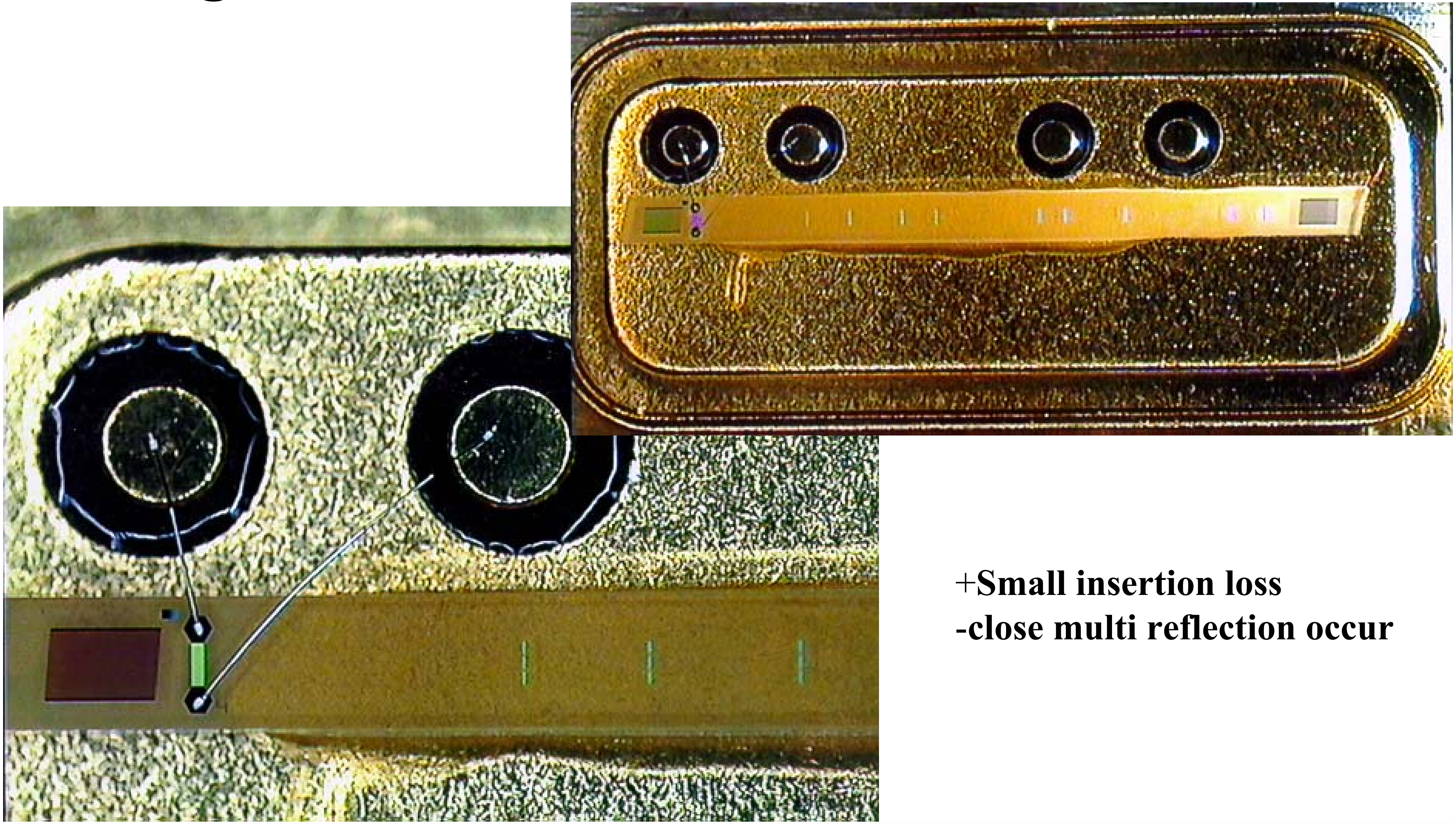
Good design for $LiNbO_3$ materials and substrates with a high dielectric and piezoelectric constants, half the chip size!

SAW ID tag with every reflector arranged in a separate track



+No close multi reflections
+No dependence of actual bit level on precursors
- need reflectors with high reflectivity
----- need a transducer with a huge aperture

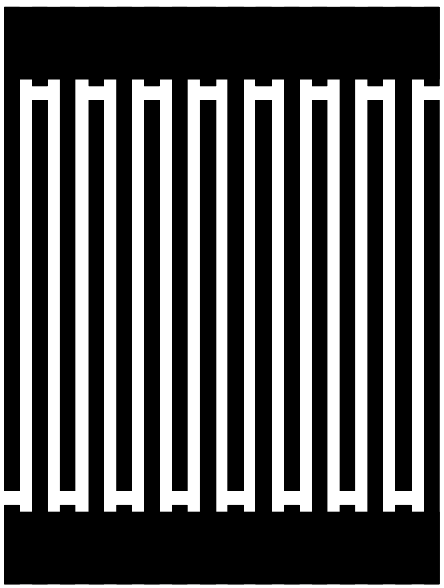
SAW ID tag where all reflectors are arranged in the same acoustic track



+Small insertion loss
-close multi reflection occur

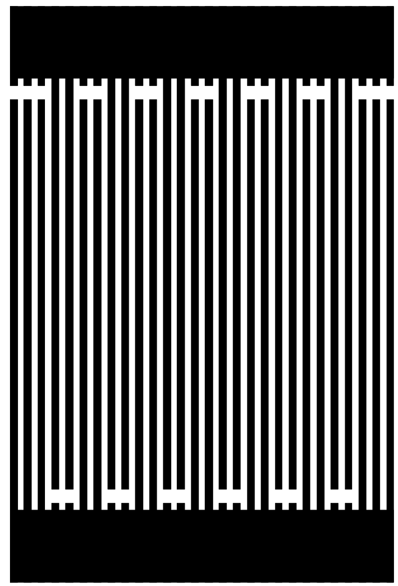
Layout of typical transducers for SAW ID tags and radio requestable sensors

uniform transducer



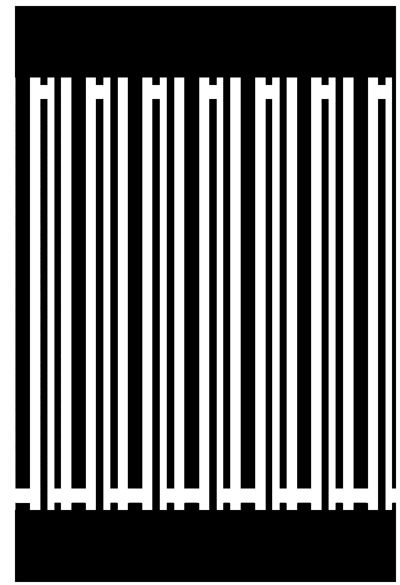
pitch: $\lambda/4$

split finger transducer



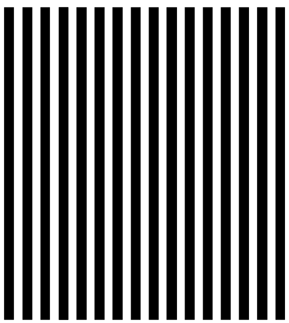
pitch: $\lambda/8$

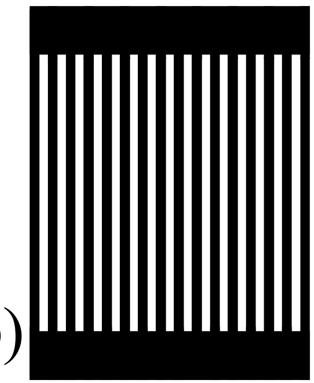
unidirectional transducer

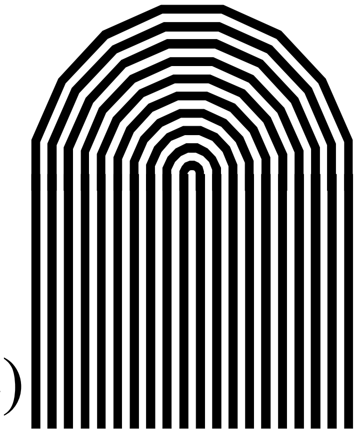


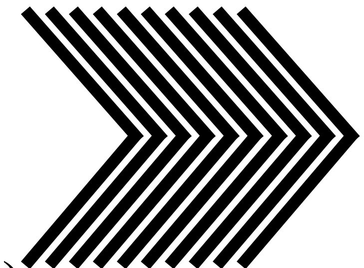
pitch: $\lambda/4$ and $\lambda/8$

Layout of reflectors

a) 

b) 

c) 

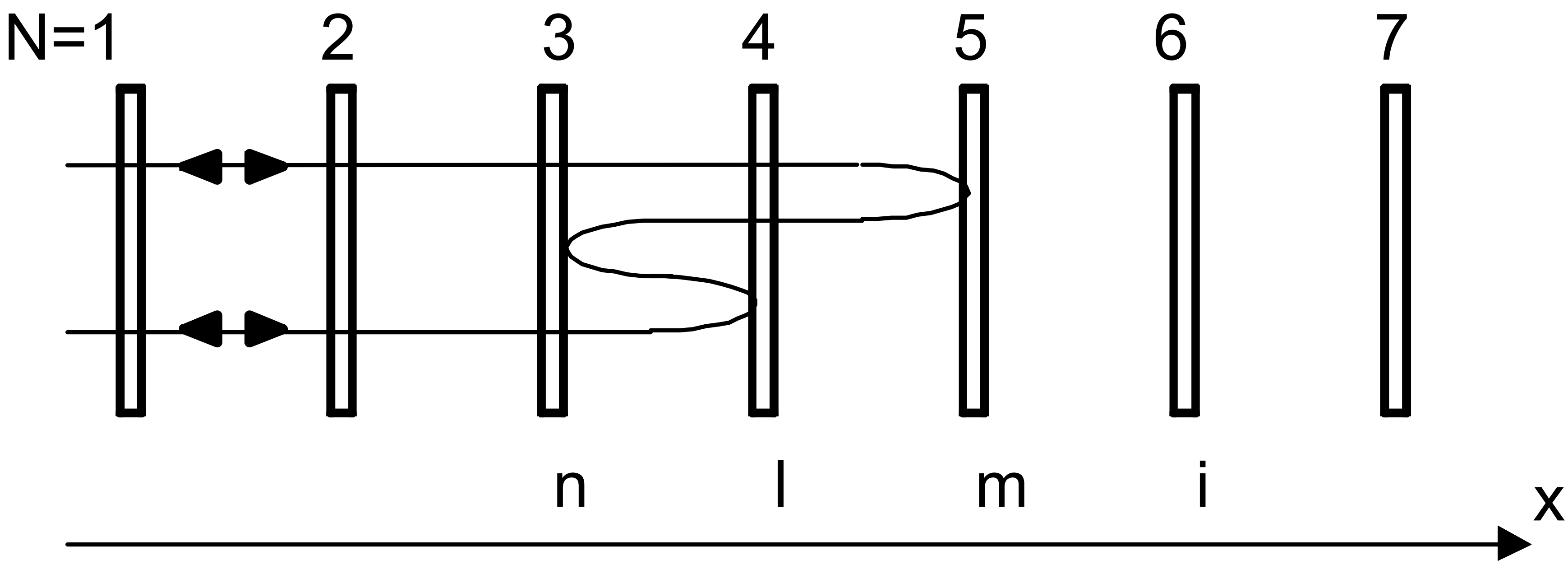
d) 

uniform open	shorted	multistrip coupler	chevron-type
multistrip coupler effects may occur		huge demand of wasted space per track	no multi reflections, but high loss

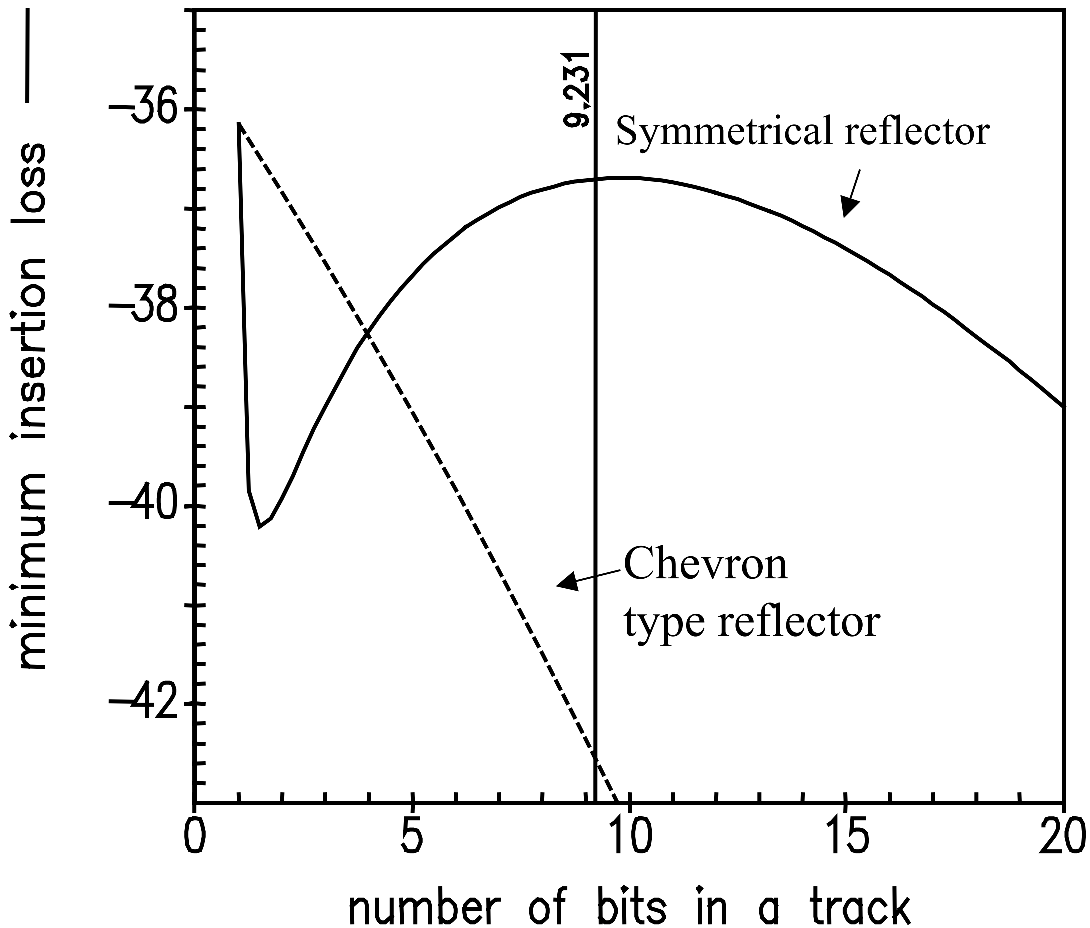
symmetrical acoustic reflection (a–c)

non-symmetrical reflection (d)

Schematic of triple reflection resulting in a delayed spurious signal



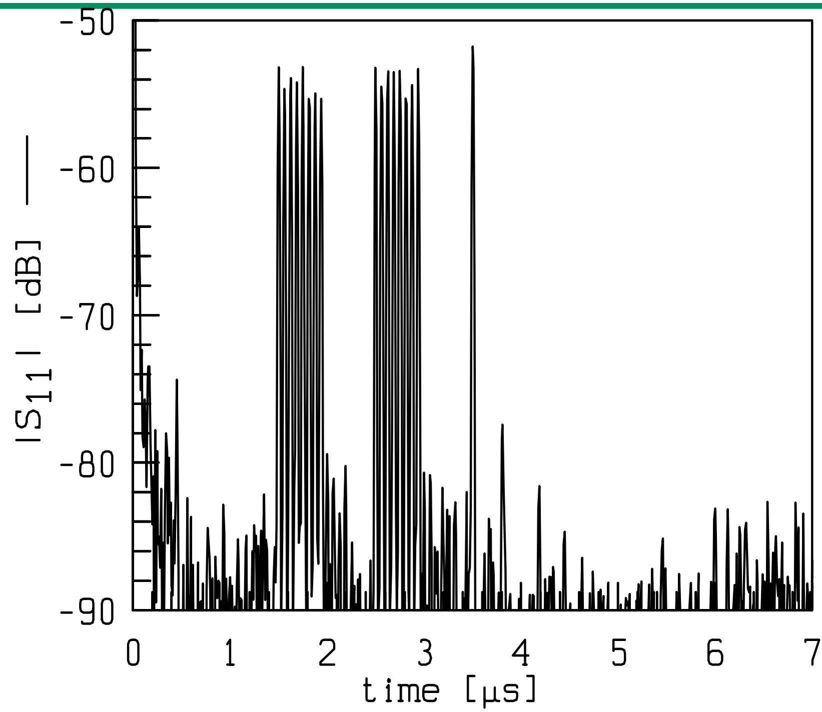
Loss of a 33 bit ID-tag as a function of the number of reflectors lined up in one track

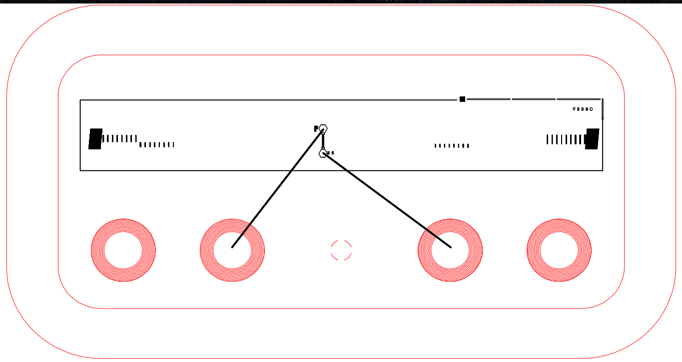


Design parameter:

- Amplitude weighting (ON/OFF)
- 33 bits
- dynamic (IL(ON)/IL(OFF)>20dB)
- propagation loss between two contiguous reflectors 0.38dB
- loss due to passing twice a reflector 0.75dB

Layout, Photo and measurements of a mounted SAW ID tag comprising 33 reflectors in 4 tracks (f_0 = 2.45 GHz) (Amplitude Coded)





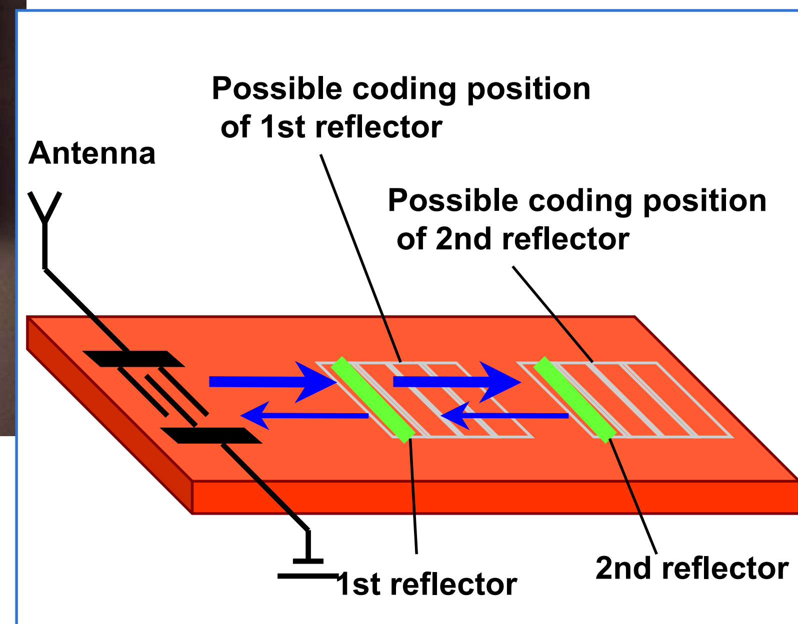
Measurements: 8 "ON", 8 "OFF", 8 "ON“, 8 "OFF", 1 "ON

Coding Schemes

- **Amplitude Coding (ON/OFF)**
  - + insensitive on small velocity variations
  - + temperature effects can be eliminated using a start and stop bit
  - ± problems with the uniformity can be avoided by using special OFF structures with the same damping but no reflective properties than ON structures
  - – high insertion loss due to the high amount of reflectors (and also due to the OFF structures)
- **Phase Coding**
  - + 2PSK: lower bit error rate by using a 2-PSK coding scheme than by ON/OFF-amplitude coding with the same signal-to noise-ratio
  - + 4-PSK and higher coding schemas are possible, which reduces the total amount of reflectors / symbols
  - – very sensitive to small velocity variations
  - – temperature effects have to be cancelled very carefully
- **Pulse Position Coding**
  - + higher coding schemas are possible
  - + insensitive on small velocity variations and temperature variations
  - + small insertion loss due to the small amount of reflectors used

Layout and Photo of a mounted SAW ID tag comprised of 5 reflectors in one tracks (f0 = 2.45 GHz) using pulse position coding

Pulse position coding schema



Baumer electric

Baumer IDENT

Outline

- Introduction: Classical SAW Sensors
- SAW Radio Request
- SAW Identification Tags
- SAW Radio Requestable Sensors
  - (Reflective) Delay Lines
  - Resonators
  - (Reflective) Dispersive Delay Lines
  - Non-linear Sensors
- Application Examples
- Conclusion

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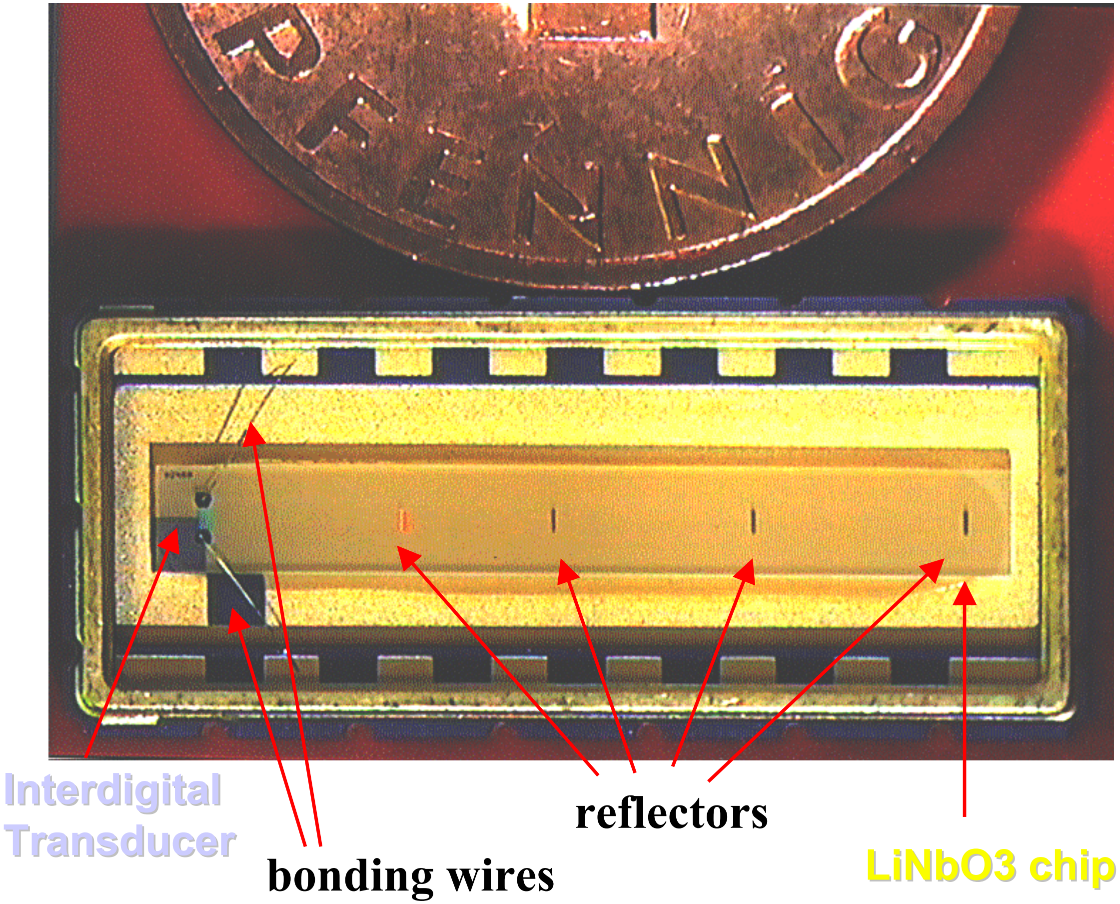
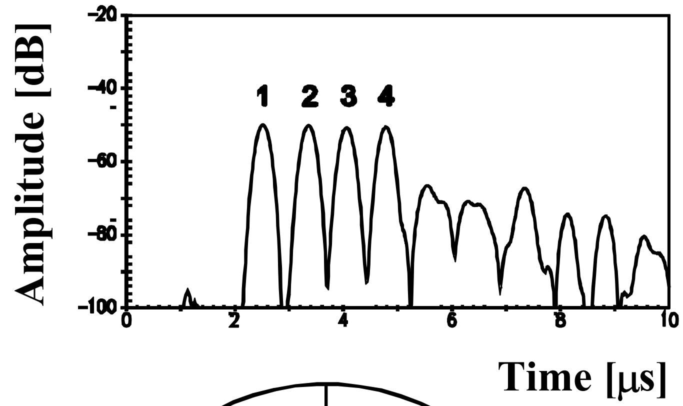
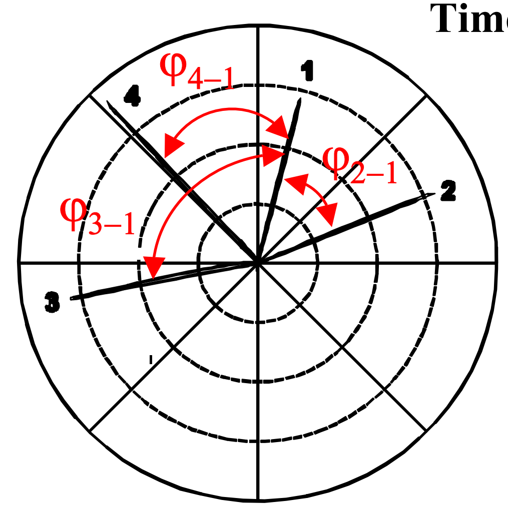
Photo of a mounted SAW radio readable temperature sensor and corresponding time domain response



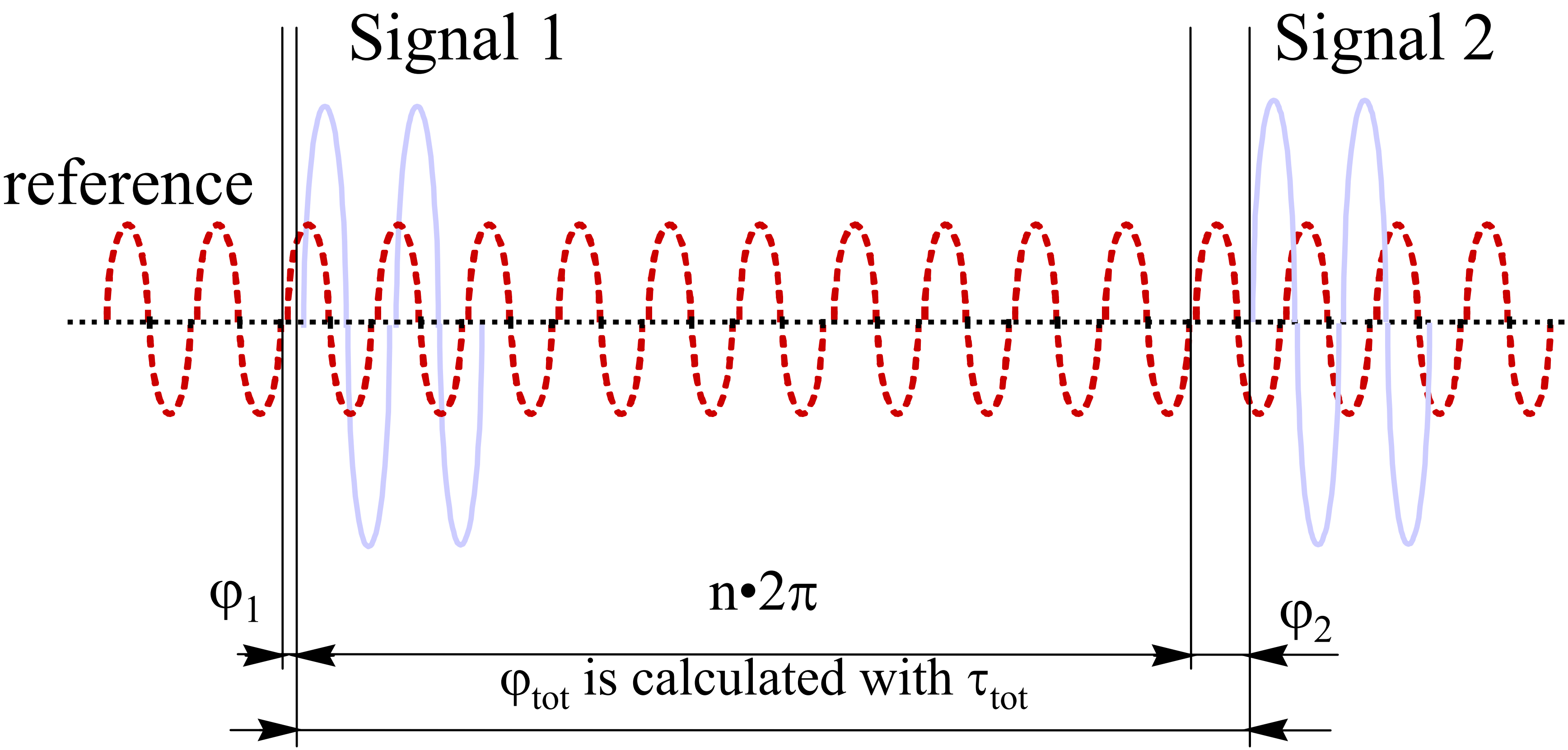
Time domain response





phases in a polar chart

Evaluation of the phase difference



... enhances the time resolution by a factor of 100 and

yields to a relative resolution of 10^{-5} to 10^{-6}.

SAW Sensors using a Delay Line Configuration

In most sensing applications using a delay line a differential arrangement is applied and the change Δ in the difference of

$$\tau_{2\text{-}1} = \tau_2 - \tau_1$$

or

$$\varphi_{2\text{-}1} = \varphi_2 - \varphi_1$$

between two signals (#1) and (#2) is evaluated.

For $\Delta\,\tau_{2-1}$ and $\Delta\,\varphi_{2-1}$ we get:

$$\Delta\tau_{2-1} = \left[\tau_2(y_0)S^{\tau}_{y,2} - \tau_1(y_0)S^{\tau}_{y,1}\right]\Delta y$$

$$\Delta\varphi_{2-1} = \left[\varphi_2(y_0)S^{\varphi}_{y,2} - \varphi_1(y_0)S^{\varphi}_{y,1}\right]\Delta y$$

SAW Sensors using a Delay Line Configuration

If the sensitivities $\mathbf{S^{\tau}_{y,2}}$ and $\mathbf{S^{\tau}_{y,1}}$ for the signals (#1) and (#2) are equal, we get

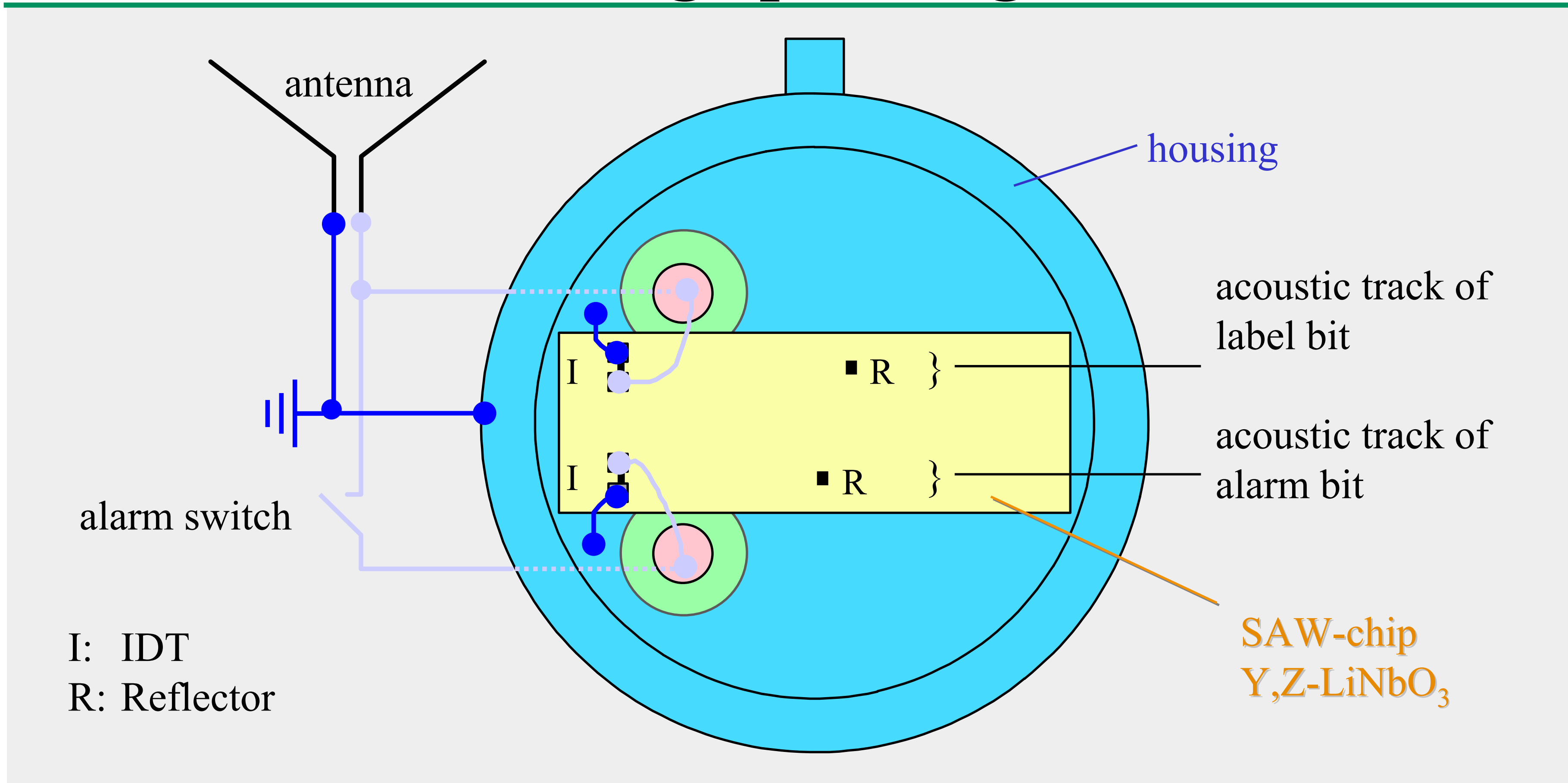
$$\Delta \tau_{2-1} = \tau_{2-1} \cdot S_y^{\tau} \cdot \Delta y$$

$$\Delta \varphi_{2-1} = 2\pi f \, \Delta \tau_{2-1} = 2\pi \cdot f \, \Delta \tau \cdot S_y^{\tau} \cdot \Delta y$$

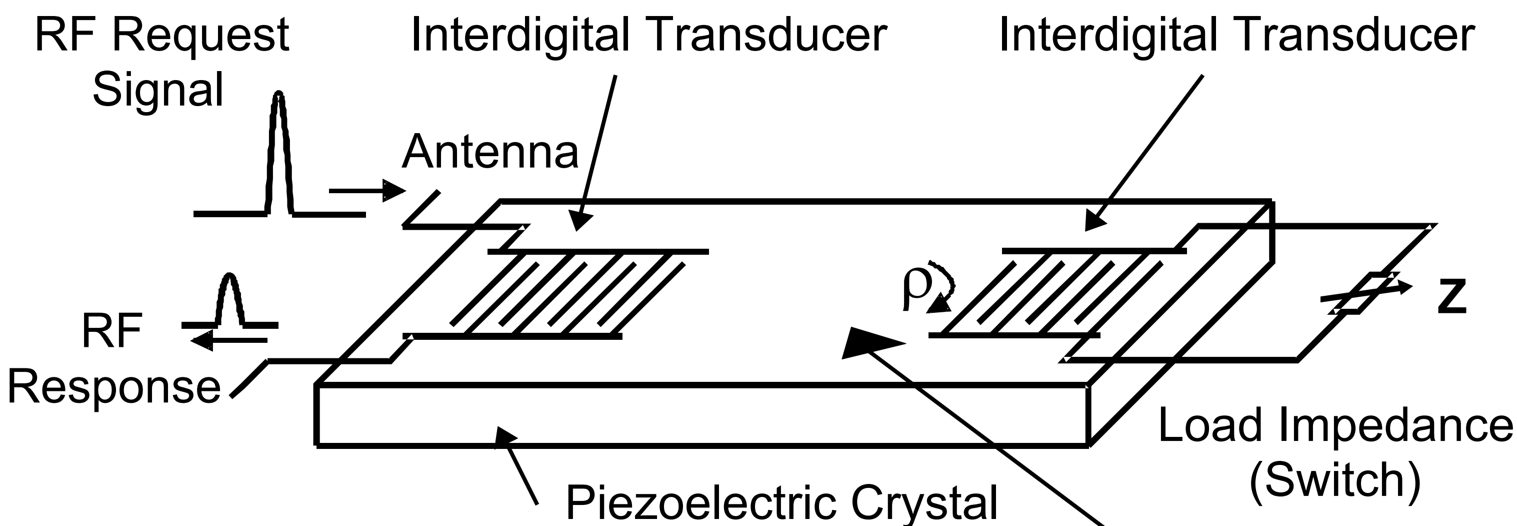
2 • (number of acoustic wave-lengths between both reflectors), typical several hundreds

The phase difference can be determined and measured very accurately.
Thus the evaluation of the phase provides a high sensitivity.

Switch able SAW Tag operating at 2,45 GHz



Special reflective delay line: SAW device combined with an external classical sensor

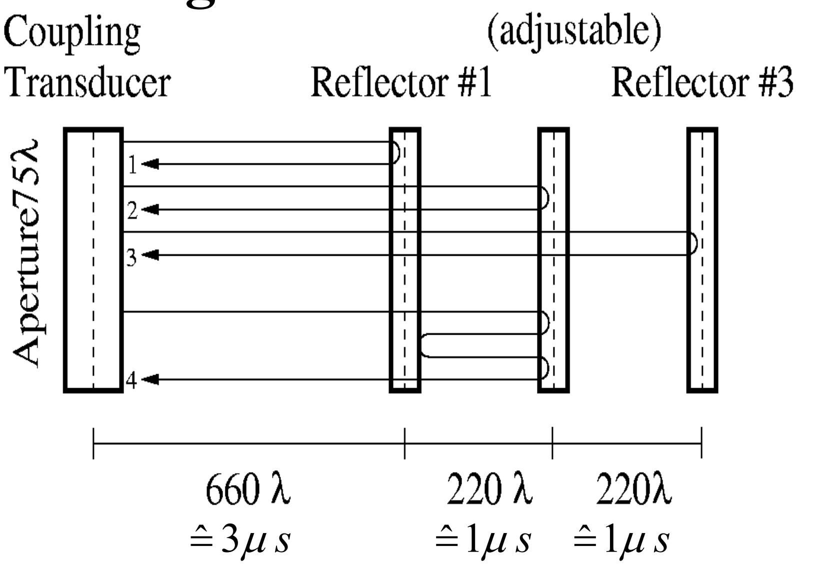


$$P_{11}(Y) = P_{11,sc} + \frac{2 \cdot P_{13}{}^{2}}{P_{33} + Y}$$

Only one reflector is shown!

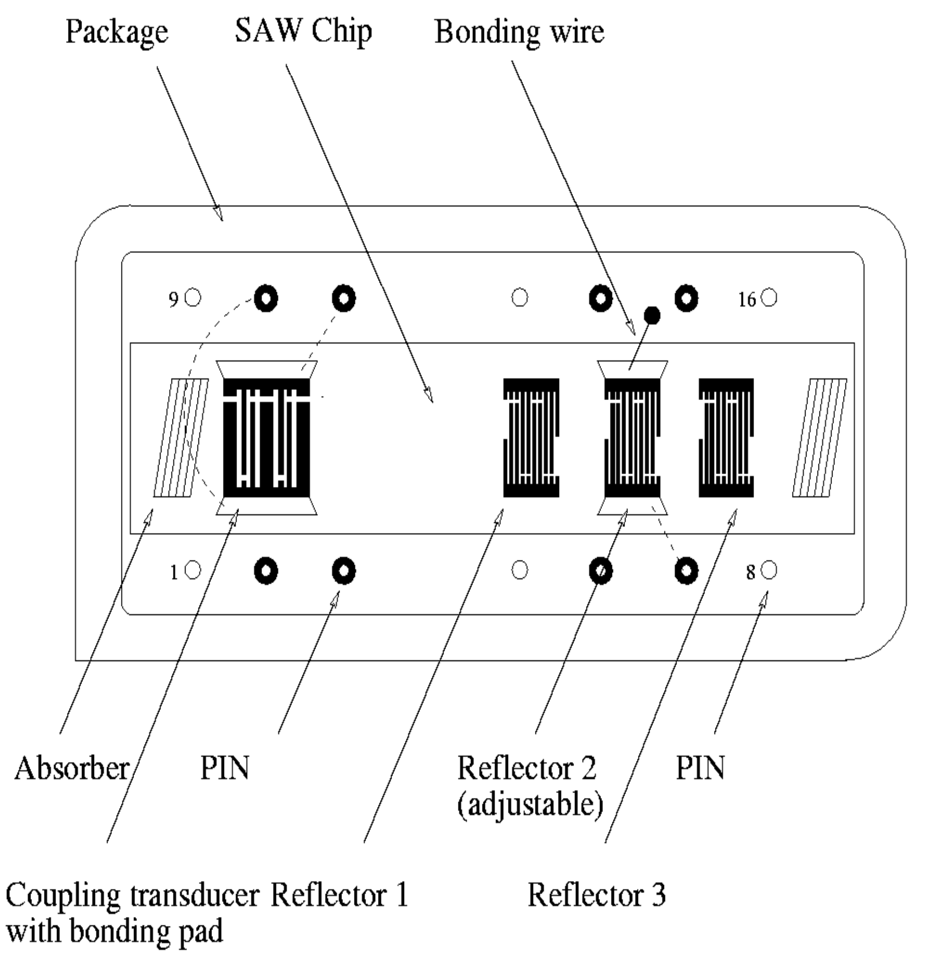
Layout of a SAW Device which can be combined with an external classical sensor

Timing

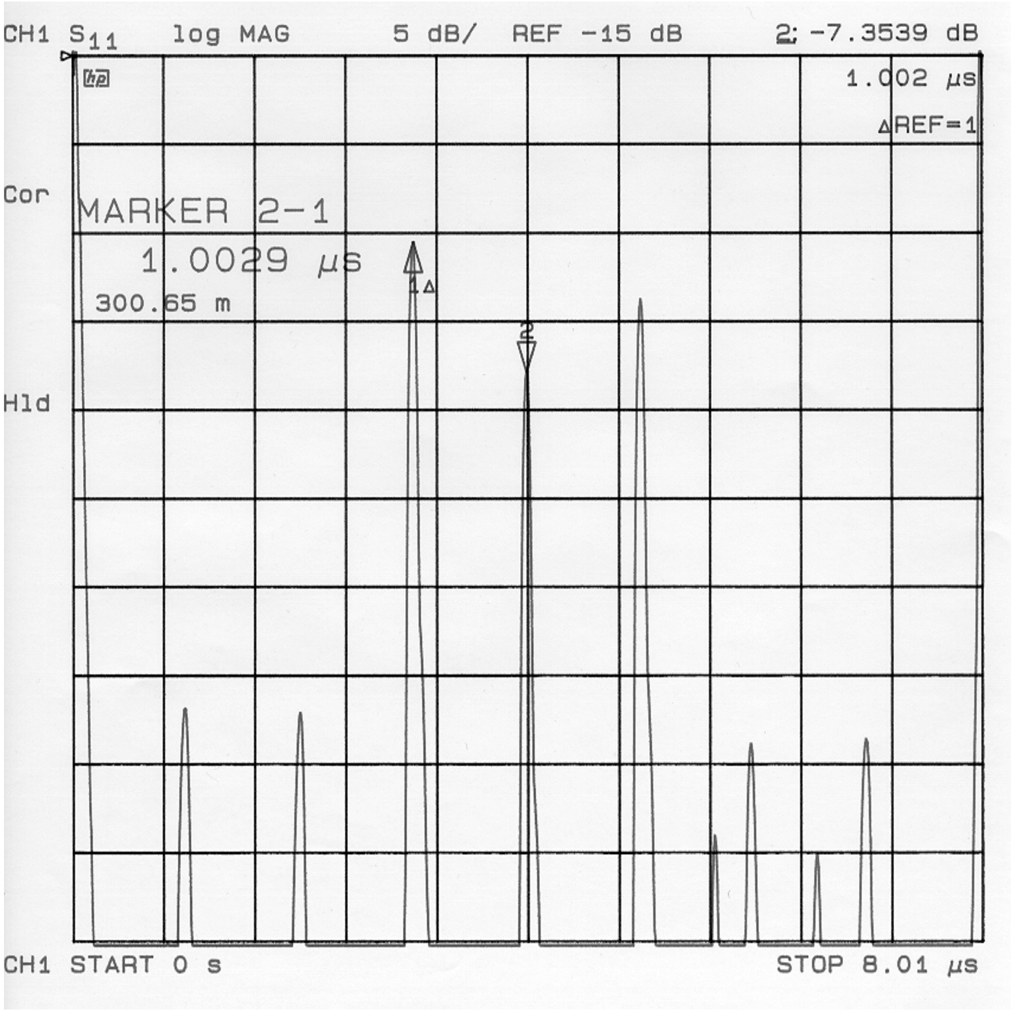


Reflector #2 is built up as transducer. The electrical port of the transducer can be loaded with the impedance of an external classical sensor. Therefore, the acoustical reflection of reflector #2 becomes a function of the applied complex load impedance, which is given by the external sensor element.

Housed SAW Chip



Typical Impulse Response

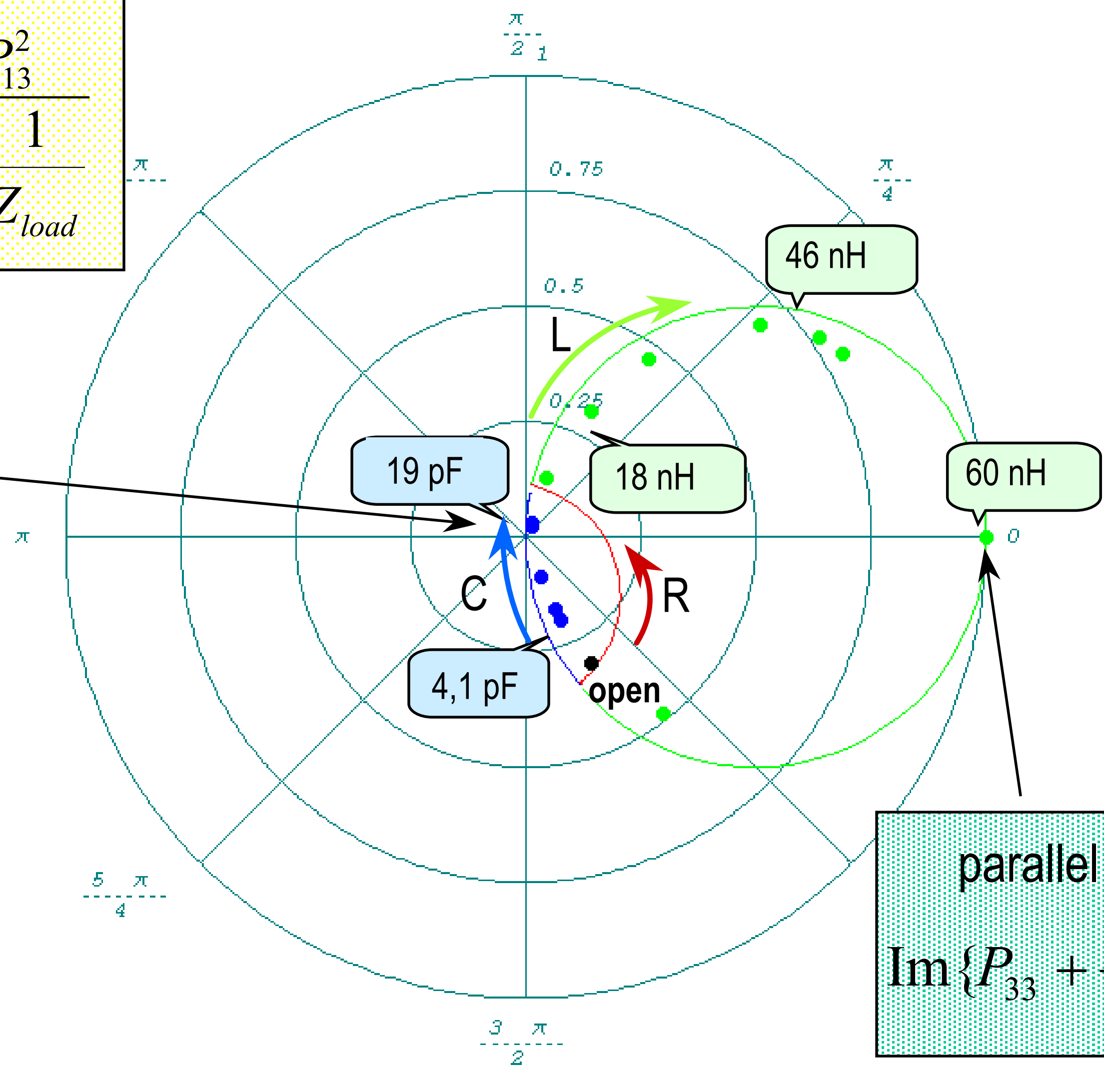


Measured acoustic reflectivity of a split finger IDT as a function of the applied electrical load

$$P_{11}(Z_{load}) = P_{11}^{sc} + \frac{2 \cdot P_{13}^2}{P_{33} + \frac{1}{Z_{load}}}$$

serial resonance:

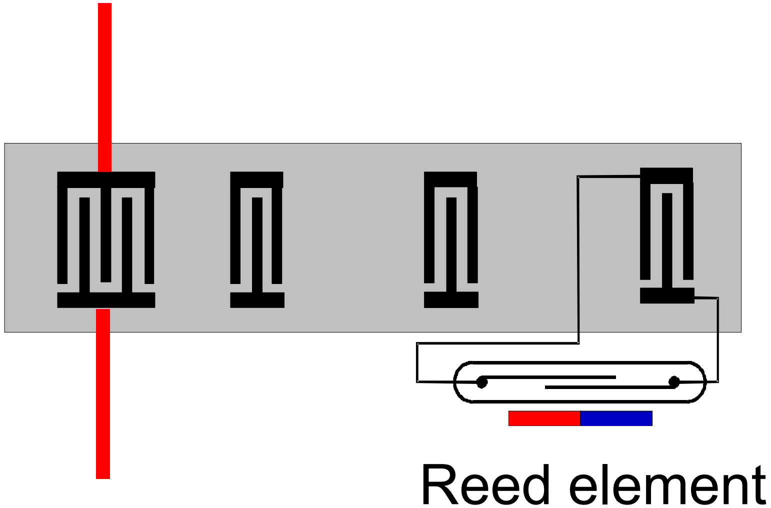
$$P_{11}(Z_{load}) = P_{11}^{sc} \approx 0$$



parallel resonance:

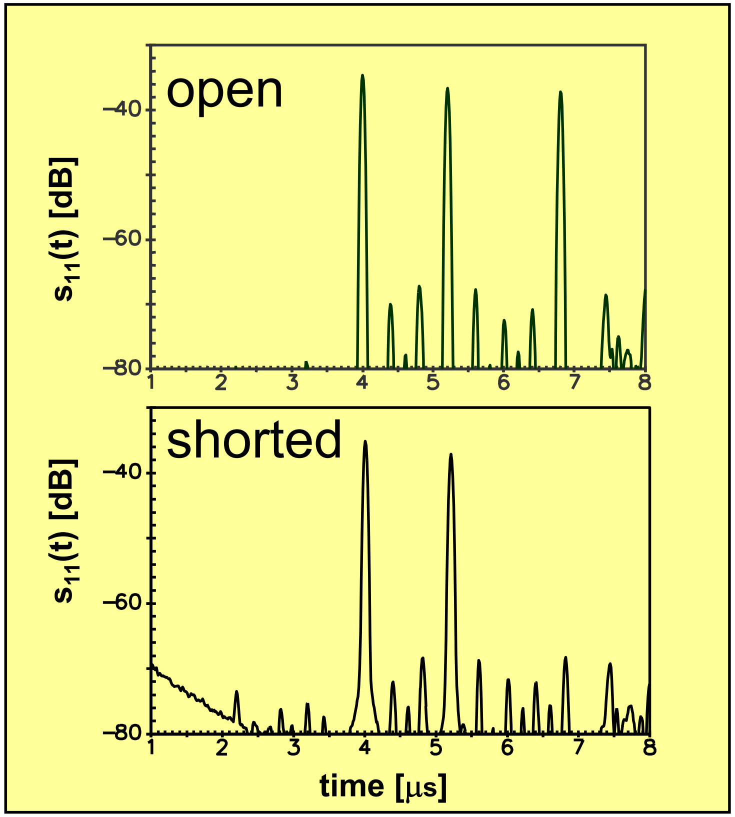
$$\mathrm{Im}\{P_{33} + \frac{1}{Z_{load}}\} = 0$$

Binary SAW Sensors

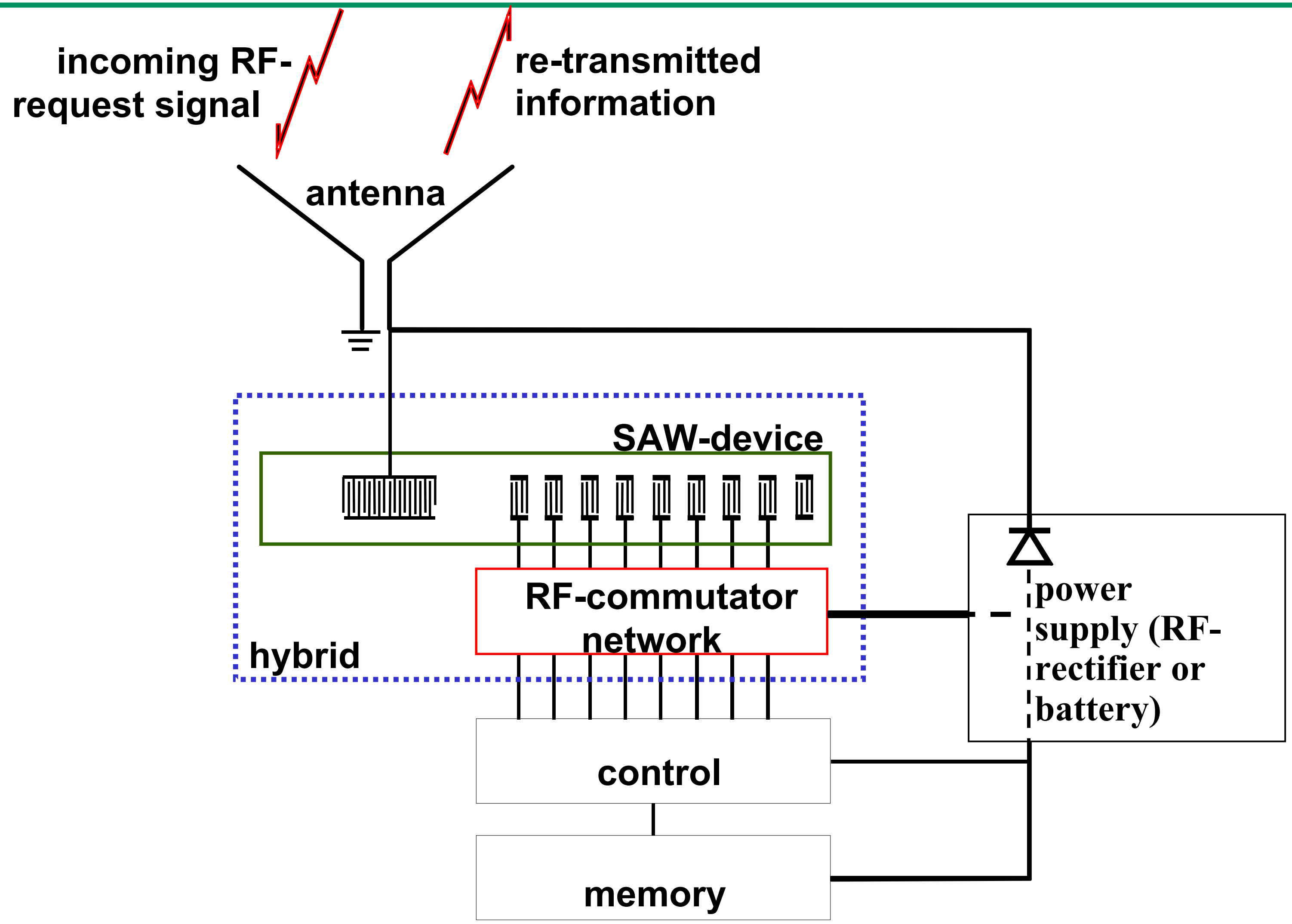


- sector alignment indicators
- radio accessible switches

- readout of classical sensors with
  varying impedance



Schematic block diagram of a semi-active SAW tag using IDT reflectors



Circuitry for dynamic switching of one IDT reflector

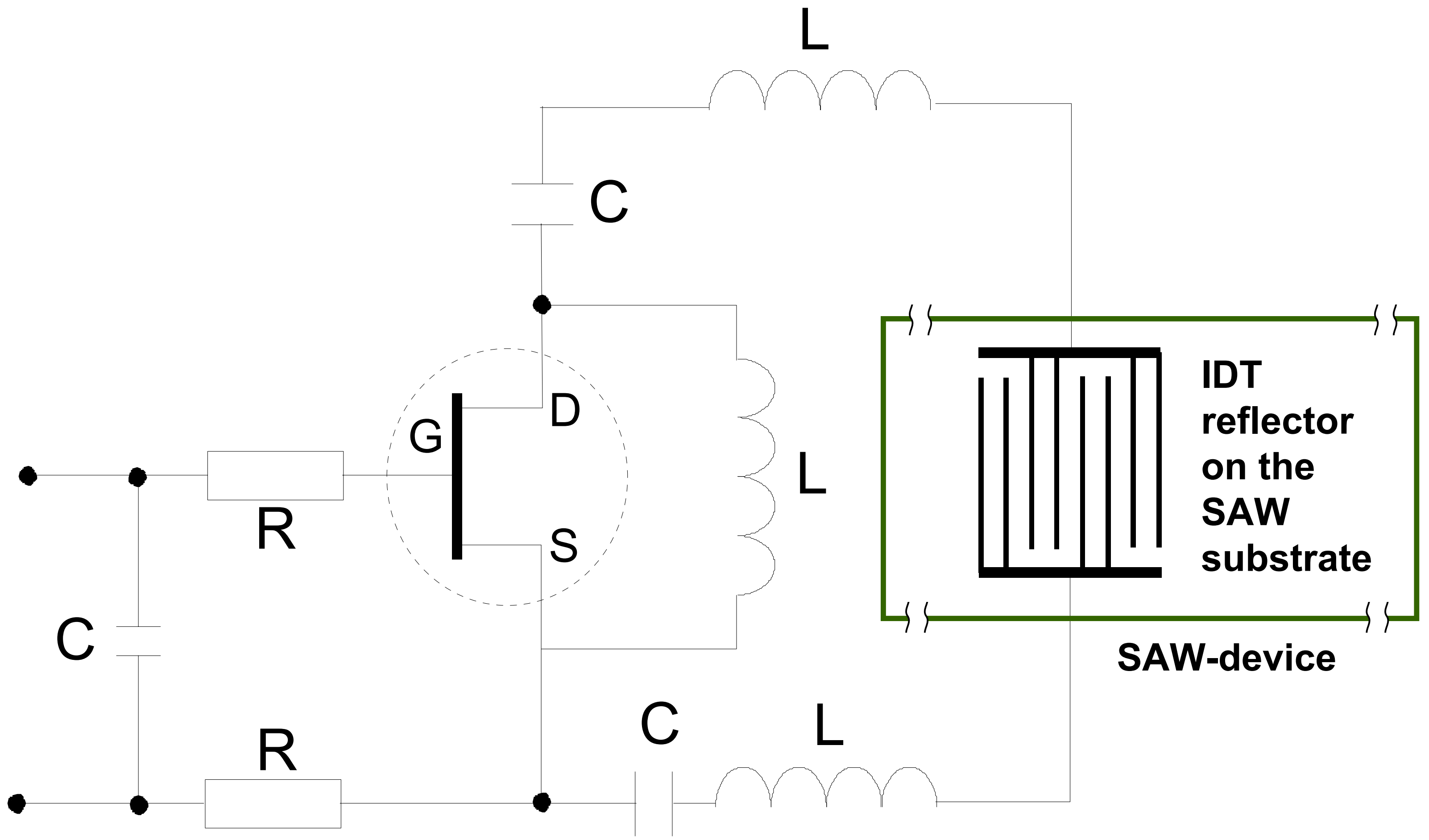
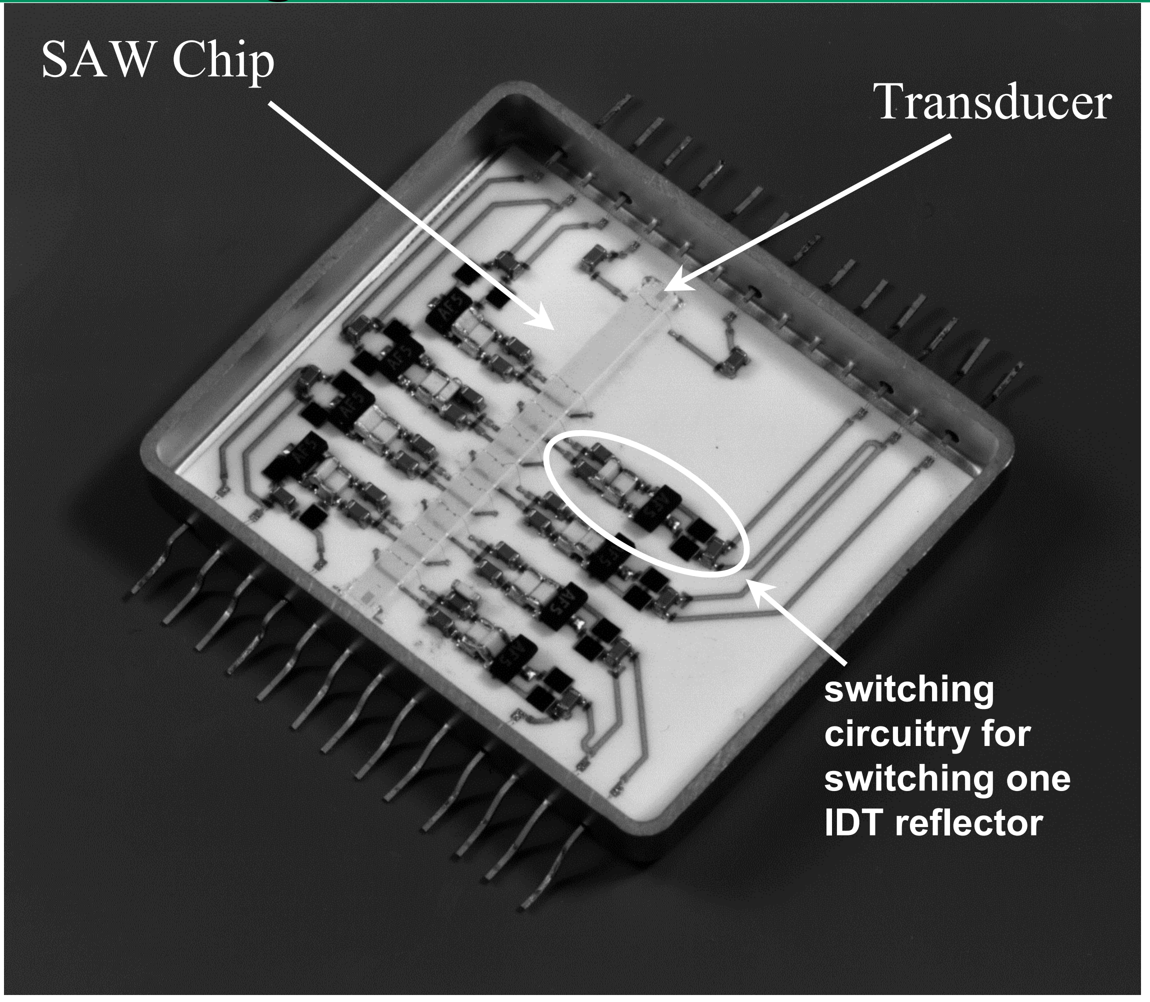
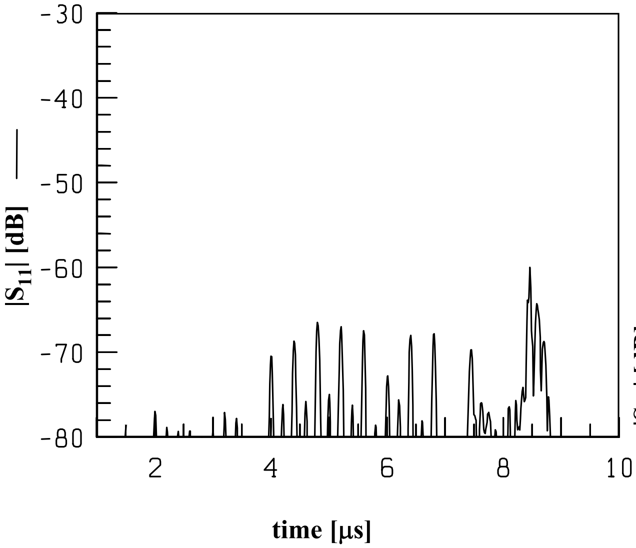


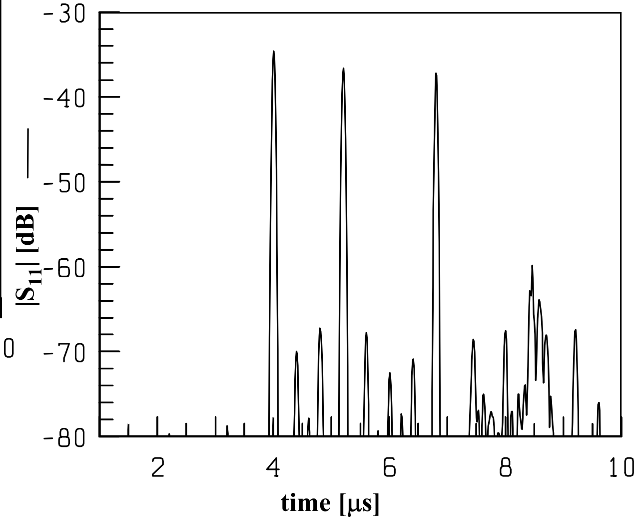
Photo of a mounted SAW chip in a hybrid commutator network for switching 8 IDT reflectors



Measurements of the switching states of the switchable SAW ID-Tag shown in the last chart

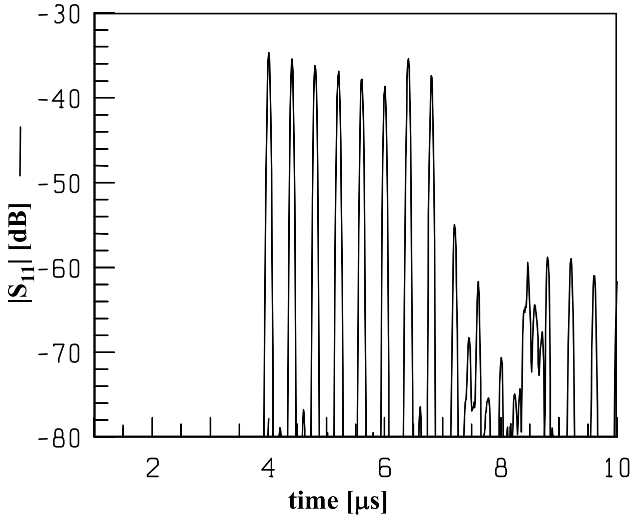


all IDT reflectors "OFF"

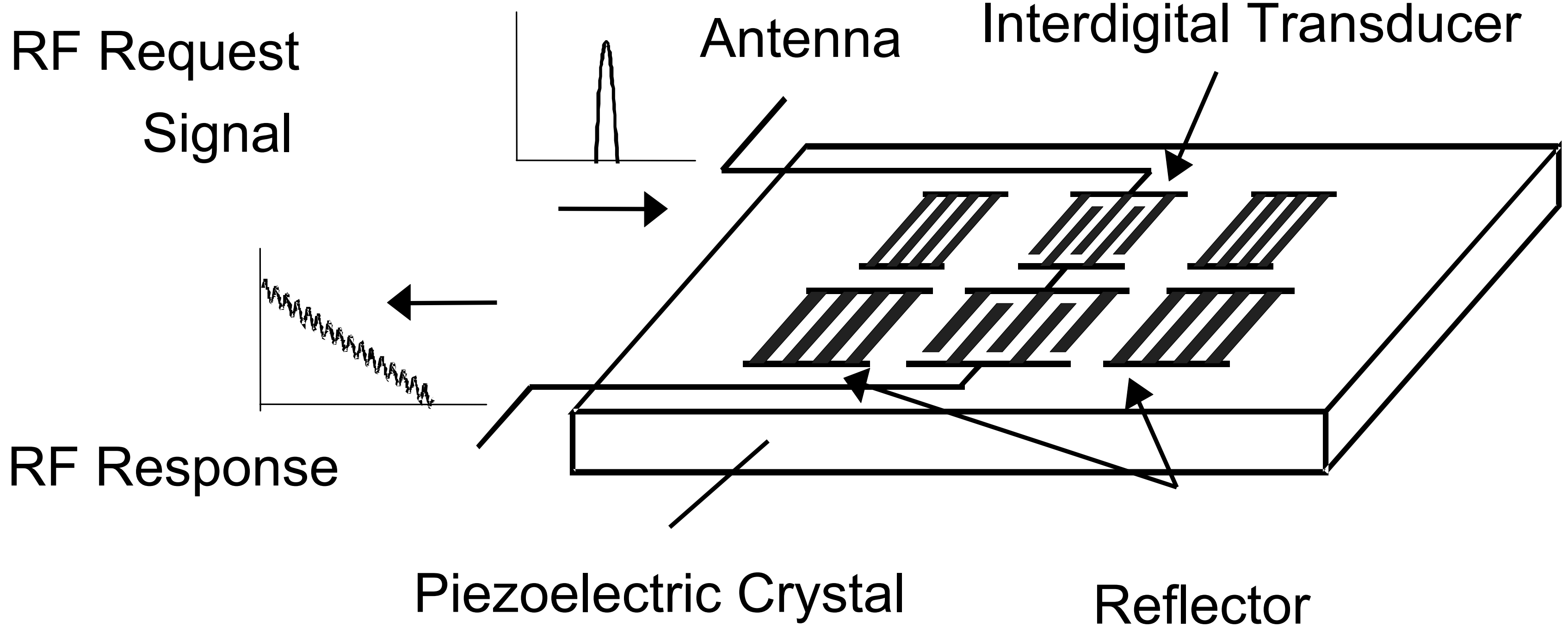


3 "ON"

all "ON"

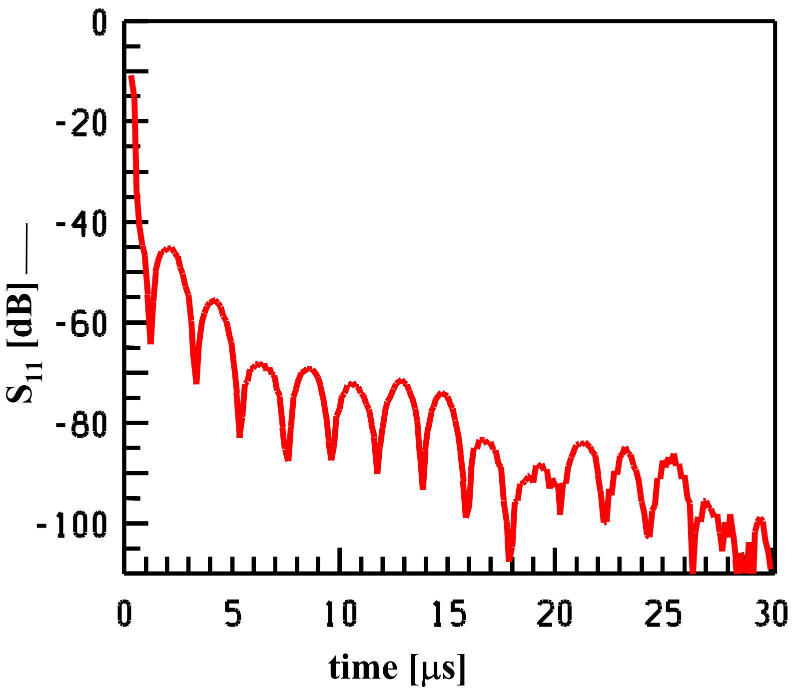


Schematic drawing of a SAW resonator used as radio requestable sensor



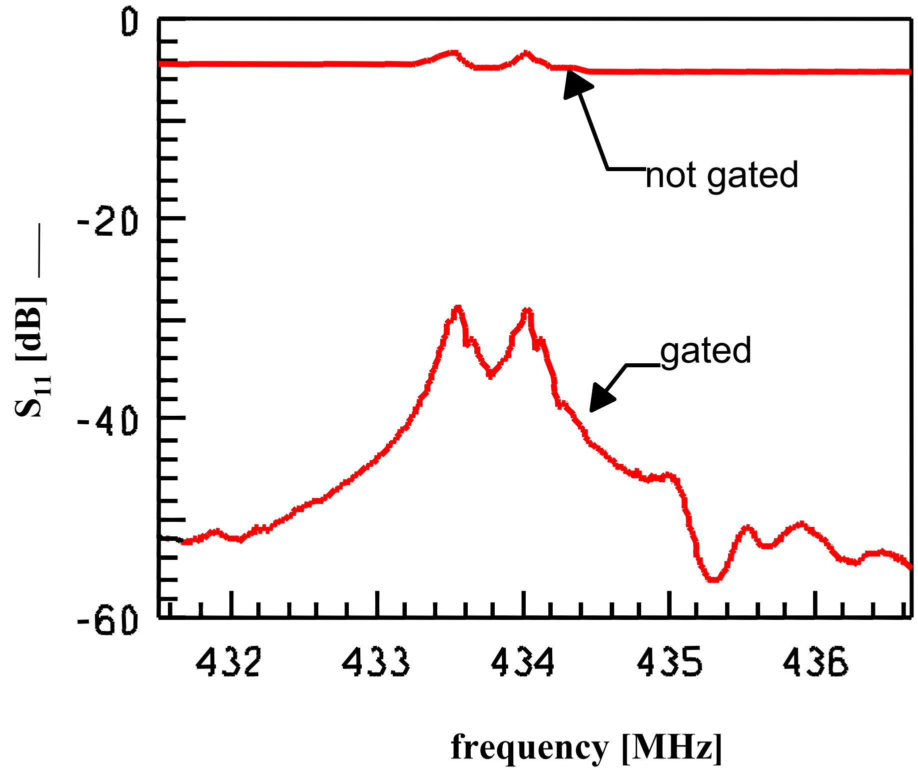
Number of stored wavelengths $n_\lambda \sim Q_{loaded}$

Signal Processing: Evaluating the Resonant Frequency of Resonators



time domain

Frequency domain



Resonator Mathematics

The change in centre frequency f and phase φ is given by:

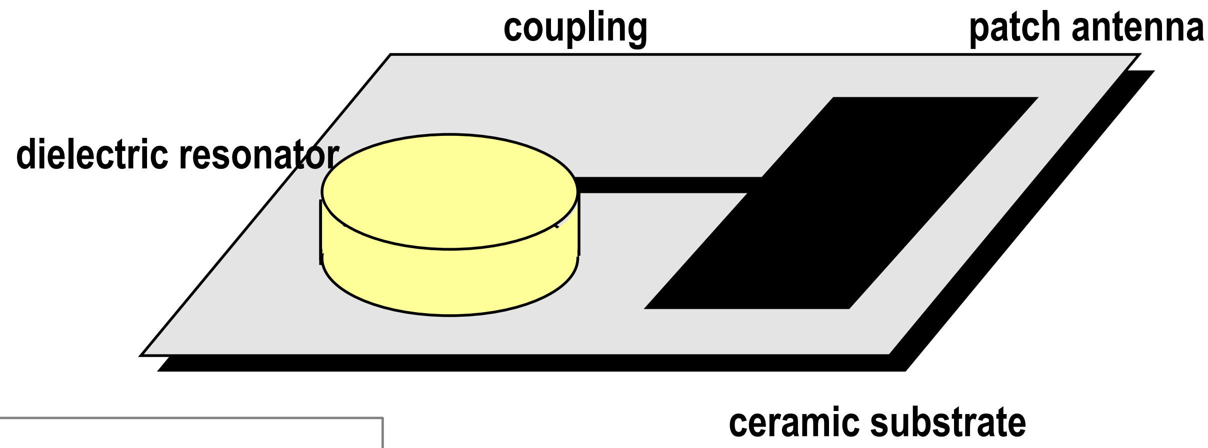
$$\Delta f = -f_0 \cdot S_y^{\tau} \cdot \Delta y$$

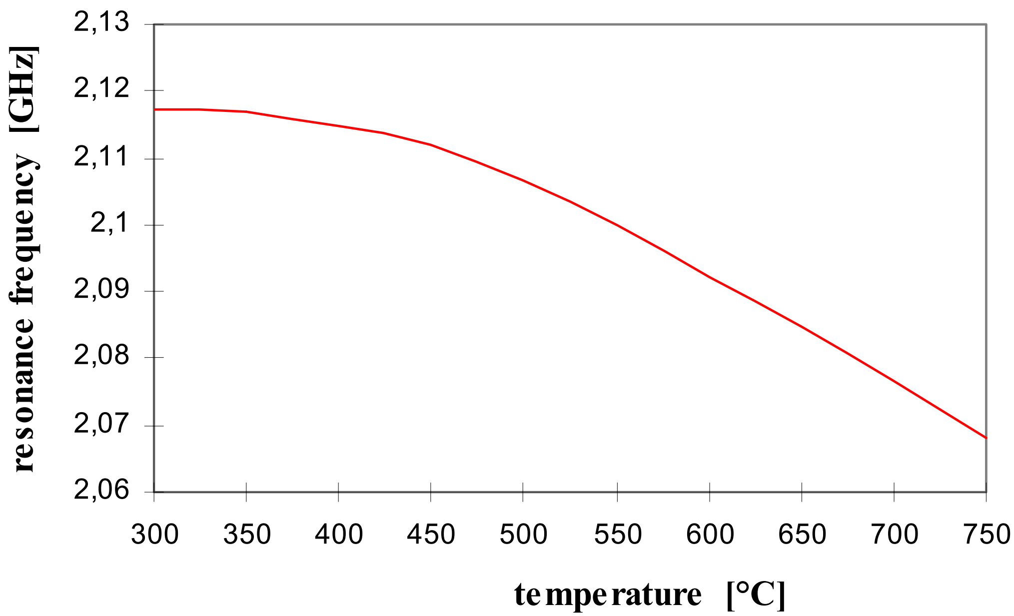
$$\Delta \varphi = 2\pi Q \cdot S_y^{\tau} \cdot \Delta y$$

$$Q_{OFW} \approx 10\,000$$

Same sensitivity as a delay line,
but significant reduction of chip size

High-Q Dielectric Resonators



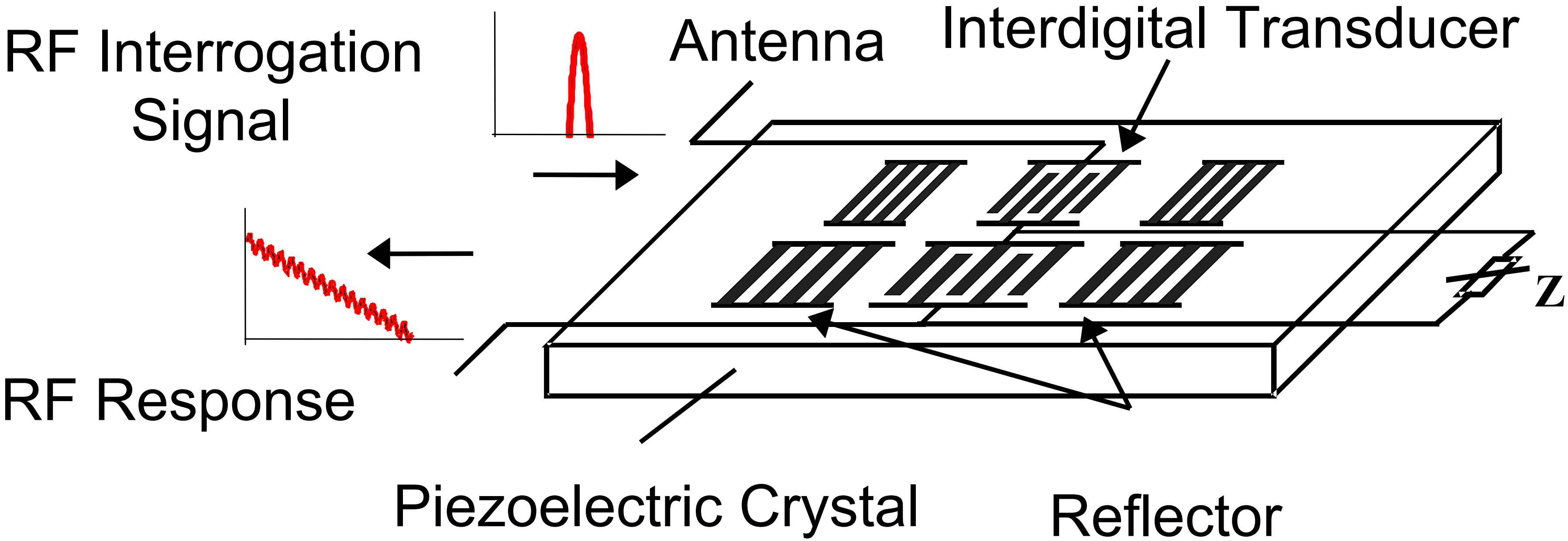


The resonator is stimulated by a RF signal, the decaying signal is detected after switching off the stimulus.

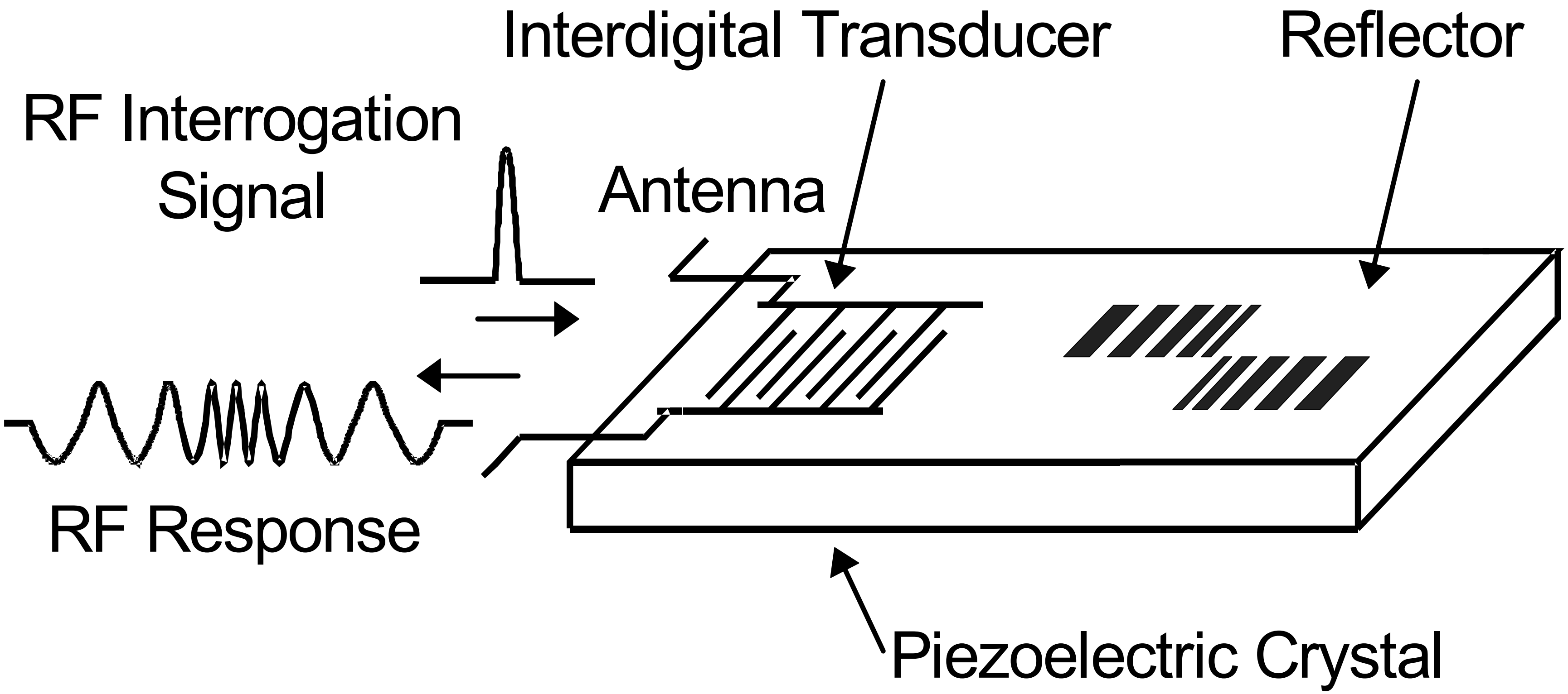
e.g. for high temperature measurements

... utilizing the temperature shift of the resonance of a dielectric microwave resonator.

Special Radio Readable Resonator: Pulling of the SAW Resonator with an External Sensor



Dispersive Delay Line - Principle



Dispersive Delay Line - Mathematics

$$\Delta\tau(\Delta y) = \tau_0 S_y \Delta y \pm \frac{T}{B} \Delta f(\Delta y)$$

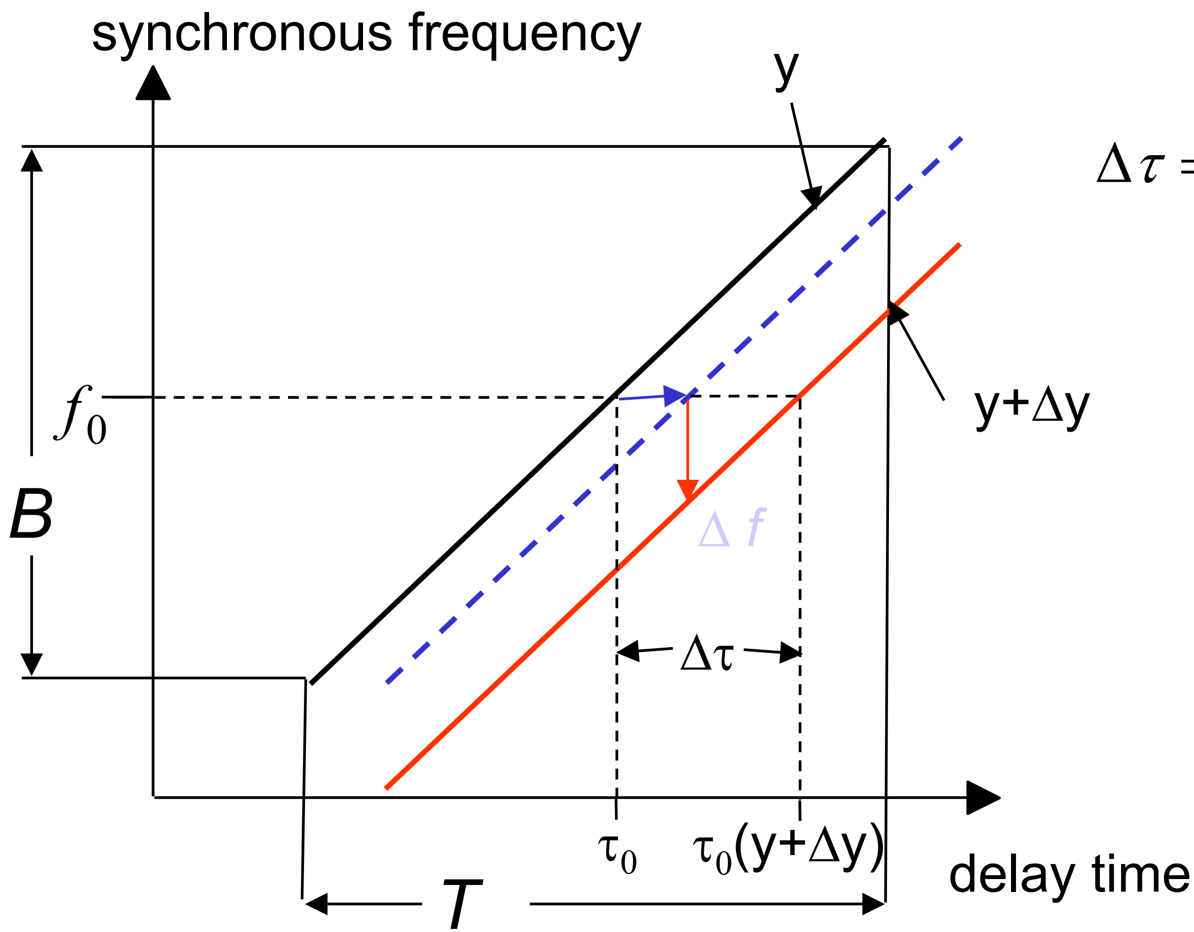
$$= \tau_0 \left[1 \mp \frac{T}{\tau_0} \frac{f_0}{B} \right] S_y^\tau \Delta y$$

sensitivity of a delay line

may be 10 - 100 times of the sensitivity of a delay line

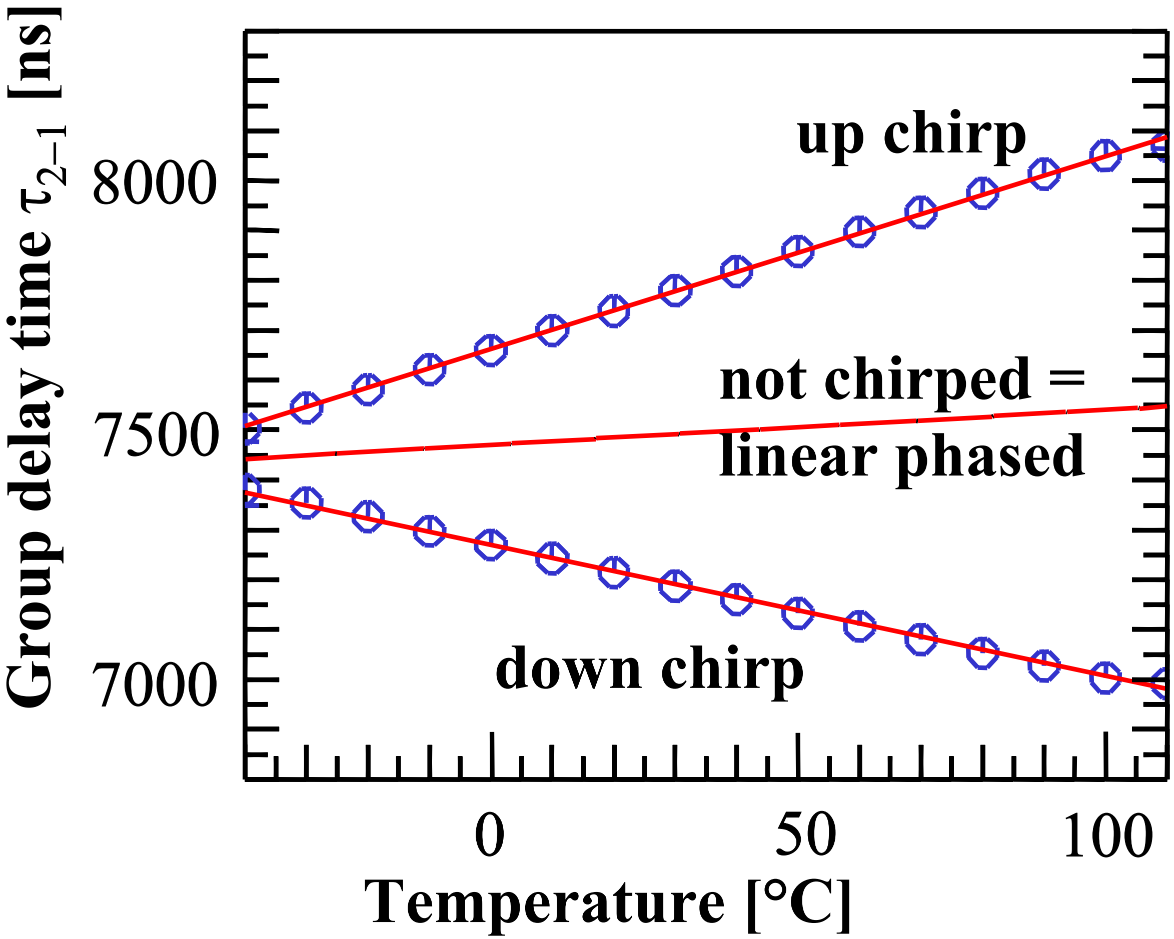
$$\Delta\varphi_{2-1} = S_{delay\ line} \cdot S_y^\tau \cdot \Delta y$$

Dispersive Delay Line - Effect



$$\Delta\tau = \left(1 \pm \frac{T}{\tau} \cdot \frac{f}{B}\right) \cdot \tau \cdot S_y^{\tau} \cdot \Delta\tau$$

Dispersive Delay Line - Measurement



Outline

- Introduction: Classical SAW Sensors
- SAW Radio Request
- SAW Identification Tags
- SAW Radio Requestable Sensors
- Application Examples
  - ID Tags
  - Temperature Sensors
  - Mechatronic Sensors
  - Current Sensors
  - Water Sensors
- Conclusion

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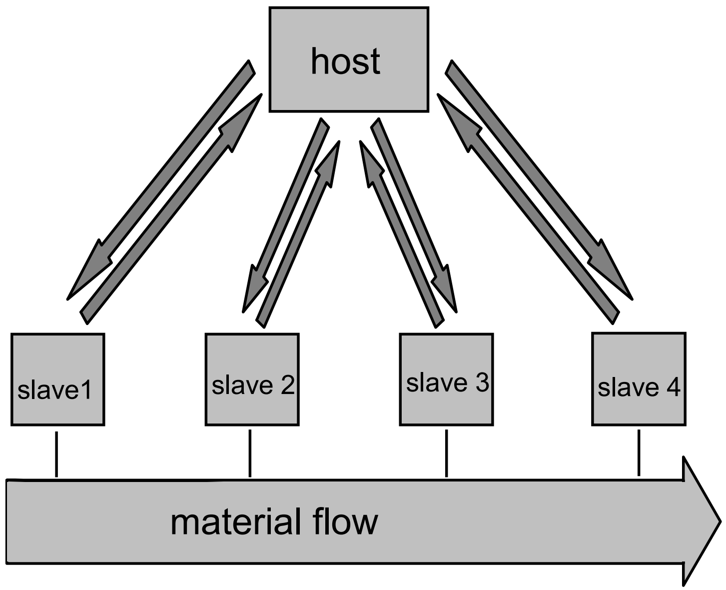
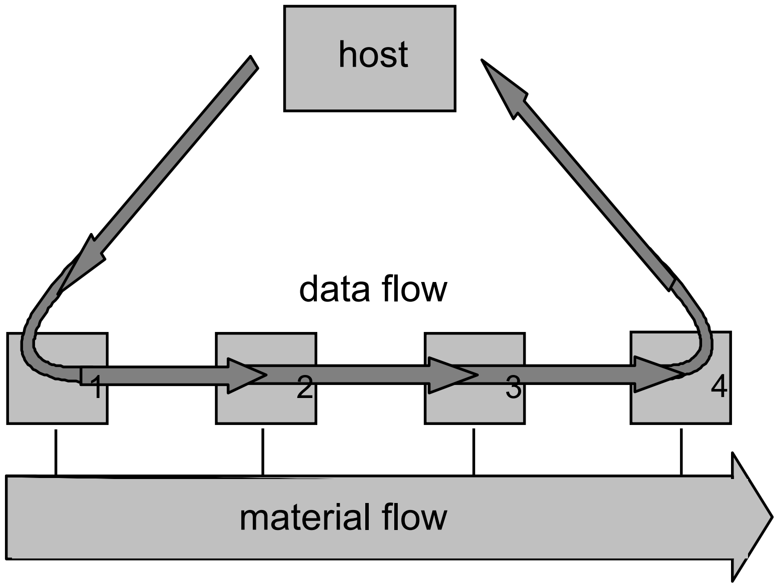
Application of fixed coded or writeable tags

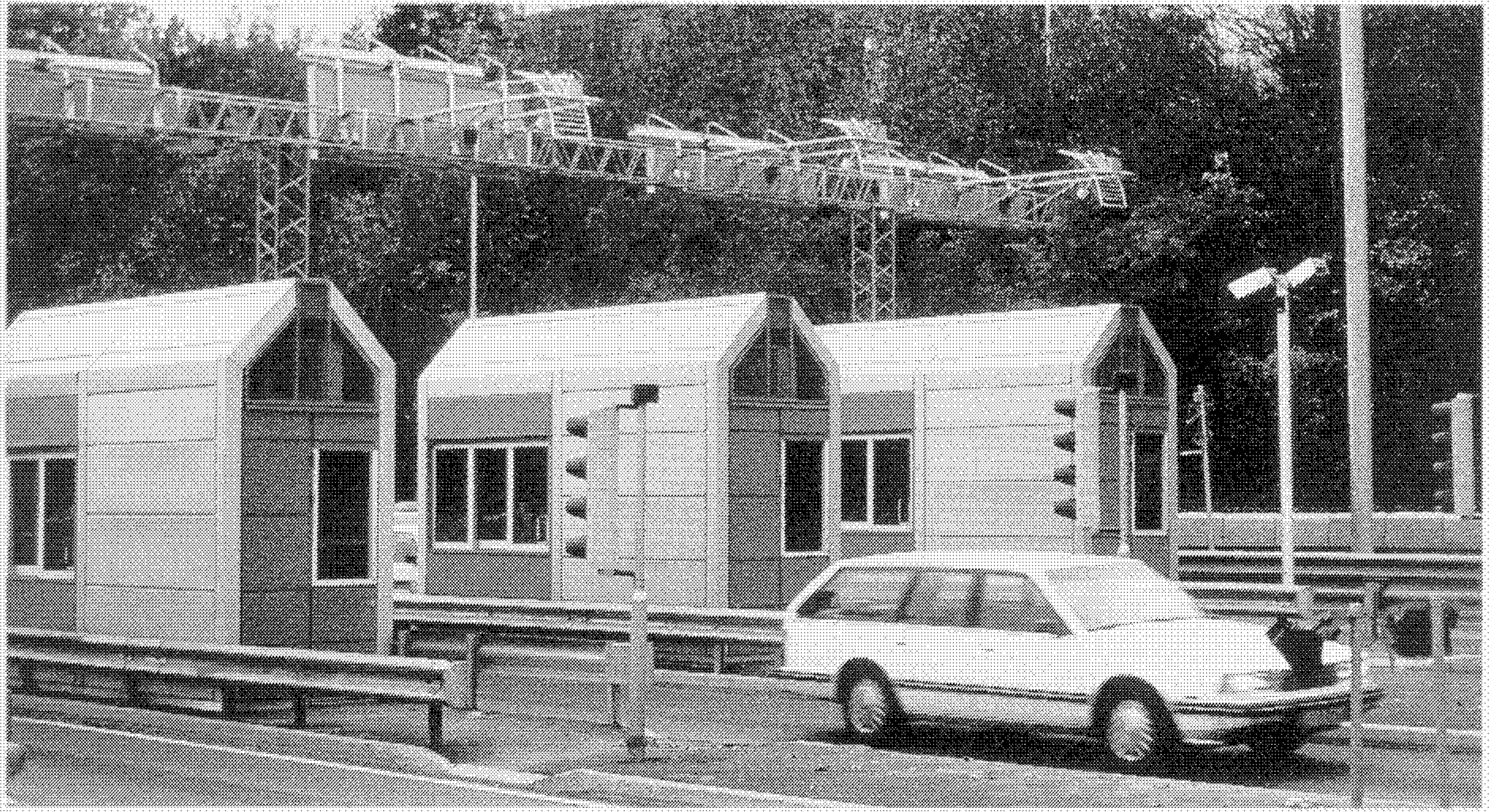




Schematic of a master-slave control system:
fixed coded tags are sufficient

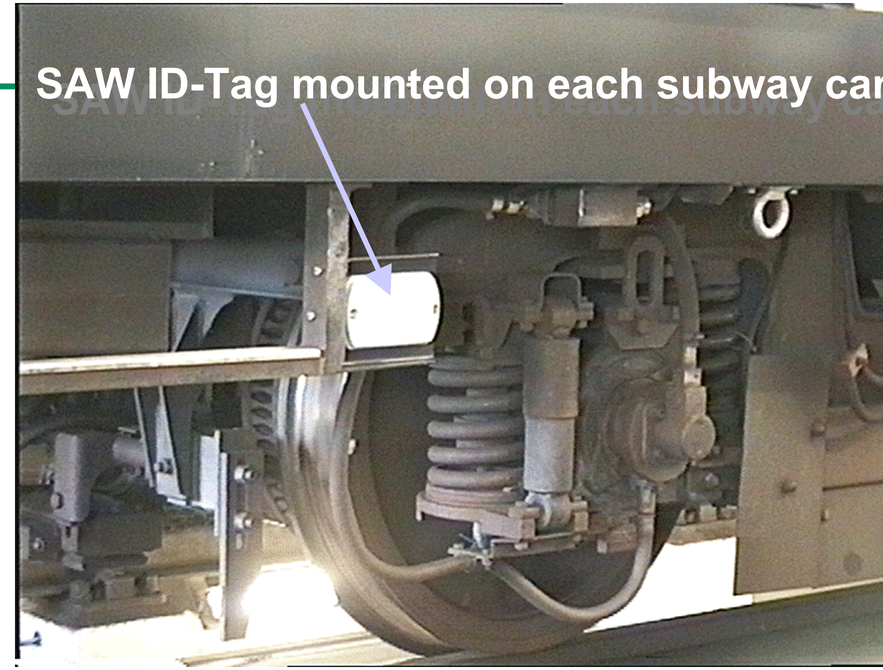
Schematic of a material accompanying control system:
write able tags are needed

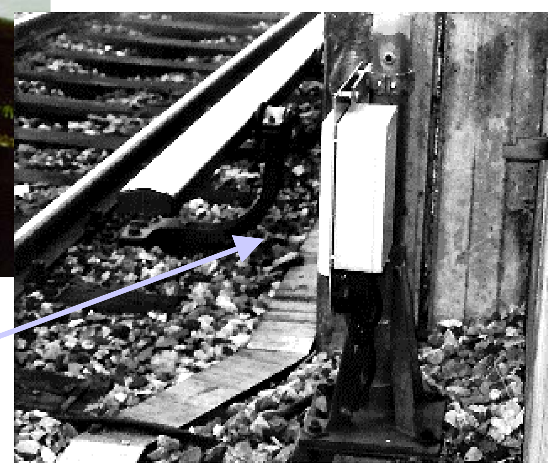
Application of SAW ID-Tags a Norway Toll System



SIEMENS

OFW ID System SOFIS installed on the Munich Subway System





antenna of the 2.45 GHz interrogation unit

Tag housing

SAW Identifikation Systems for Manufacturing/ Logistics Management

Baumer IDENT

SAW ID-Tags

Reader Unit

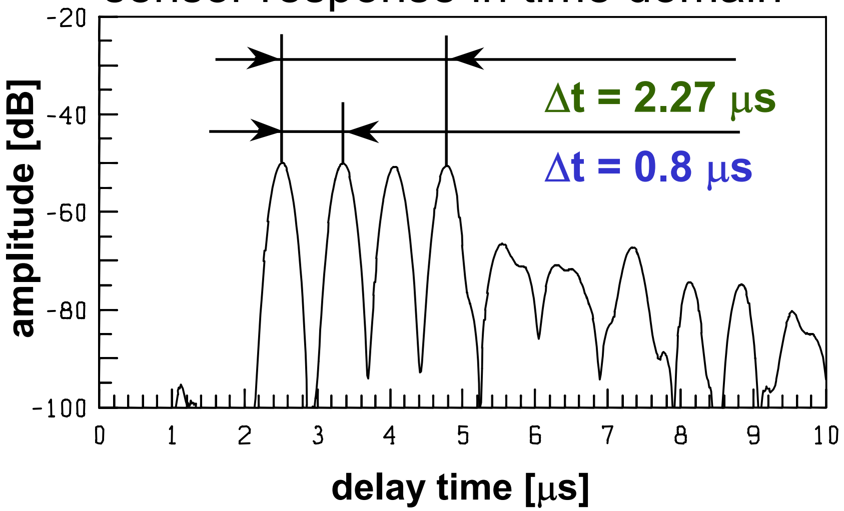
long readout distance, high temperature stability ➡ **- highly flexible assembly set-up,**
- only one single ID system for entire production process

SAW Temperature Sensors

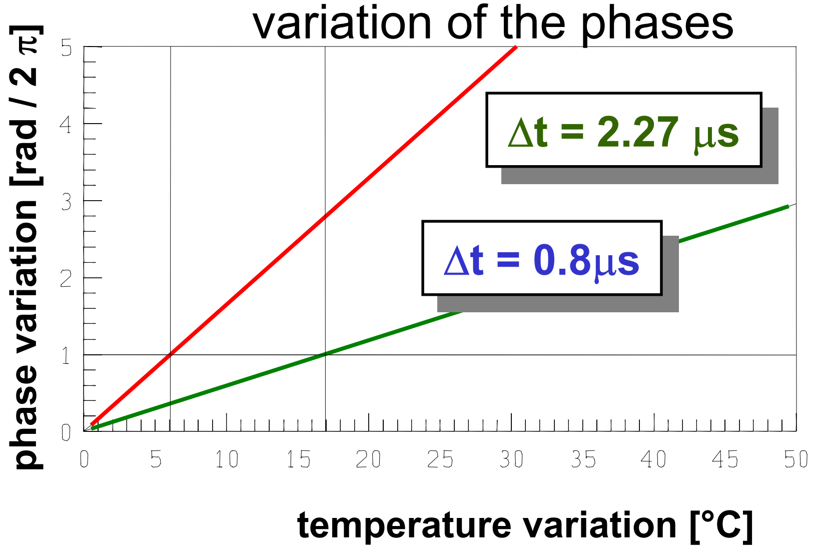
$$\frac{\Delta\tau}{\tau} = \left(\frac{1}{l}\frac{\Delta l}{\Delta T} - \frac{1}{v}\frac{\Delta v}{\Delta T}\right)\Delta T = \mathrm{TCD}_1 \cdot \Delta T$$

$$\Delta\varphi = 2\pi f_0 \Delta\tau$$

sensor response in time domain



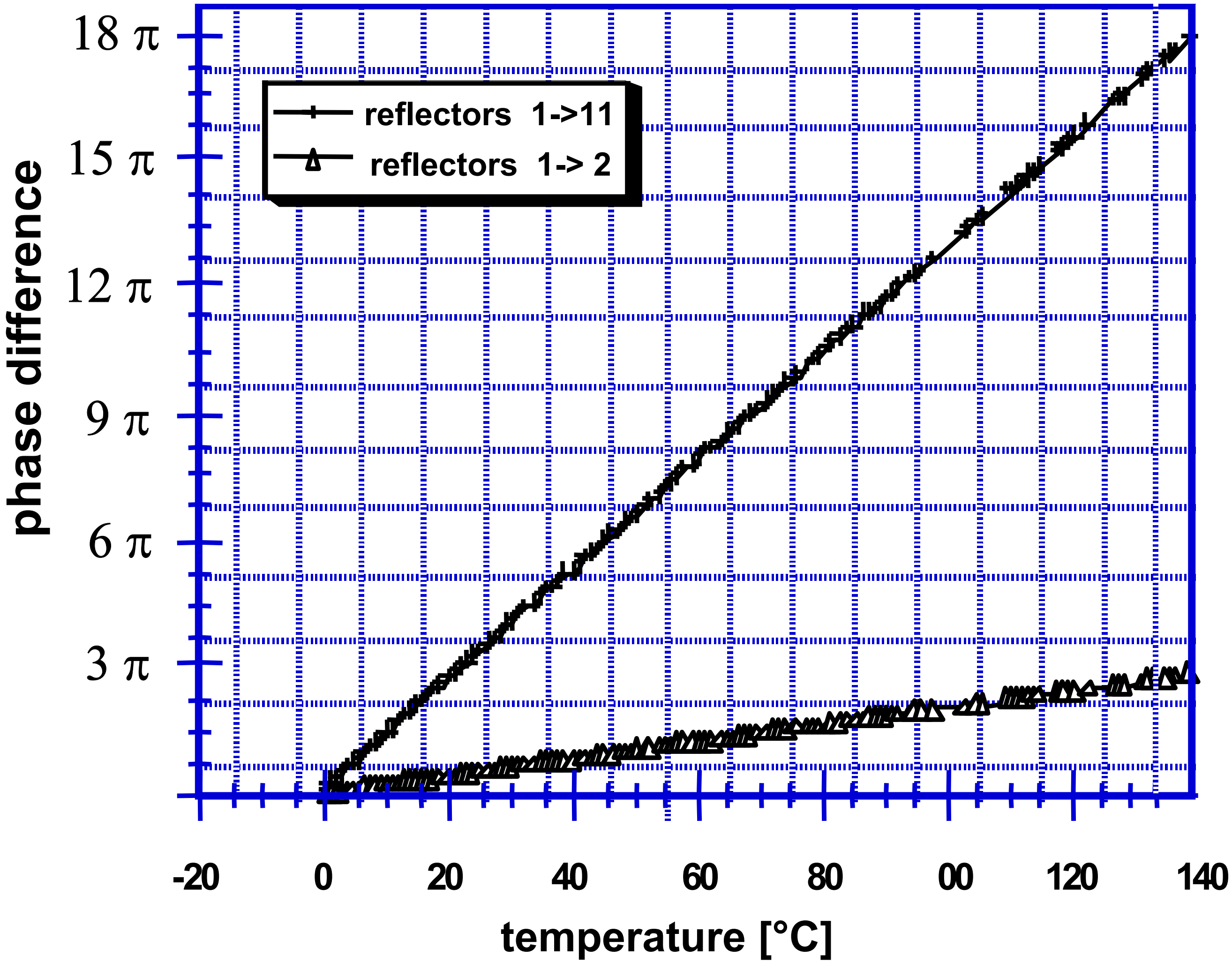
variation of the phases



Δt_{max}=2.27µs → accuracy: 0.02 °C, but small range of unambiguity

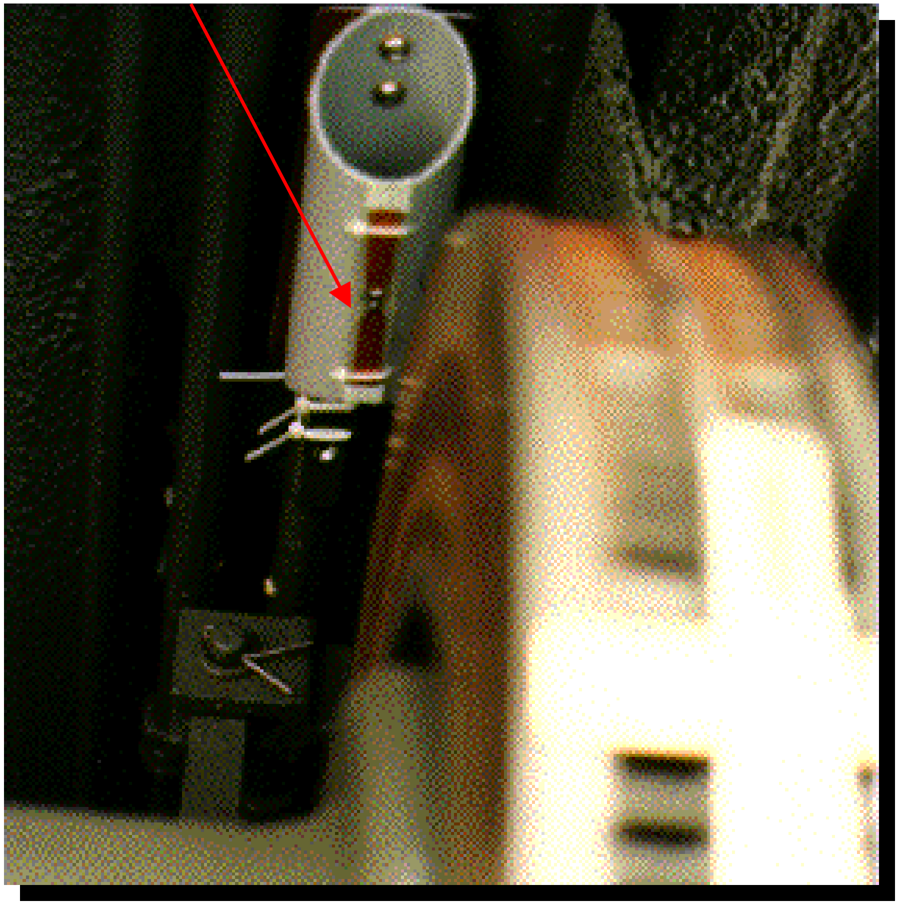
Δt_{min}=0.03µs → range: 450 °C

Phase difference between 3 selected reflectors on $LiNbO_3$-YZ-Cut versus temperature

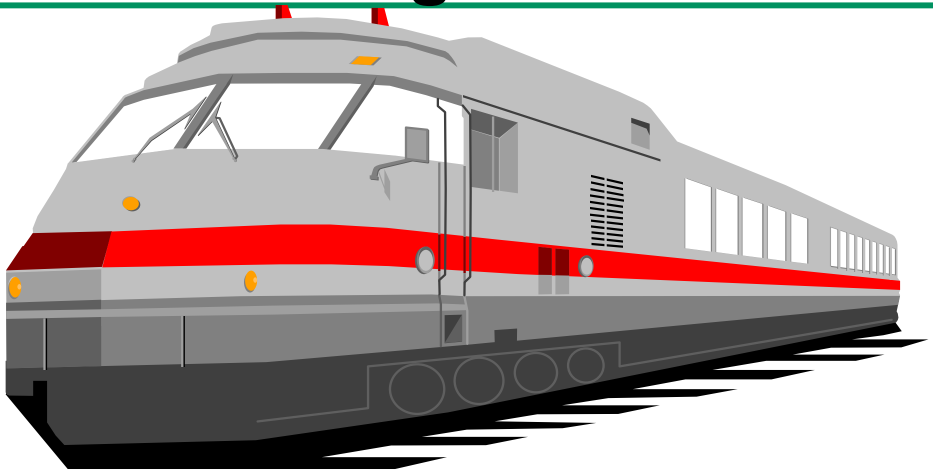


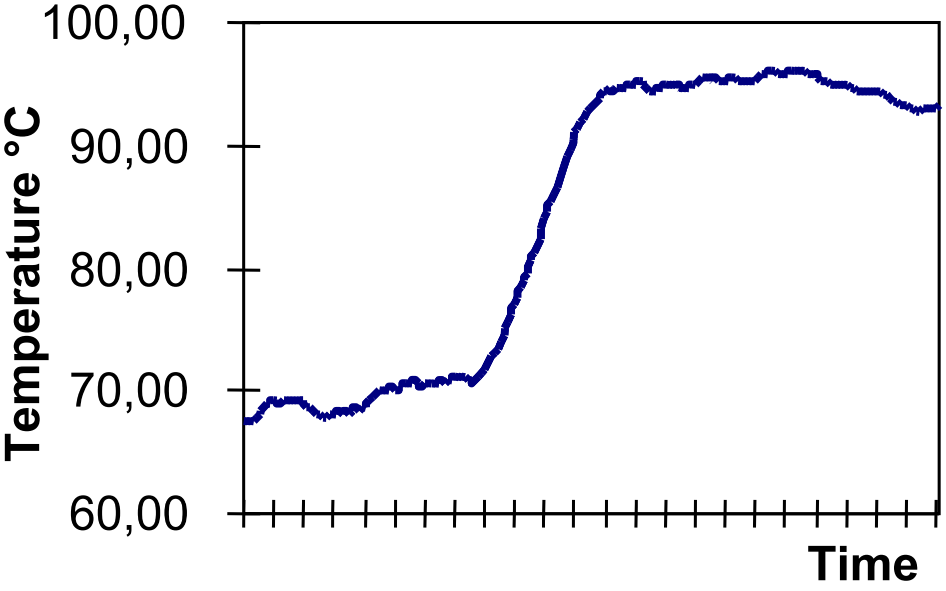
Brake temperature of a train entering a station

reader antenna



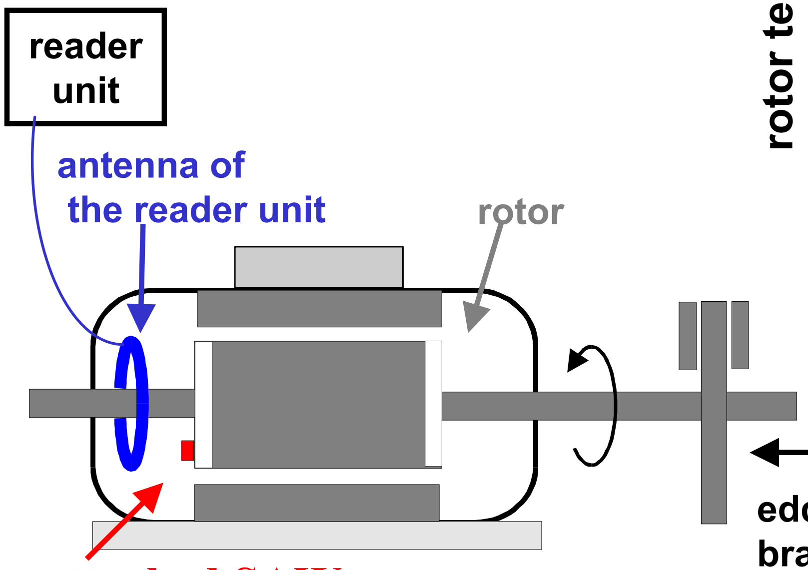
Brake (with attached SAW temperature transponder, not seen)

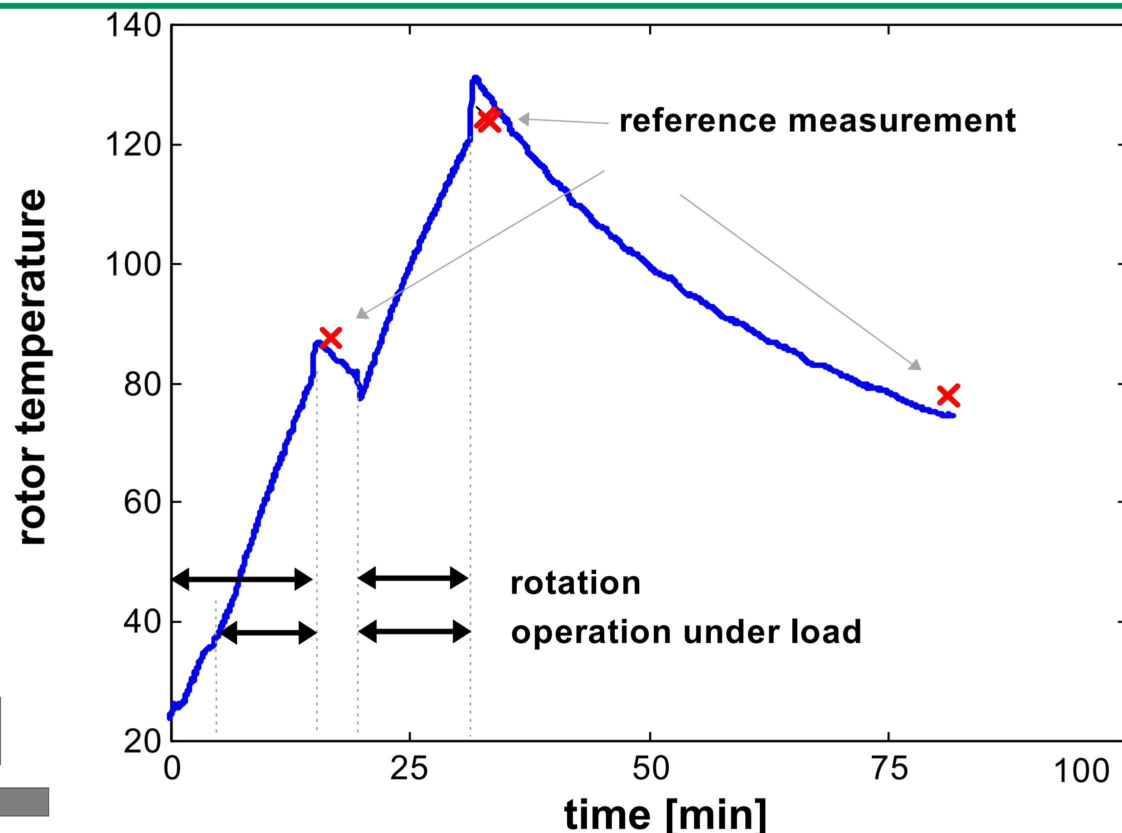




Measurement of the rotor temperature in a 11 kW asynchronous motor

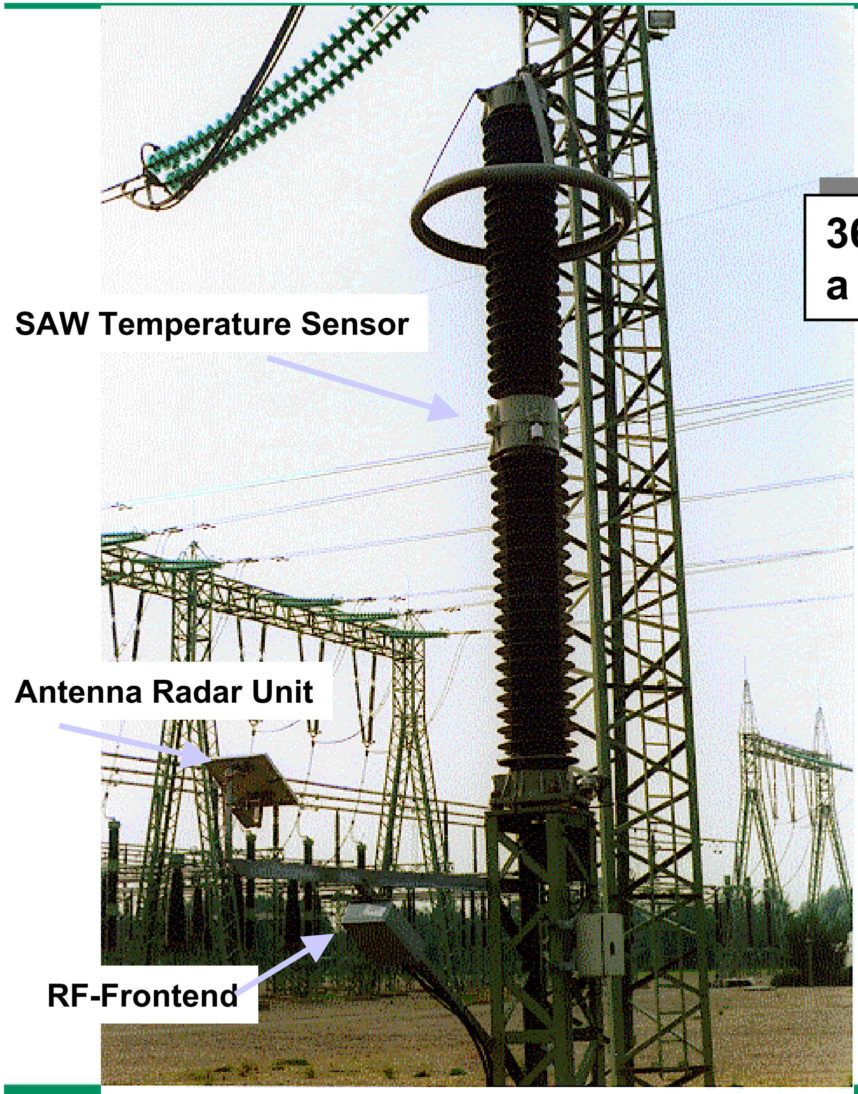
Sketch of the set-up





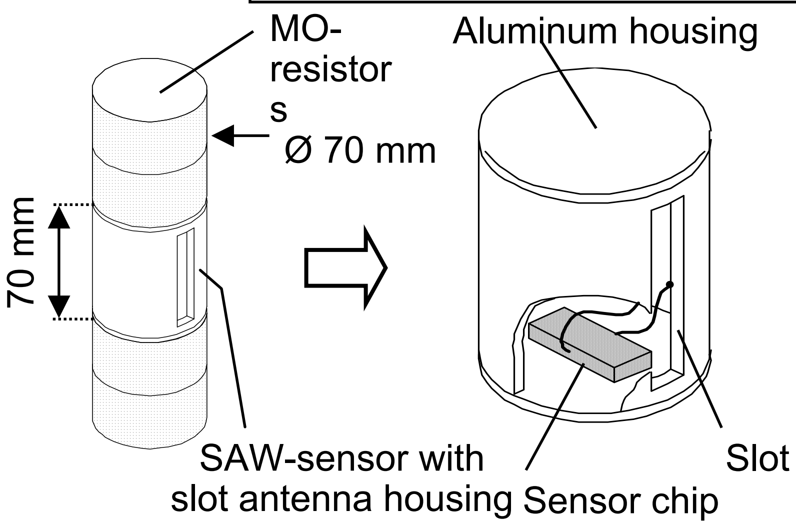
measurement curve

Online Temperature Monitoring System for High-Voltage Surge Arresters

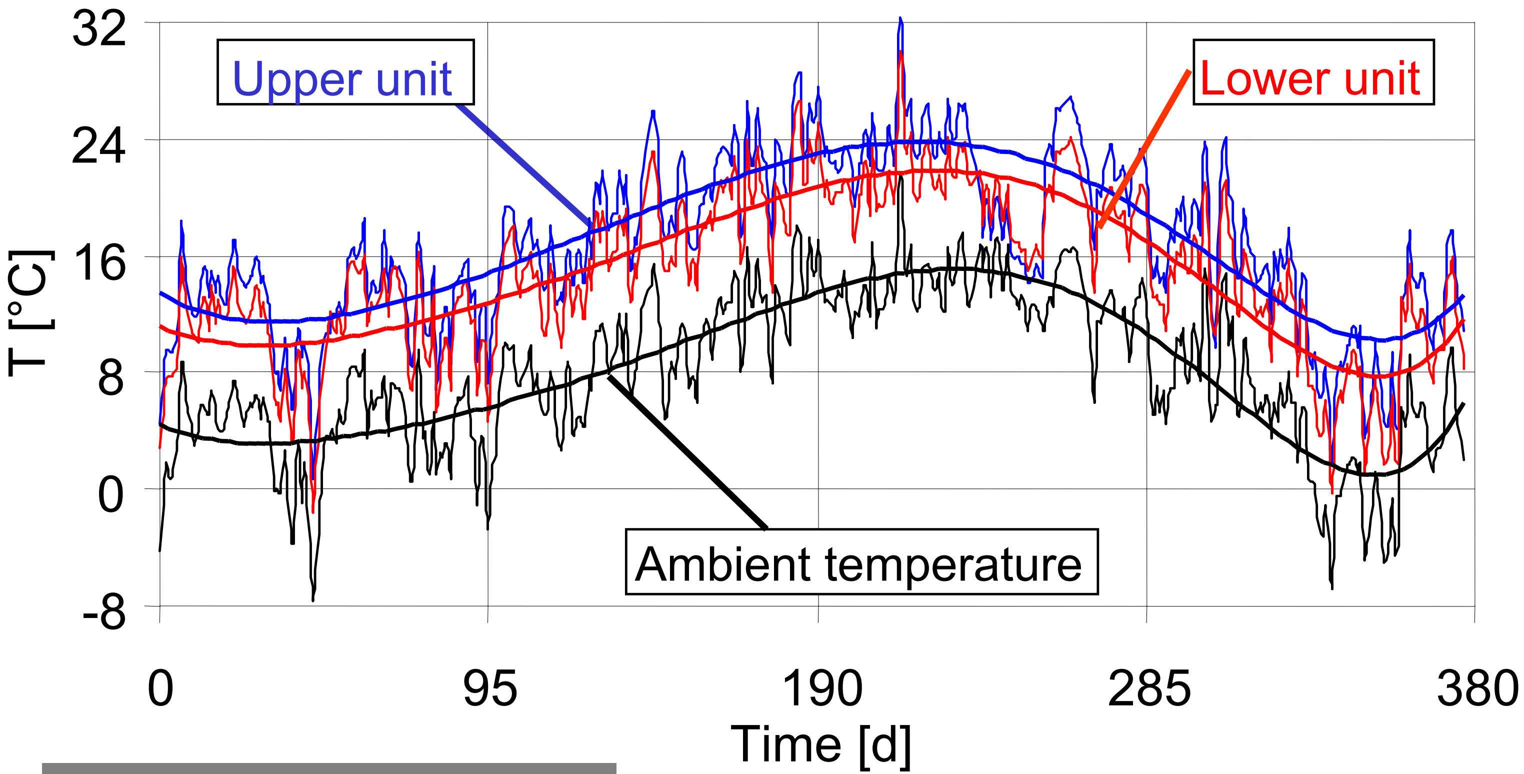


360 kV surge arresters equipped with a SAW temperature monitoring system

SAW temperature sensor in a stack of MO varistors



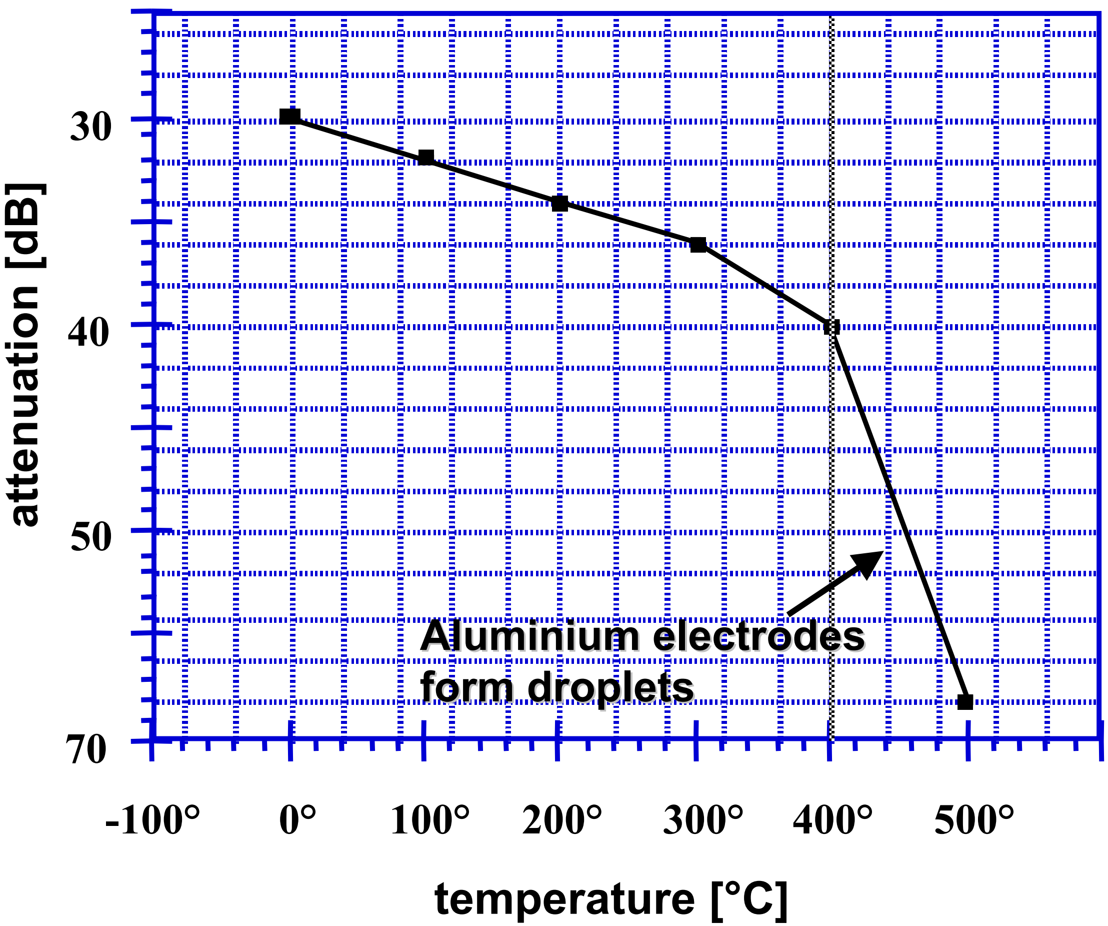
Field Test Results



the main features

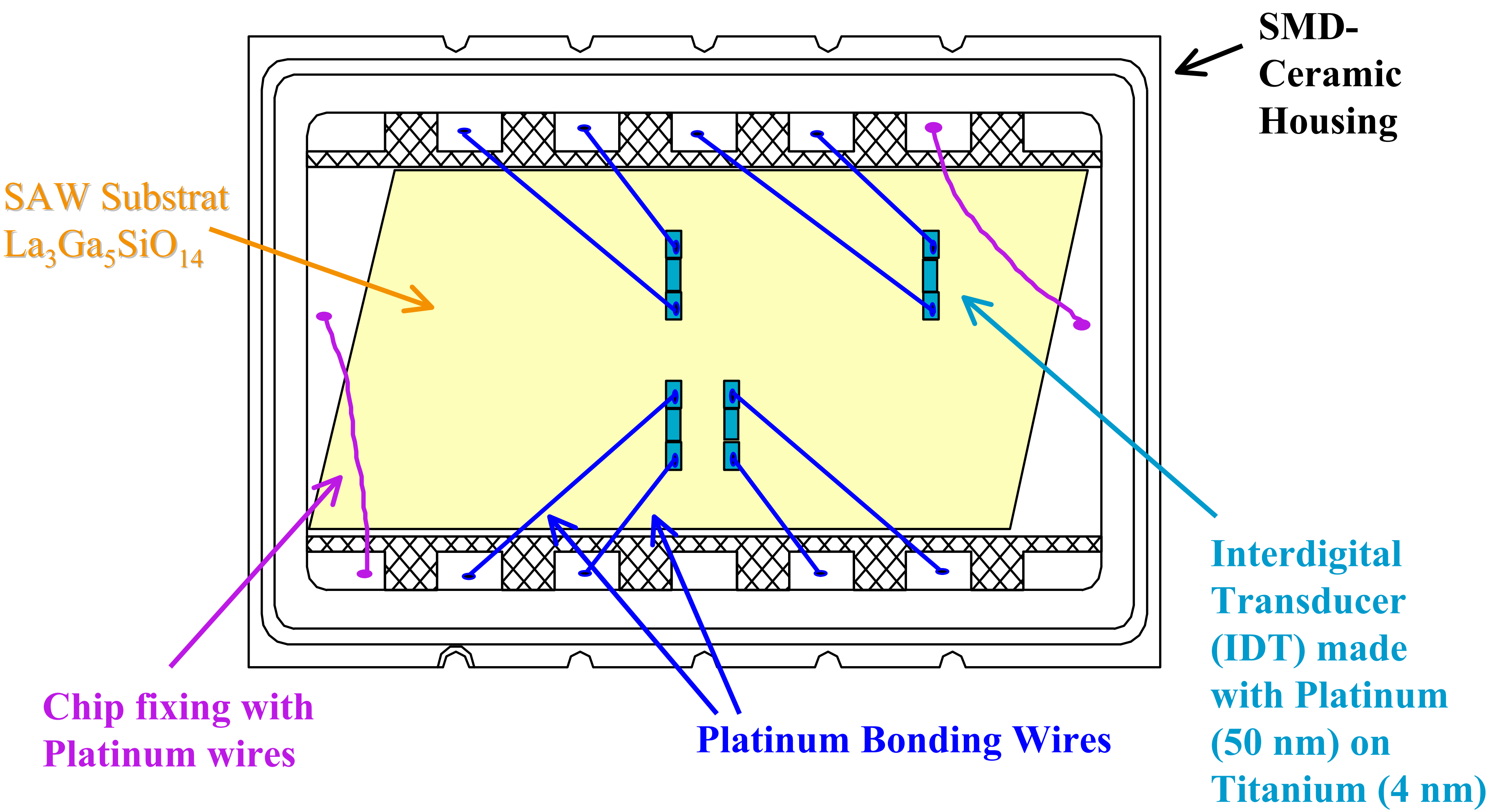
- **aging:** long term temperature increase
- **event counter:** sudden temperature rises
- **energy monitoring:** due to a simple correlation between temperature and absorbed energy

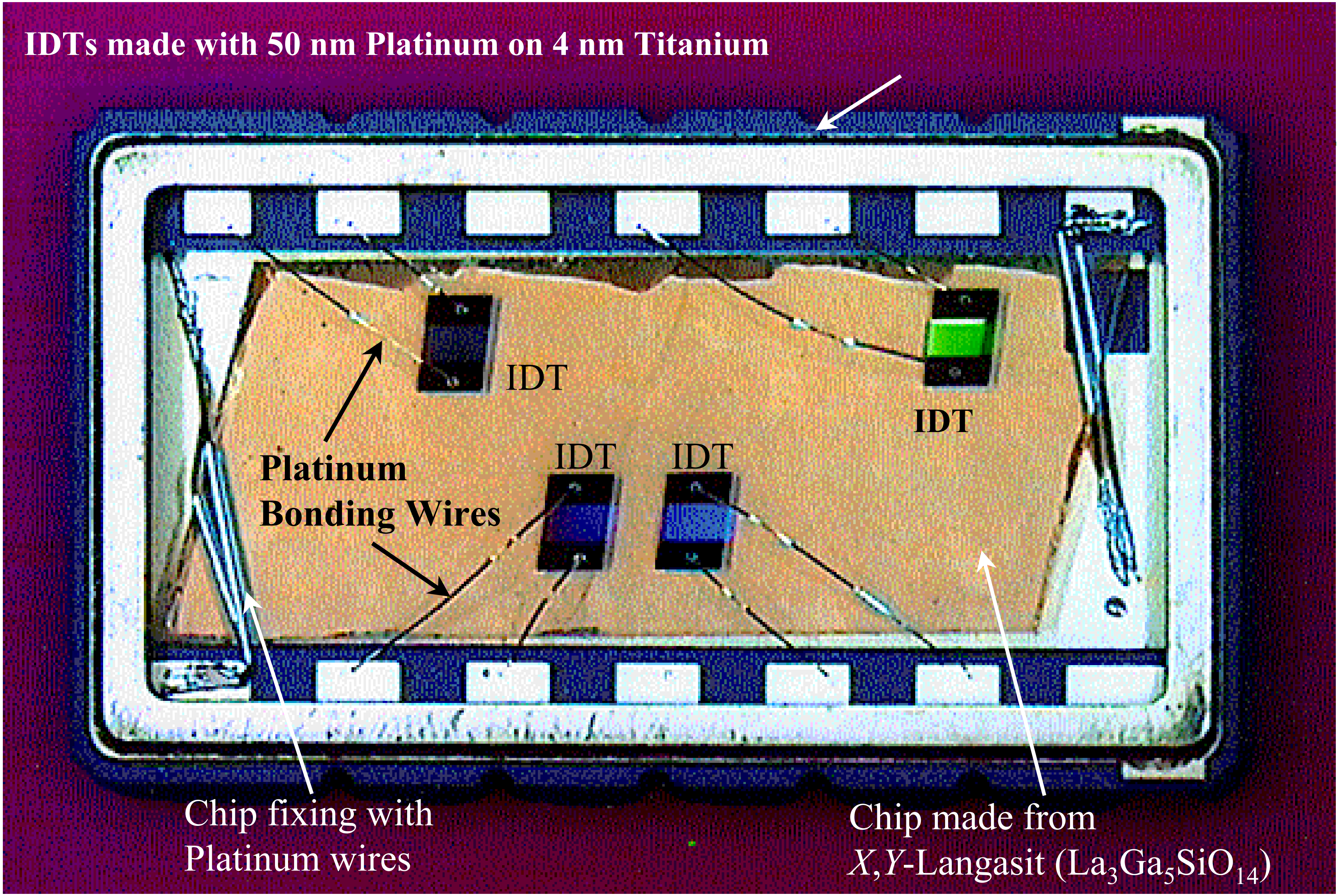
Signal attenuation versus temperature on $LiNbO_3$-YZ



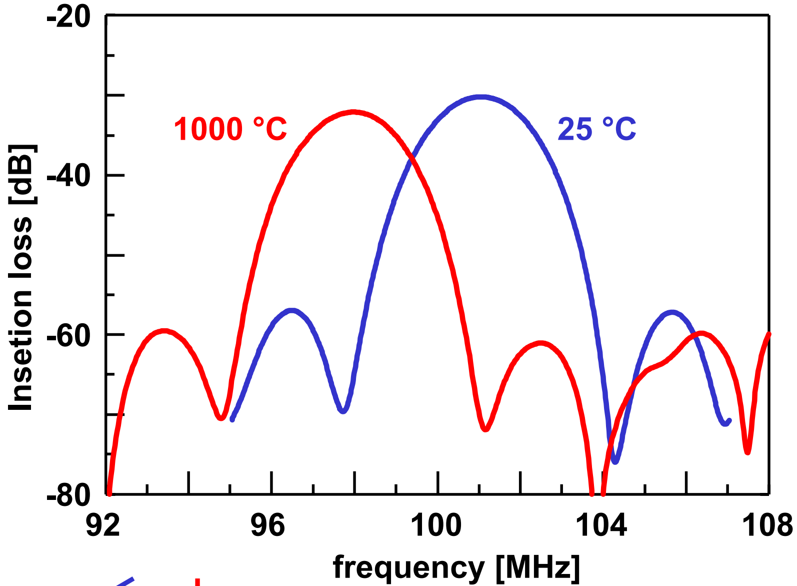
- Up to 200ºC standard assembly, interconnect and package techniques can be used.
- Up to 350ºC aluminium can be used for electrodes material
- $LINBO_3$ can not be used for temperatures higher than 400ºC for short time and 300ºC for long time operation.

Delay line for testing the high temperature features of Langasit ($La_3Ga_5SiO_{14}$)

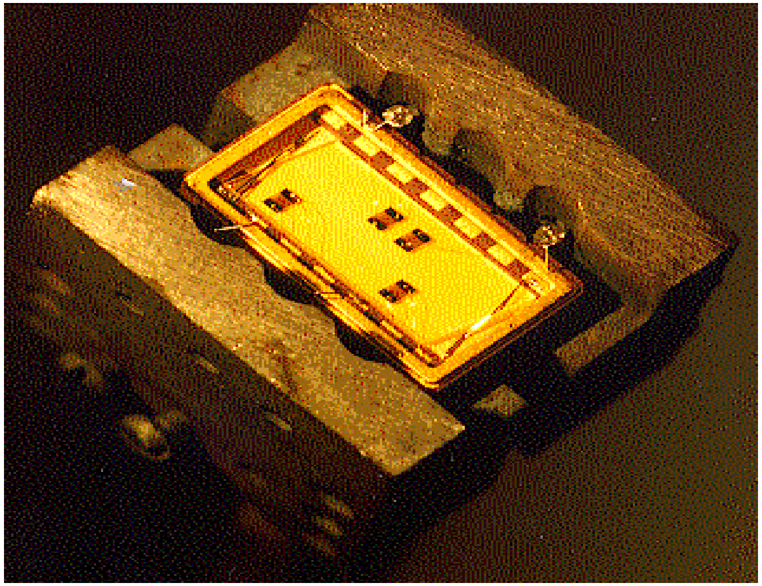



IDTs made with 50 nm Platinum on 4 nm Titanium
IDT
IDT
IDT
IDT
Platinum
Bonding Wires
Chip fixing with
Platinum wires
Chip made from
X,Y-Langasit (La3Ga5SiO14)

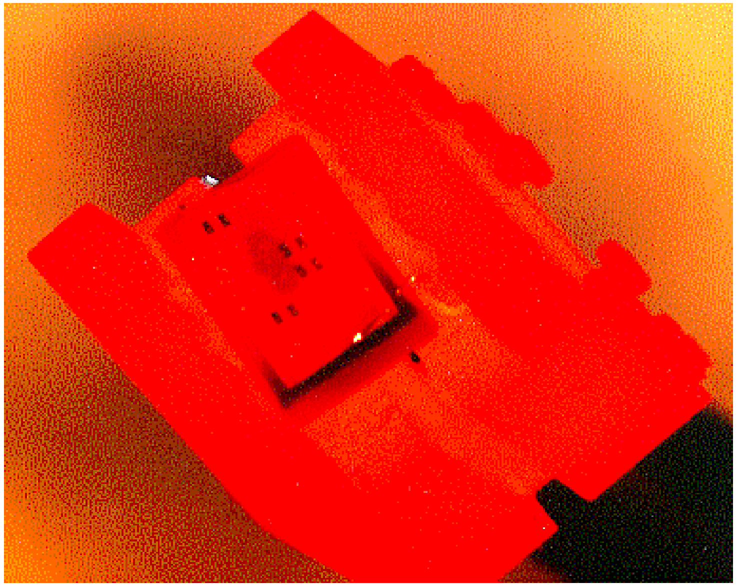
High Temperature SAW Sensors with Platinum Electrodes on Langasit ($La_3Ga_5SiO_{14}$)



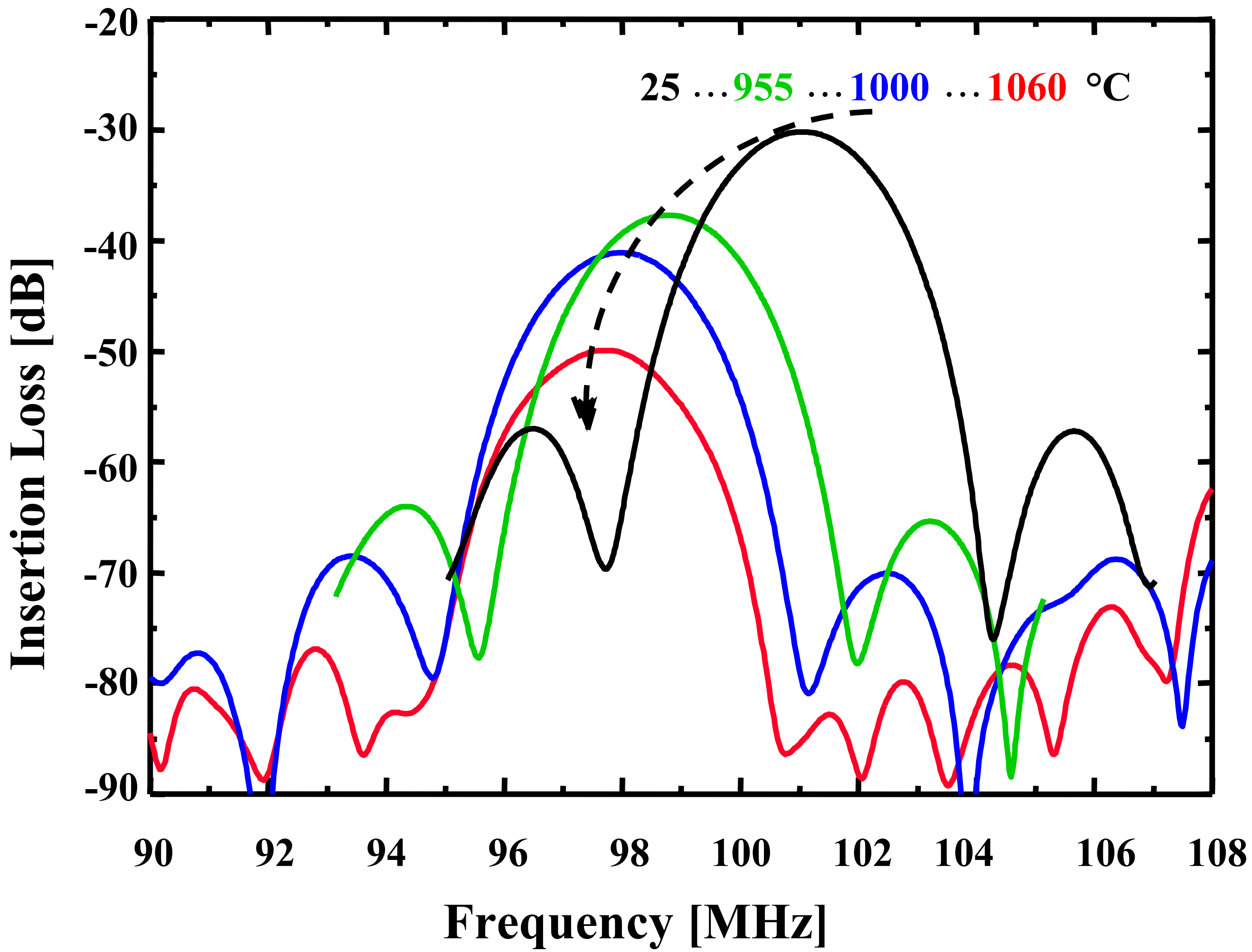
Test chip at room temperature



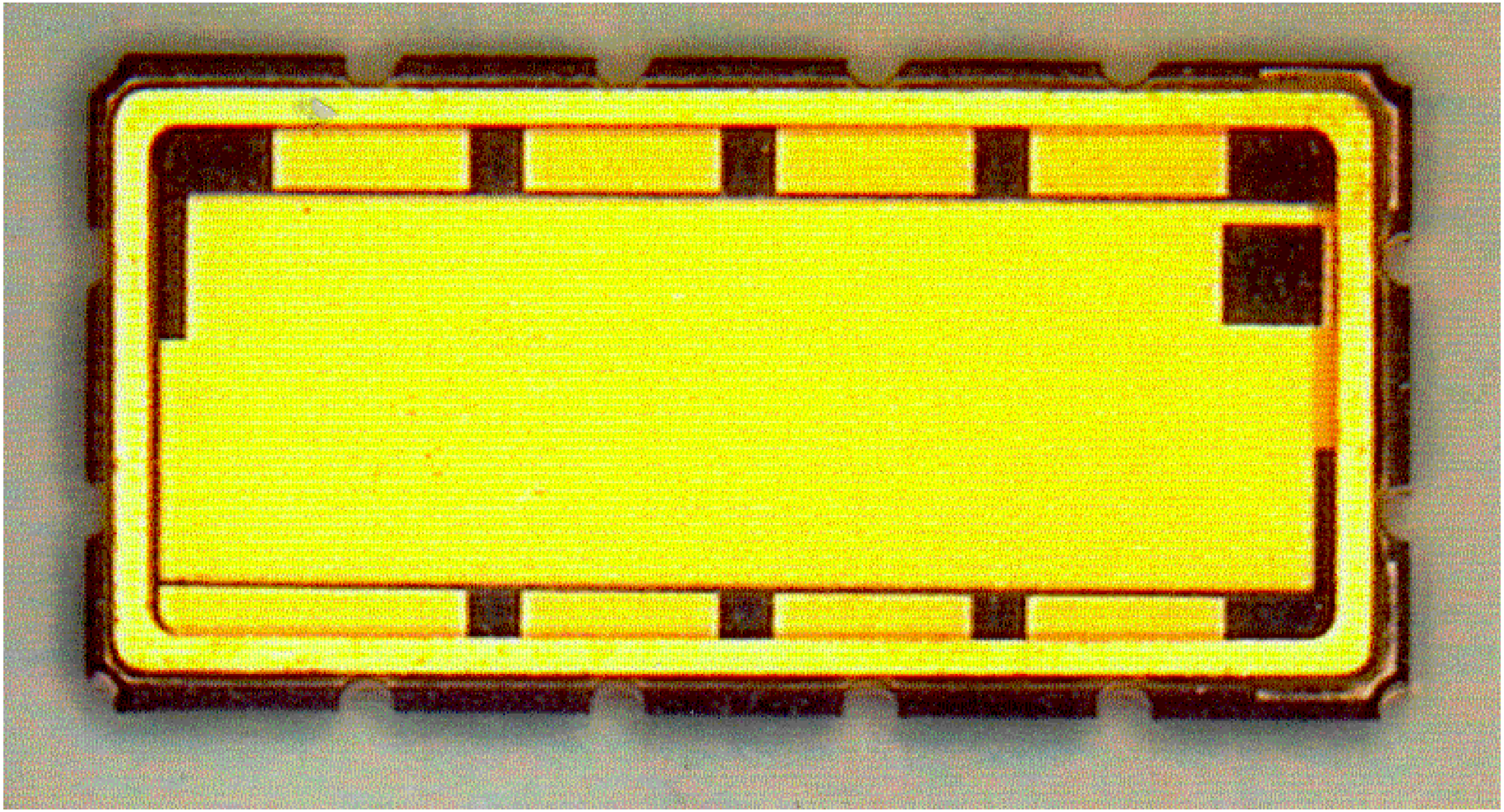
Test chip at 1000°C

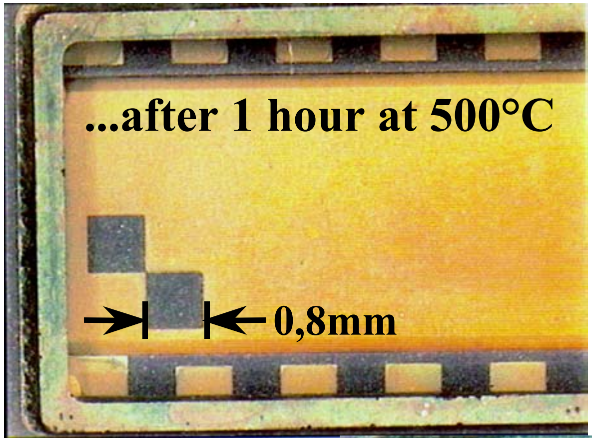


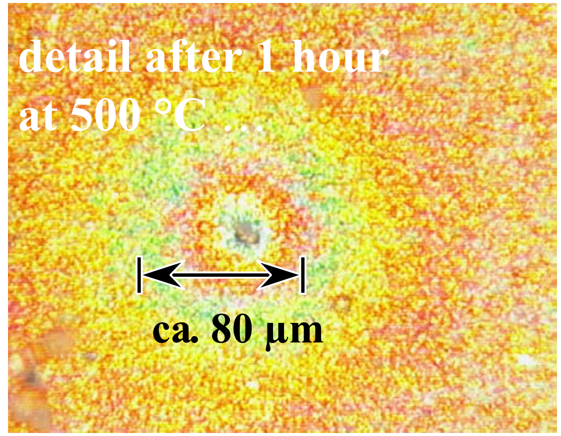
Increase in Insertion Loss of a Delay Line on X,Y-Langasit ($La_3Ga_5SiO_{14}$) with Pt-electrodes with Increasing Temperature



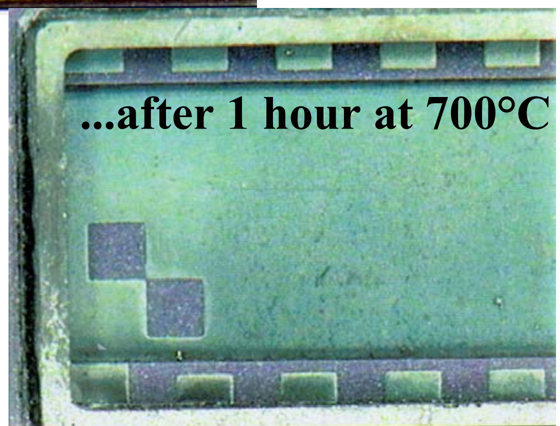
SMD - packaging with W/Ni/Au-metallization before heating

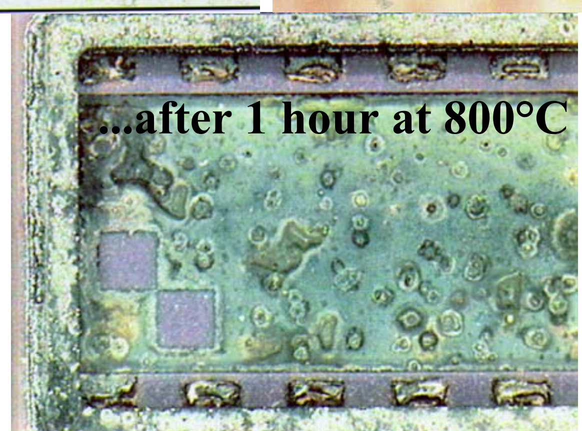




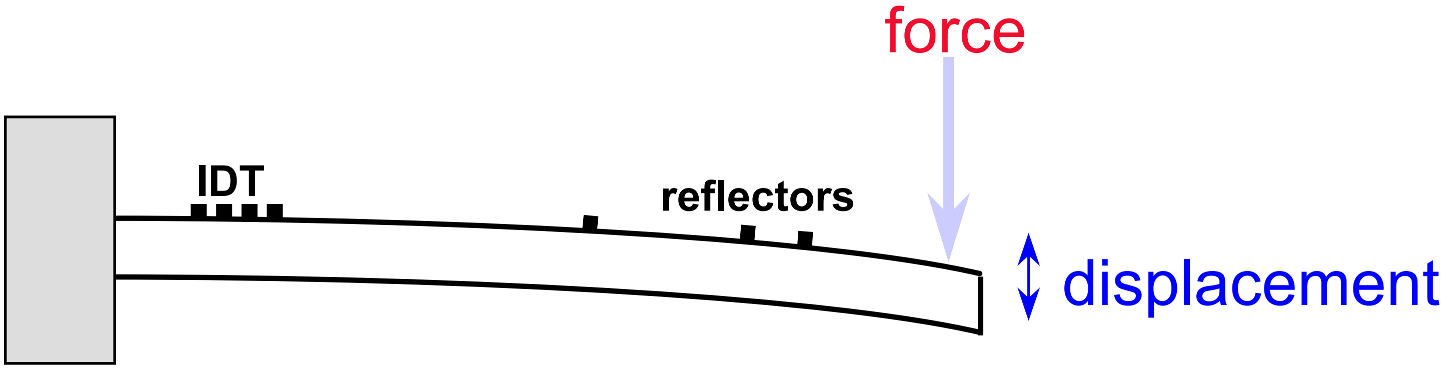


... and after heating at higher temperatures



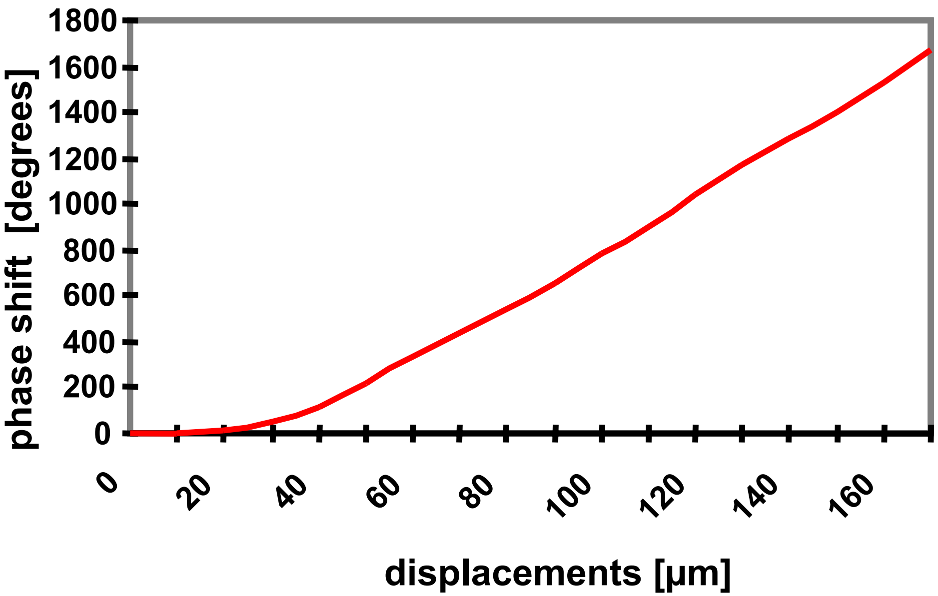


Wirelessly Readable Passive Sensors for Force and Mechanical Displacement



... if a mounting is chosen, which lets forces act on the SAW chip to bend it, we get a wirelessly readable passive sensor for force or mechanical displacement.

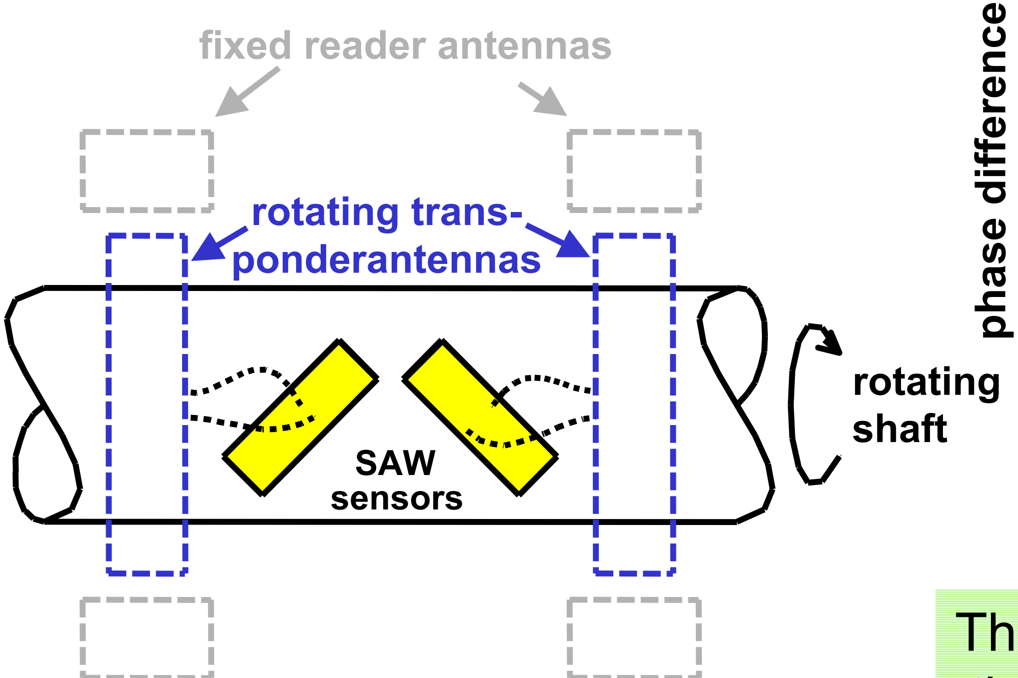
... due to the bending of the substrate, both the surface's length and the elasticity constants are changed.



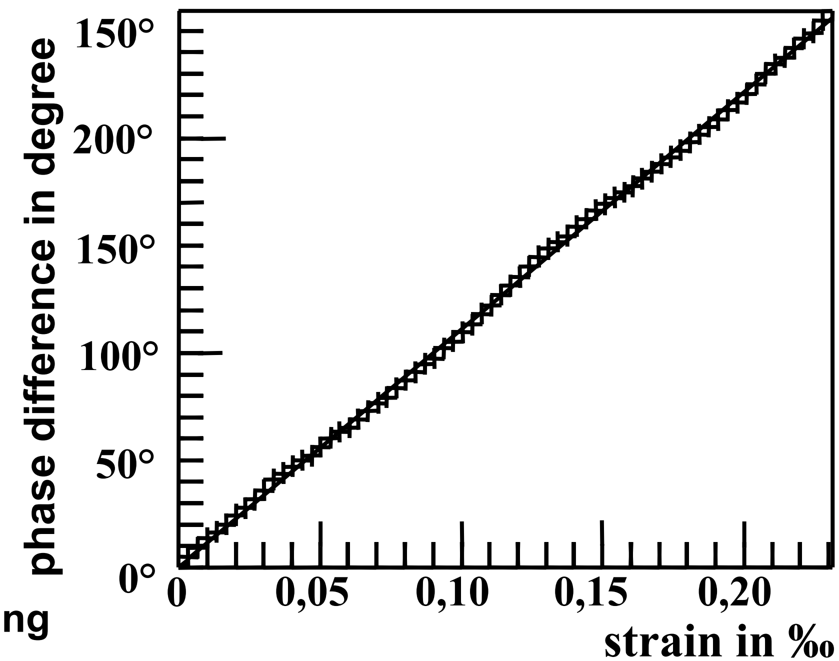
The dynamic range of monitoring the forces with SAW can be up to several tenths of kHz

SAW Torque Sensor

An applied torque induces a stretching of one and a corresponding compressing of the other sensor.



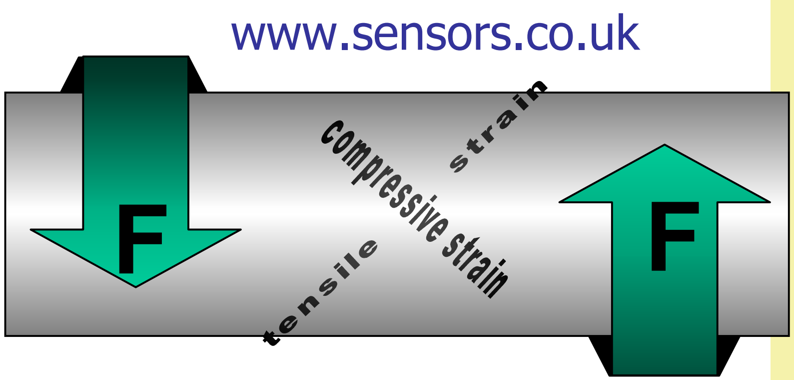
measurement set-up



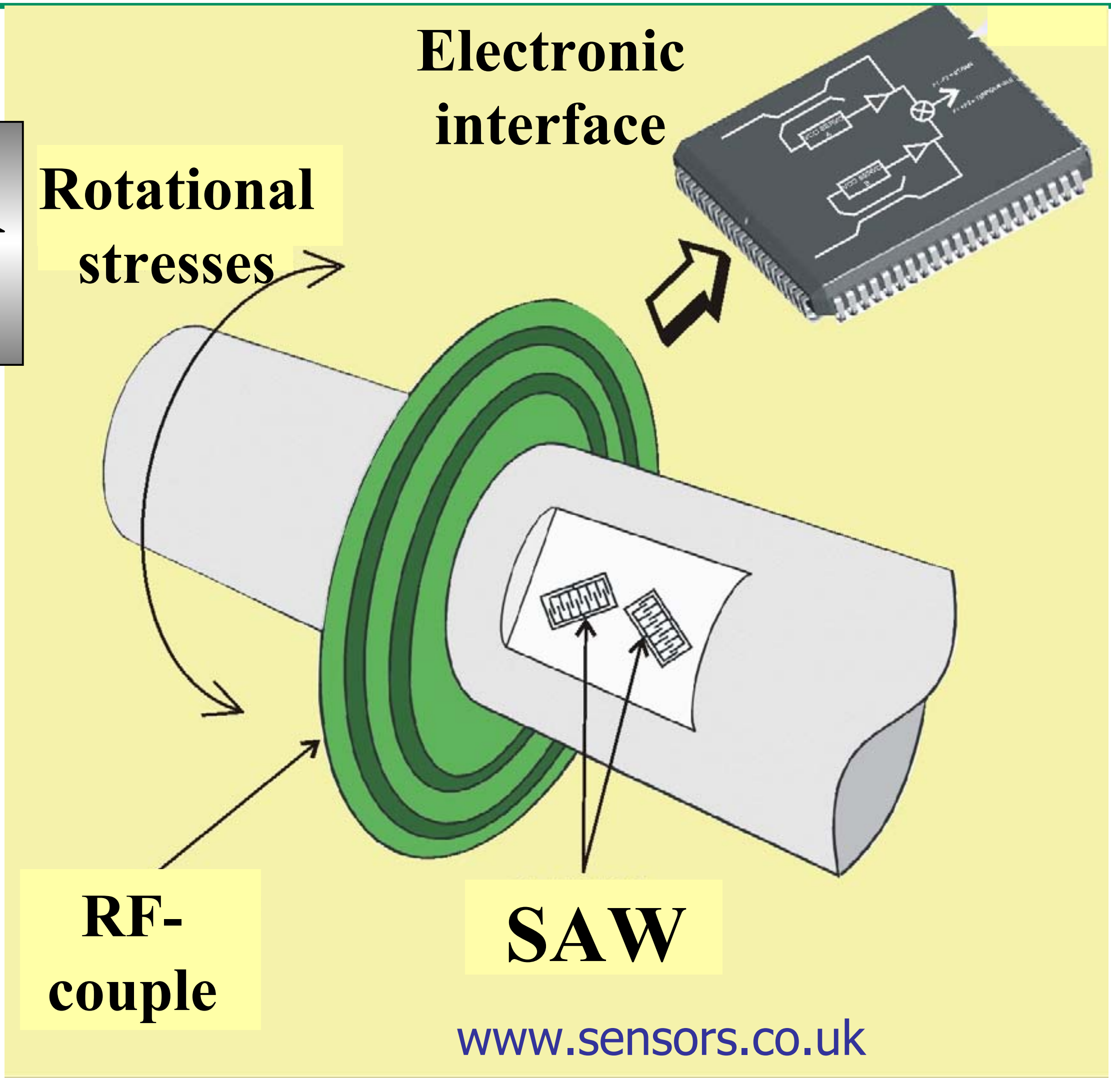
The torque is calculated from the phase differences.

The dynamic range of monitoring the torque with SAW can be up to several tenths of kHz

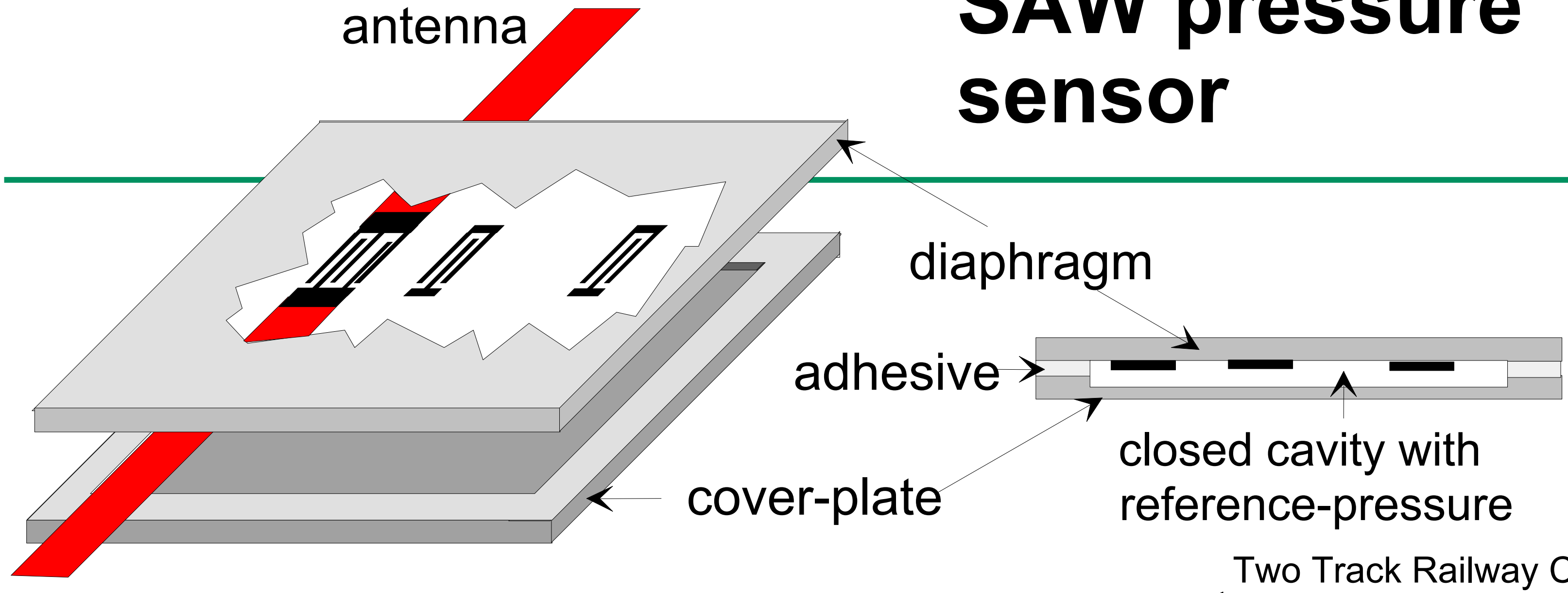
SAW Rotary Torque Sensor

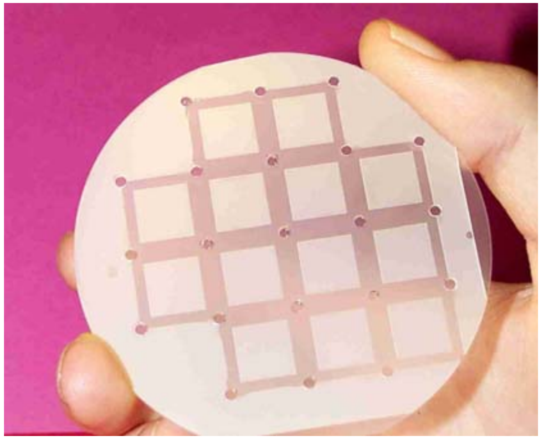


Surface strain due to torque acting on a shaft

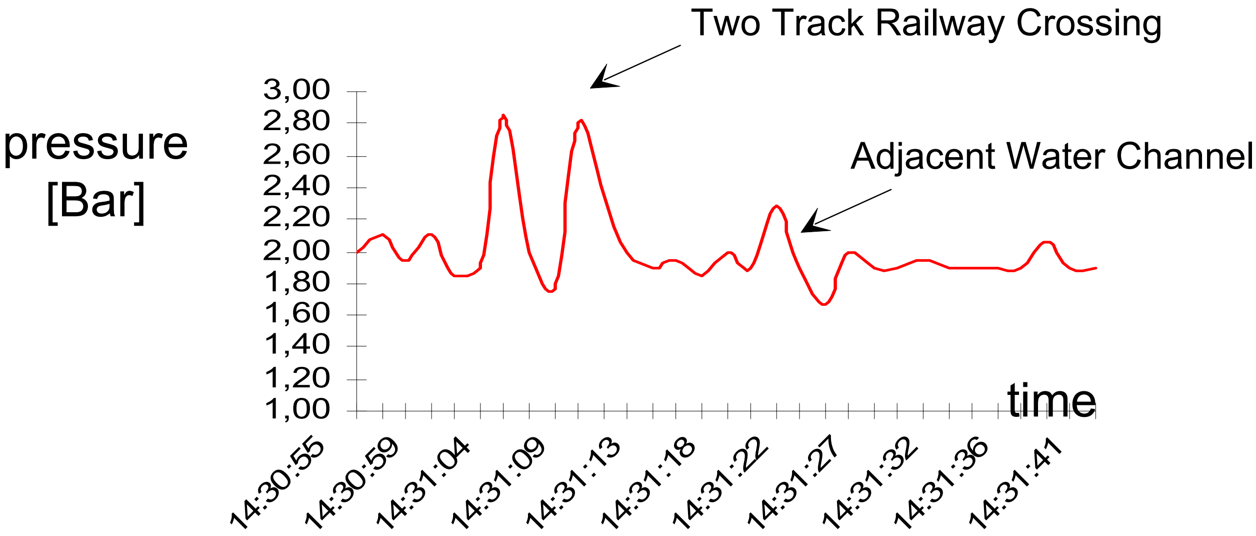


SAW pressure sensor



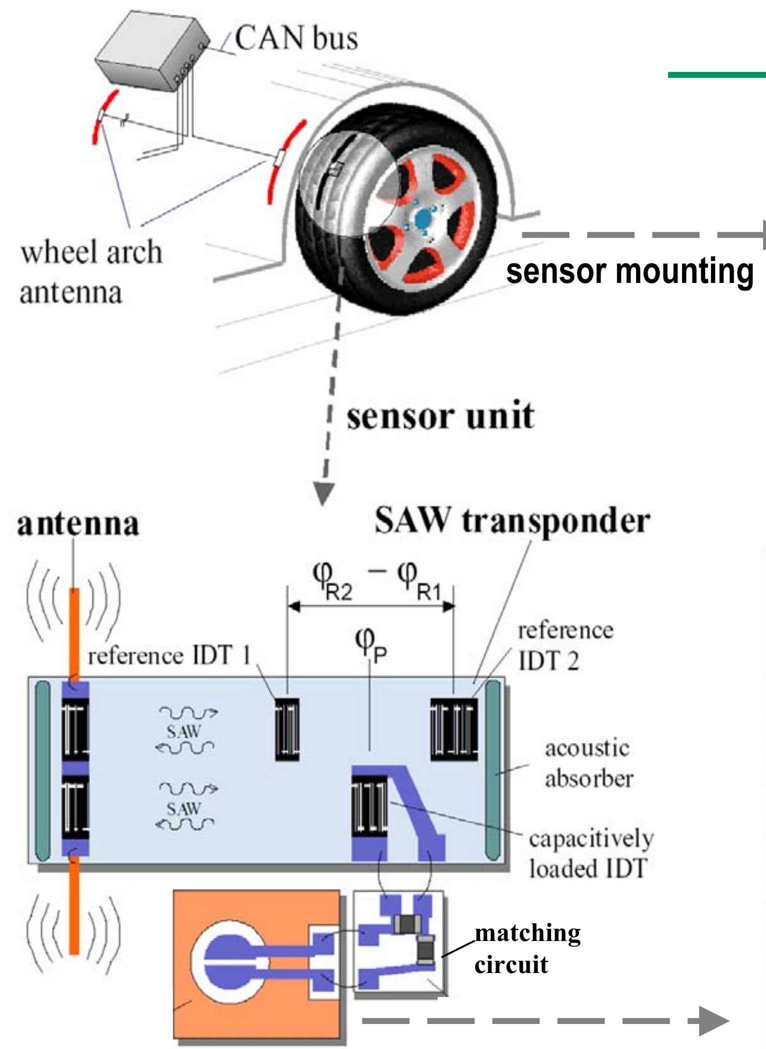


**Wafer processing
of SAW pressure sensors**

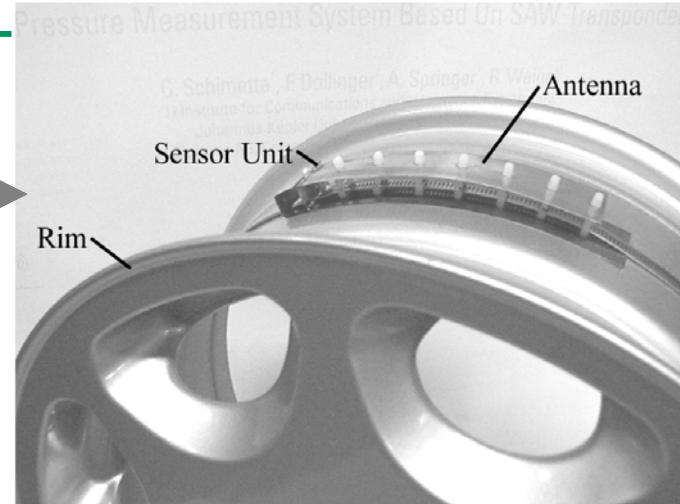


A SAW pressure sensor type, which uses a direct bending of the SAW chip, results in a resolution of about 1% of full range.

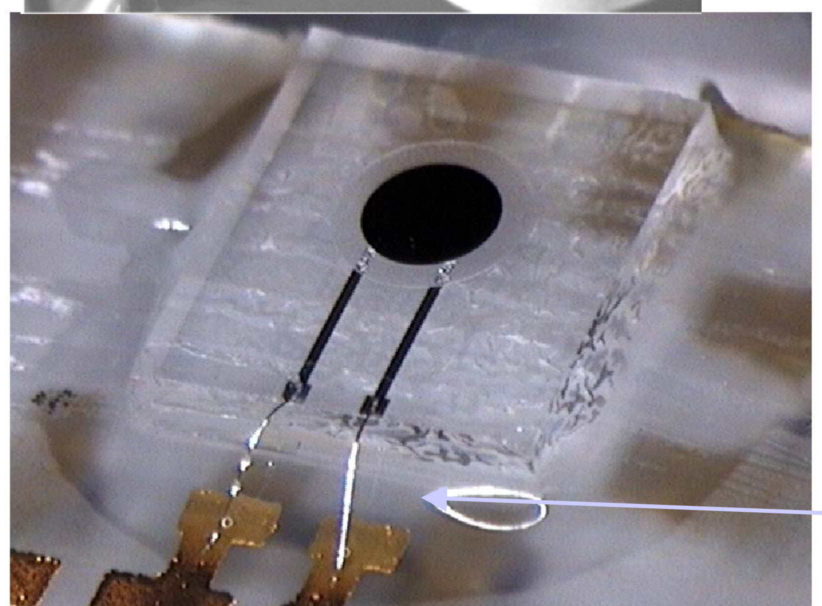
tire pressure sensor, presented by G. Schimetta



capacitive micro-machined pressure sensor

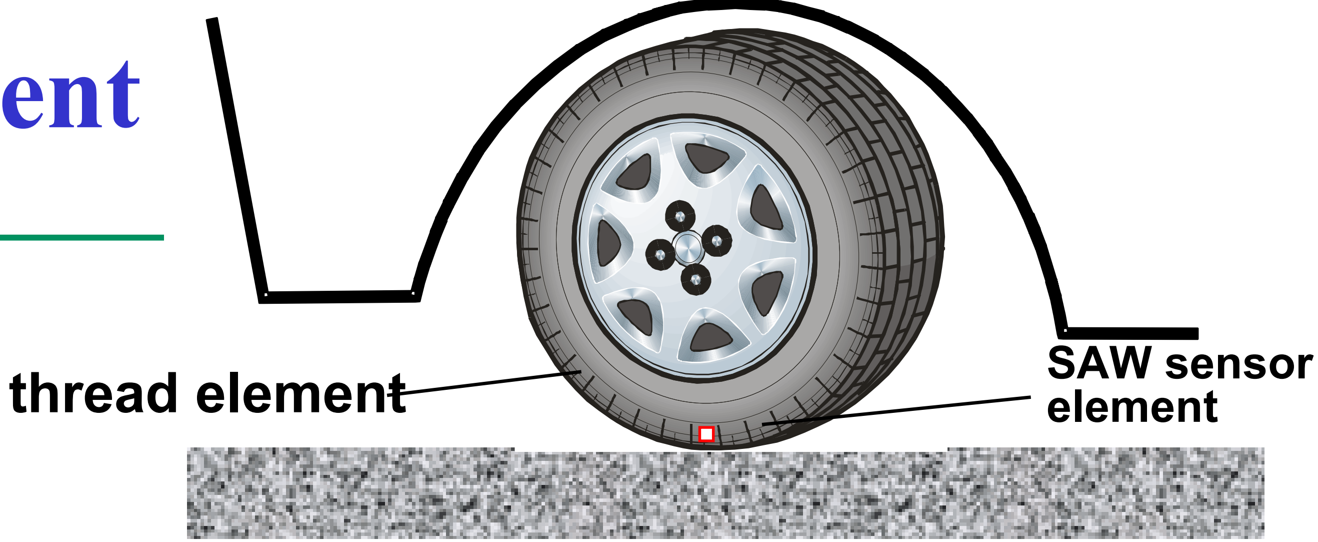


The patch antenna with the integrated sensor board is mounted on the rim with a stress ribbon.

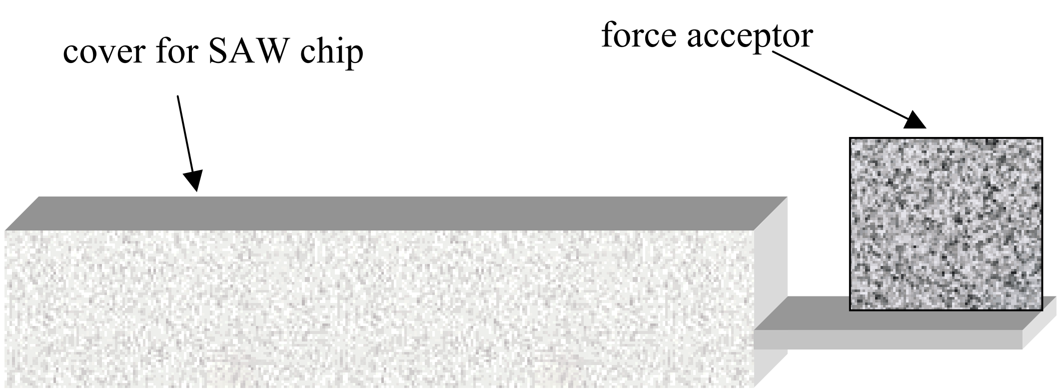


bond wires

The intelligent tire



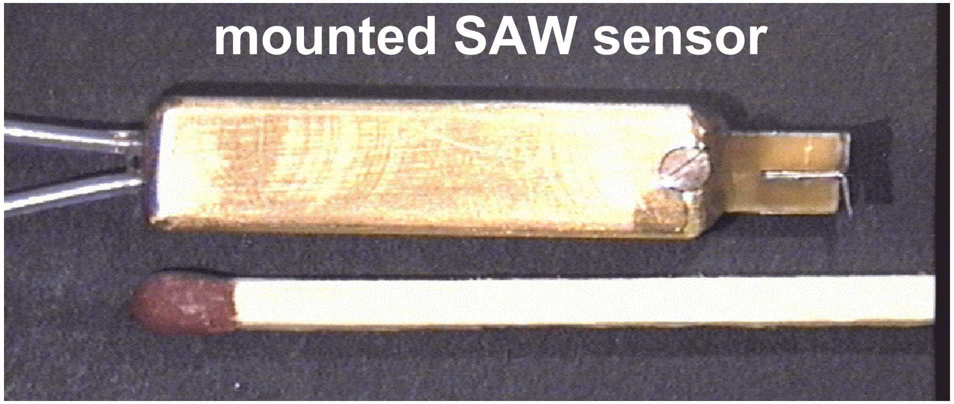
Schematic drawing of an experimental SAW bending beam



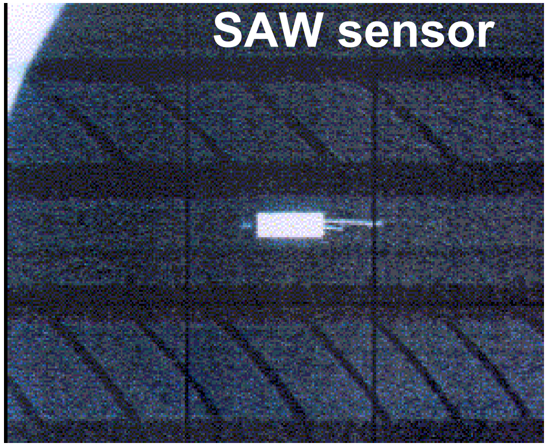
The friction coefficient between a car tire and the road surface, which is a key parameter when stabilising a vehicle in critical situations, can be measured by evaluating the mechanical strain in the tire surface contacting the road. This can be done by monitoring the deforming of the tread elements.

➔ **Intelligent tire due to a sensor in the tire / road contact area**

SAW sensor for tire friction control



mounted SAW sensor

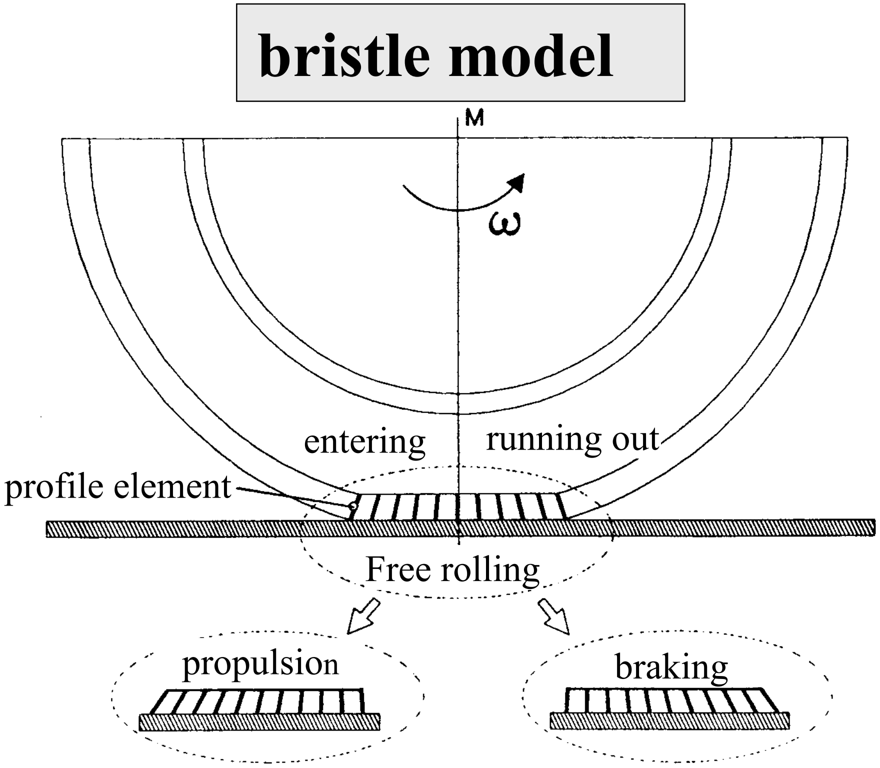


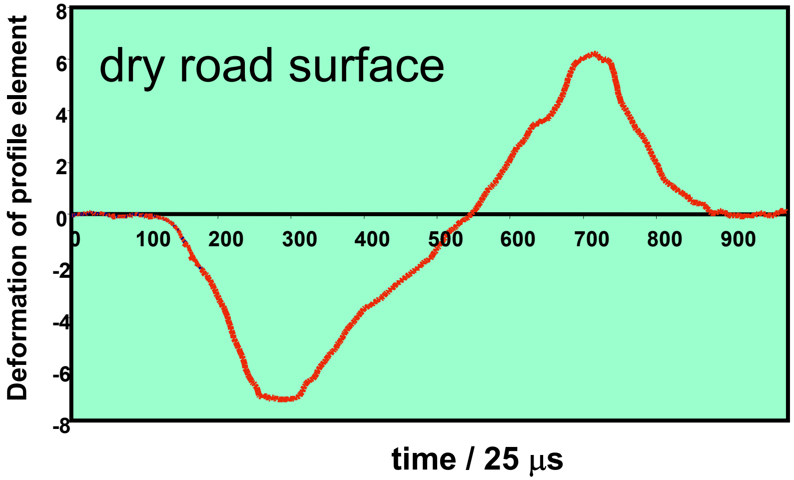
Radiography of a tire with integrated SAW sensor

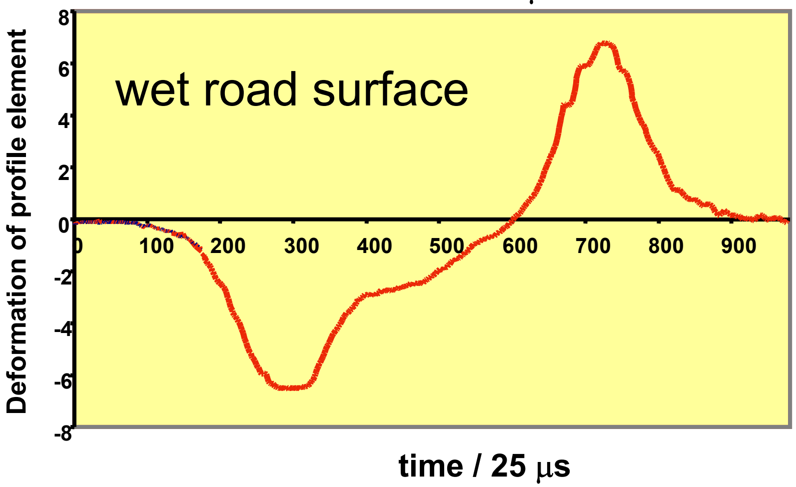
SAW sensor integrated into a standard tire

SAW sensor for tire friction control

The deformation of a profile element gives information of the friction coefficient between tire and road

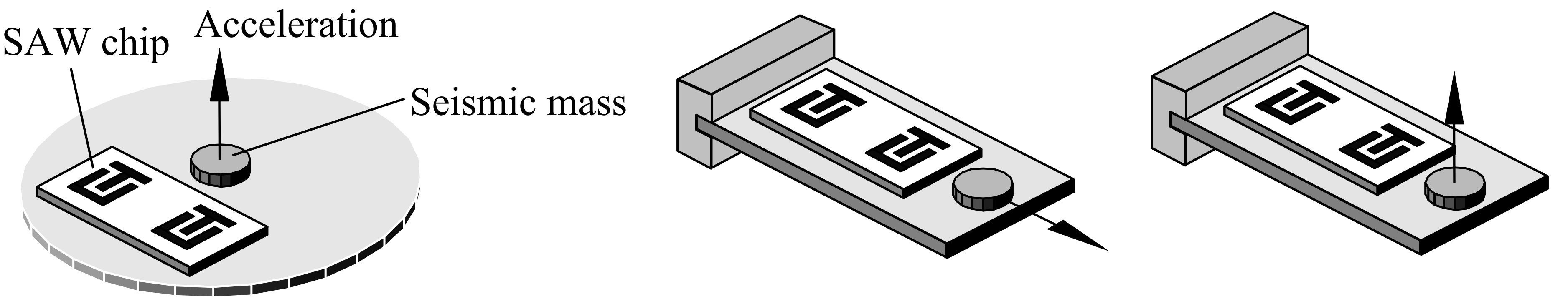






A radio requestable SAW accelerometer can be attained if seismic mass is added

SAW accelerometer configurations:

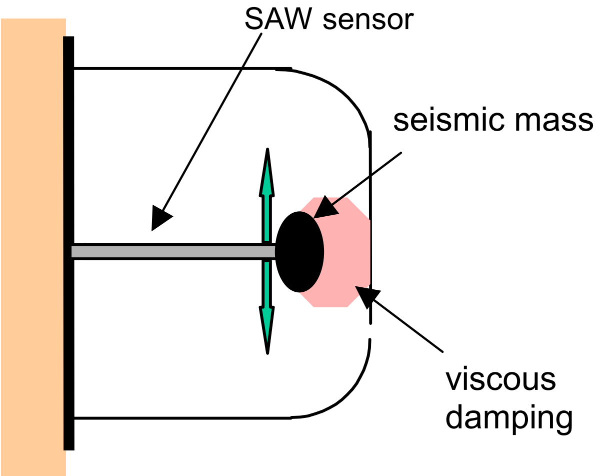


Circular diaphragm

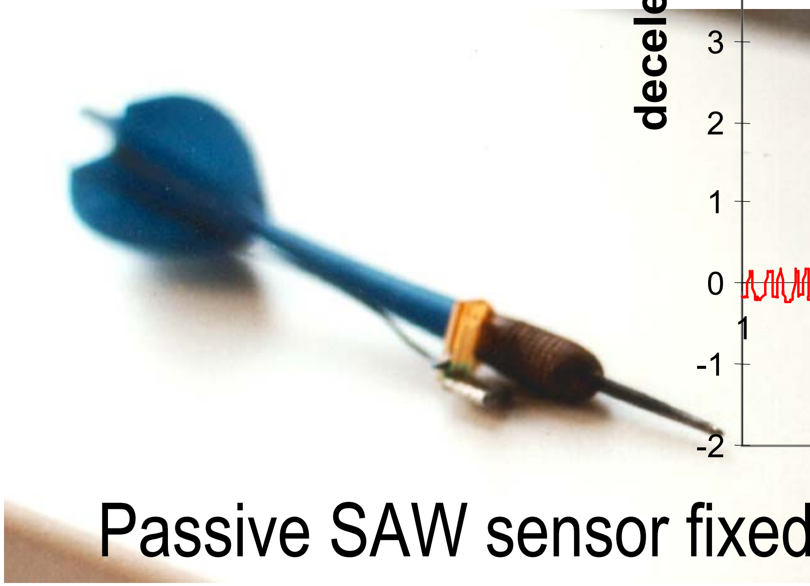
Tensioned cantilever beam

Flexured cantilever beam

Wireless Measurement of Deceleration

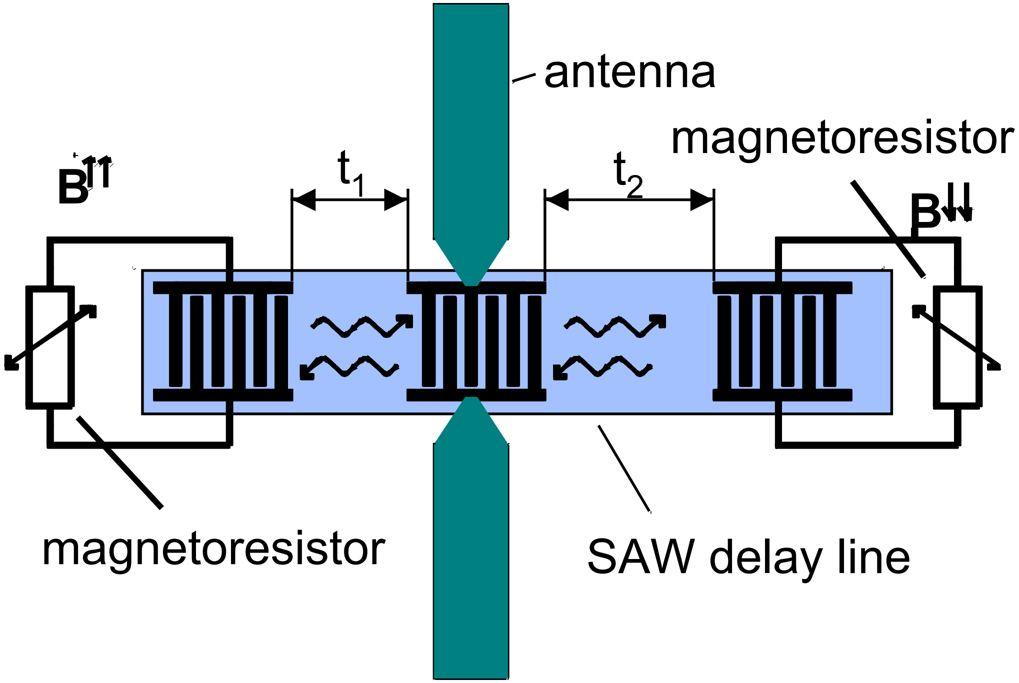


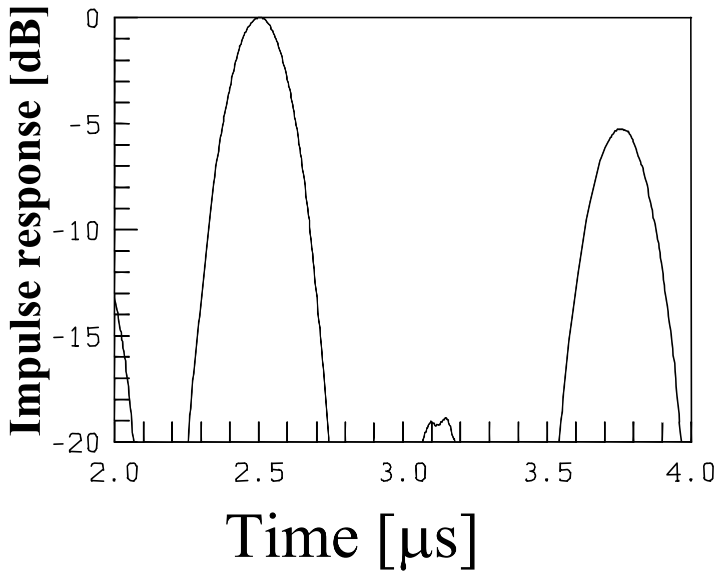
SAW accelerometer using a seismic mass and a flexured SAW cantilever beam

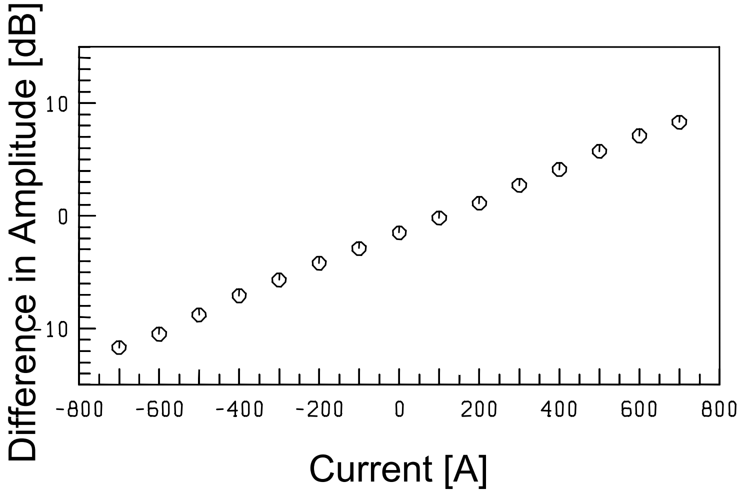


Passive SAW sensor fixed to a dDart arrow, invading the target

SAW Current Sensors

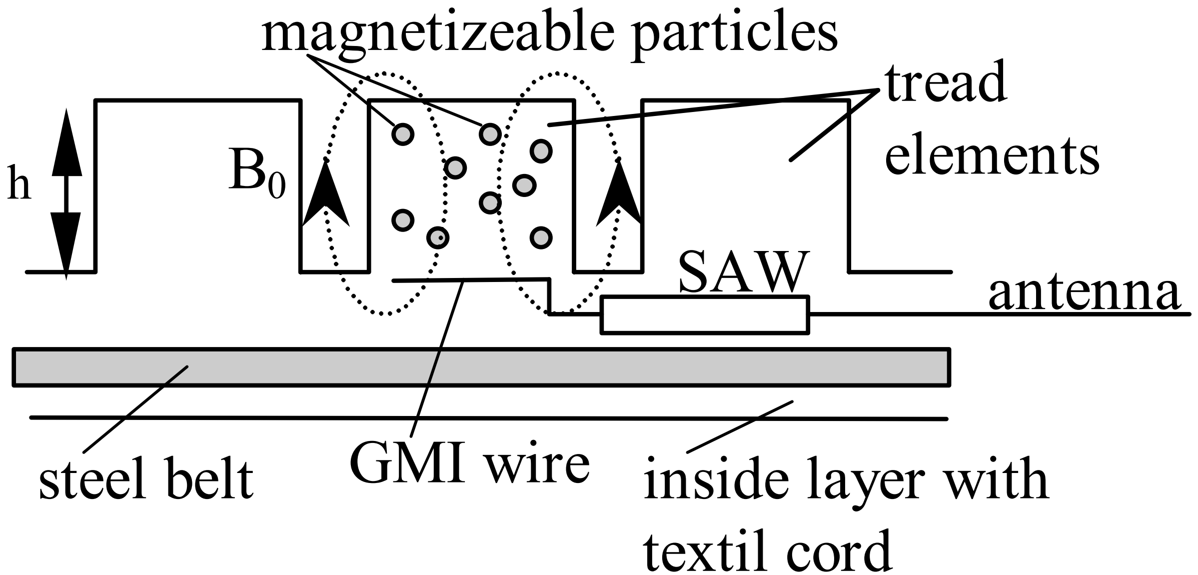




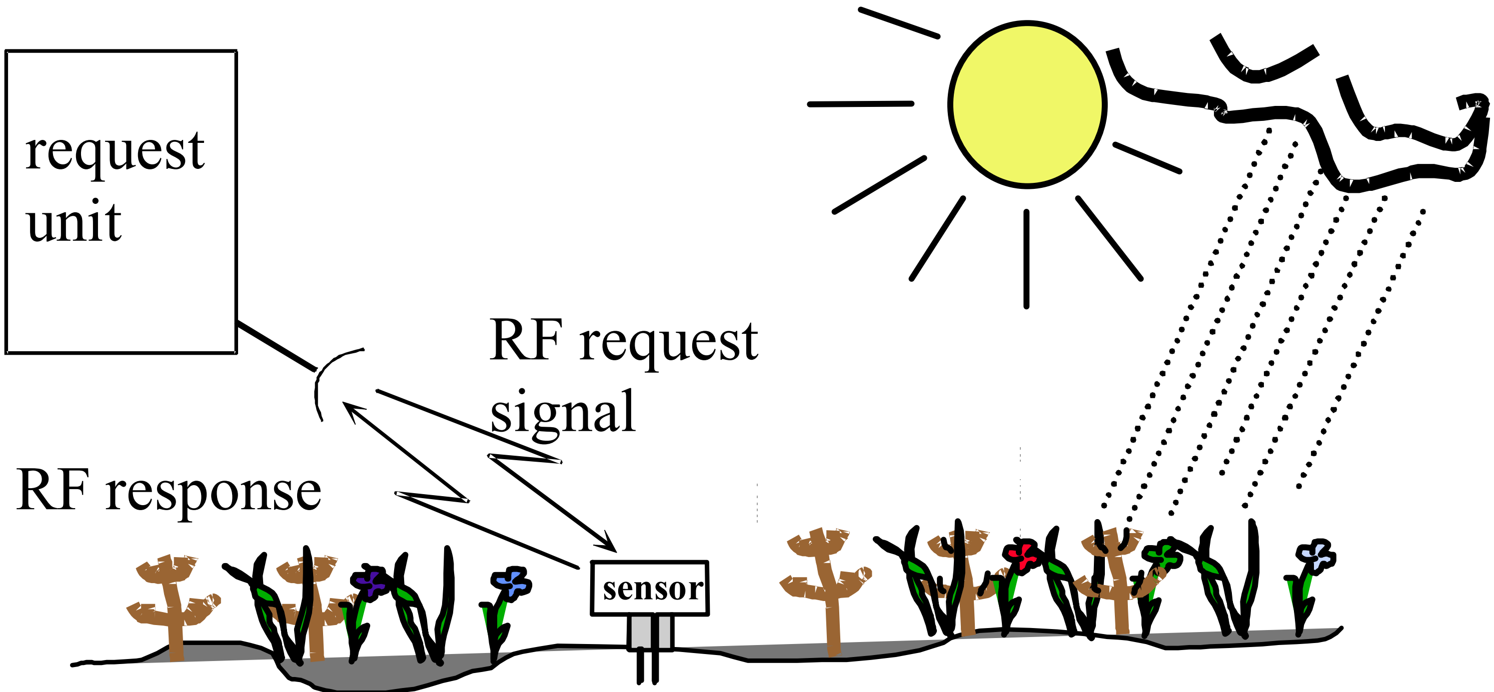


resolution ~ 5% of full scale

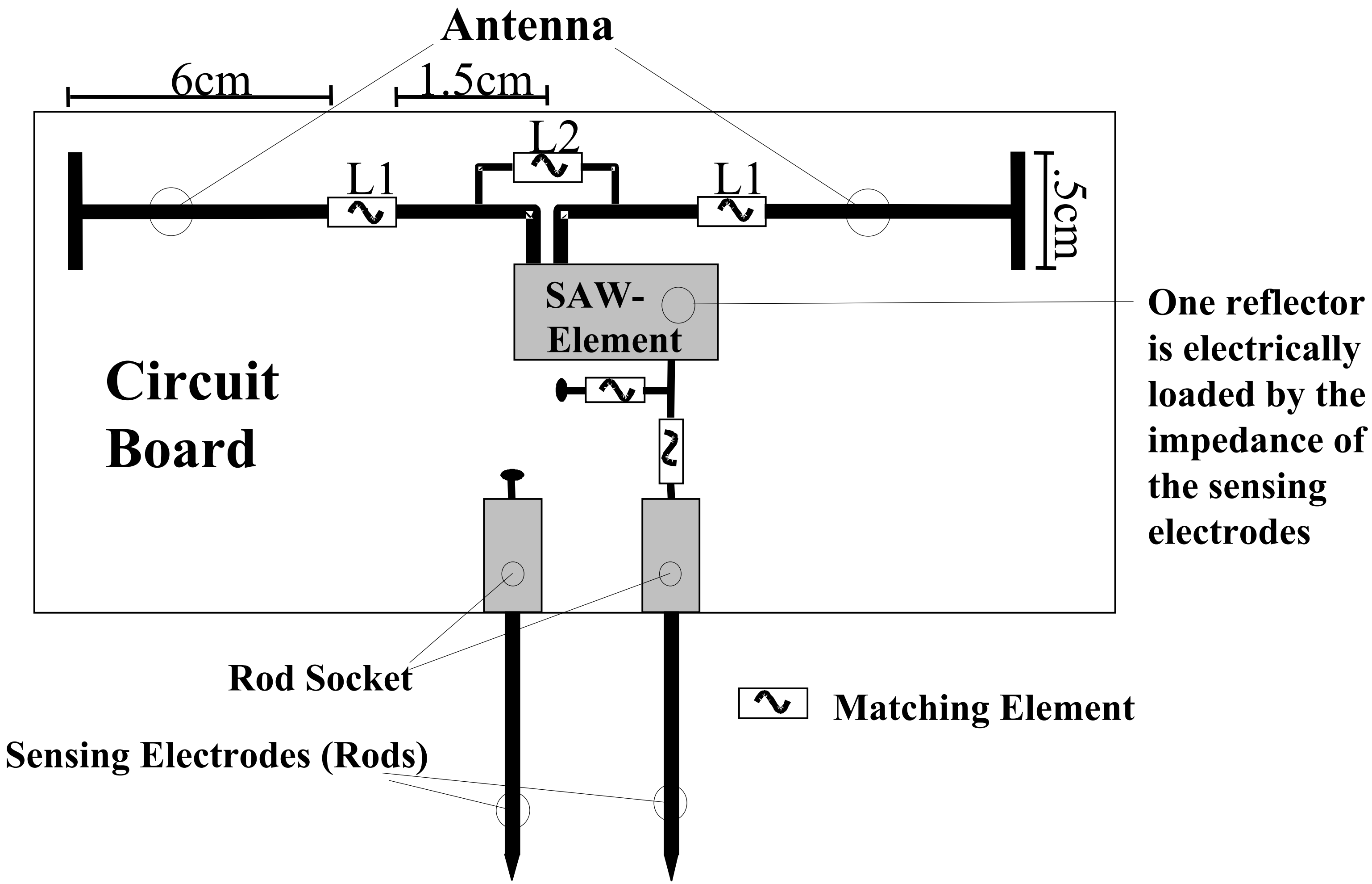
Sketch of a tire wear sensor using a GMI wire and magnetize able particles



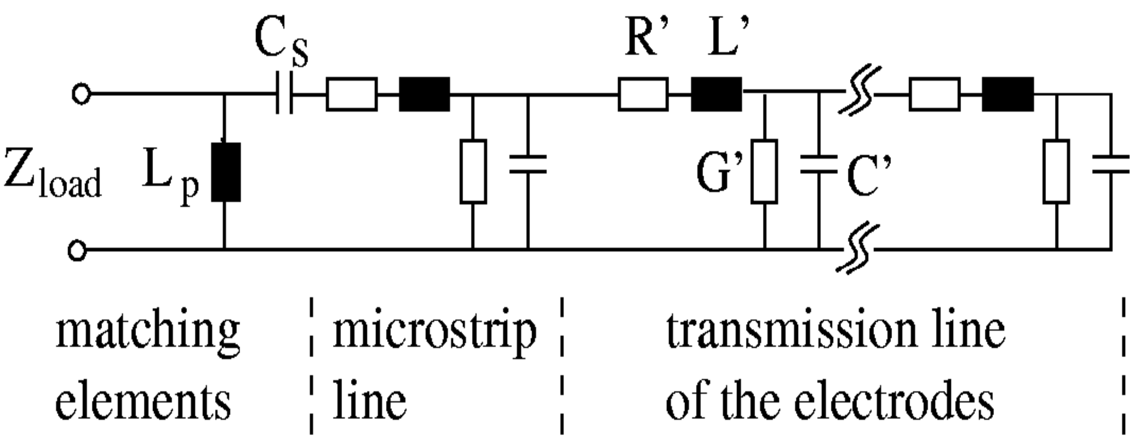
Water Content Sensor: Scenario



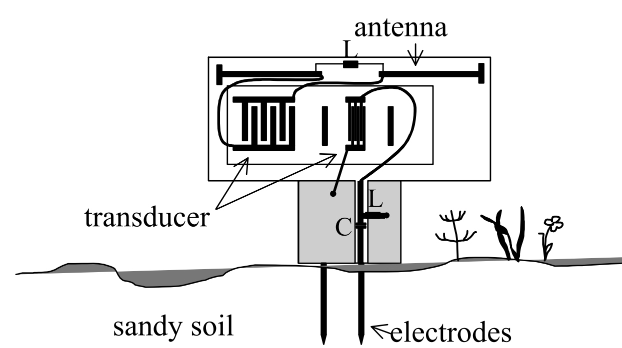
Schematic of the SAW Water Content Sensor



Schematic of the Water Content Sensor Electrodes (Rods) and Corresponding Matching Circuitry

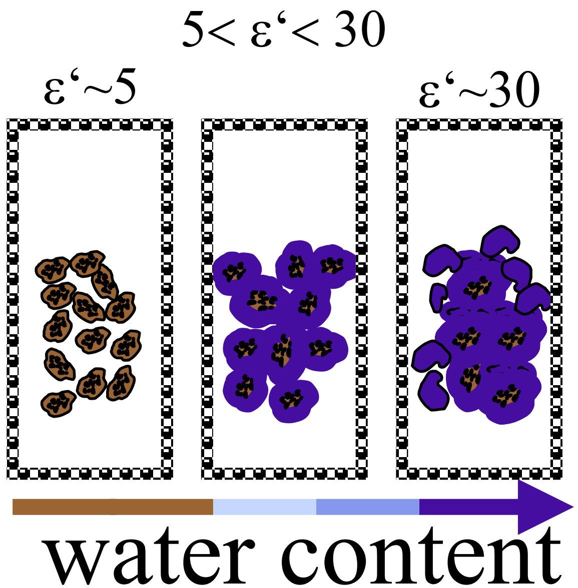


Overall sensor circuitry

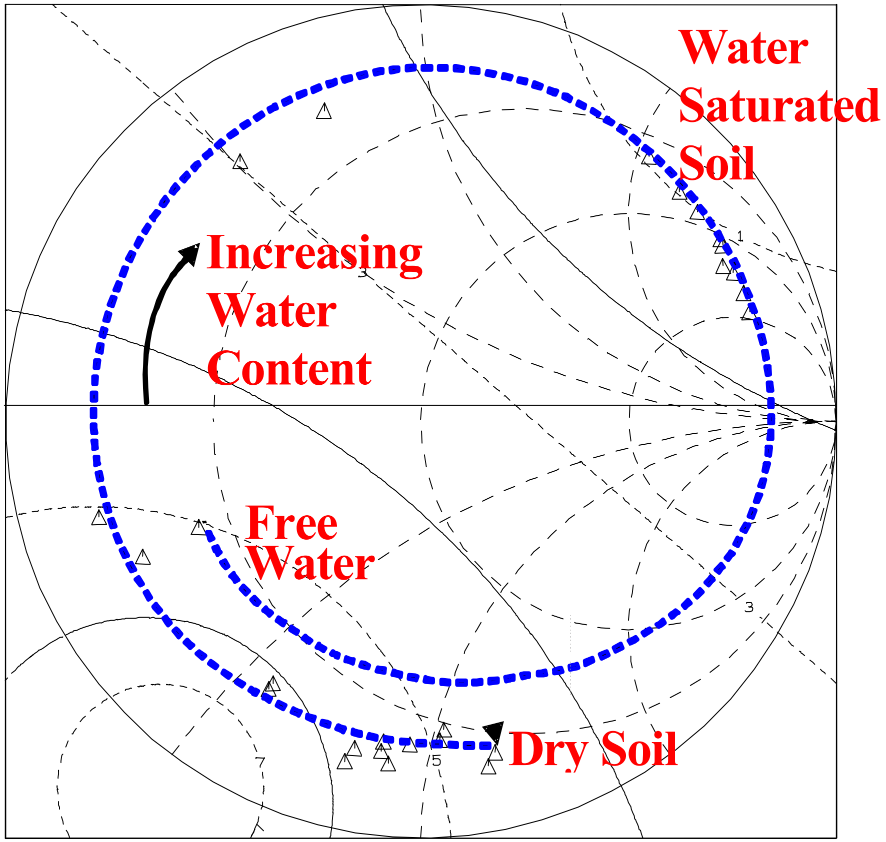


Electrical Reflection Coefficient of the Sensor Electrodes (including Matching Circuitry) versus Water Content

Change of the permitivity ε‘ of sandy soil with increasing water content

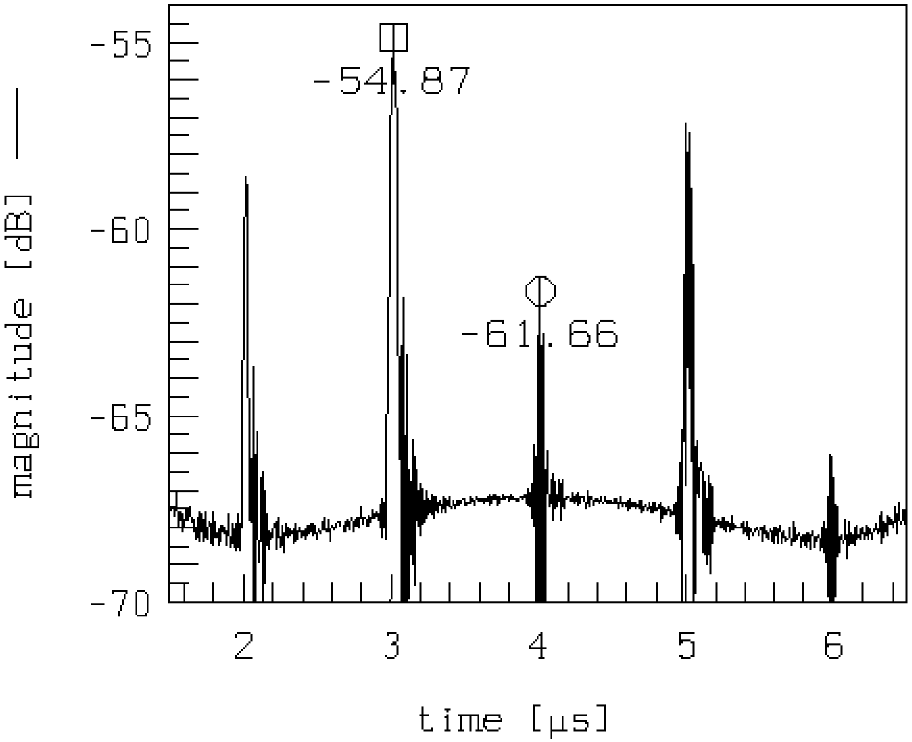


$$\Delta\varphi = -\sqrt{\varepsilon'} \cdot \frac{4\pi \cdot l \cdot f}{c_0}$$

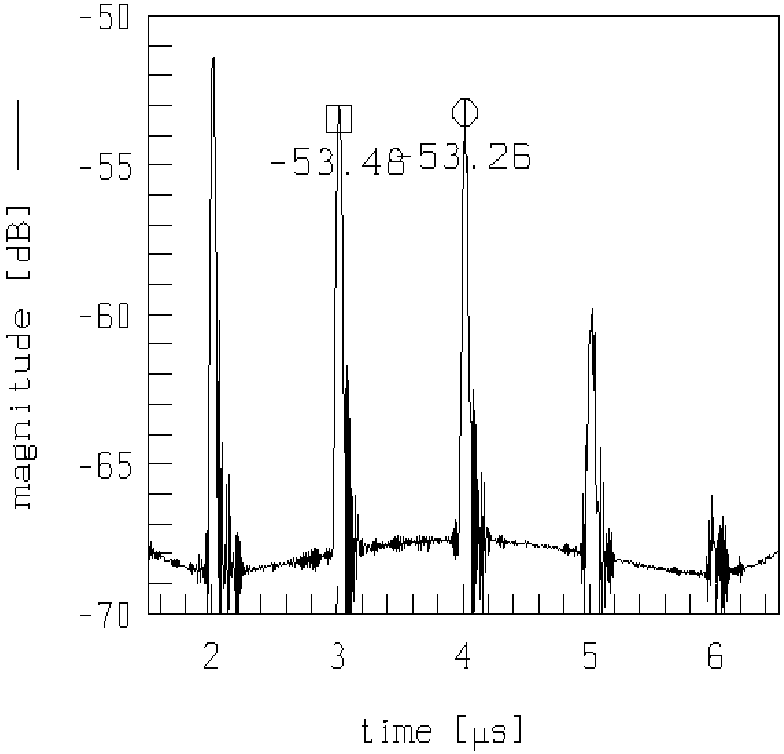


Two Measurements

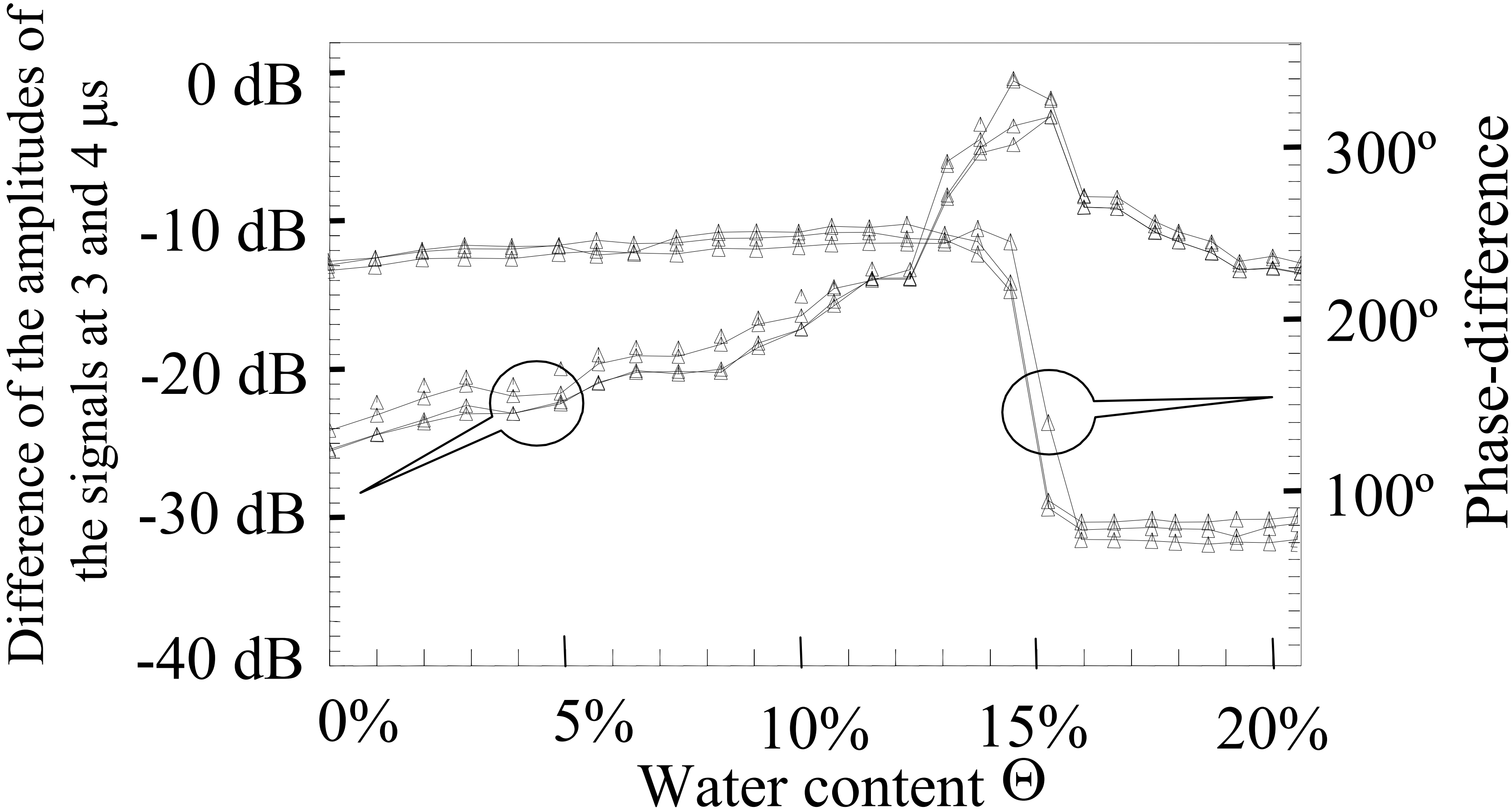
Dry Soil (7 %)



Moist Soil (21 %)



Amplitude and Phase Differences of the Echo Signals of Reflector #2 and #1



Outline

- Introduction: Classical SAW Sensors
- SAW Radio Request
- SAW Identification Tags
- SAW Radio Requestable Sensors
- Application Examples
- Conclusion

The potential of remotely read SAW sensors

Monitoring of physical and chemical quantities in inaccessible or hazardous zones (heat, cold, moving parts, high voltage, radiation, vacuum, poison, behind concrete, danger of explosion).

Examples:

- Identification marks (cars, persons, ...)
- Temperature of moving parts (drives, turbine blades, rotating anodes) or in vivo
- Torque of a rotating shaft
- Force, pressure, light, corpuscular radiation, contamination, current, voltage, humidity, …
- Burning off in high-power switches
- Chemical concentration in closed containers or in waste water
- Numbered sensors (identification function), "read-me flag", positioning sensors
- Hybrid devices comprising variable-impedance elements and SAW devices

Resolution of SAW Passive Wireless Remote Sensing

measurand	physical effect	resolution
identitification	analysis of signal	32 Bit
temperature	variation of SAW velocity	0.1 K
mechatronic measurands (pressure, torque, acceleration, tire-road friction)	variation of elastic constants	1% of full scale
impedance sensors	variation of amplitude and phase of reflected signal	5% of full scale
distance	signal delay	20cm
relative position	continuous measurement of Doppler phase	2cm
angular positioning	measurement of Doppler phase	3 degrees

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Conclusion

- The generation and the physical properties of SAWs,
- the operating of a SAW identification system,
- the design of SAW ID tags and radio sensors
- applications of SAW ID tags
- and SAW radio readable sensors

has been presented.