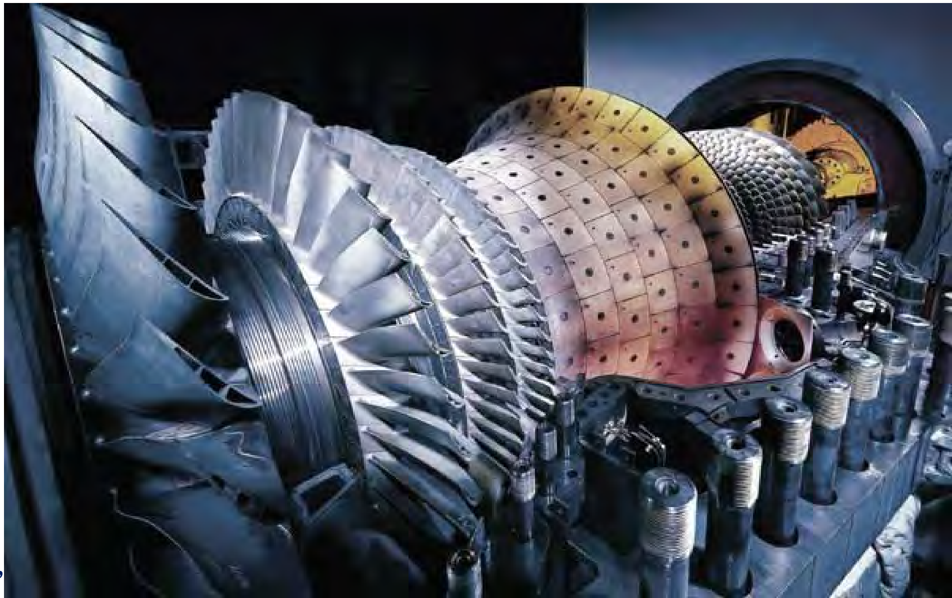
Wireless Sensor Systems for Harsh Environment

Chair for Electrical Instrumentation
Prof. Dr. Leonhard Reindl

- Wireless sensor & actuator networks using ICs
- RF chipless sensors

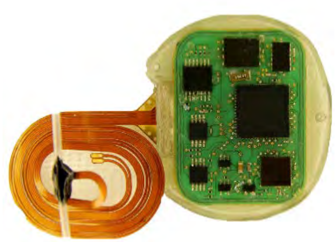
"We enable autonomous devices to perceive the environment."

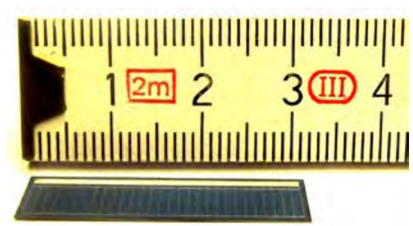


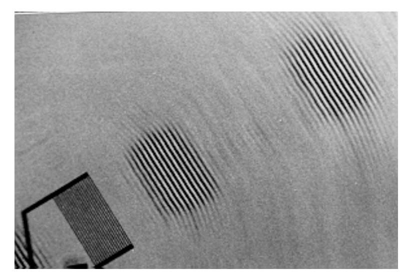
Outline

Wireless sensing

- **Wireless networking**
  - Low Power Commu-nication
  - Moni-toring
  - Locali-zation
- **Near field coupling**
  - Inductive coupled
  - RFID
- **Energy harvesting**
  - RF
  - Photo-voltaic
  - Thermo-electric
- **Chipless sensing**
  - Acoustic
  - Electro-magnetic







Motivation for Wireless

On the long run we can increase prosperity only if run all technical processes more and more efficiently at their optimum!

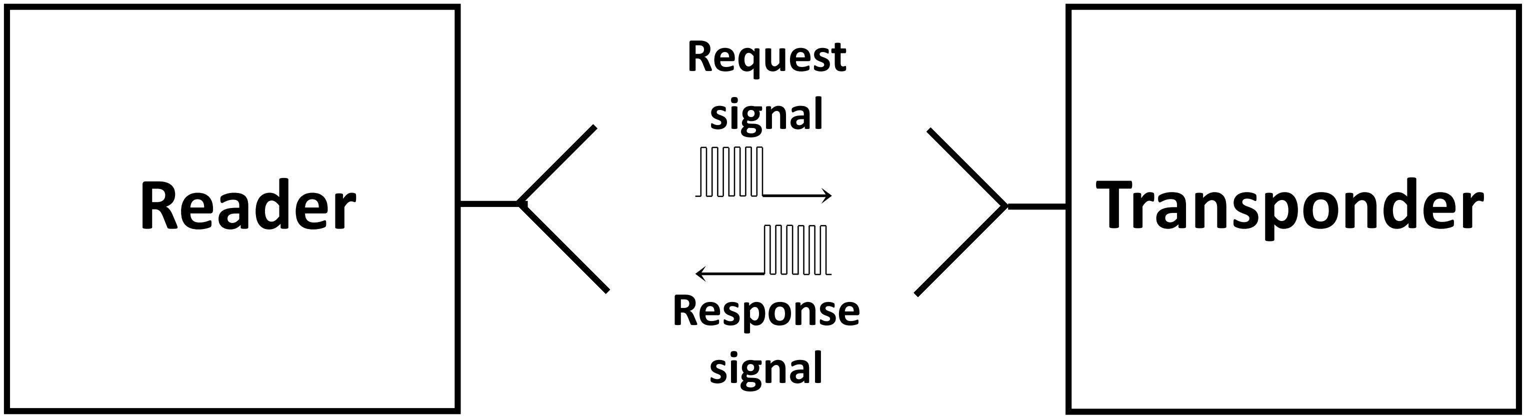
This can only be achieved by closed loop controls of the processes.

Sensors and actuators are fundamental parts in each control.

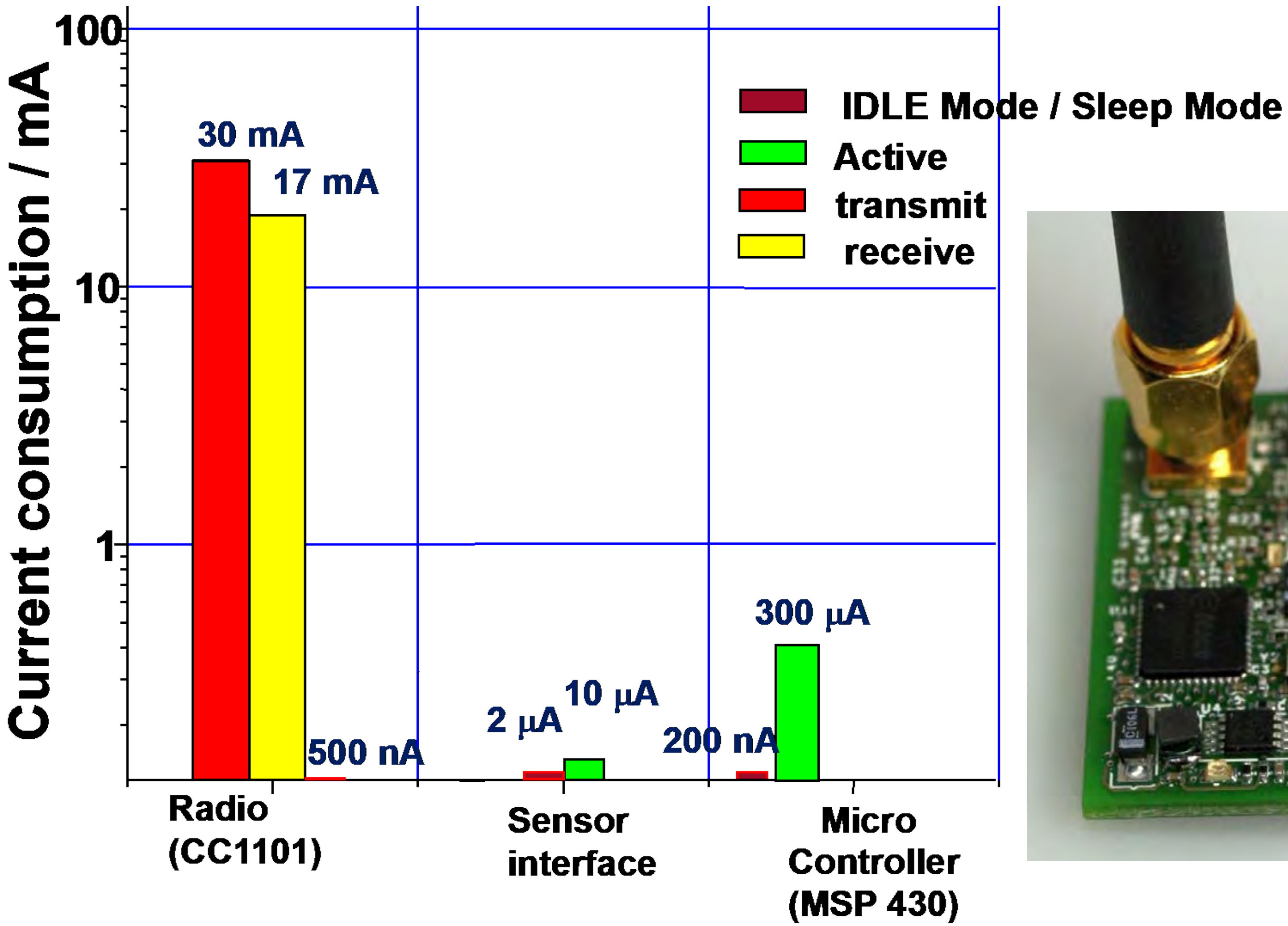
Wireless sensors are used

- on rotating or movable parts,
- on animals or human beings,
- or when a wireless connection saves installation costs.

Operating Principle of a Wireless Sensor Systems

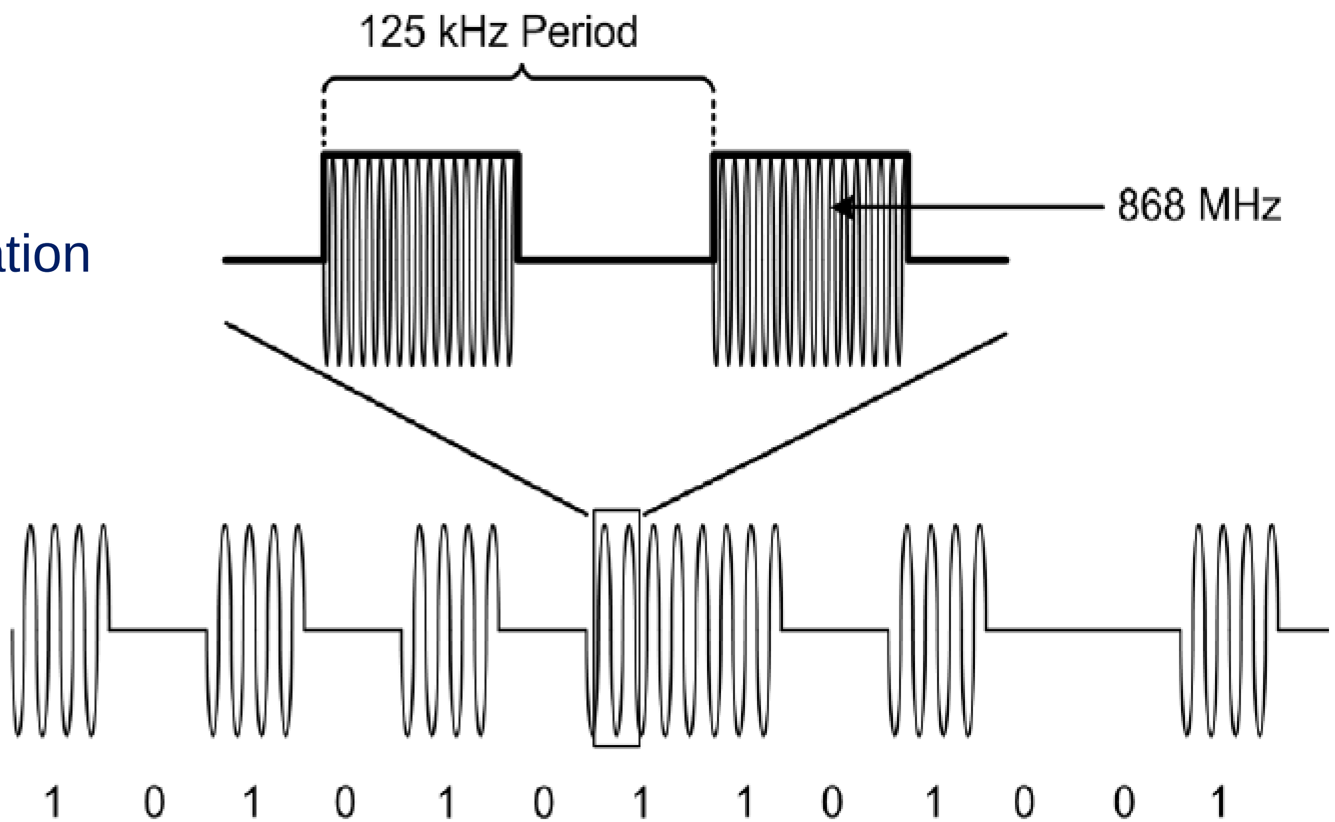


Energy consumption of an active sensor node

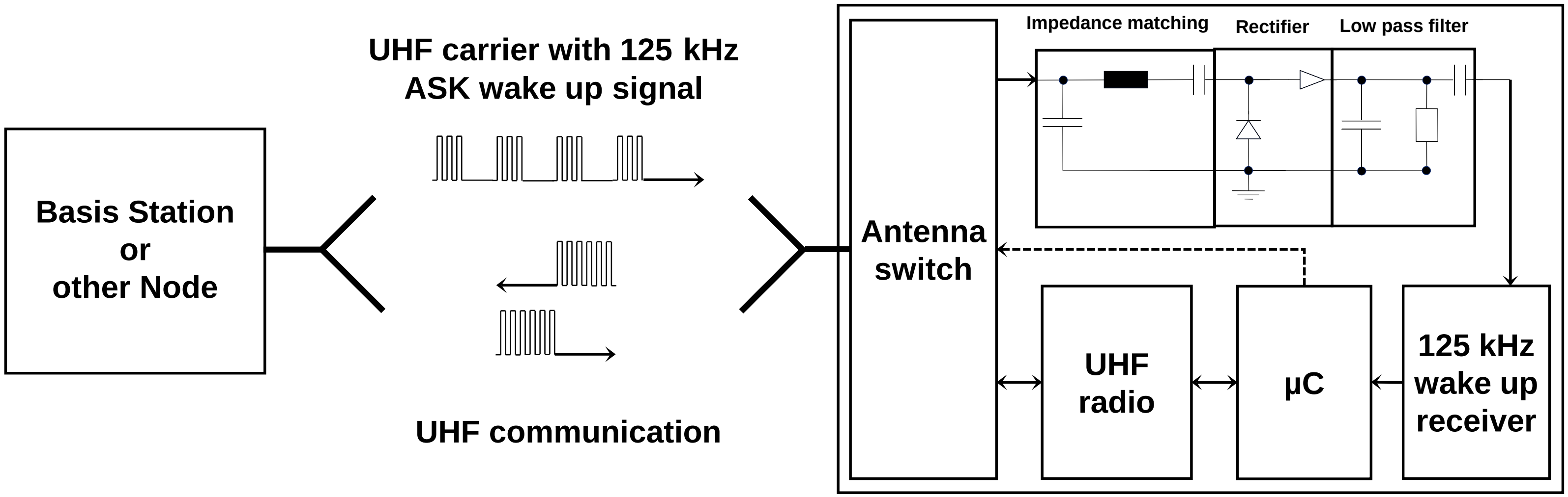


Wake Up Signals

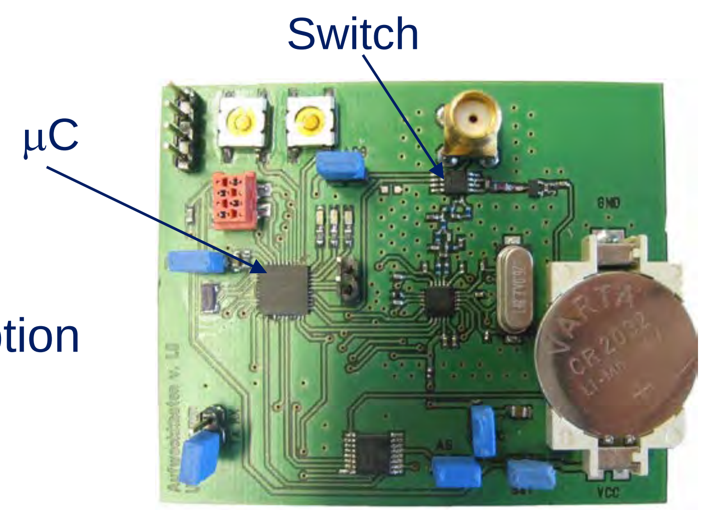
- Carrier modulation
- Address modulation



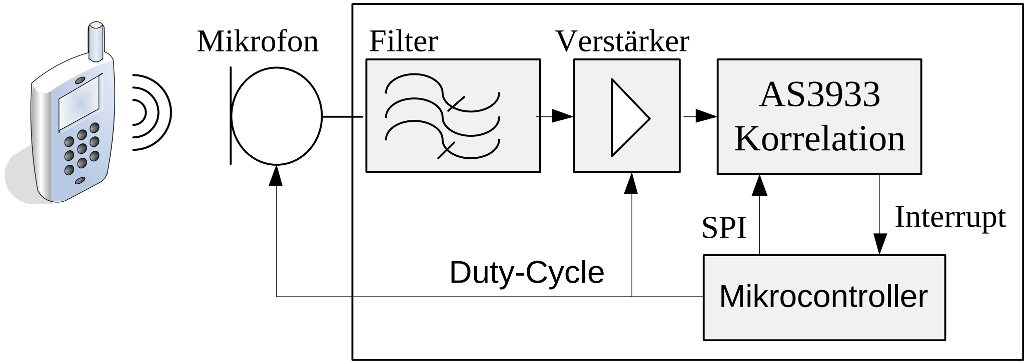
Wake up receiver



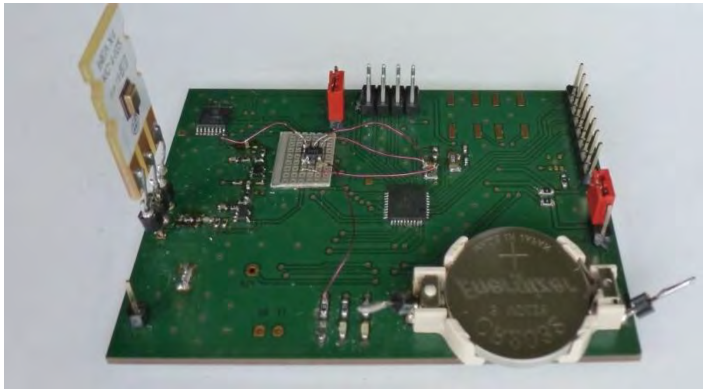
- 868 MHz or 2.4 GHz standard bands
- Addressable wake-up with 125 kHz
- Wake up distance 50 … 100 m
- Real-time wake-up @ 10 µW power consumption
- Network protocols for wake-up and multi-hop networks



Ultrasonic Wake Up Receiver



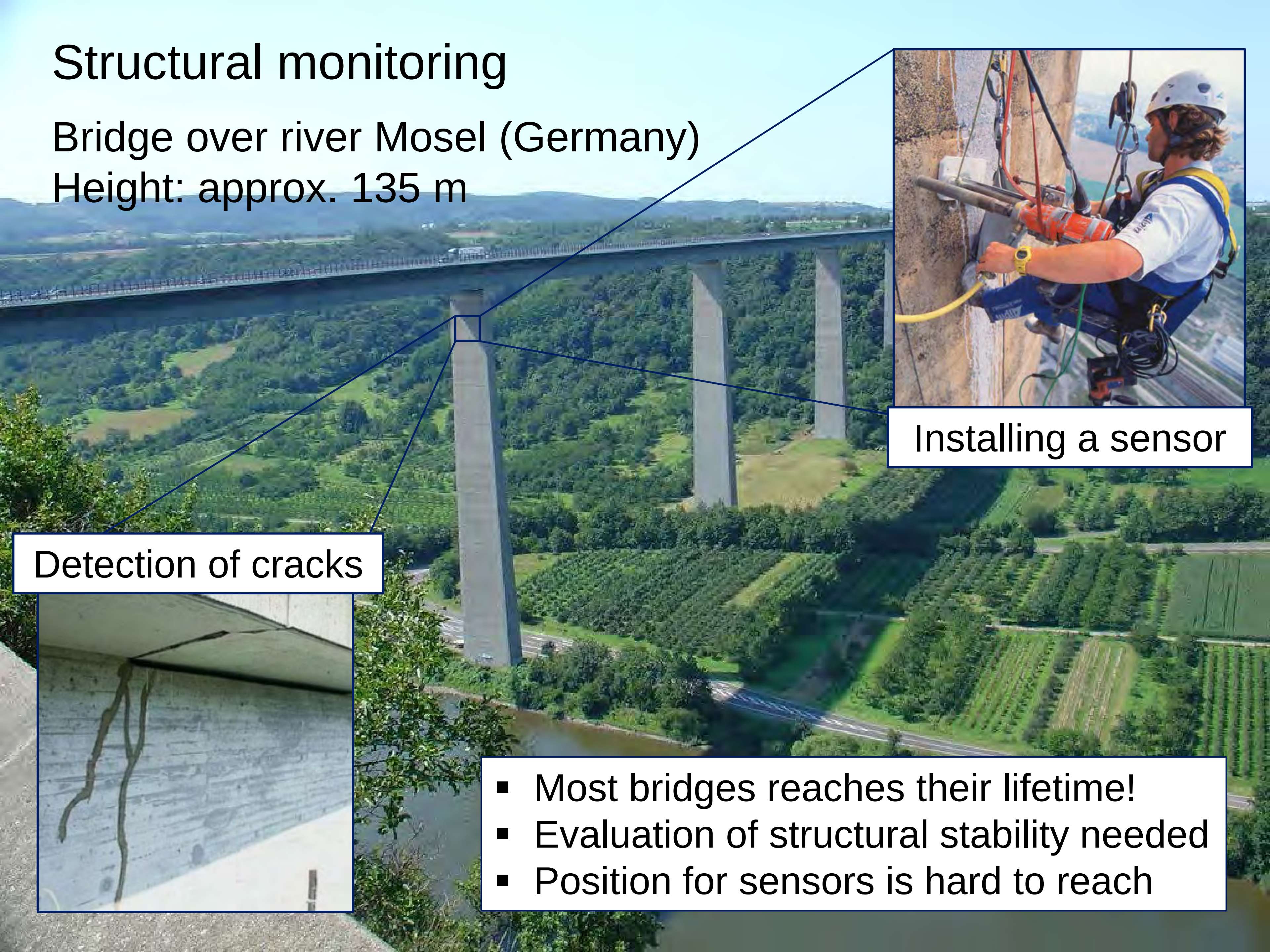
16 bit address



- 45 µW in sleep mode
- Frequency >20 kHz
- Wake up distance using Smartphone Samsung S4 Mini ≈ 25 m

Structural monitoring

Bridge over river Mosel (Germany)
Height: approx. 135 m

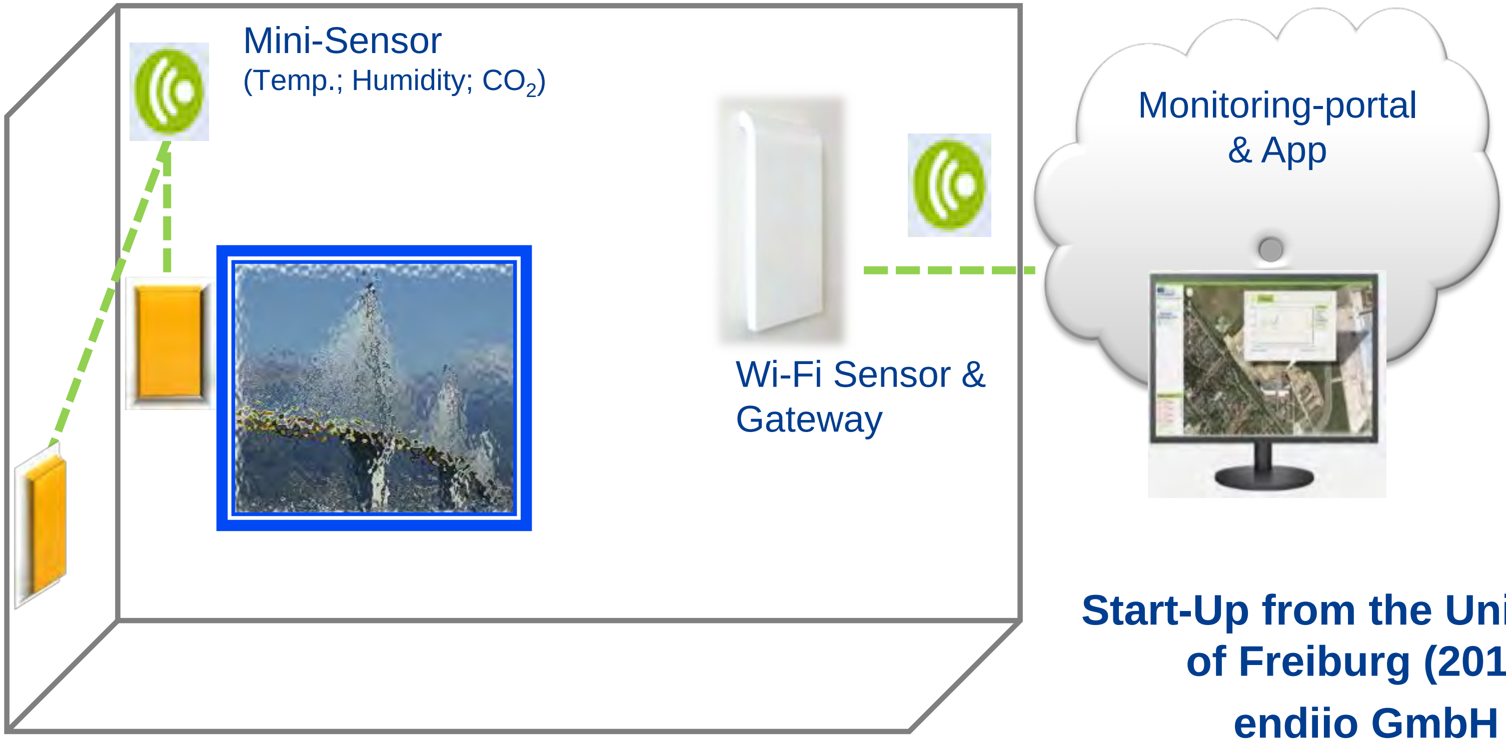


Installing a sensor

Detection of cracks

- Most bridges reaches their lifetime!
- Evaluation of structural stability needed
- Position for sensors is hard to reach

Smart Home System



Start-Up from the University of Freiburg (2013)

endiio GmbH

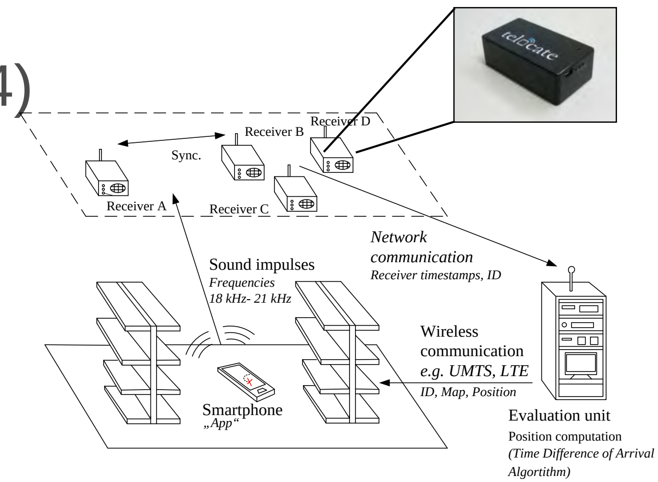
https://www.endiio.com/

- Self powered Gateway (Wi-Fi and GSM)
- Self powered and real-time Mini-Sensor mesh-network
- Molt and Oxygen monitoring and warning system

- 10 -

- Start-Up for Localisation
  from the University of Freiburg (2014)
  - Using frequency < 21 kHz
  - Team of 12 people
  - Precise Indoor-localization (< 30 cm)

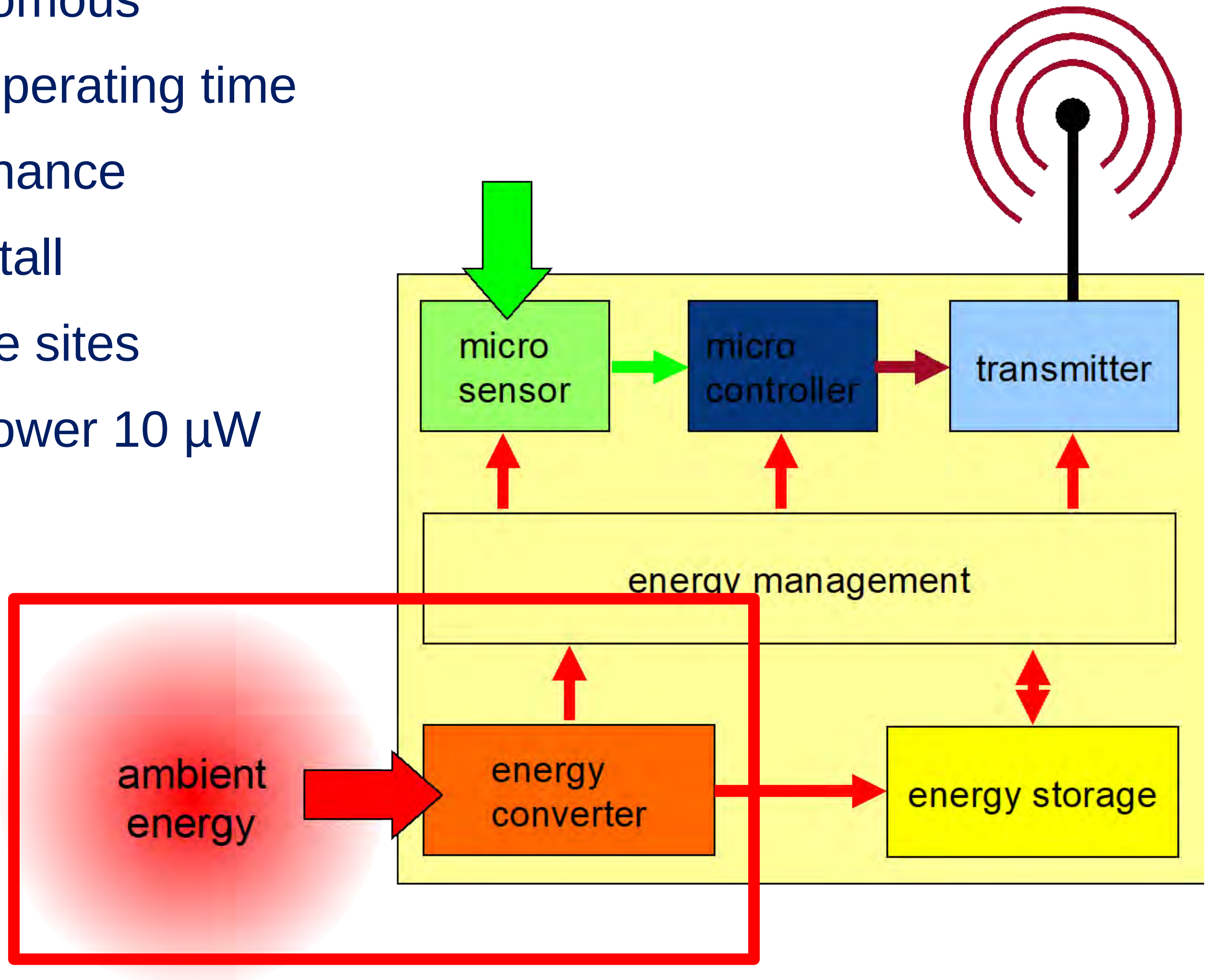
  Telocate GmbH
  https://de.telocate.de/



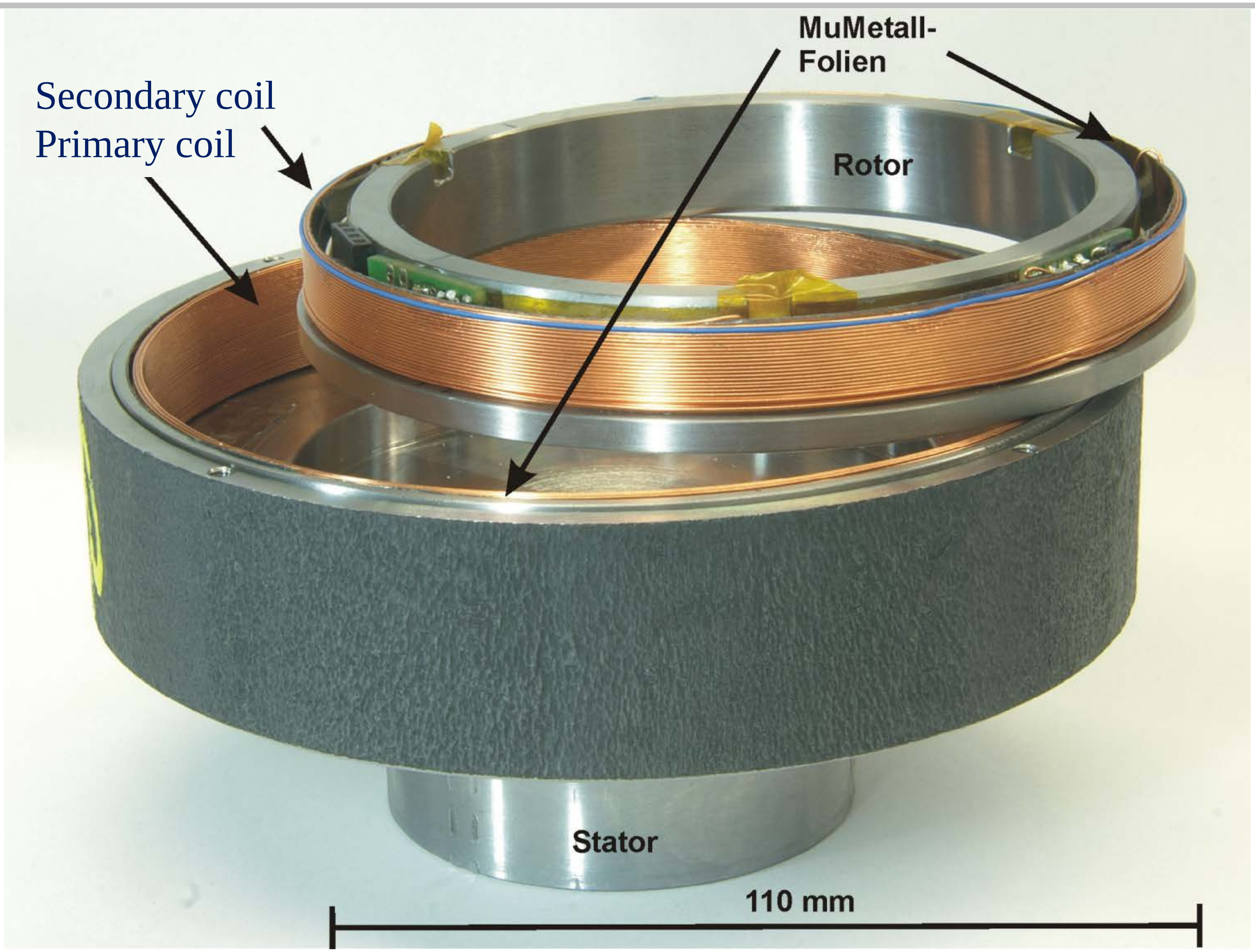
- Find things and places interactively with your **smartphone**
  - Places in a shopping mall, public building (e.g. hospital), booth at an exhibition, etc.

Wireless Sensors using Energy Harvesting

- fully autonomous
- unlimited operating time
- No maintenance
- easy to install
- …at remote sites
- Average power 10 µW



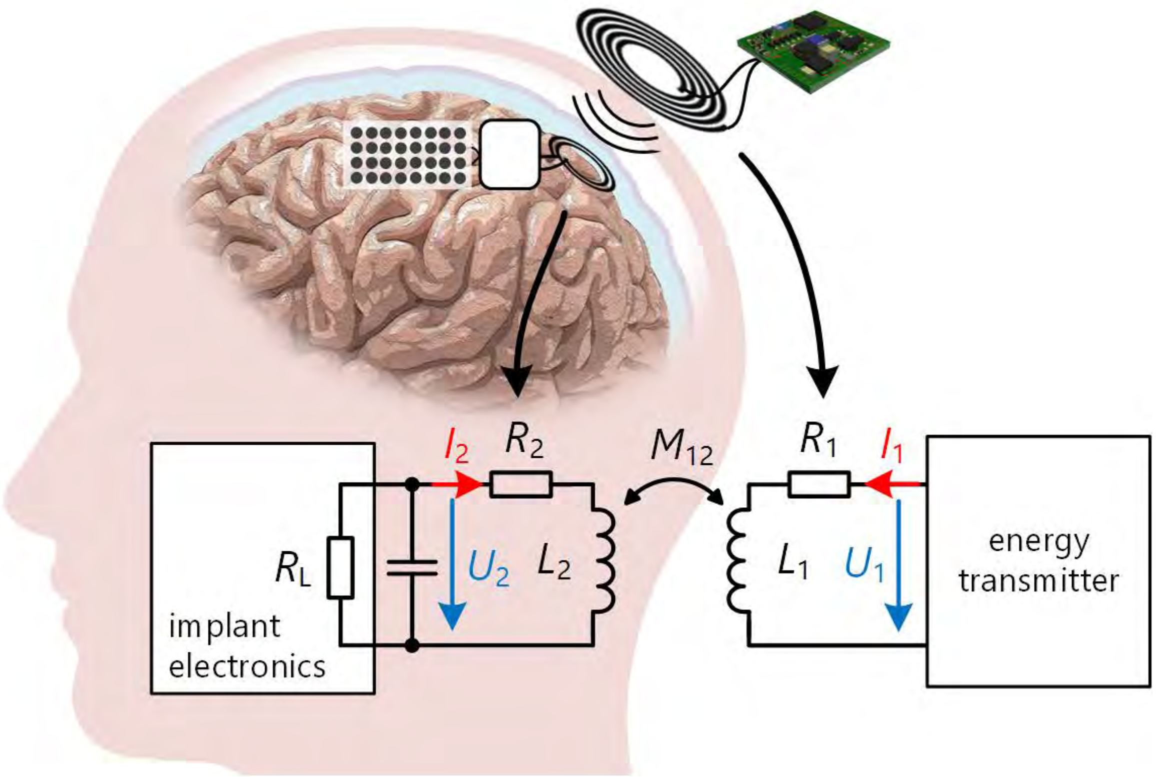
Inductive Coupled Sensor Systems



To the rotor of a high speed drill or a rotary cuter

For Biomedical Implants

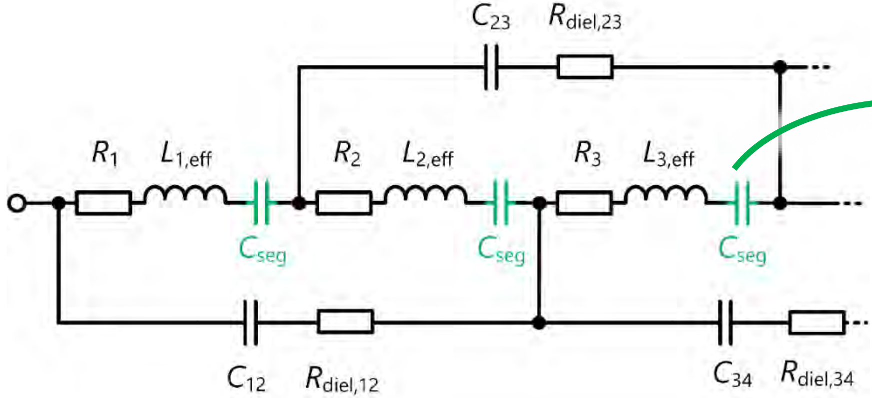
- Neural read-out for Epilepsy treatment and brain-computer-interfaces
  - small size
  - high efficiency
  - low tissue heating
  - variable operational conditions
  - large data streams

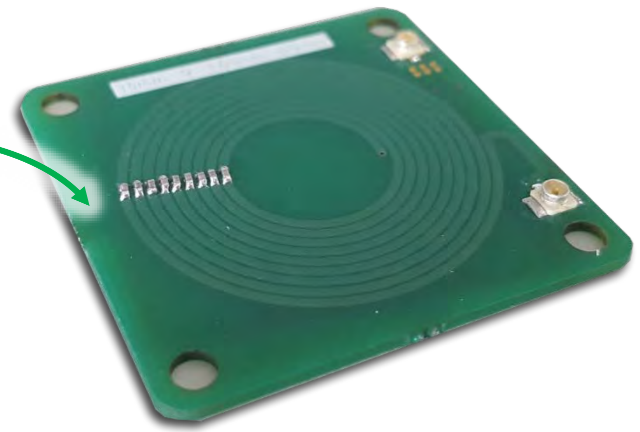


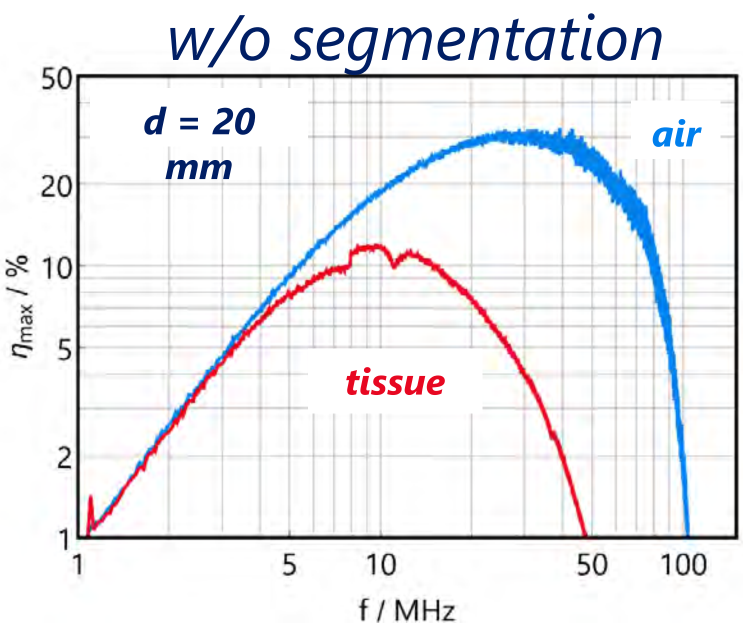
BrainLinks BrainTools

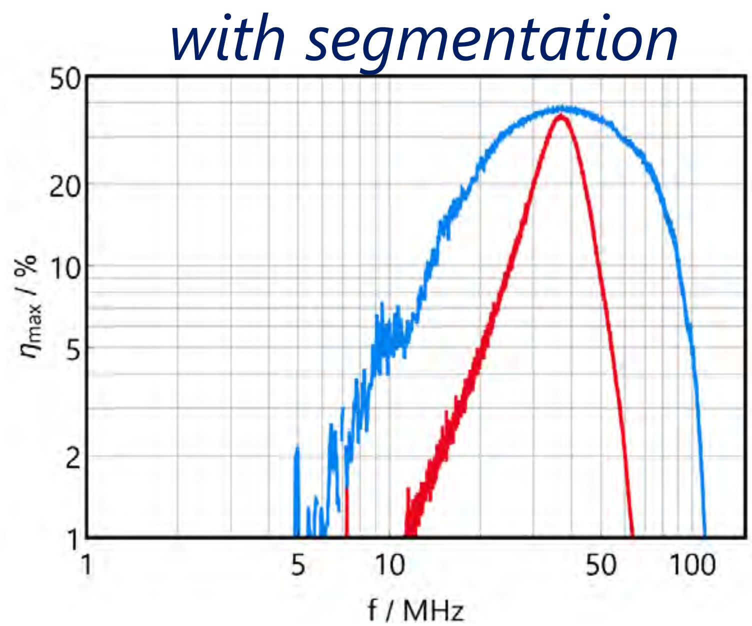
Segmented Coils

Concept: Cancelling $L_{i,eff}$ by C_{seg}

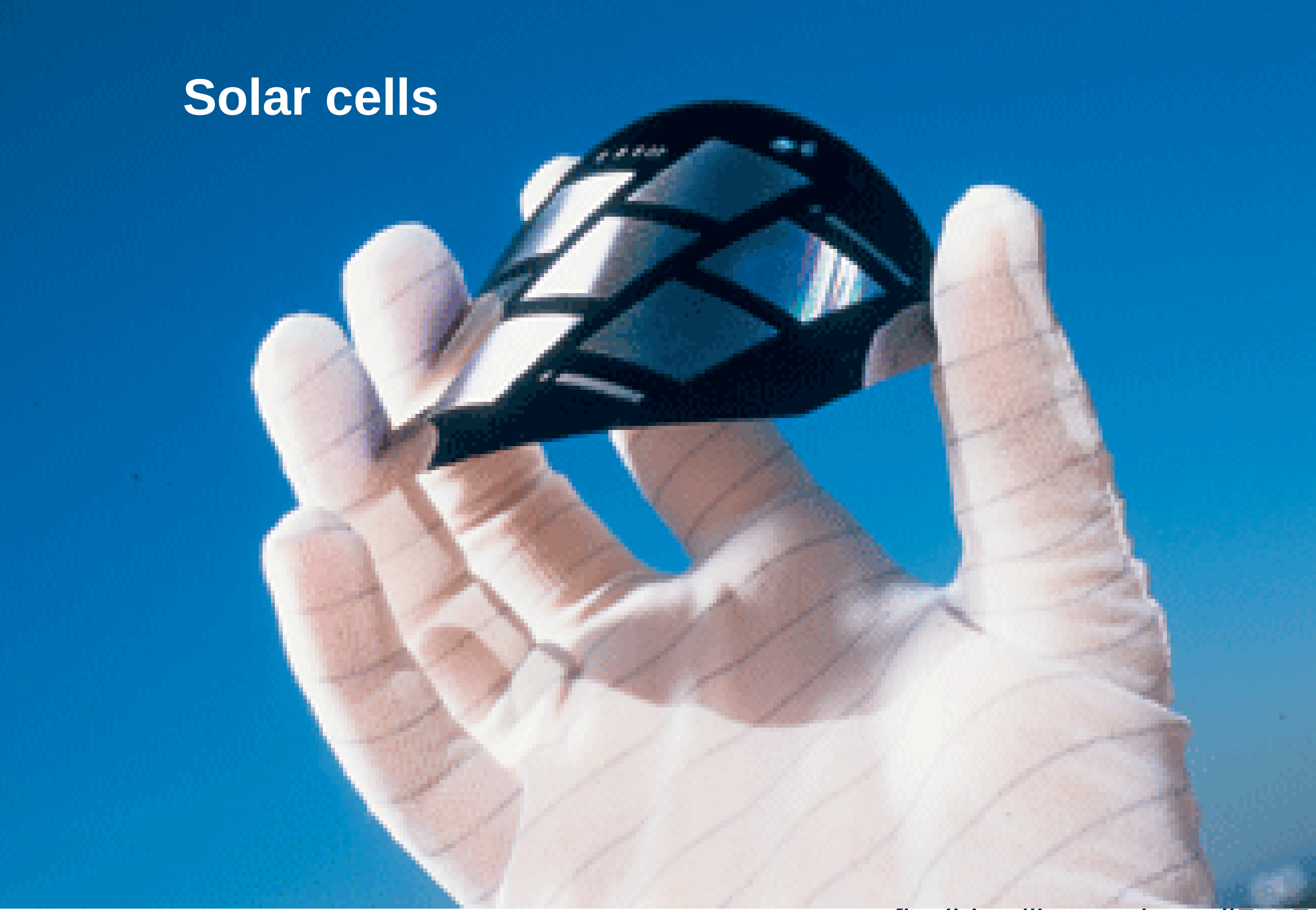








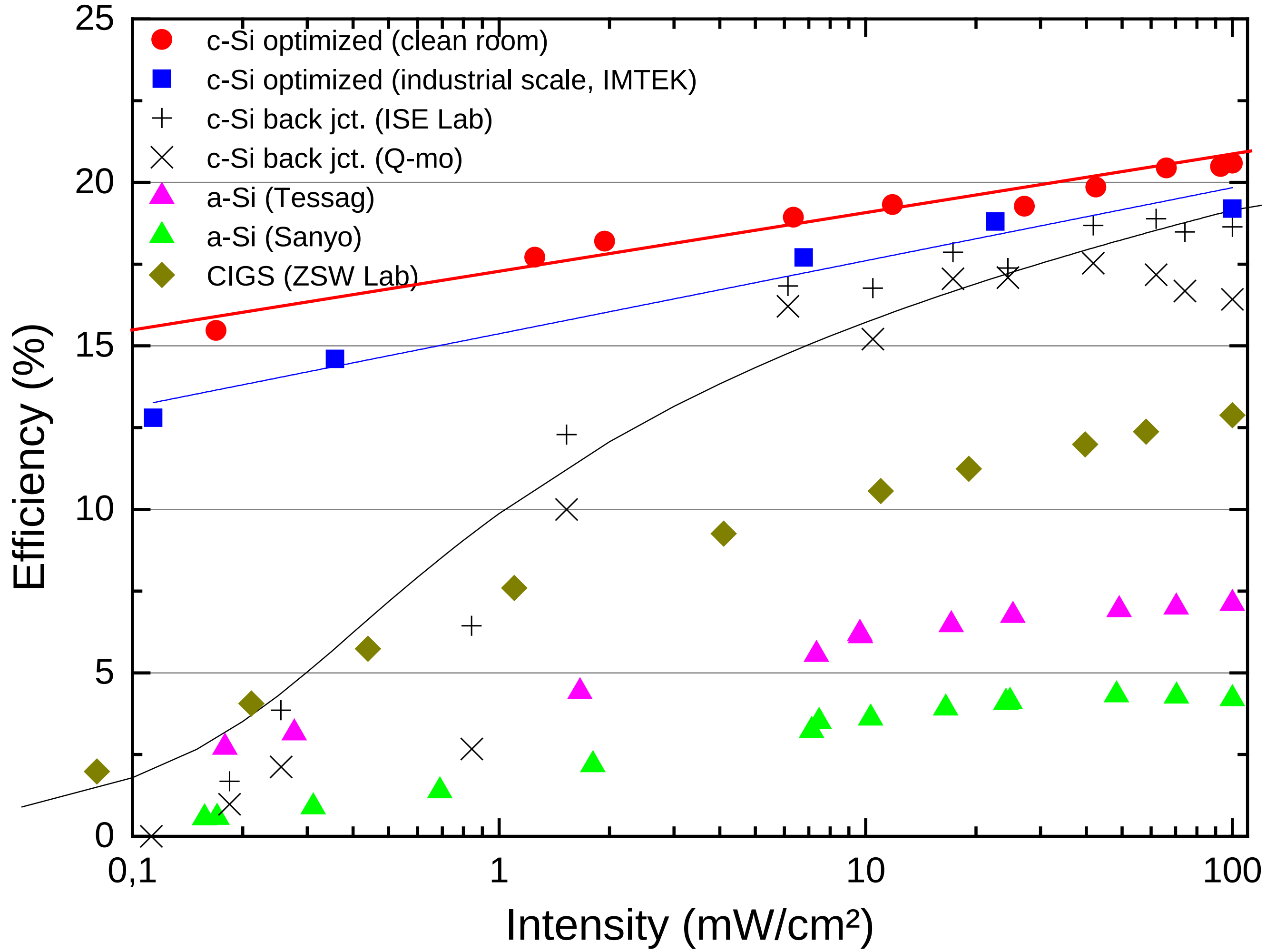
Solar cells



flexible silicon solar cell

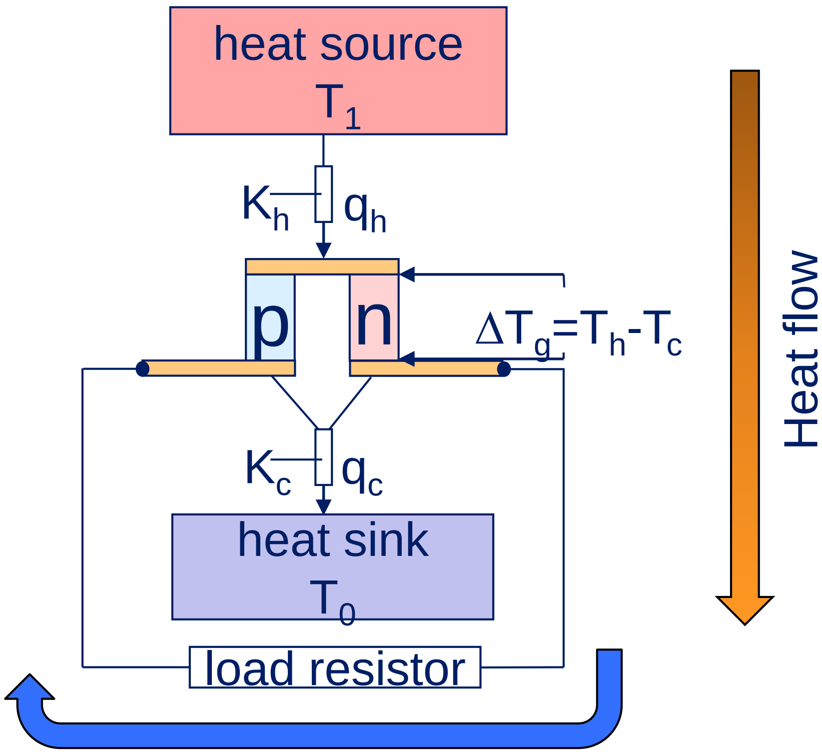
© FhG-ISE, Freiburg

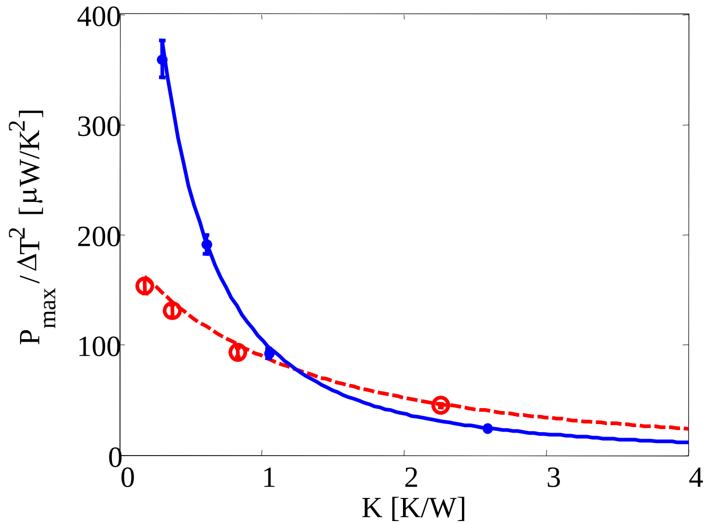
Energy Harvesting: Optimized Si Indoor Solar Cell



* Part of data taken from Randall and Jacot, Renewable Energy, 28, 2003, pp. 1851-1864

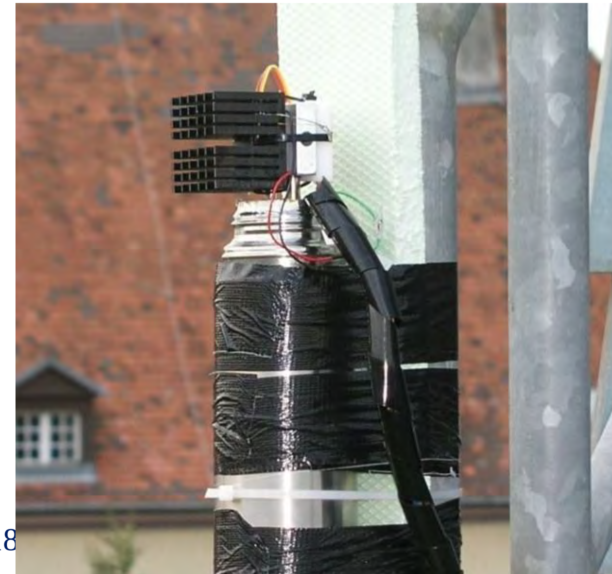
Thermoelectric Harvesting





Electrical Circuit

$$P_{opt} = 0.15\,\frac{\Delta T^2}{4T_0 K}$$



Thermo-electric harvesting of day – night cycle using a thermos flask

Piezoelectric transmitter module by EnOcean (PTM 100)

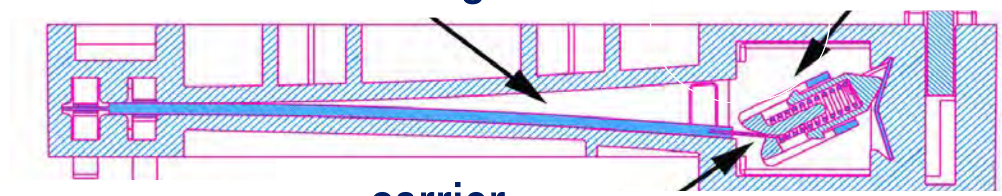
1st generation

A pre-stressed biomorph Piezo cantilever bends over two circular surface from one opposite to the other .

C = 60 nF
E = 80 µWs

Operating range:

- 300m in free space
- up to 30m inside buildings

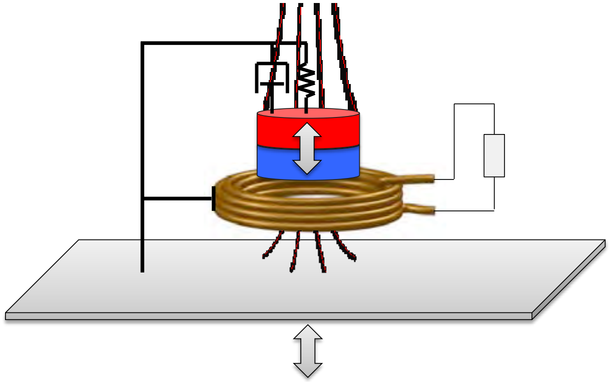


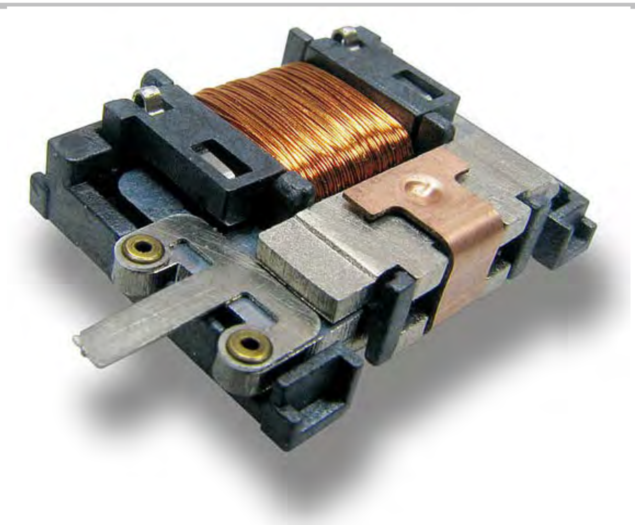
- Transmitter module
- Piezoelectric harvester
- Energy conversion mechanism

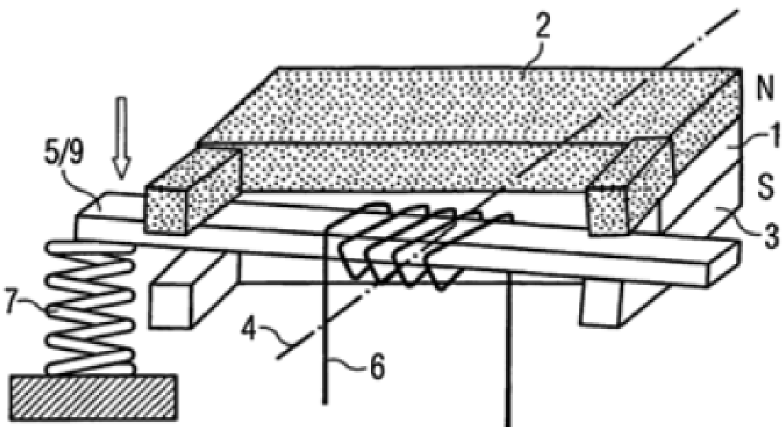
The Goal:

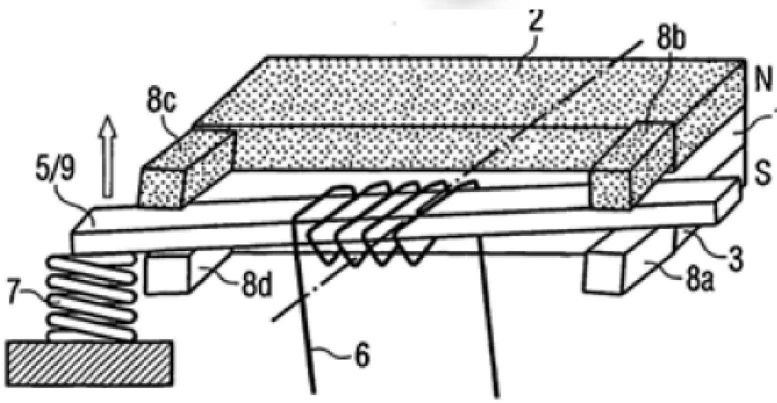
- ➢ Increase Life time
- ➢ Increase the efficiency
- ➢ Reduce the cost of the harvester

Electromagnetic Generators





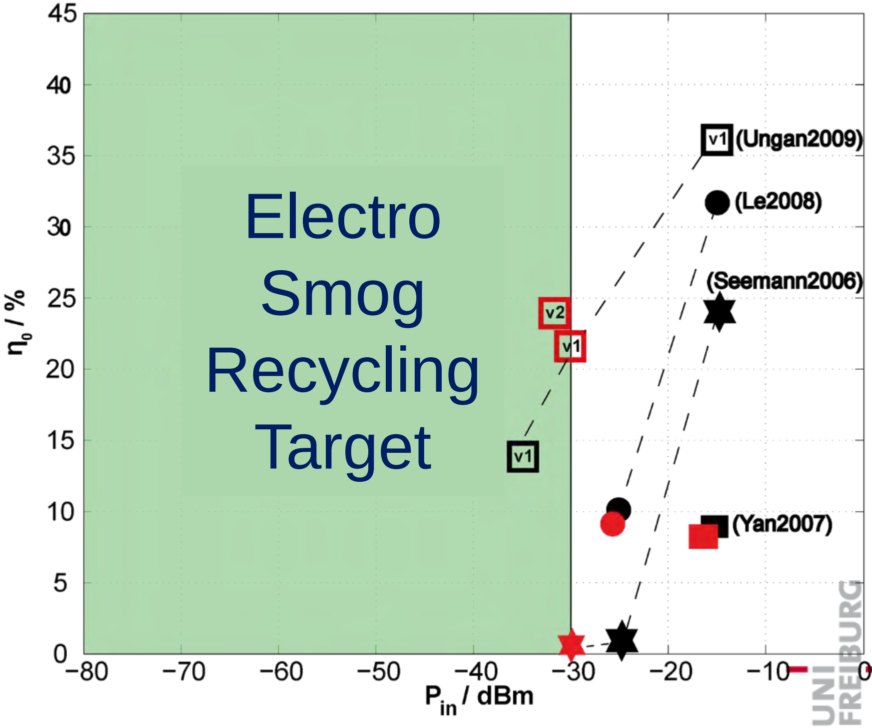




EnOcean, 2nd generation, Munich, 2006

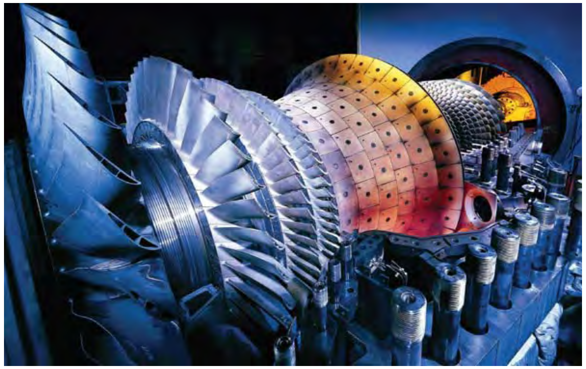
Is even Electro Smog Recycling possible?

- Ambient UHF energies in urban areas:
  - Radio and TV transmitter
  - base stations
  - cell phones
  - various radio services
- Maximum power density in urban areas: 0,3 - 1 µW/cm²
- Electro smog harvesting is not yet possible!
- But, we still work on it…



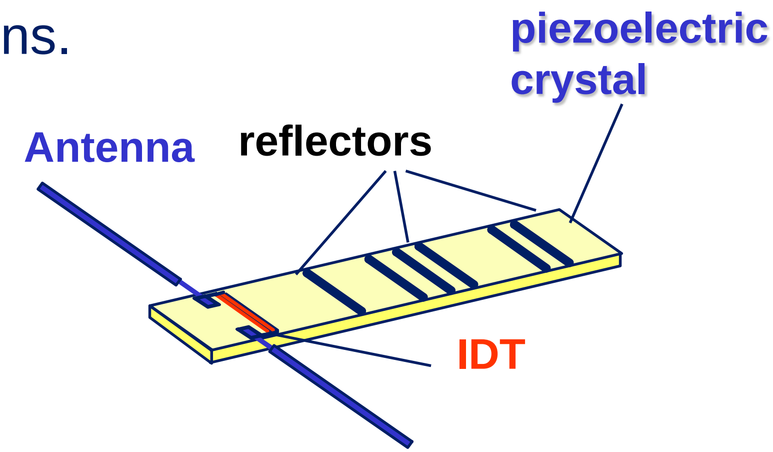
Why chipless sensing

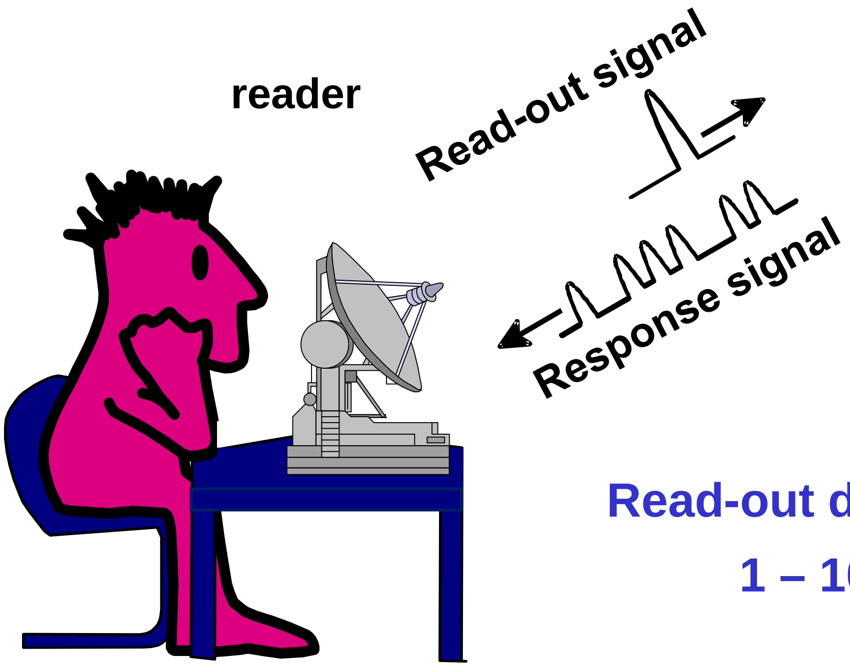
- Sensing in harsh environments.
  - Moving parts
  - High humidity
  - High temperature
- Condition based monitoring
  - Safety
  - Reliability.
- Reduced overall system cost.
- No batteries – low environmental impact.
- Large scale manufacturability.
- **Pervasive sensing!**



Wireless SAW Sensors

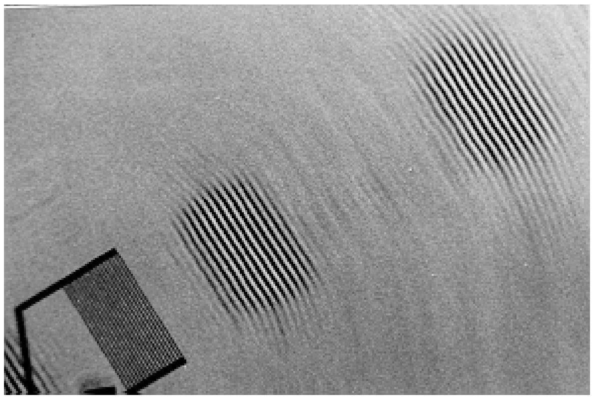
- Discovered in mid 1990's at Siemens.
- Surface acoustic delay lines
- Core team still active in WPS



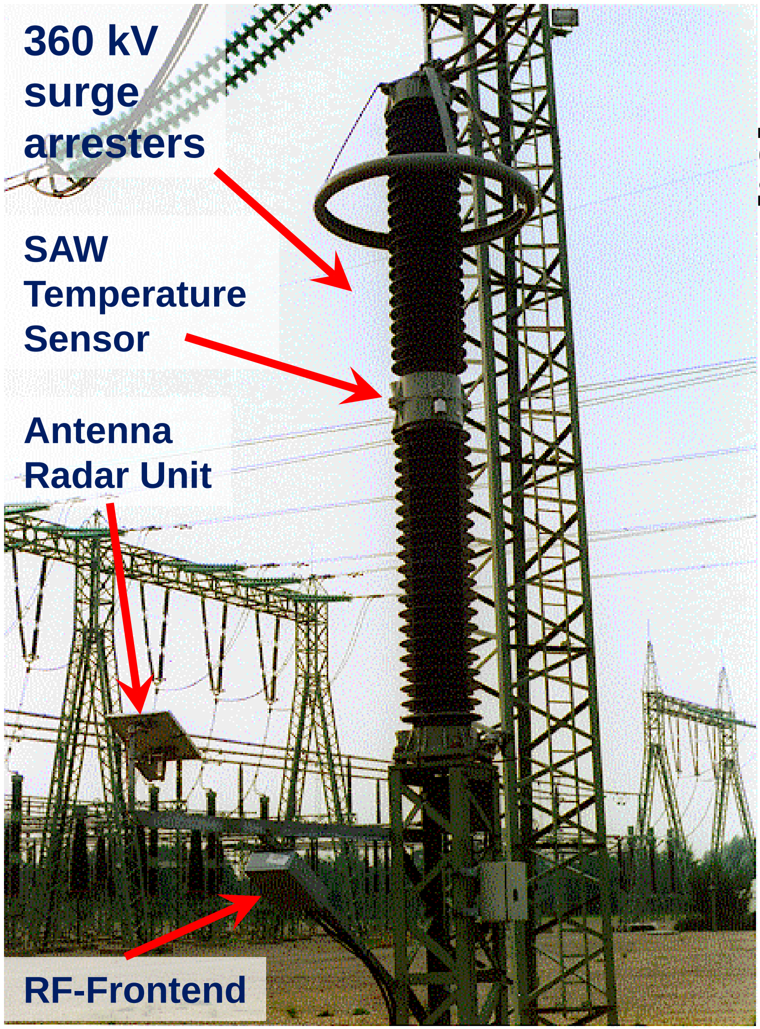


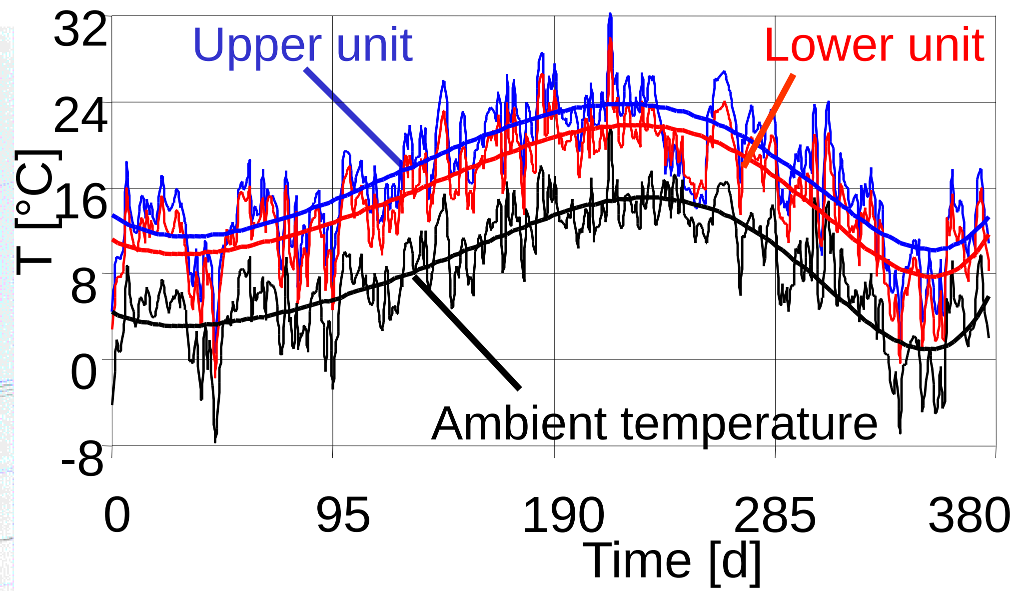
Read-out distance:

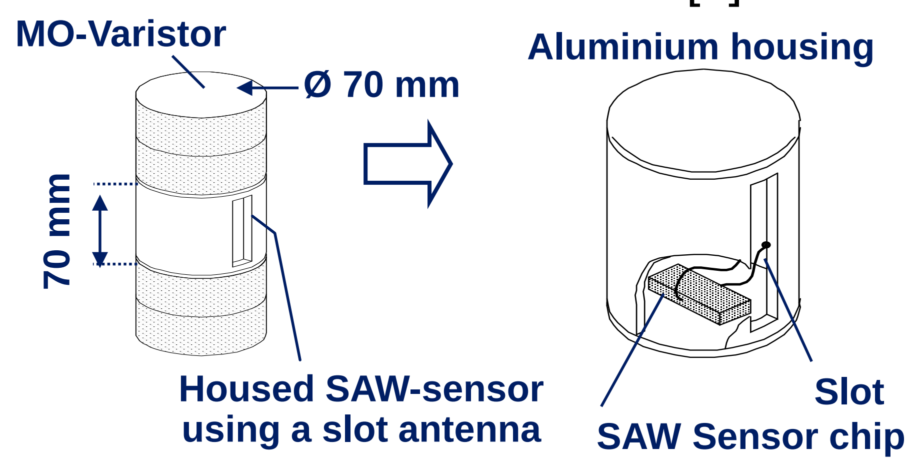
1 – 10 m



Temperature sensors: Online Monitoring for High-Voltage Surge Arresters



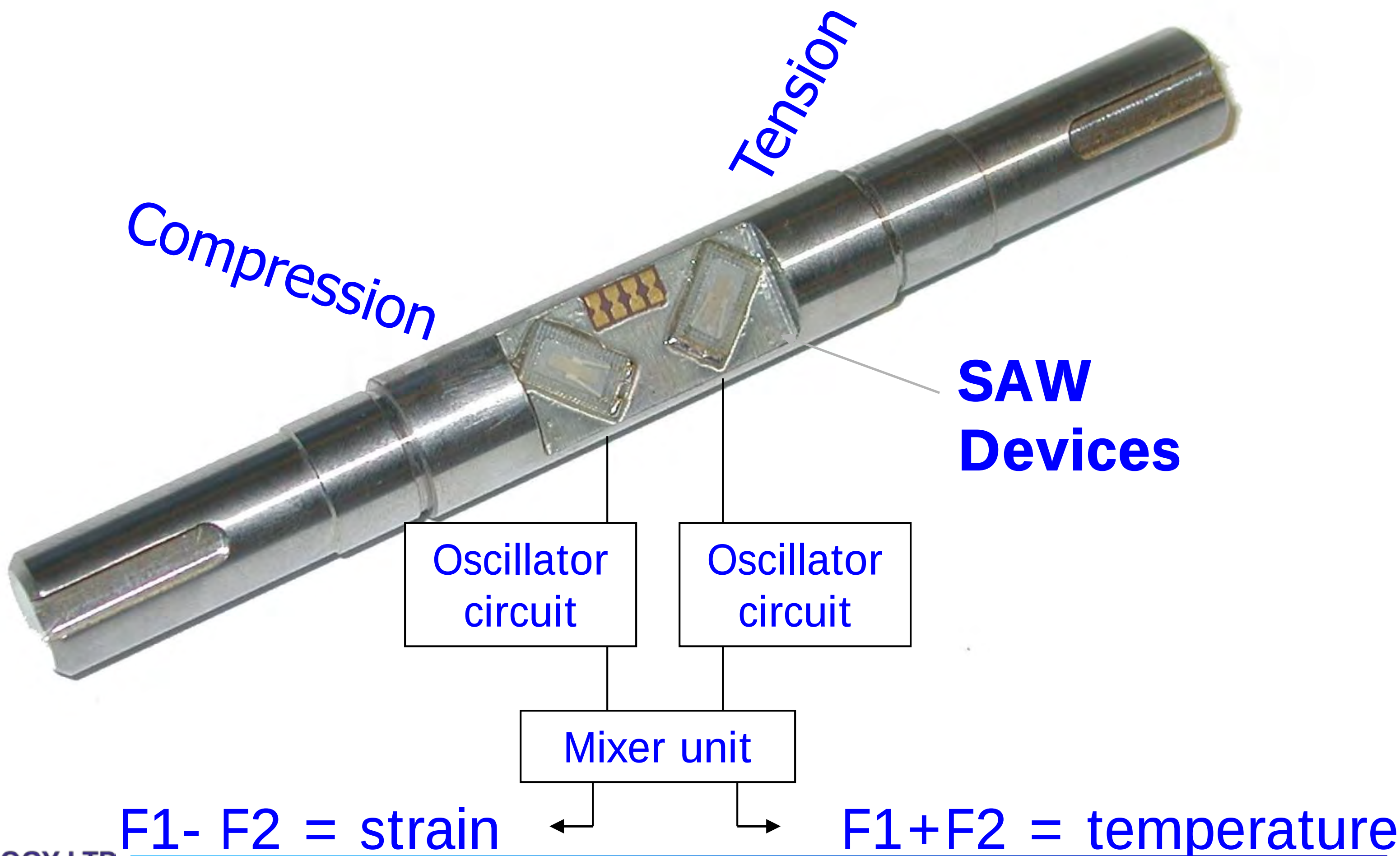




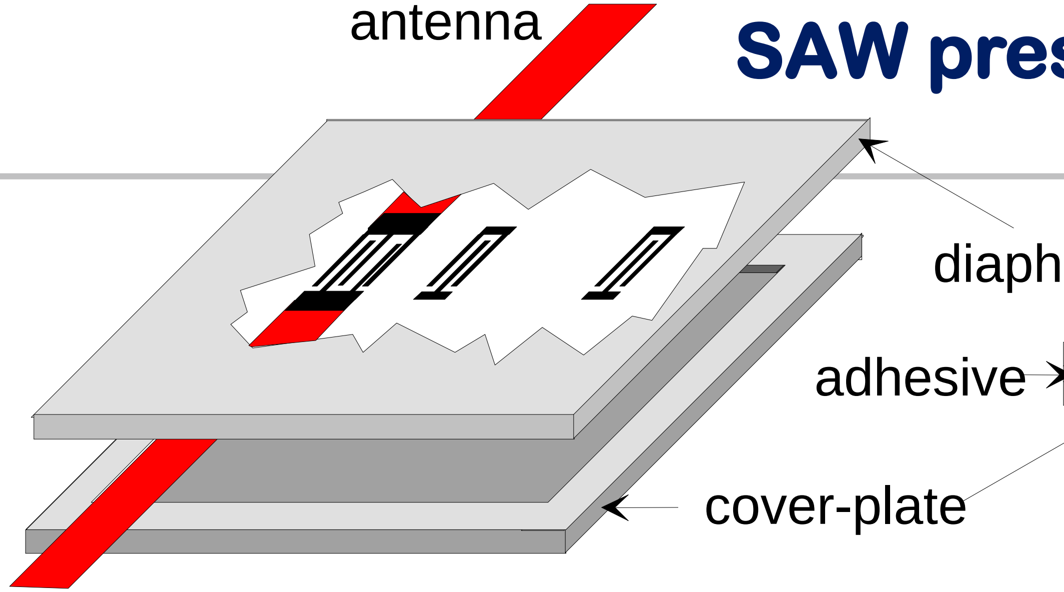
G. Scholl, C. Korden, E. Riha, C.C.W. Ruppel, U. Wolff, G. Riha, L. Reindl, R. Weigel, „SAW-Based Radio Sensor Systems for Short-Range Applications", *IEEE microwave magazine*, pp. 68-76 , December 2003

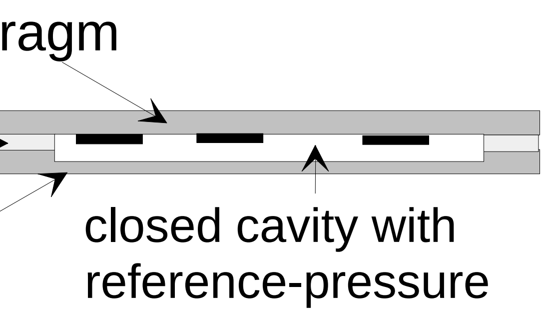
torque sensors: Sensor Technology

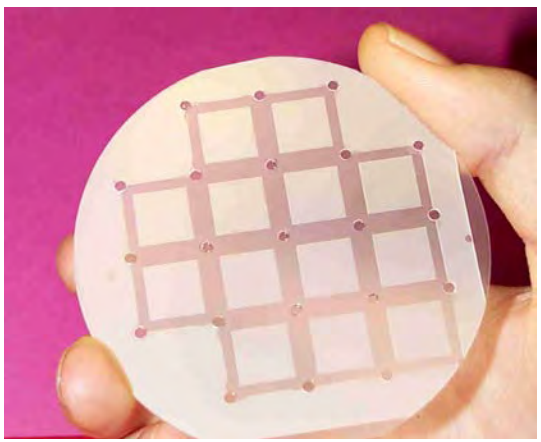
TORQSENSE™ E300 RWT 1 System



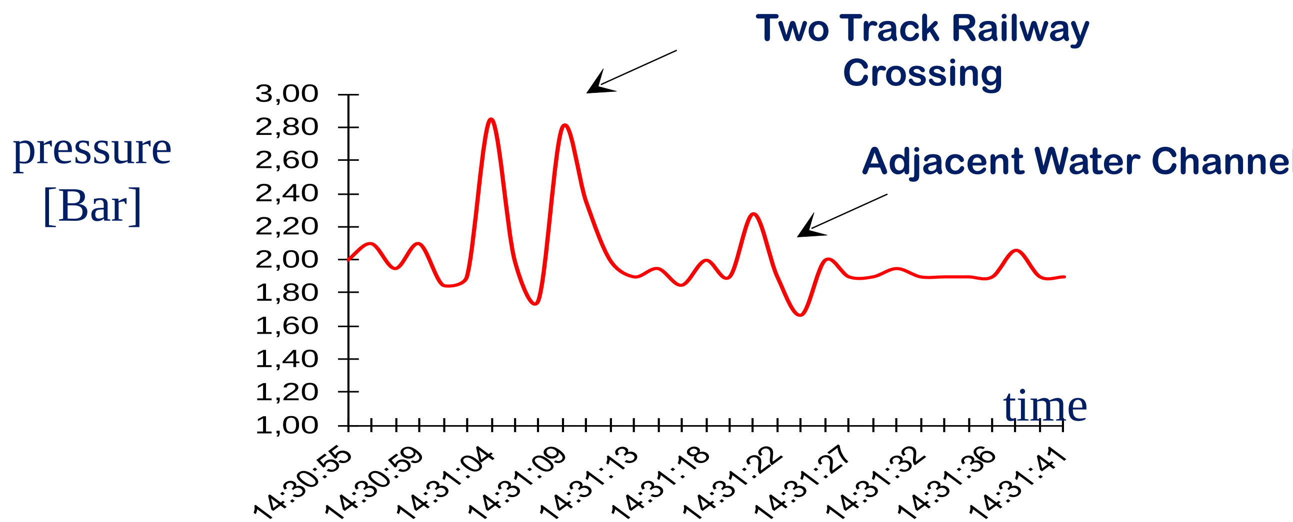
SAW pressure sensor







Wafer processing of SAW pressure sensors

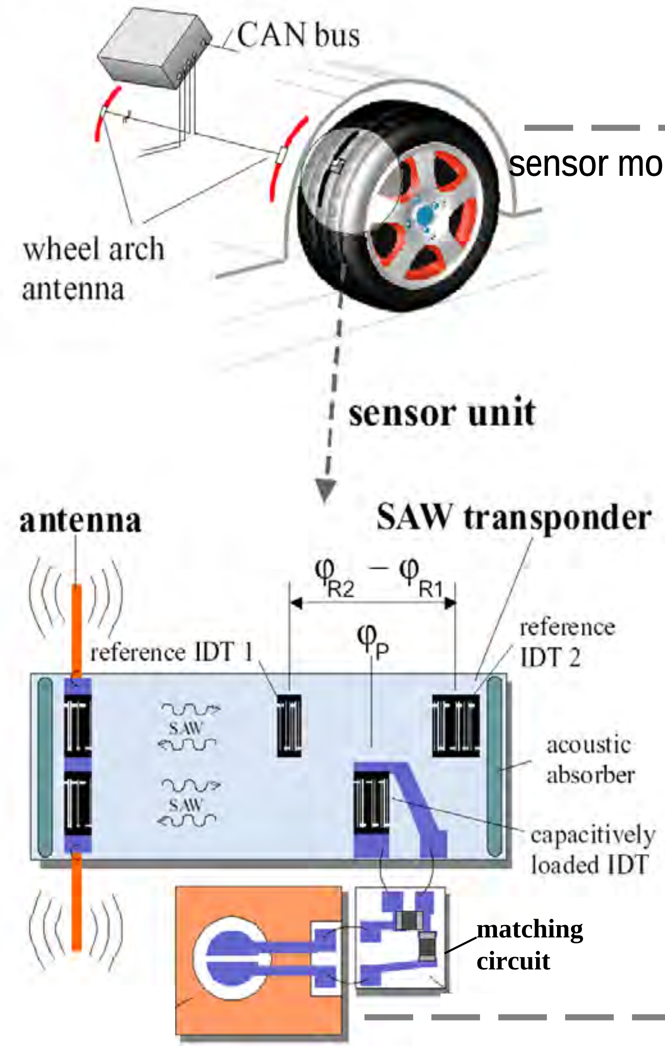


A SAW pressure sensor type, which uses a direct bending of the SAW chip, results in a resolution of about 1% of full range.

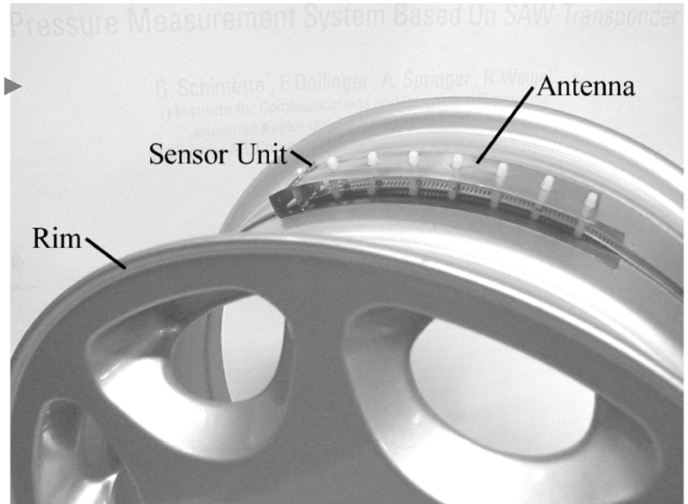
tire pressure sensor, 2nd Generation

SIEMENS

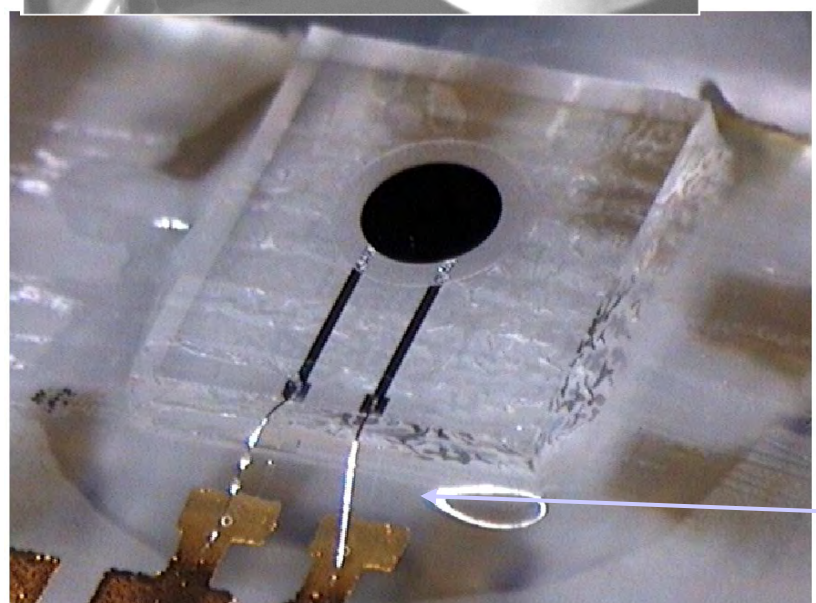
transceiver unit



sensor mounting



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



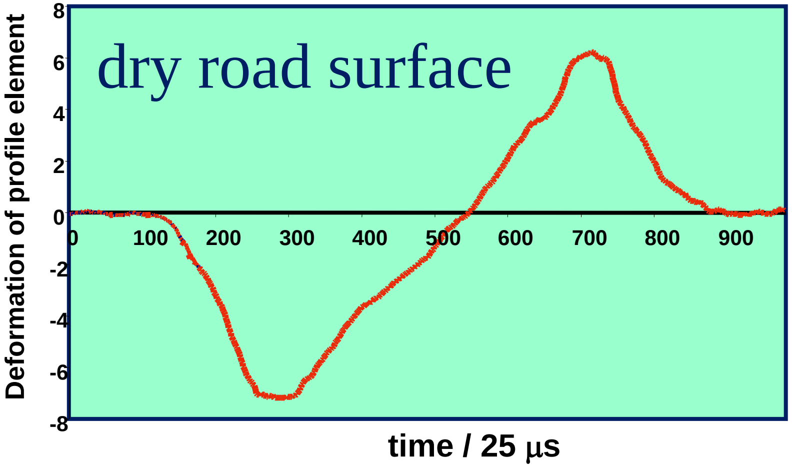
bond wires

capacitive micro-machined pressure sensor

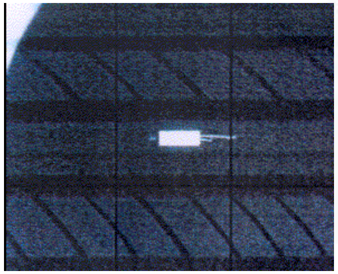
SAW Sensor for Tire Friction Control

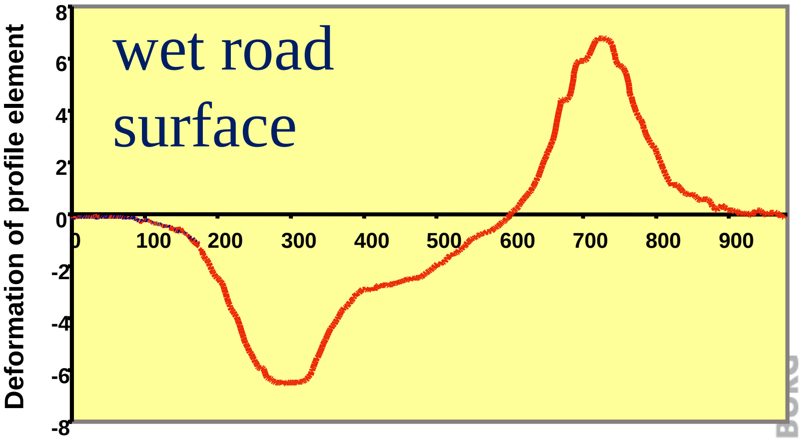
The deformation of a profile element gives information of the friction coefficient between tire and road

SAW sensor integrated into a standard tire



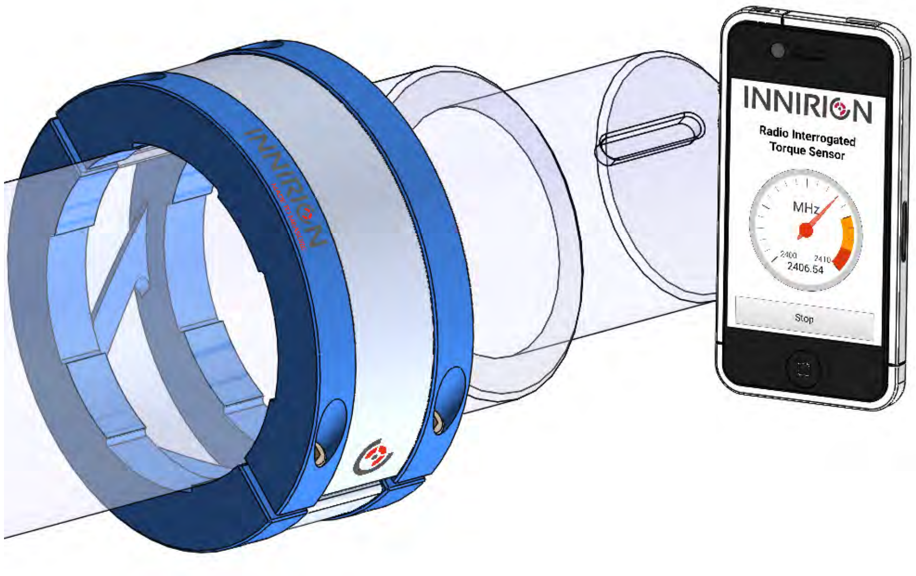
Radiography of a tire with integrated SAW sensor





A. Pohl, R. Steindl, L. Reindl, „The 'intelligent tire' utilizing passive SAW sensors - measurement of tire friction“, *IEEE Trans.Instrumentation and Measurement*, 48 (6), pp. 1041-1046, 1999

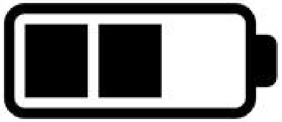
Torque Clamp



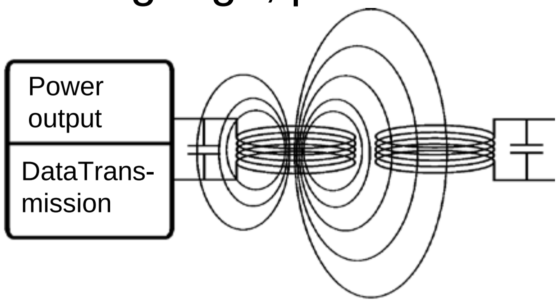
- Innovative clamp-on design

INNIRION GmbH
Dr. Thomas Jäger
Phone: +49 761 1542 6611
jaeger@innirion.com

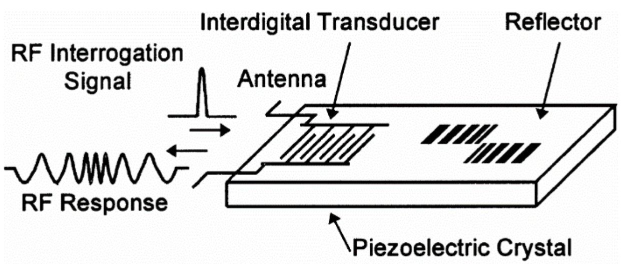
Strain gauge, µC / RF



Strain gauge, µC / RF

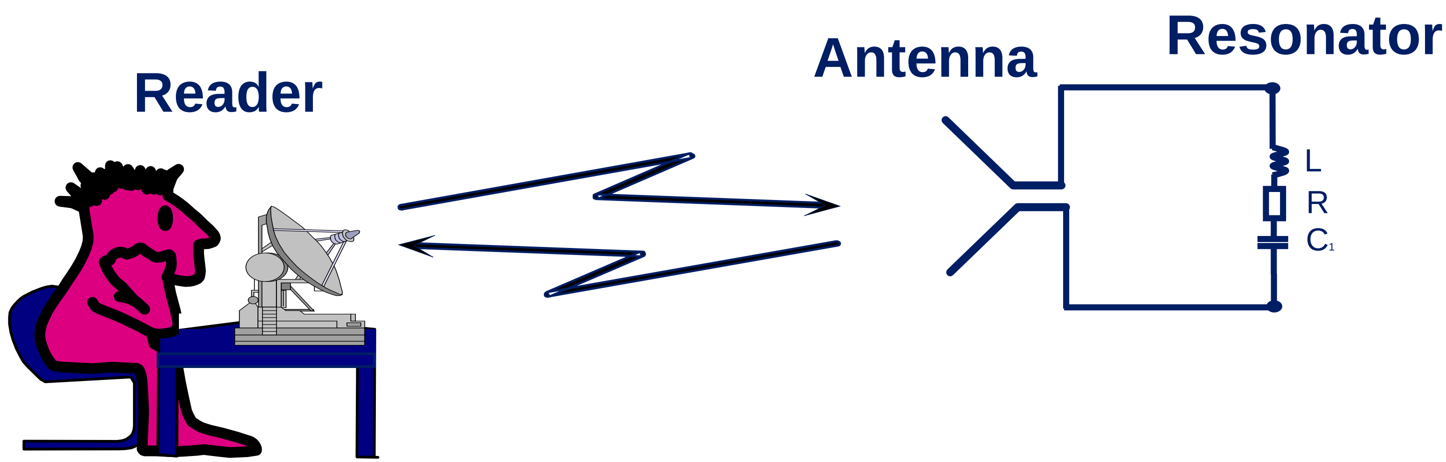


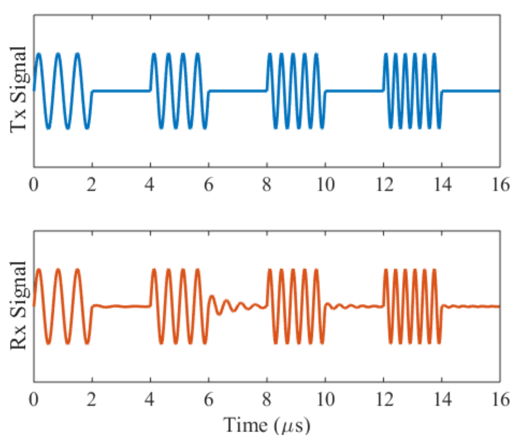
SAW / DRO, passiv

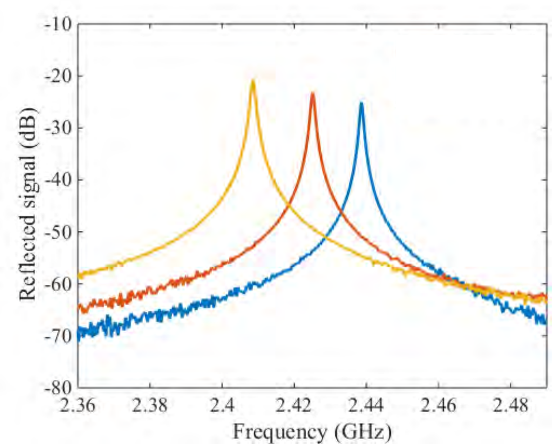


Wireless sensing using electromagnetic resonators

- Interrogation of high-Q resonators.



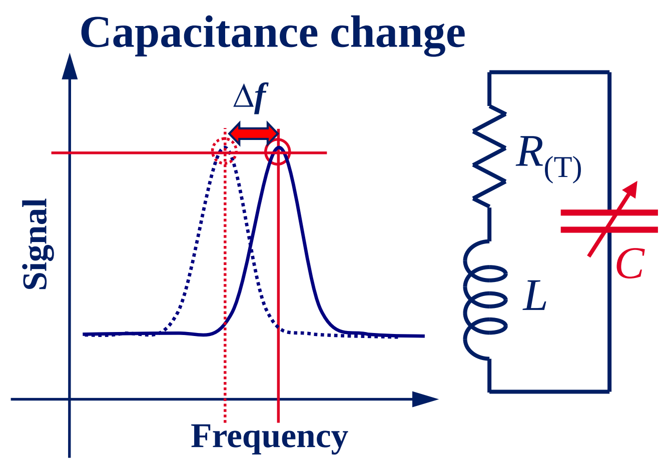




LC Based Wireless Passive Sensor Systems

- Resonance circuit: capacitive sensor and planar coil;
  f ~ quantity to be measured
- Wireless resonance detection
- Sensor Q factor allows for compensation of temperature cross-sensitivity

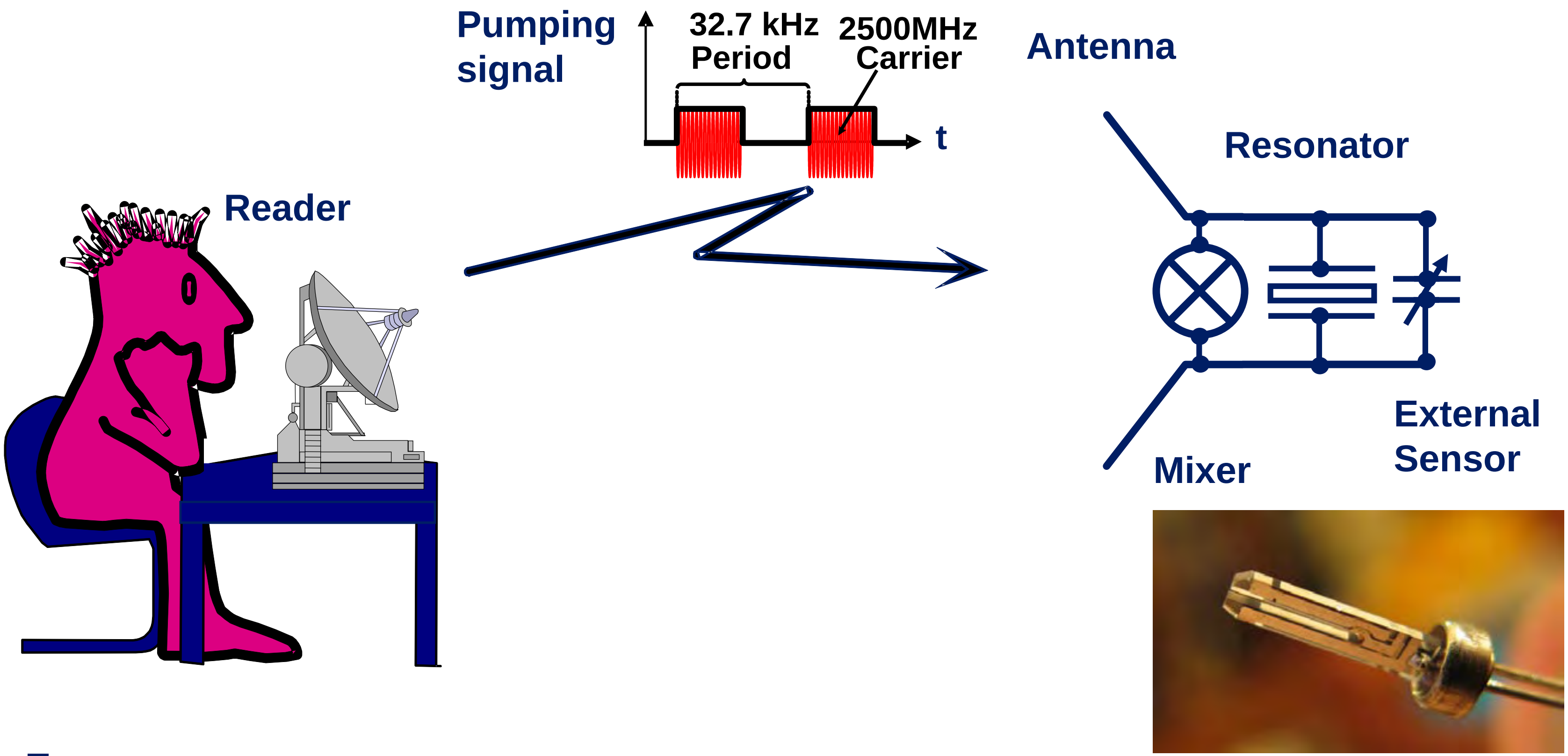
Silicon micromachined wireless pressure sensor prototype by Bosch



R. Nopper, R.Niekrawietz, L. Reindl, “Wireless Readout of Passive LC Sensors”, IEEE Trans. on Instrumentation and Measurement, Vol 59 (9), pp. 2450-2457, Sep 10, 2010

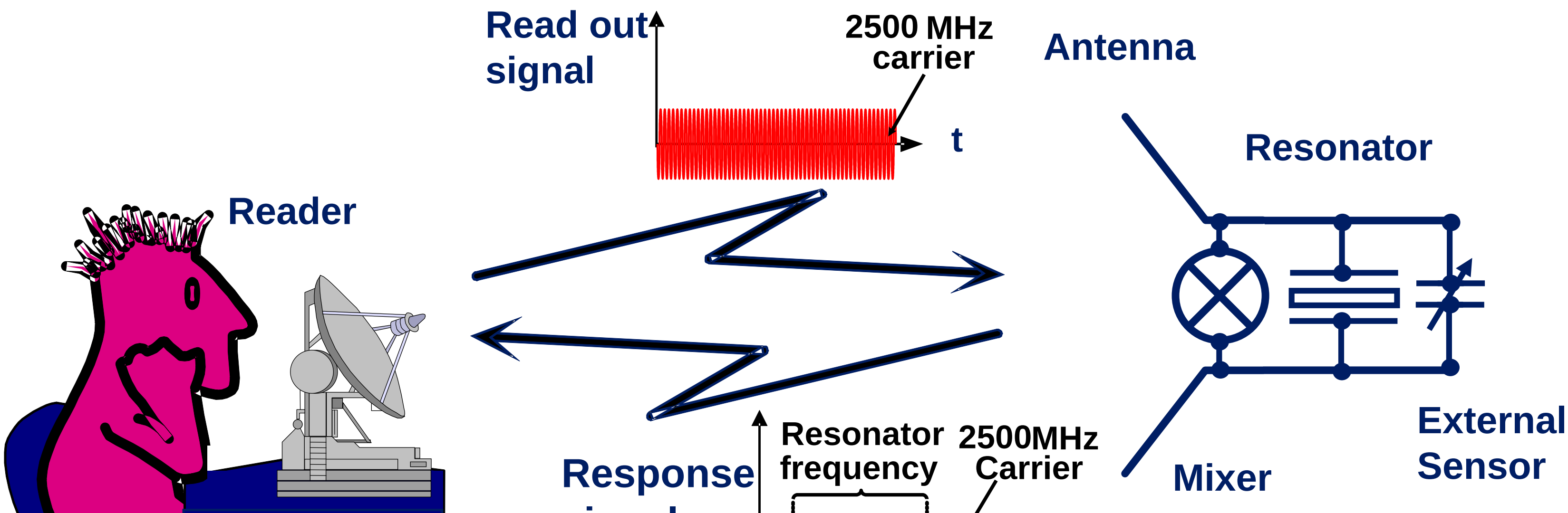
“Inductively Coupled Passive Sensors for Measurements in Difficultly Accessible Environments”, Reinhard Nopper[1], Dr. Remigius Has[1], Prof. Dr. Leonhard Reindl[2], VDI/VDE congress “Sensoren und Messsysteme“, Nurenburg, 19. Mai 2010,
[1]: Robert Bosch GmbH, Gerlingen-Schillerhöhe, Germany, 2: Laboratory for Electrical Instrumentation, IMTEK, Albert-Ludwigs-Universität Freiburg, Germany

Wireless Passive Sensor Systems Based on Quartz Crystal Resonators



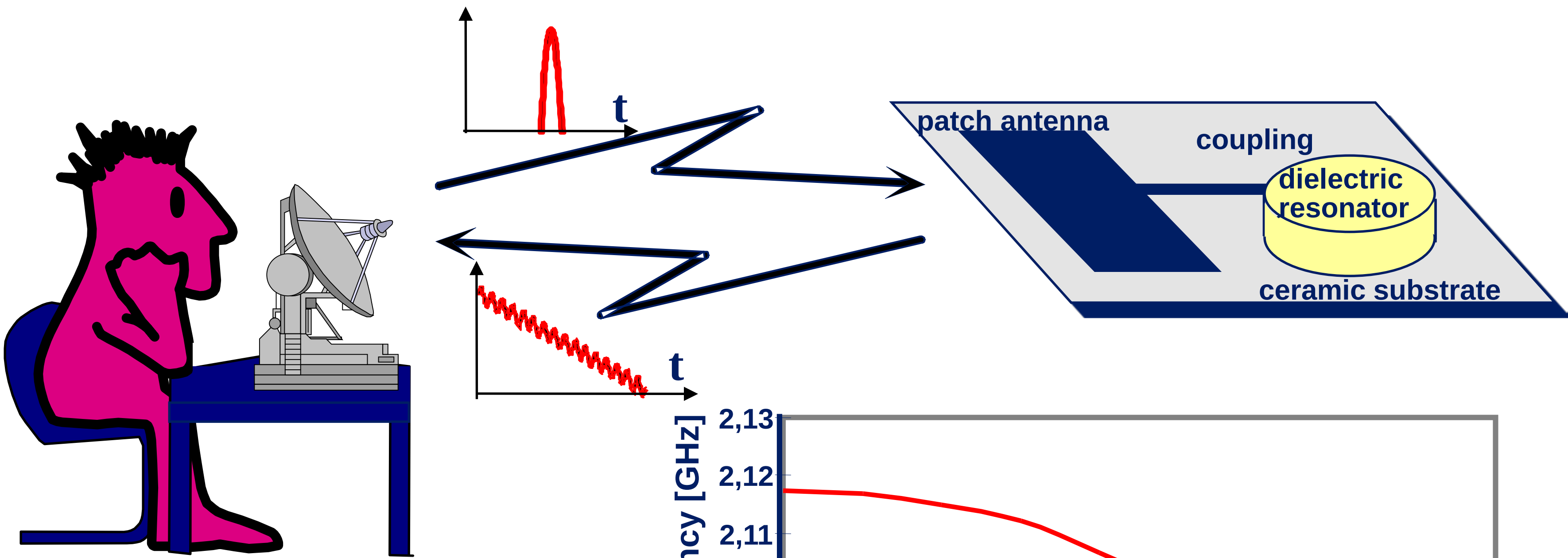
- An external sensor pulls the Quartz resonant frequency
- Might be combined with the mixing sensor

Wireless Passive Sensor Systems Based on Quartz Crystal Resonators

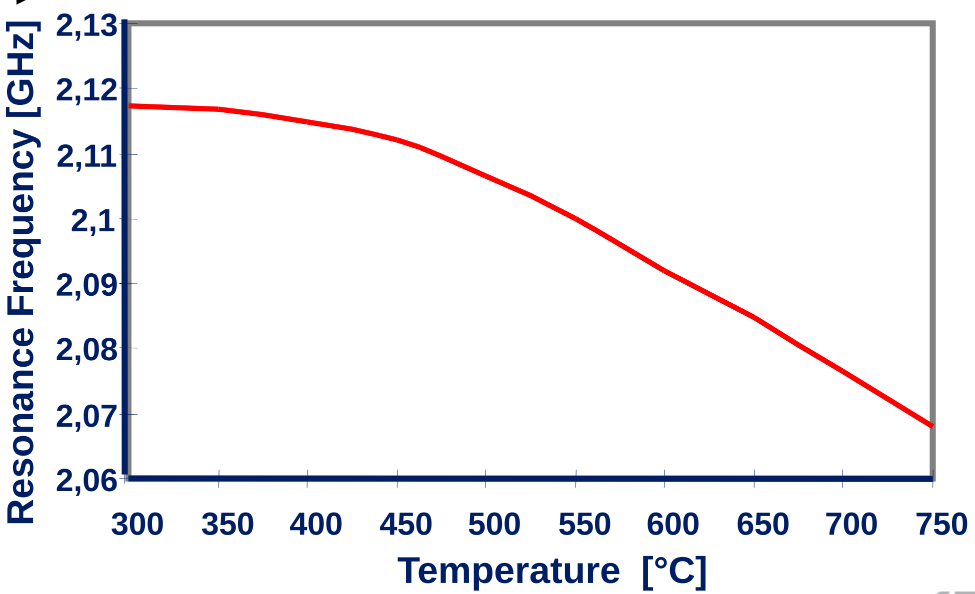


- An external sensor pulls the Quartz resonant frequency
- Might be combined with the mixing sensor

Wireless Passive Sensor Systems Based on High-Q Dielectric Resonators

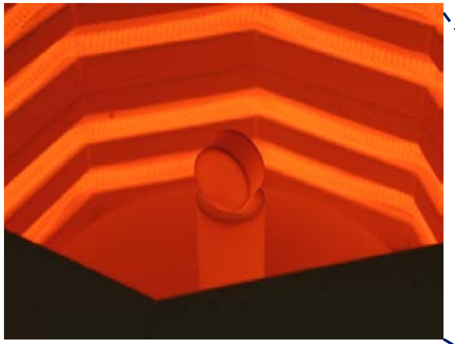


- high Q dielectric microwave resonator
- Temperature of operation > 750°C

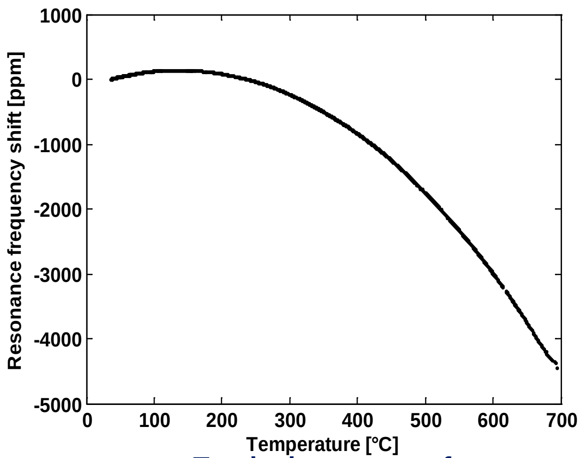


Wireless Dielectric Temperature Sensor

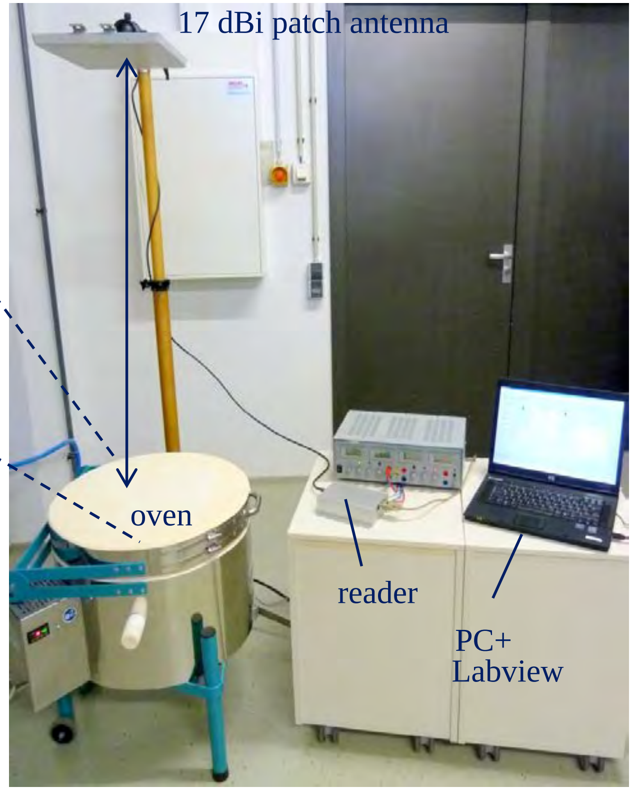
- **Metallization free dielectric resonator based high temperature sensing**



Inner view of the oven at 700 °C with a dielectric resonator placed inside



Tracked resonance frequency shift
Maximum frequency shift of -4500 ppm



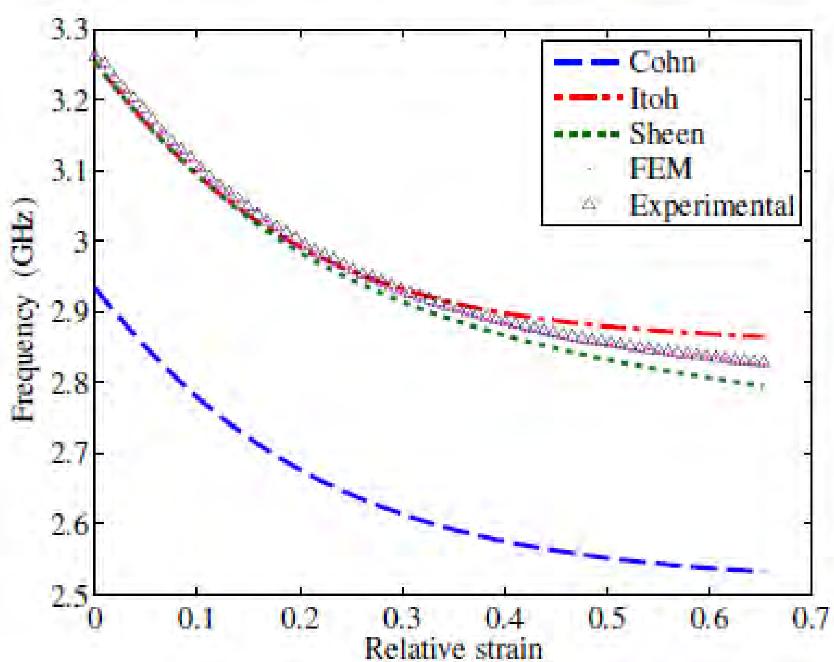
Complete measurement setup
Reading distance: 1.20 m

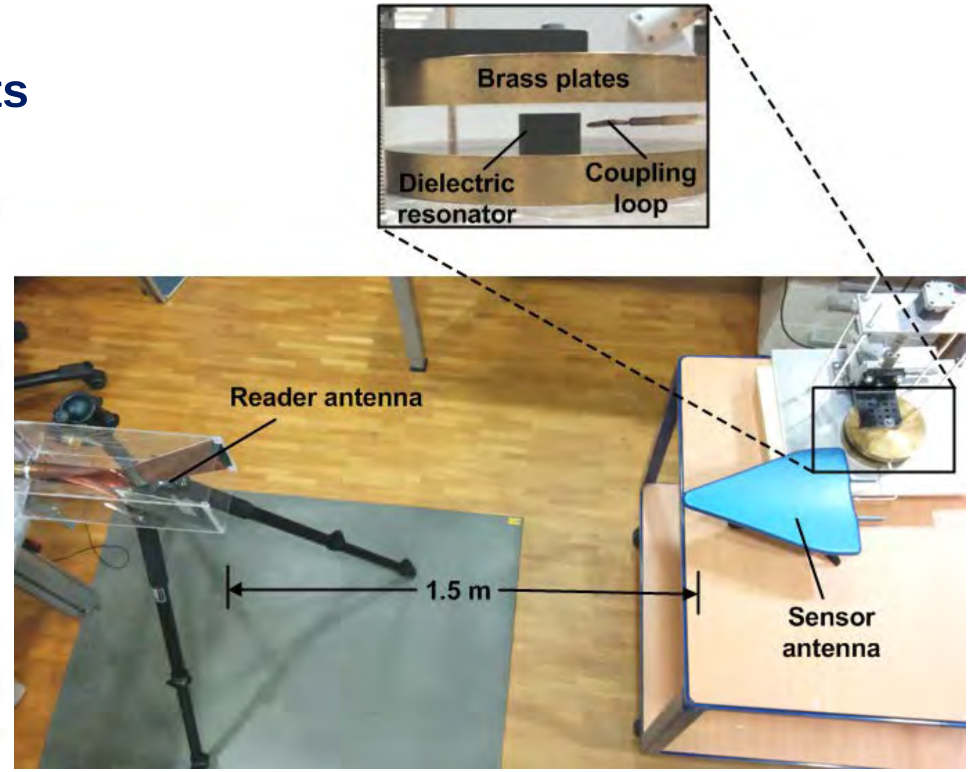
J.-M. Boccard, T. Aftab, J. Hoppe, A. Yousaf, R. Hütter, L. M. Reindl,Far- Field passive temperature sensing up to 700 °C using a dielectric resonator 2014 IEEE International Conference on Wireless for Space and Extreme Environments, Wisee, European Space Agency, ESTEC,

- 35 -

Wireless Passive Strain Sensor

- Parallel Plate Dielectric Resonator (PPDR) as Wireless Passive Sensor
- High Q factor
- High operational frequencies
- Suitable for extreme environments

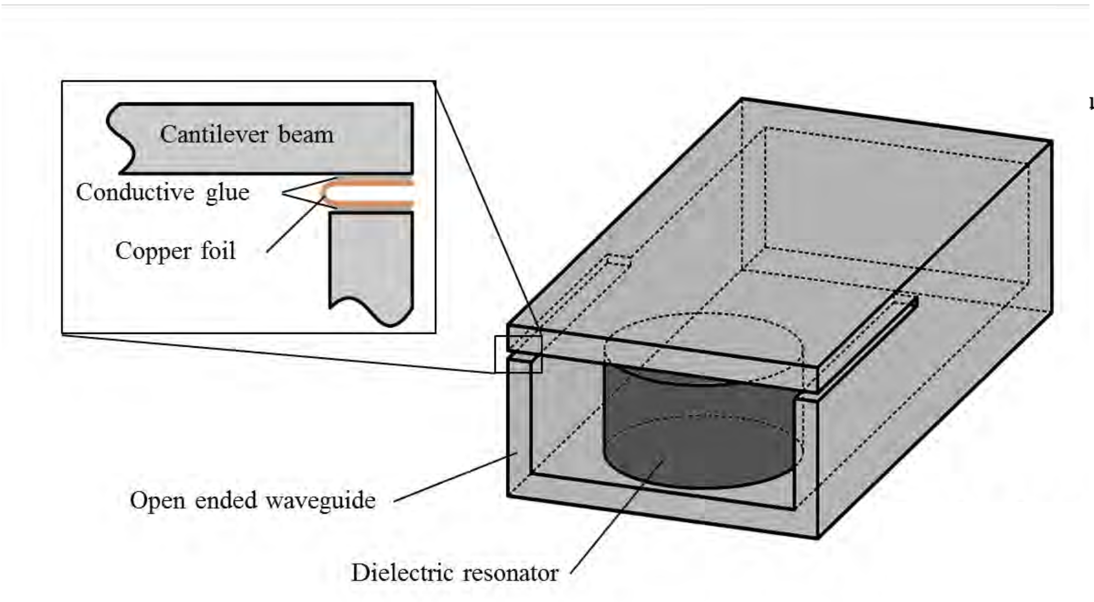


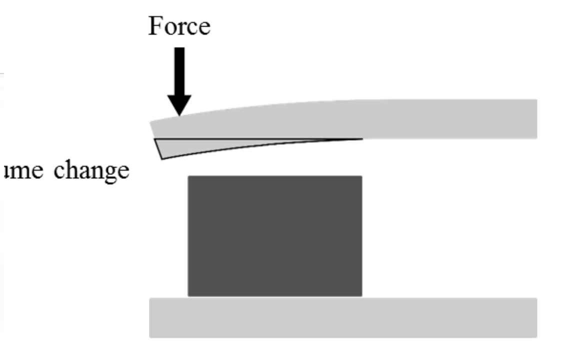


T. Aftab, A. Yousaf, J. Hoppe, S. Stöcklin, T.Ostertag and L.M Reindl (2015): A parallel plate dielectric resonator as a wireless passive strain sensor, IEEE Sensors Applications Symposium, April 13-15, Zadar Croatia

Force Sensor

- Evanescent open ended waveguide antenna.
- Loaded with a dielectric resonator
- Cantilever beam spring.
- Force → Displacement → Frequency shift



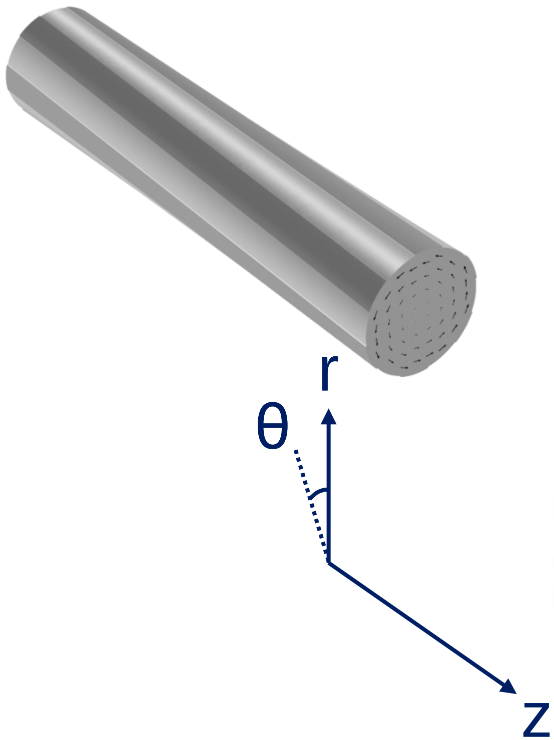


Wireless Passive Torque Sensor

- Dielectric resonator as a transducer.

  Shaft as a linear elastic torsional spring

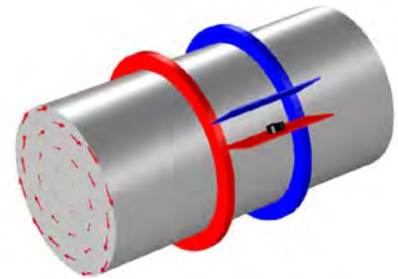
  St. Venant's Torsion Theory

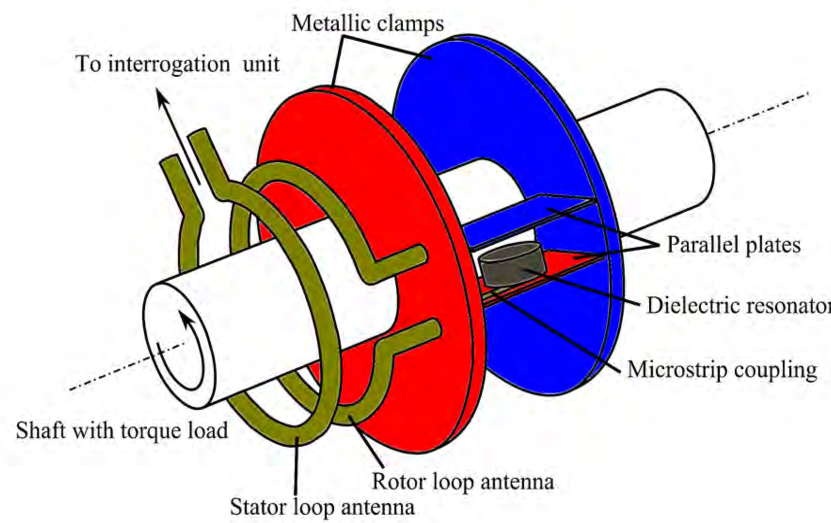


$$G = \frac{E}{2(1+\nu)}$$

$$T = G\, I_T \frac{d\theta}{dz}$$

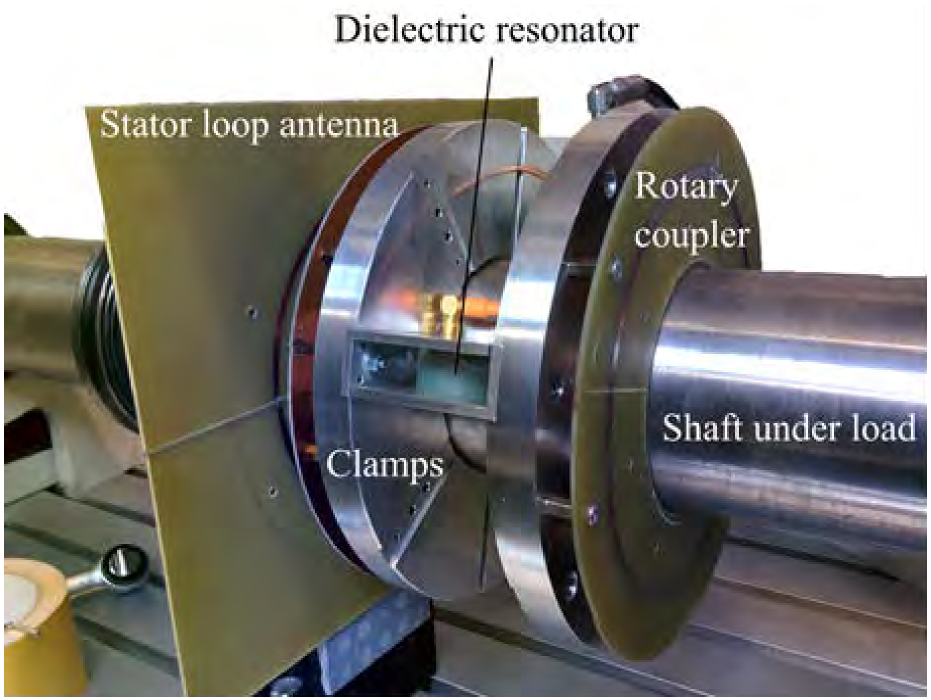
$$I_T = \frac{\pi d^4}{32}$$





Implementation: Torque sensor

- Clamp on device.
- Low installation time.
- 2.4 GHz ISM band compatible
- Dual sensors on each side for offset compensation
- Offset due to
  - Temperature
  - Sideways force
  - Coupler imperfections
- Field Test @ 2000 Nm



Thanks for your attention!

IMTEK

- Thanks to

- and

DFG Deutsche Forschungsgemeinschaft

Bundesministerium für Bildung und Forschung

SEVENTH FRAMEWORK PROGRAMME

AiF ALLIANZ INDUSTRIE FORSCHUNG

FVA Forschungsvereinigung Antriebstechnik e.V.

Ministerium für Wissenschaft, Forschung und Kunst Baden-Württemberg

SIEMENS

sensors

IMPACT FACTOR 2.677

Section: Sensor Networks

sensors

IMPACT FACTOR 2.677

Journal's Aims and Scope:

Sensors (ISSN 1424-8220) is an open access journal that provides an advanced forum for studies of sensors, the scope includes:

Physical sensors	Chemical sensors
Biosensors	Sensor technology
Sensor networks	Remote sensors
Sensing principles	Applications of sensors

Author Benefits:

1. High visibility, Rapid publication
2. Unlimited and free access for readers
3. No Copyright Constraints
4. Thorough Peer-Review
5. Coverage by SCIE (Clarivate Analytics), MEDLINE (NLM), PubMed (NLM), Scopus (Elsevier)
6. No Space Constraints, No Extra Space or Color Charges

Page views: 8,500,000+
Citations: 23,000+
Published papers: 12,000+

Journal website:
mdpi.com/journal/sensors

Contact us:
sensors@mdpi.com

Follow us on Twitter:
@Sensors_MDPI

MDPI OPEN ACCESS