Circuit Design for Micro-Electromechanical Resonators for Sensing Applications

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Ultra Low Power Analog Interfaces

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Outline

- ☐ **Motivation and Previous Work**
- ☐ **Internal Resonator Background**
- ☐ **Readout Specifications and Implementation**
- ☐ **Proof of concept with Ethanol**

Motivation for Gas Detection Systems

Pollution

Breath

☐ **Applications**

- Health and environment monitoring

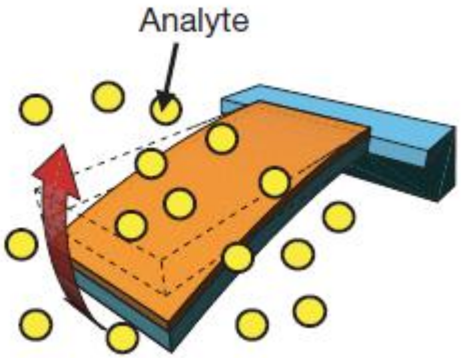
☐ **System requirements**

- Highly sensitive
- Selective
- Scalable/Wearable
- Low Power

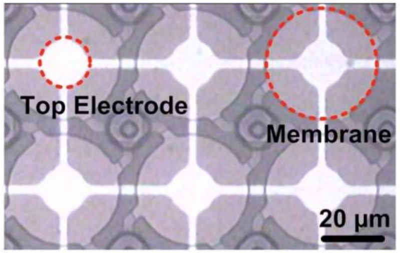
→ **Good candidate : MEMS-based oscillator sensor**

Previous Work

☐ **[1] Cantilever**
  - Thermal actuation
  - Wheatstone bridge sensing
  - Co-integration



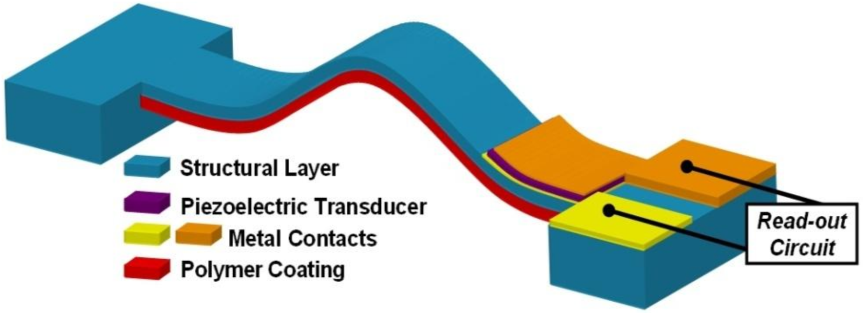
☐ **[2] CMUT**
  - 40-60V DC biasing
  - Large area for parallelism
  - Amplifier and band-pass filter readout



☐ **This work:** Transimpedance amplifier interfacing a piezoelectric doubly-clamped beam

[1] C. Hagleitner et al, IEEE J. Solid-State Circuits, 37, 1867-1878, 2002.
[2] K.K.Park et al, Appl. Phys. Letters, 91, 094102, 2007.

Internal Doubly-clamped Resonator Background

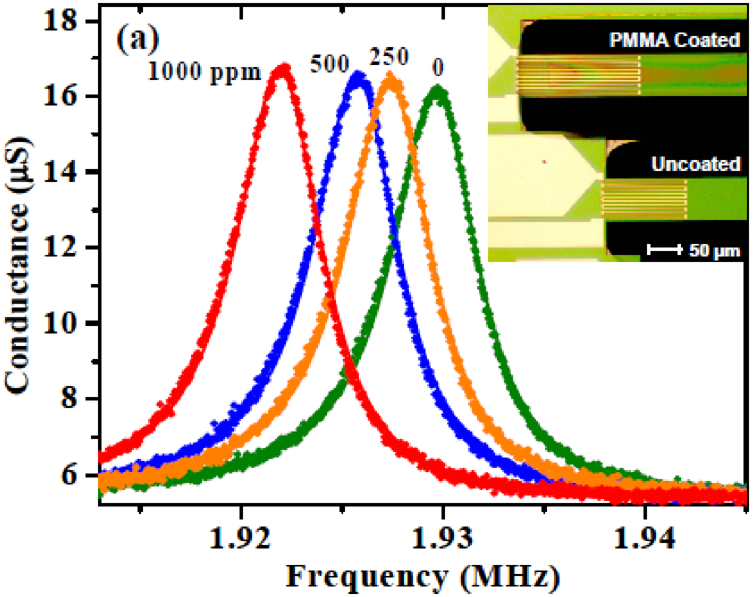


- ☐ **Piezoelectric transducer**
- ☐ **Sensing mechanism**
  - Coated polymer layer
  - Swelling-induced frequency shift

Mass increase $\Delta m>0$

Swelling $\Delta\sigma<0$

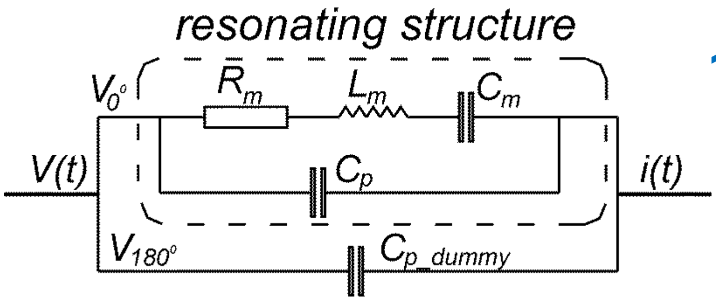
$$\boxed{\frac{\Delta fn}{f_n}=\frac{1}{2}\left(-\frac{\Delta m}{m}+\frac{\Delta k}{k}+\frac{\alpha n\,\Delta\sigma}{1+\alpha_n\sigma}\right)}$$

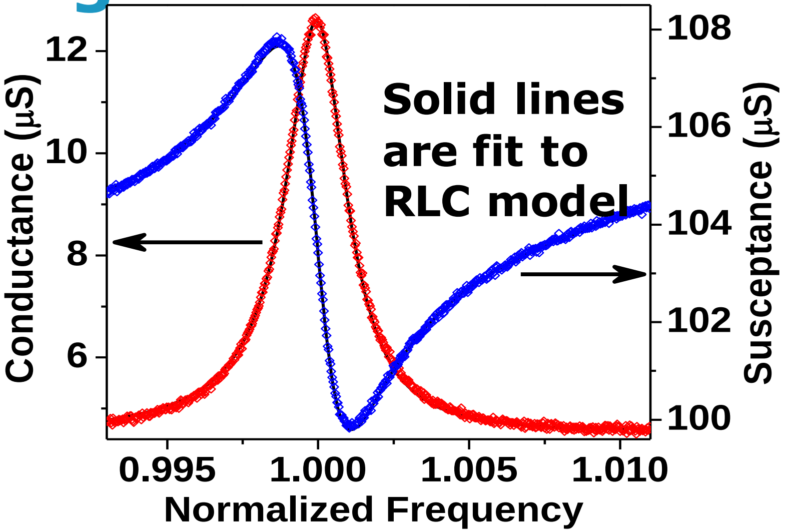


D.M. Karabacak *et al,* Lab on a Chip,2010, 10, 1976-1982

Resonator Electrical Modeling

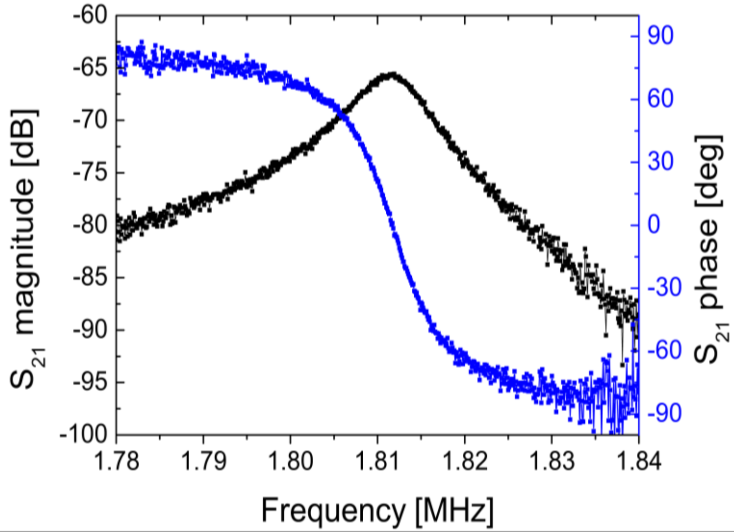
- ❑ **Lumped-element model**





Solid lines are fit to RLC model

- ❑ **Parasitic capacitance cancellation**
  - Integrated dummy capacitance



J. Lee, A. Seshia, Sensors and Actuators A, 2009, 156, 1,36–42

Sensor Interface Challenges

☐ Resonator Characteristics

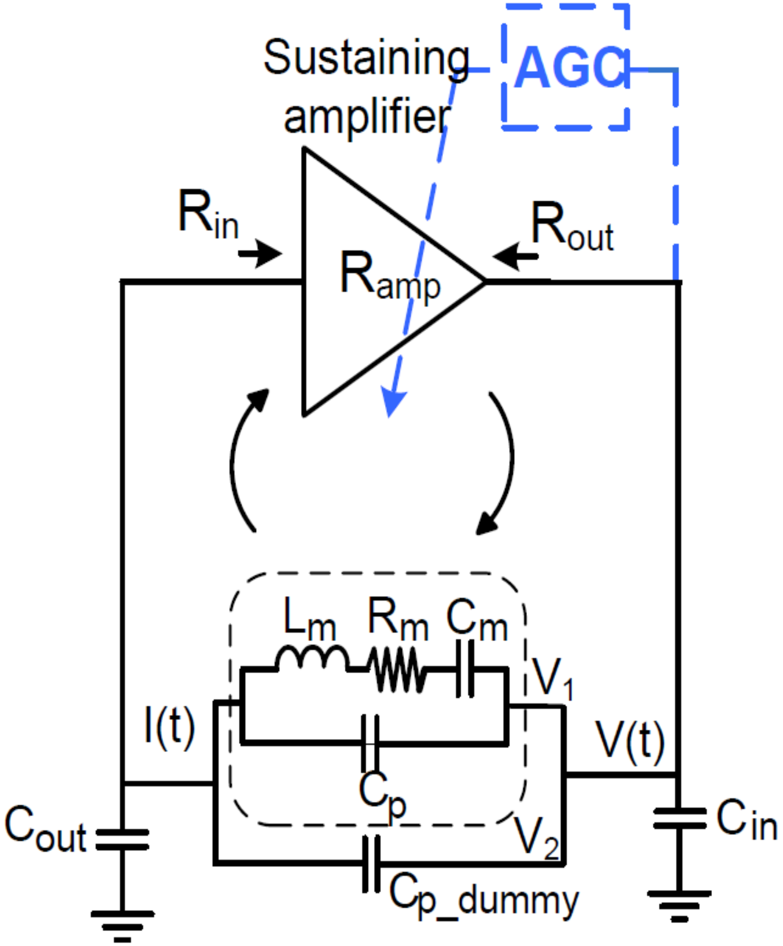
Resonance frequency [MHz]	Motional impedance R_m [kΩ]	Quality factor Q	Parasitic capacitance C_p [pF]
1.8-2.1	50-150	100-300	3-4

☐ Interface Challenges

- Minimize the parasitic interconnections
- Define the circuit specifications to account for sensor process variability

→ Obtain an optimal detection resolution

From a Resonator to an Oscillator



☐ Barkhausen’s conditions

- Loop gain ≥ 1
- Loop phase =0

☐ Readout specifications

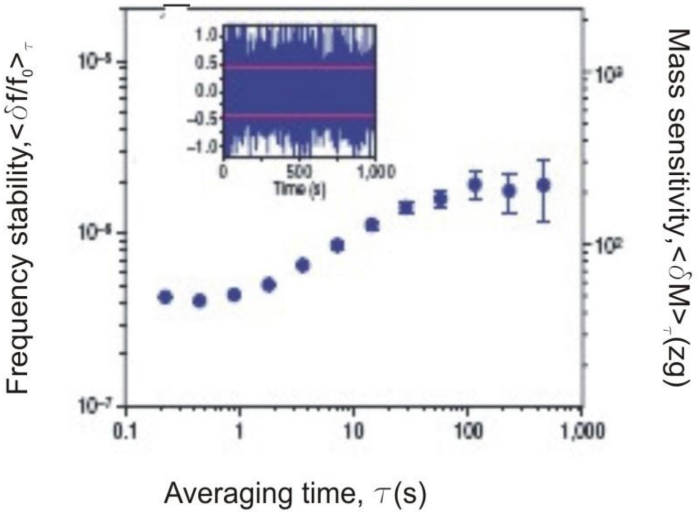
- $R_{amp} \geq R_m + R_{in} + R_{out}$
- Bandwidth≥ 5 f_{osc}
- Maximum loaded

$$Q_l = \frac{R_m \cdot Q}{R_m + R_{in} + R_{out}}$$

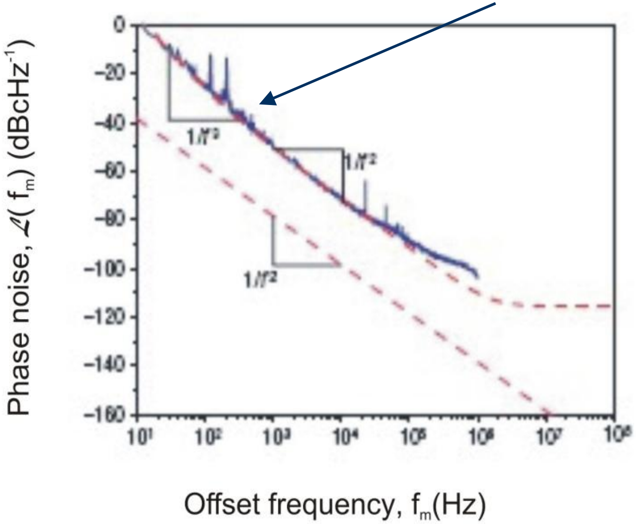
- Loop gain control

→ Allan deviation @2 MHz= 2 Hz → Phase noise?

From Allan deviation to Phase noise



1/f³ oscillator phase noise



- ☐ Target Allan deviation $< \frac{\delta f}{f_0} >_\tau = \sigma_y(\tau) = 10^{-6}$

- ☐ In the region of τ^0 corresponding to flicker of frequency

  $\sigma_y^2(\tau) = h_{-1} 2 \ln 2 \tau^0$ and $L(f_m) = \frac{1}{2} h_{-1} f_0^2 f_m^{-3}$

→ **For 2 MHz oscillator** $L(1k) = -88 dBc / Hz$

→ For NEMSIC 150 MHz resonators→ $L(1k) = -51 dBc / Hz$

X.L Feng *et al*, Nature Nanotechnology, 2008, 3, 342-346

Oscillator Phase Noise

❑ Phase noise formula

$$L\{f_m\} = 10\log\{\frac{2kT}{P_o}\cdot[2+\frac{\overline{v_{n,ia}^2/\Delta f}}{4kTR_m}(1+R_m^2(2\pi f_o)^2C_i^2)]\left[1+(\frac{f_o}{2Q\ f_m})^2\right]\}$$

Phase noise α 1/P_o

contribution of R_m and R_f

contribution of amplifier noise

$v_{n,ia}$ is the amplifier input referred voltage noise

$P_0 = \frac{v_o^2}{2R_m}$ v_o is the max output swing of the oscillator ~ 100mV

C_i is the input parasitic capacitance (few pF)

→ **Minimize parasitic effects and electronic noise contribution**

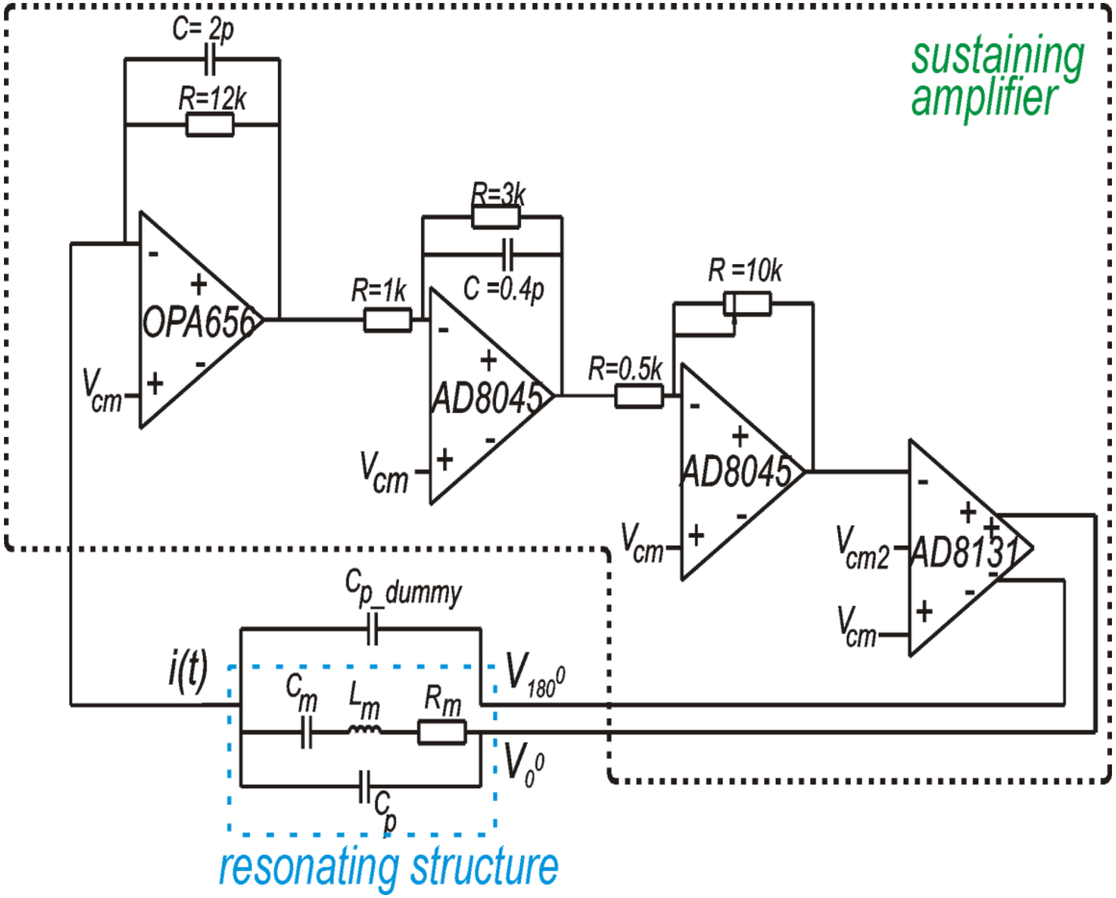
Discrete Oscillator-based Readout

❑ **Readout**

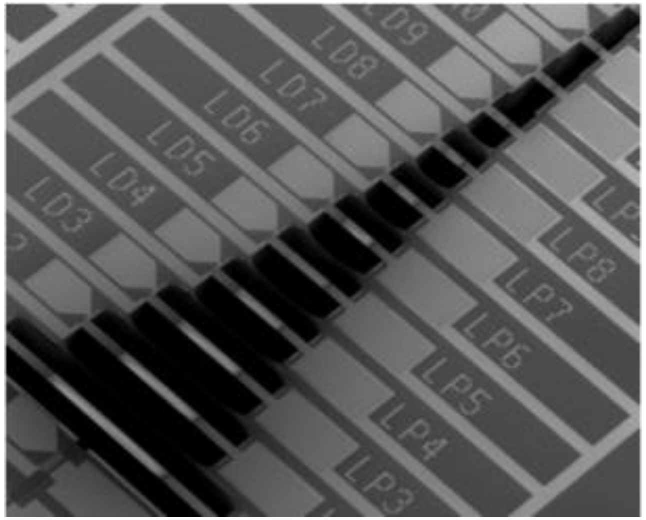
- 4-stage TIA
- Differential outputs

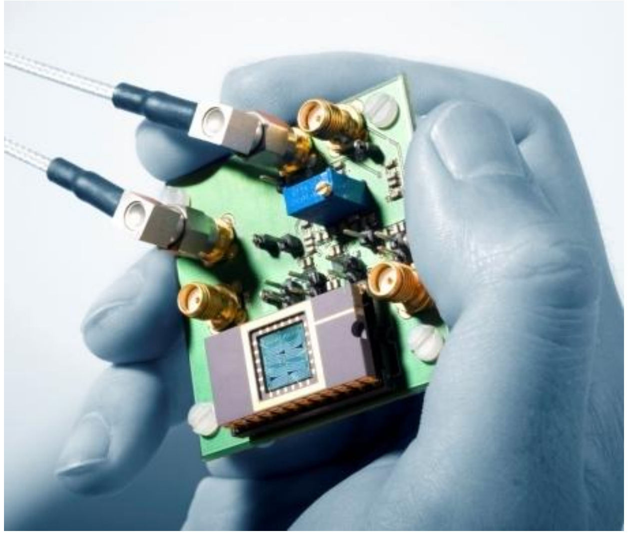
❑ **Measurements**

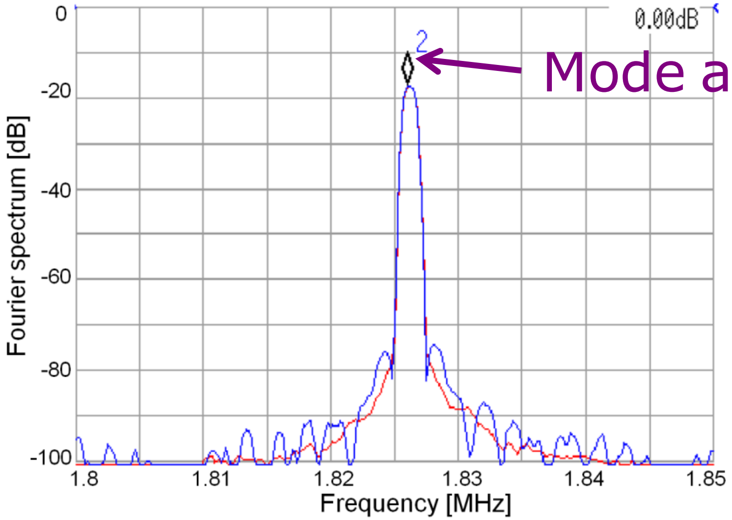
- R_{amp} [36 k-720 kΩ]
- input noise<80 nV/sqrt(Hz)
- BW~10 MHz



Discrete Oscillator Characterization



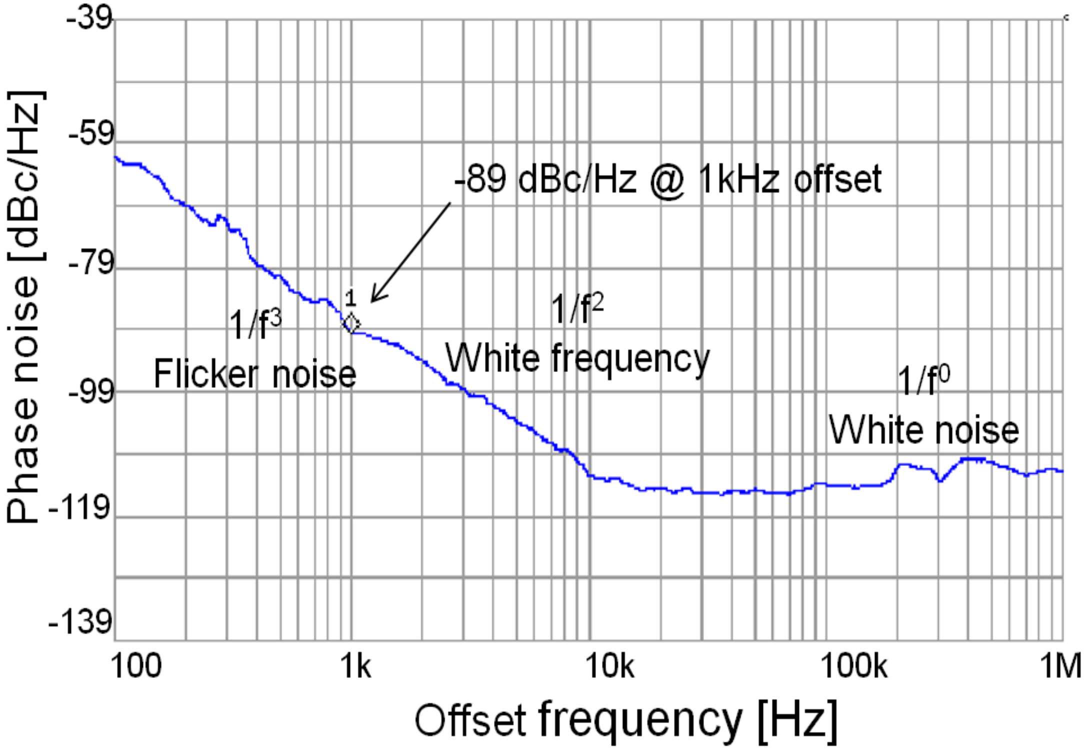




Mode at 1.8 MHz

M. Patrascu, J.Pettine et.al, Proc. Eurosensors XXV, accepted for publication, 2011.

Discrete Oscillator Phase Noise

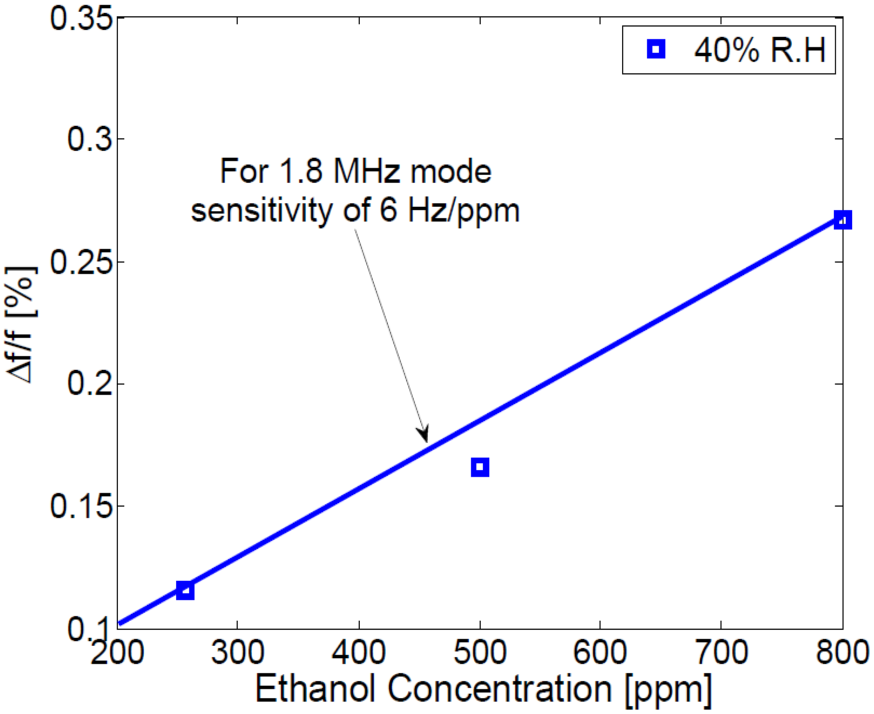


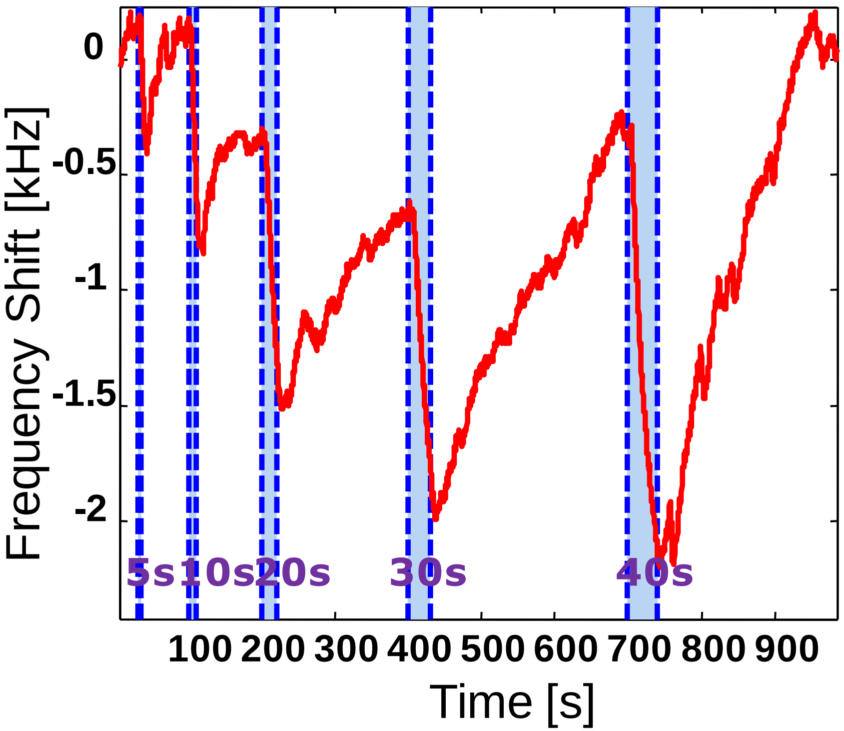
- ☐ Phase noise @ 1 kHz offset =-89 dBc/ Hz
- ☐ Equivalent Allan deviation (1s) ~ 2 Hz

D. Allan et. al, Freq.Control Symp, 1988, 419-425

Proof of concept with Ethanol

- ❑ **Response to intermittent flows with 1000 ppm of ethanol**





Sensitivity (S_v) to ethanol with (40% RH)=6 Hz/ppm

Good tracking with specific frequency shift according to the exposure time

Conclusions

- ☐ **Design of oscillator-based readout for sensing applications**
  - Methodology for specifications definition
  - Discrete implementation
  - Proof of concept with ethanol detection
- ☐ **NEMSIC**
  - Readout design for NEMSIC resonators (VBFET, Nano-wires) under development
  - Characterization of the oscillator and the sensing functionality

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Thank you for your attention

Any questions ?