Digitally Tuned Low Power Gyroscope

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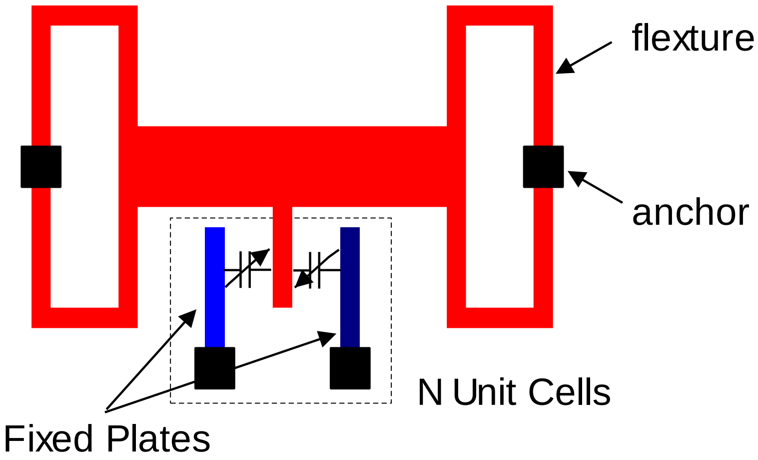
Outline

- Objective:
  - 100x power reduction in MEMS gyroscope
- What are gyroscopes?
- Power reduction techniques
  - Mechanical gain
  - Low power, low noise amplification
- Results

Accelerometer



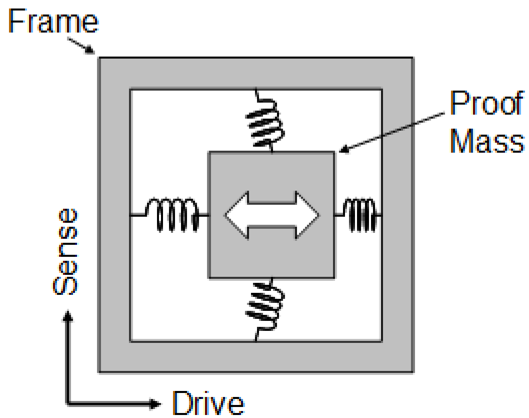
$$x = \frac{a}{\omega^2}$$

$$= \frac{1\text{mG}}{\left(2\pi \times 10\text{kHz}\right)^2}$$

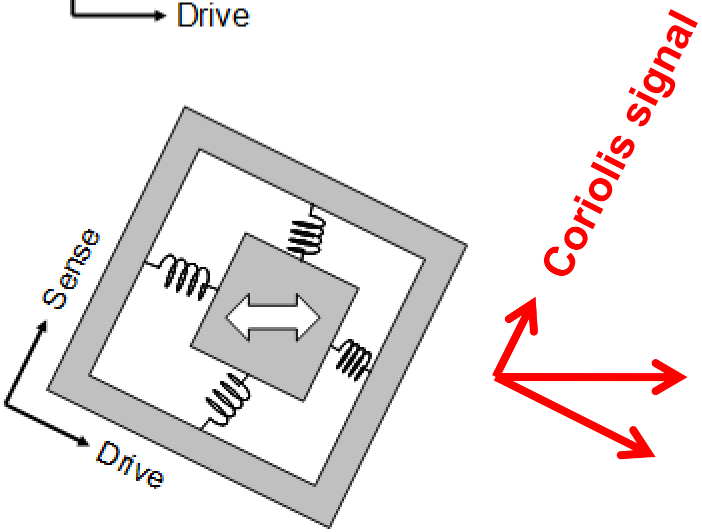
$$= 2.5\text{pm}$$

$$= \frac{1}{40}\text{Angstrom}$$

Vibratory Gyroscope



- Vibrate along drive axis with oscillator @ f_{drive}



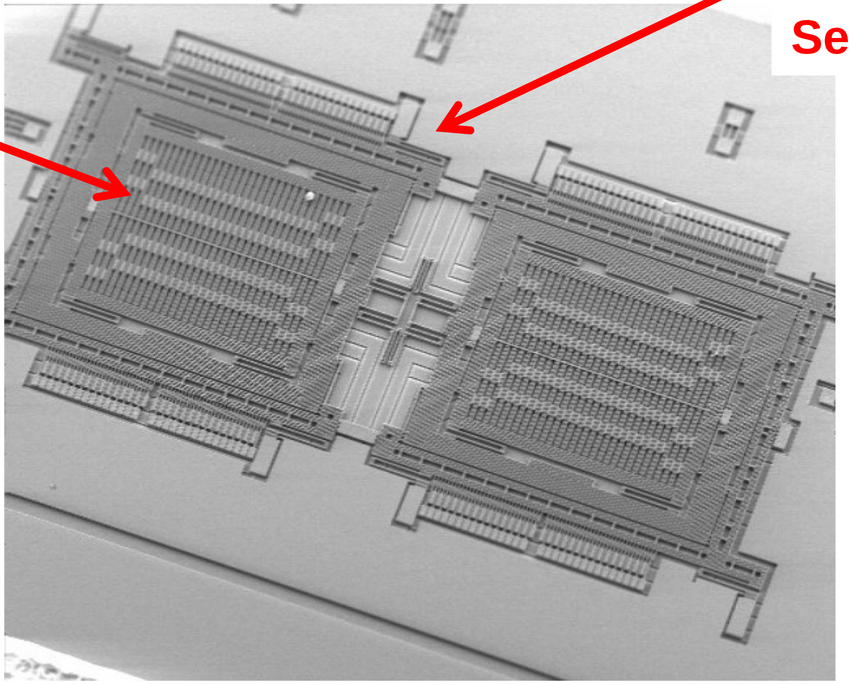
- Detect vibration @ f_{drive} about sense axis with accelerometer

$$x \cong \frac{1}{4000} \text{Angstrom}$$

Gyroscope Design

Electrostatic Drive

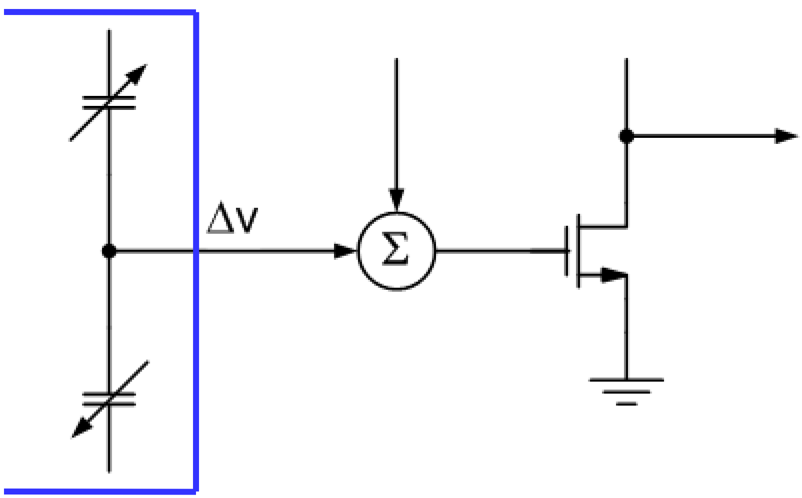
Electrostatic Sense Pickup



Power / Accuracy Tradeoff

$$\overline{v_n^2} \propto \frac{1}{g_m} \propto \frac{1}{I_D}$$

$$SNR = \frac{\text{signal}}{\text{noise}} = \text{const}$$



gyro

<u>Design options</u>:

1) Lower amplifier noise
2) Increase signal Δv

<u>without power penalty</u>

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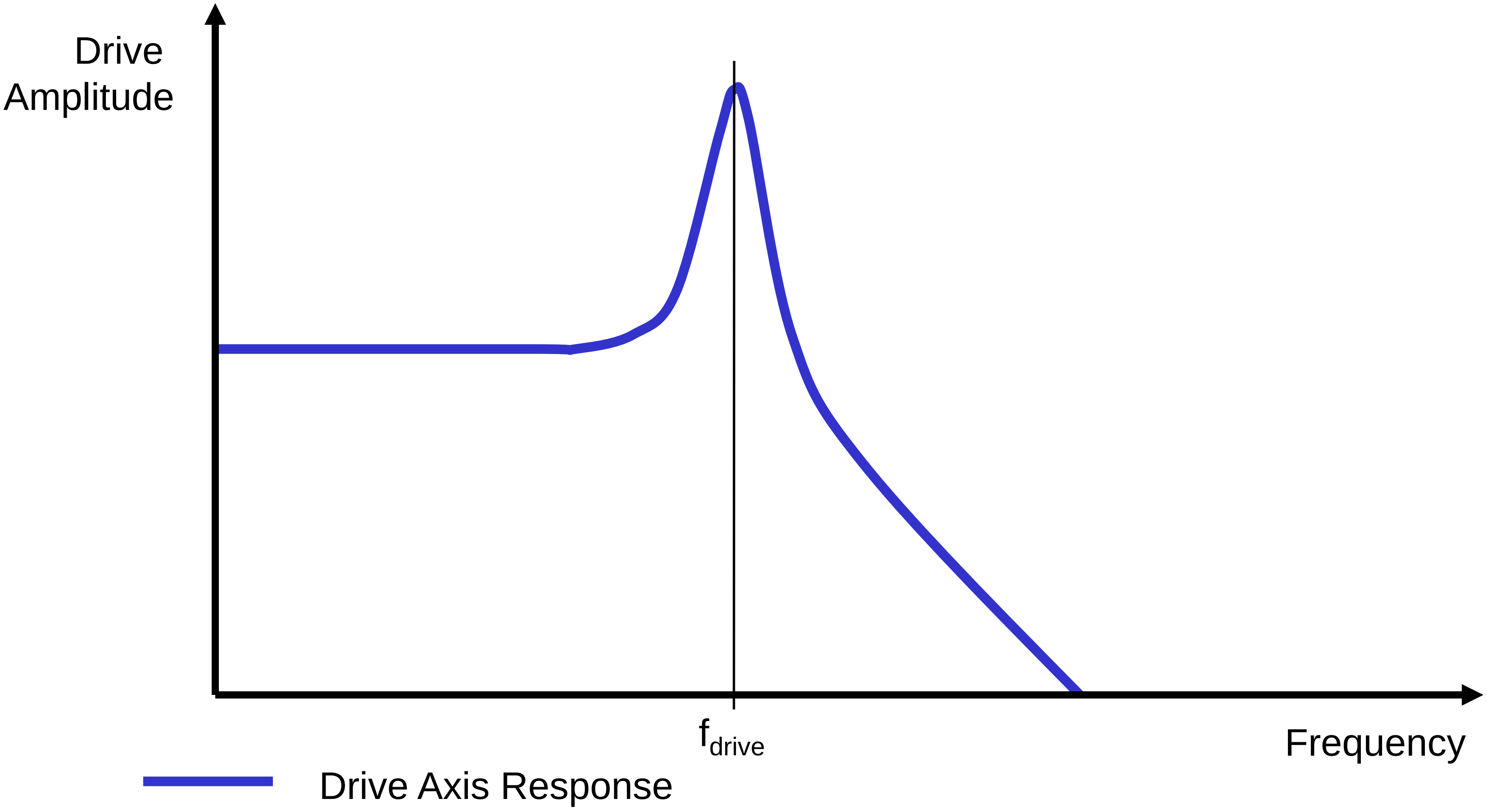
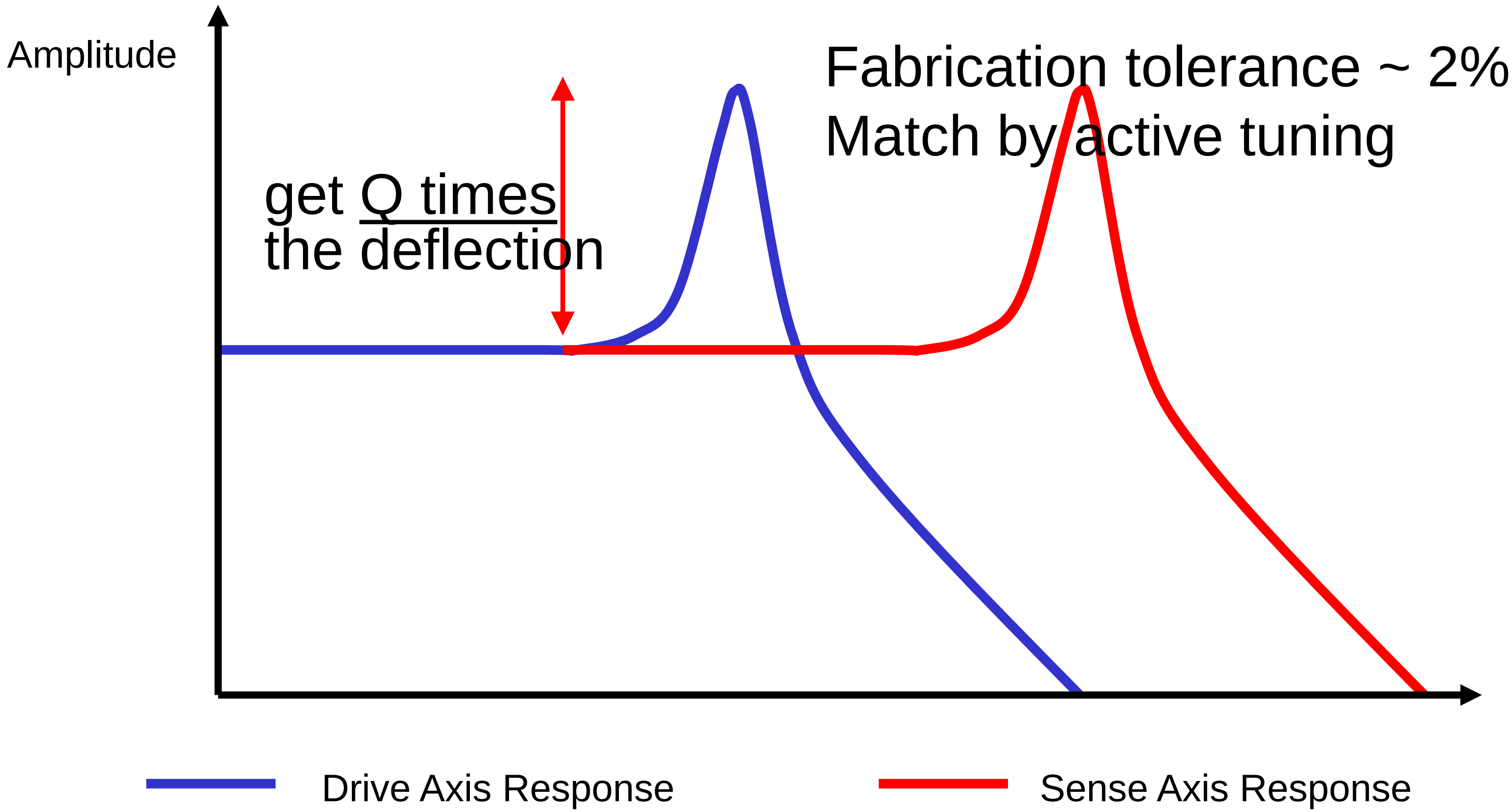
Mode-Matching

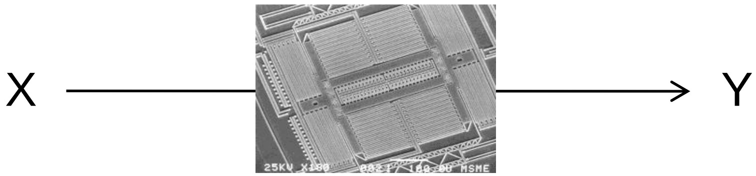


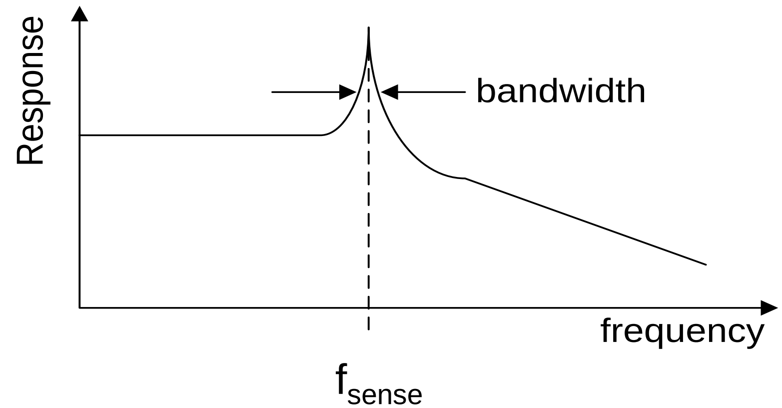
Mode-Matching



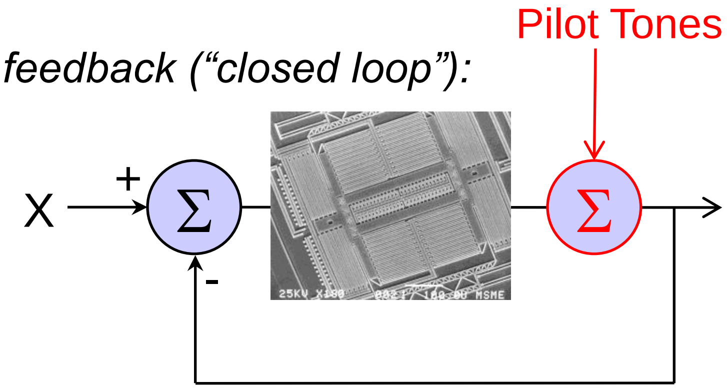
Frequency Error Estimation

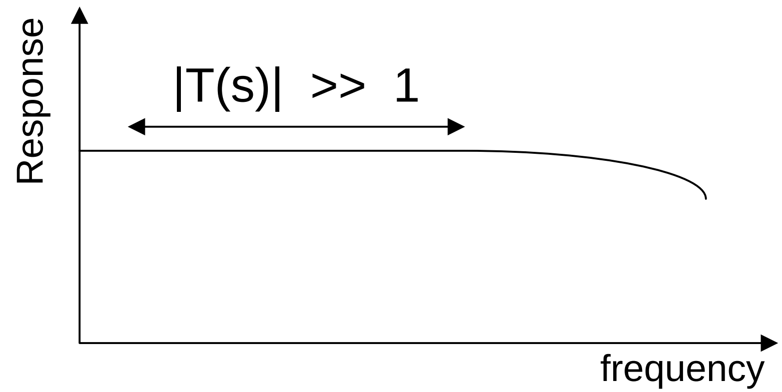
open loop response:



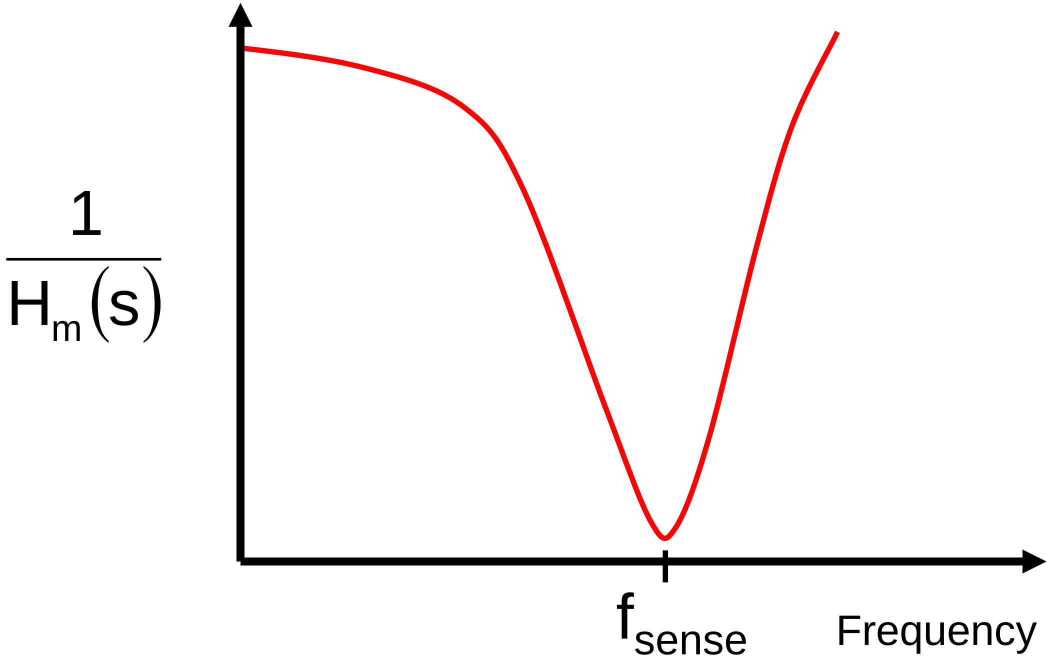


feedback (“closed loop”):



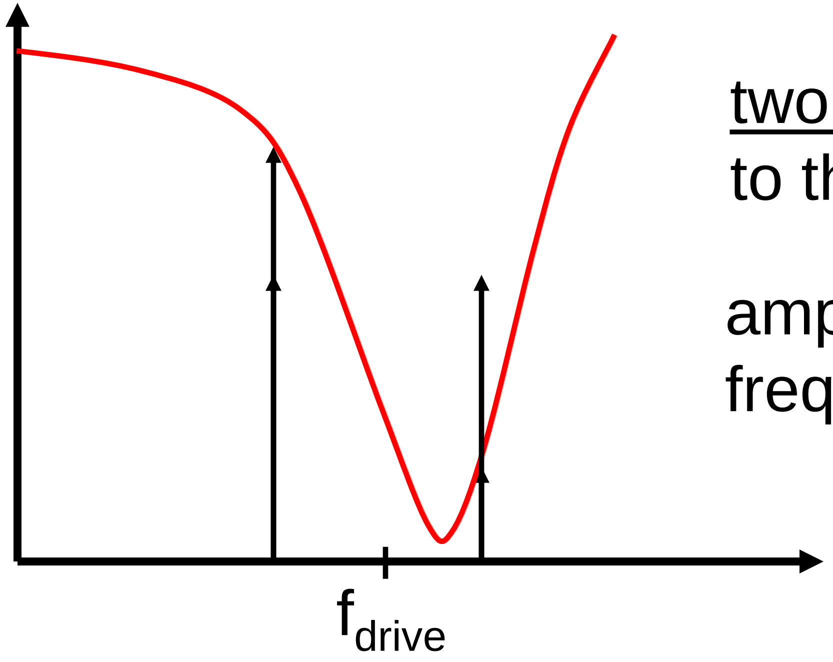


Sense Resonance Estimation



Key Idea

$$\frac{1}{K_f H_m(s)}$$

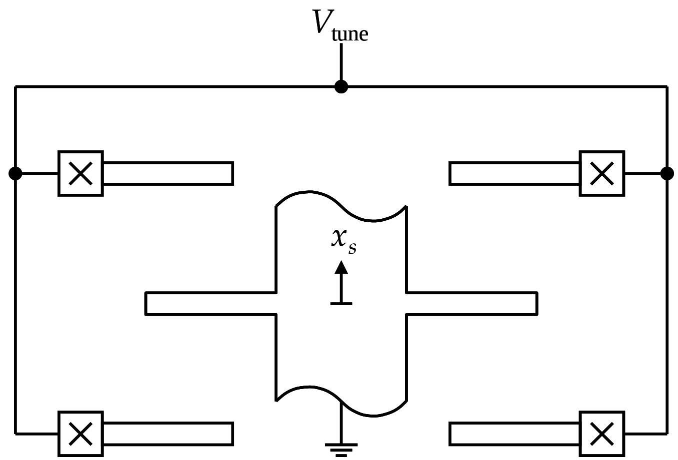


<ins>two pilot tones</ins> locked to the drive frequency

amplitudes depend on frequency mismatch!

force amplitude difference to zero

Electrostatic Tuning



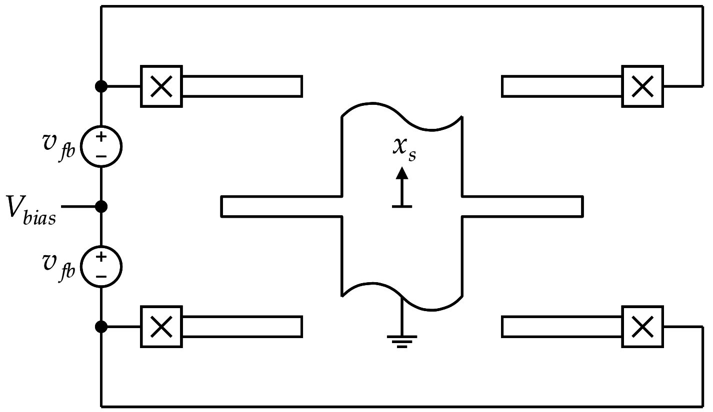
Voltage-Tunable Spring

Net Stiffness → $$k_s = k_m - \frac{C_{tune}}{gap^2} V_{tune}^2$$

Mechanical

Electrostatic Spring

Electrostatic Force Feedback



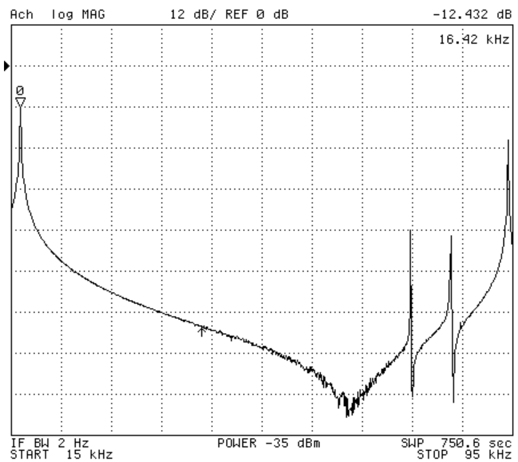
$$F_e = 2\frac{C_{s0}}{gap}V_{bias}v_{fb} - 2\frac{C_{s0}}{gap^2}\left(V_{bias}^2 + v_{fb}^2\right)x_s$$

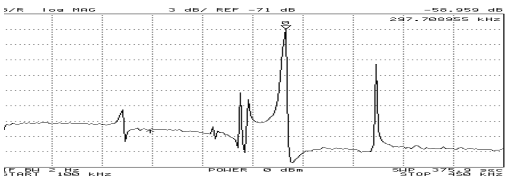
Voltage-To-Force Gain

Signal Dependent Stiffness

2-level feedback (Sampled Data "ΣΔ")

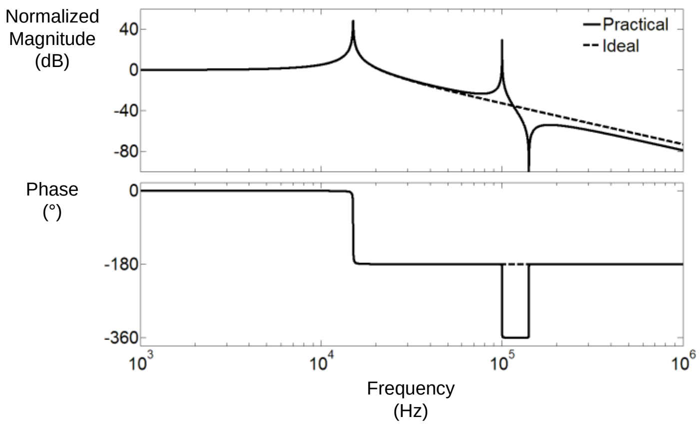
Sensor Frequency Response



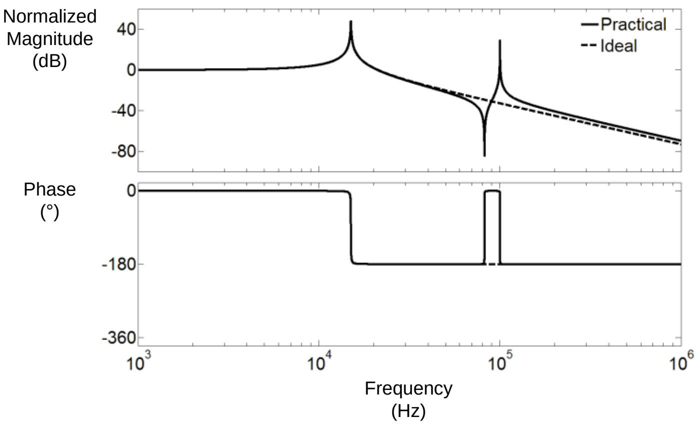


- Main mode near 15kHz
- Big parasitic modes near 95kHz and 300kHz
- Smaller parasitic modes all over
- Feedback?

Parasitic Resonances

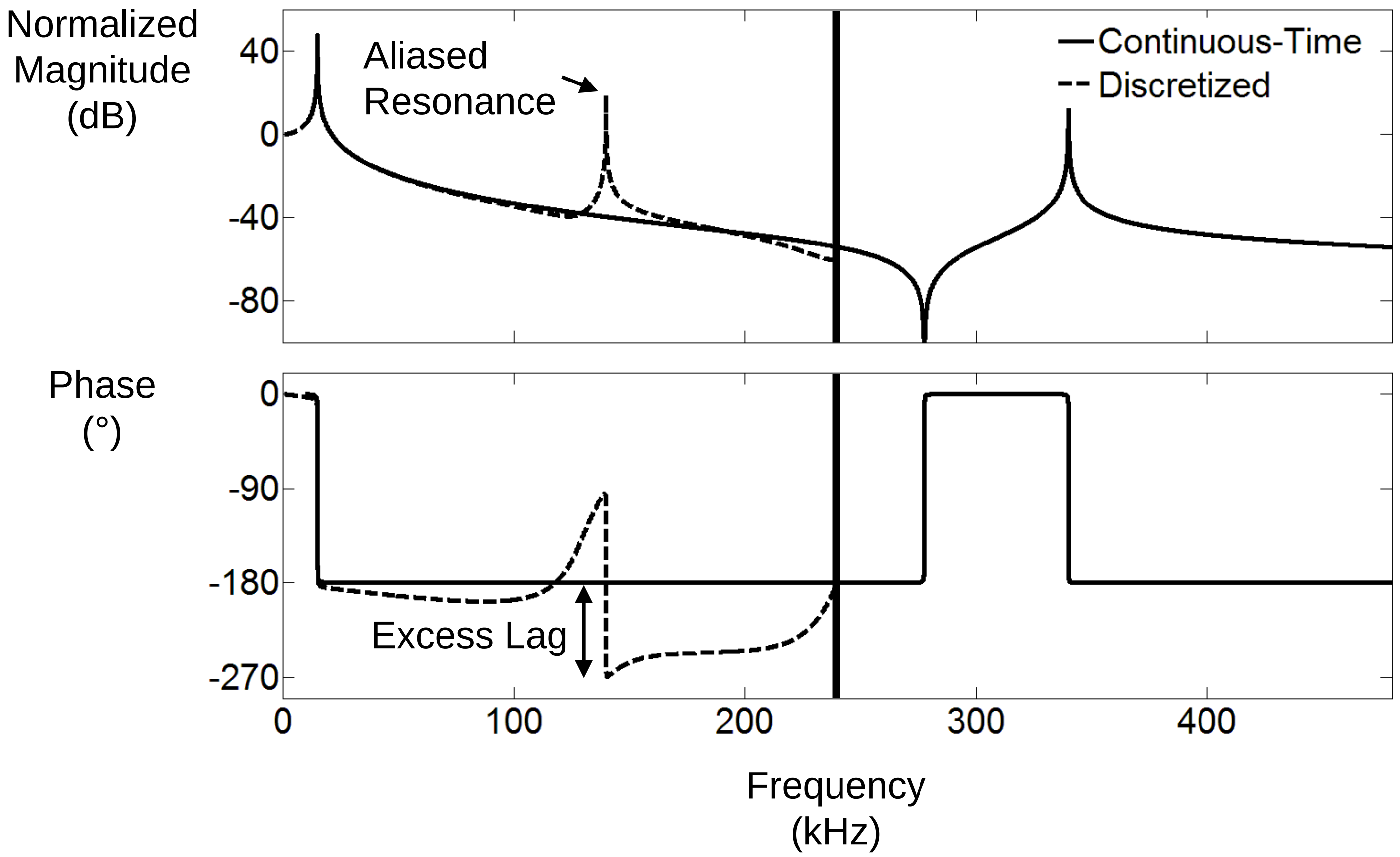


Non-collocated Control
(separate electrodes)

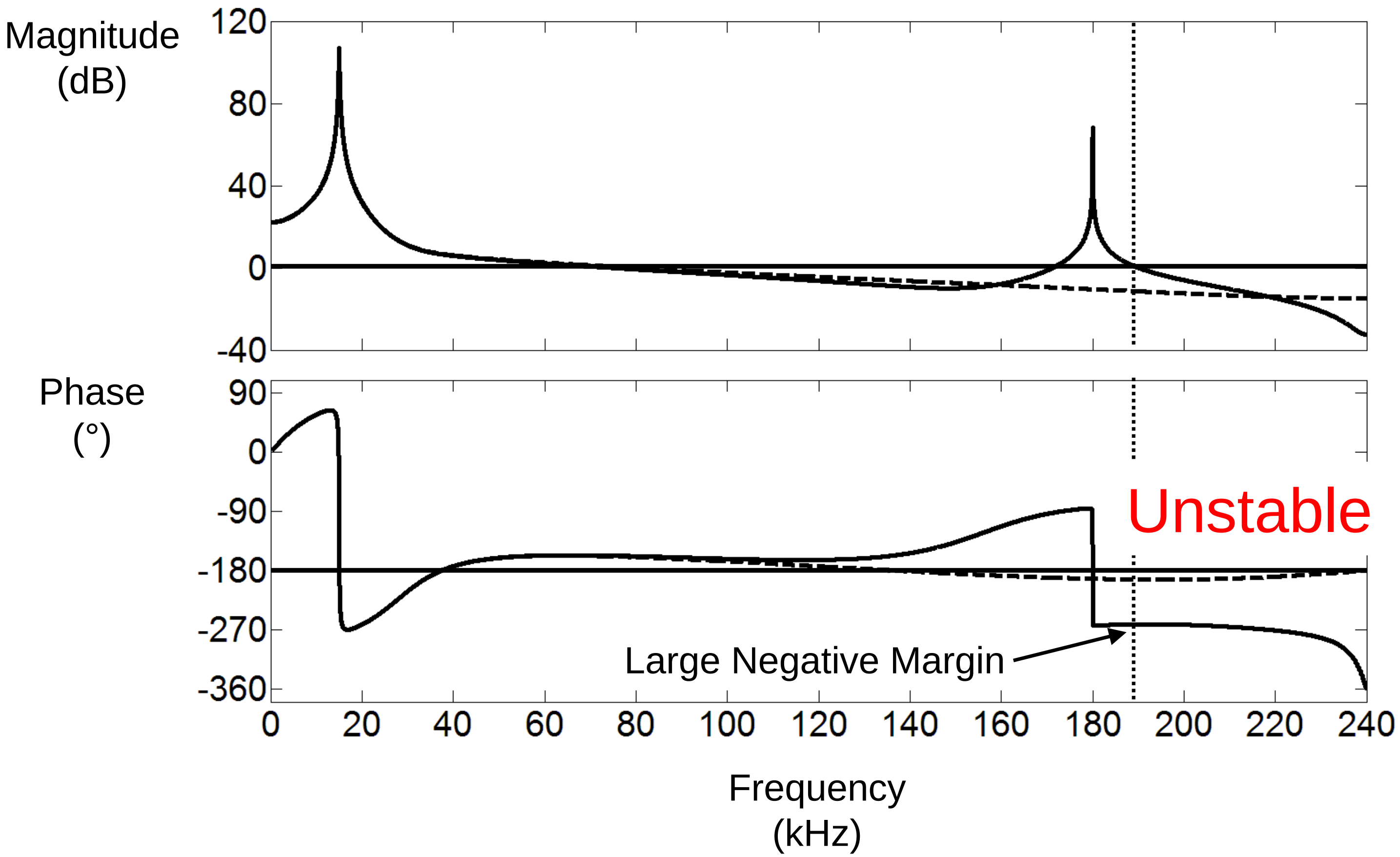


Collocated Control
(same electrode)

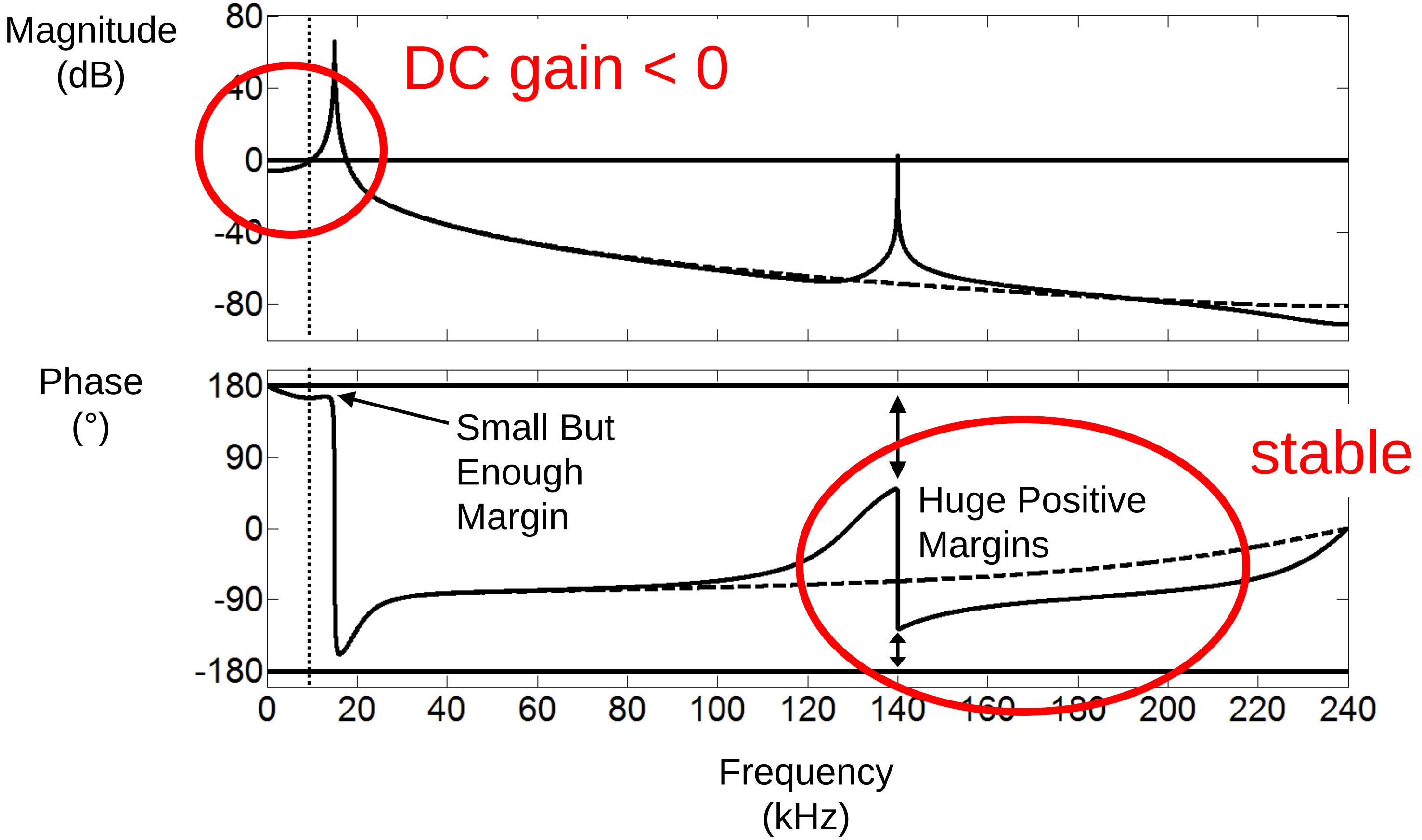
Sampled Data System



Negative Feedback



Positive Feedback

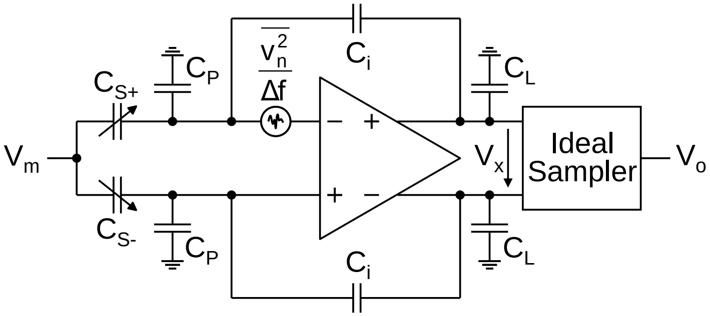


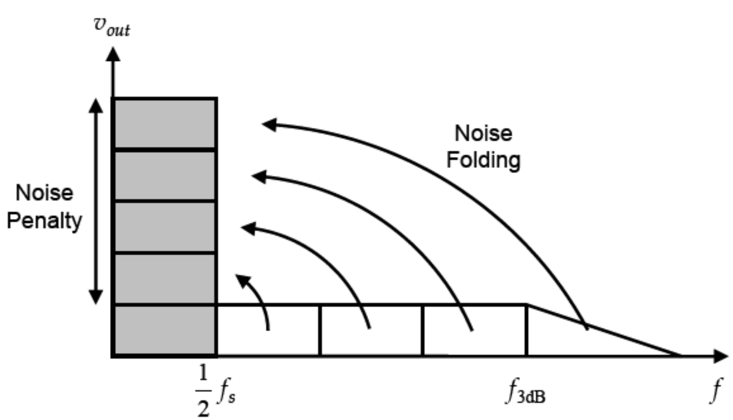
Mode-Matching Summary

- >100x increased signal
- ***100x power savings***
- Fabrication tolerances, drift → mismatch
  - Background calibration
  - Electrostatic tuning
- Sensitivity = f(Q, environment)
  - Force feedback
  - Stability → positive feedback

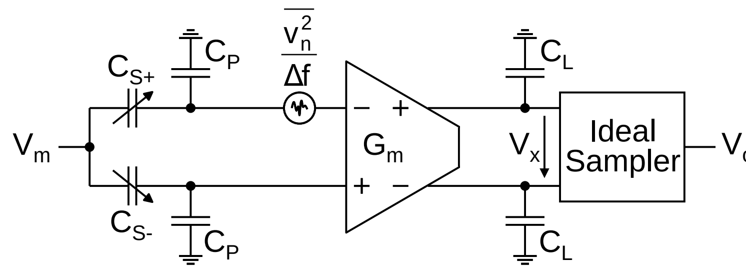
Sampling Noise

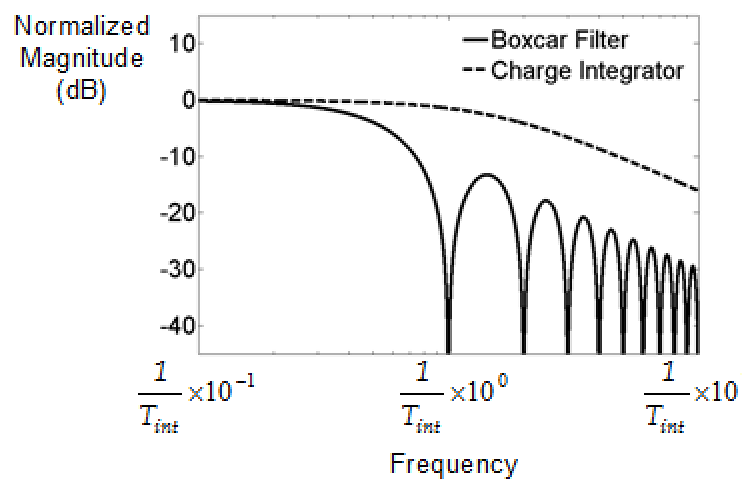
Closed Loop





Open Loop



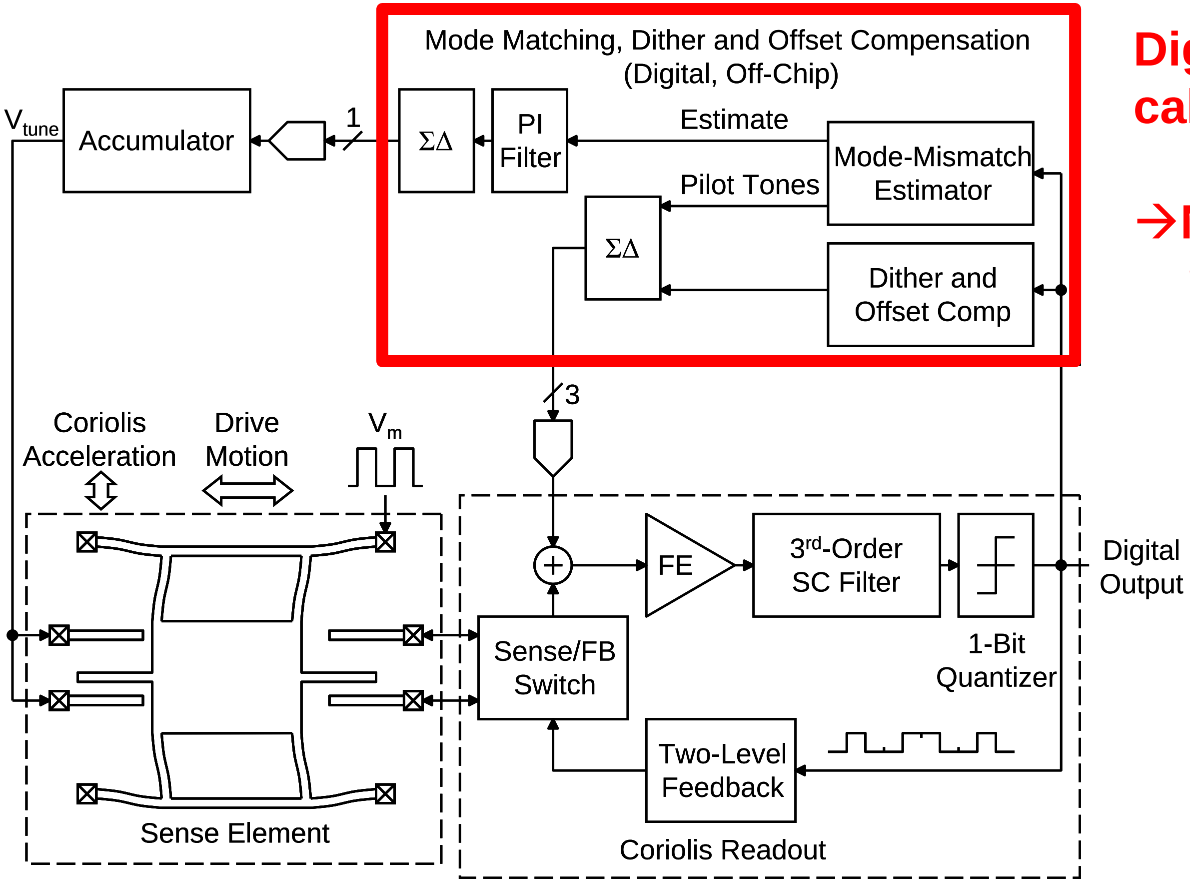


Boxcar Sampler versus Charge Integrator

$$\frac{SNR_{BS}}{SNR_{CI}} = \underbrace{\left(\frac{1}{1-F}\right)^2}_{\text{feedback penalty}} \underbrace{\left(\frac{n_\tau}{2}\right)}_{\text{settling penalty}}$$

- $n_\tau = T_s / \tau_{amp}$ of charge integrator
- F = feedback factor of charge integrator
- Typical SNR improvement ~10dB
- ***10x power savings!***

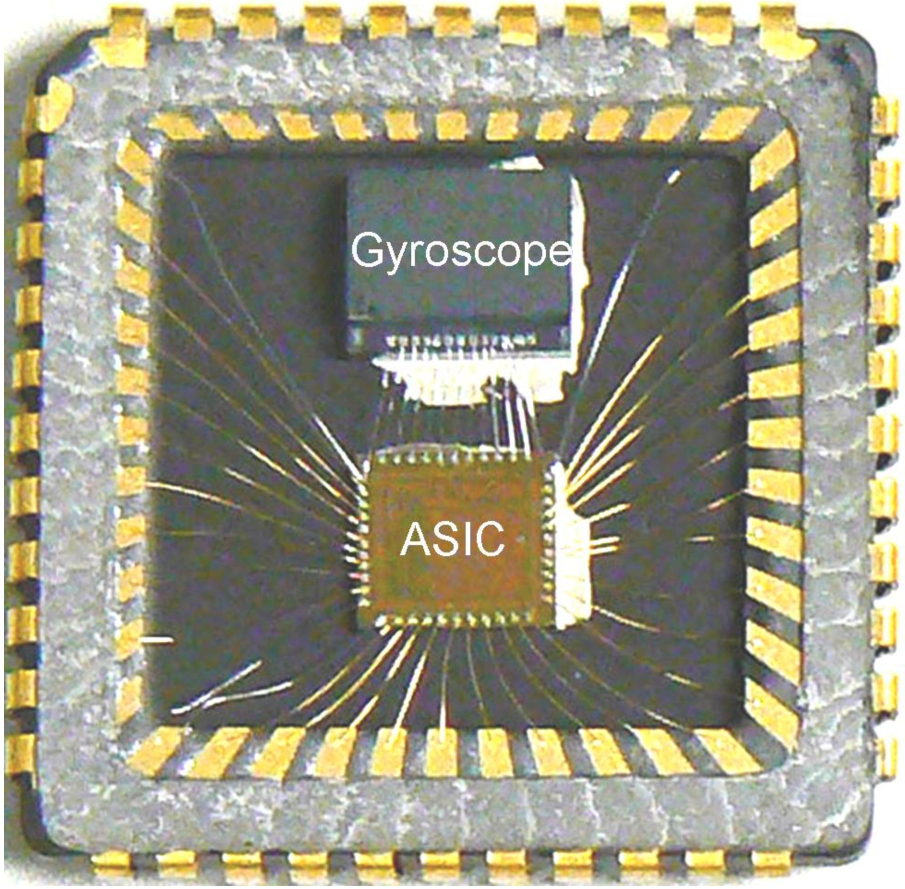
System Block Diagram



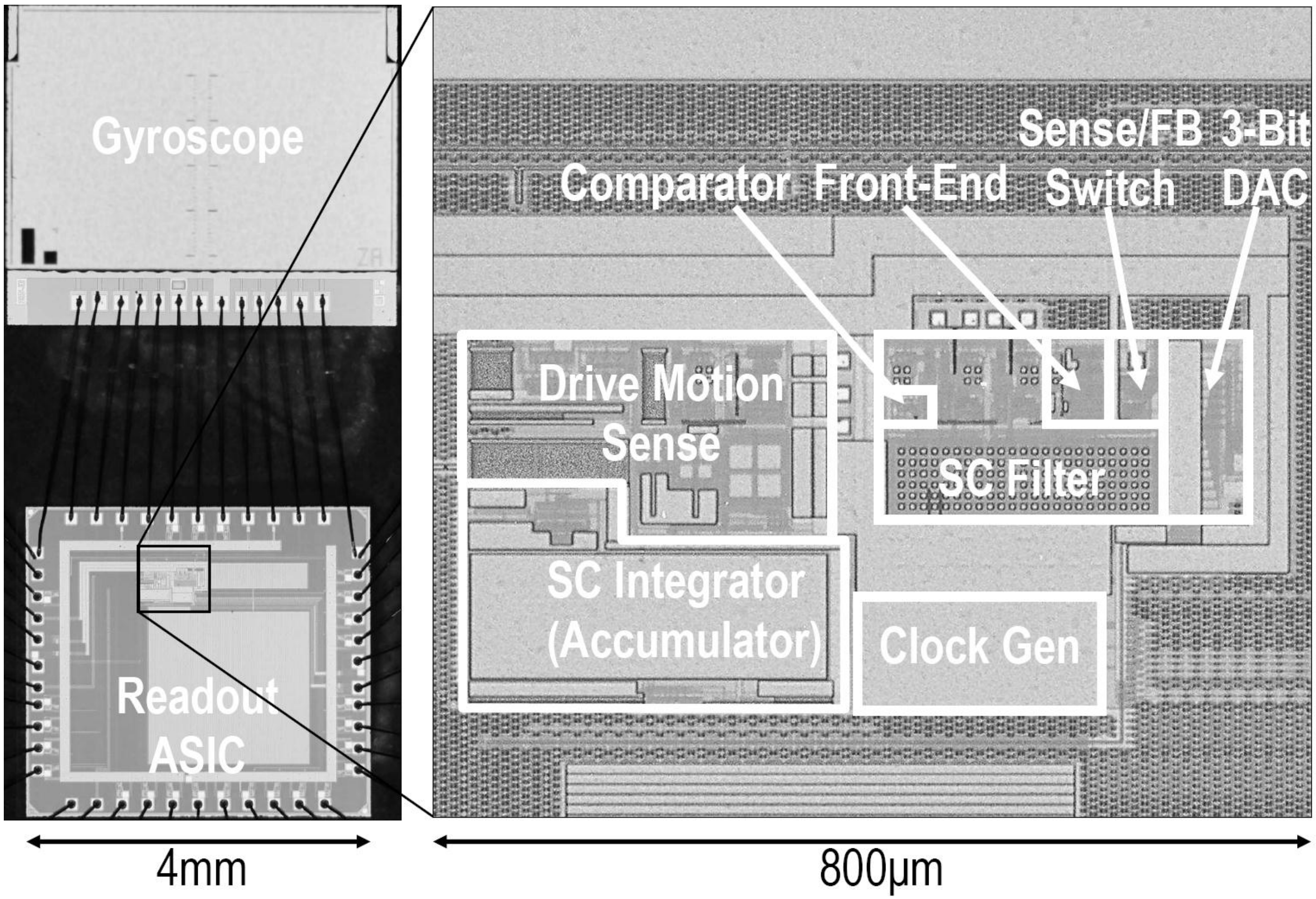
Digital background calibration

→Negligible power penalty

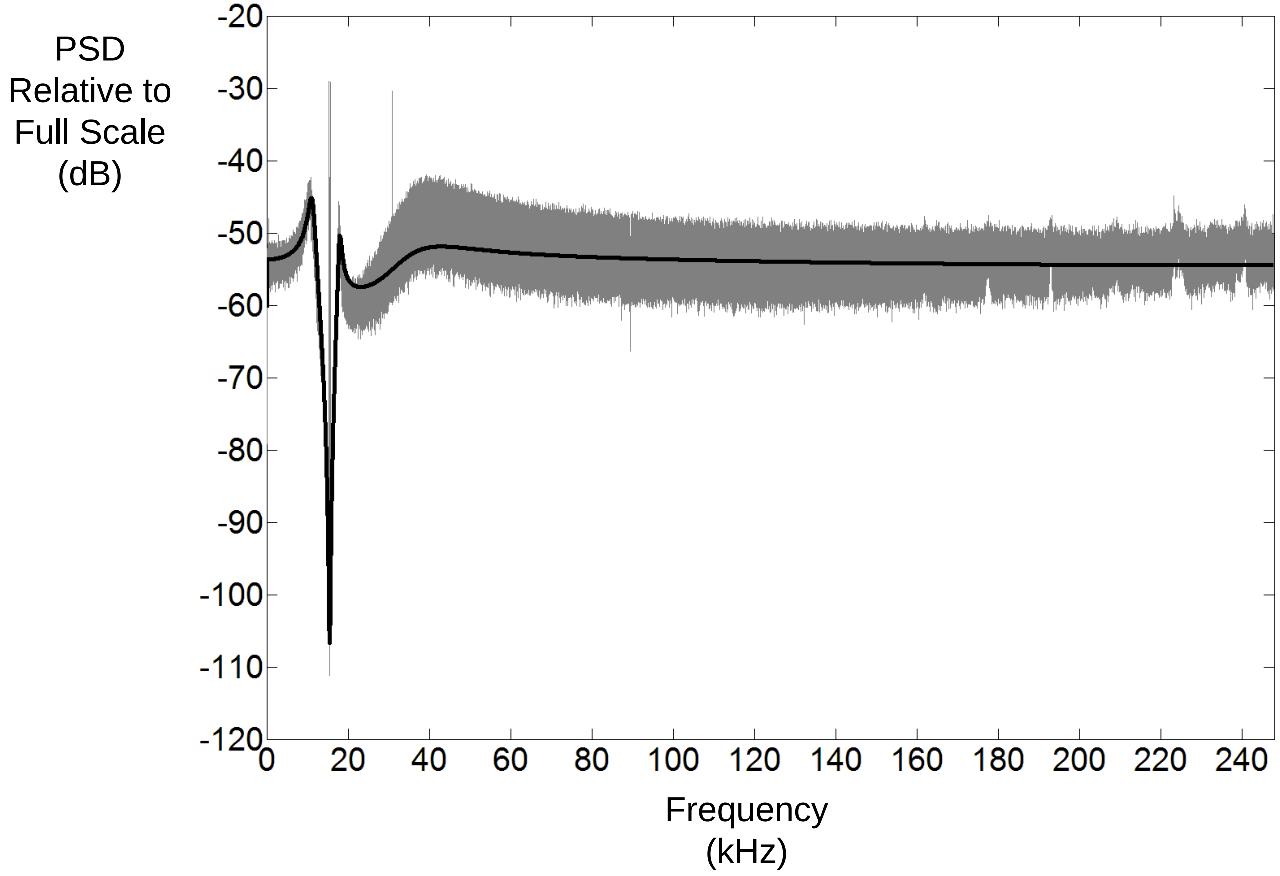
Chip Photo



Chip Micrograph



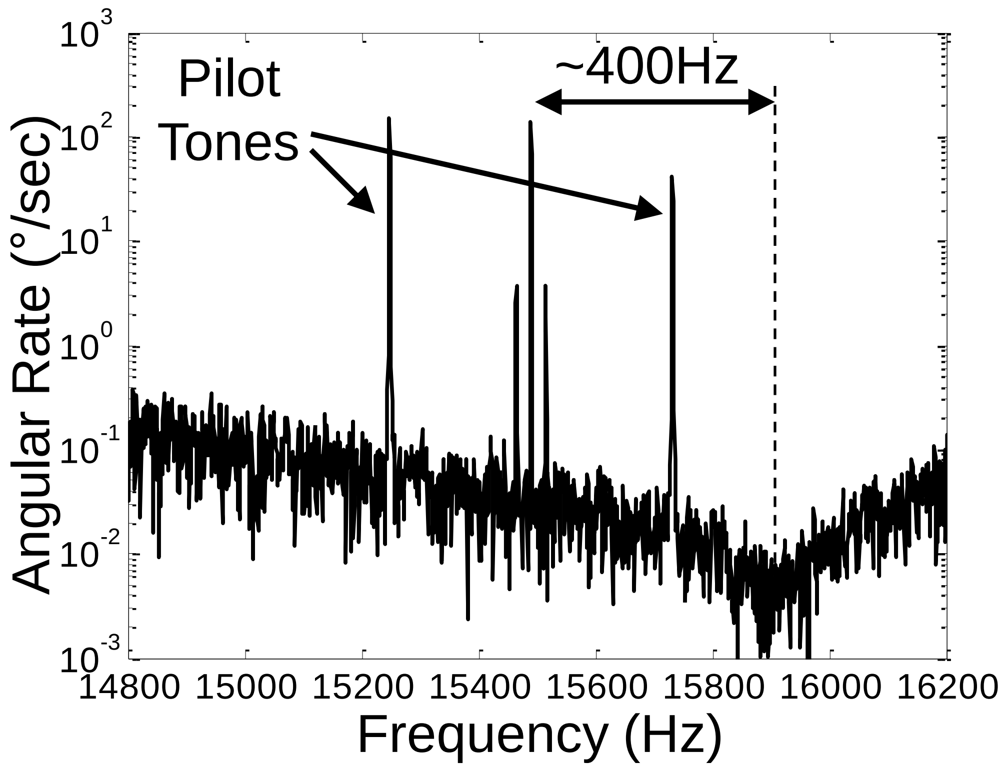
Output Spectrum



Output Spectrum

Without calibration

- Noise Floor:
  0.03°/s/√Hz
- Mismatch:
  ~400Hz (2.6%)



Output Spectrum

Without calibration

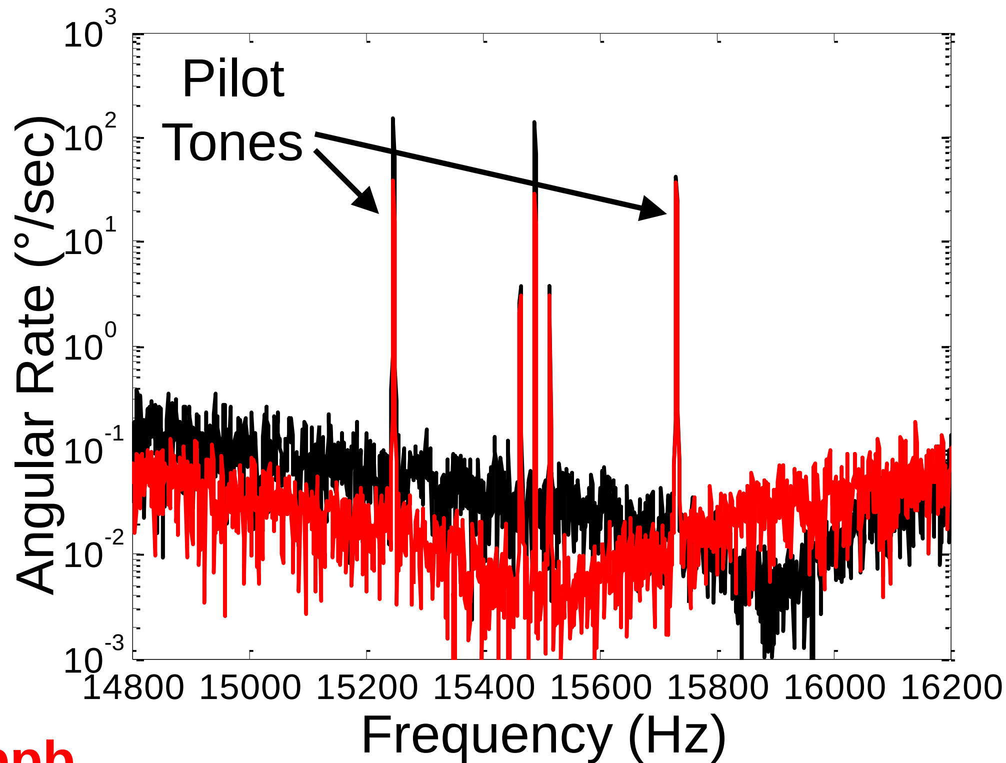
- Noise Floor:
  0.03°/s/√Hz
- Mismatch:
  ~400Hz (2.6%)

With Calibration

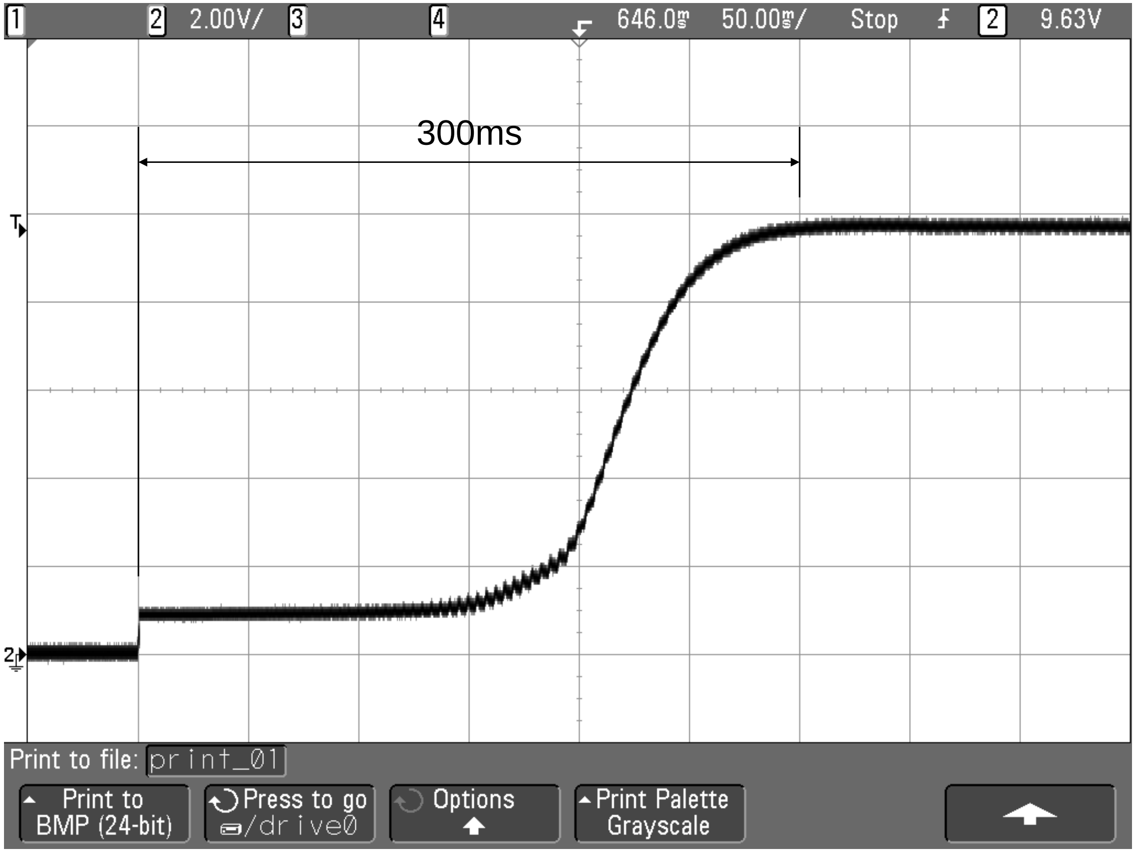
- **Noise Floor:**
  0.004°/s/√Hz
- **Mismatch:**
  << 50Hz (0.3%)

Capacitance resolution

- **1Hz bandwidth**
  0.3aF/12.5pF = 24ppb



Tuning Voltage Startup Transient



Results Summary

- Power dissipation:
  1mW (excluding drive)
- Front-end power reduction:
  - Mode-matching: 100x
  - Boxcar sampling: 10x
- 1000x combined power savings!

Comparison to previous work

Reference	Power (mW)	Noise (°/sec/√Hz)	BW (Hz)	Tuning Time (sec)
[1]	30	0.05	20	-
[2]	13	1	40	-
[3]	31	0.05	36	-
[4]	6	-	0.2	140
This work	**1**	**0.004**	**50**	**0.3**

[1] Geen, JSSC 2002

[2] Petkov, ISSCC 2004

[3] Saukoski, ESSCIRC 2006

[4] Sharma, ISSCC 2007

Conclusions

- Power savings
  - Mechanical gain → 100x reduction
  - Open-loop charge amplifier → 10x reduction
  - Digital processing occurs minimum power overhead
- Techniques
  - Background calibrated mode matching
    → insensitive to process variations
  - Positive feedback
    → insensitive to parasitic modes

Acknowledgements

- Christoph Lang & Vladimir Petkov
- Robert Bosch Corporation
  Gyroscope and financial support