CMOS Systems & Interfaces for Sub-deg/hr Microgyroscopes

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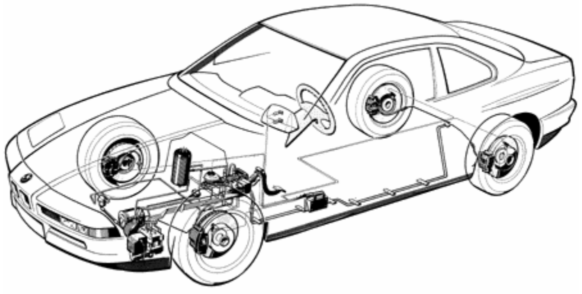
Outline

- ❑ Mode-Matched Tuning Fork Gyroscope (M^2-TFG)
- ❑ System level considerations for MEMS interfacing
- ❑ Transimpedance amplifier (TIA) front-ends
- ❑ T-network TIA
- ❑ Circuit implementation of gyro sub-systems
- ❑ Interfacing results
- ❑ Conclusions

Market Demands

- Automotive Applications



- Consumer Applications
  - Image stabilization in digital cameras
  - Smart user interfaces
  - Short range navigation

- High-Performance Applications
  - Aerospace
  - Defense
  - Precision inertial measurement units

Performance Classes

	Rate Grade	*Navigation Grade*
Bias drift	10 to 1000 deg/hr	0.01 to 1 deg/hr
Angle random walk	> 0.5 deg/ √ hr	< 0.005 deg/ √ hr
Scale factor accuracy	0.1% to 1%	< 10 ppm
Full scale range	50 - 1000 deg/sec	~ 500 deg/sec
Bandwidth	> 70 Hz	~10Hz

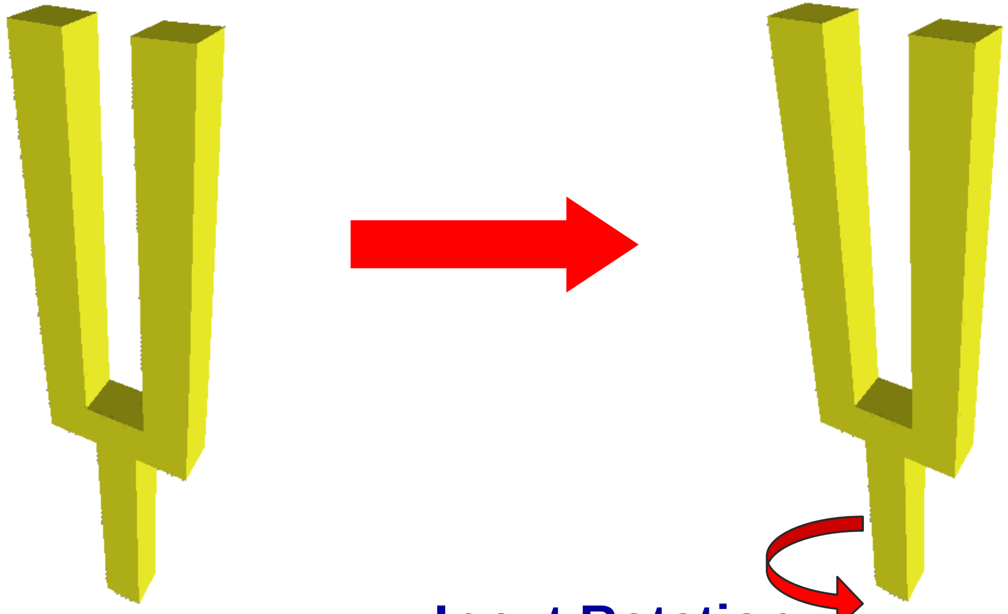
º/hr/√Hz
Resolution

×60

º/√hr
Angle Random Walk

Principle of Operation

- Coriolis Effect
- Tuning Fork
  - Transfer of energy between two vibration modes
  - Deflection proportional to rotation rate

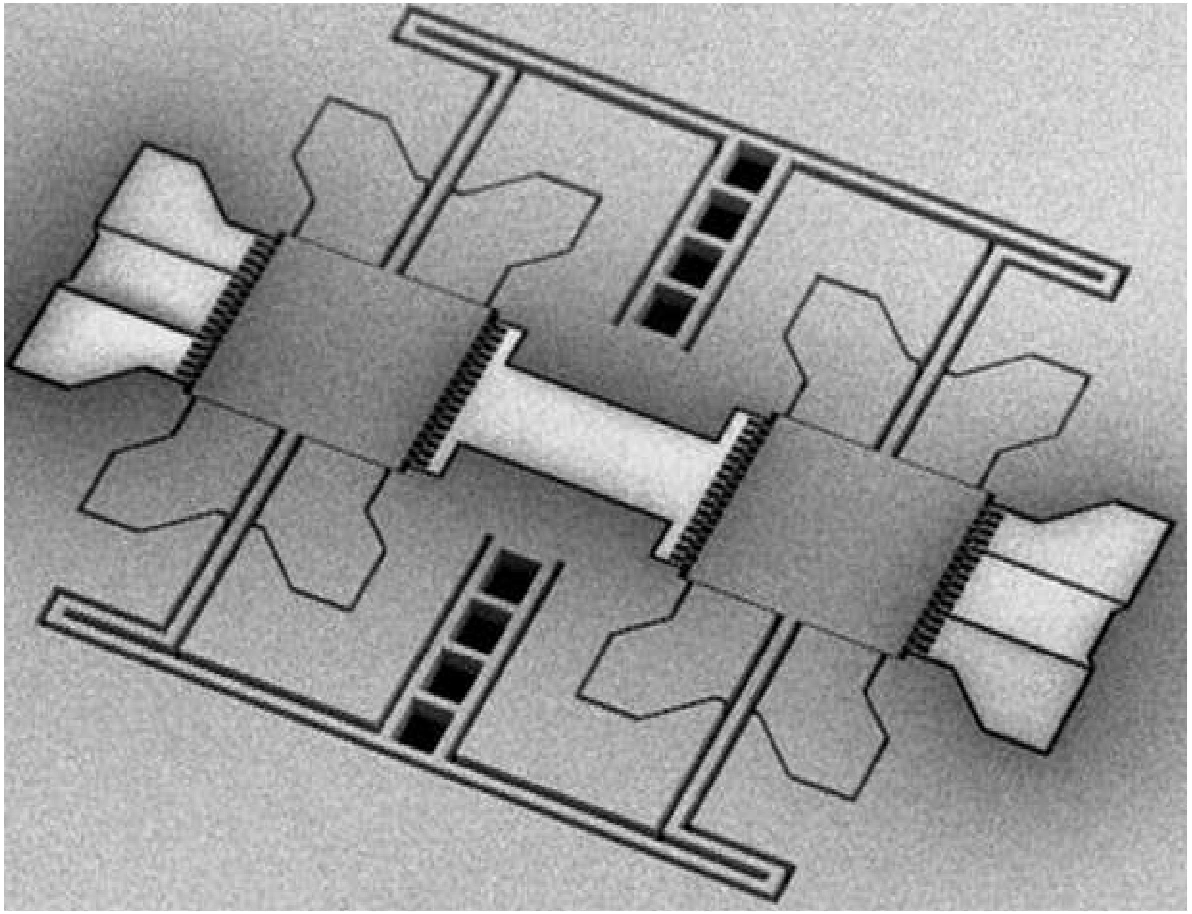


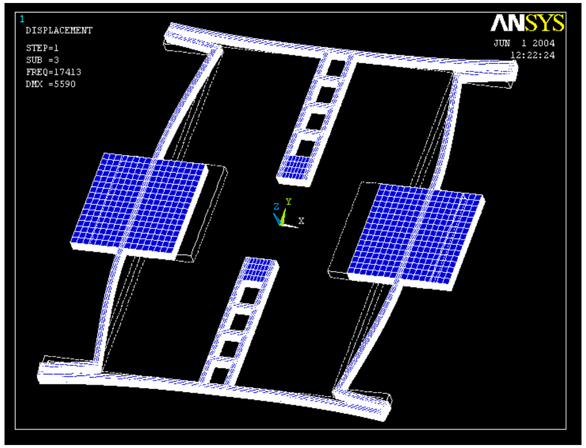
Drive Mode
(x-axis)

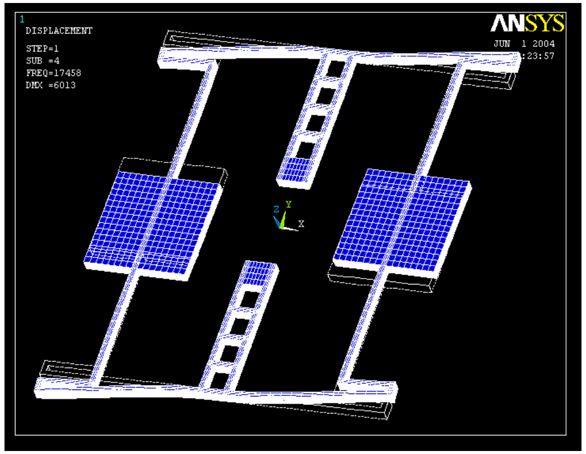
Sense Mode
(y-axis)

Input Rotation
(z-axis)

Mode-Matched Tuning Fork Gyroscope







- ☐ Fabricated on 60µm thick Silicon-on-insulator (SOI)
- ☐ Fully differential and symmetric

Performance Scaling

☐ **Resolution:** Minimum detectable rotation rate

$$\Omega_{min}(Total) = \sqrt{\Omega_{min}(Brownian)^2 + \Omega_{min}(Electronic)^2}$$

$$\Omega_{min}(Brownian) \propto \frac{1}{x_{drive}}\sqrt{\frac{4k_BT}{\omega_0 M Q_{EFF}}}$$

$$\Omega_{min}(Electronic) \propto \frac{\omega_0 V_n}{Q_{EFF}}\left(\frac{\text{sense gap}}{\text{thickness}}\right)$$

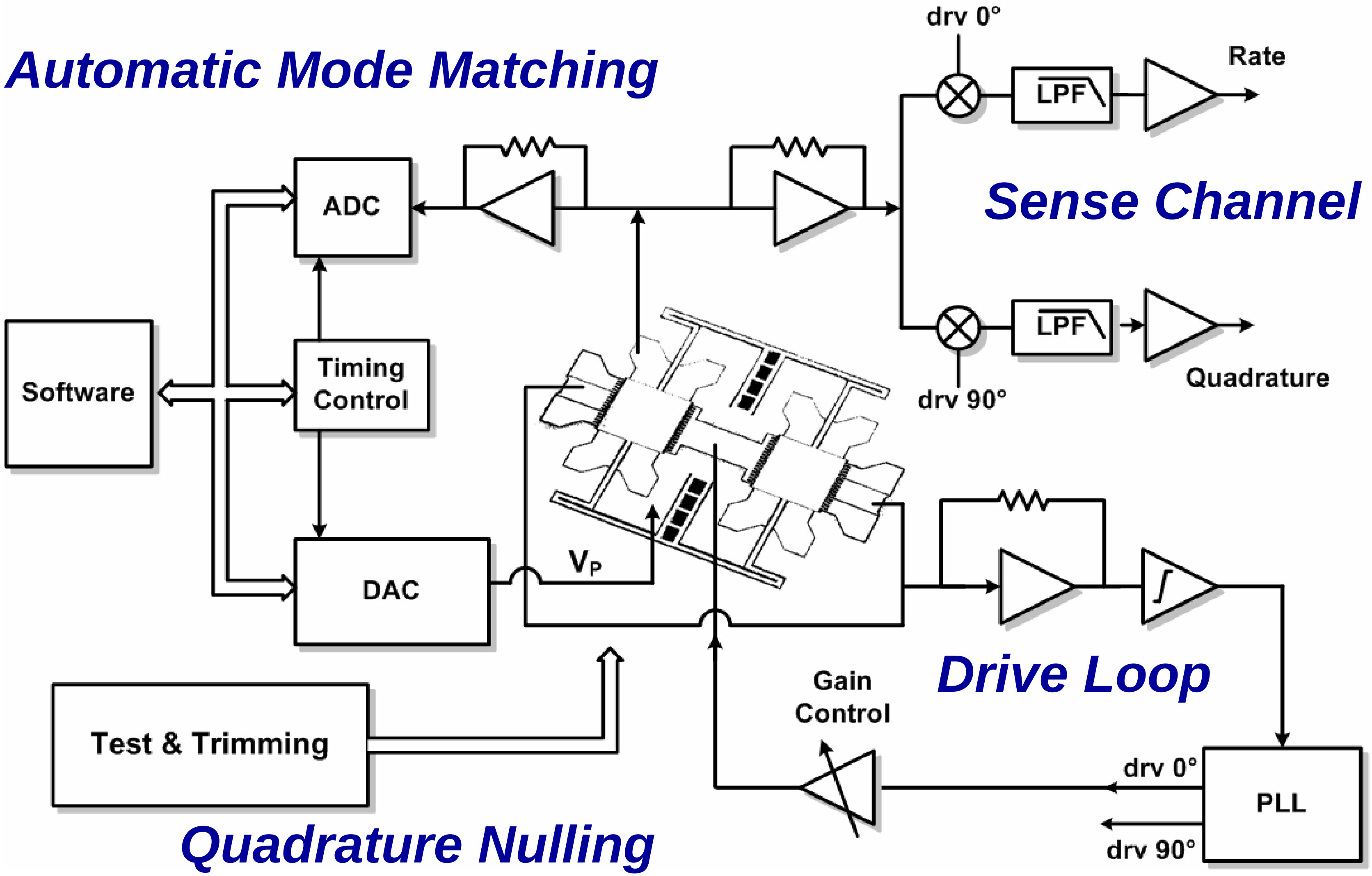
☐ **Scale Factor:** Sensitivity to rotation

$$S_{OUT} \propto \frac{V_P Q_{EFF}}{\text{sense gap}}\Omega_Z$$

☐ **Drift:** Long-term accuracy & stability

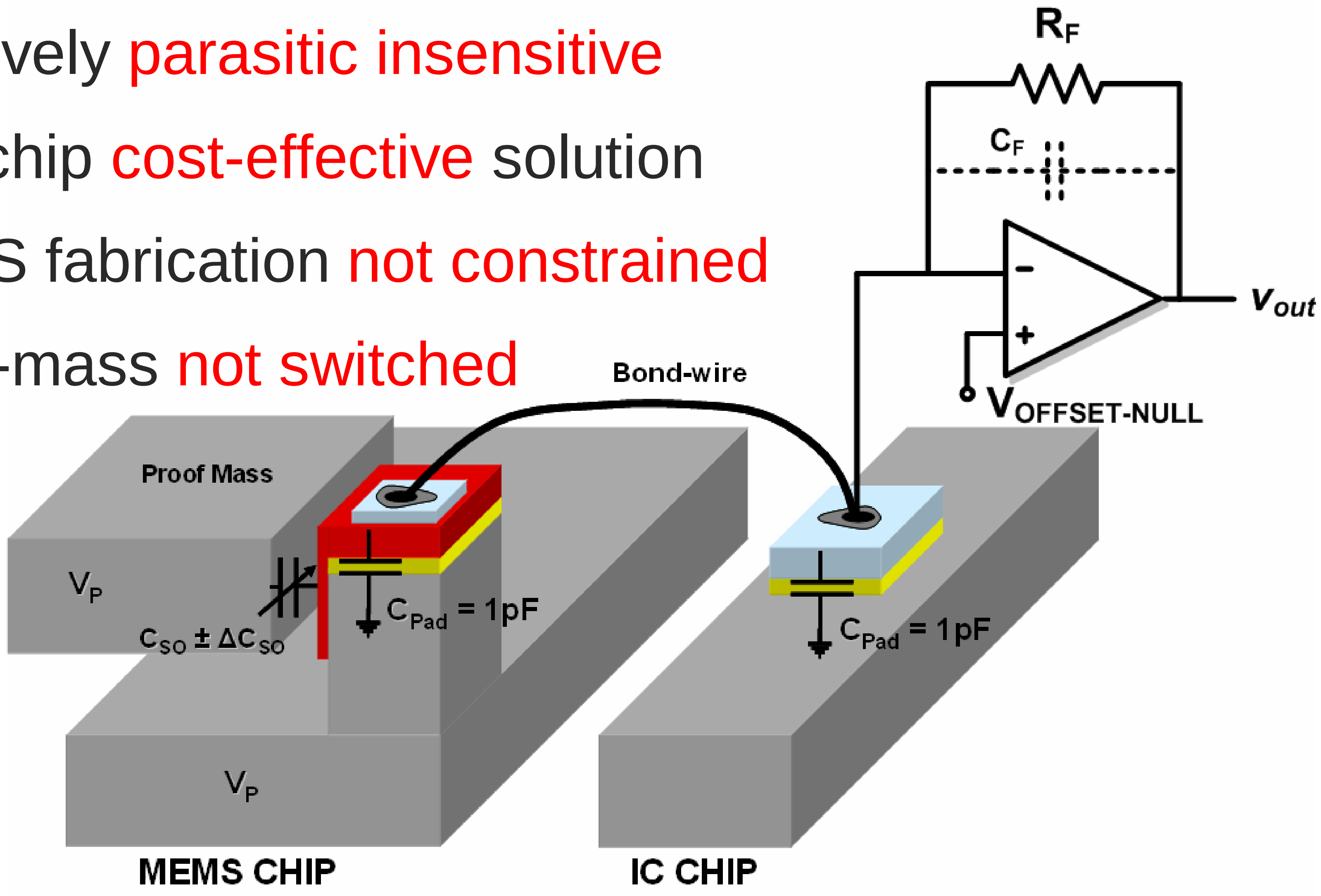
$$N_B \propto \frac{\omega_0^2}{Q_{EFF}^2 Area_{electrodes}}$$

M^2-TFG System Electronics



Transimpedance Amplifier (TIA) Front-end

- Relatively parasitic insensitive
- Two-chip cost-effective solution
- MEMS fabrication not constrained
- Proof-mass not switched



Motional Current and Impedance

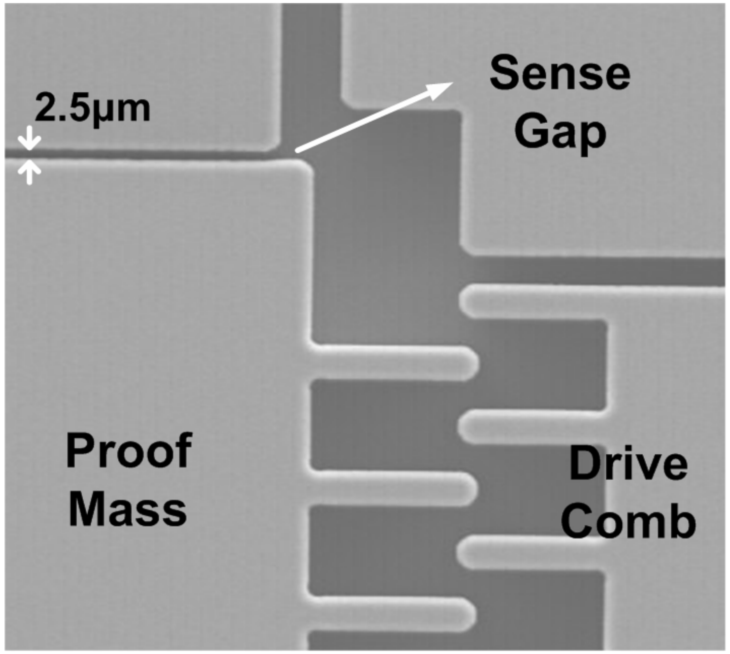
- ☐ Current due to input rotation

$$I_{SENSOR} \ \alpha \ \frac{V_P Q_{sense} \, q_{drive}}{d_{so}} \ \Omega_Z$$

Typical motional current levels 1pA – 1nA

Implication of large motional impedance

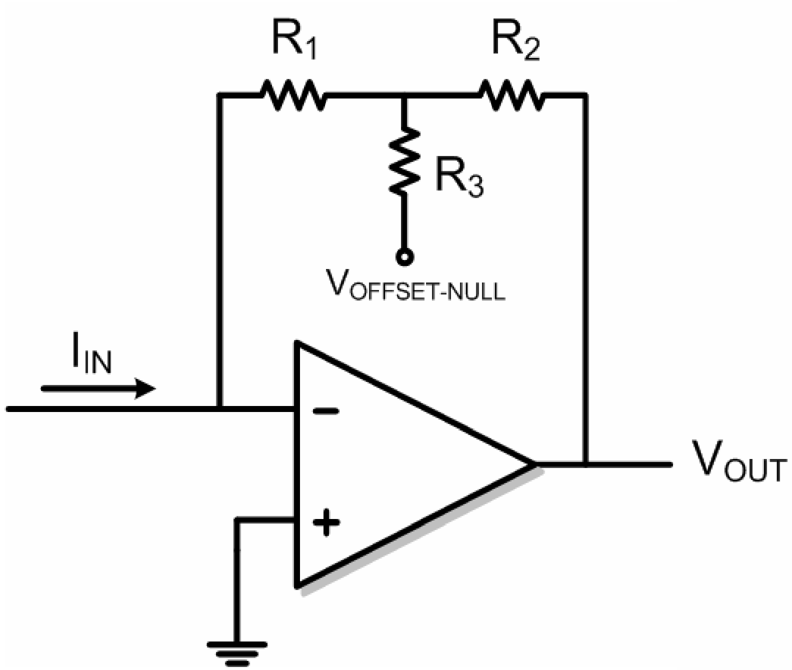
- ☐ Higher drive voltages
- ☐ Large on-chip transimpedances
- ☐ Higher power dissipation

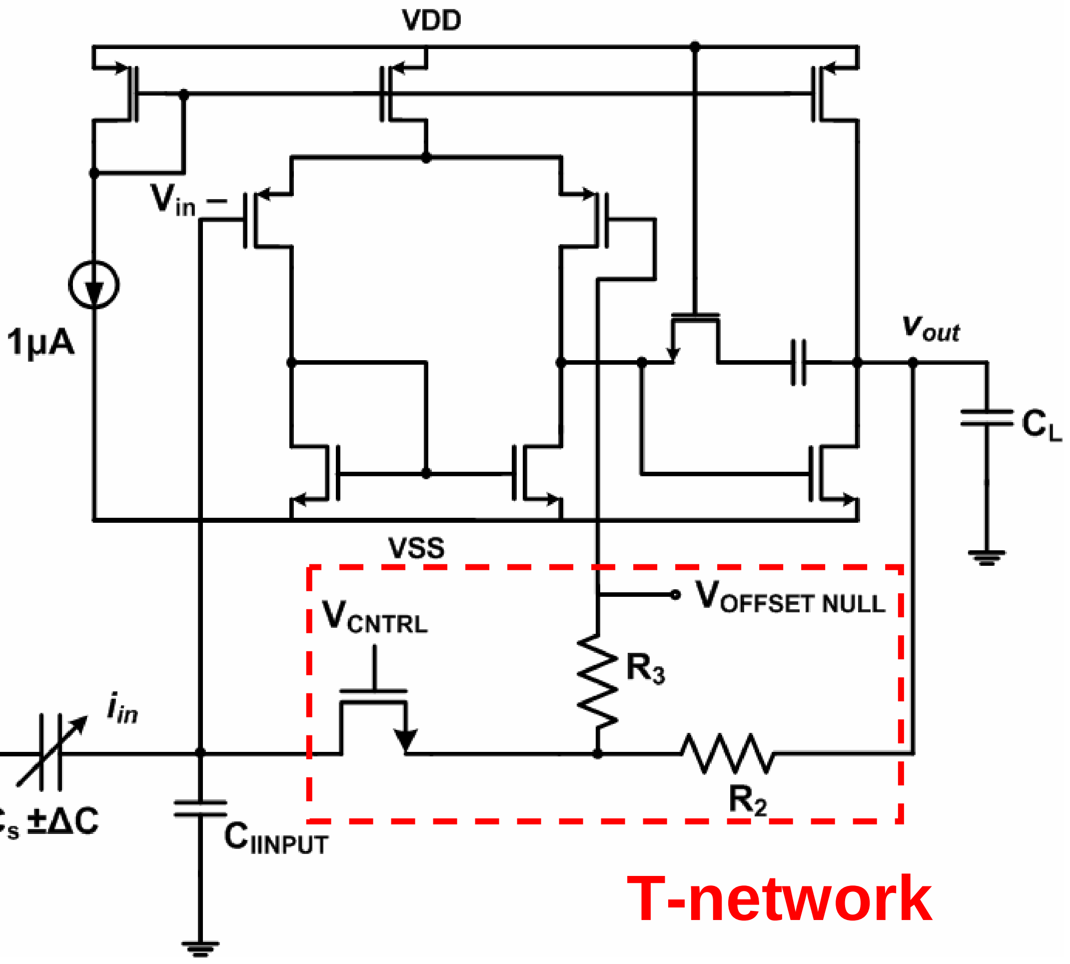


Close-up of sense gap and drive combs

Typical Impedance values 1 – 10 MΩ

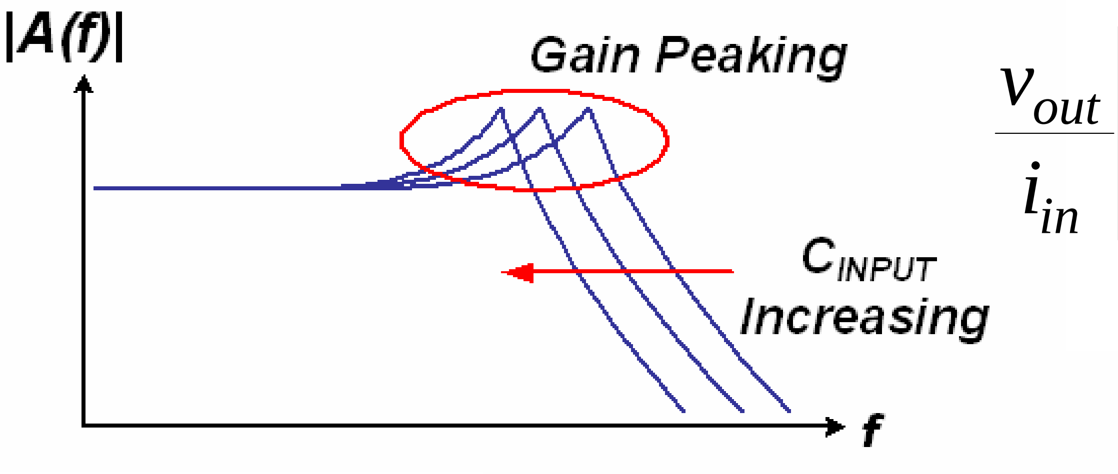
T-network TIA





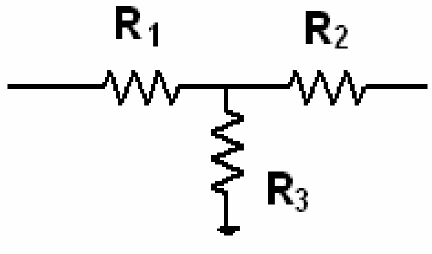
$$\frac{V_{out}}{I_S} = \frac{R_1 R_2}{R_2 \| R_3} + R_2$$

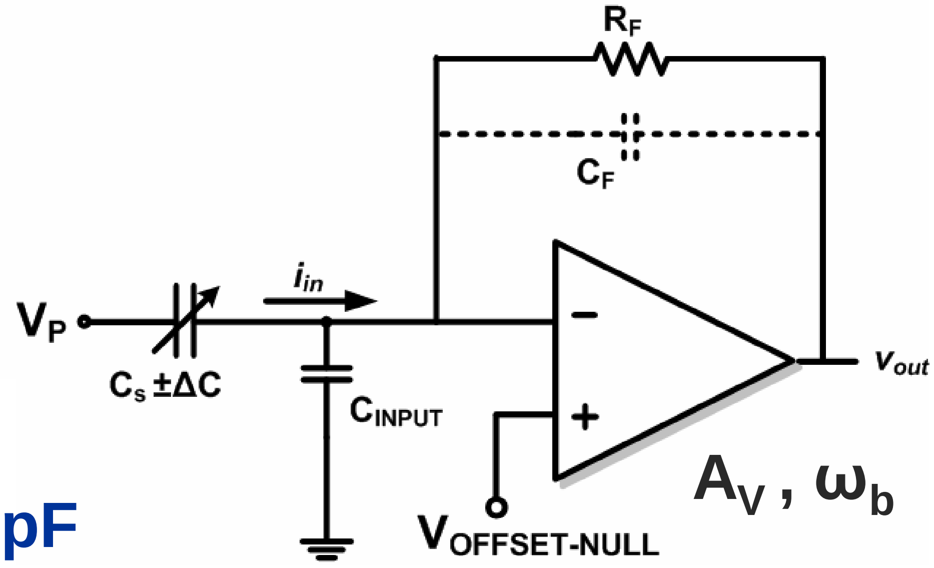
Design Considerations



$$\left.\frac{v_{out}}{i_{in}}\right|_{OL} = \frac{A_v R_F}{\left(1 + \frac{s}{\omega_b}\right)\left(1 + \frac{s}{\omega_{in}}\right)}$$

$$\boxed{\frac{R_2}{R_3} \leq \frac{C_{INPUT}}{C_F}}$$



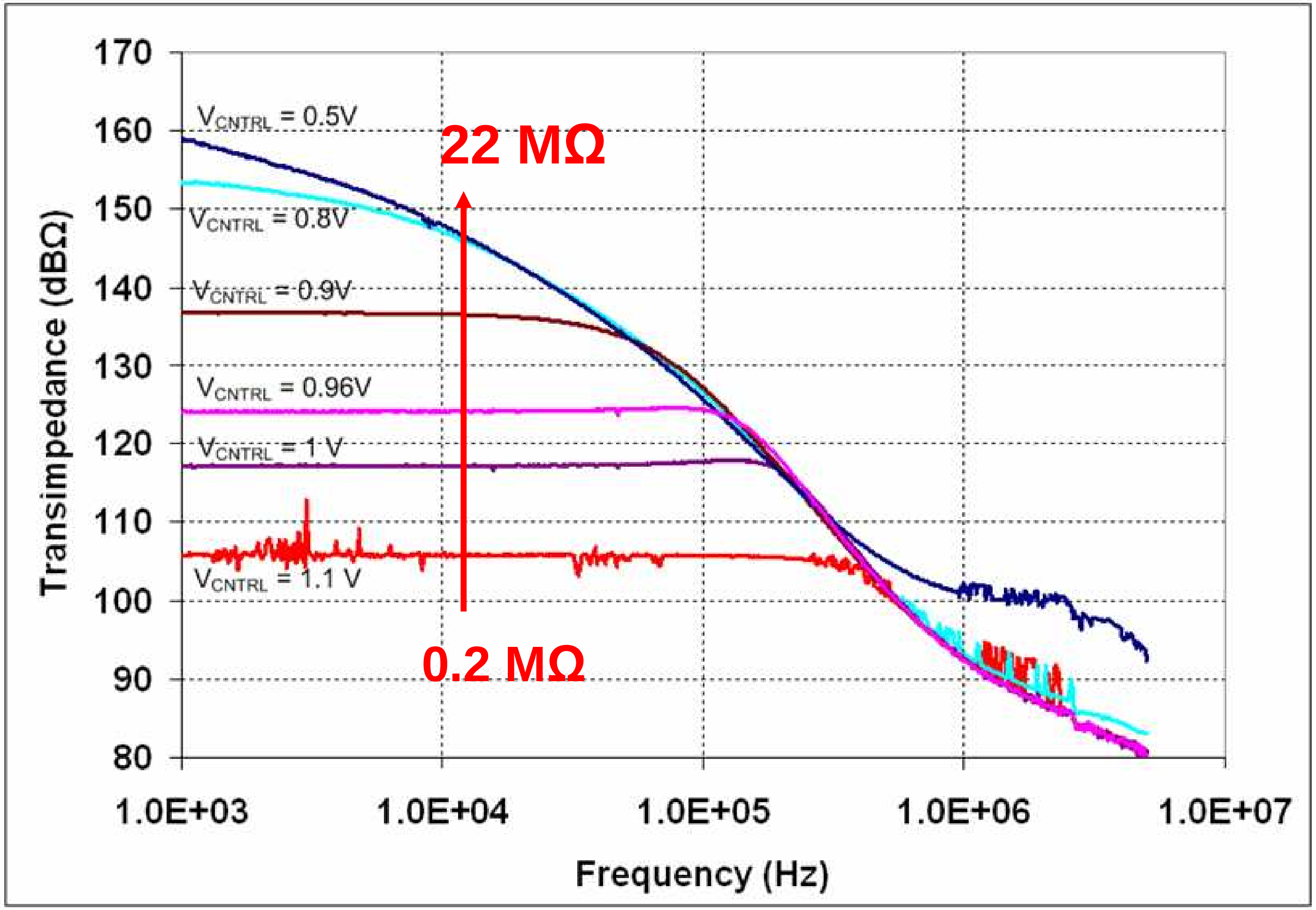


C_{INPUT} ~ 2 – 10pF

C_F ~ 0.5pF

Transimpedance Gain of T-network TIA

- Maximum transimpedance (at 10kHz) ~ 22MΩ

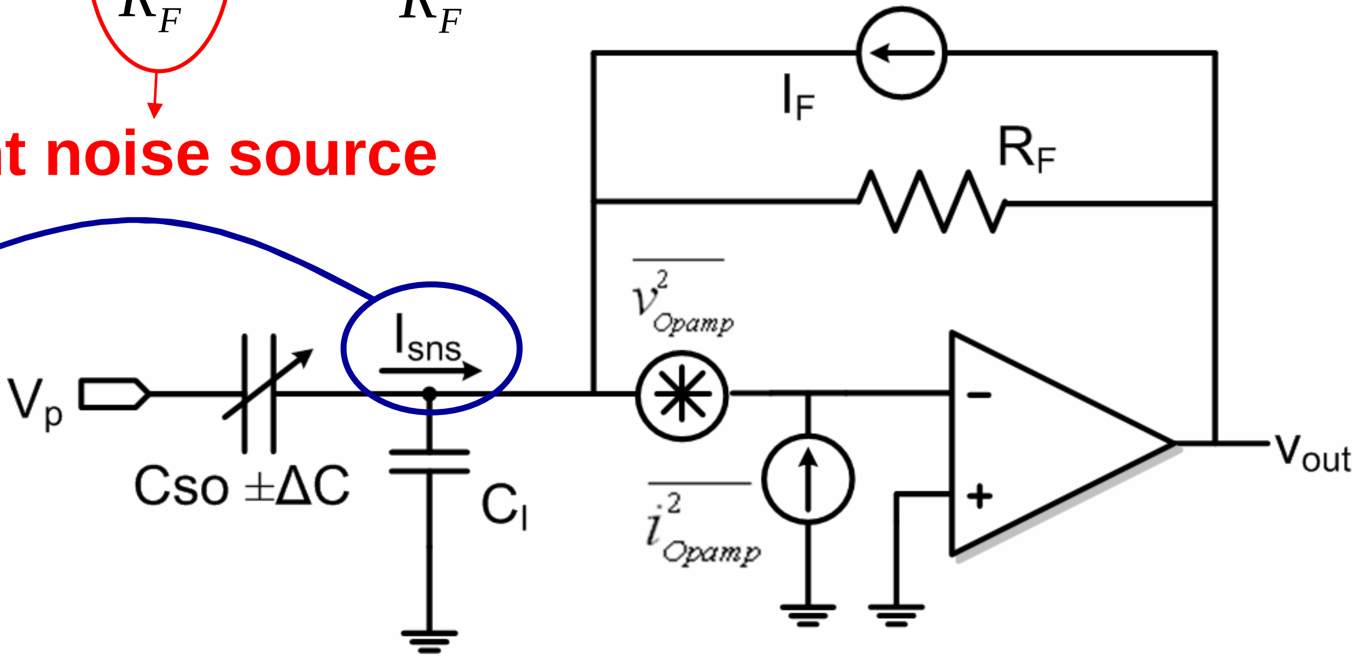


Noise and SNR in TIAs

$$\overline{i^2_{TOT}} \approx \overline{i^2_{OPAMP}} + \boxed{\frac{4kT}{R_F}} + \frac{\overline{v^2_{OPAMP}}}{R_F^2}$$

R_F is dominant noise source

$i_{in} = V_P \omega_o \Delta C$

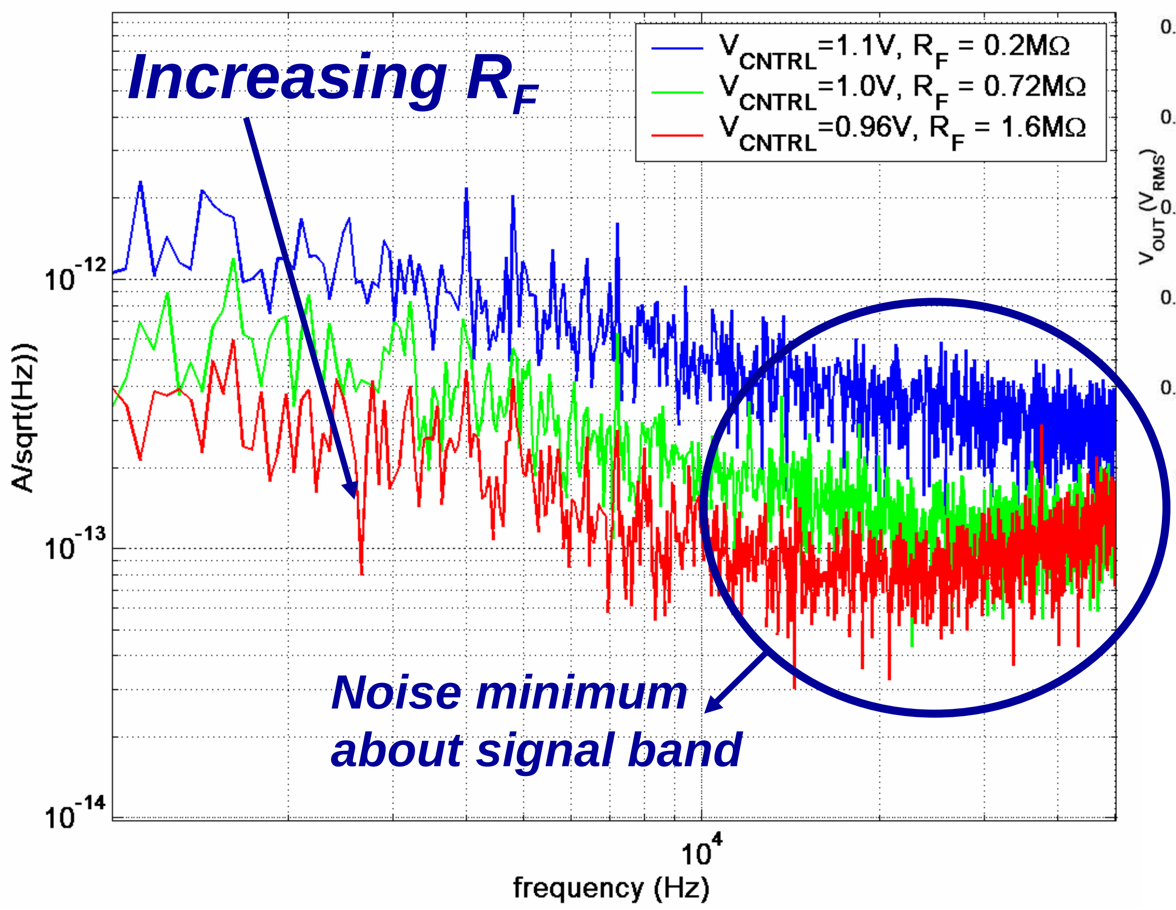


$$SNR = \frac{S_O}{N_O} = \frac{I_{SNS}}{I_{NOISE}} = \frac{I_{SNS}\boxed{\sqrt{R_F}}}{\sqrt{4kT}}$$

Noise Characterization of the T-network TIA

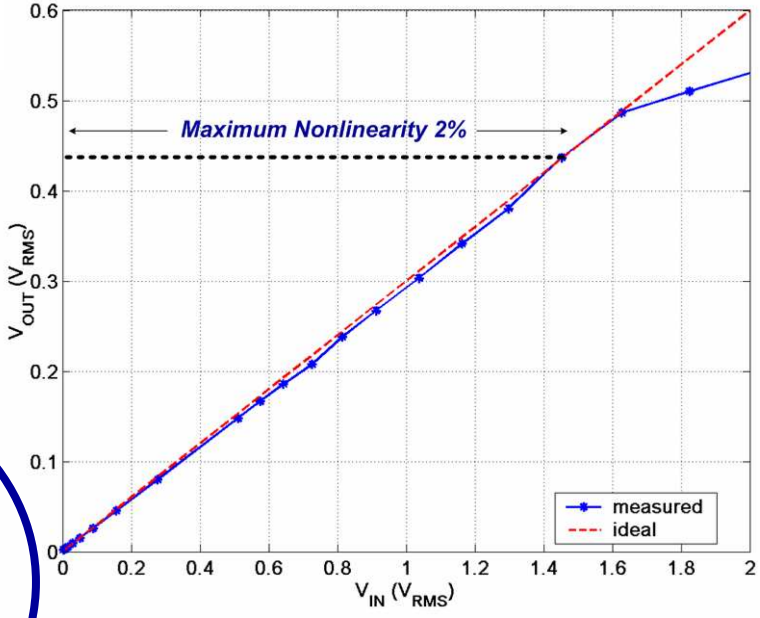
- ☐ Input referred current noise ~ **88fA/√Hz** i.e. ΔC_{MIN} = **0.02aF/√Hz**

  (for R_F =1.6MΩ)



Increasing R_F

Noise minimum about signal band

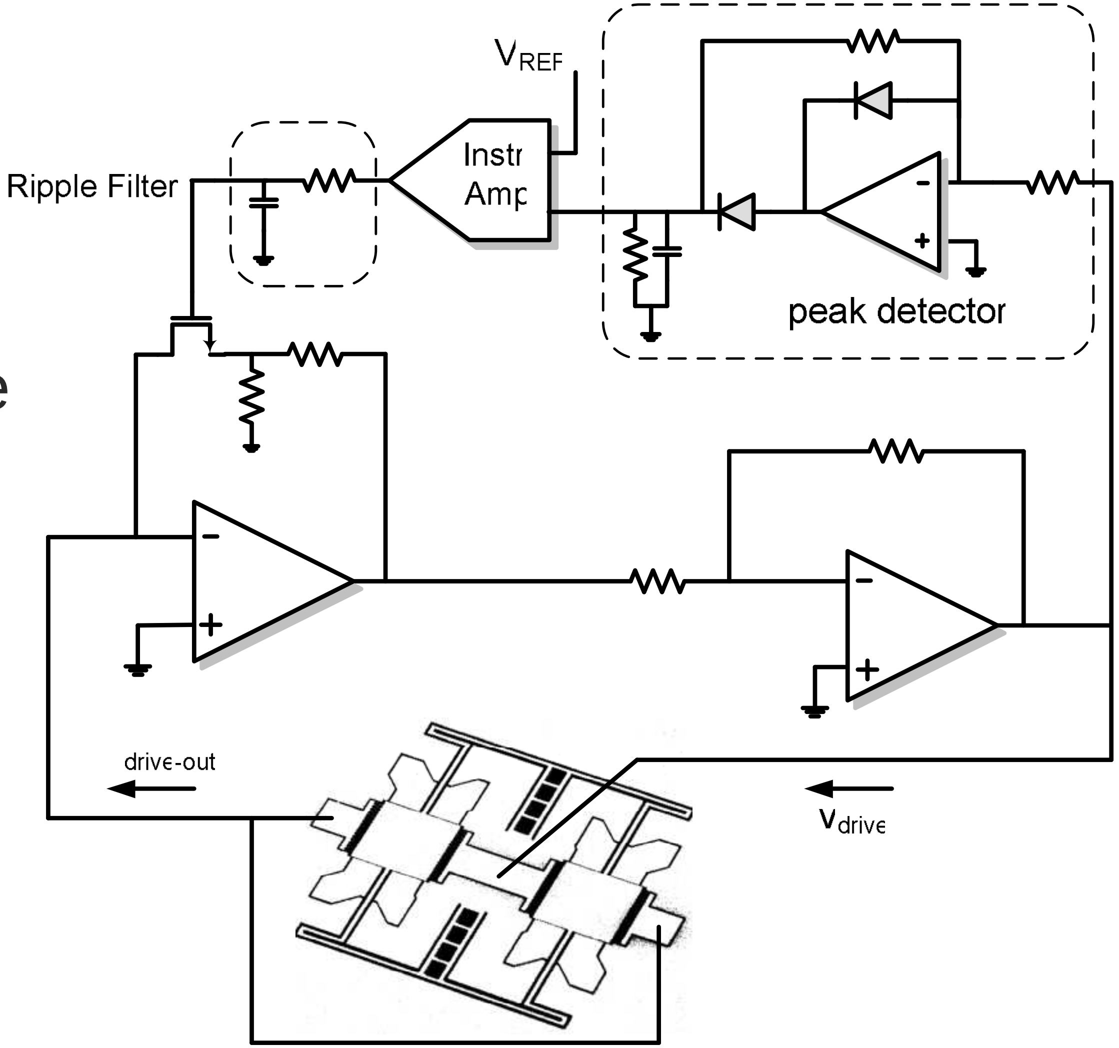


$$DR_{MAX} = \frac{max\ output\ signal}{noise\ floor \times Bandwidth}$$

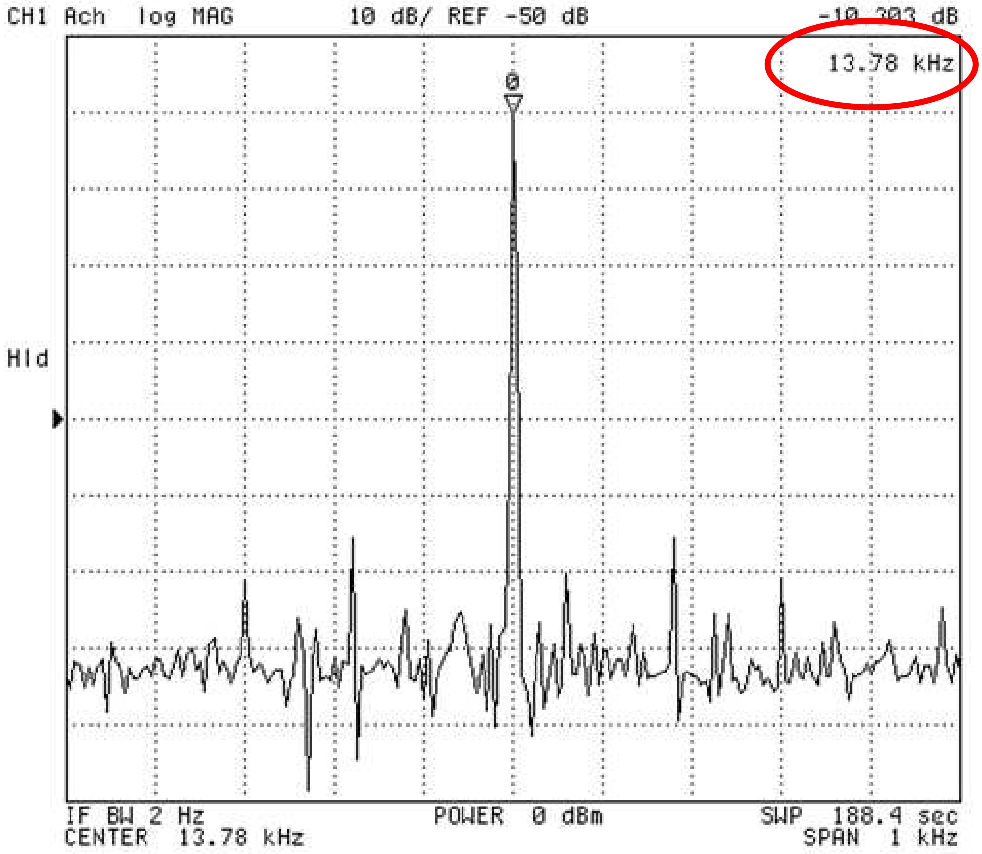
$$\boxed{DR_{MAX} \sim 104dB}$$

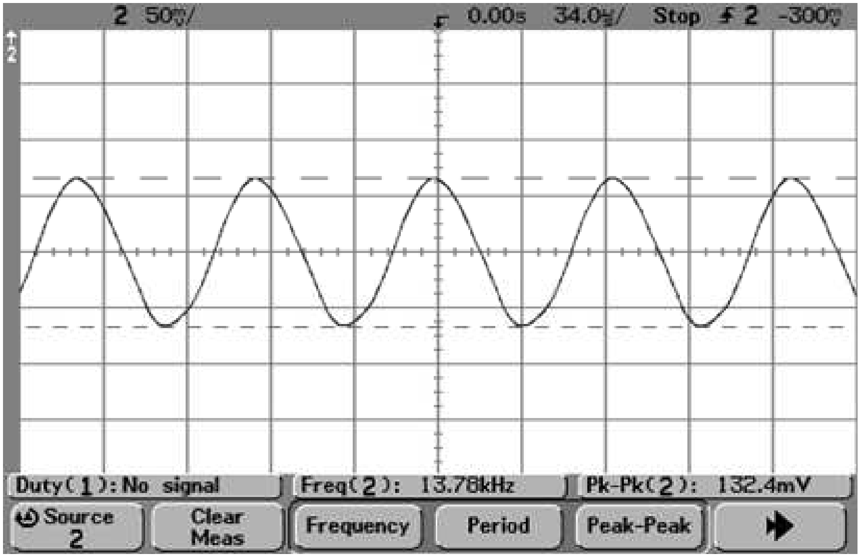
Electromechanical Drive Oscillator

- ❑ Satisfy Barkhausen criteria
- ❑ Automatic Level Control (ALC) maintains constant drive amplitude



Drive Oscillator – spectrum and waveform





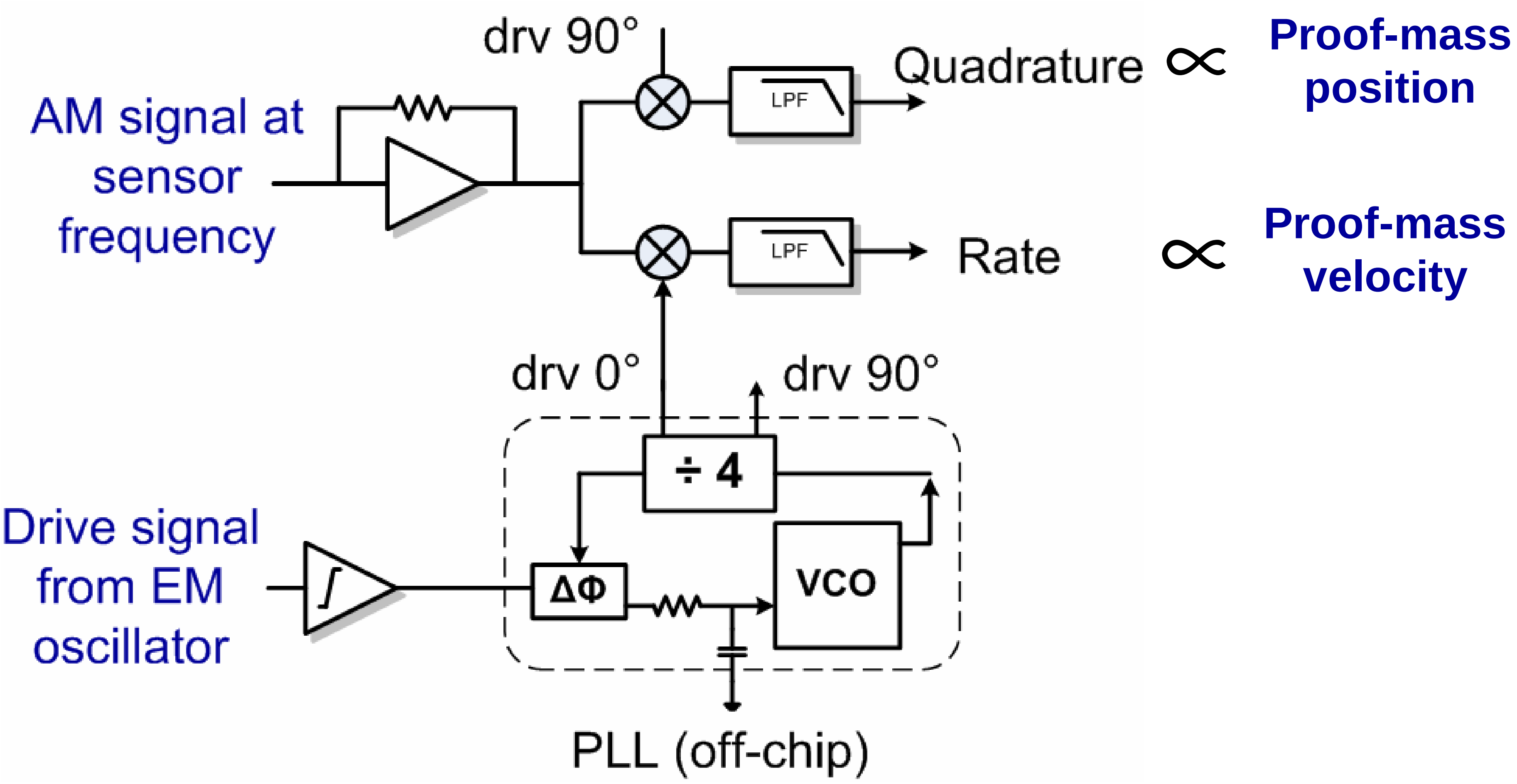
Duty(1): No signal Freq(2): 13.78kHz Pk-Pk(2): 132.4mV

f_{drive} = 13.78kHz

$v_{Pk\text{-}Pk}$ = 132mV

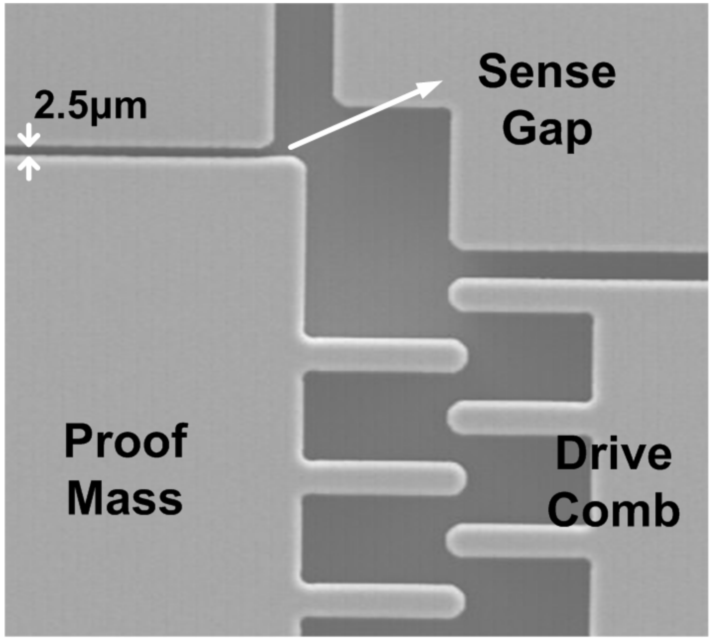
Rate Sensing

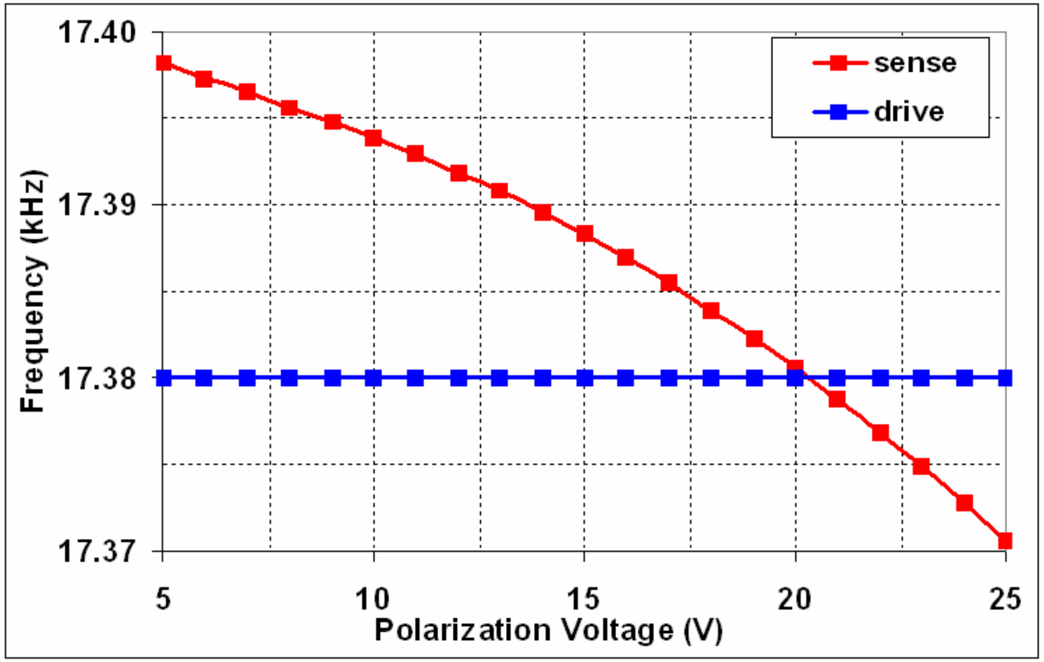
- ❑ Synchronous I-Q demodulation extracts rate information



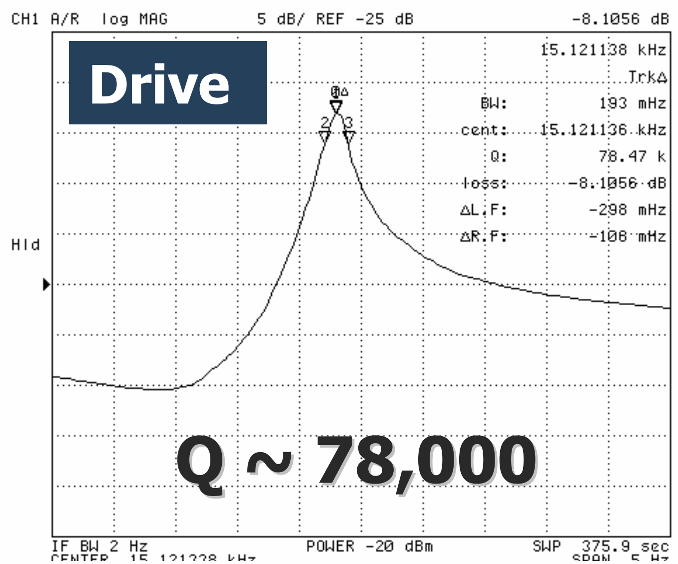
Electronic Frequency Control

- Electrostatic spring softening allows control of *sense mode frequency only* via DC polarization voltage (V_P)
- $f_{SENSE} > f_{DRIVE}$ → Enables tuning despite process variations



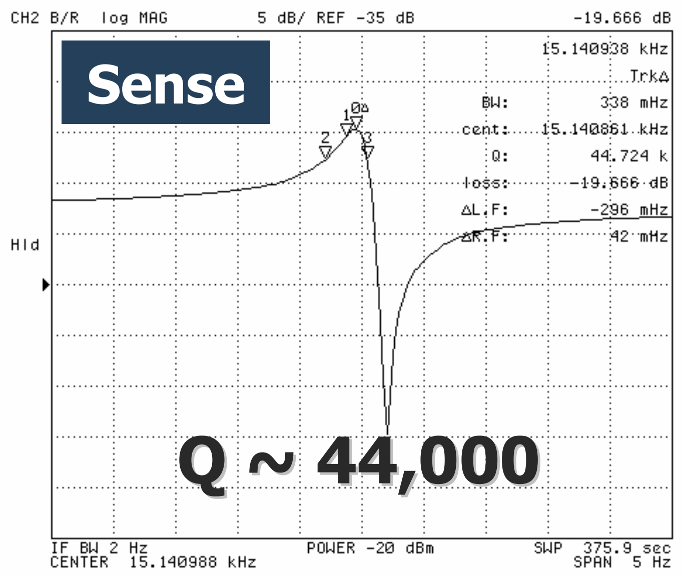


Resonant Modes and Mode Matching



Drive

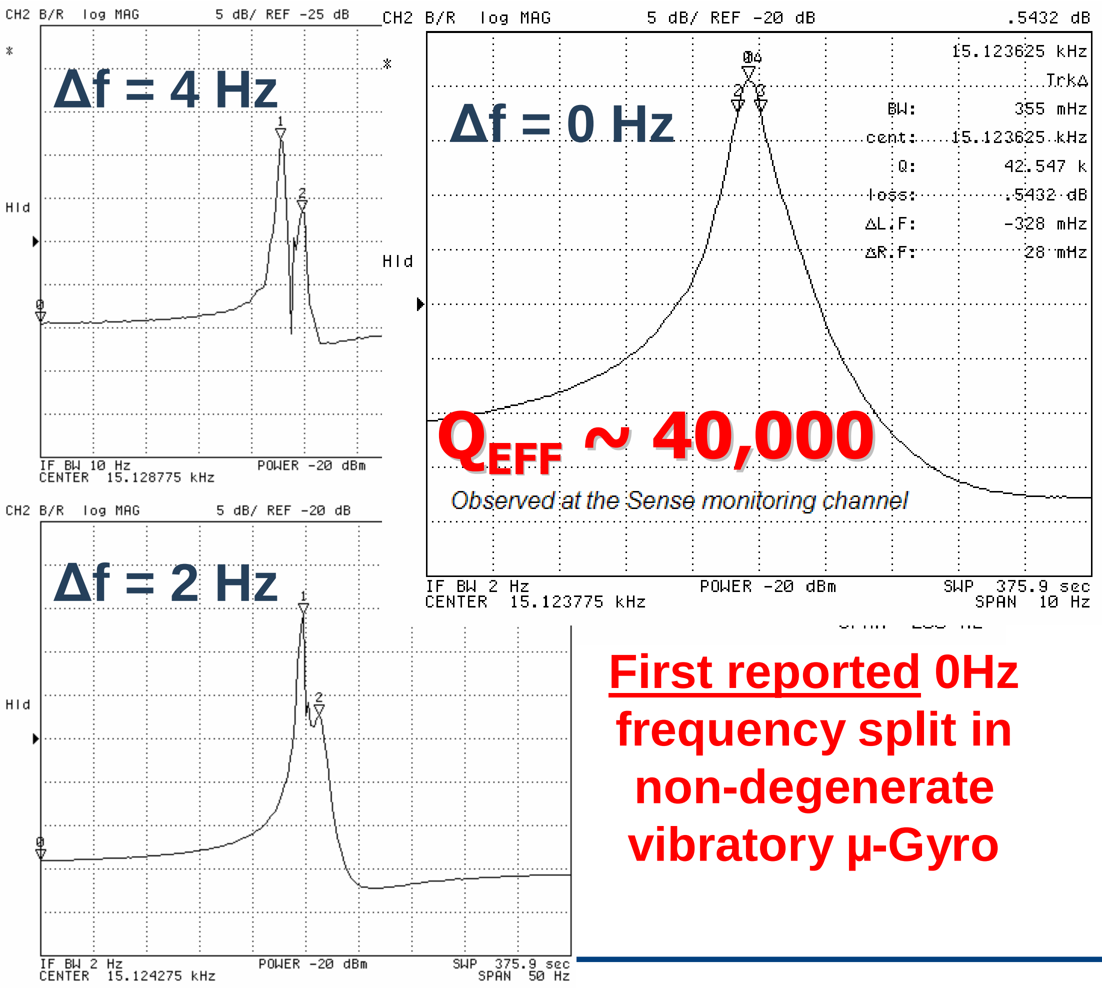
Q ~ 78,000



Sense

Q ~ 44,000

Device Mode-Matching



∆f = 4 Hz

∆f = 2 Hz

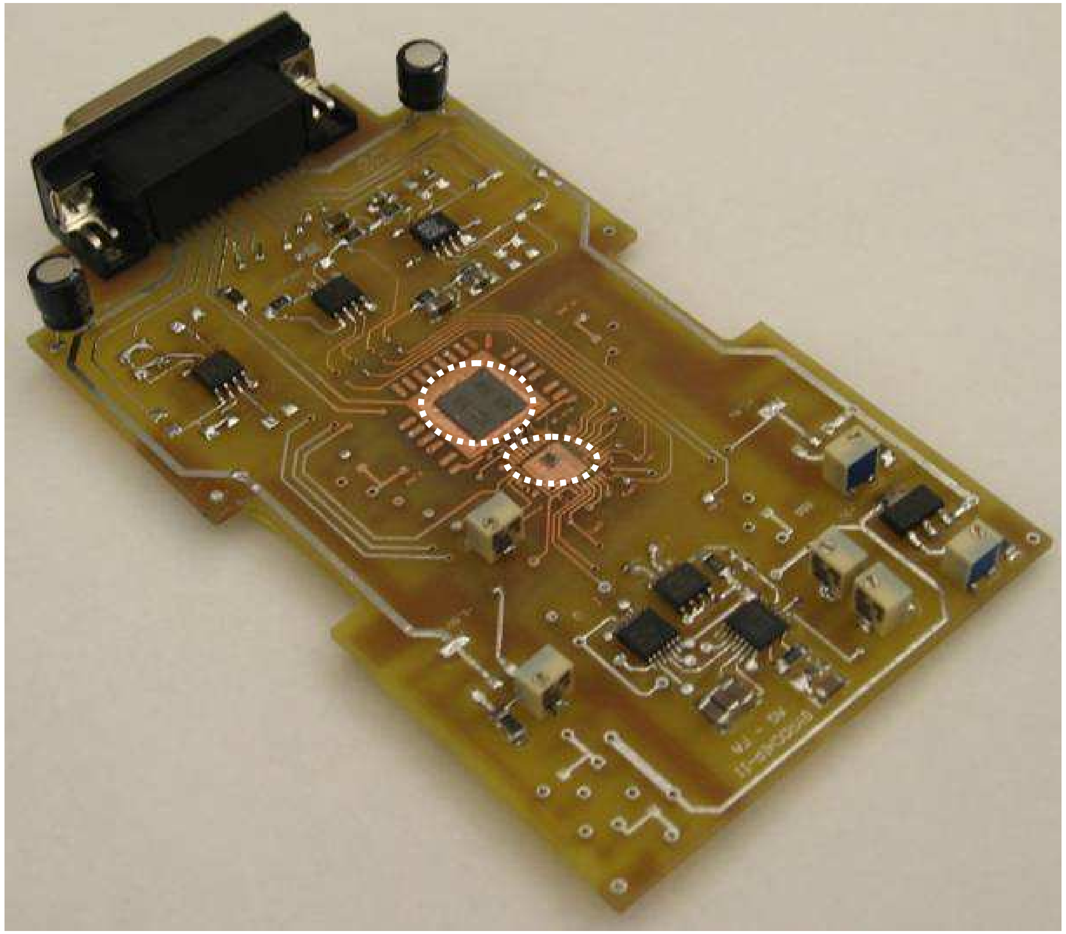
∆f = 0 Hz

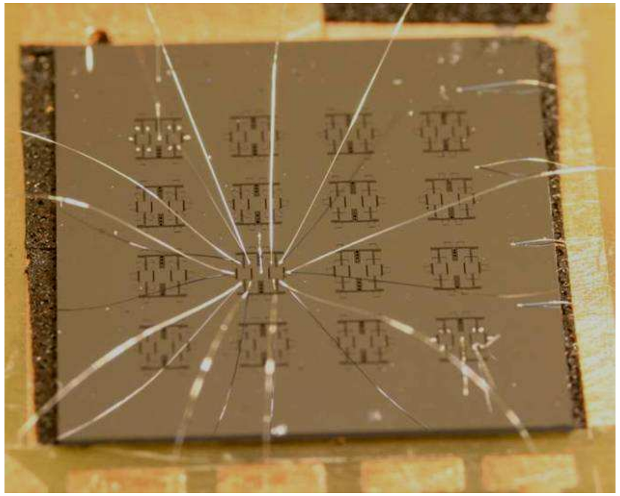
Q_{EFF} ~ 40,000

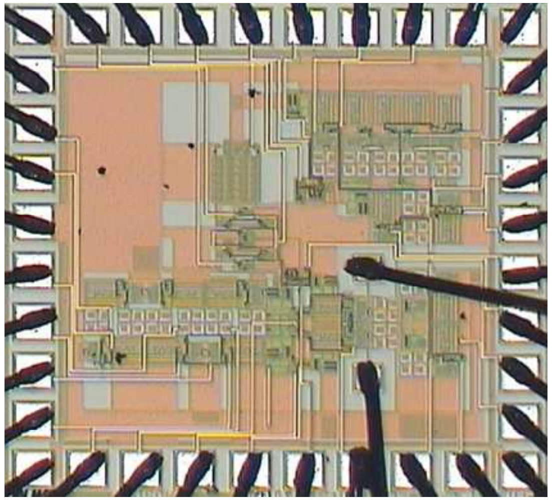
Observed at the Sense monitoring channel

First reported 0Hz frequency split in non-degenerate vibratory µ-Gyro

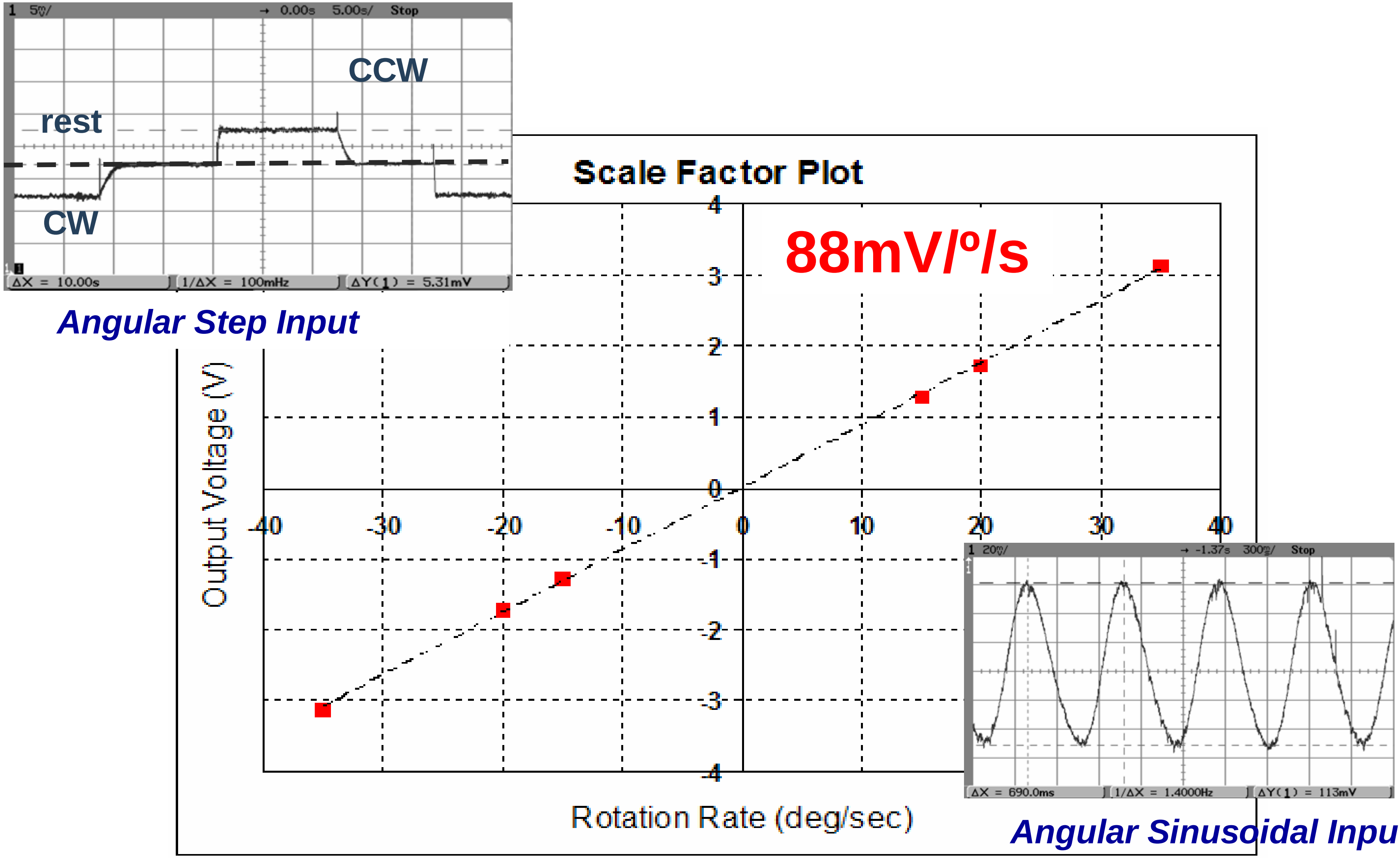
System Implementation







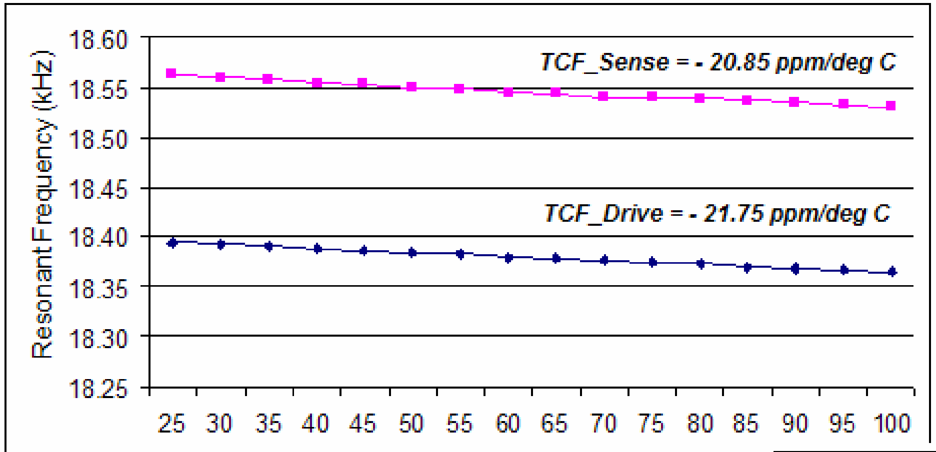
Scale Factor Characterization



Angular Step Input

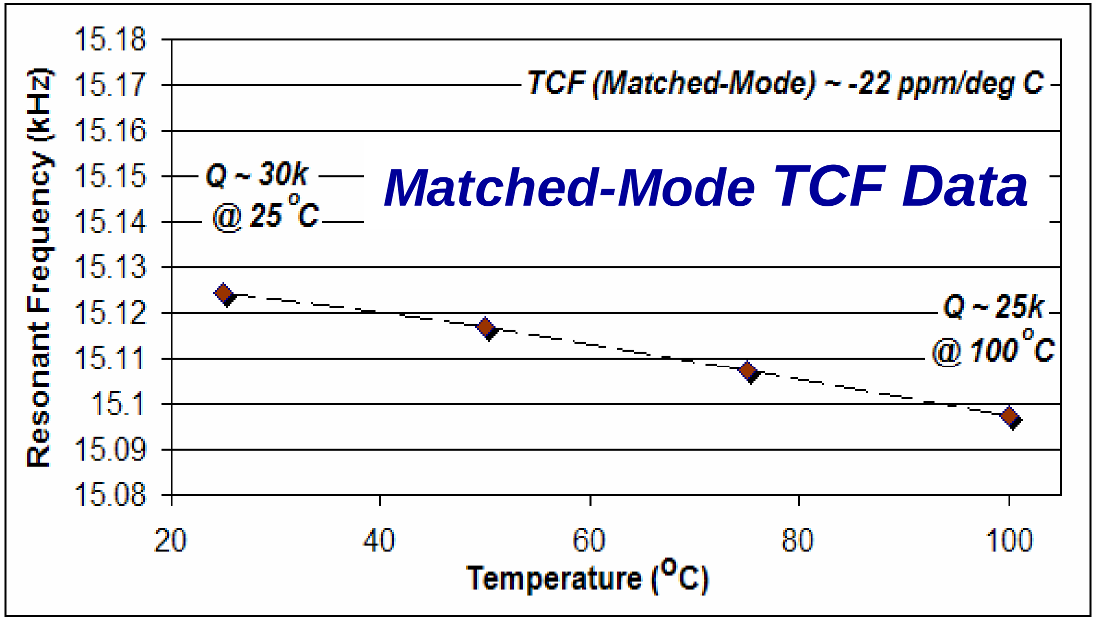
Angular Sinusoidal Input

Temperature Characterization



TCF Data of Individual Modes

Mode-Matching *maintained* over 25°C – 100°C



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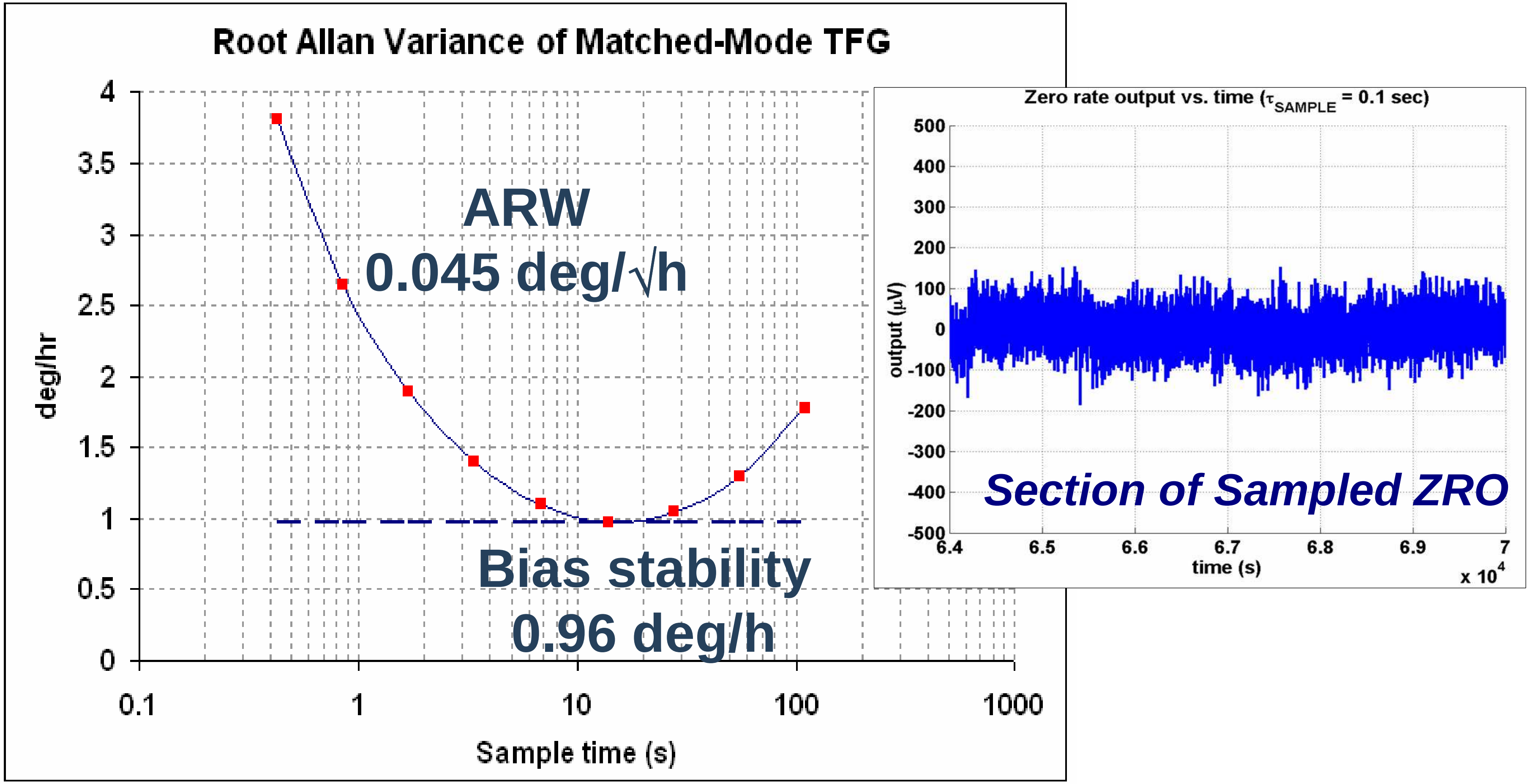
Bias Drift Characterization

- ☐ Bias drift measured for 12 hours without pre-filtering



ARW
0.045 deg/√h

Bias stability
0.96 deg/h

Section of Sampled ZRO

Microsystem Performance Summary

Parameter	**Value**
Sensor Brownian Noise Floor	0.5 º/hr/√Hz
Sensor Bias Stability	**< 1 º/hr**
Capacitive Sensitivity of Gyro	38 aF/º/s
Drive Motional Impedance	>10 MΩ
Min. detectable ΔC	**0.02 aF/√Hz**
Minimum SNDR of T-network TIA	**104 dB**
Rate sensitivity of Gyro + IC	2mV/º/s
Supply Voltage	±1.5 V
Die Area (0.6 µm CMOS)	2.25 mm^2
Total power consumption	**15 mW**

Conclusions & Future Work

Summary:

- The Matched-Mode Tuning Fork Gyroscope (M^2-TFG)
- T-network TIA with 0.02aF/$\sqrt{\text{Hz}}$ capacitive resolution and 104dB linear dynamic range
- MEMS-based angular rate sensor with 0.5 °/hr/$\sqrt{\text{Hz}}$ noise floor and < 1°/hr bias drift

Future Work:

- Wafer-level vacuum packaging of MEMS devices
- Process Variation
- Voltages

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