ULTRA-LOW-NOISE TRANSIMPEDANCE AMPLIFIER FOR HIGH-PERFORMANCE MEMS RESONANT GYROSCOPES

Jong-Kwan Woo, Christopher Boyd, Jae Yoong Cho, and Khalil Najafi
Center for Wireless Integrated MicroSensing and Systems (WIMS^2),
University of Michigan, Ann Arbor, Michigan, USA

Motivation

- The performance of MEMS gyroscopes is rapidly approaching the level that can be adopted in a wide range of military and high-end industrial applications.
- One of the most highly desired applications for a high-performance gyroscope is GPS-free inertial navigation for autonomous cars, drones, and indoor pedestrians and it is required to have very high bias stability (< 0.1 deg/hr)

Objective

- Implementation of a front-end capacitive readout circuitry with extremely low noise, wide dynamic range, and high tolerance to variations in voltage and temperature to **overcome the performance limits of existing gyroscopes.**
- Implementation of a front-end capacitive readout circuitry with a wide feedback control range to **detect a wide range of capacitances and frequencies**

Challenges of Front-End Circuitry

- Large output swing to cover a wide range of sensitivity
- Low distortion to get the high linearity
- Large and controllable feedback gain to cover a wide range of capacitances
- Easy on-chip integration to reduce parasitic

Trans-impedance Amplifier for Front-End

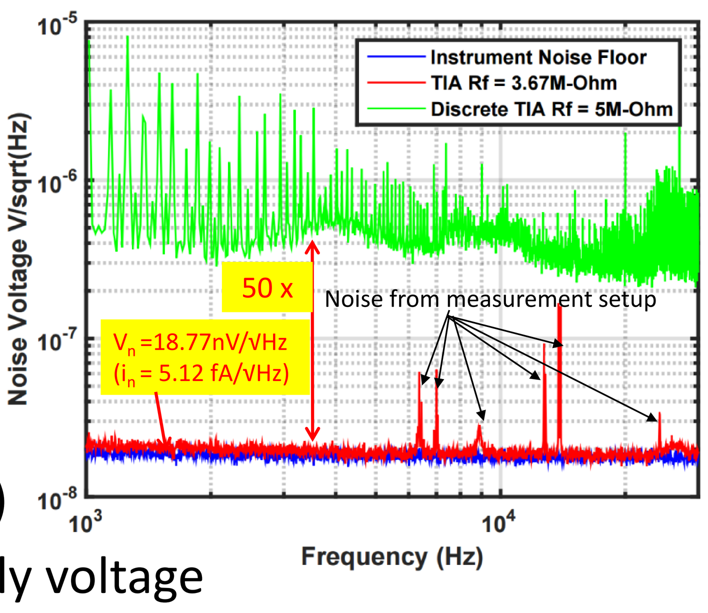
- Relatively insensitive to parasitic
- Two-chip cost effective solution
- Easy control of feedback gain
- Proof-mass not switched

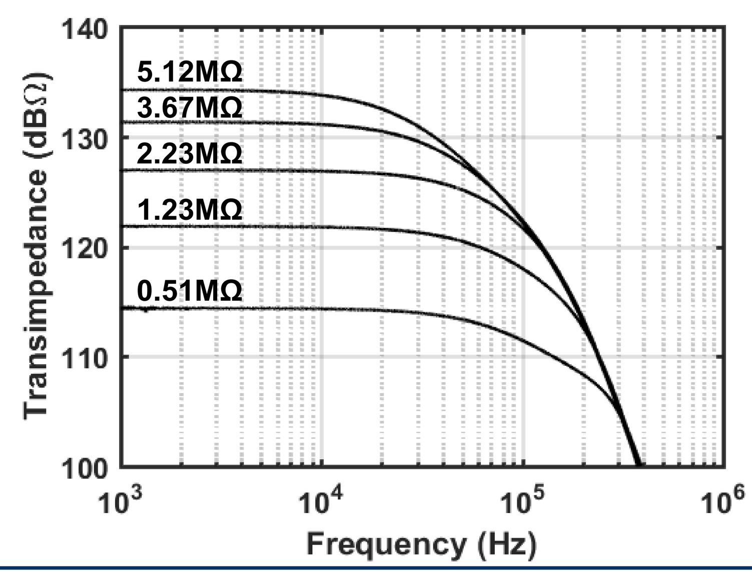
Accomplishments

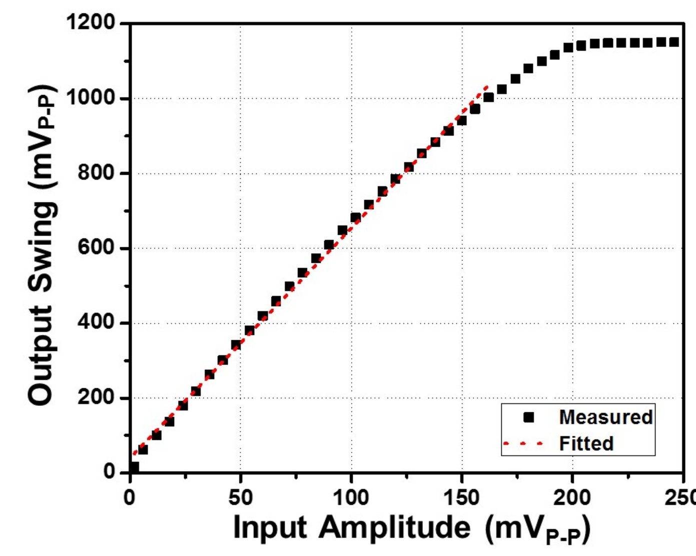
- Implemented a new TIA that employs an on-chip digitally-controlled floating resistor as the variable resistor for a resistor T-network to lower the noise and obtain higher linearity .
- Measured **very low input current noise (i_n=5.12fA/√Hz) which translates to 0.45 zF/√Hz minimum detectable capacitance and very wide dynamic range (123 dB)**.
- Demonstrated **near-navigation-grade bias instability (0.0391 deg/hr).**

Evaluation of Proposed CMOS TIA

- Comparison between output noise spectral densities of TIA ASIC and discrete low-noise TIA (Right)
  - ❑ ~50 times lower noise floor
- Measured T-network TIA gain (Lower Left)
  - ❑ Wide and controllable feedback gain
- Measured T-network TIA gain (Lower Right)
  - ❑ Large output swing even with low supply voltage

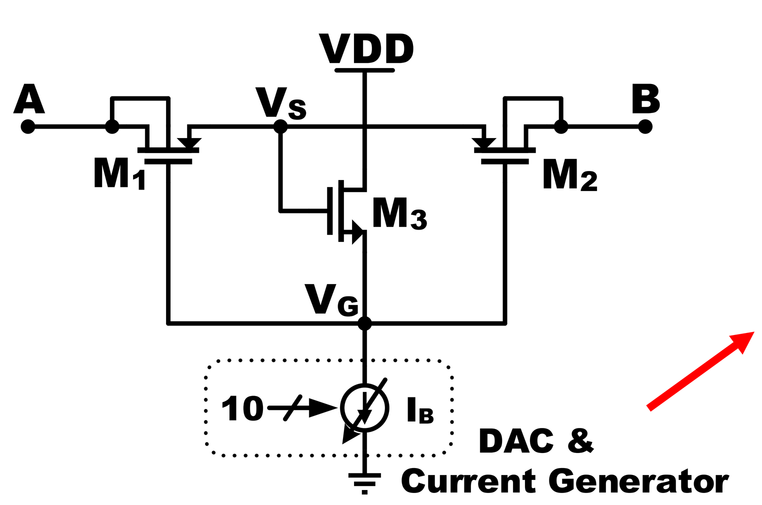


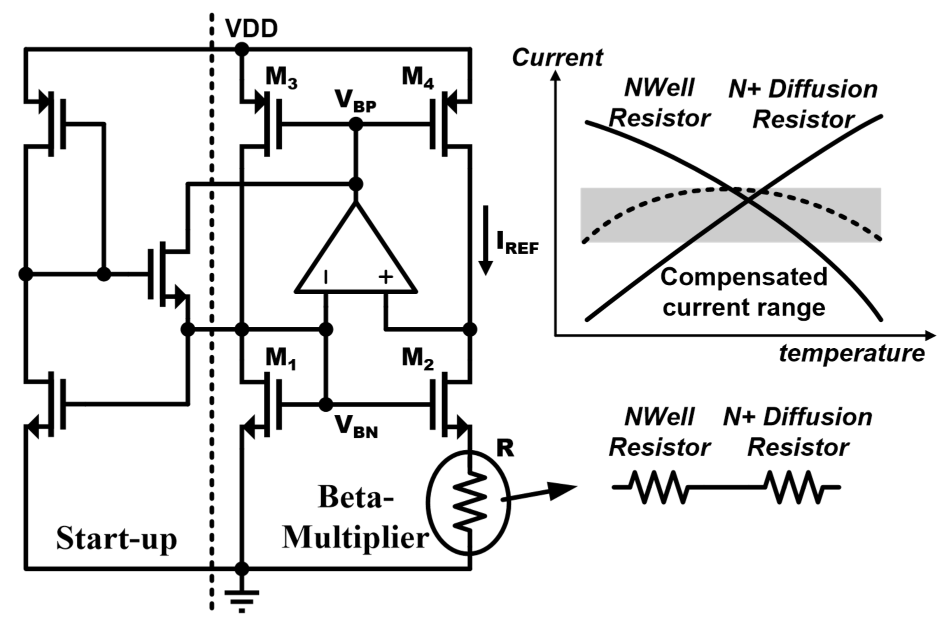




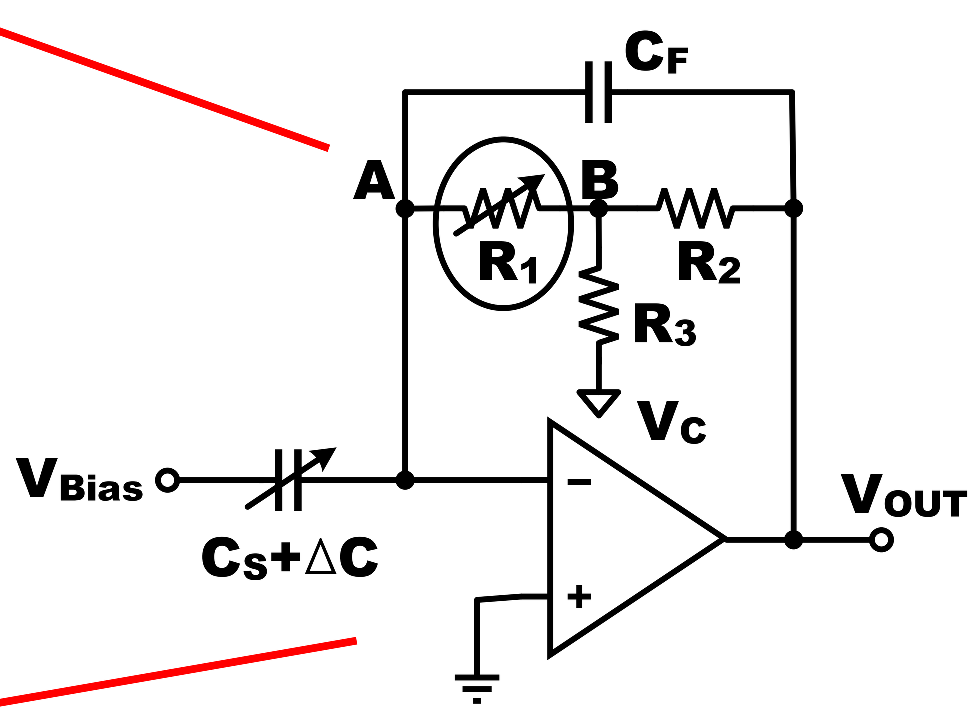
Entire Circuit Implementation

- Variable Floating Resistor with 10-b Current Steering DAC
- Voltage-Temperature tolerant Current Generator

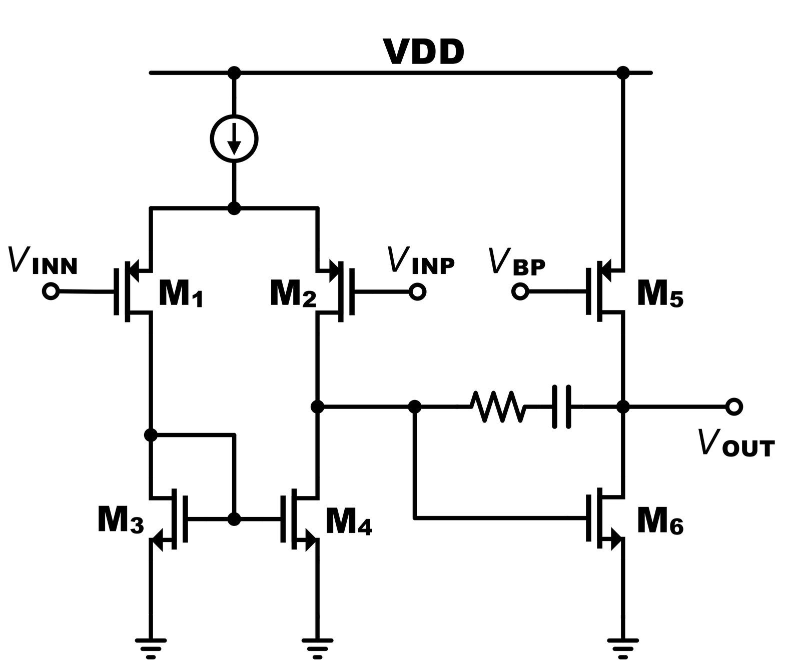




- TIA with Floating Resistor T-Network
  - ❑ Covers wide range of readout capacitances and frequency ranges
  - ❑ Compensates for process and temperature variations
  - ❑ Reduces TIA noise by the integrated resistance control block



- Low-noise Two Stage Amplifier

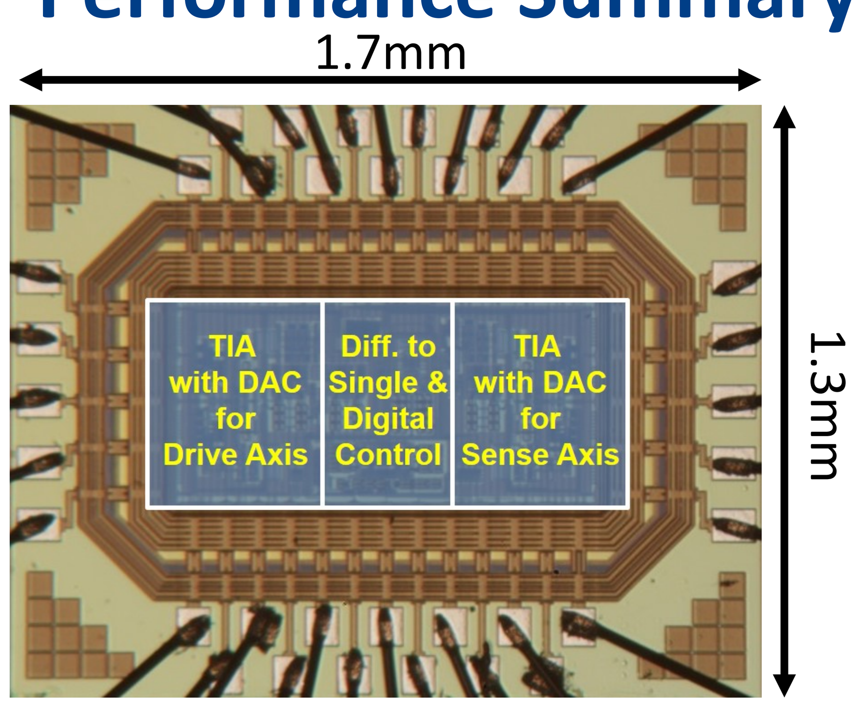


$$\overline{V^2_{n,thermal}} \approx \frac{16kT}{3}\frac{1}{g^2_{m1}}(g_{m1}+g_{m3})$$

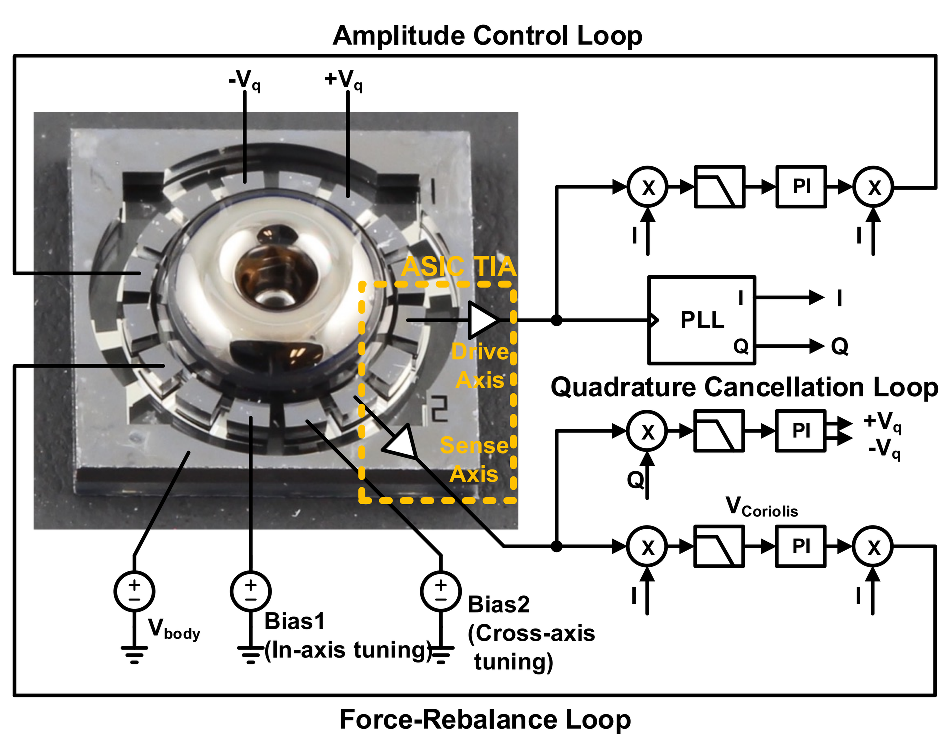
$$\overline{V^2_{n,flicker}} \approx \frac{2}{C_{ox}f}\left(\frac{K_P}{W_1L_1}+\frac{\mu_n K_n L_1}{\mu_p W_1 L_3^2}\right)$$

- W_1 ↑
  - g_{m1} ↑
  - Thermal noise ↓
  - Flicker noise ↓
- L_3 ↑
  - Sig. swing ↓
  - Flicker noise ↓

Performance Summary and Comparison Results



Technology	0.18 µm 1P6M CMOS
Feedback Gain Range	510kΩ-5.12MΩ
Output swing	Up to 955mV$_{P-P}$
Input referred current noise	5.12 fA/√Hz (@10KHz)
Min. detectable capacitance	0.45 zF/√Hz
Dynamic Range	123dB



Resonator Dimension	Radius (R): 2.5 mm Height (H): 1.55 mm
Frequency (f_n=2)	9030.925 Hz 9030.998 Hz
Quality Factor	419.047k (14.77s) 410.176k (14.14s)
Scale Factor	100 mV/deg/s
Bias Stability	0.0391 deg/h

References	J.A. Geen et al.	A. Sharma et al.	L. Aaltonen et al.	This work
Front-End Architecture	CSA*	TIA	CSA*	TIA
Input Current Noise (fA/√Hz)	-	88	-	5.12
Minimum Detectable Cap. (zF/√Hz)	12 (zF)	20**	220	0.45***
Bias instability (deg/h)	50	0.16	25	0.0391

*: Charge sense amplifier **: V_{Bias}=40V, f=15kHz ***: V_{Bias}=200V, f=9.03kHz

Summary and Future Work

- Demonstrated the fully integrated CMOS TIA with **one-of-the lowest reported noise performance and very wide dynamic range.**
- Demonstrated the rate-mode operation of FS µ-BRG with **one-of-the-best performance among existing MEMS gyroscopes.**
- Will implement a miniaturized system with low-noise and high performance.

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