ESSCIRC 2012
Session B3L-E

A 3-axis PZT based MEMS Gyroscope in 0.18µm CMOS

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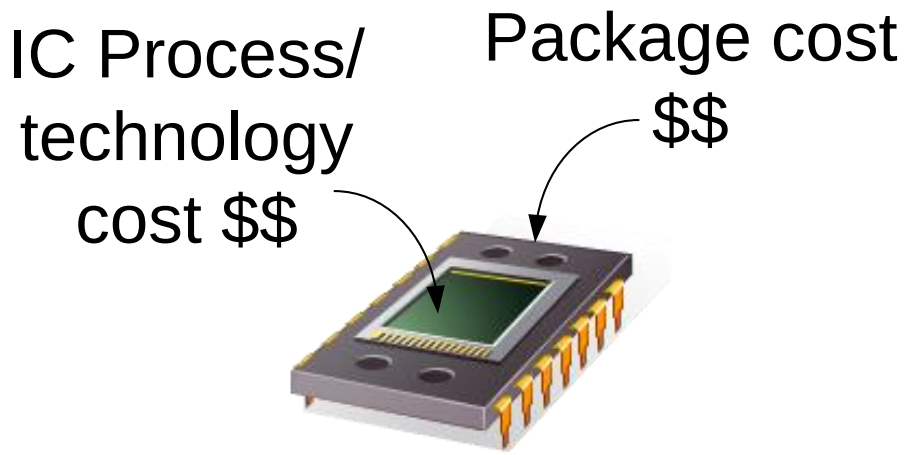
Overview

- Motivations
- State of the art
- Approach of this work
- Measurement results
- Summary

Motivation: Low-cost

- Consumer applications
- High volume → cost driven
- IC process and package determine cost



State of the art

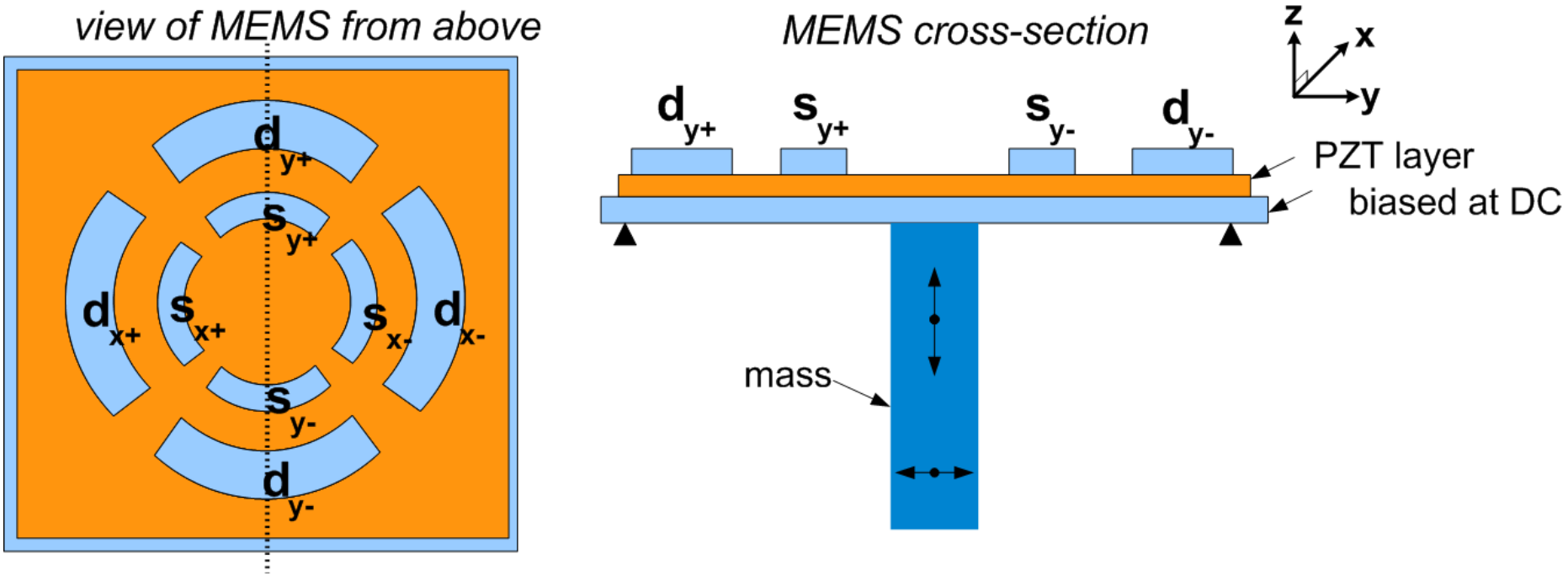
Paper	# axes	Current (mA)	Min Noise (°/s/√Hz)	MEMS bias (V)	Process	MEMS element/ Package	PLL?
ISSCC 2011	3	6.1	0.03	11	0.13µm	Electrostatic	yes
JSSC 2009	2	1.8	0.015	9.1	0.35µm HVCMOS	Electrostatic	yes
JSSC 2009	1	2	0.0001	40	0.6µm	Electrostatic Vacuum Pkg	yes
CICC 2011	1	64	0.001	10	0.18µm HVCMOS	Electrostatic	yes

- Expensive packaging (vacuum) ~3x more cost
- Large voltage requirement → expensive process (HV)

This work

- **Low cost Piezoelectric based MEMS sensor**
  - No vacuum packaging required
  - No high voltage process or charge pumps required
- **Circuit innovations**
  - No PLL required
  - Single gain stage for actuation and readout
- **Reasonable noise floor & power**

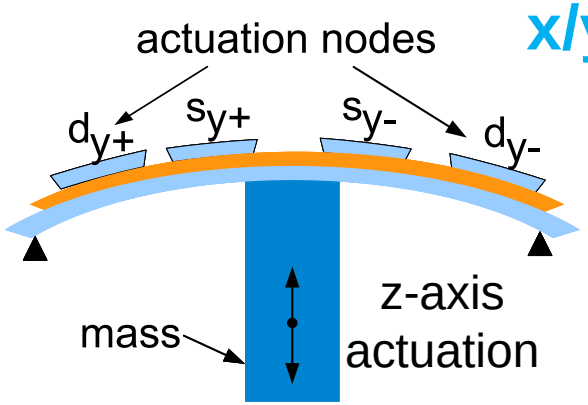
PZT (piezoelectric) MEMS Gyroscope

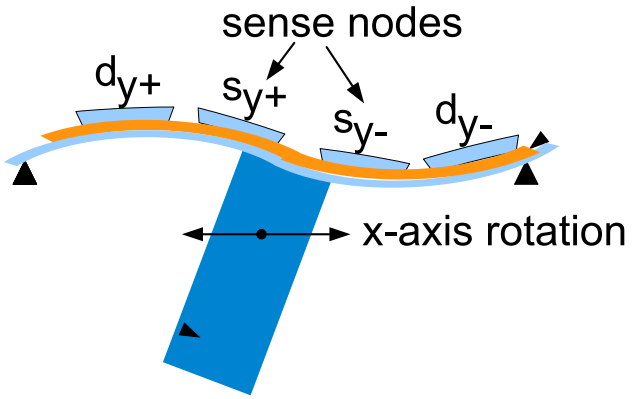


- MEMS acts like a trampoline with mass attached to middle
- High PZT sensitivity → small voltage → large displacement
- No vacuum package required

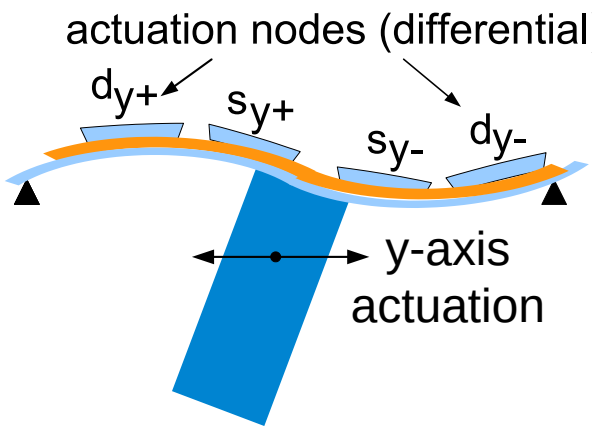
MEMS actuation/sense

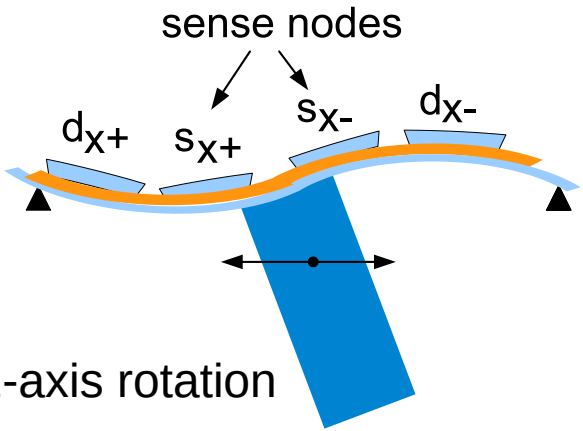
x/y axis sense





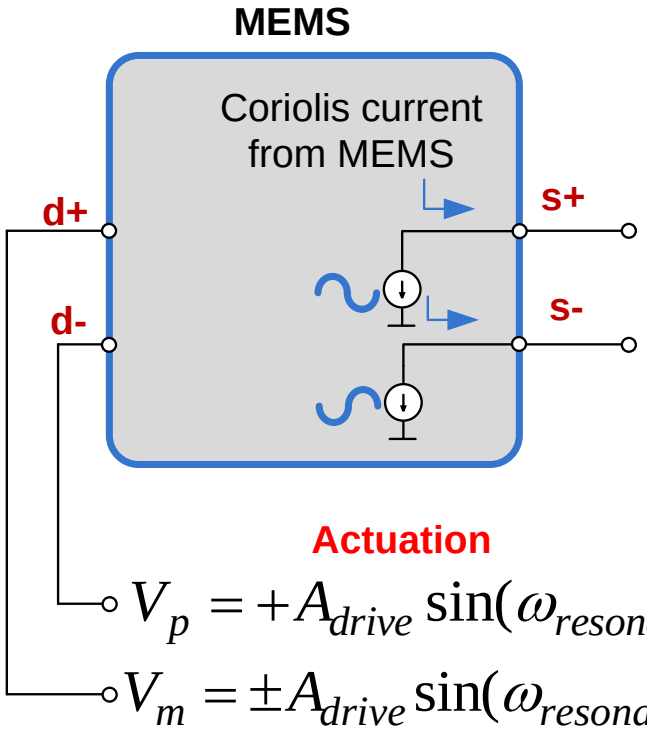
z axis sense





- Rotation based tension/compressions on surface induce current

MEMS behavioral model



Sense

$$I_p = +A_{coriolis}\cos(\omega_{resonant}t) + A_{off-axis}\sin(\omega_{resonant}t)$$

$$I_m = -A_{coriolis}\cos(\omega_{resonant}t) - A_{off-axis}\sin(\omega_{resonant}t)$$

$$A_{off-axis} >> A_{coriolis}$$

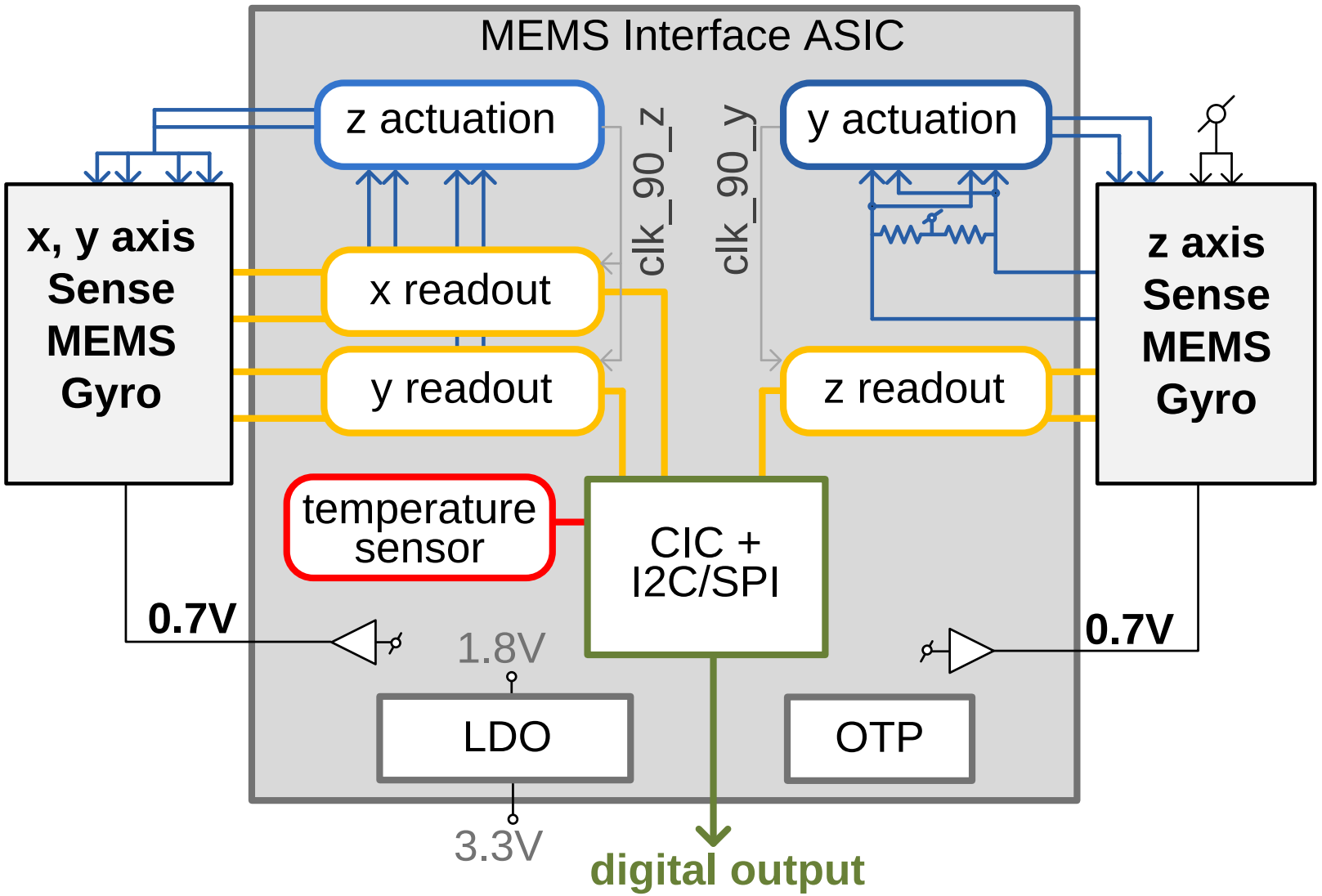
Actuation

$$V_p = +A_{drive}\sin(\omega_{resonant}t)$$

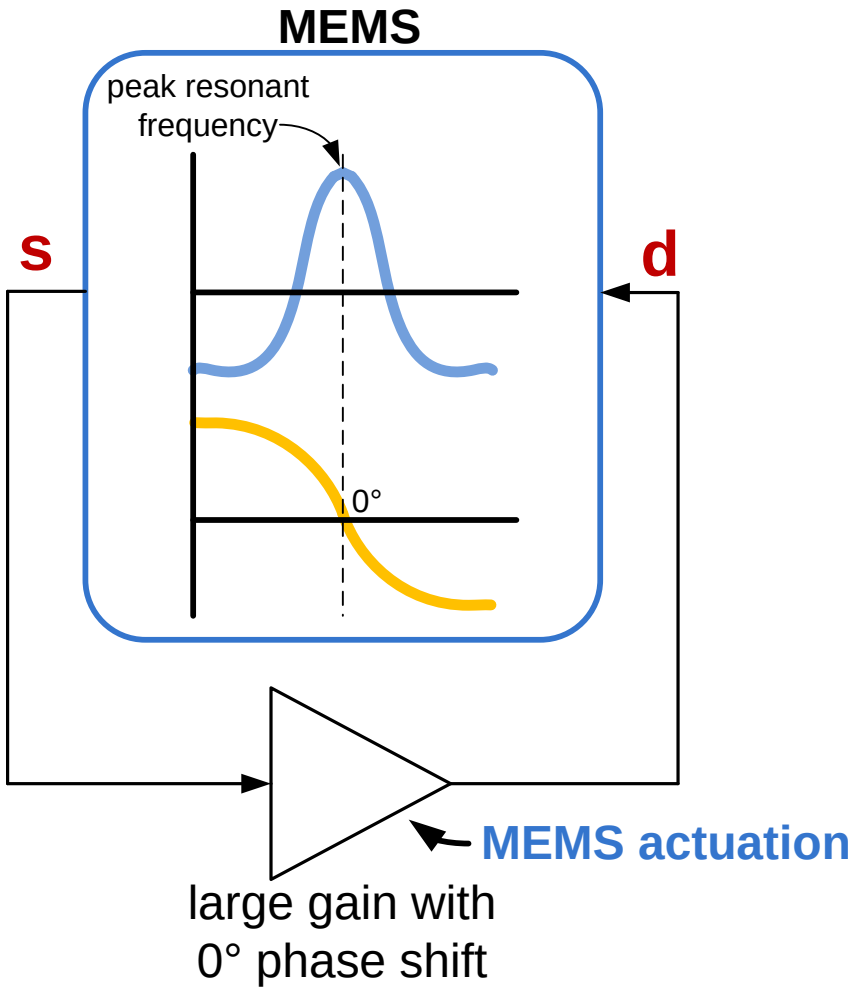
$$V_m = \pm A_{drive}\sin(\omega_{resonant}t)$$

- Need clock orthogonal to $\sin(\omega_{resonant}t)$ to avoid having mixer output dominated by $A_{off\text{-}axis}$

Sensor architecture

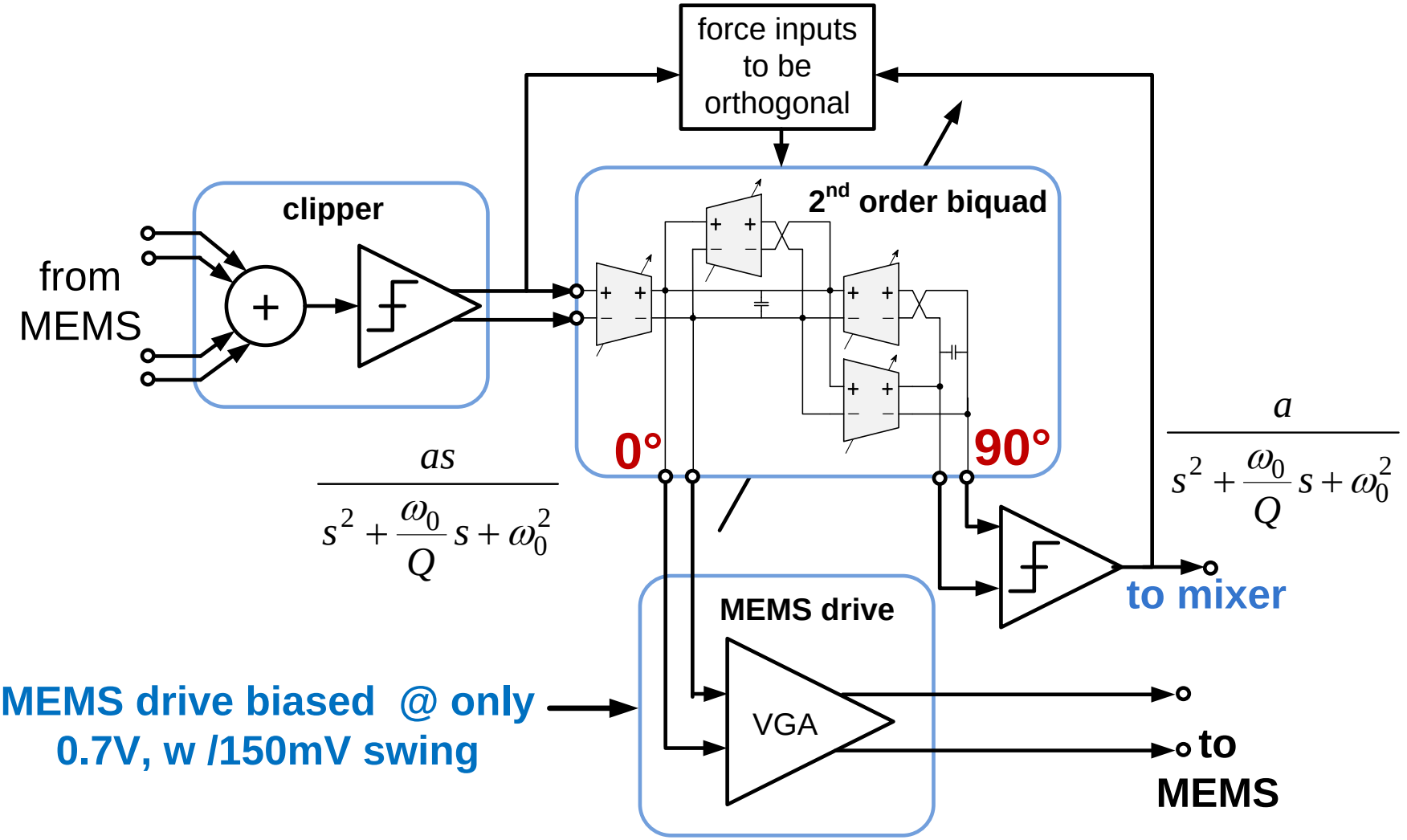


MEMS Actuation path



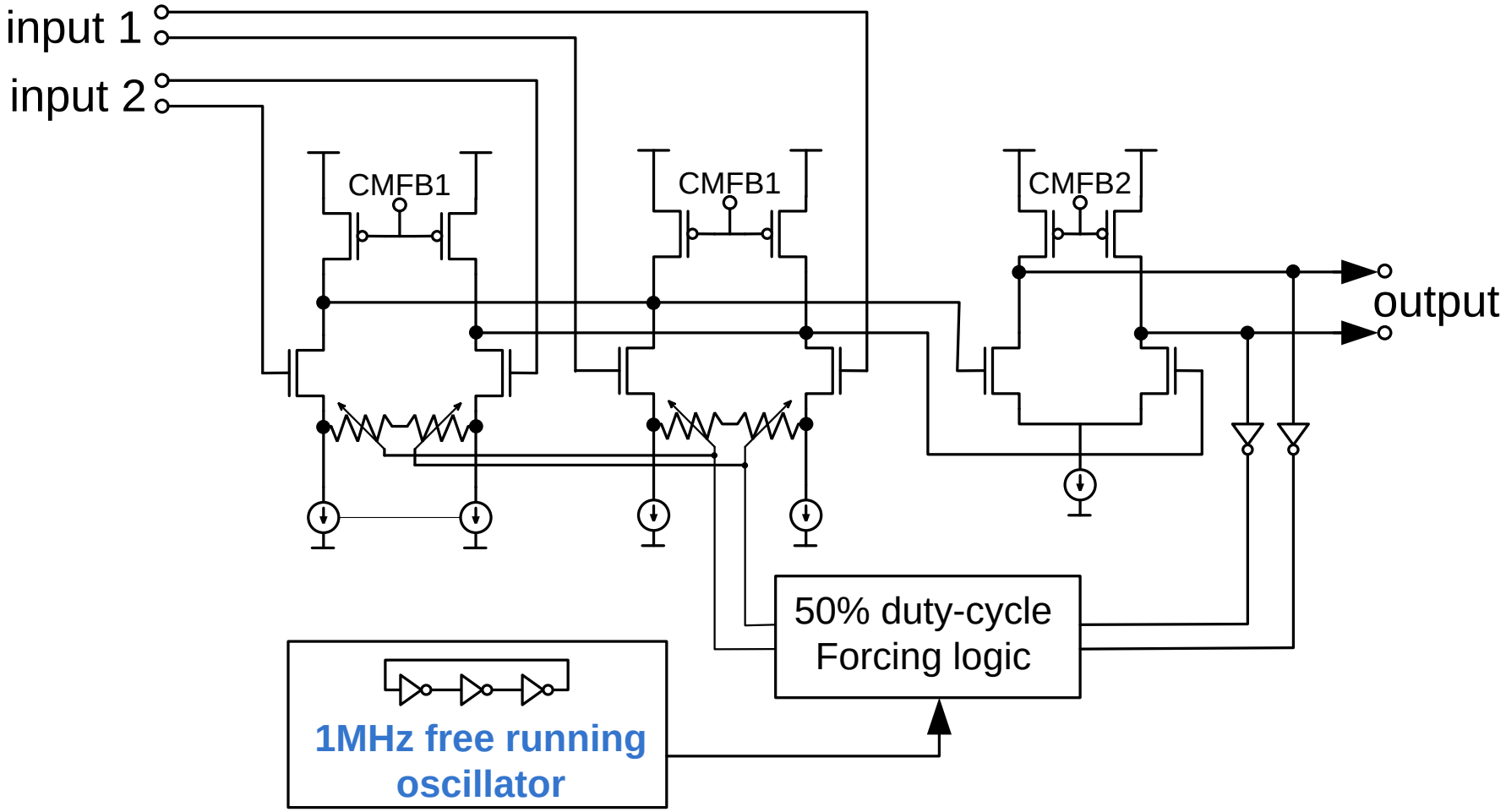
- MEMS in feedback loop → resonates at peak frequency
- loop satisfies Barkhausen criteria at peak resonance

MEMS Actuation – system level



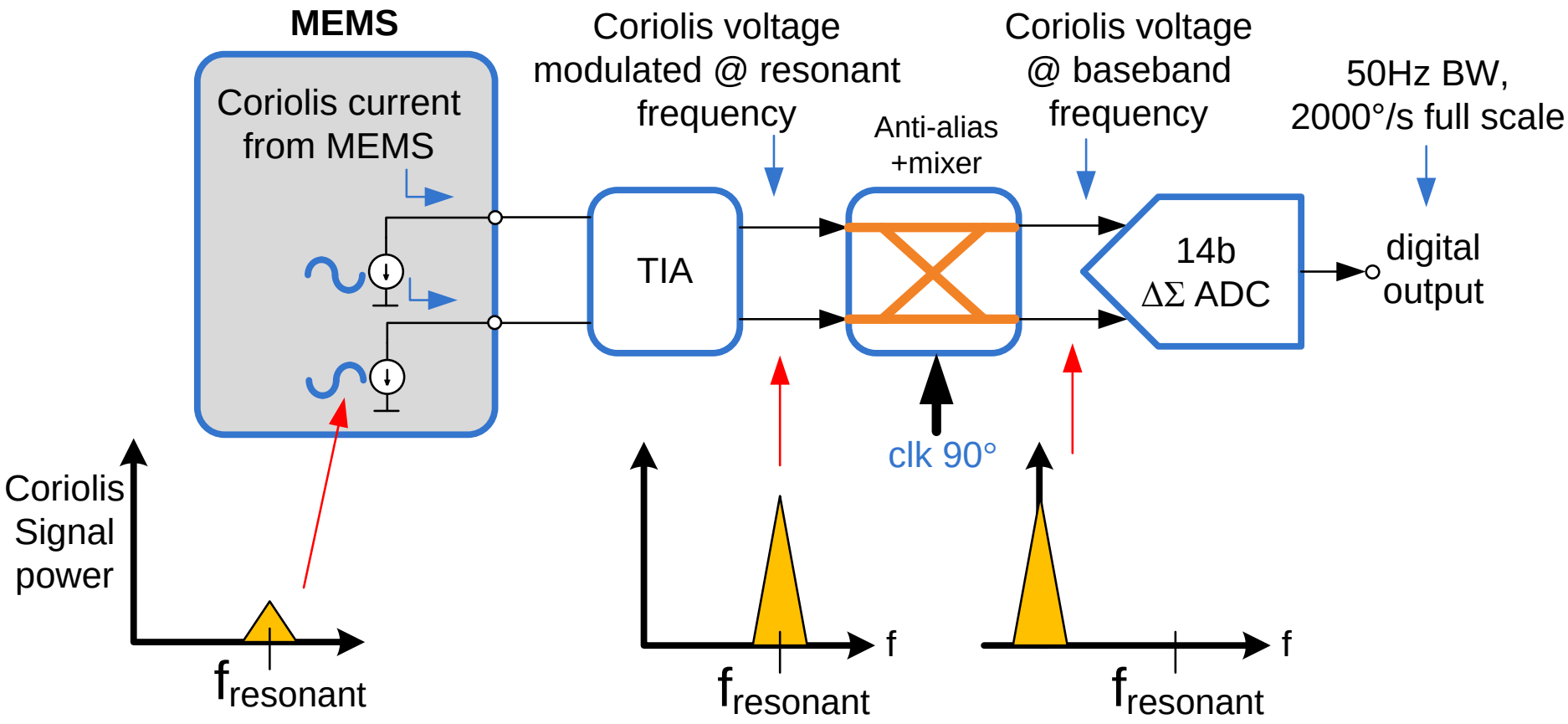
- 90° clock for mixer inherently available with bi-quad
- **No need for additional PLL**

Clipper with offset cancellation



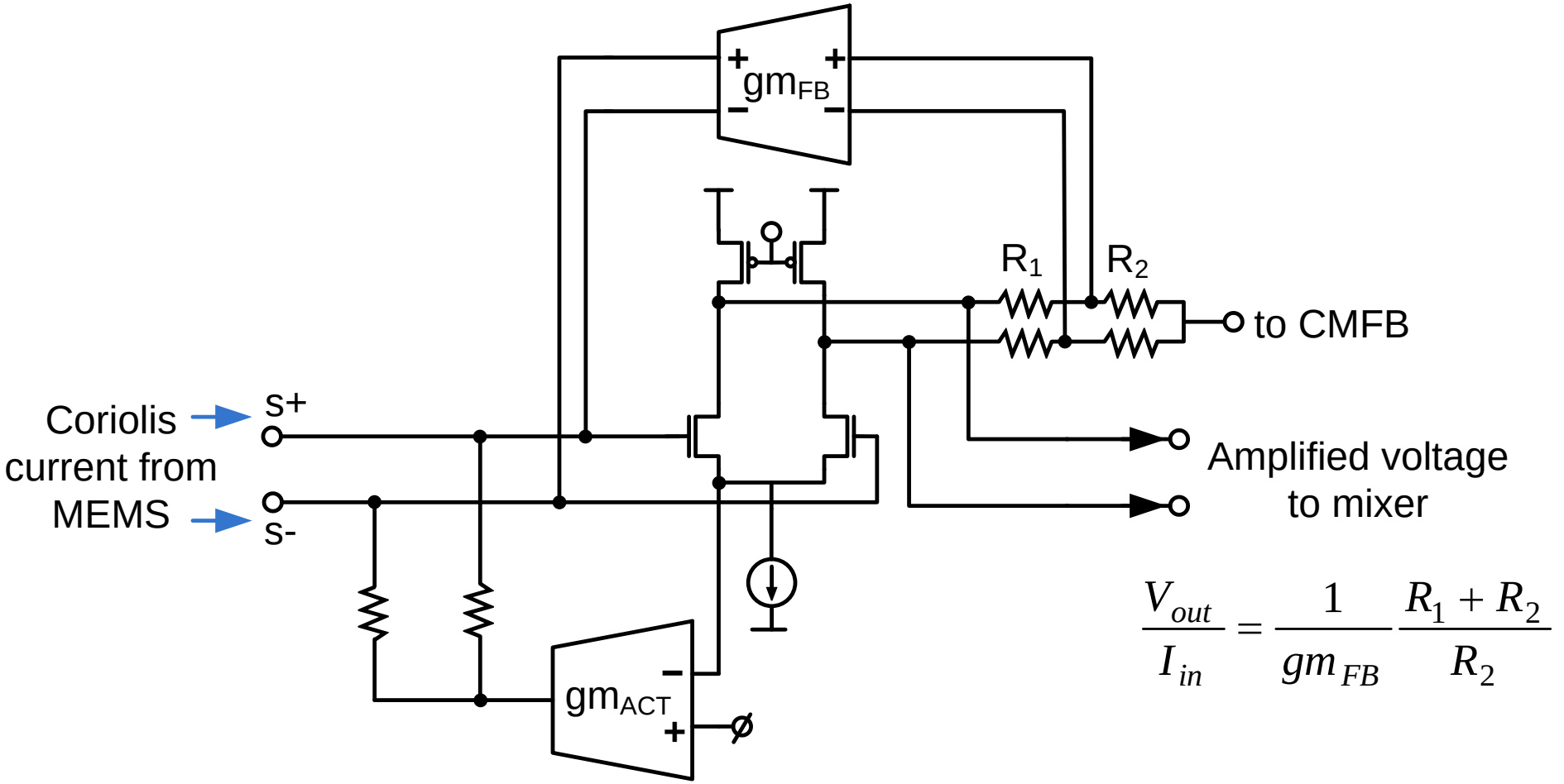
- Duty cycle correction cancels input offset, guarantees start-up

MEMS readout path



- TIA converts current from MEMS into amplified voltage
- Mixer brings signal back to baseband

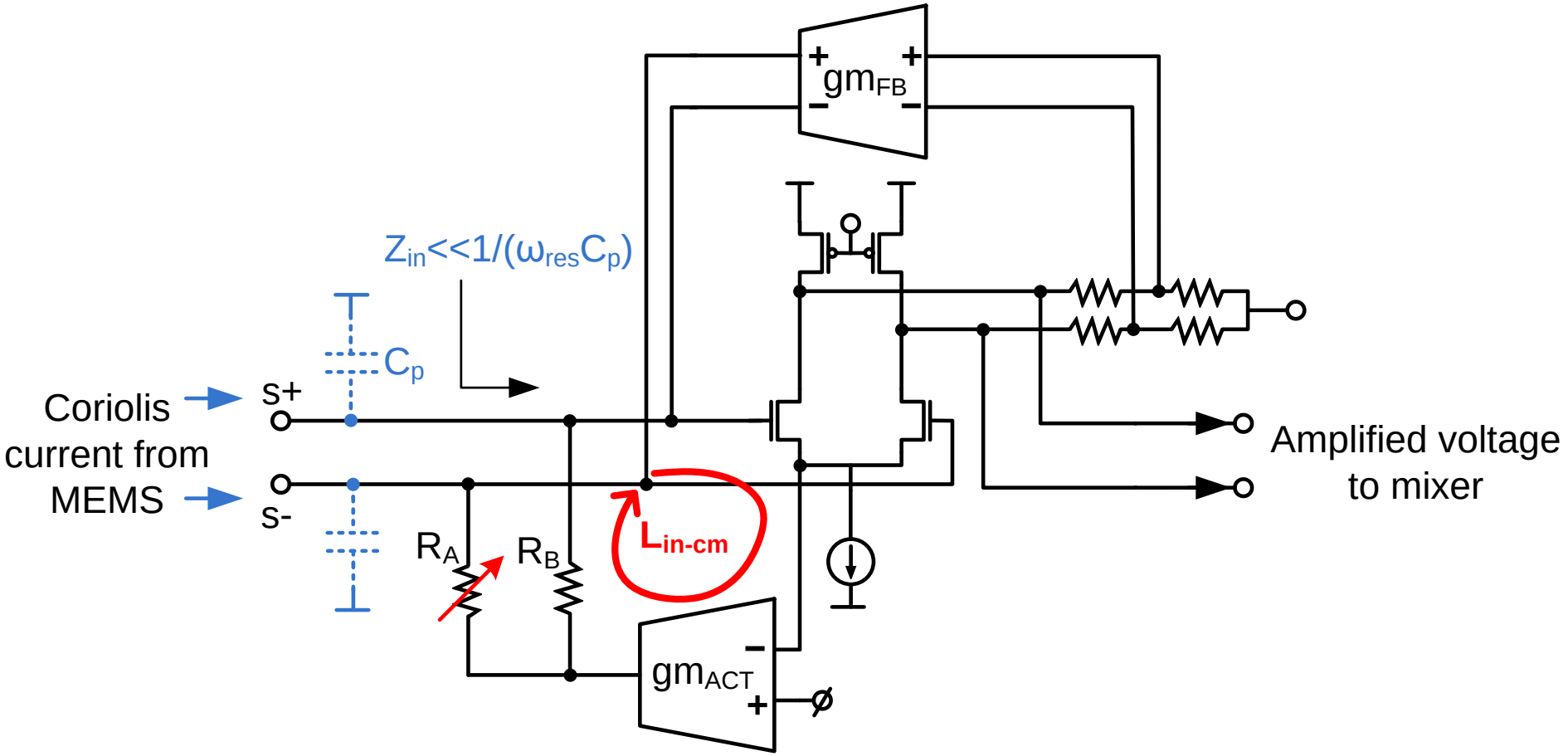
TIA – input current, output voltage



$$\frac{V_{out}}{I_{in}} = \frac{1}{gm_{FB}} \frac{R_1 + R_2}{R_2}$$

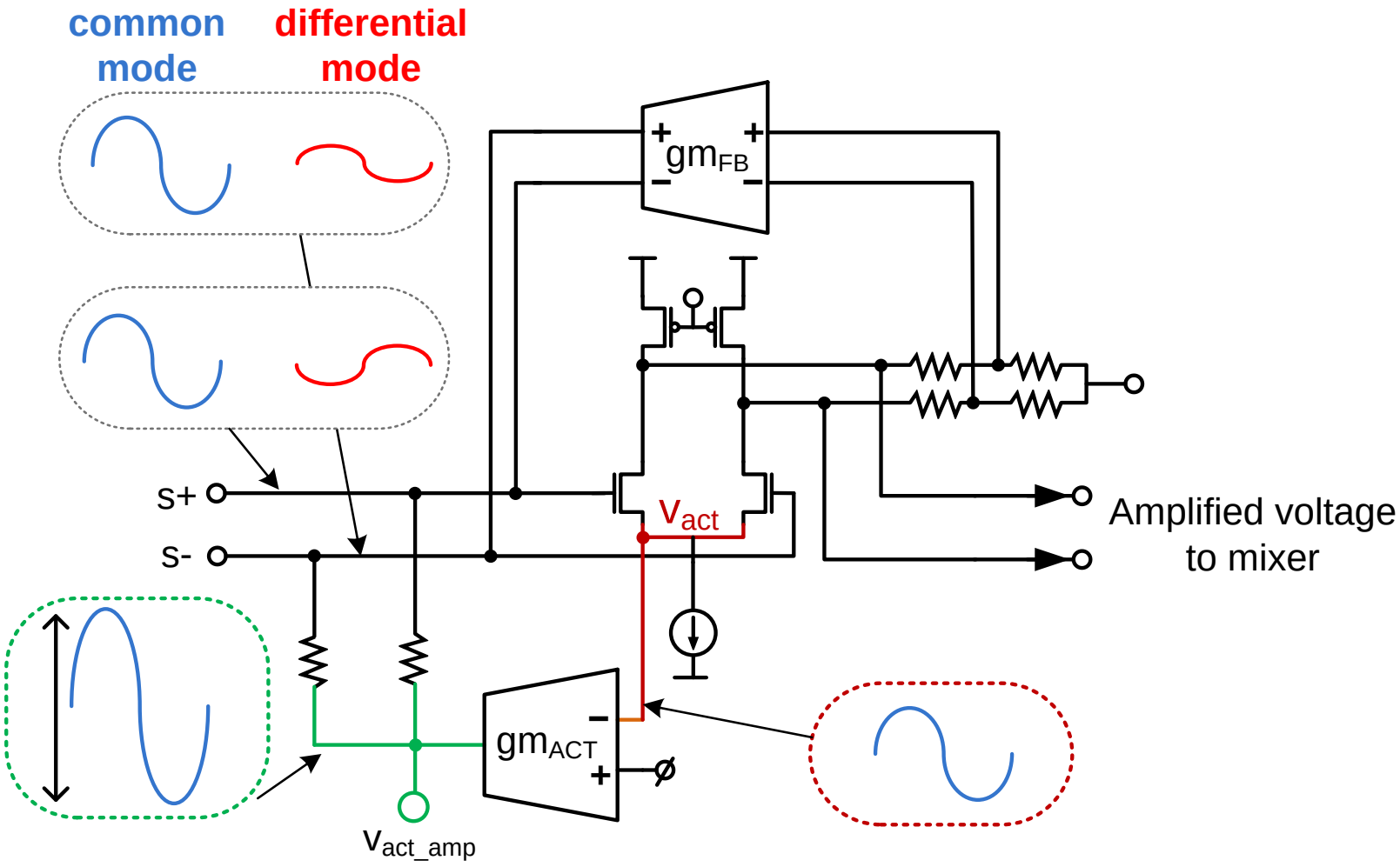
- Transconductance in feedback w/divider determines gain

TIA: off-axis correction



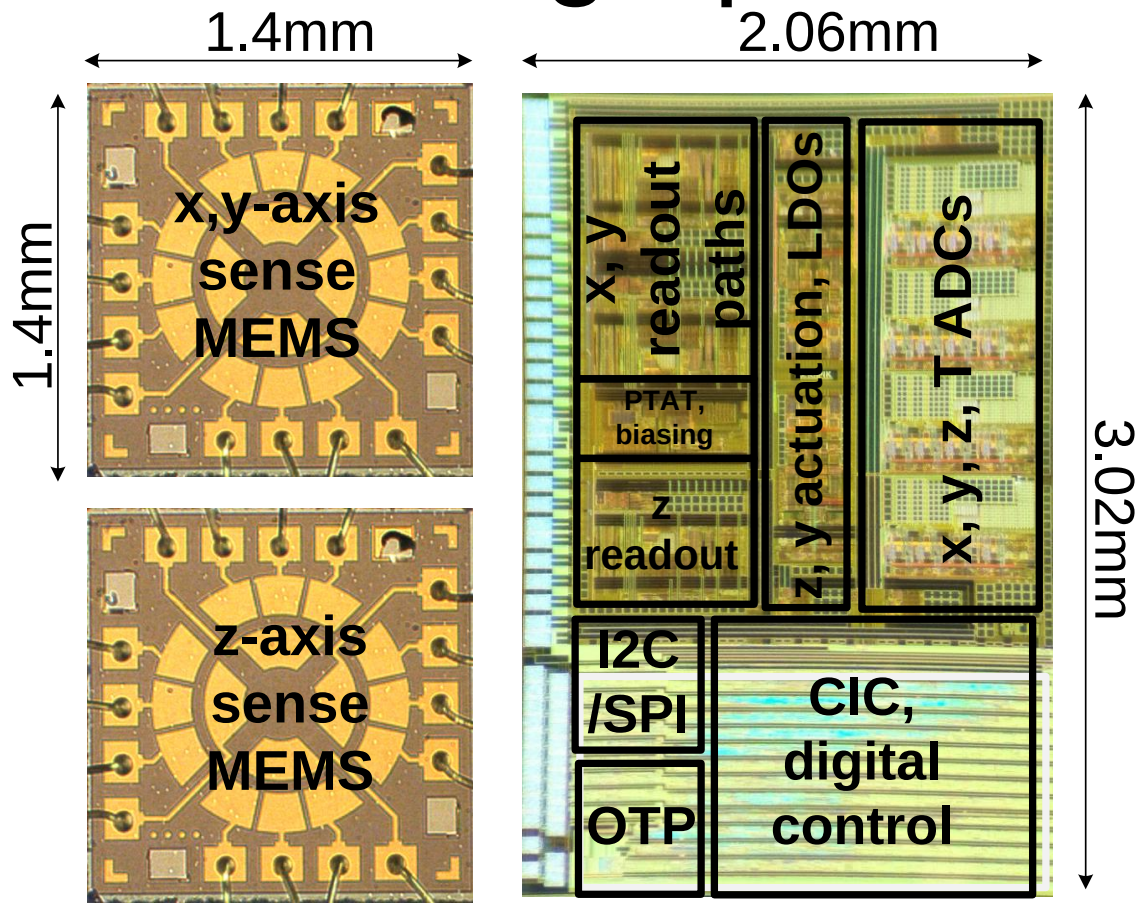
- Loop $L_{in\text{-}cm}$ establishes input impedance, common-mode
- Tune R_A relative to R_B to cancel off-axis mismatch

Actuation amplification (x, y readout)



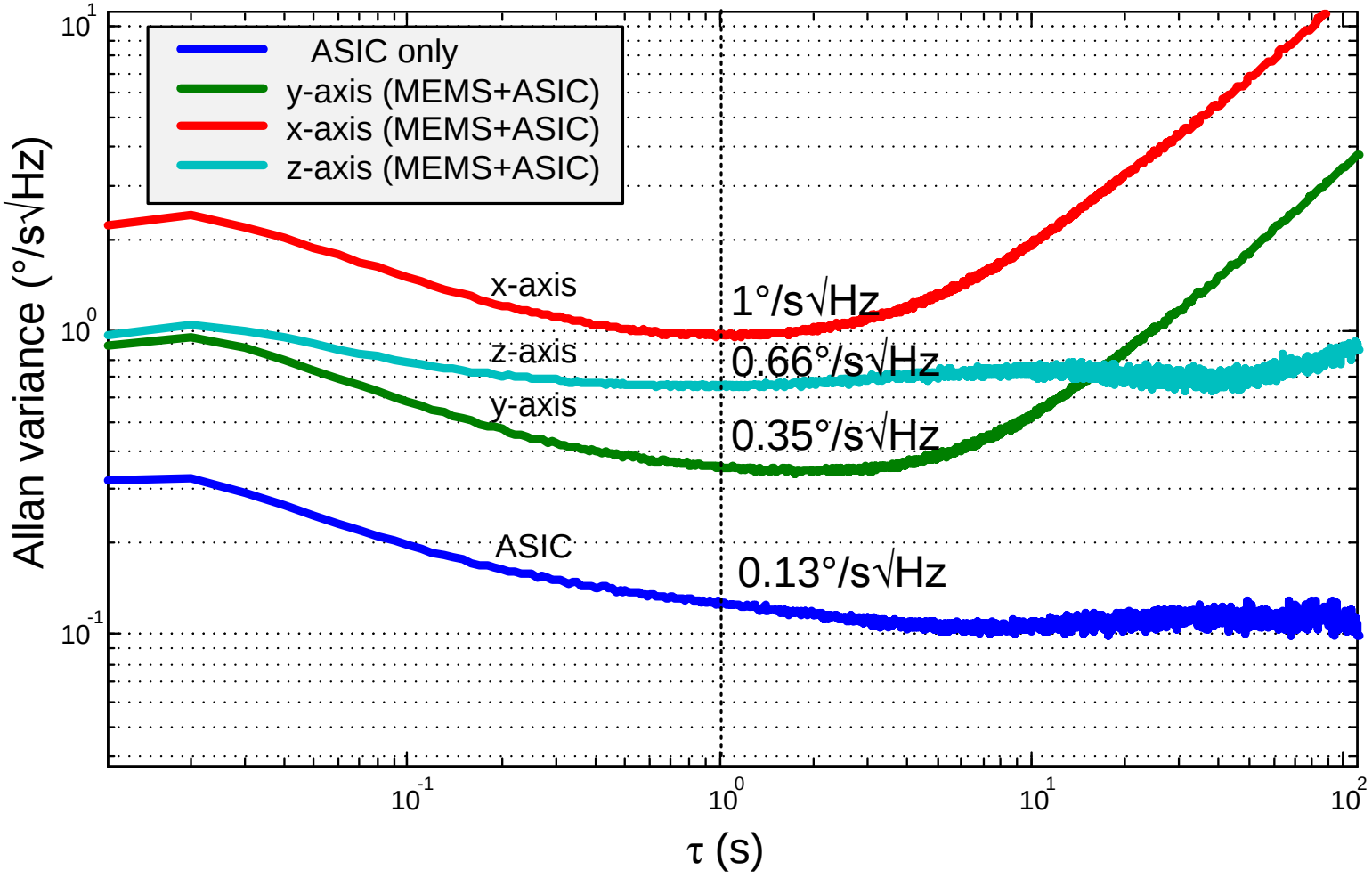
- TIA **simultaneously** amplifies actuation and Coriolis input
- Improved phase match between actuation and sense path

Micrograph



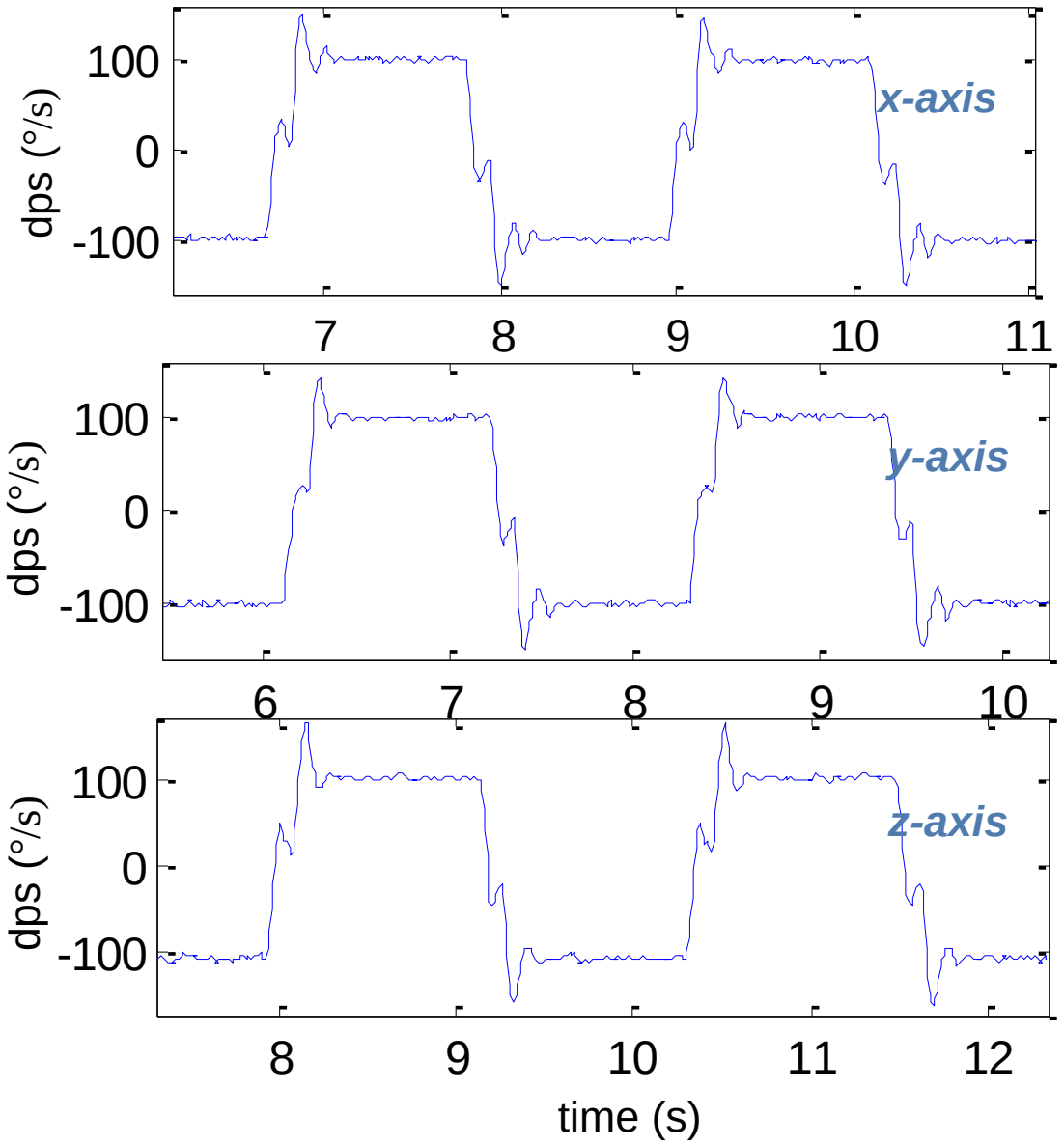
- ASIC in 3.3V/1.8 0.18µm CMOS process w/MiM caps
- MEMS in commercial PZT based process
- Dies packaged separately in proof-of-concept prototype (no vacuum required)

Allan variance



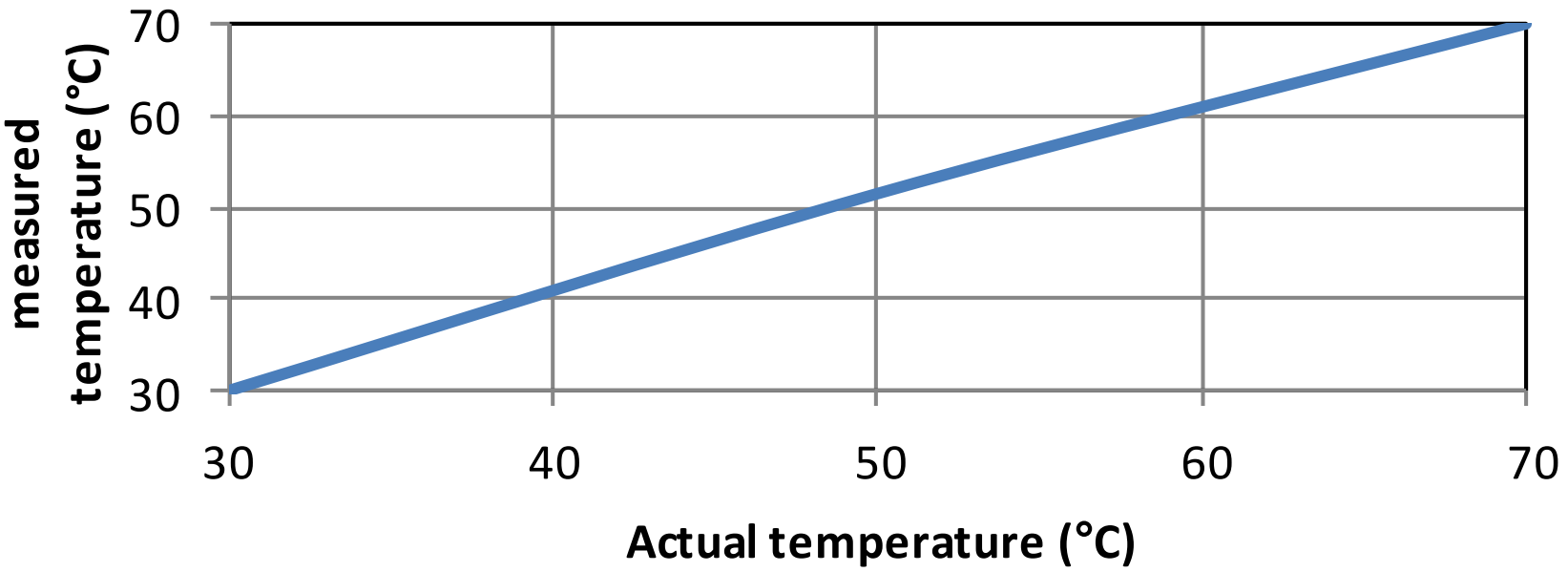
- Reasonable noise levels
- Noise dominated by MEMS

Transient outputs (x, y, z axes)



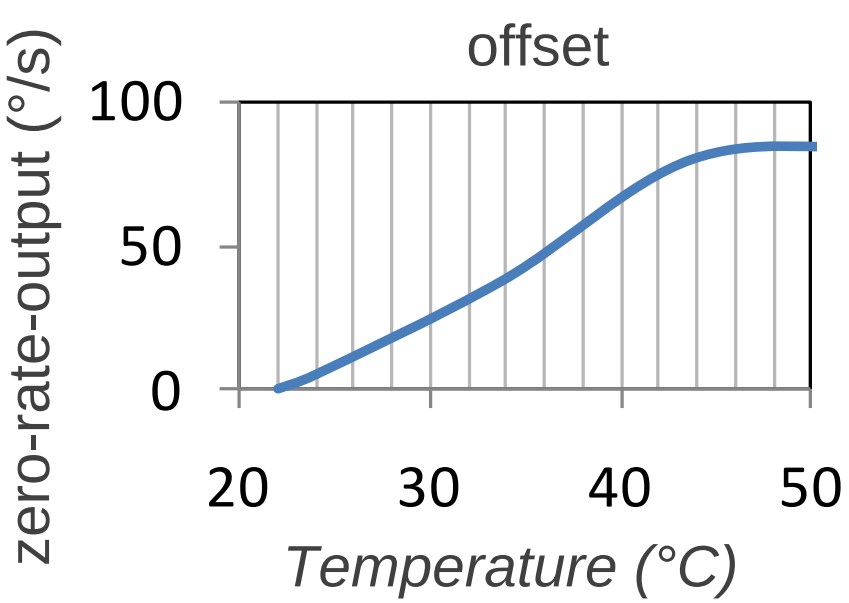
- ±100°/s constant rotation
- Ringing in output is transient settling of rate-table

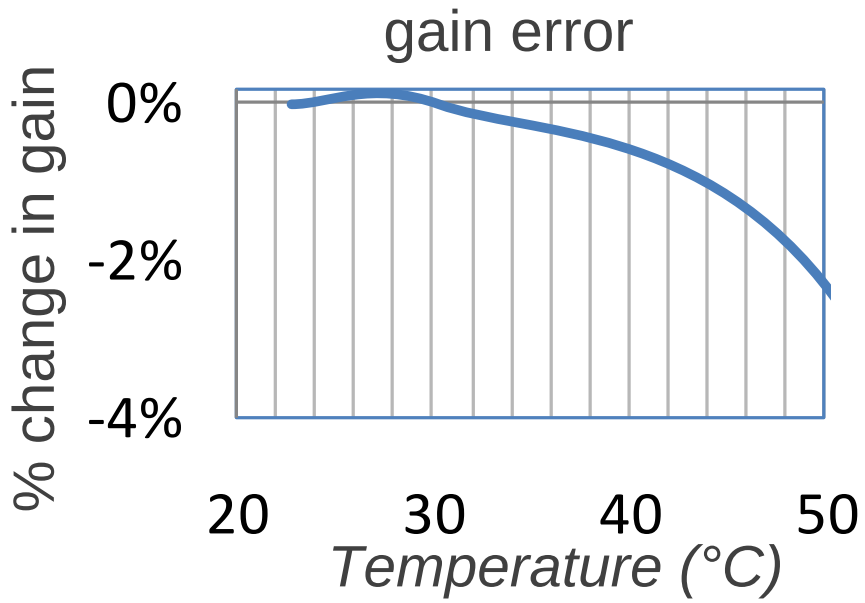
Temperature sensor output



- Temperature readings can be used to compensate for gain/offset errors

Offset, gain error vs. temperature





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Performance comparison

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This work	**3**	**6.2**	**0.35**	**0.7**	**0.18µm CMOS**	**PZT Standard package**	**no**

Conclusions

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  - No vacuum packaging required
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Thank you!