Positive Feedback, Negative Feedback
A closer look at phase margin

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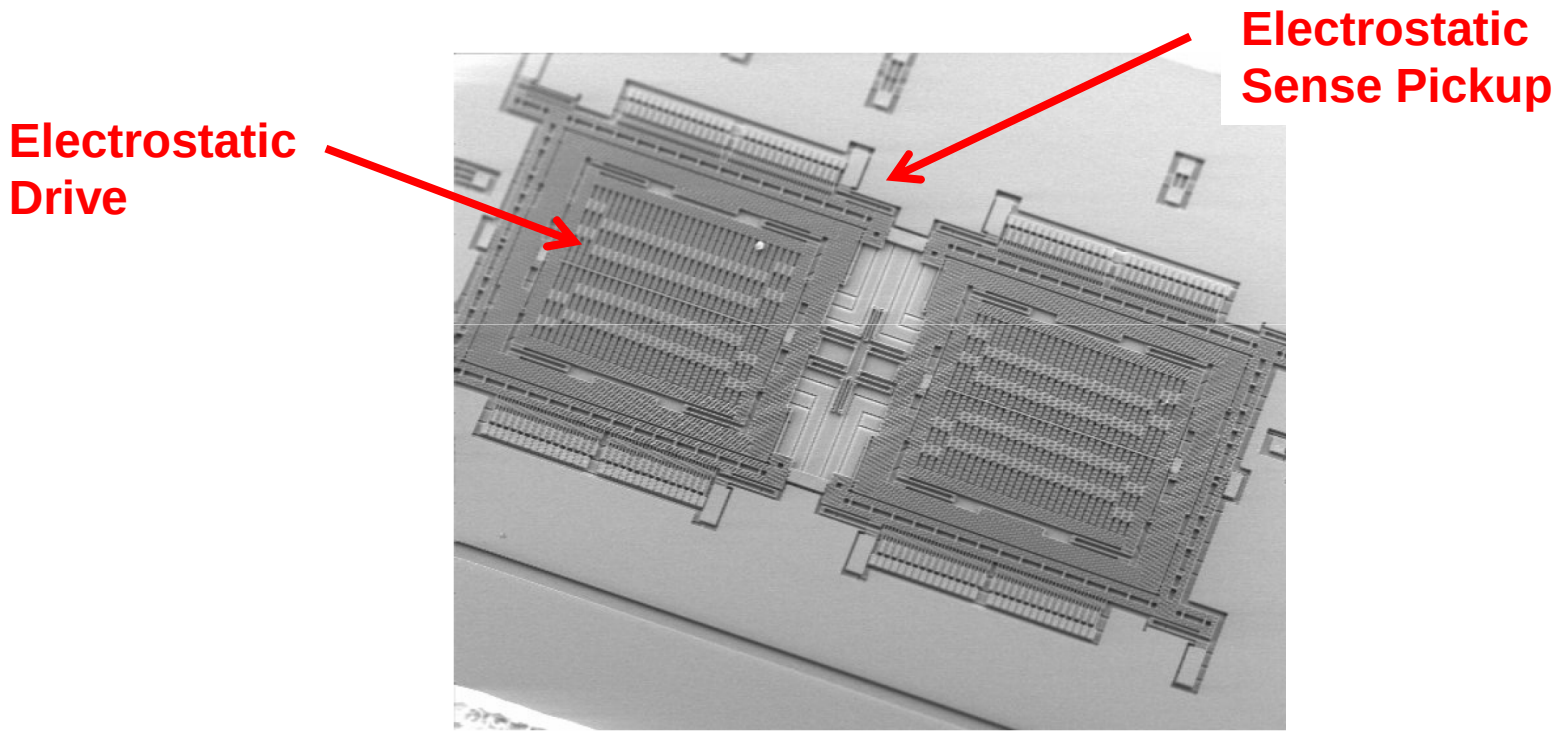
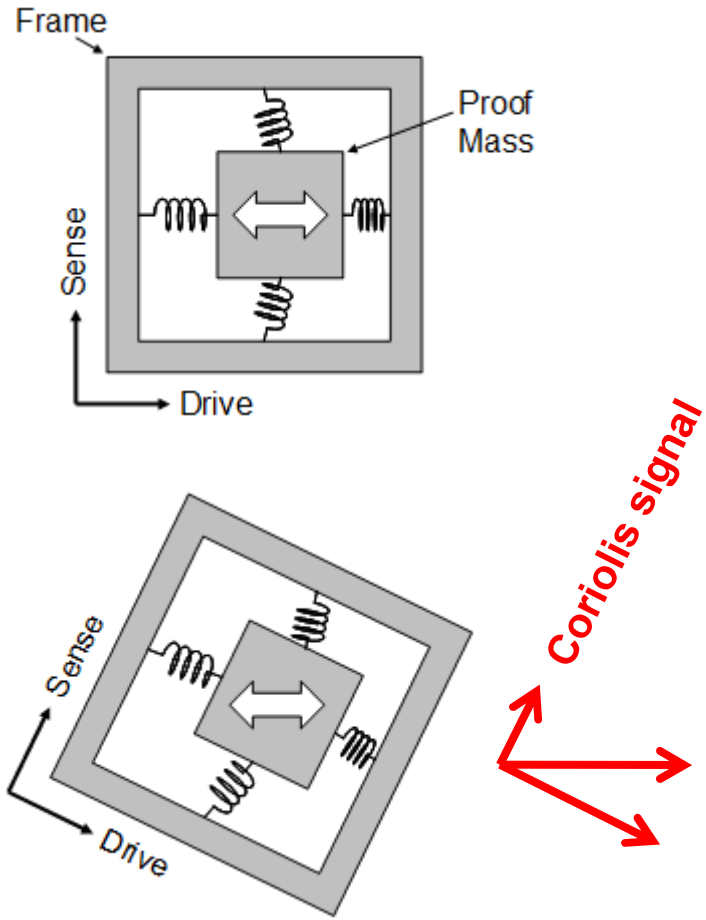
MEMS Gyroscope



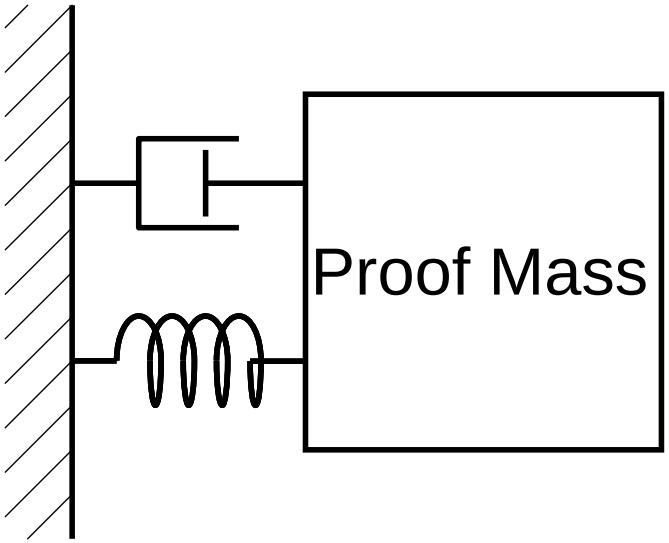
Vibratory Gyroscope

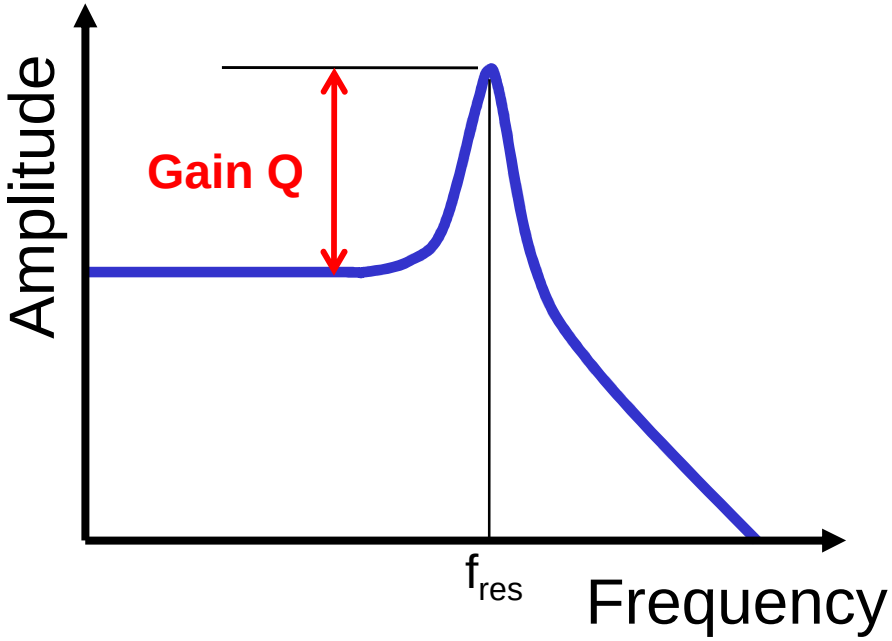


- Vibrate along drive axis with oscillator @ f_{drive}
- Detect vibration @ f_{drive} about sense axis with accelerometer

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

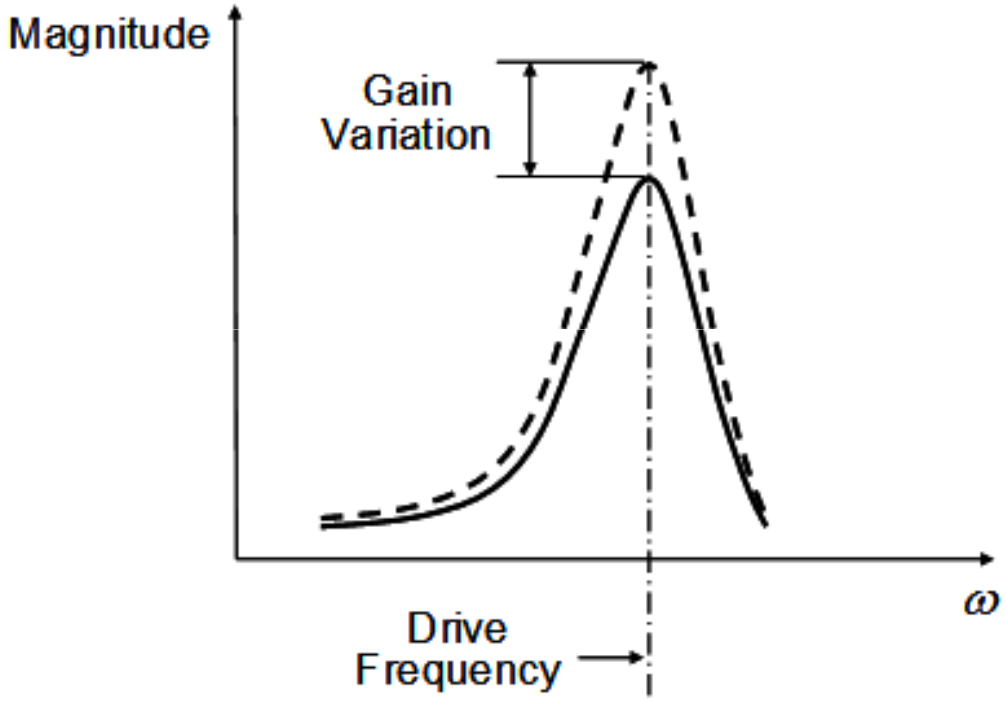
Operation at Resonance





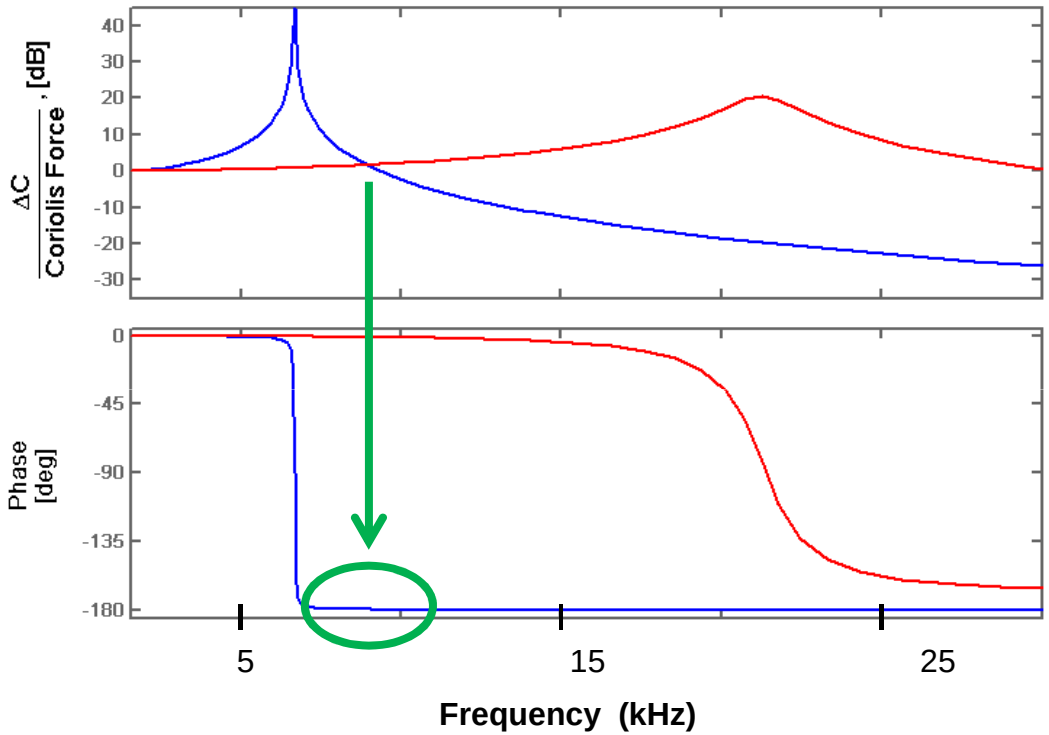
- Signal amplification at resonance
- $Q_{gyro} > 1000$

Gyro Sensitivity



- Limited bandwidth
- Sensitivity is a function of Q, temperature

Feedback



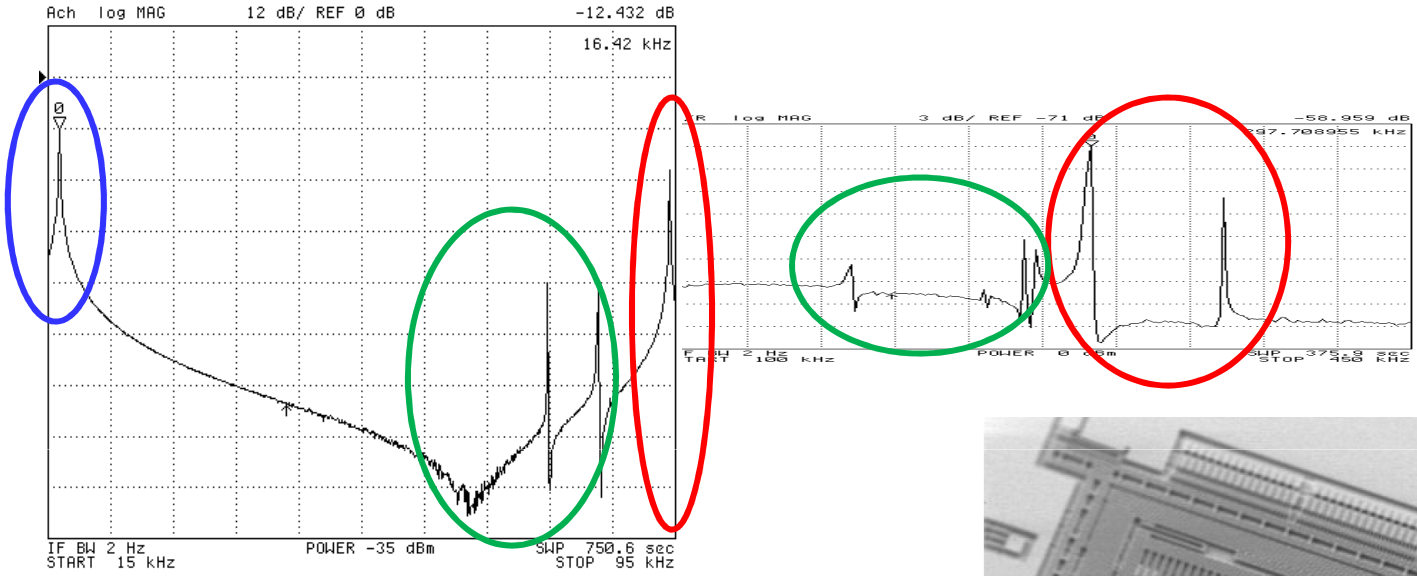
Open-loop

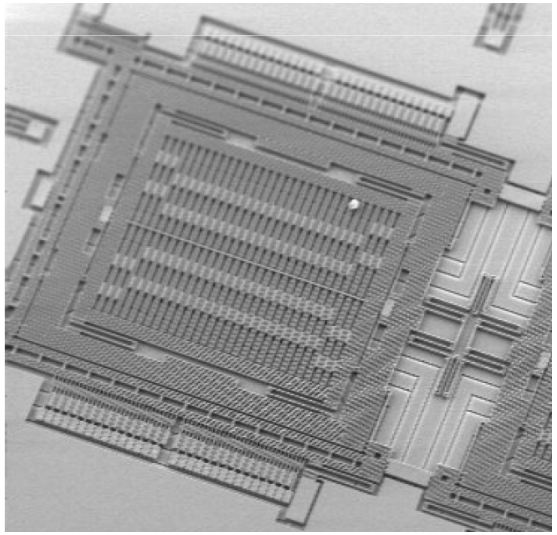
Feedback

Stability?

Virtually no phase margin

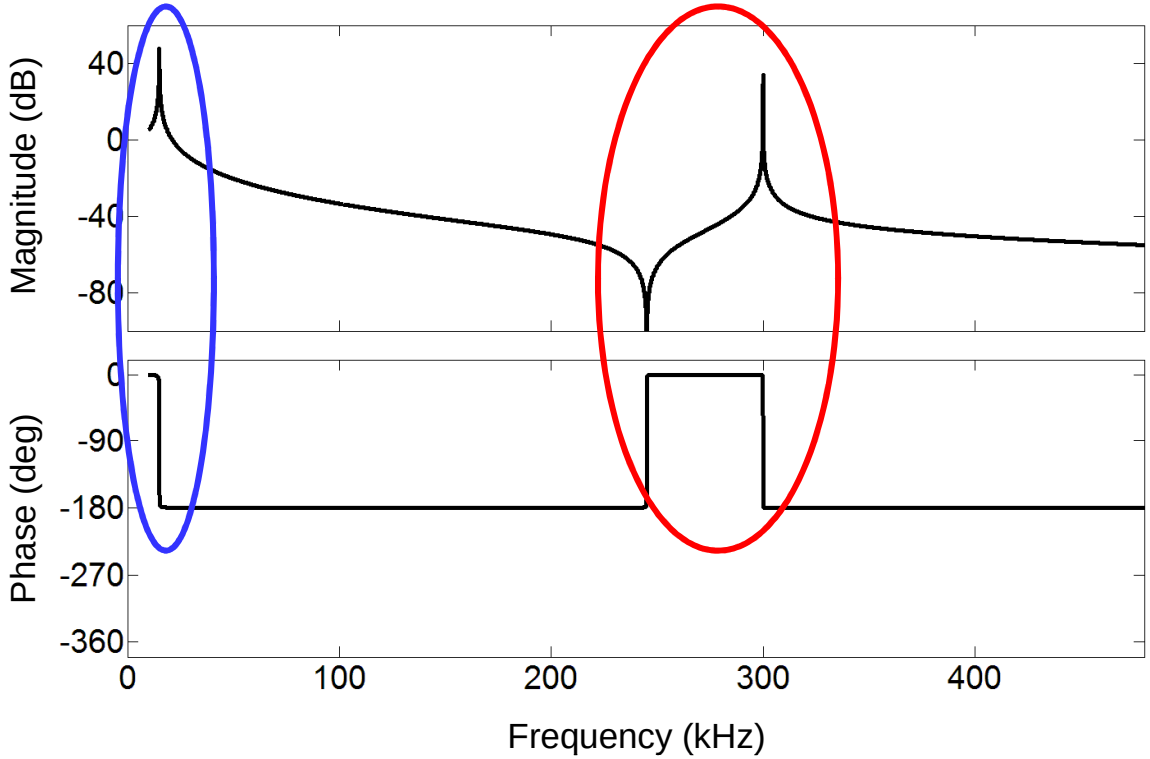
Sensor Frequency Response





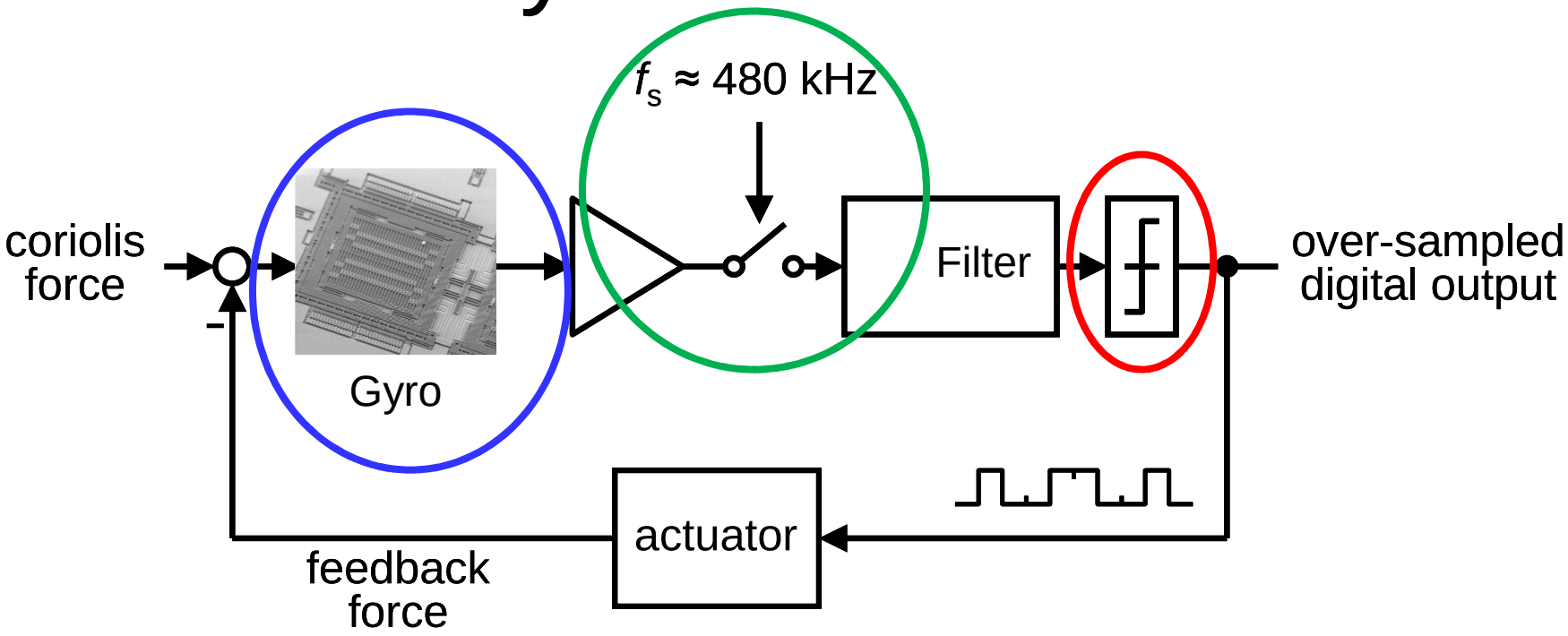
- Main mode near 15kHz
- Big parasitic modes near 95kHz and 300kHz
- Smaller parasitic modes all over

Example Frequency Response



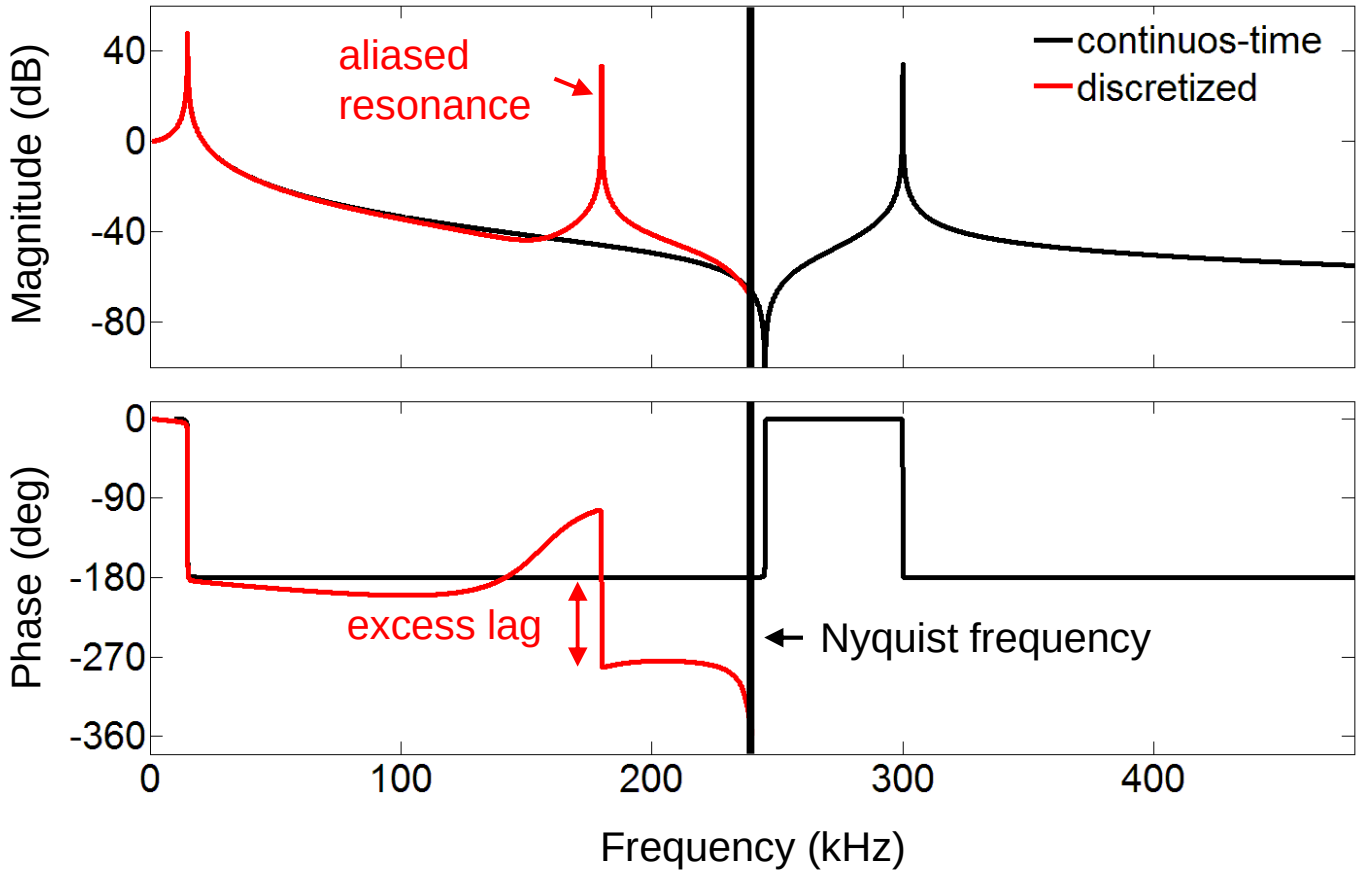
- Main resonance
- Single parasitic mode

System Model

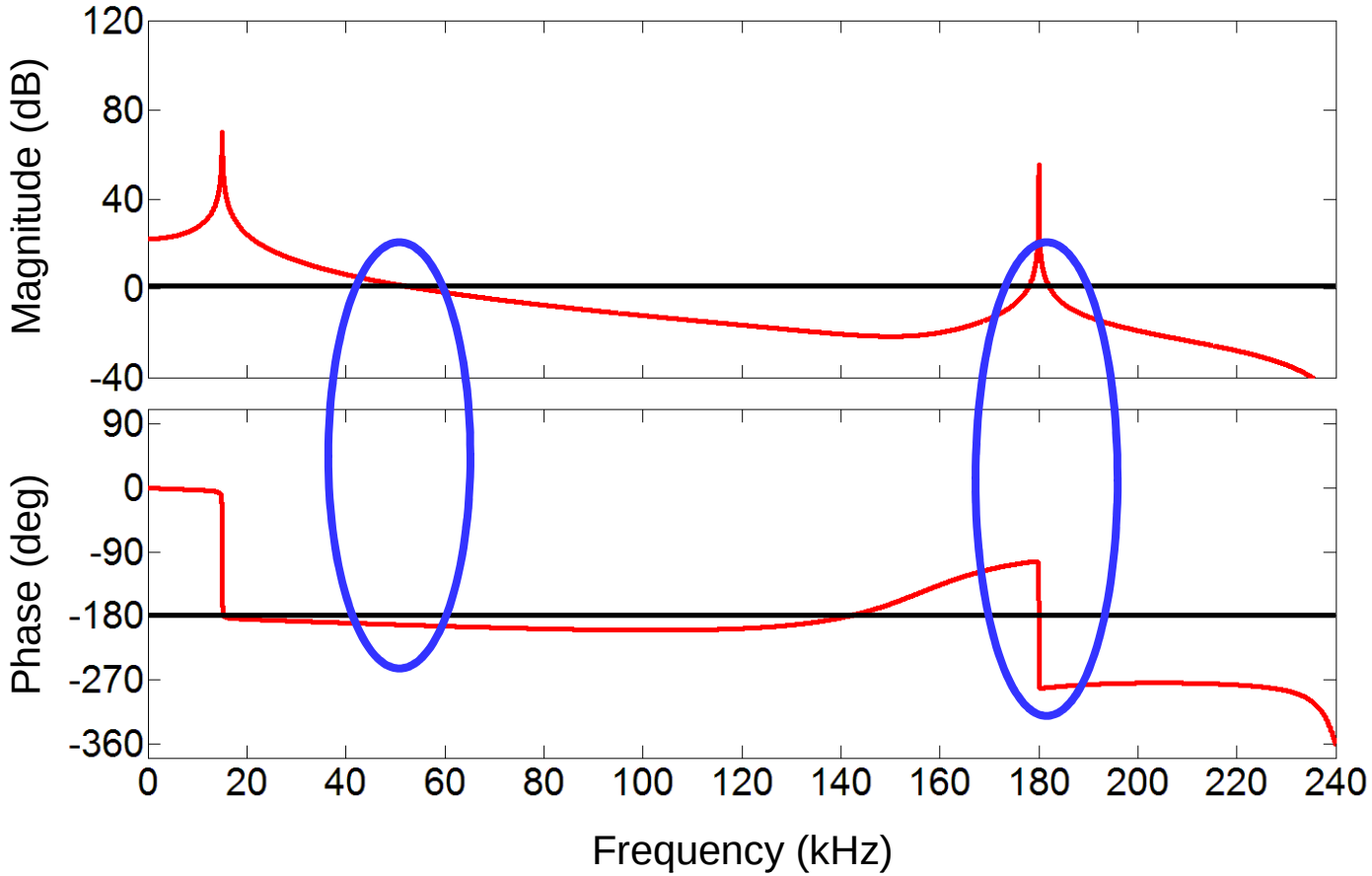


- MEMS Gyroscope
- Sampler
- Two-level (ΣΔ) feedback (linearize)

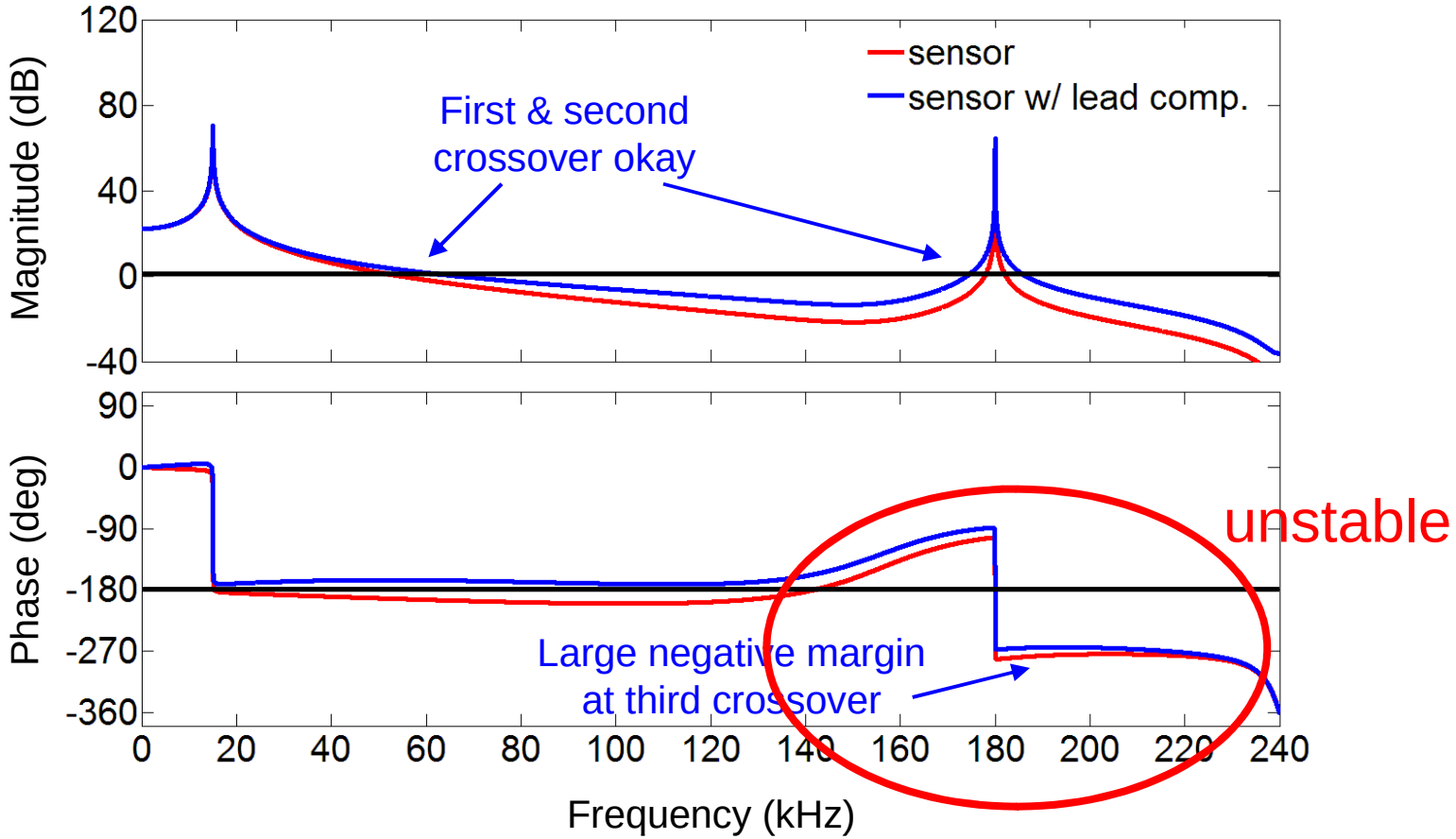
Sampled Frequency Response



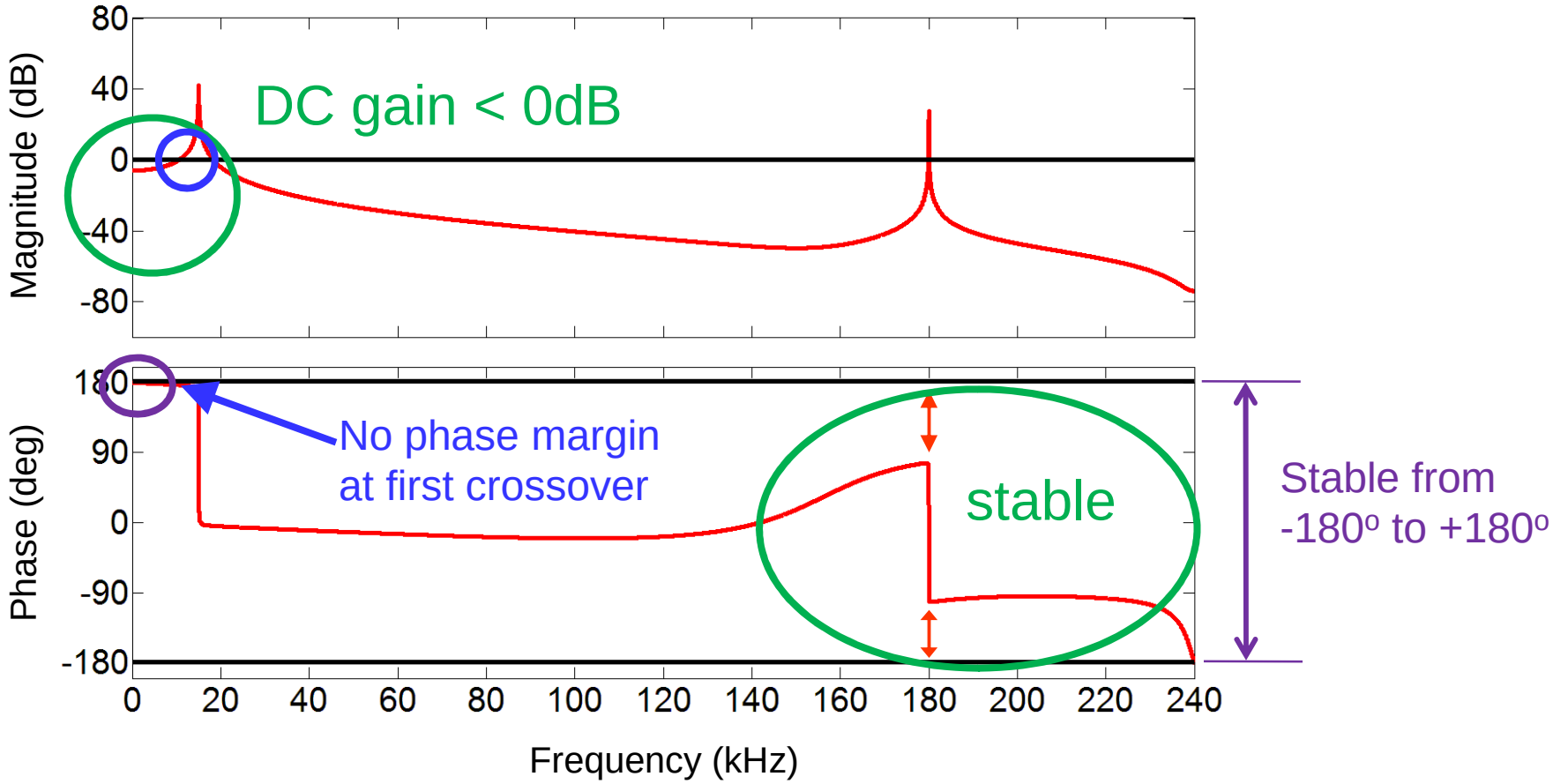
Negative Feedback



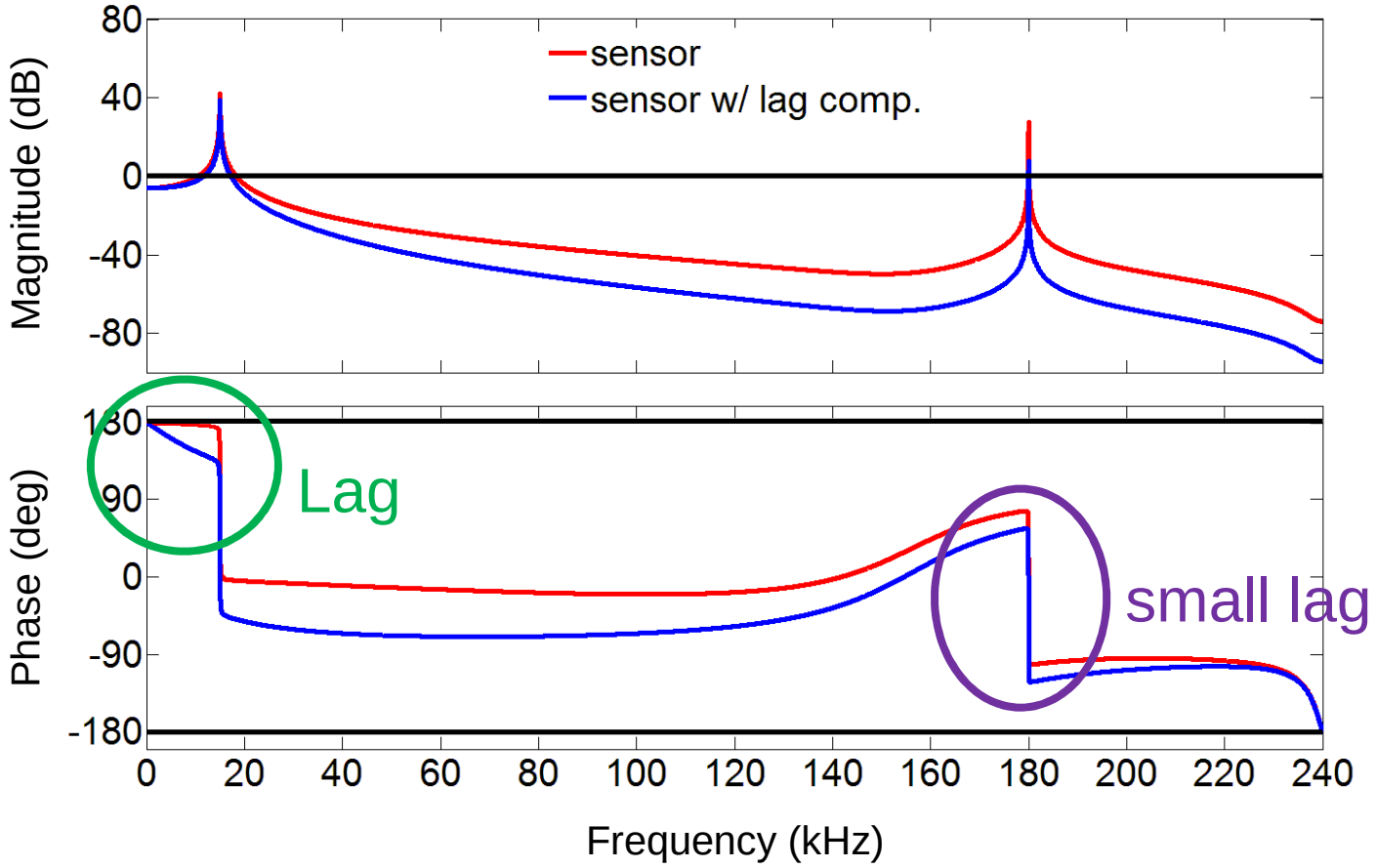
Negative Feedback w/ Lead Comp.



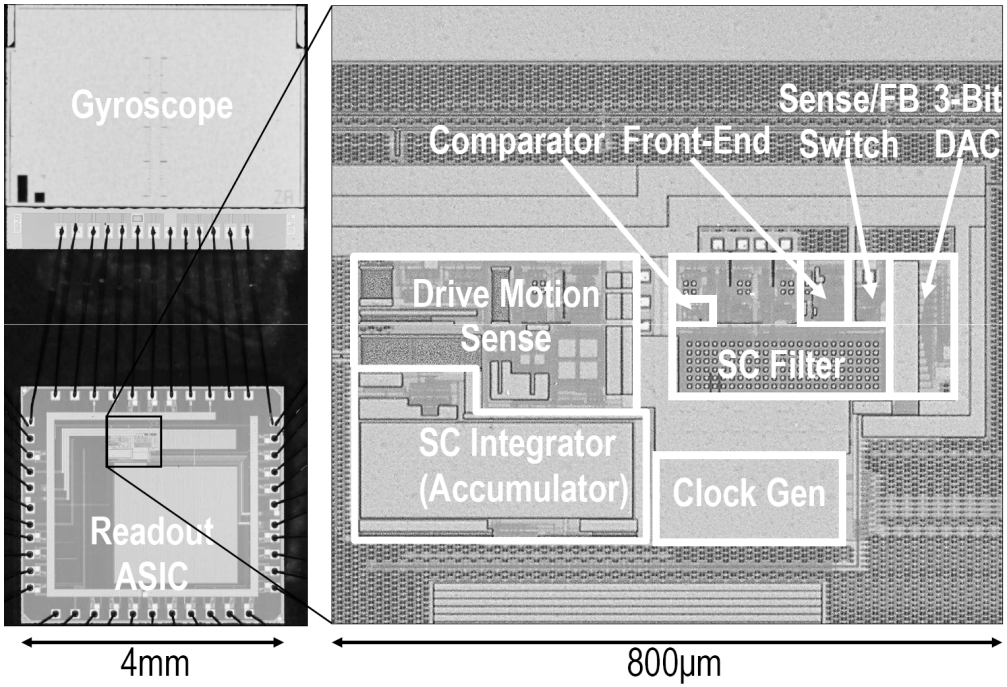
Positive Feedback

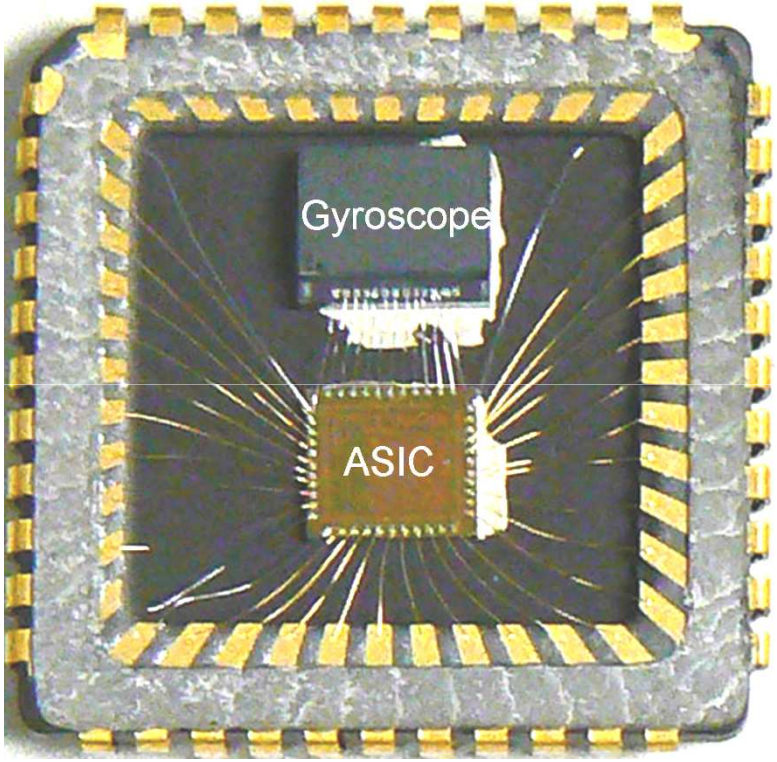


Positive Feedback w/ Lag Comp.



Results


Gyroscope
Readout ASIC
Comparator
Front-End
Sense/FB Switch
3-Bit DAC
Drive Motion Sense
SC Filter
SC Integrator (Accumulator)
Clock Gen
4mm
800µm


Gyroscope
ASIC

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

- Stable phase range is -180^{o} to +180^{o}
- Negative feedback phase starts at 0^{o}
  - Accommodates only 180^{o} phase lag
- Positive feedback phase starts at +180^{o}
  - Accommodates up to 360^{o} phase lag
  - Unstable for DC gain ≥ 1

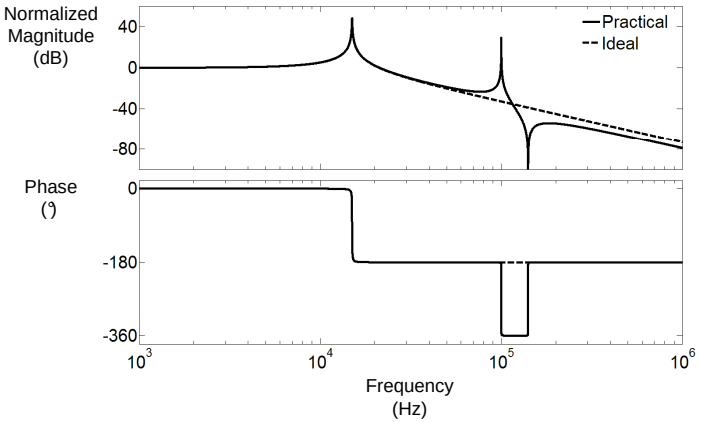
Acknowledgements

- Chinwuba Ezekwe
  Christoph Lang
  Vladimir Petkov

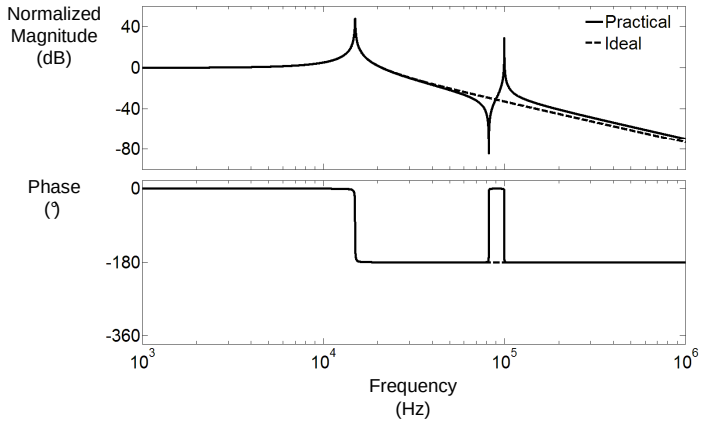
- Robert Bosch Corporation
  Gyroscope and financial support


BSAC

Parasitic Resonances



Non-collocated Control
(separate electrodes)



Collocated Control
(same electrode)