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EE C247B – ME C218 Introduction to MEMS Design Spring 2020

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Lecture Module 15: Gyros, Noise, & MDS

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Lecture Outline

- Reading: Senturia, Chpt. 14, Chpt. 16, Chpt. 21
- Lecture Topics:
  - Gyroscopes
  - Gyro Circuit Modeling
  - Minimum Detectable Signal (MDS)
    - Noise
    - Angle Random Walk (ARW)

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Gyroscopes

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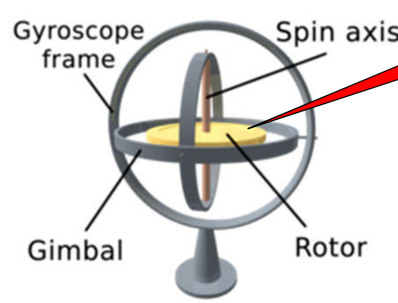
Classic Spinning Gyroscope

- A gyroscope measures rotation rate, which then gives orientation → very important, of course, for navigation
- Principle of operation based on conservation of momentum
- Example: classic spinning gyroscope



Rotor will preserve its angular momentum (i.e., will maintain its axis of spin) despite rotation of its gimbled chassis

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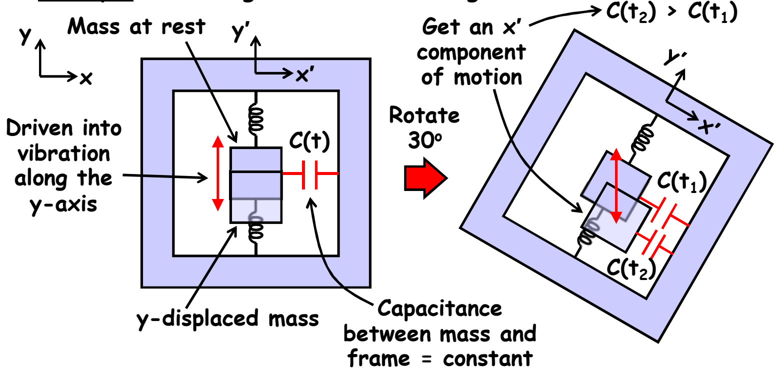
Vibratory Gyroscopes

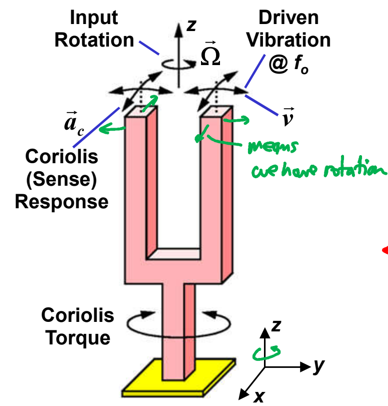
- Generate momentum by vibrating structures
- Again, conservation of momentum leads to mechanisms for measuring rotation rate and orientation
- Example: vibrating mass in a rotating frame

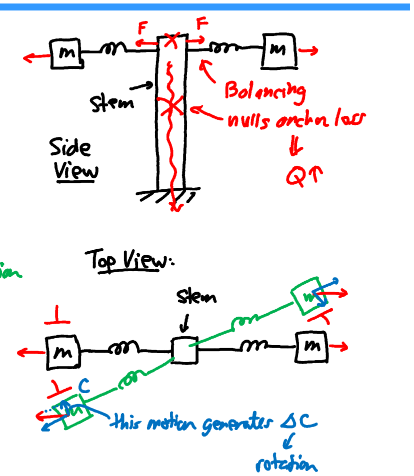


Basic Vibratory Gyroscope Operation

Principle of Operation

- Tuning Fork Gyroscope:





Basic Vibratory Gyroscope Operation

Principle of Operation

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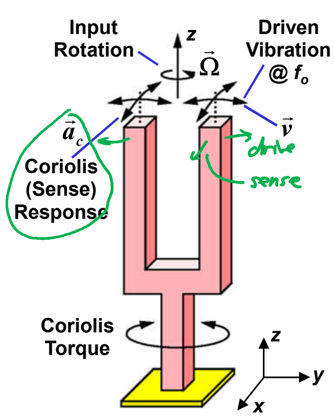
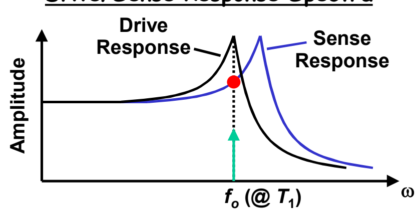


Drive/Sense Response Spectra:



Coriolis Acceleration, Driven Velocity, Rotation Rate:

$$\vec{a}_c = 2\vec{v}\times\vec{\Omega}$$

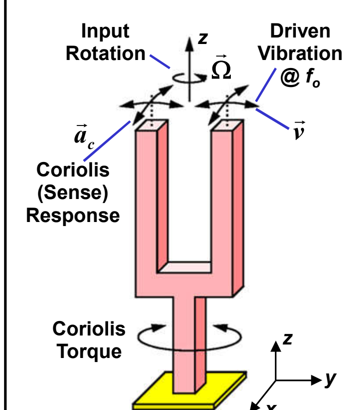
Coriolis Displacement, Coriolis Force, Beam Stiffness, Beam Mass, Sense Frequency:

$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2}$$

Vibratory Gyroscope Performance

Principle of Operation

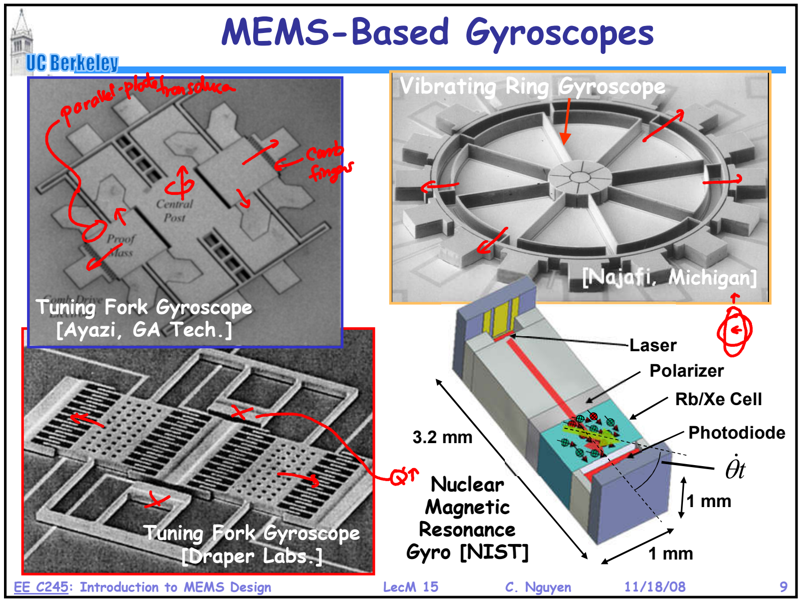
- Tuning Fork Gyroscope:



$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2} \qquad \vec{a}_c = 2\vec{v}\times\vec{\Omega}$$

Beam Mass, Beam Stiffness, Sense Frequency, Driven Velocity

- To maximize the output signal x, need:
  - Large sense-axis mass
  - Small sense-axis stiffness
  - (Above together mean low resonance frequency)
  - Large drive amplitude for large driven velocity (so use comb-drive)
  - If can match drive freq. to sense freq., then can amplify output by Q times


MEMS-Based Gyroscopes
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Central Post
Proof Mass
Tuning Fork Gyroscope [Ayazi, GA Tech.]
Vibrating Ring Gyroscope
[Najafi, Michigan]
Tuning Fork Gyroscope [Draper Labs.]
Laser
Polarizer
Rb/Xe Cell
Photodiode
3.2 mm
1 mm
1 mm
Nuclear Magnetic Resonance Gyro [NIST]
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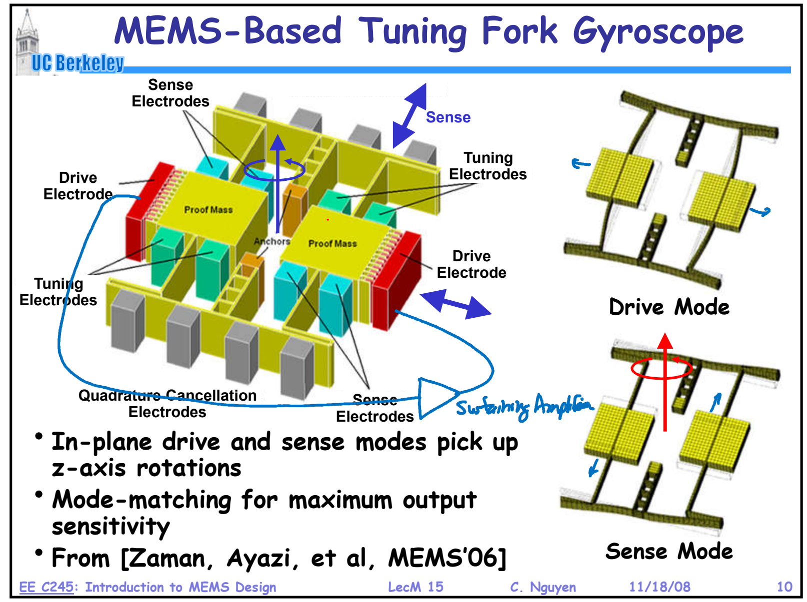
MEMS-Based Tuning Fork Gyroscope
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Sense Electrodes
Sense
Tuning Electrodes
Drive Electrode
Proof Mass
Anchors
Proof Mass
Drive Electrode
Tuning Electrodes
Quadrature Cancellation Electrodes
Sense Electrodes
Drive Mode
Sense Mode
• In-plane drive and sense modes pick up z-axis rotations
• Mode-matching for maximum output sensitivity
• From [Zaman, Ayazi, et al, MEMS'06]
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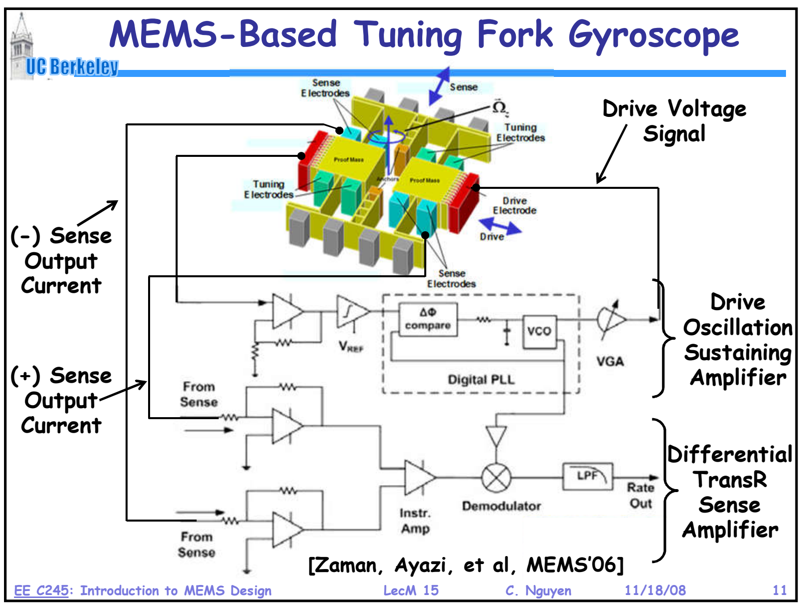
MEMS-Based Tuning Fork Gyroscope
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Sense Electrodes
Sense
Tuning Electrodes
Drive Electrode
Drive
Sense Electrodes
Drive Voltage Signal
(-) Sense Output Current
(+) Sense Output Current
ΔΦ compare
VCO
VGA
Digital PLL
From Sense
Instr. Amp
Demodulator
LPF
Rate Out
From Sense
Drive Oscillation Sustaining Amplifier
Differential TransR Sense Amplifier
[Zaman, Ayazi, et al, MEMS'06]
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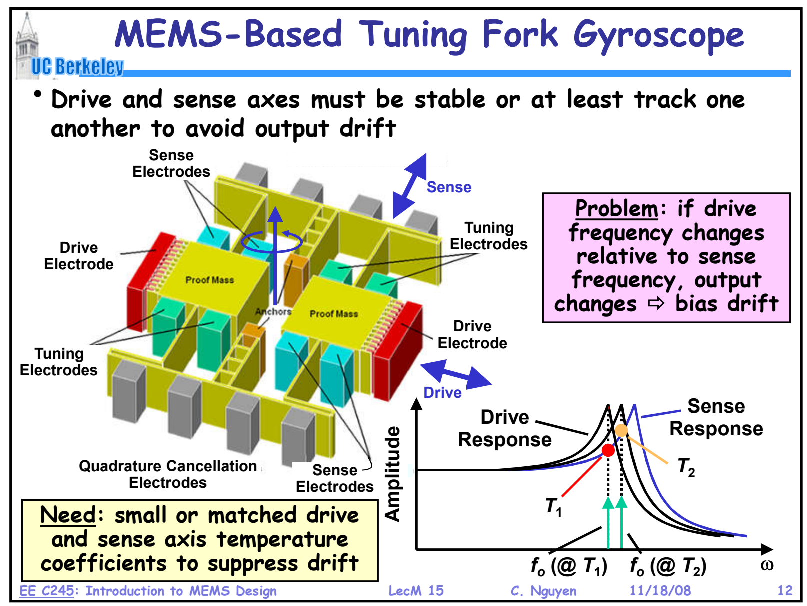
MEMS-Based Tuning Fork Gyroscope
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• Drive and sense axes must be stable or at least track one another to avoid output drift
Sense Electrodes
Sense
Tuning Electrodes
Drive Electrode
Proof Mass
Anchors
Proof Mass
Drive Electrode
Tuning Electrodes
Drive
Quadrature Cancellation Electrodes
Sense Electrodes
Problem: if drive frequency changes relative to sense frequency, output changes ⇨ bias drift
Need: small or matched drive and sense axis temperature coefficients to suppress drift
Amplitude
Drive Response
Sense Response
T_2
T_1
f_o (@ T_1)
f_o (@ T_2)
ω
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Mode Matching for Higher Resolution

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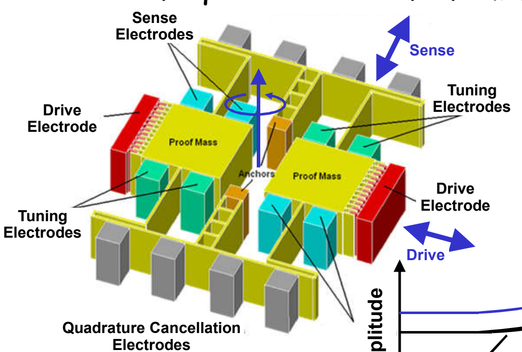
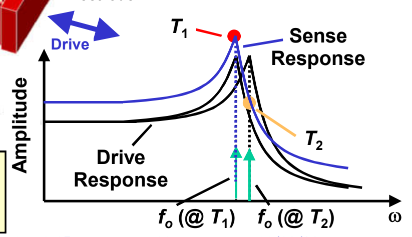
- For higher resolution, can try to match drive and sense axis resonance frequencies and benefit from Q amplification



Problem: mismatch between drive and sense frequencies ⇨ even larger drift!



Need: small or matched drive and sense axis temperature coefficients to make this work

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Issue: Zero Rate Bias Error

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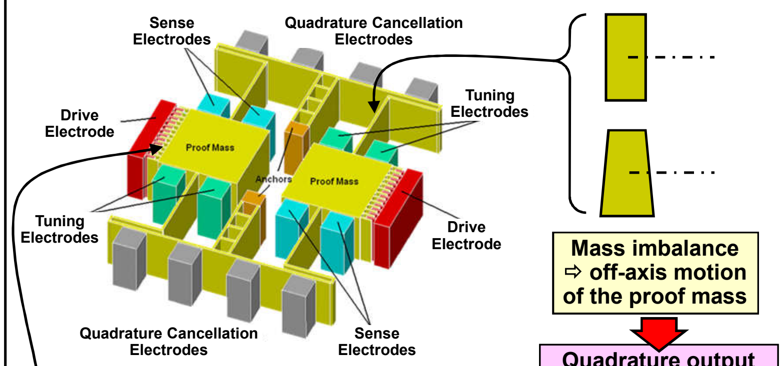
- Imbalances in the system can lead to zero rate bias error



Mass imbalance ⇨ off-axis motion of the proof mass

Quadrature output signal that can be confused with the Coriolis acceleration

Drive imbalance ⇨ off-axis motion of the proof mass

Output signal in phase with the Coriolis acceleration

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Nuclear Magnetic Res. Gyroscope

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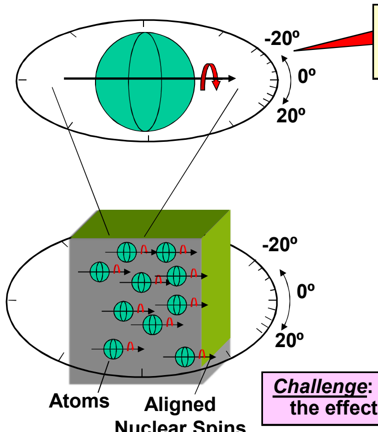
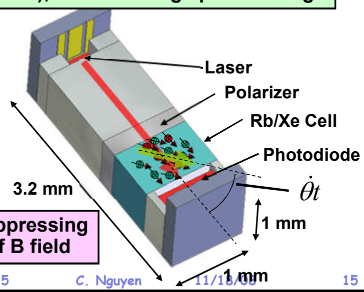
- The ultimate in miniaturized spinning gyroscopes?
  - ⇘ from CSAC, we may now have the technology to do this



Better if this is a noble gas nucleus (rather than e-), since nuclei are heavier ⇨ less susceptible to B field

Soln: Spin polarize Xe^{129} nuclei by first polarizing e- of Rb^{87} (a la CSAC), then allowing spin exchange



Challenge: suppressing the effects of B field

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MEMS-Based Tuning Fork Gyroscope

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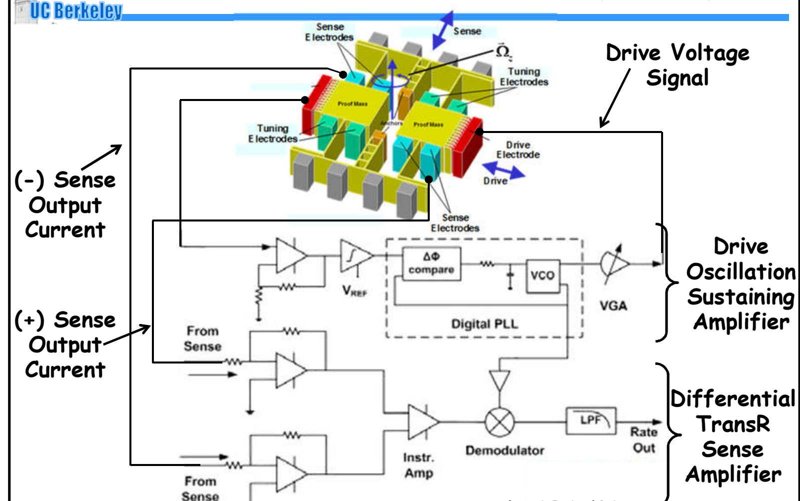

[Zaman, Ayazi, et al, MEMS'06]

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Determining Sensor Resolution

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