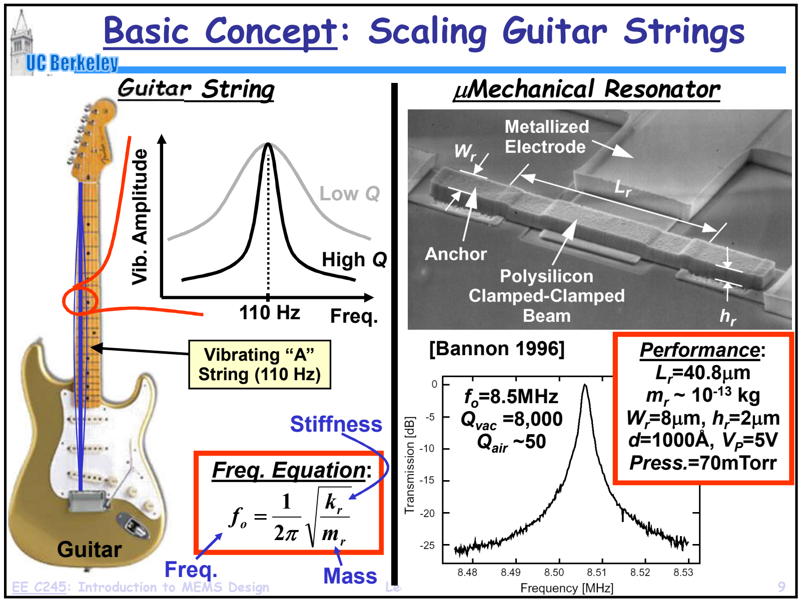
Basic Concept: Scaling Guitar Strings
UC Berkeley
Guitar String
μMechanical Resonator
Vib. Amplitude
Low Q
High Q
110 Hz
Freq.
Vibrating "A" String (110 Hz)
Guitar
Stiffness
Freq. Equation:
$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$
Freq.
Mass
Metallized Electrode
W_r
L_r
Anchor
Polysilicon Clamped-Clamped Beam
h_r
[Bannon 1996]
f_o=8.5MHz
Q_{vac} =8,000
Q_{air} ~50
Transmission [dB]
Frequency [MHz]
Performance:
L_r=40.8μm
m_r ~ 10^{-13} kg
W_r=8μm, h_r=2μm
d=1000Å, V_P=5V
Press.=70mTorr
EE C245: Introduction to MEMS Design
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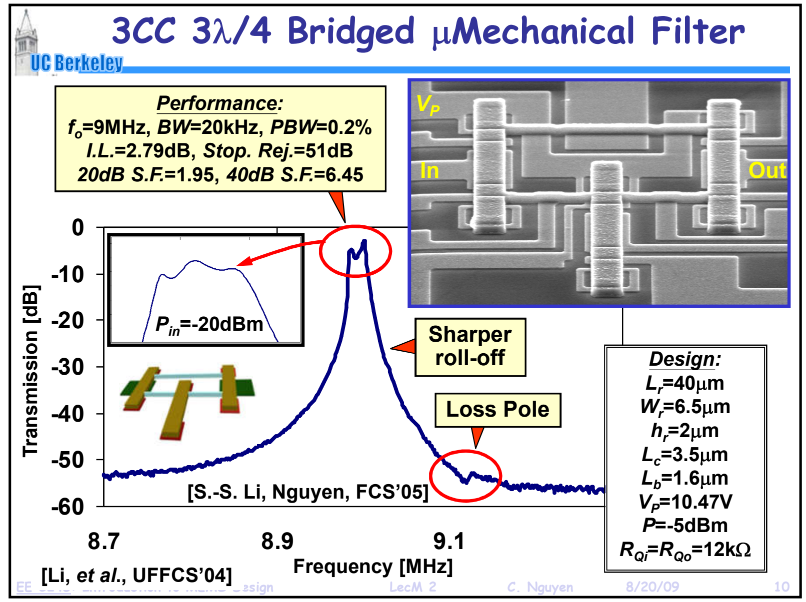
3CC 3λ/4 Bridged μMechanical Filter
UC Berkeley
Performance:
f_o=9MHz, BW=20kHz, PBW=0.2%
I.L.=2.79dB, Stop. Rej.=51dB
20dB S.F.=1.95, 40dB S.F.=6.45
V_P
In
Out
Transmission [dB]
P_{in}=-20dBm
Sharper roll-off
Loss Pole
[S.-S. Li, Nguyen, FCS'05]
Design:
L_r=40μm
W_r=6.5μm
h_r=2μm
L_c=3.5μm
L_b=1.6μm
V_P=10.47V
P=-5dBm
R_{Qi}=R_{Qo}=12kΩ
Frequency [MHz]
[Li, et al., UFFCS'04]
LecM 2
C. Nguyen
8/20/09
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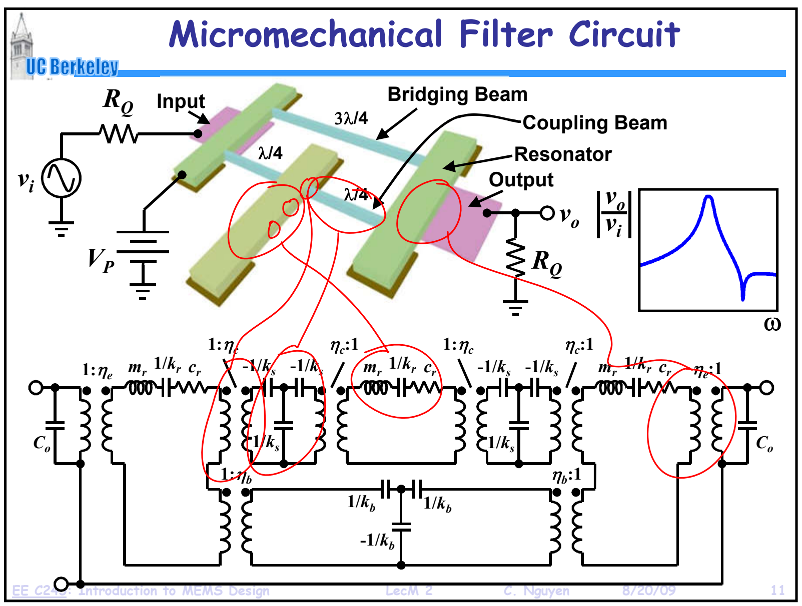
Micromechanical Filter Circuit
UC Berkeley
R_Q
Input
Bridging Beam
3λ/4
Coupling Beam
λ/4
Resonator
Output
v_i
V_P
v_o
R_Q
$\left|\frac{v_o}{v_i}\right|$
ω
1:η_e
m_r $1/k_r$ c_r
$-1/k_s$
$1/k_s$
η_c:1
1:η_c
η_e:1
C_o
1:η_b
η_b:1
$1/k_b$
$-1/k_b$
EE C245: Introduction to MEMS Design
LecM 2
C. Nguyen
8/20/09
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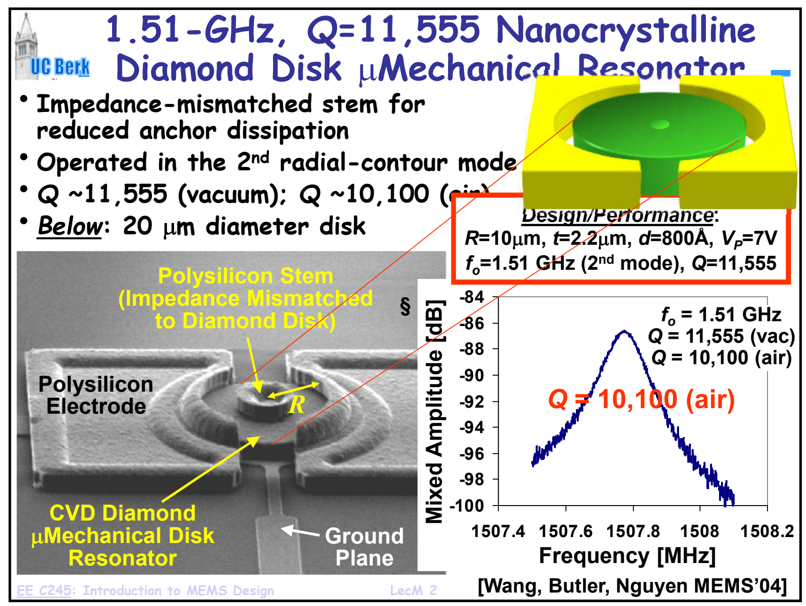
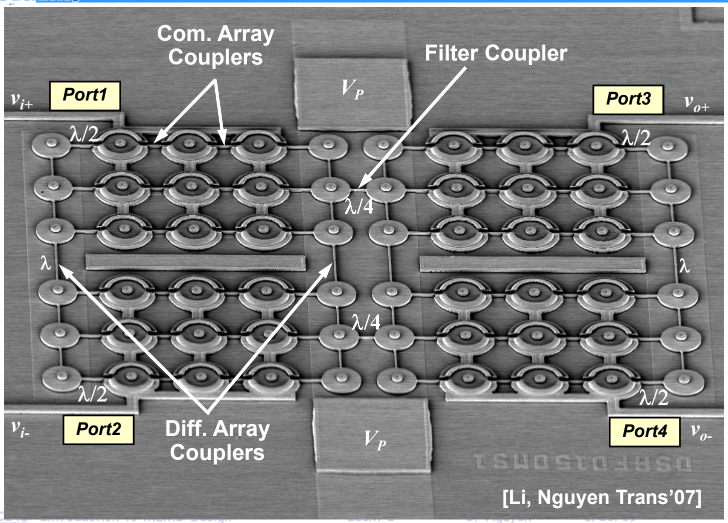
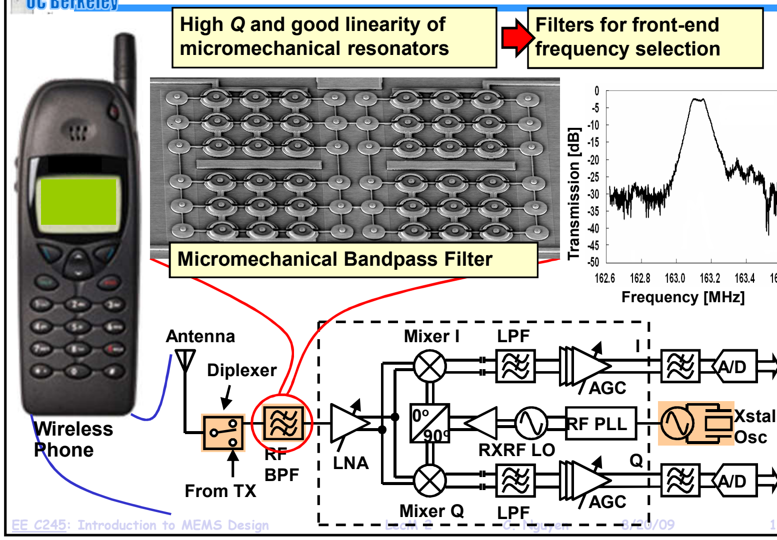

1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator
UC Berk
• Impedance-mismatched stem for reduced anchor dissipation
• Operated in the 2nd radial-contour mode
• Q ~11,555 (vacuum); Q ~10,100 (air)
• Below: 20 μm diameter disk
Design/Performance:
R=10μm, t=2.2μm, d=800Å, V_P=7V
f_o=1.51 GHz (2nd mode), Q=11,555
Polysilicon Stem (Impedance Mismatched to Diamond Disk)
Polysilicon Electrode
R
CVD Diamond μMechanical Disk Resonator
Ground Plane
Mixed Amplitude [dB]
f_o = 1.51 GHz
Q = 11,555 (vac)
Q = 10,100 (air)
Q = 10,100 (air)
Frequency [MHz]
[Wang, Butler, Nguyen MEMS'04]
EE C245: Introduction to MEMS Design
LecM 2

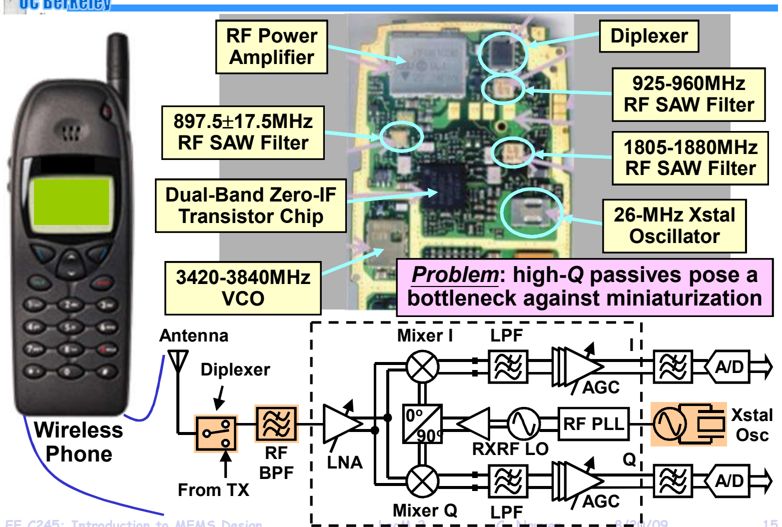
163-MHz Differential Disk-Array Filter



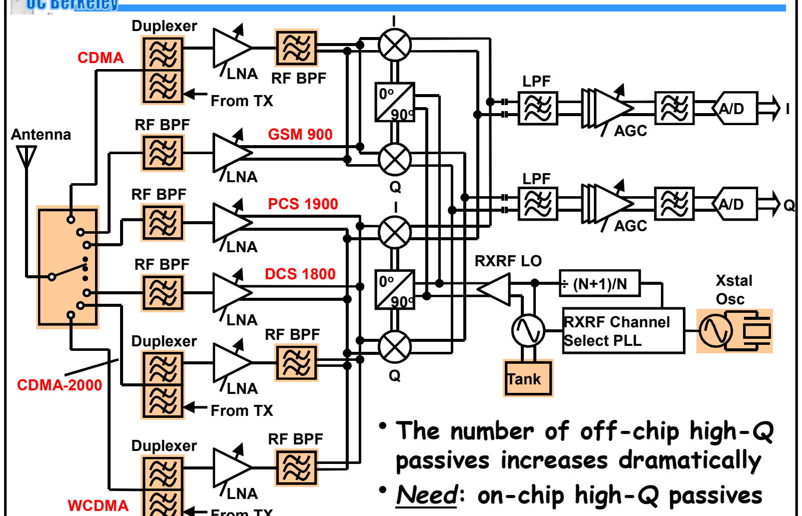
Linear MEMS in Wireless Comms



Miniaturization of RF Front Ends

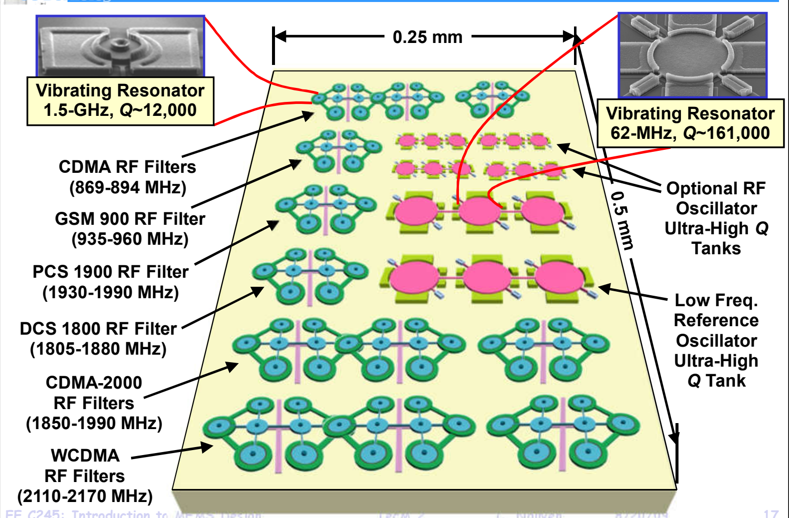


Multi-Band Wireless Handsets



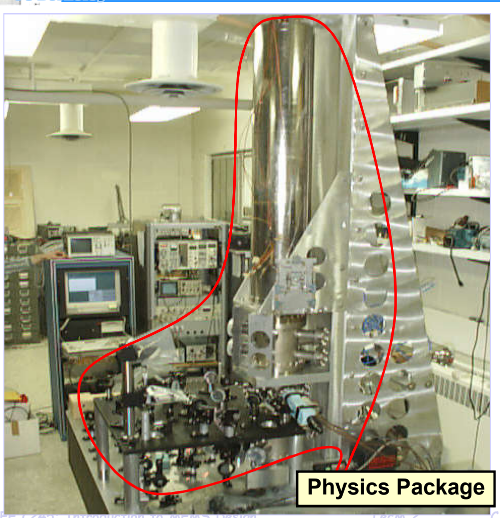
- The number of off-chip high-Q passives increases dramatically
- *Need*: on-chip high-Q passives

All High-Q Passives on a Single Chip



Chip-Scale Atomic Clocks (CSAC)

NIST F1 Fountain Atomic Clock

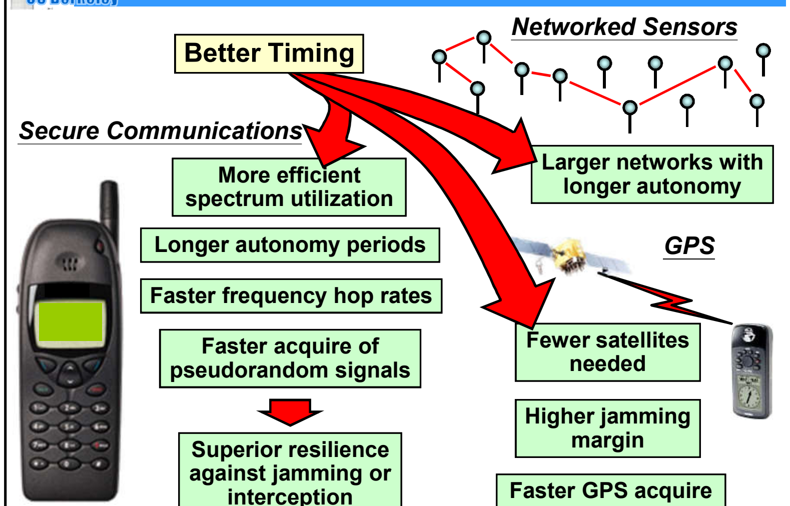


Vol: ~3.7 m^3
Power: ~500 W
Acc: 1×10^{-15}
Stab: 3.3×10^{-15}/hr

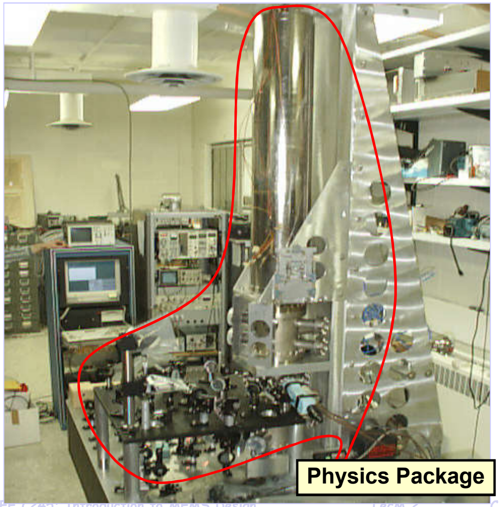
After 1 sec ⇨
Error: 10^{-15} sec

Loses 1 sec every 30 million years!

Benefits of Accurate Portable Timing



NIST F1 Fountain Atomic Clock

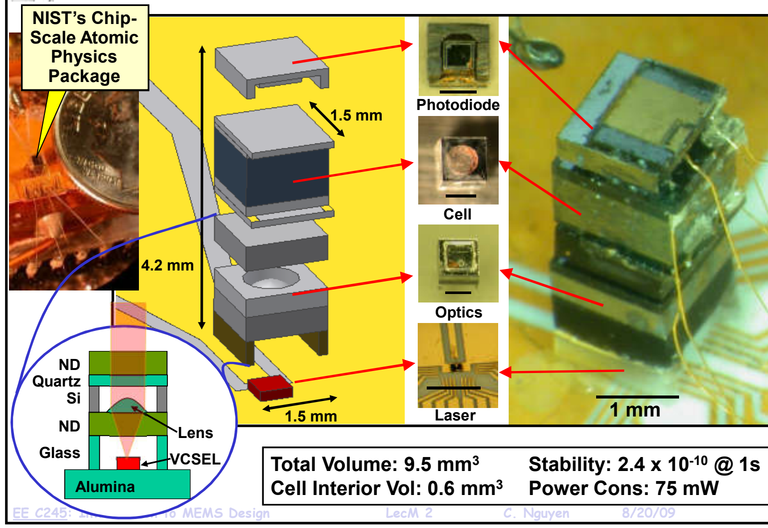


Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

After 1 sec ⇨ *Error*: 10⁻¹⁵ sec

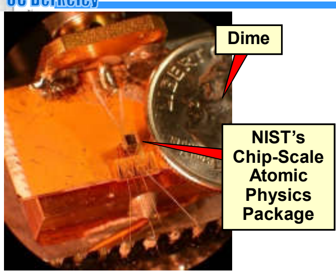
Loses 1 sec every 30 million years!

1st Chip-Scale Atomic Physics Package



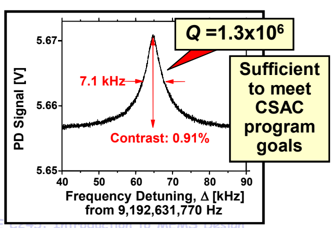
Total Volume: 9.5 mm³ Stability: 2.4 x 10⁻¹⁰ @ 1s
Cell Interior Vol: 0.6 mm³ Power Cons: 75 mW

Tiny Physics Package Performance

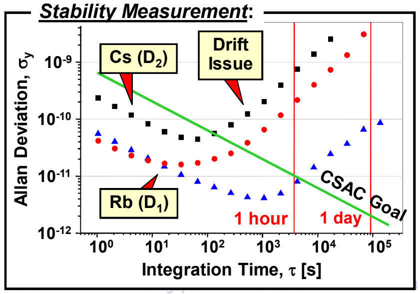


- ***Experimental Conditions***:
  Cs D2 Excitation
  External (large) Magnetic Shielding
  External Electronics & LO
  Cell Temperature: ~80 °C
  Cell Heater Power: 69 mW
  Laser Current/Voltage: 2mA / 2V
  RF Laser Mod Power: 70μW

Open Loop Resonance:



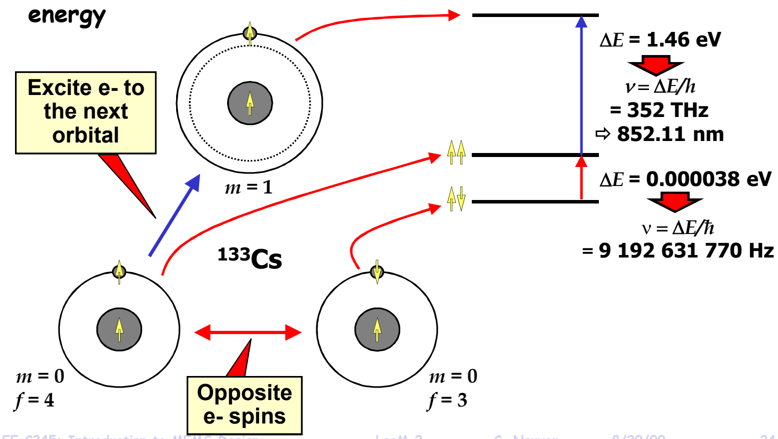
Stability Measurement:

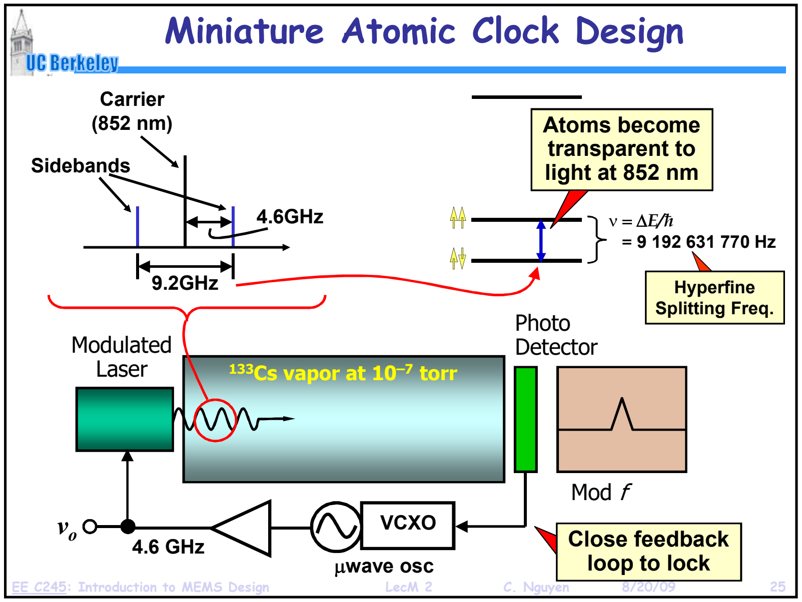


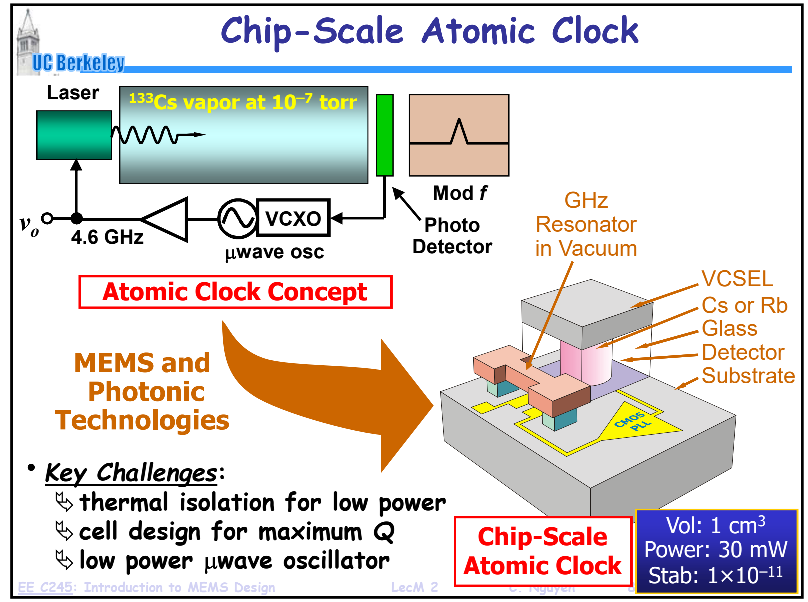
Atomic Clock Fundamentals

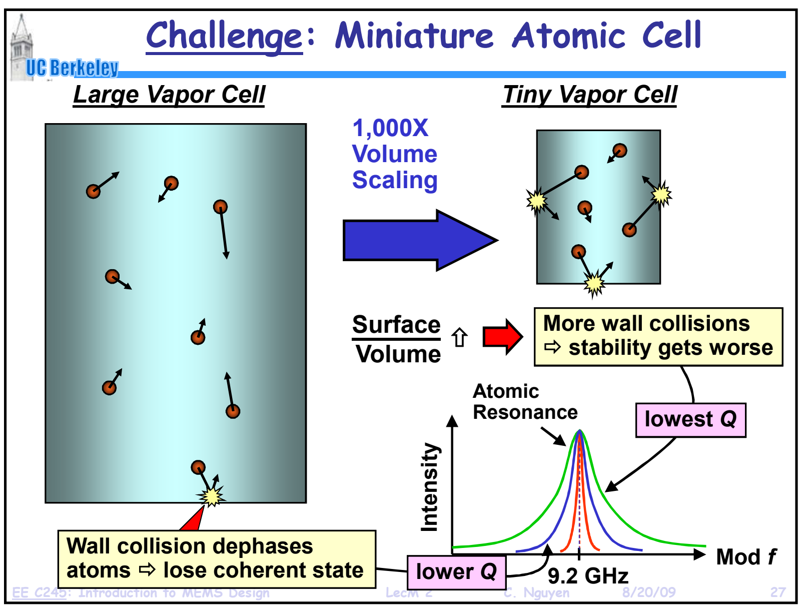
- Frequency determined by an atomic transition energy

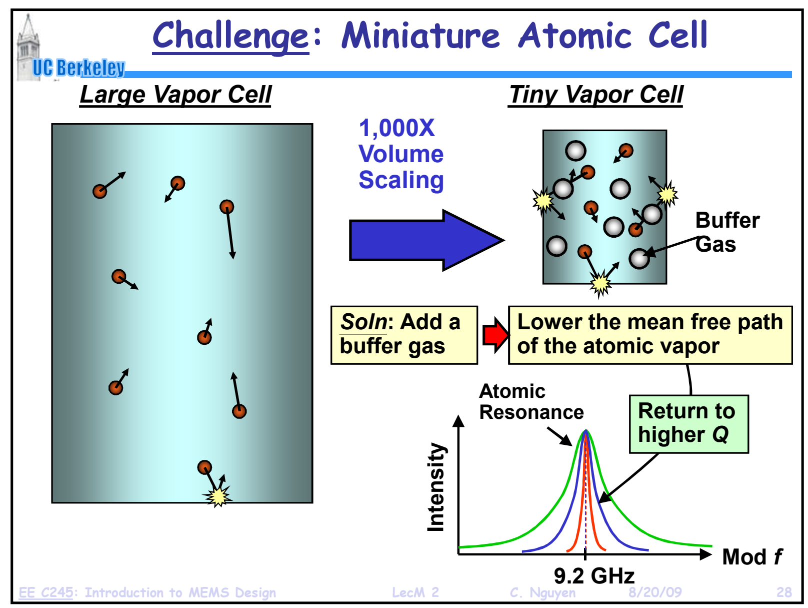
Energy Band Diagram

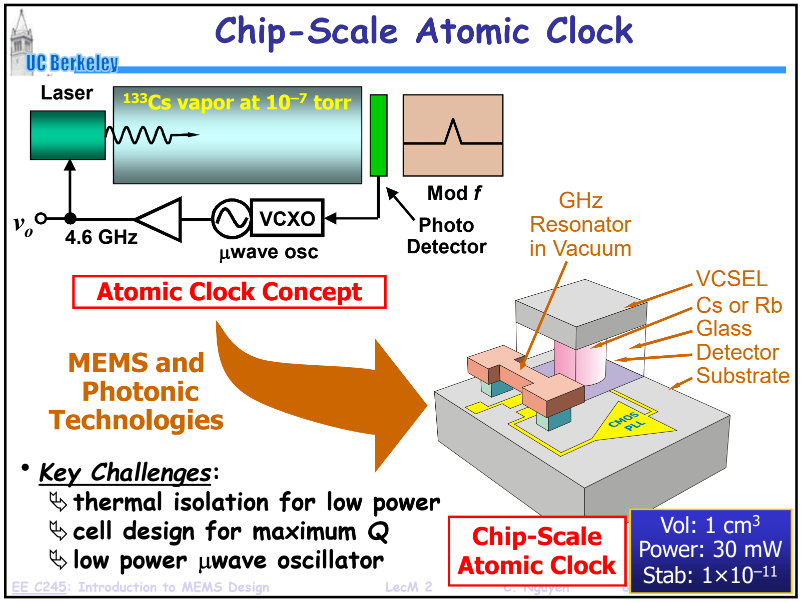


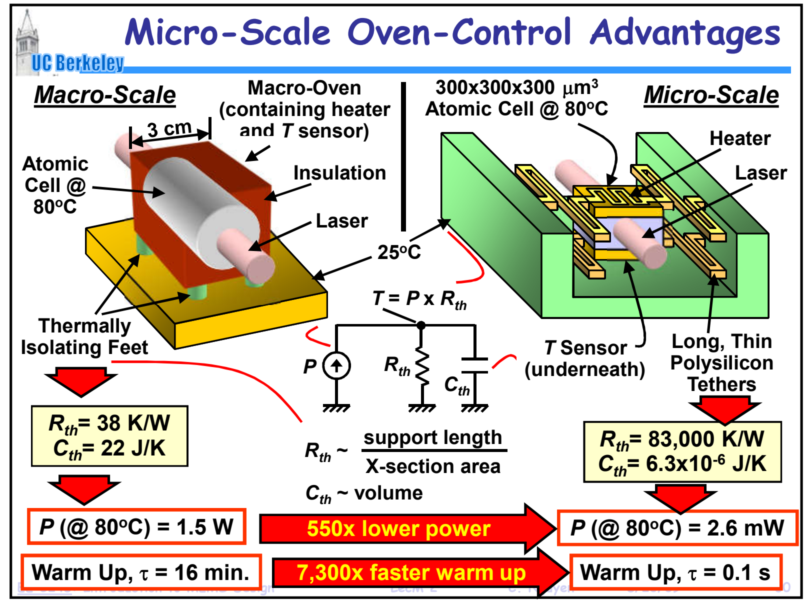

Miniature Atomic Clock Design
UC Berkeley
Carrier
(852 nm)
Sidebands
4.6GHz
9.2GHz
Atoms become
transparent to
light at 852 nm
ν = ΔE/ħ
= 9 192 631 770 Hz
Hyperfine
Splitting Freq.
Modulated
Laser
133Cs vapor at 10−7 torr
Photo
Detector
Mod f
vo
4.6 GHz
VCXO
μwave osc
Close feedback
loop to lock
EE C245: Introduction to MEMS Design LecM 2 C. Nguyen 8/20/09 25


Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo
Detector
vo
4.6 GHz
VCXO
μwave osc
GHz
Resonator
in Vacuum
Atomic Clock Concept
VCSEL
Cs or Rb
Glass
Detector
Substrate
MEMS and
Photonic
Technologies
• Key Challenges:
thermal isolation for low power
cell design for maximum Q
low power μwave oscillator
Chip-Scale
Atomic Clock
Vol: 1 cm3
Power: 30 mW
Stab: 1×10−11
EE C245: Introduction to MEMS Design LecM 2


Challenge: Miniature Atomic Cell
UC Berkeley
Large Vapor Cell
Tiny Vapor Cell
1,000X
Volume
Scaling
Surface
Volume
More wall collisions
⇨ stability gets worse
Atomic
Resonance
lowest Q
Intensity
Mod f
9.2 GHz
lower Q
Wall collision dephases
atoms ⇨ lose coherent state
EE C245: Introduction to MEMS Design LecM 2 C. Nguyen 8/20/09 27


Challenge: Miniature Atomic Cell
UC Berkeley
Large Vapor Cell
Tiny Vapor Cell
1,000X
Volume
Scaling
Buffer
Gas
Soln: Add a
buffer gas
Lower the mean free path
of the atomic vapor
Atomic
Resonance
Return to
higher Q
Intensity
Mod f
9.2 GHz
EE C245: Introduction to MEMS Design LecM 2 C. Nguyen 8/20/09 28


Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo Detector
VCXO
μwave osc
4.6 GHz
vo
Atomic Clock Concept
GHz Resonator in Vacuum
VCSEL
Cs or Rb
Glass
Detector
Substrate
CMOS PLL
MEMS and Photonic Technologies
• Key Challenges:
thermal isolation for low power
cell design for maximum Q
low power μwave oscillator
Chip-Scale Atomic Clock
Vol: 1 cm3
Power: 30 mW
Stab: 1×10−11


Micro-Scale Oven-Control Advantages
UC Berkeley
Macro-Scale
Macro-Oven (containing heater and T sensor)
3 cm
Atomic Cell @ 80°C
Insulation
Laser
25°C
Thermally Isolating Feet
300x300x300 μm3 Atomic Cell @ 80°C
Micro-Scale
Heater
Laser
T Sensor (underneath)
Long, Thin Polysilicon Tethers
T = P x Rth
P
Rth
Cth
Rth= 38 K/W
Cth= 22 J/K
Rth ~ support length / X-section area
Cth ~ volume
Rth= 83,000 K/W
Cth= 6.3x10-6 J/K
P (@ 80°C) = 1.5 W
550x lower power
P (@ 80°C) = 2.6 mW
Warm Up, τ = 16 min.
7,300x faster warm up
Warm Up, τ = 0.1 s