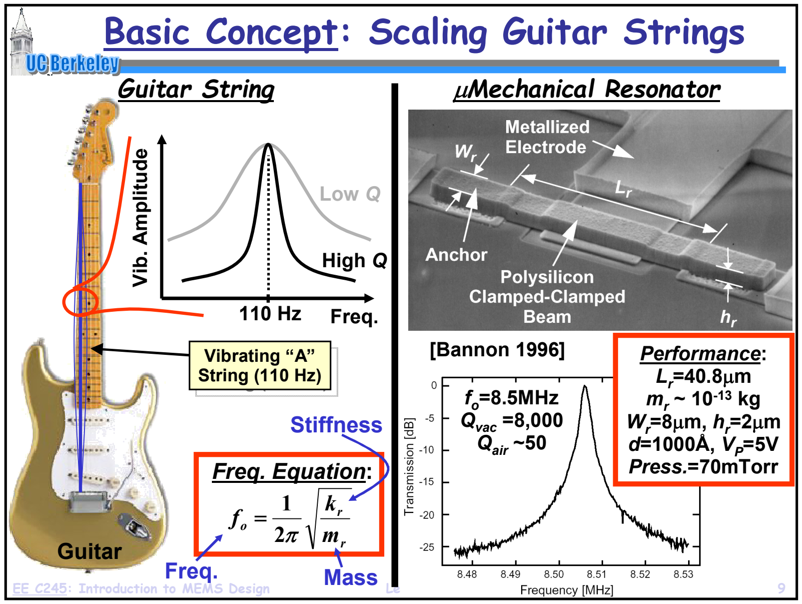
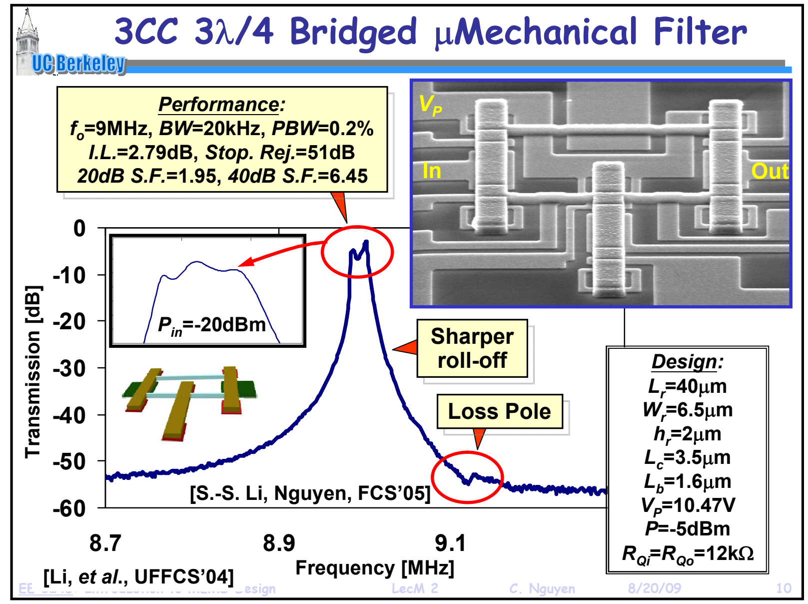
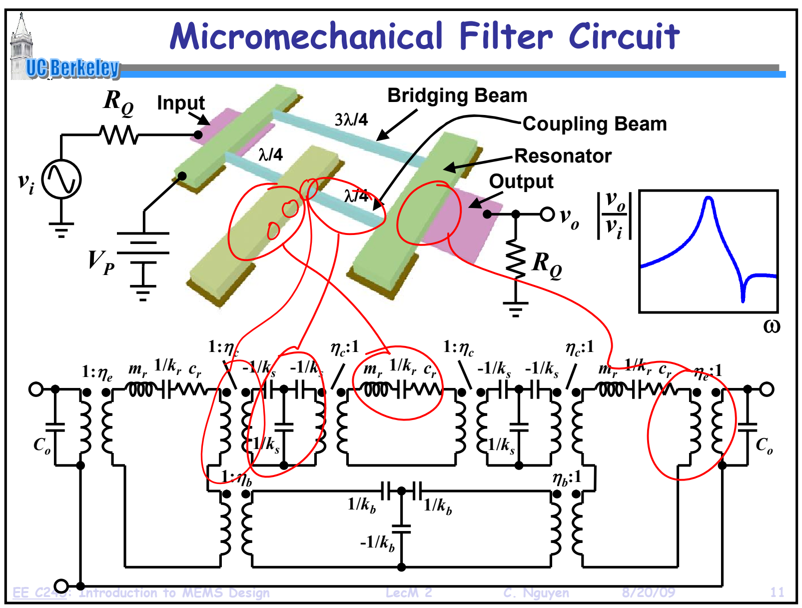
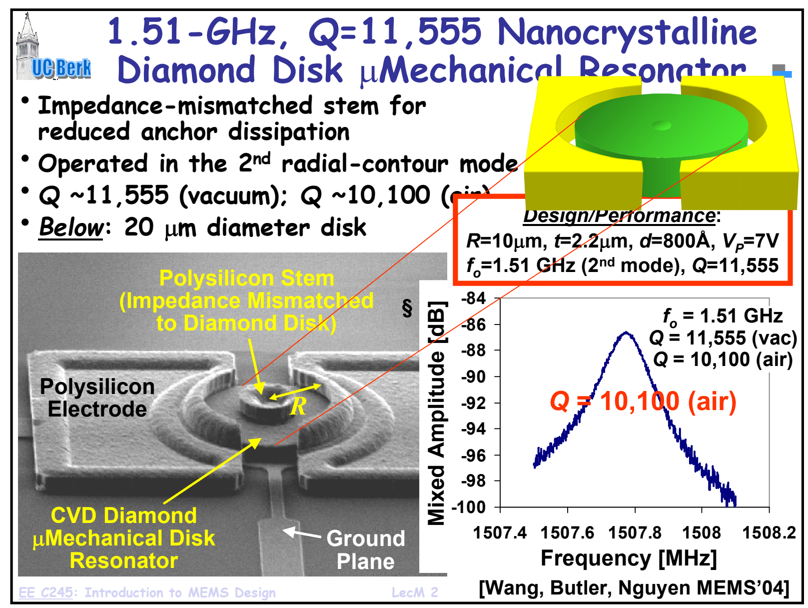
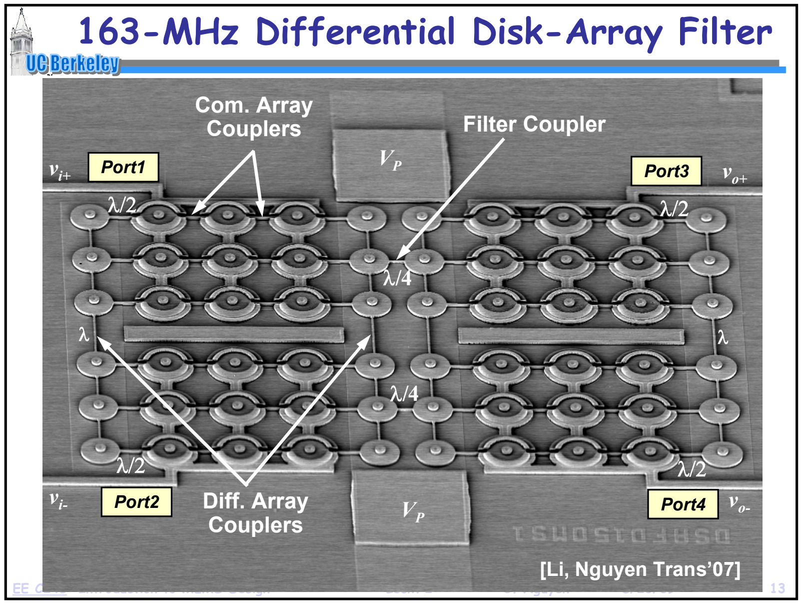
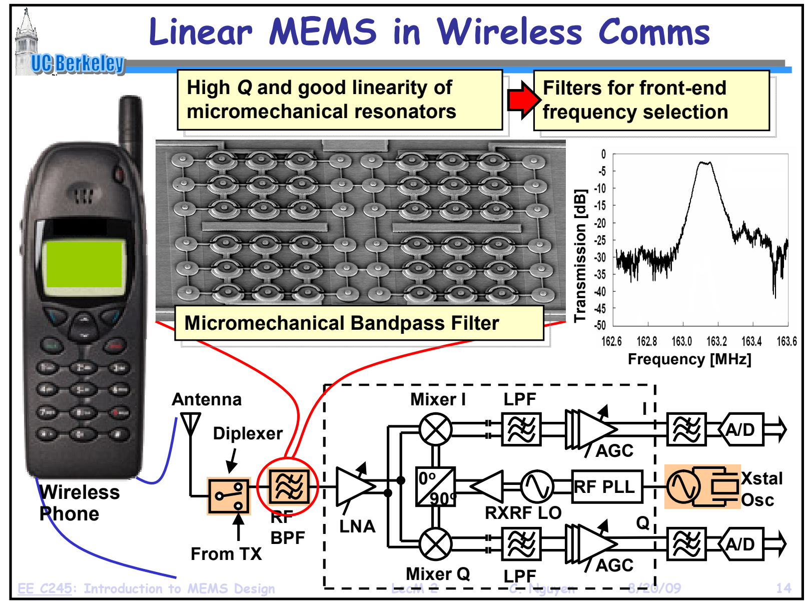

Basic Concept: Scaling Guitar Strings
UC Berkeley
Guitar String
μMechanical Resonator
Vib. Amplitude
Low Q
High Q
110 Hz
Freq.
Metallized Electrode
Anchor
Polysilicon Clamped-Clamped Beam
[Bannon 1996]
Vibrating "A" String (110 Hz)
Guitar
Stiffness
Freq. Equation:
$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$
Freq.
Mass
f_o=8.5MHz
Q_{vac} =8,000
Q_{air} ~50
Performance:
L_r=40.8μm
m_r ~ 10^{-13} kg
W_r=8μm, h_r=2μm
d=1000Å, V_P=5V
Press.=70mTorr
Transmission [dB]
Frequency [MHz]

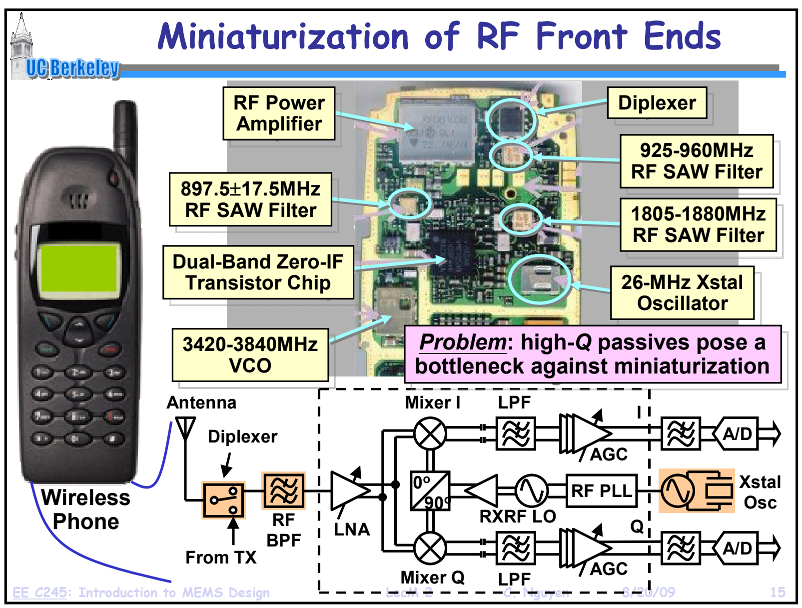

3CC 3λ/4 Bridged μMechanical Filter
UC Berkeley
Performance:
f_o=9MHz, BW=20kHz, PBW=0.2%
I.L.=2.79dB, Stop. Rej.=51dB
20dB S.F.=1.95, 40dB S.F.=6.45
V_P
In
Out
P_{in}=-20dBm
Sharper roll-off
Loss Pole
Transmission [dB]
[S.-S. Li, Nguyen, FCS'05]
Frequency [MHz]
[Li, et al., UFFCS'04]
Design:
L_r=40μm
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

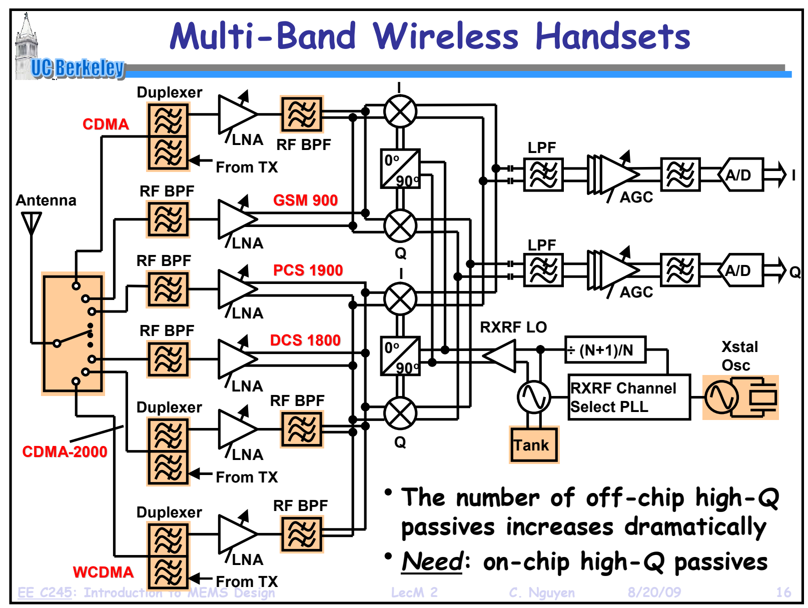

Micromechanical Filter Circuit
UC Berkeley
R_Q
Input
Bridging Beam
3λ/4
Coupling Beam
λ/4
Resonator
Output
v_i
V_P
v_o
$\left|\frac{v_o}{v_i}\right|$
ω


1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μMechanical Resonator
• 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
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]

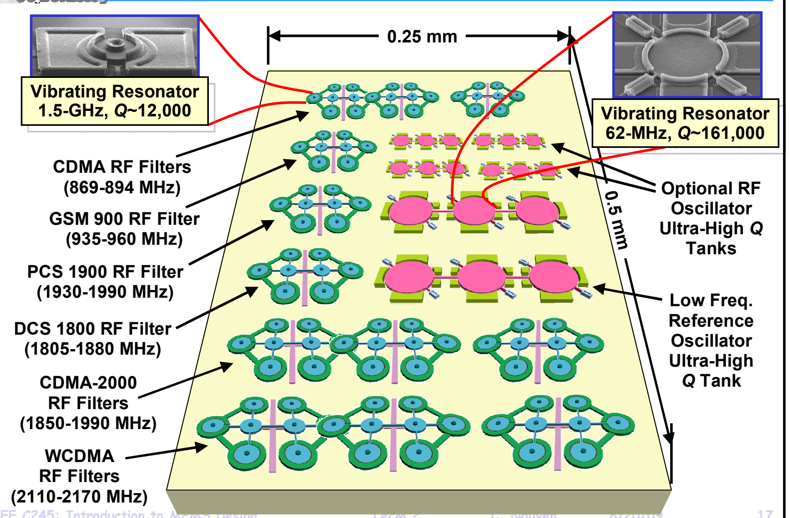

163-MHz Differential Disk-Array Filter
UC Berkeley
Com. Array Couplers
Filter Coupler
Port1
Port2
Port3
Port4
λ/2
λ/4
λ
Diff. Array Couplers
[Li, Nguyen Trans'07]


Linear MEMS in Wireless Comms
UC Berkeley
High Q and good linearity of micromechanical resonators
Filters for front-end frequency selection
Micromechanical Bandpass Filter
Transmission [dB]
Frequency [MHz]
Antenna
Diplexer
Wireless Phone
From TX
RF BPF
LNA
Mixer I
Mixer Q
LPF
AGC
A/D
RXRF LO
RF PLL
Xstal Osc
I
Q
EE C245: Introduction to MEMS Design


Miniaturization of RF Front Ends
UC Berkeley
RF Power Amplifier
Diplexer
925-960MHz RF SAW Filter
897.5±17.5MHz RF SAW Filter
1805-1880MHz RF SAW Filter
Dual-Band Zero-IF Transistor Chip
26-MHz Xstal Oscillator
3420-3840MHz VCO
Problem: high-Q passives pose a bottleneck against miniaturization
Wireless Phone
Antenna
Diplexer
From TX
RF BPF
LNA
Mixer I
Mixer Q
LPF
AGC
A/D
RXRF LO
RF PLL
Xstal Osc
EE C245: Introduction to MEMS Design

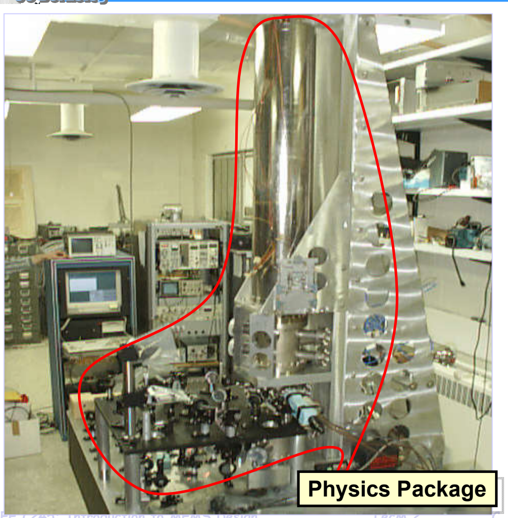

Multi-Band Wireless Handsets
UC Berkeley
CDMA
Duplexer
LNA
RF BPF
From TX
Antenna
GSM 900
PCS 1900
DCS 1800
CDMA-2000
WCDMA
LPF
AGC
A/D
RXRF LO
÷ (N+1)/N
RXRF Channel Select PLL
Xstal Osc
Tank
• The number of off-chip high-Q passives increases dramatically
• Need: on-chip high-Q passives
EE C245: Introduction to MEMS Design

All High-Q Passives on a Single Chip



Chip-Scale Atomic Clocks (CSAC)

NIST F1 Fountain Atomic Clock

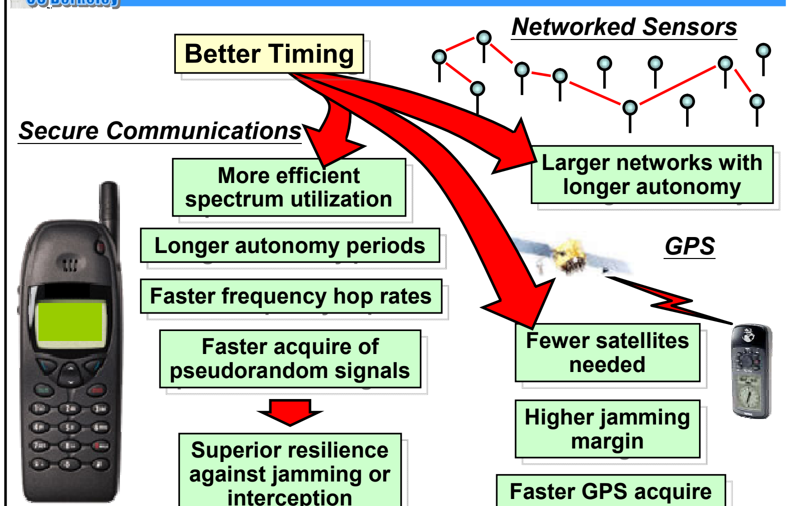


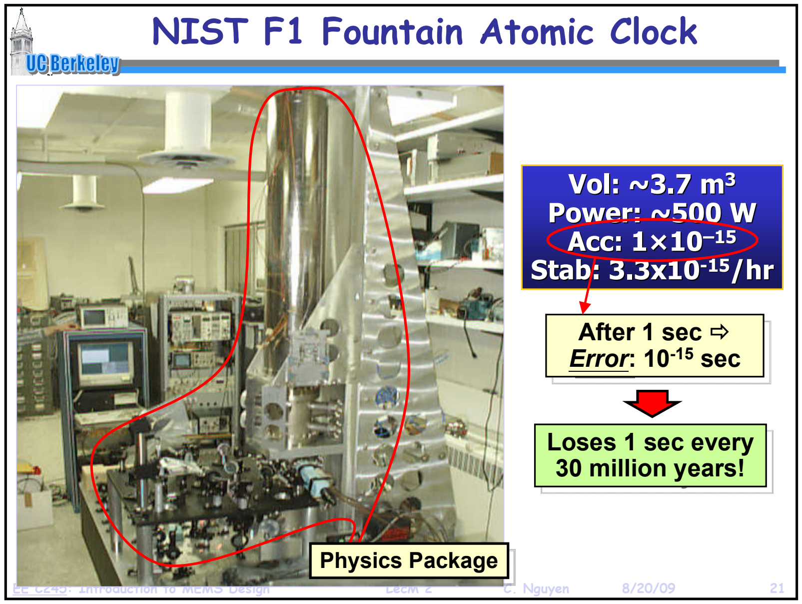
Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr

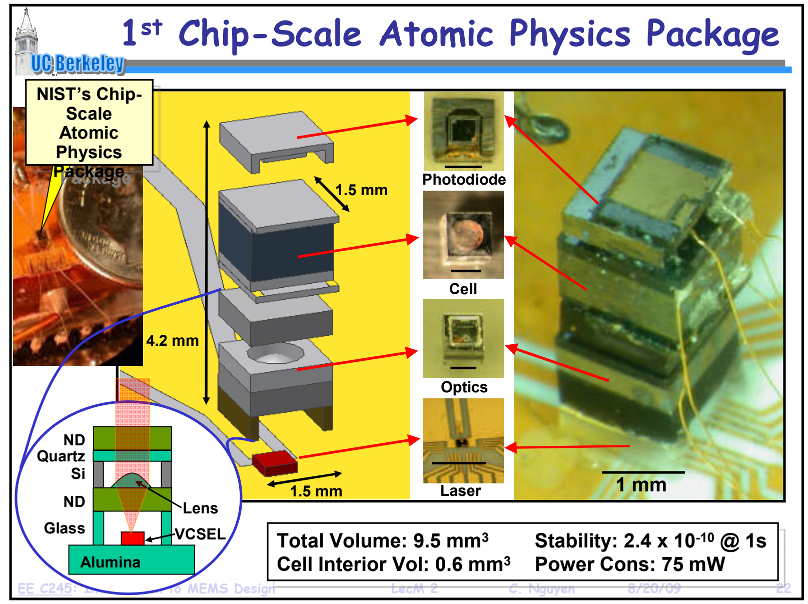
After 1 sec ⇨ *Error*: 10⁻¹⁵ sec

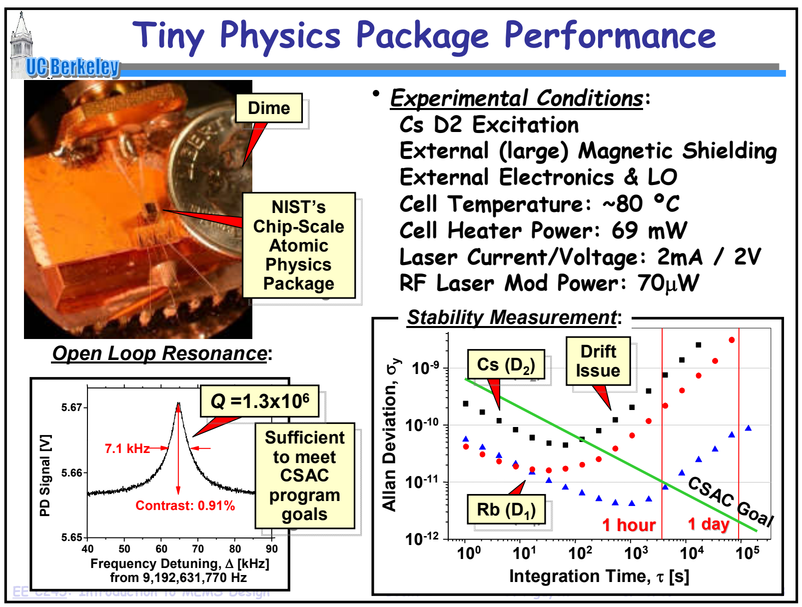
Loses 1 sec every 30 million years!

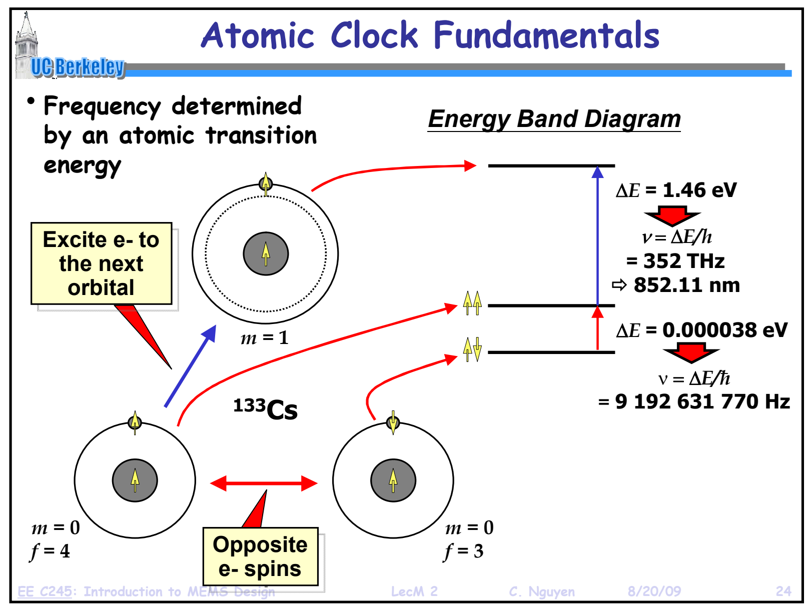
Benefits of Accurate Portable Timing

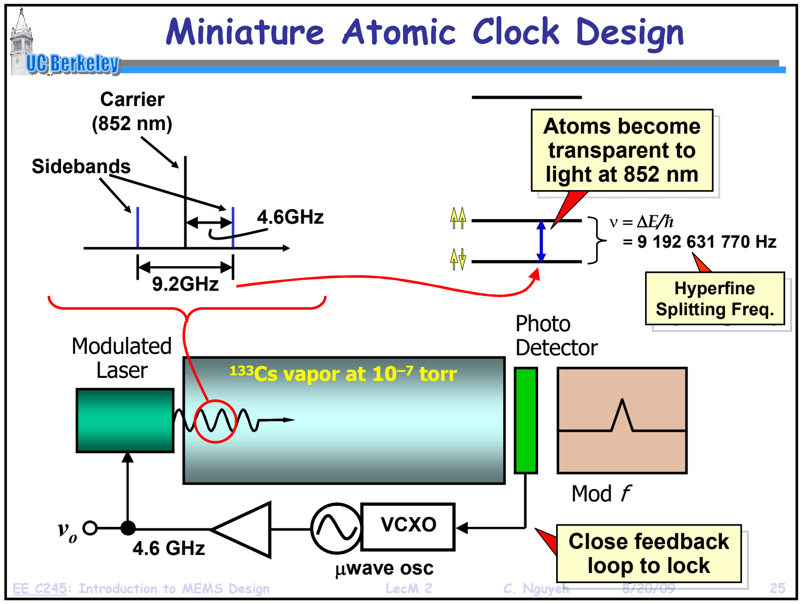


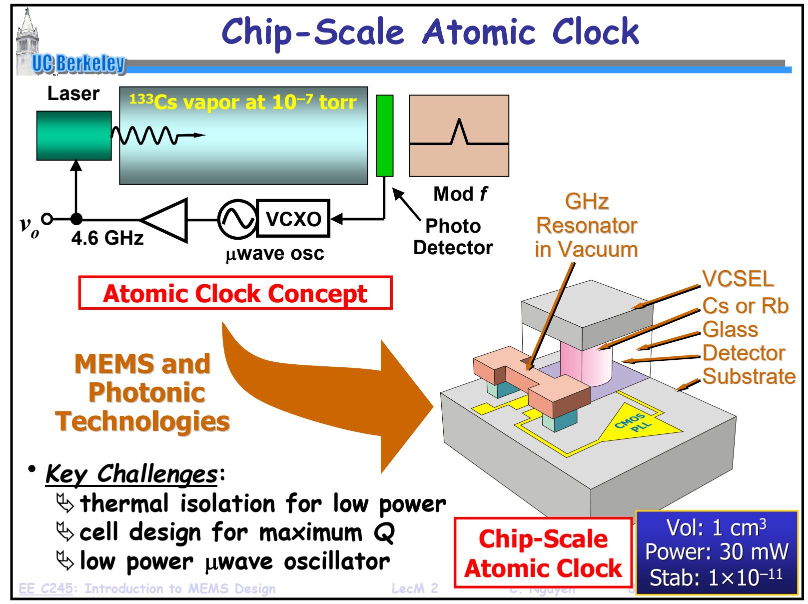

NIST F1 Fountain Atomic Clock
UC Berkeley
Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr
After 1 sec ⇨ Error: 10⁻¹⁵ sec
Loses 1 sec every 30 million years!
Physics Package

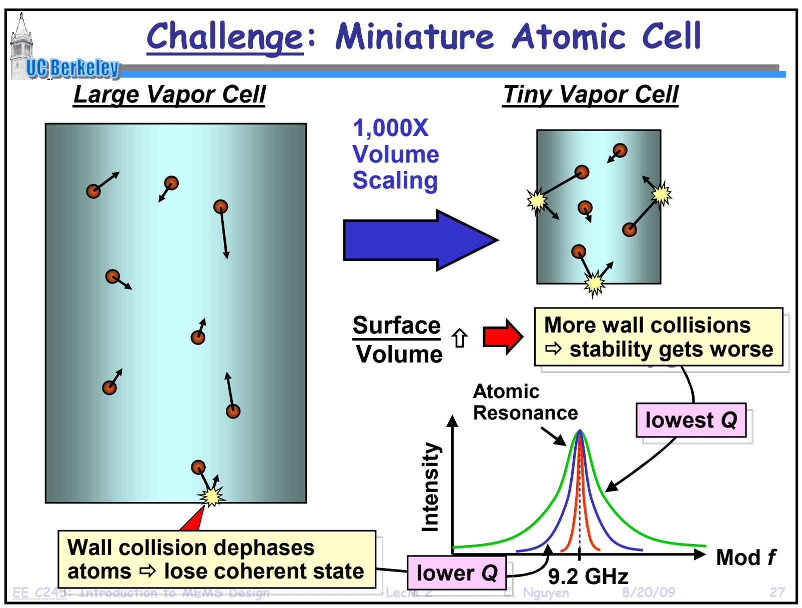

1st Chip-Scale Atomic Physics Package
UC Berkeley
NIST's Chip-Scale Atomic Physics Package
1.5 mm
4.2 mm
1.5 mm
Photodiode
Cell
Optics
Laser
1 mm
ND
Quartz
Si
ND
Glass
Lens
VCSEL
Alumina
Total Volume: 9.5 mm³
Cell Interior Vol: 0.6 mm³
Stability: 2.4 x 10⁻¹⁰ @ 1s
Power Cons: 75 mW

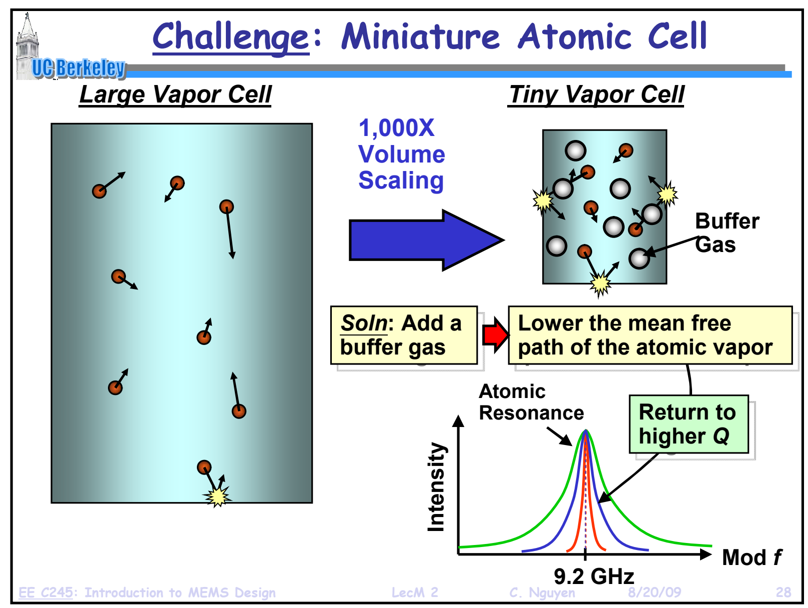

Tiny Physics Package Performance
UC Berkeley
Dime
NIST's Chip-Scale Atomic Physics Package
Open Loop Resonance:
Q =1.3x10⁶
Sufficient to meet CSAC program goals
7.1 kHz
Contrast: 0.91%
PD Signal [V]
Frequency Detuning, Δ [kHz] from 9,192,631,770 Hz
• Experimental Conditions:
Cs D2 Excitation
External (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
Stability Measurement:
Cs (D2)
Drift Issue
Rb (D1)
CSAC Goal
1 hour
1 day
Allan Deviation, σy
Integration Time, τ [s]

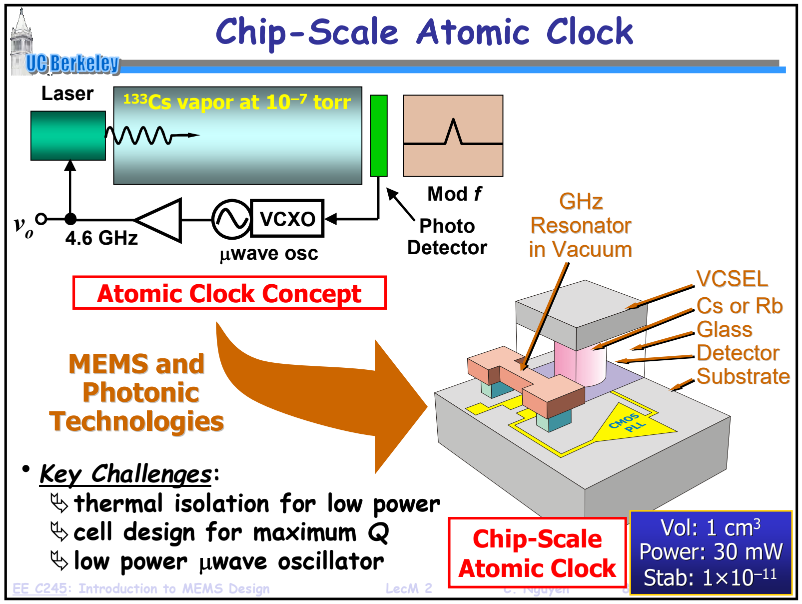

Atomic Clock Fundamentals
UC Berkeley
• Frequency determined by an atomic transition energy
Energy Band Diagram
Excite e- to the next orbital
m = 1
133Cs
m = 0
f = 4
m = 0
f = 3
Opposite e- spins
ΔE = 1.46 eV
ν = ΔE/h
= 352 THz
⇨ 852.11 nm
ΔE = 0.000038 eV
ν = ΔE/h
= 9 192 631 770 Hz

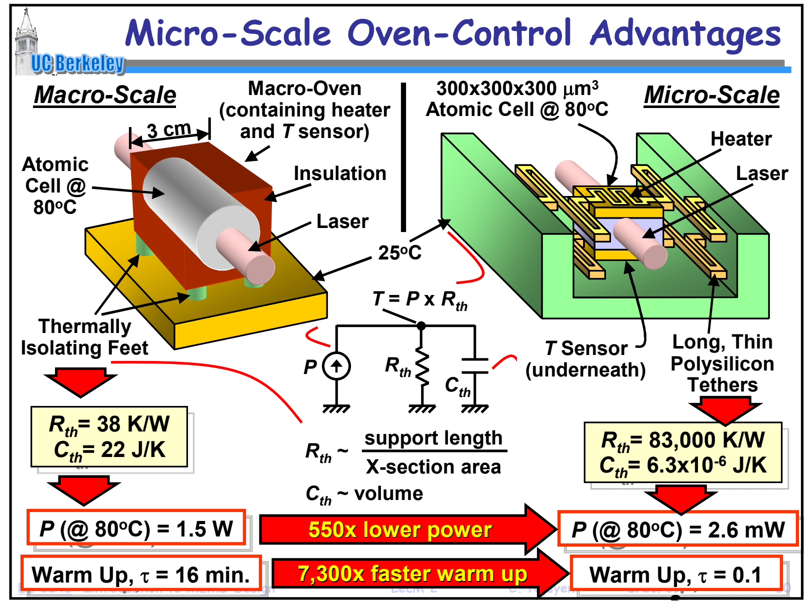

Miniature Atomic Clock Design
UC Berkeley
Carrier
(852 nm)
Sidebands
4.6GHz
9.2GHz
Atoms become
transparent to
light at 852 nm
ν = ΔE/ħ
= 9 192 631 770 Hz
Hyperfine
Splitting Freq.
Modulated
Laser
133Cs vapor at 10⁻⁷ torr
Photo
Detector
Mod f
v_o
4.6 GHz
VCXO
μwave osc
Close feedback
loop to lock
EE 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
v_o
4.6 GHz
VCXO
μwave osc
GHz
Resonator
in Vacuum
Atomic Clock Concept
VCSEL
Cs or Rb
Glass
Detector
Substrate
MEMS and
Photonic
Technologies
CMOS PLL
• 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
C. Nguyen


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


Challenge: Miniature Atomic Cell
UC Berkeley
Large Vapor Cell
1,000X
Volume
Scaling
Tiny Vapor Cell
Buffer
Gas
Soln: Add a
buffer gas
Lower the mean free
path of the atomic vapor
Atomic
Resonance
Return to
higher Q
Intensity
9.2 GHz
Mod f
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
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


Micro-Scale Oven-Control Advantages
UC Berkeley
Macro-Scale
Macro-Oven (containing heater and T sensor)
3 cm
Atomic Cell @ 80oC
Insulation
Laser
Thermally Isolating Feet
25oC
300x300x300 µm3 Atomic Cell @ 80oC
Micro-Scale
Heater
Laser
T = P x Rth
P
Rth
Cth
T Sensor (underneath)
Long, Thin Polysilicon Tethers
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 (@ 80oC) = 1.5 W
550x lower power
P (@ 80oC) = 2.6 mW
Warm Up, τ = 16 min.
7,300x faster warm up
Warm Up, τ = 0.1