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EE C247B - ME C218 Introduction to MEMS Design Spring 2015

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Lecture Module 2: Benefits of Scaling

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Basic Concept: Scaling Guitar Strings

Guitar String

Vib. Amplitude vs Freq. (110 Hz)

Vibrating "A" String (110 Hz)

Freq. Equation:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{k_r}{m_r}}$$

Stiffness (k_r) ↑ Mass (m_r) ↓

μMechanical Resonator

Metallized Electrode
 Anchor
 Polysilicon Clamped-Clamped Beam

[Bannon 1996]

Performance:

$L_r = 40.8 \mu\text{m}$
 $m_r \sim 10^{-13} \text{ kg}$
 $W_r = 8 \mu\text{m}, h_r = 2 \mu\text{m}$
 $d = 1000 \text{ \AA}, V_P = 5 \text{ V}$
 $\text{Press.} = 70 \text{ mTorr}$

$f_o = 8.5 \text{ MHz}$
 $Q_{vac} = 8,000$
 $Q_{air} \sim 50$

Transmission [dB] vs Frequency [MHz]

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3CC 3λ/4 Bridged μMechanical Filter

Performance:

$f_o = 9 \text{ MHz}, BW = 20 \text{ kHz}, PBW = 0.2\%$
 $I.L. = 2.79 \text{ dB}, \text{Stop. Rej.} = 51 \text{ dB}$
 $20 \text{ dB S.F.} = 1.95, 40 \text{ dB S.F.} = 6.45$

Transmission [dB] vs Frequency [MHz]

$P_{in} = -20 \text{ dBm}$

In Out

Design:

$L = 40 \mu\text{m}$
 $W_r = 6.5 \mu\text{m}$
 $h_r = 2 \mu\text{m}$
 $L_c = 3.5 \mu\text{m}$
 $L_p = 1.6 \mu\text{m}$
 $V_P = 10.47 \text{ V}$
 $P = -5 \text{ dBm}$
 $R_{Qi} = R_{Qo} = 12 \text{ k}\Omega$

[S.-S. Li, Nguyen, FCS'05] [Li, et al., UFFCS'04] LecM 2 C. Nguyen 8/20/09 3

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Micromechanical Filter Circuit

Input Bridging Beam (3λ/4) Coupling Beam (λ/4) Resonator Output

v_i v_o $\frac{v_o}{v_i}$

Equivalent circuit with components: $C_o, m_r, 1/k_r, c_r, 1/k_s, \eta_c, 1/k_b, \eta_b, 1/k_s, \eta_c, C_o$

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1.51-GHz, Q=11,555 Nanocrystalline Diamond Disk μ Mechanical 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 μ m diameter disk

Design/Performance:
 $R=10\mu\text{m}$, $t=2.2\mu\text{m}$, $d=800\text{\AA}$, $V_p=7\text{V}$
 $f_o=1.51\text{ GHz}$ (2nd mode), $Q=11,555$

EE C245: Introduction to MEMS Design LecM 2 [Wang, Butler, Nguyen MEMS'04]

163-MHz Differential Disk-Array Filter

EE C245: Introduction to MEMS Design [Li, Nguyen Trans'07]

Linear MEMS in Wireless Comms

High Q and good linearity of micromechanical resonators → Filters for front-end frequency selection

Micromechanical Bandpass Filter

Antenna, Diplexer, RF BPF, LNA, Mixer I, LPF, AGC, A/D, Mixer Q, LNA, RF PLL, RXRF LO, Xstal Osc, A/D

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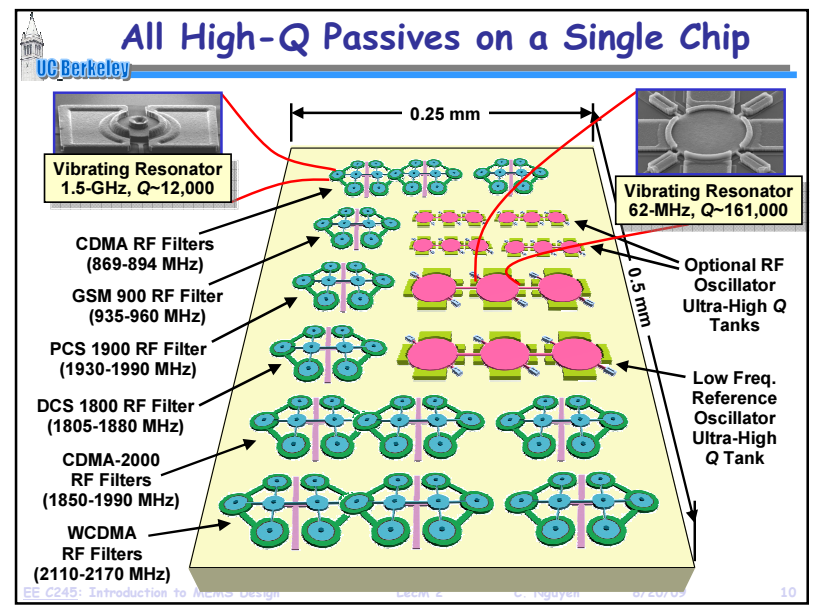
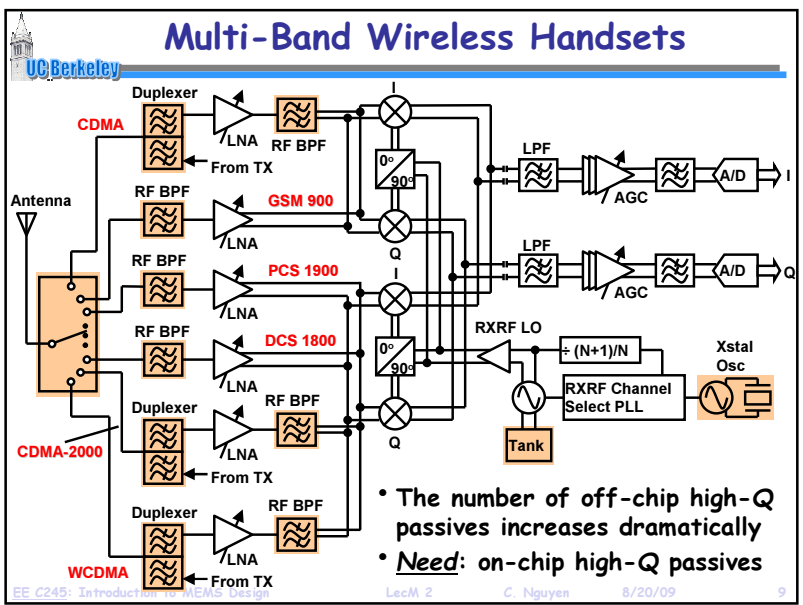
Miniaturization of RF Front Ends

- RF Power Amplifier
- 897.5±17.5MHz RF SAW Filter
- Dual-Band Zero-IF Transistor Chip
- 3420-3840MHz VCO
- Diplexer
- 925-960MHz RF SAW Filter
- 1805-1880MHz RF SAW Filter
- 26-MHz Xstal Oscillator

Problem: high-Q passives pose a bottleneck against miniaturization

Antenna, Diplexer, RF BPF, LNA, Mixer I, LPF, AGC, A/D, Mixer Q, LNA, RF PLL, RXRF LO, Xstal Osc, A/D

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Chip-Scale Atomic Clocks (CSAC)

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NIST F1 Fountain Atomic Clock

The photograph shows the NIST F1 Fountain Atomic Clock. A red circle highlights the Physics Package. The clock's performance is summarized in the following table:

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

Looses 1 sec every 30 million years!

Physics Package

Benefits of Accurate Portable Timing

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Better Timing

Secure Communications

- More efficient spectrum utilization
- Longer autonomy periods
- Faster frequency hop rates
- Faster acquire of pseudorandom signals
- Superior resilience against jamming or interception

Networked Sensors

- Larger networks with longer autonomy

GPS

- Fewer satellites needed
- Higher jamming margin
- Faster GPS acquire

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NIST F1 Fountain Atomic Clock

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Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10^{-15}
Stab: $3.3 \times 10^{-15}/hr$

After 1 sec ⇨ Error: 10^{-15} sec

Loses 1 sec every 30 million years!

Physics Package

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1st Chip-Scale Atomic Physics Package

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Total Volume: 9.5 mm³
Cell Interior Vol: 0.6 mm³
Stability: 2.4×10^{-10} @ 1s
Power Cons: 75 mW

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Tiny Physics Package Performance

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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:

Open Loop Resonance: $Q = 1.3 \times 10^6$, Contrast: 0.91%

Sufficient to meet CSAC program goals

Stability Measurement: Allan Deviation, σ_y vs Integration Time, τ [s]. Shows Cs (D₂), Rb (D₁), and CSAC Goal.

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Atomic Clock Fundamentals

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- Frequency determined by an atomic transition energy

Energy Band Diagram

Excite e- to the next orbital

Opposite e- spins

$\Delta E = 1.46 \text{ eV}$
 $\nu = \Delta E/h = 352 \text{ THz}$
 $\Rightarrow 852.11 \text{ nm}$

$\Delta E = 0.000038 \text{ eV}$
 $\nu = \Delta E/h = 9\,192\,631\,770 \text{ Hz}$

^{133}Cs

$m=1$

$m=0$ $f=4$

$m=0$ $f=3$

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Miniature Atomic Clock Design

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Carrier (852 nm)

Sidebands

4.6GHz

9.2GHz

Atoms become transparent to light at 852 nm

$\nu = \Delta E/h = 9\,192\,631\,770 \text{ Hz}$

Hyperfine Splitting Freq.

Modulated Laser

^{133}Cs vapor at 10^{-7} torr

Photo Detector

Mod f

Close feedback loop to lock

VCXO

$\mu\text{wave osc}$

4.6 GHz

ν_o

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Chip-Scale Atomic Clock

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Laser

^{133}Cs vapor at 10^{-7} torr

Mod f

Photo Detector

VCXO

$\mu\text{wave osc}$

4.6 GHz

ν_o

Atomic Clock Concept

MEMS and Photonic Technologies

GHz Resonator in Vacuum

VCSEL

Cs or Rb

Glass

Detector

Substrate

Key Challenges:

- thermal isolation for low power
- cell design for maximum Q
- low power μwave oscillator

Chip-Scale Atomic Clock

Vol: 1 cm^3

Power: 30 mW

Stab: 1×10^{-11}

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Challenge: Miniature Atomic Cell

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Large Vapor Cell

Tiny Vapor Cell

1,000X Volume Scaling

Surface Volume \uparrow

More wall collisions \Rightarrow stability gets worse

Atomic Resonance

Intensity

Mod f

lowest Q

lower Q

9.2 GHz

Wall collision dephases atoms \Rightarrow lose coherent state

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Challenge: Miniature Atomic Cell

Large Vapor Cell

Tiny Vapor Cell

1,000X Volume Scaling

Soln: Add a buffer gas → Lower the mean free path of the atomic vapor

9.2 GHz

Chip-Scale Atomic Clock

Atomic Clock Concept

4.6 GHz VCXO μ wave osc

Mod f Photo Detector

MEMS and Photonic Technologies

GHZ Resonator in Vacuum

Key Challenges:

- thermal isolation for low power
- cell design for maximum Q
- low power μ wave oscillator

Chip-Scale Atomic Clock

Vol: 1 cm³
 Power: 30 mW
 Stab: 1x10⁻¹¹

Micro-Scale Oven-Control Advantages

Macro-Scale

Atomic Cell @ 80°C

Thermally Isolating Feet

$R_{th} = 38 \text{ K/W}$
 $C_{th} = 22 \text{ J/K}$

$P (@ 80^\circ\text{C}) = 1.5 \text{ W}$

Warm Up, $\tau = 16 \text{ min.}$

Micro-Scale

300x300x300 μm^3 Atomic Cell @ 80°C

Heater Laser

Long, Thin Polysilicon Tethers

$R_{th} = 83,000 \text{ K/W}$
 $C_{th} = 6.3 \times 10^{-6} \text{ J/K}$

$P (@ 80^\circ\text{C}) = 2.6 \text{ mW}$

Warm Up, $\tau = 0.1 \text{ s}$

$T = P \times R_{th}$

$R_{th} \sim \frac{\text{support length}}{\text{X-section area}}$

$C_{th} \sim \text{volume}$

550x lower power

7,300x faster warm up

Physics Package Power Diss. < 10 mW

Achieved via MEMS-based thermal isolation

7 mm

20 pin LCC

Only ~5 mW heating power needed to achieve 80°C cell temperature

Power [mW]

Temperature [°C]

Measured Model

Symmetricom / Draper Physics Package Assembly