Integrated Micromechanical Circuits for RF Front-Ends

Clark T.-C. Nguyen

Dept. of Electrical Engineering & Computer Sciences
University of California at Berkeley
Berkeley, California 94720
E-mail: ctnguyen@eecs.berkeley.edu

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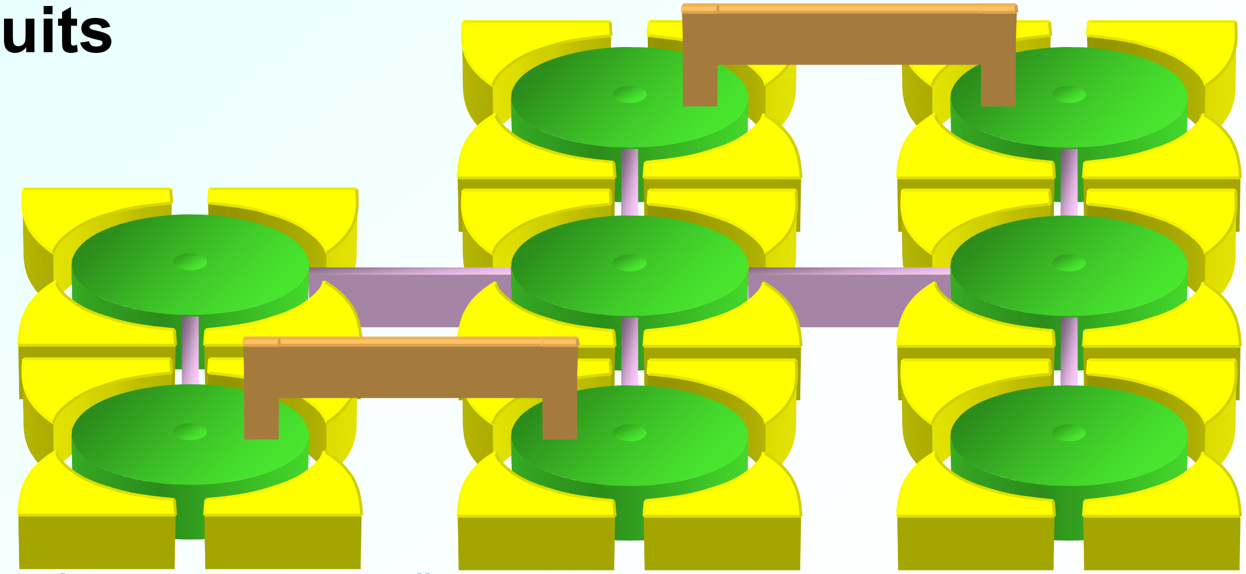
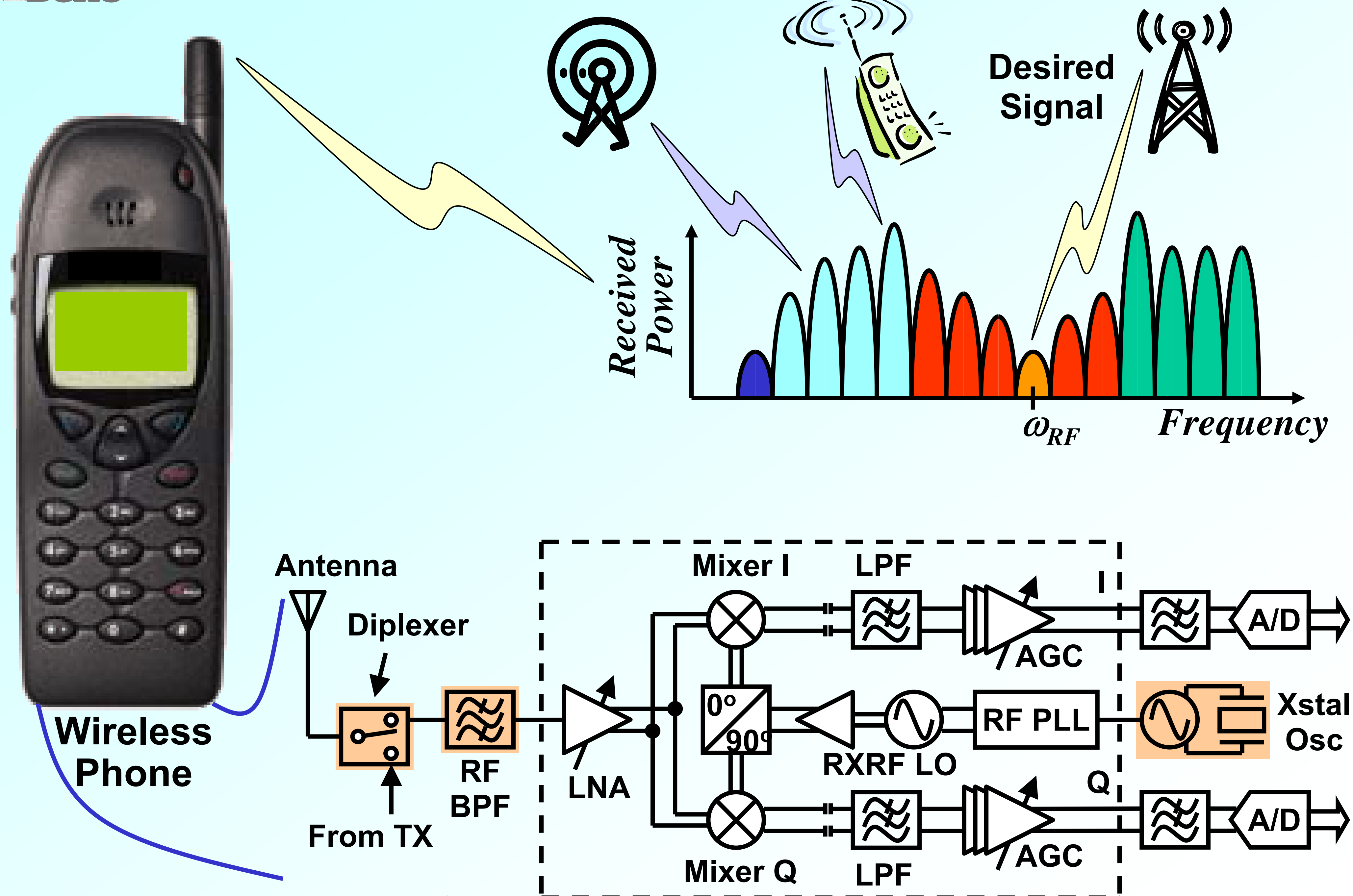
Outline

- **Introduction: Miniaturization of Transceivers**
  - ↳ **need for high-*Q***
- **Micromechanical Resonators**
  - ↳ **clamped-clamped beams**
  - ↳ **micromechanical disks**
- **Micromechanical Resonator Oscillators**
- **Micromechanical Circuits**
  - ↳ **micromechanical filters**
  - ↳ **impedance matching**
  - ↳ **MSI mechanical circuits**
- **Conclusions**



Motivation: Miniaturization of RF Front Ends



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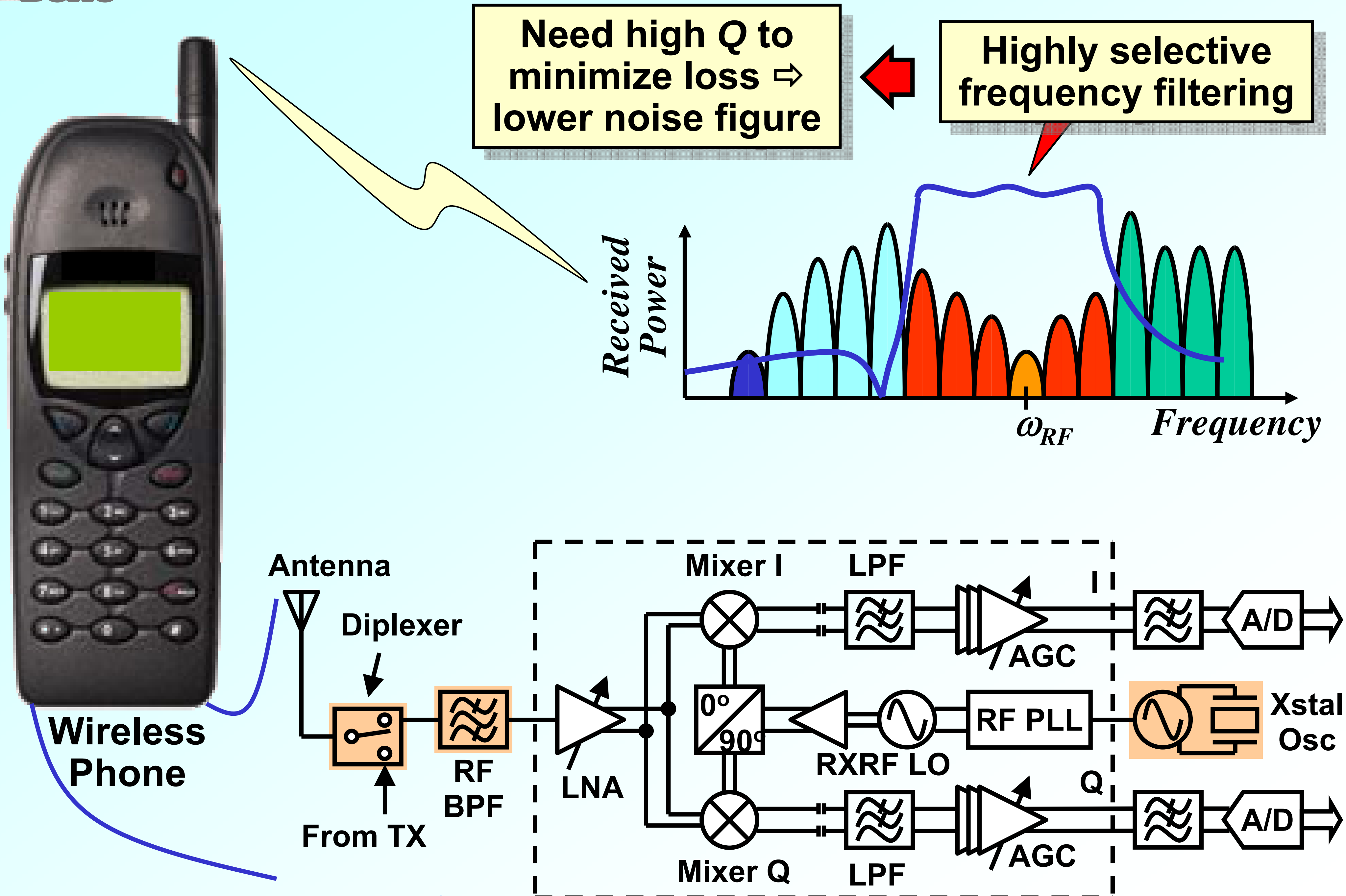

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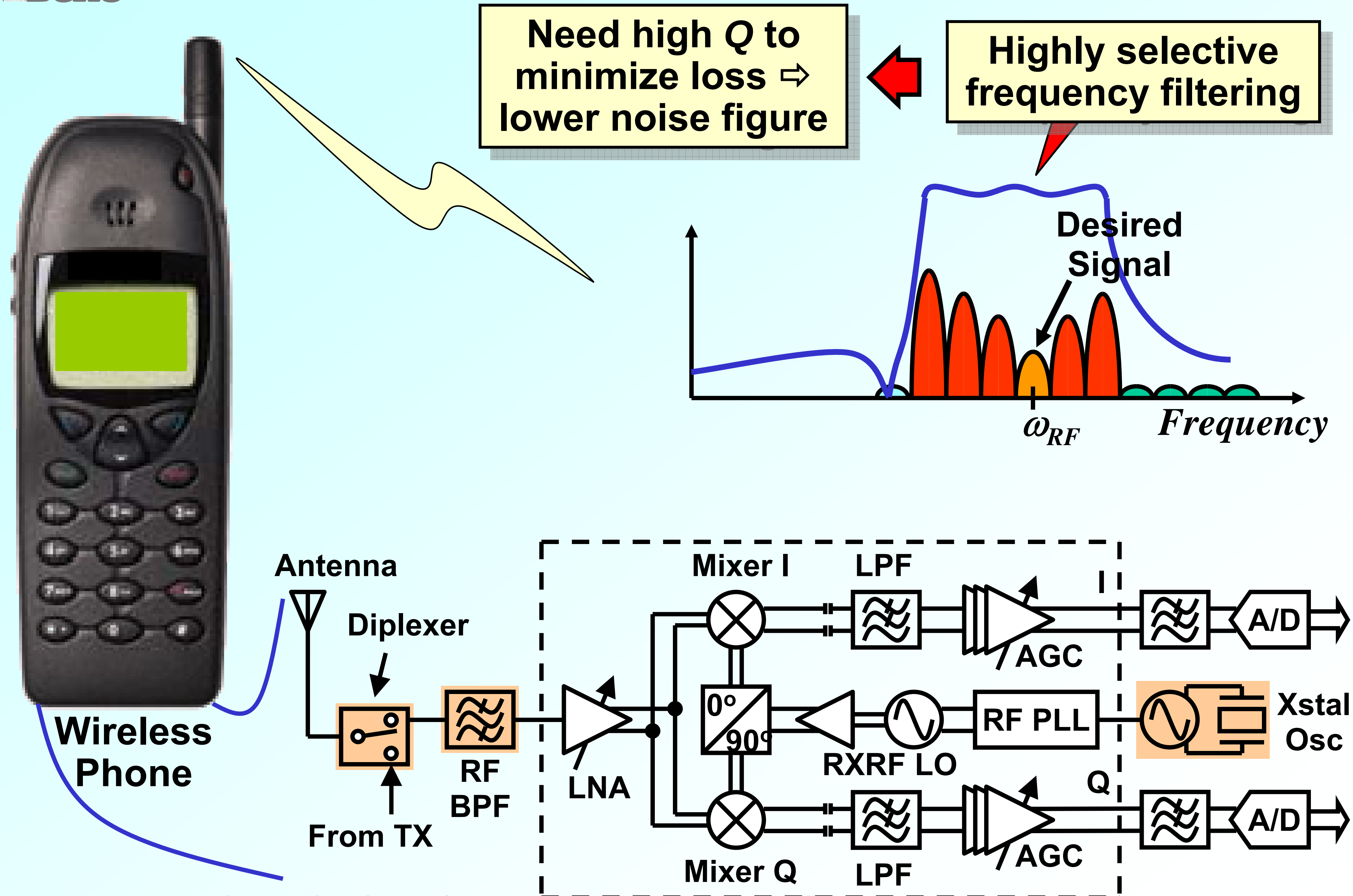

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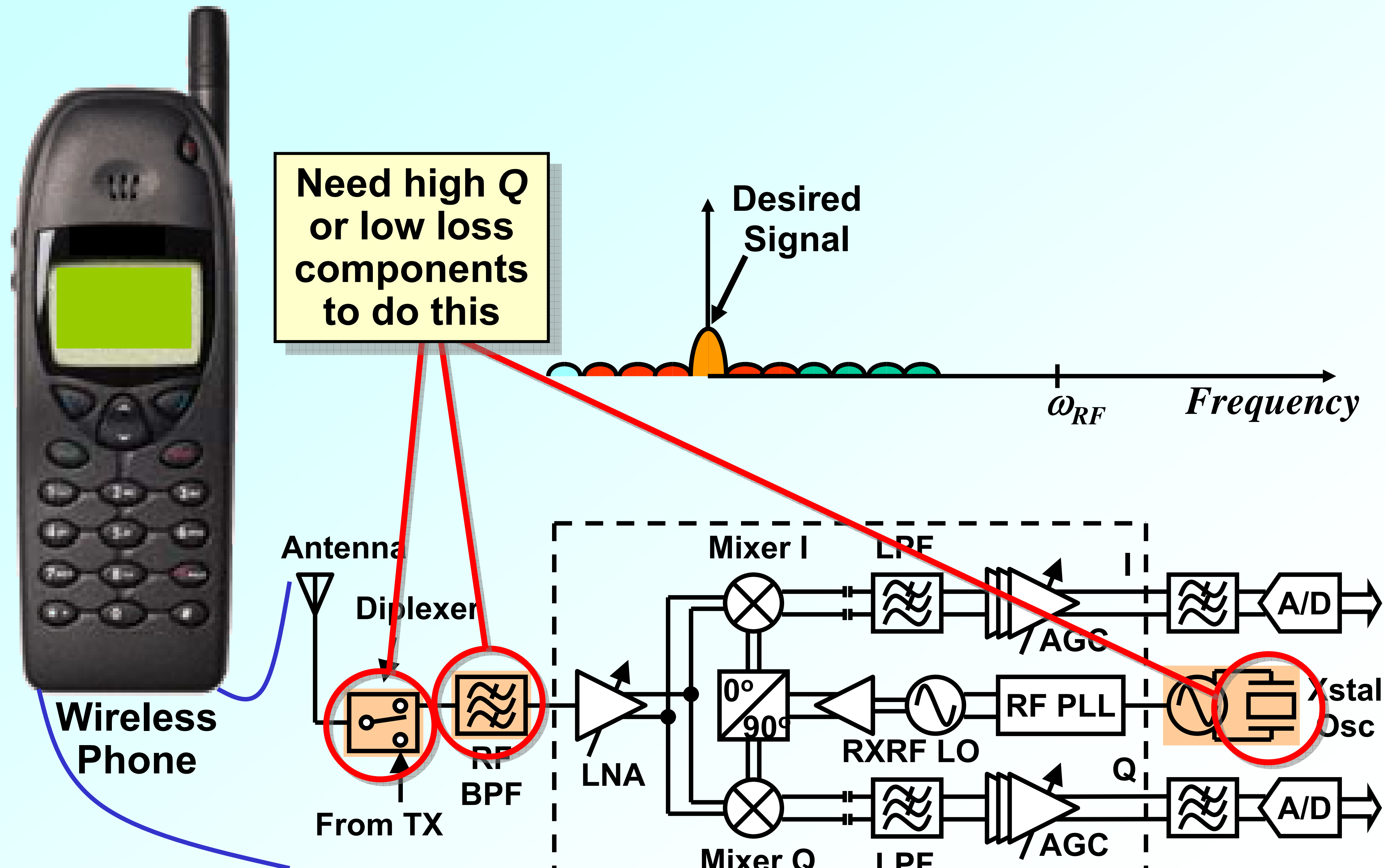
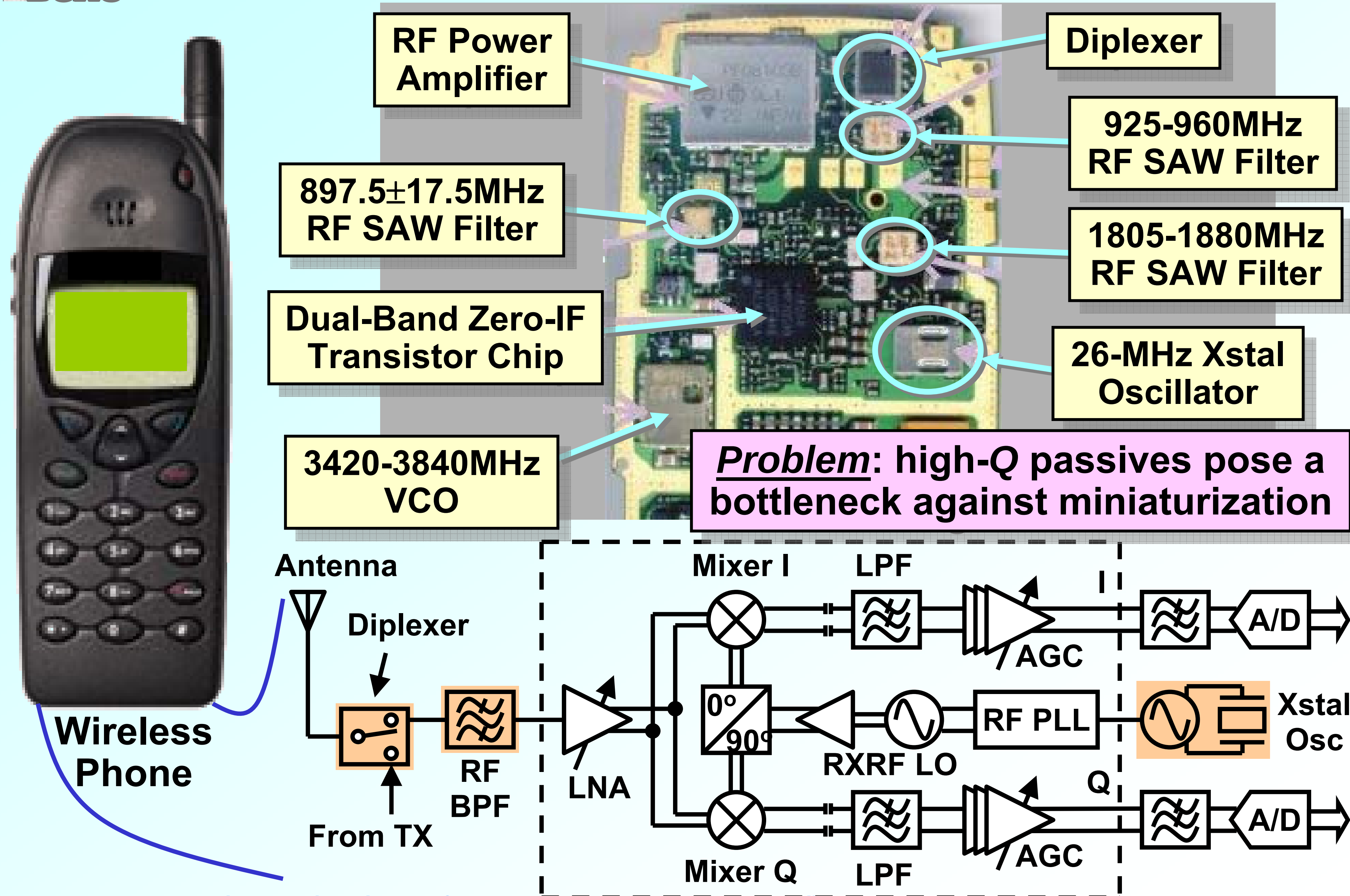
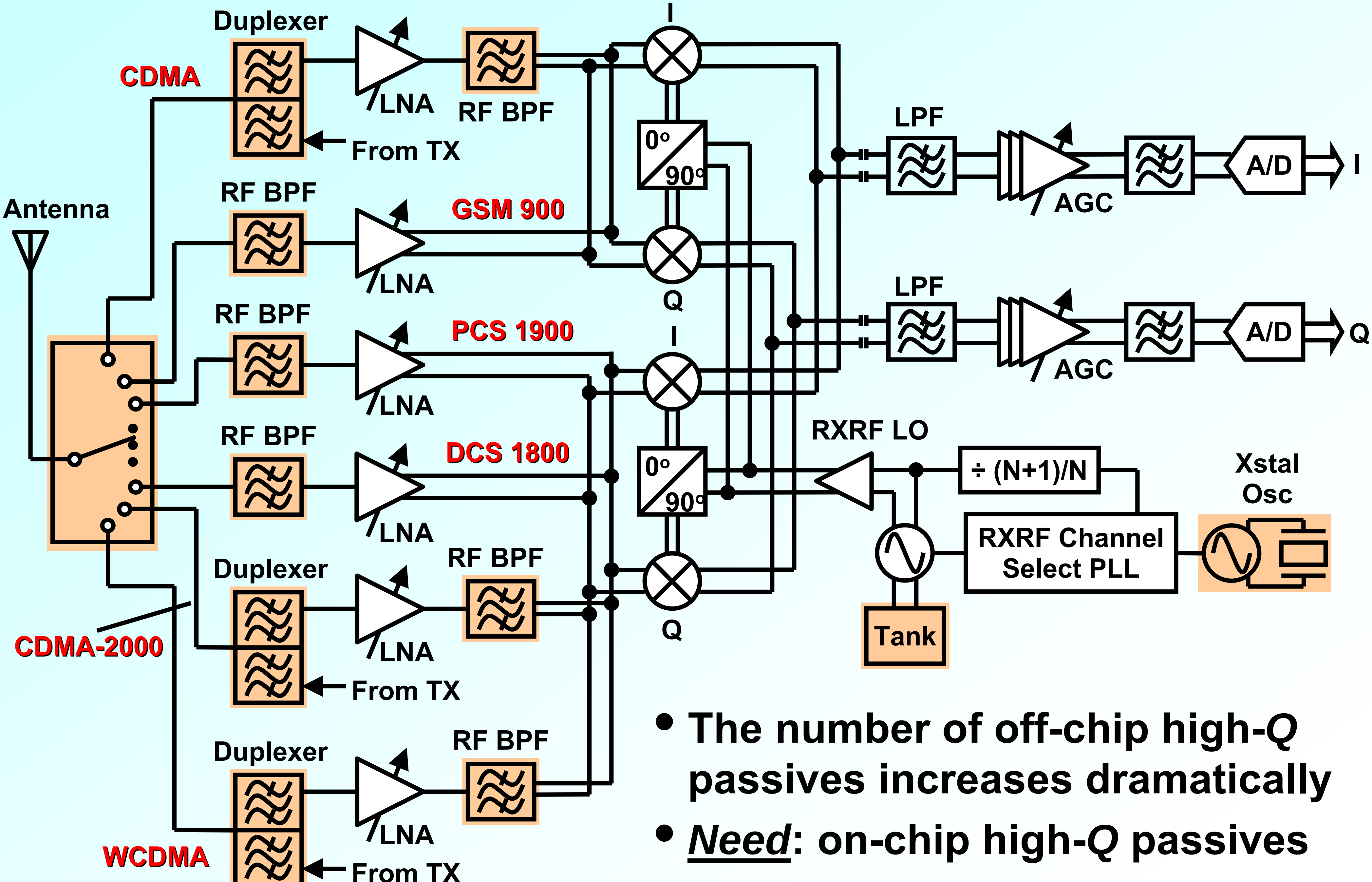


So Many Passive Components!



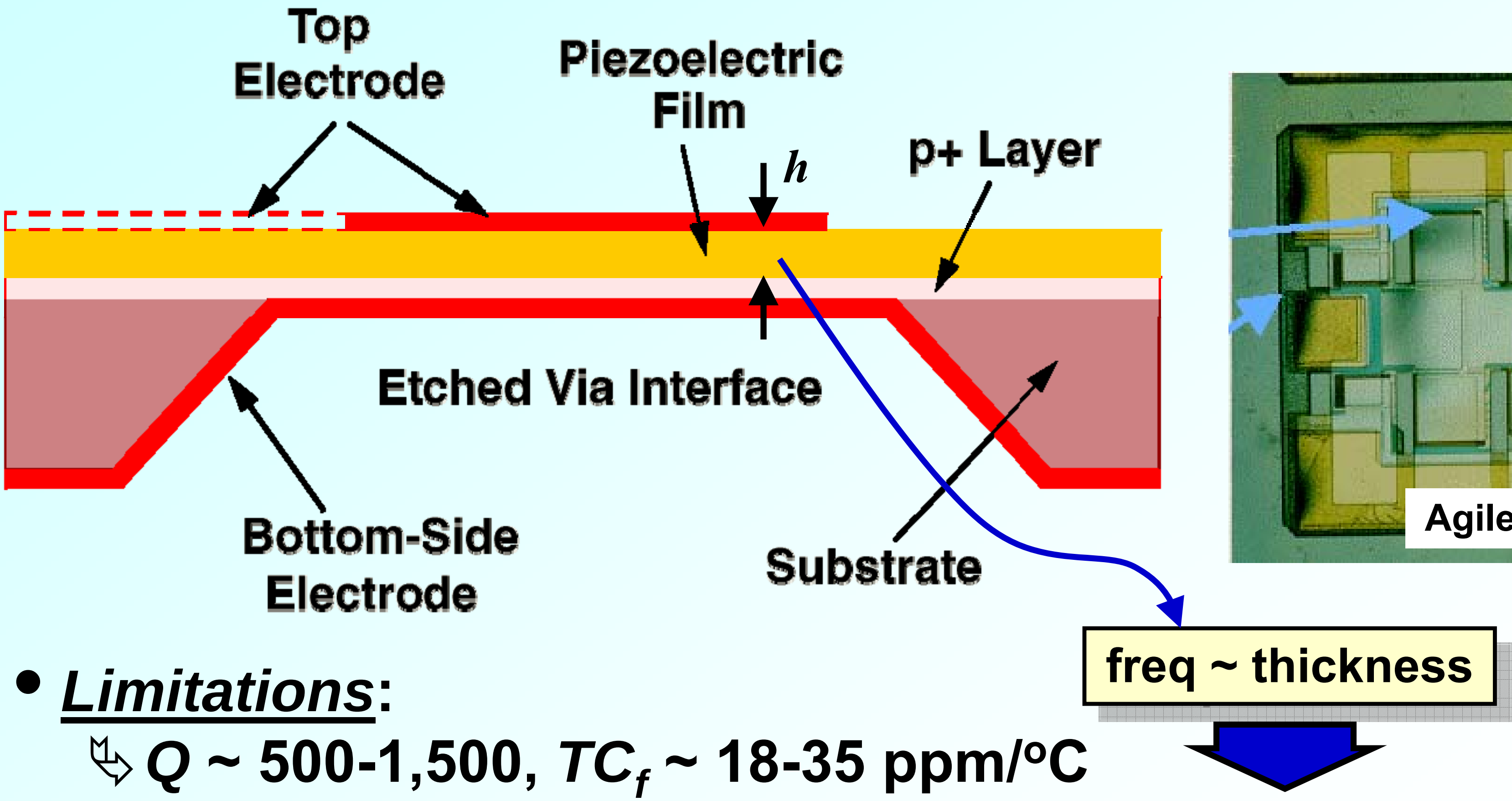
Multi-Band Wireless Handsets

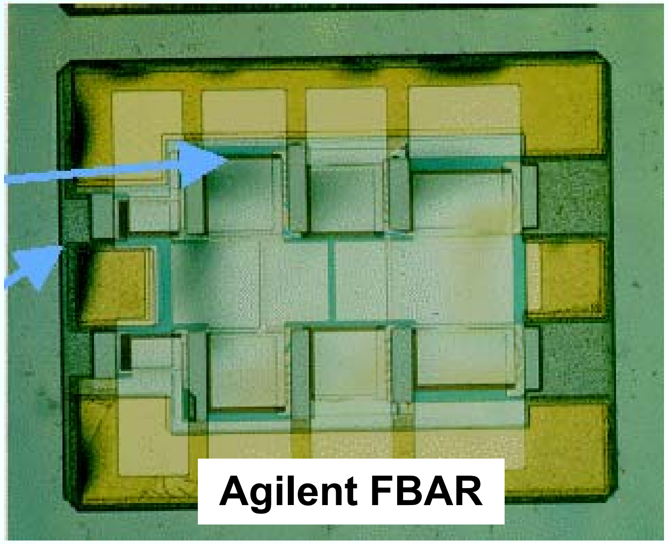


- **The number of off-chip high-*Q* passives increases dramatically**
- ***Need*: on-chip high-*Q* passives**

Thin-Film Bulk Acoustic Resonator (FBAR)

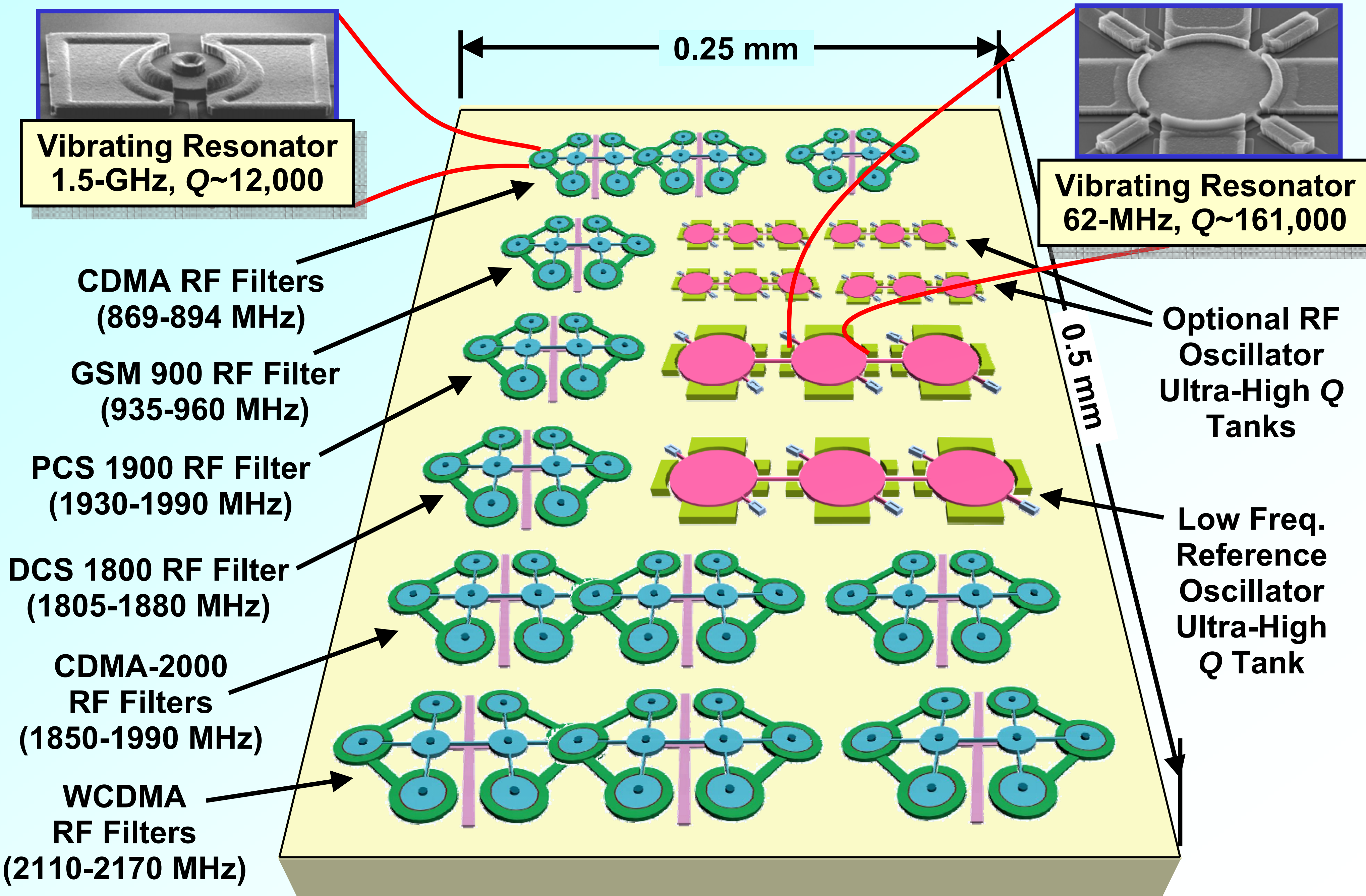
- Piezoelectric membrane sandwiched by metal electrodes
  - extensional mode vibration: 1.8 to 7 GHz, *Q* ~500-1,500
  - dimensions on the order of 200μm for 1.6 GHz
  - link individual FBAR's together in ladders to make filters





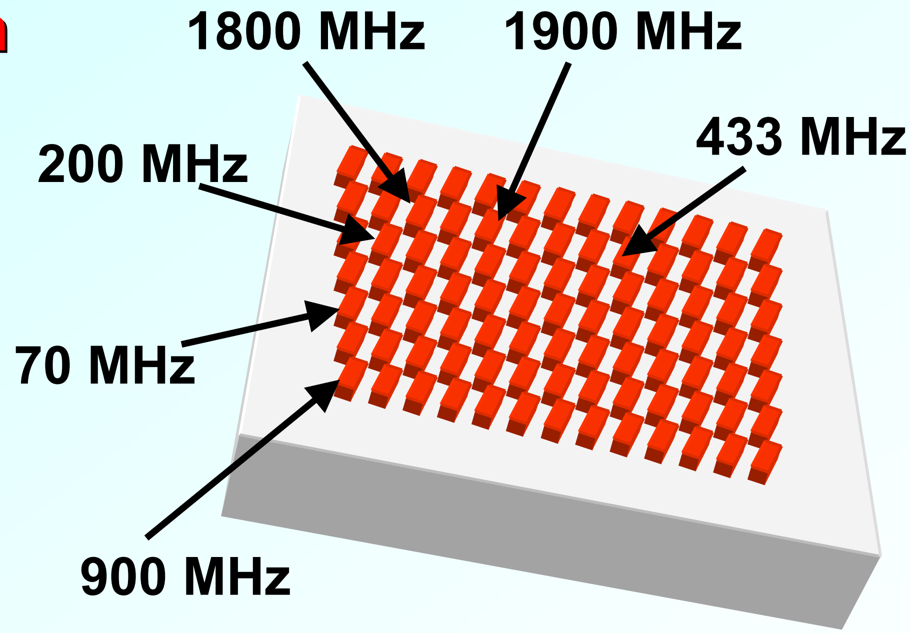
- ***Limitations***:
  - *Q* ~ 500-1,500, TC_f ~ 18-35 ppm/°C
  - difficult to achieve several different freqs. on a single-chip

All High-*Q* Passives on a Single Chip



Vibrating RF MEMS Wish List

- **Micro-scale wafer-level fabrication**
  - would like >1,000 parts per die to at least achieve large-scale integration (LSI) complexity
  - need wafer-level packaging
- **Single-chip integrated circuit or system capability**
  - discrete parts not interesting
  - must allow many different frequencies on a single-chip
  - need on-chip connectivity
  - integration w/ transistors desired
  - need real time reconfigurability
- ***Q*'s >10,000 at RF might have a revolutionary impact**



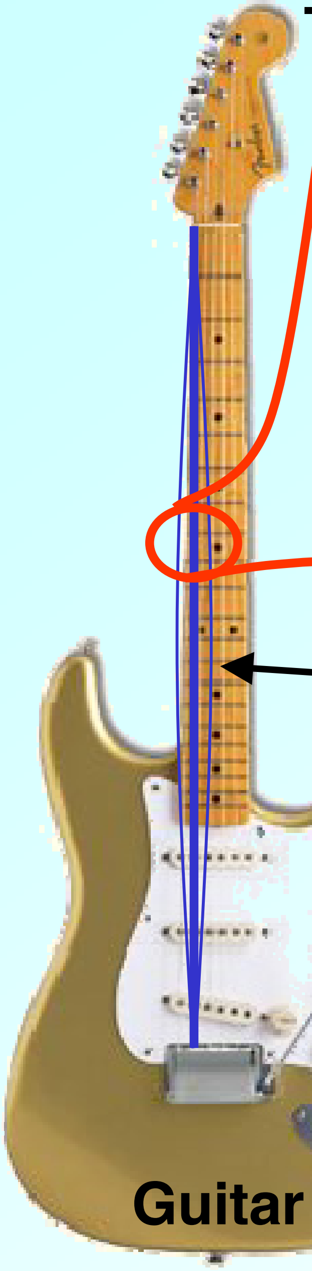
Frequencies should be determined by lateral dimensions (e.g., by layout)

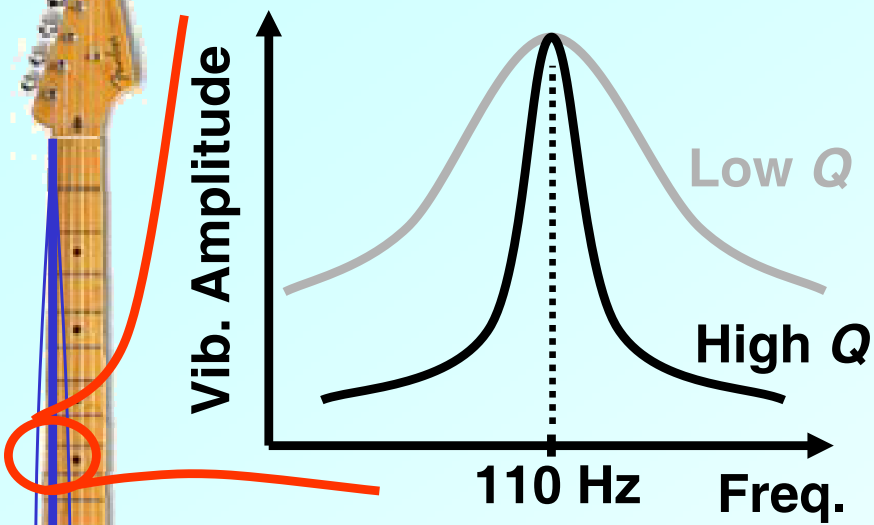
Best if systems can be reconfigured w/o the need for RF MEMS switches

Vibrating RF MEMS

Basic Concept: Scaling Guitar Strings

Guitar String





Vibrating "A" String (110 Hz)

Freq. Equation:

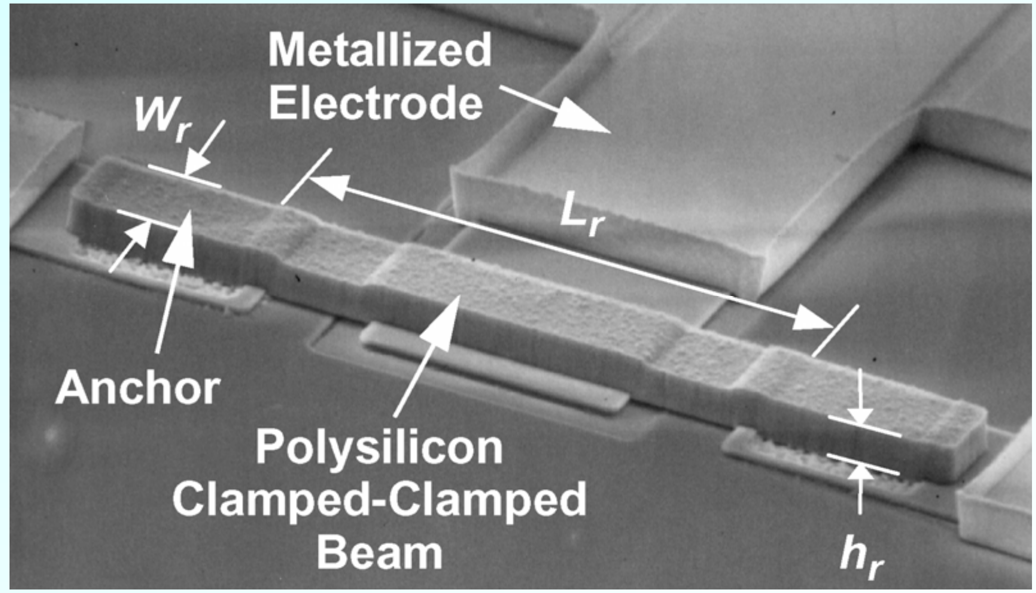
$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}}$$

Stiffness

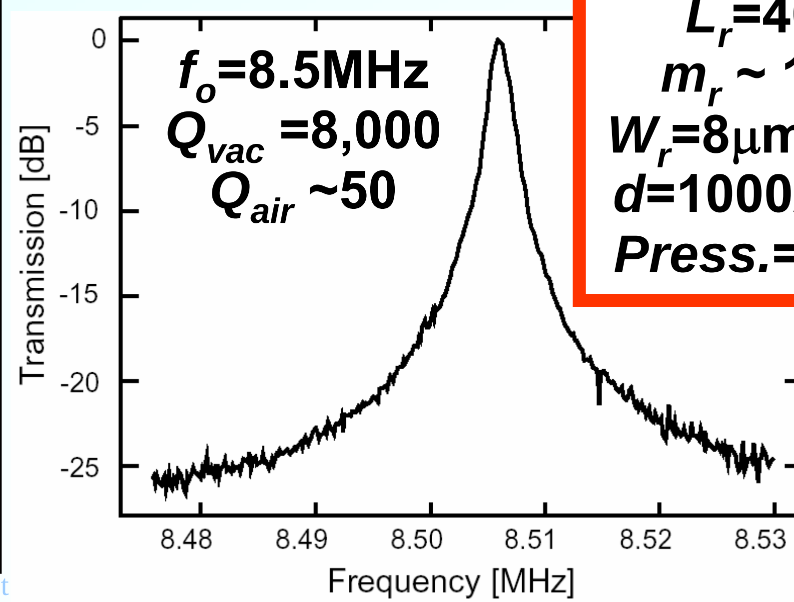
Freq.

Mass

µMechanical Resonator



[Bannon 1996]



Performance:

L_r=40.8µm

m_r ~ 10^{-13} kg

W_r=8µm, h_r=2µm

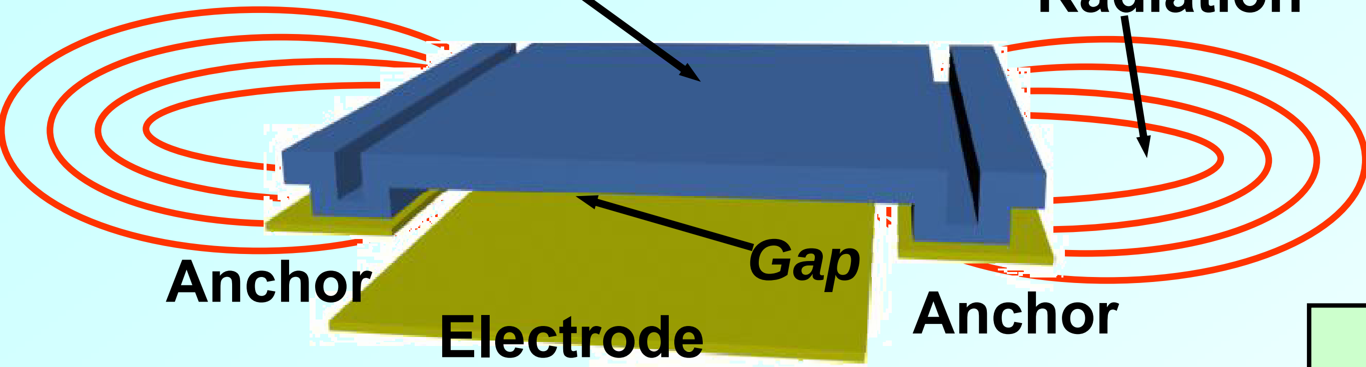
d=1000Å, V_P=5V

Press.=70mTorr

Anchor Losses

Fixed-Fixed Beam Resonator

Elastic Wave Radiation

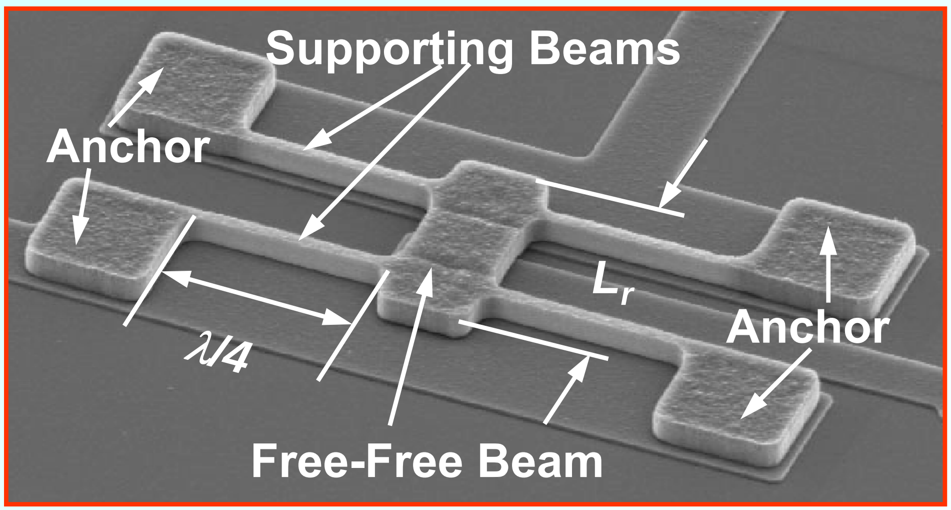


Q = 300 at 70MHz

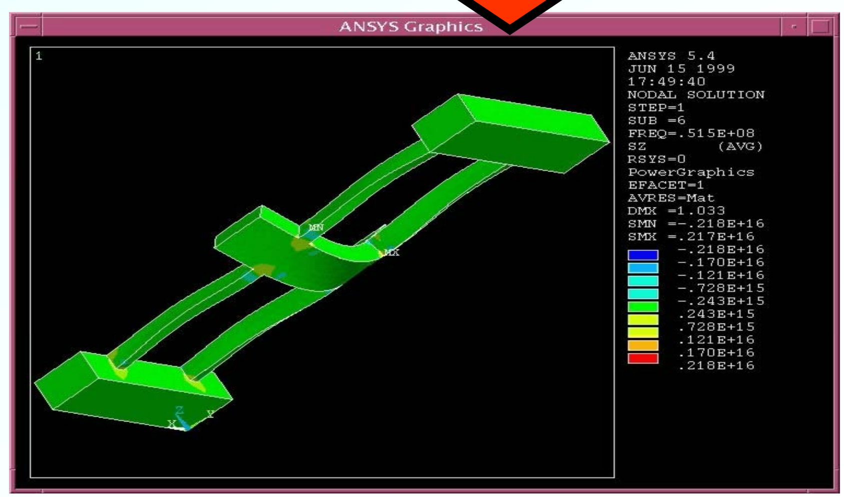
Problem: direct anchoring to the substrate ⇨ anchor radiation into the substrate ⇨ lower Q

Solution: support at motionless nodal points ⇨ isolate resonator from anchors ⇨ less energy loss ⇨ higher Q

Free-Free Beam Resonator

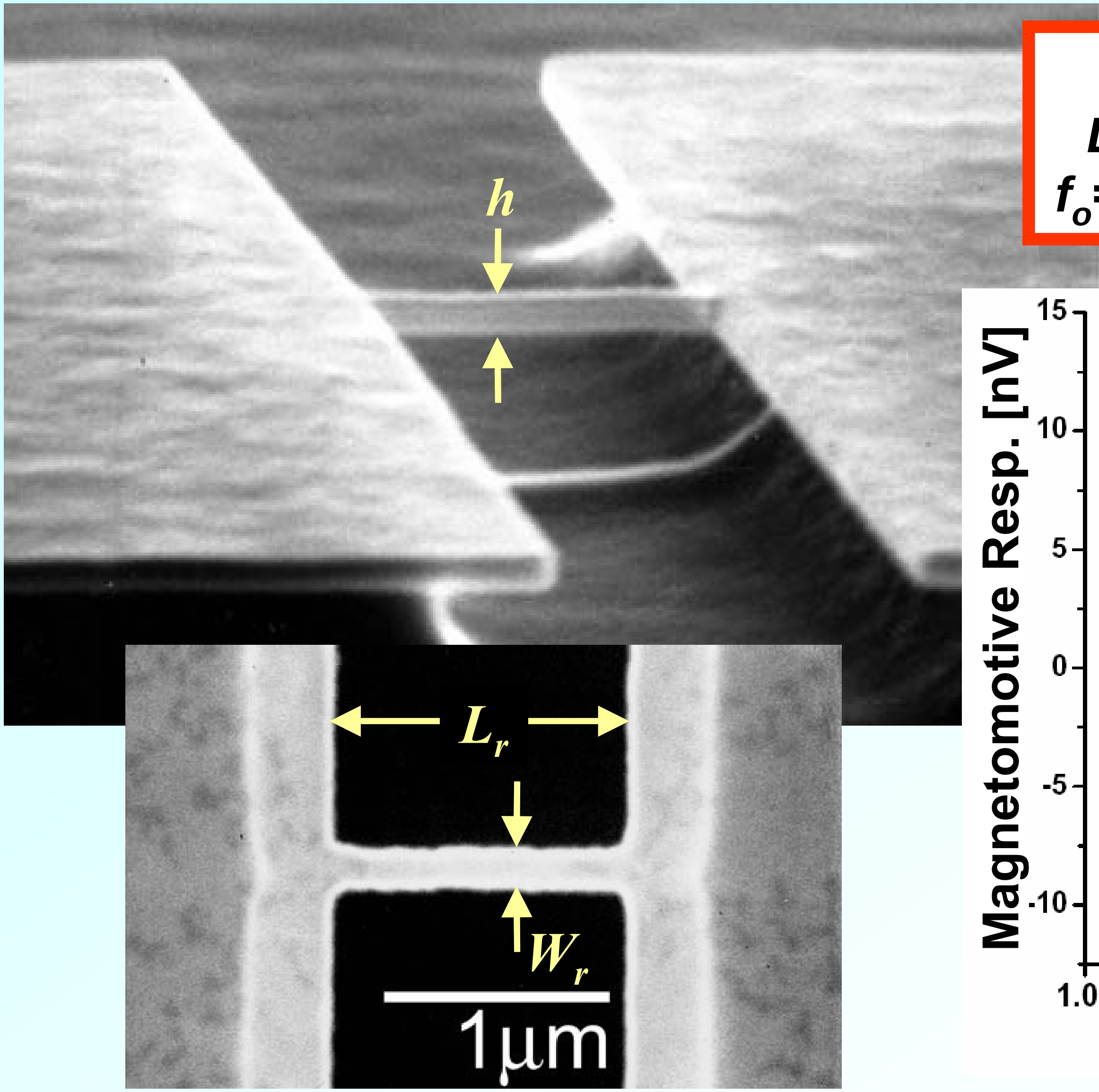


Q = 15,000 at 92MHz

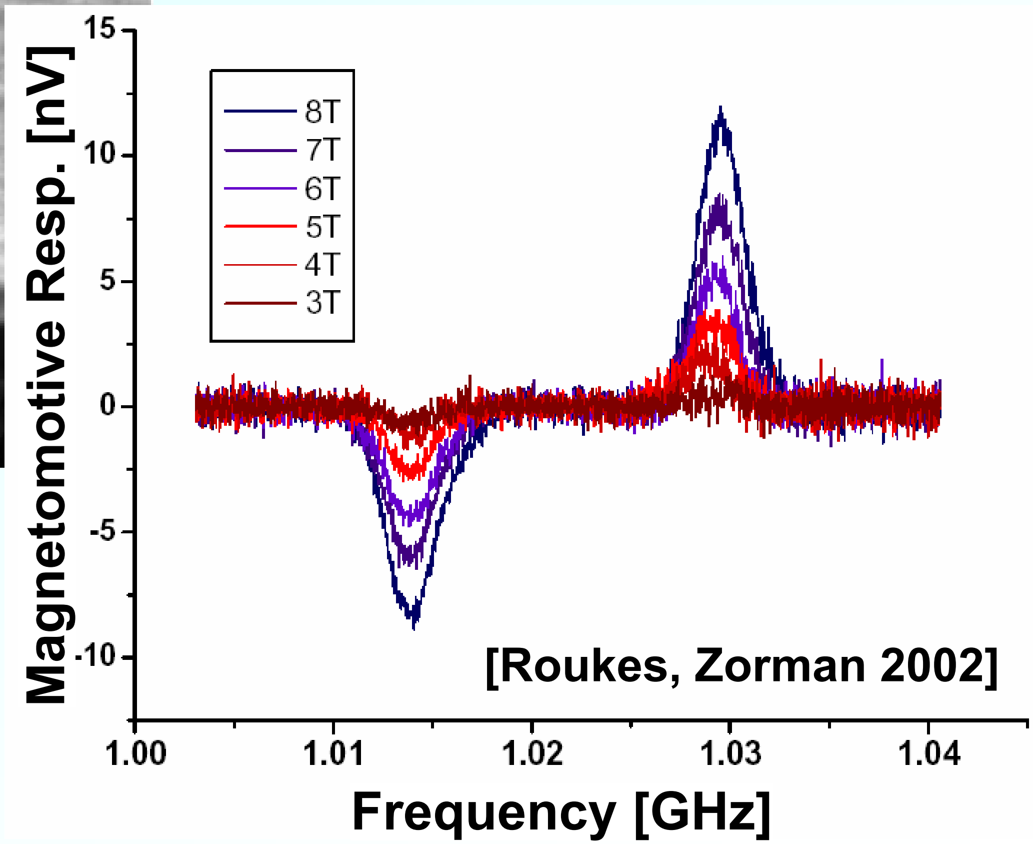


Nanomechanical Vibrating Resonator

- **Constructed in SiC material w/ 30 nm Al metallization for magnetomotive pickup**



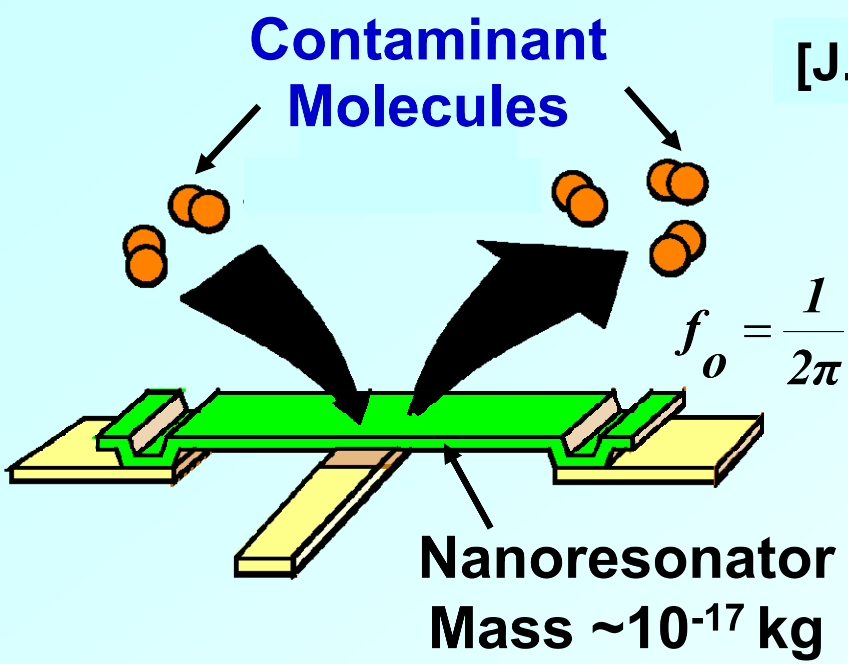
Design/Performance:
L_r =1.1 μm, W_r =120 nm, h= 75 nm
f_o=1.029 GHz, Q =500 @ 4K, vacuum



Scaling-Induced Performance Limitations

Mass Loading Noise

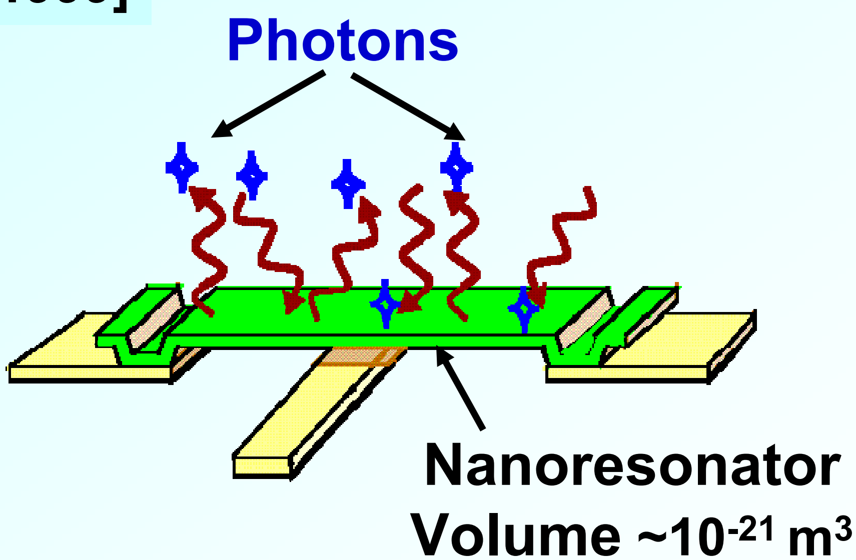
[J. R. Vig, 1999]



$$f_o = \frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

- Differences in rates of adsorption and desorption of contaminant molecules
  - ⇨ mass fluctuations
  - ⇨ frequency fluctuations

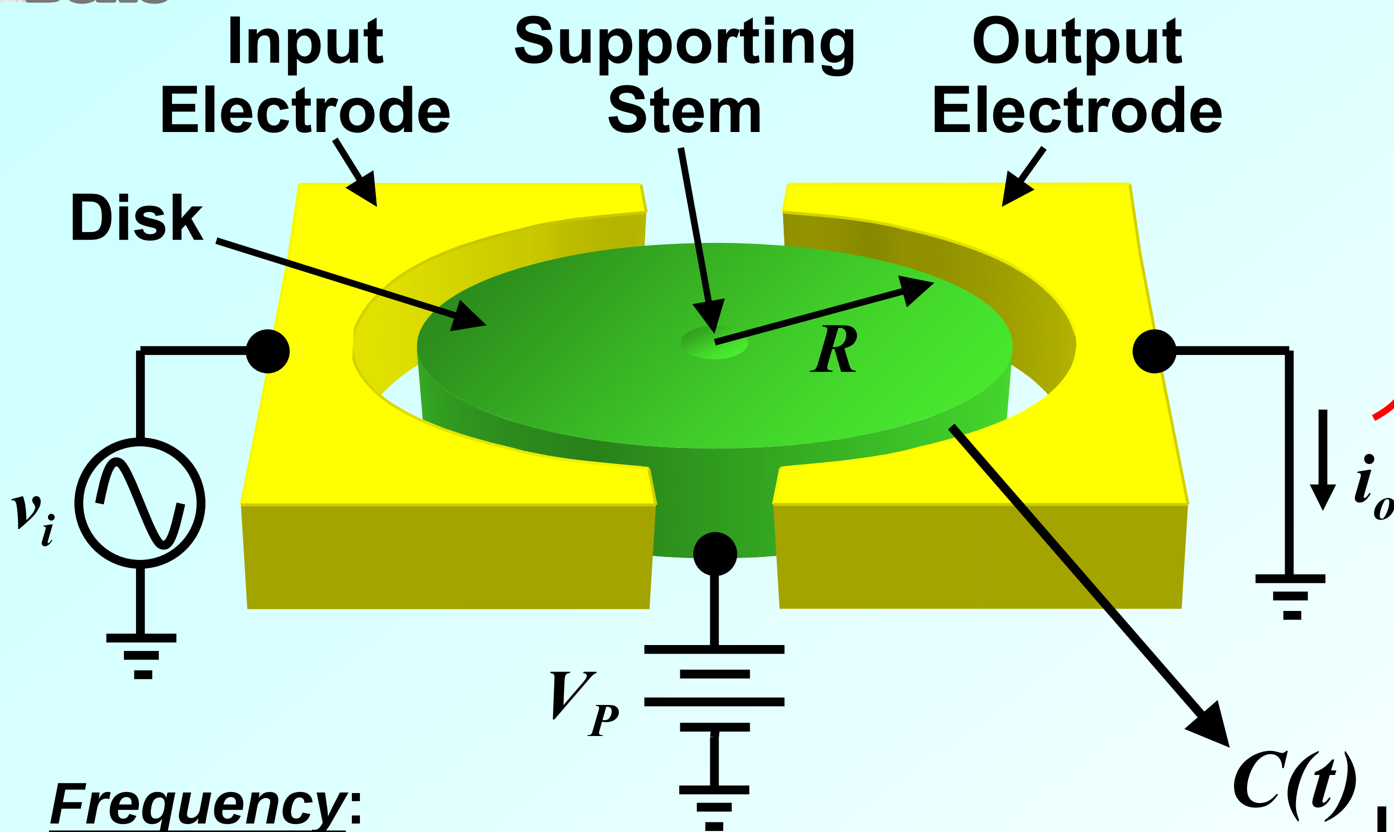
Temperature Fluctuation Noise

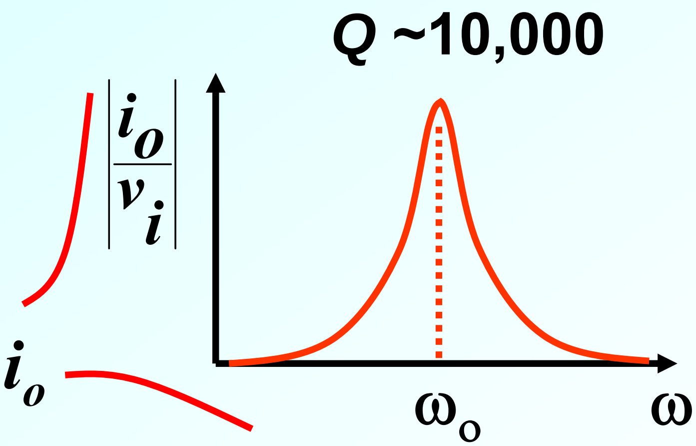


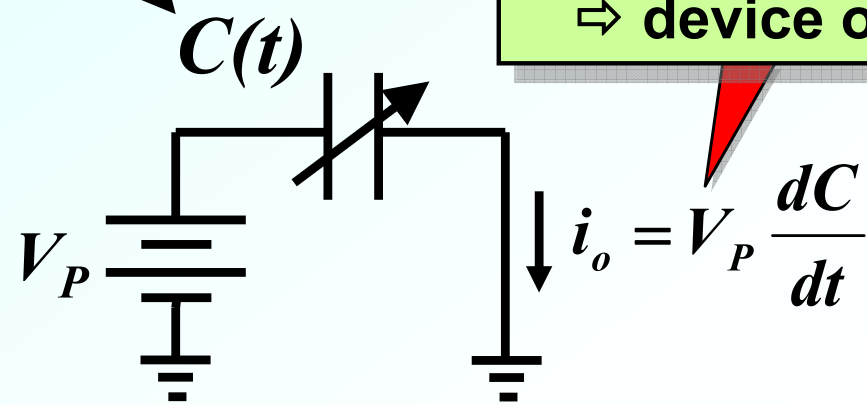
- Absorption/emission of photons
  - ⇨ temperature fluctuations
  - ⇨ frequency fluctuations

- ***Problem***: if dimensions too small ⇨ phase noise significant!
- ***Solution***: operate under optimum pressure and temperature

Radial-Contour Mode Disk Resonator







Note: If V_P = 0V ⇨ device off

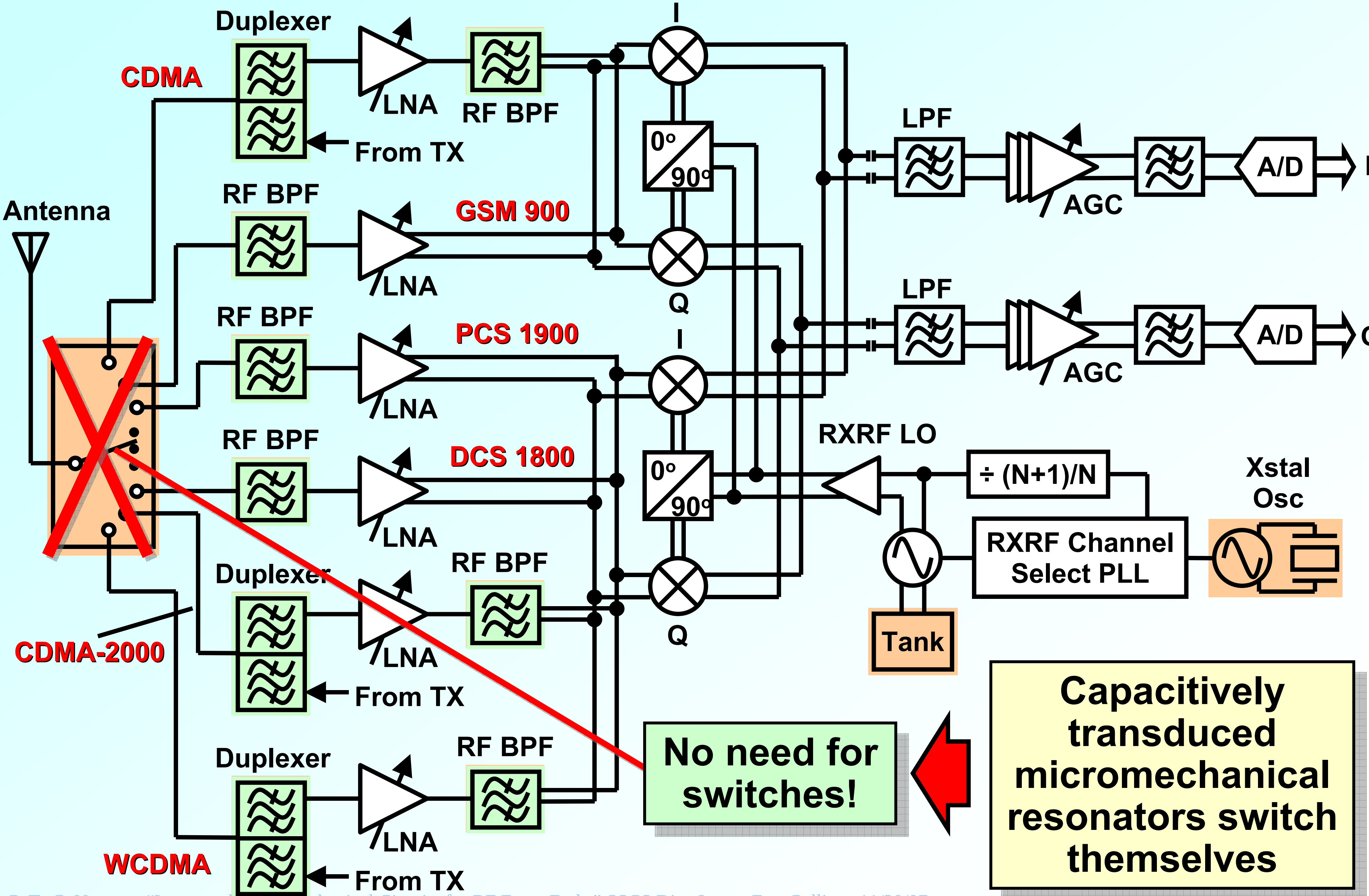
Frequency:

$$f_o = \frac{1}{2\pi}\sqrt{\frac{k_r}{m_r}} \propto \sqrt{\frac{E}{\rho}} \cdot \frac{1}{R}$$

Stiffness (k_r), Mass (m_r), Young's Modulus (E), Density (ρ)

Mass ⇨ (e.g., $m_r = 10^{-13}$ kg) ⇨ **Smaller mass ⇨ higher freq. range and lower series R_x**

Multi-Band Wireless Handsets

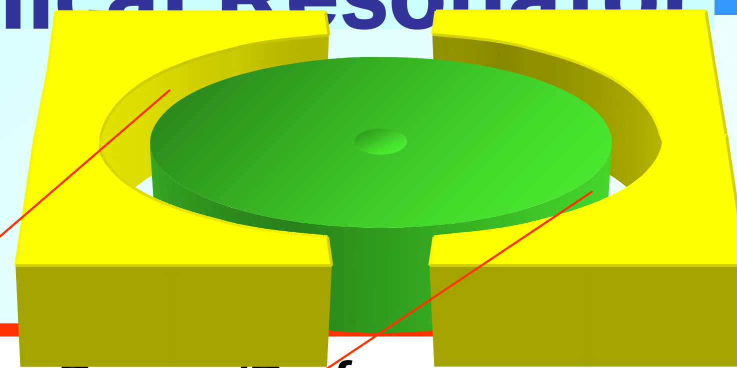


No need for switches!

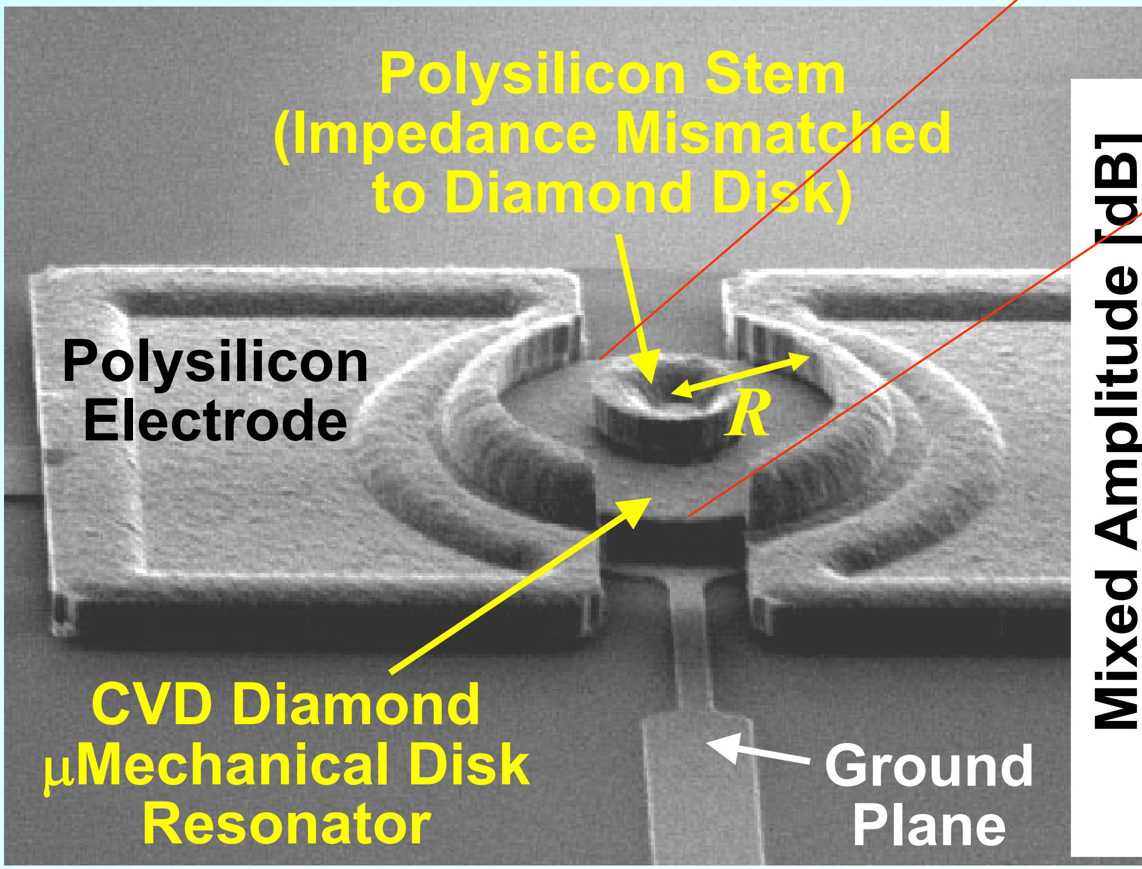
Capacitively transduced micromechanical resonators switch themselves

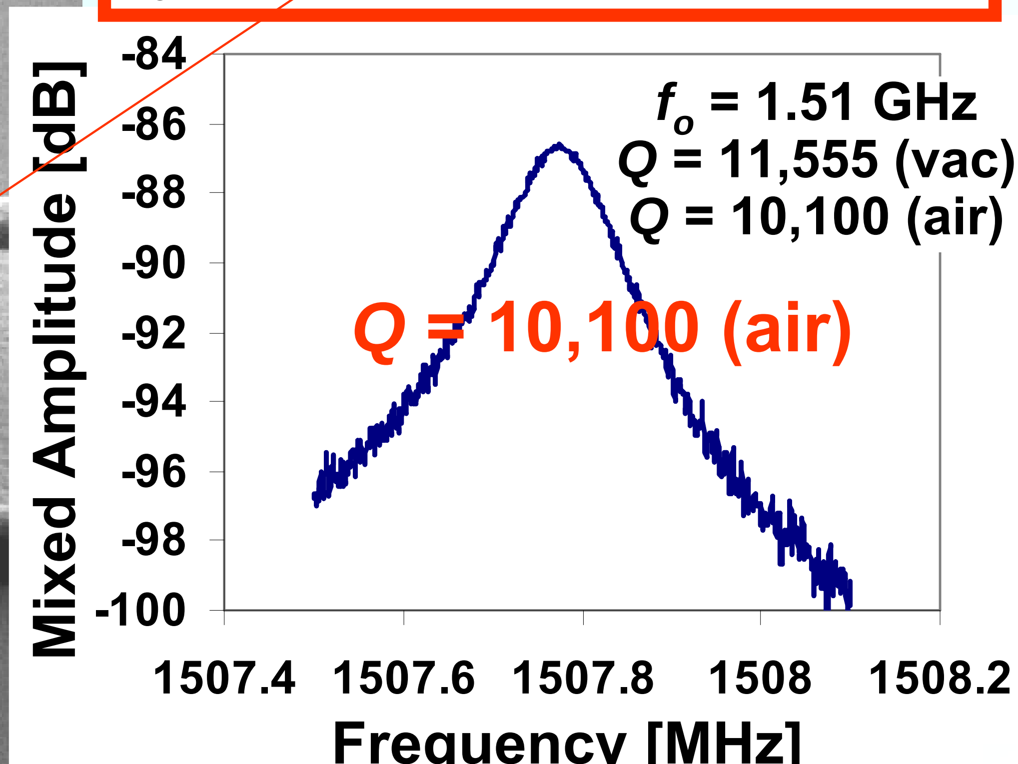
1.51-GHz, *Q*=11,555 Nanocrystalline Diamond Disk μMechanical Resonator

- 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

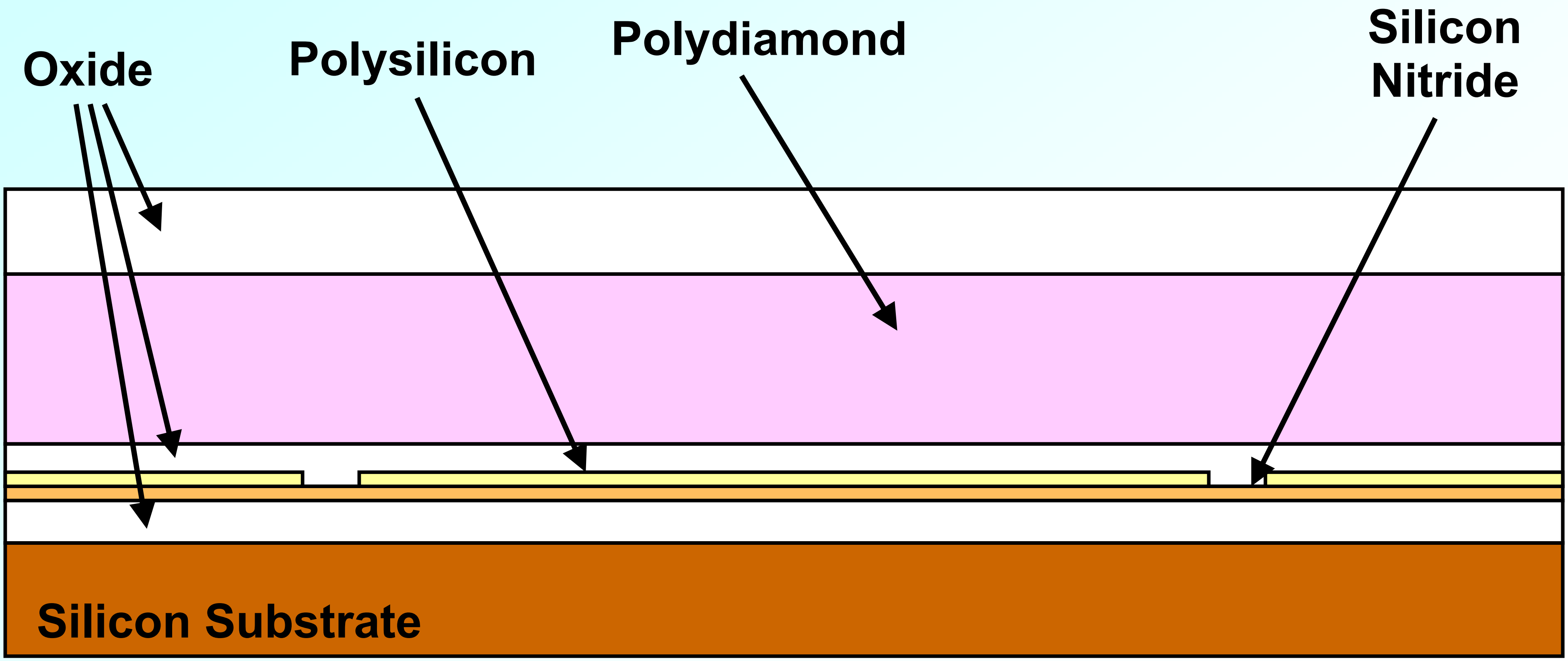




[Wang, Butler, Nguyen MEMS'04]

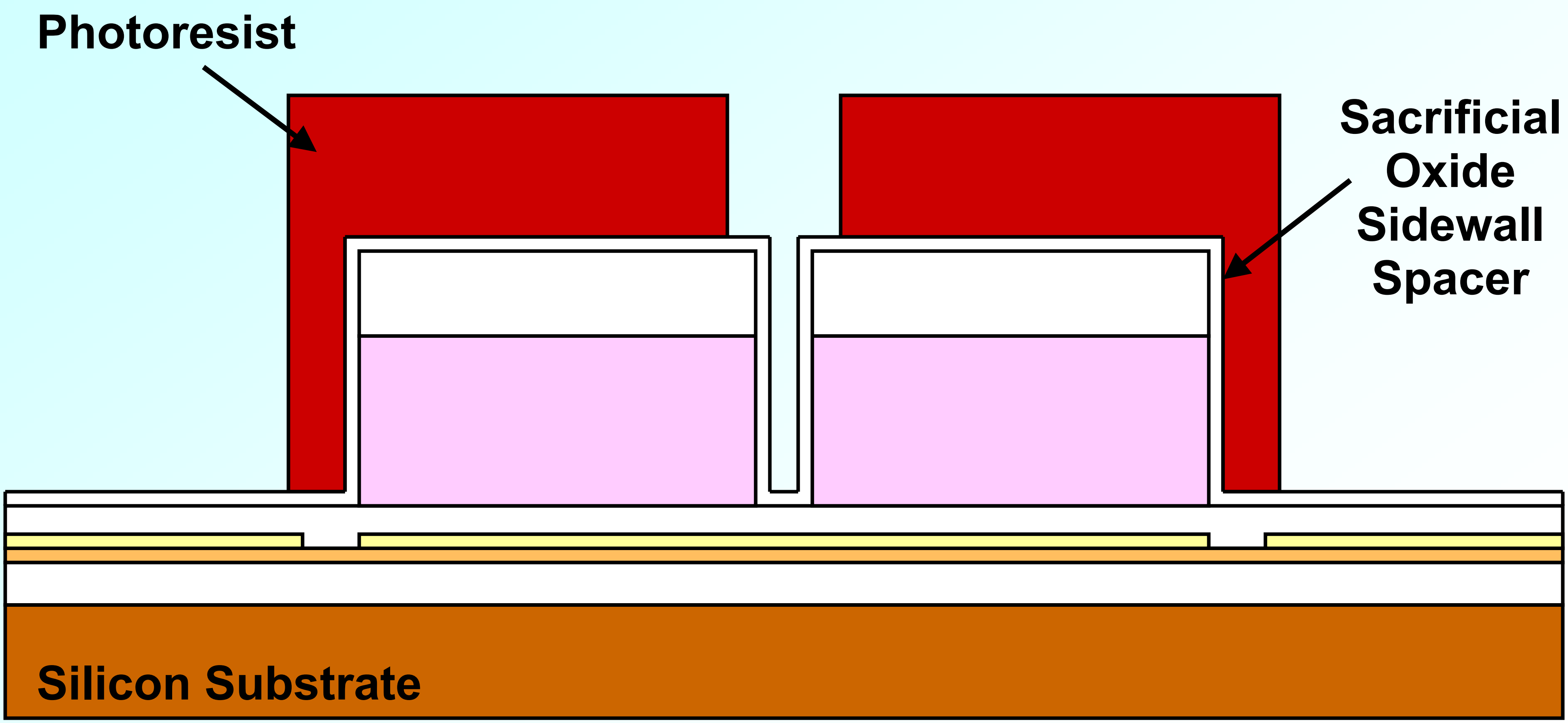
Self-Aligned Fabrication Process

- ***Strategy***: make stem misalignment impossible
- ***Below***:
  - successive film depositions
  - simultaneous definition of disk shape and stem location



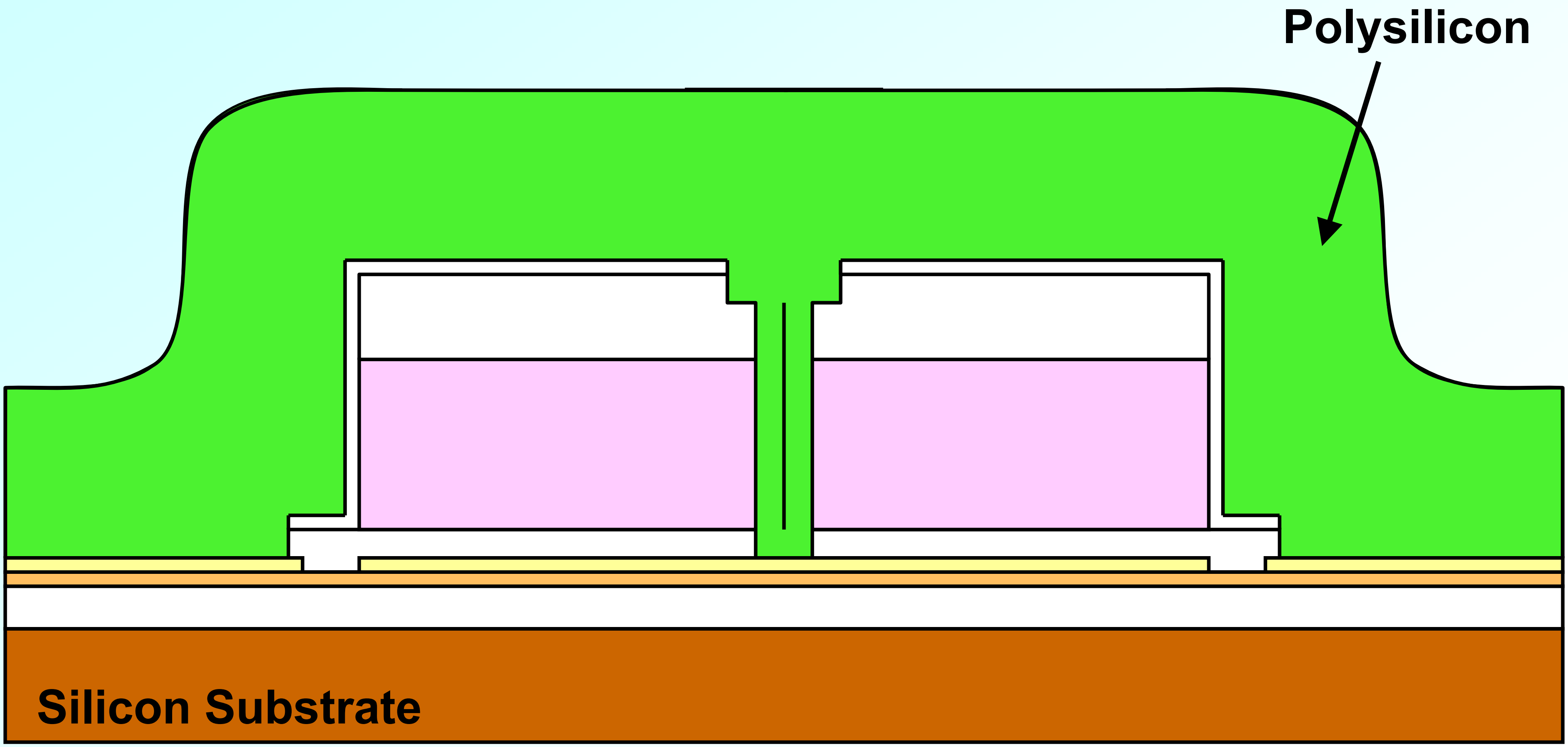
Self-Aligned Fabrication Process

- ***Below***:
  - define electrode-to-resonator gap spacing via sacrificial oxide sidewall spacer
  - etch stem anchor



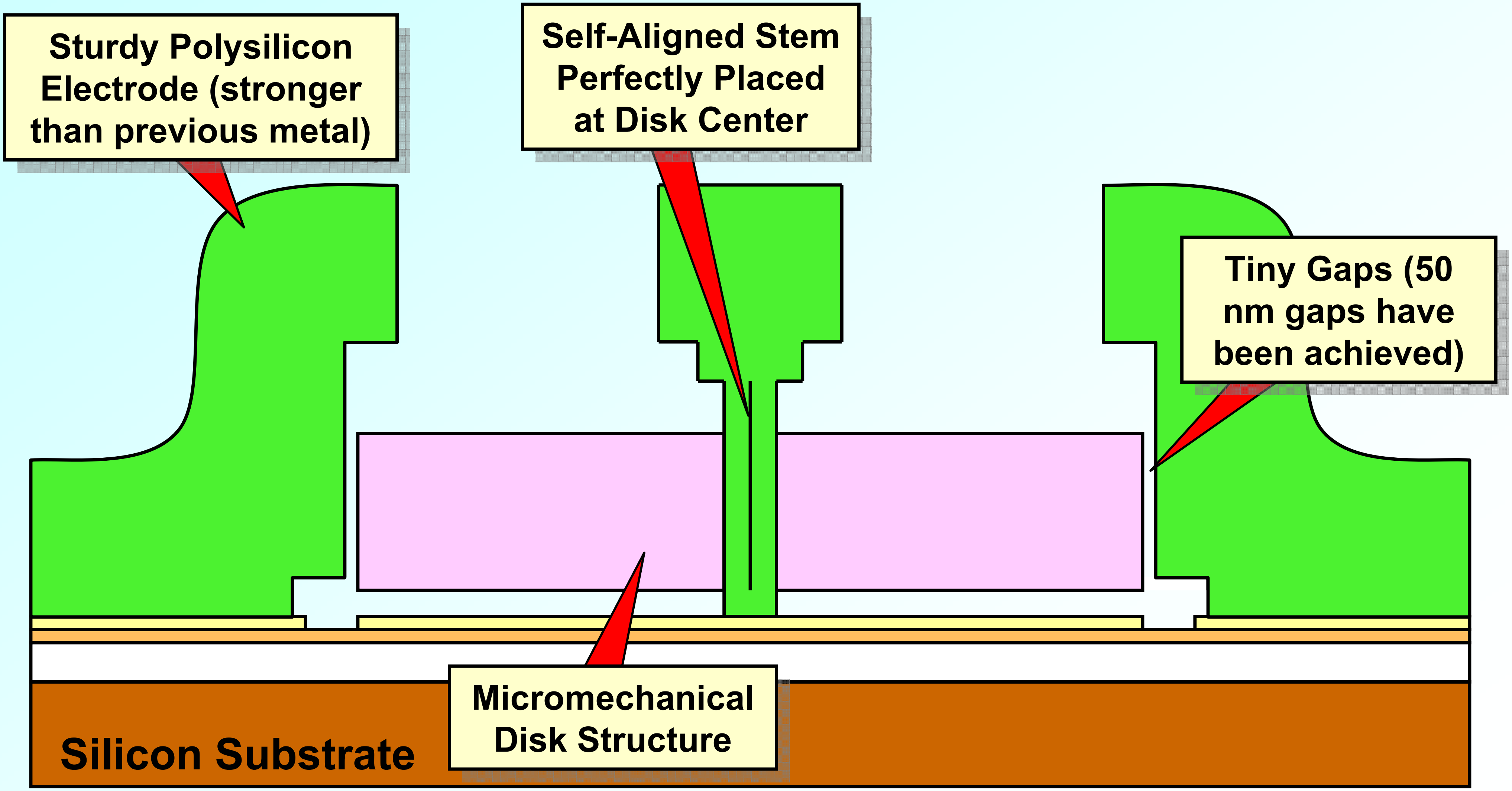
Self-Aligned Fabrication Process

- ***Below***:
  - deposit thick polysilicon
  - pattern to define stem and electrodes

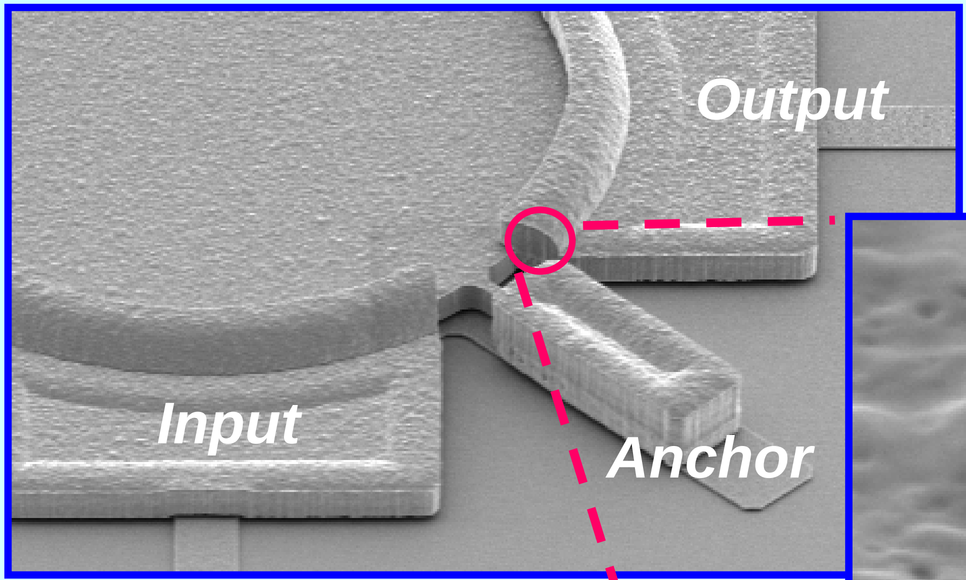


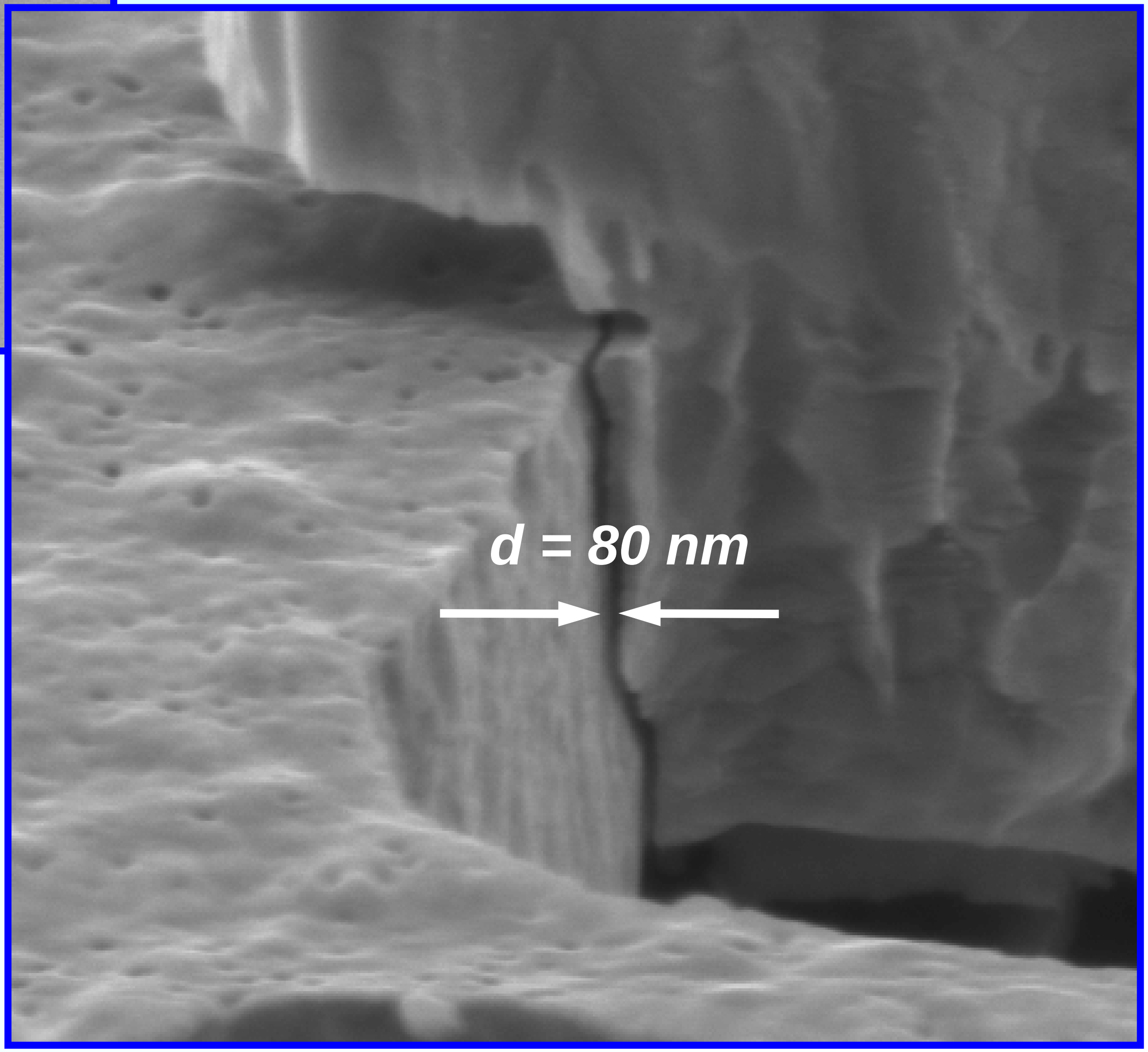
Self-Aligned Fabrication Process

- ***Result***: micromechanical disk with perfectly centered stem and nano-scale electrode-to-resonator gaps



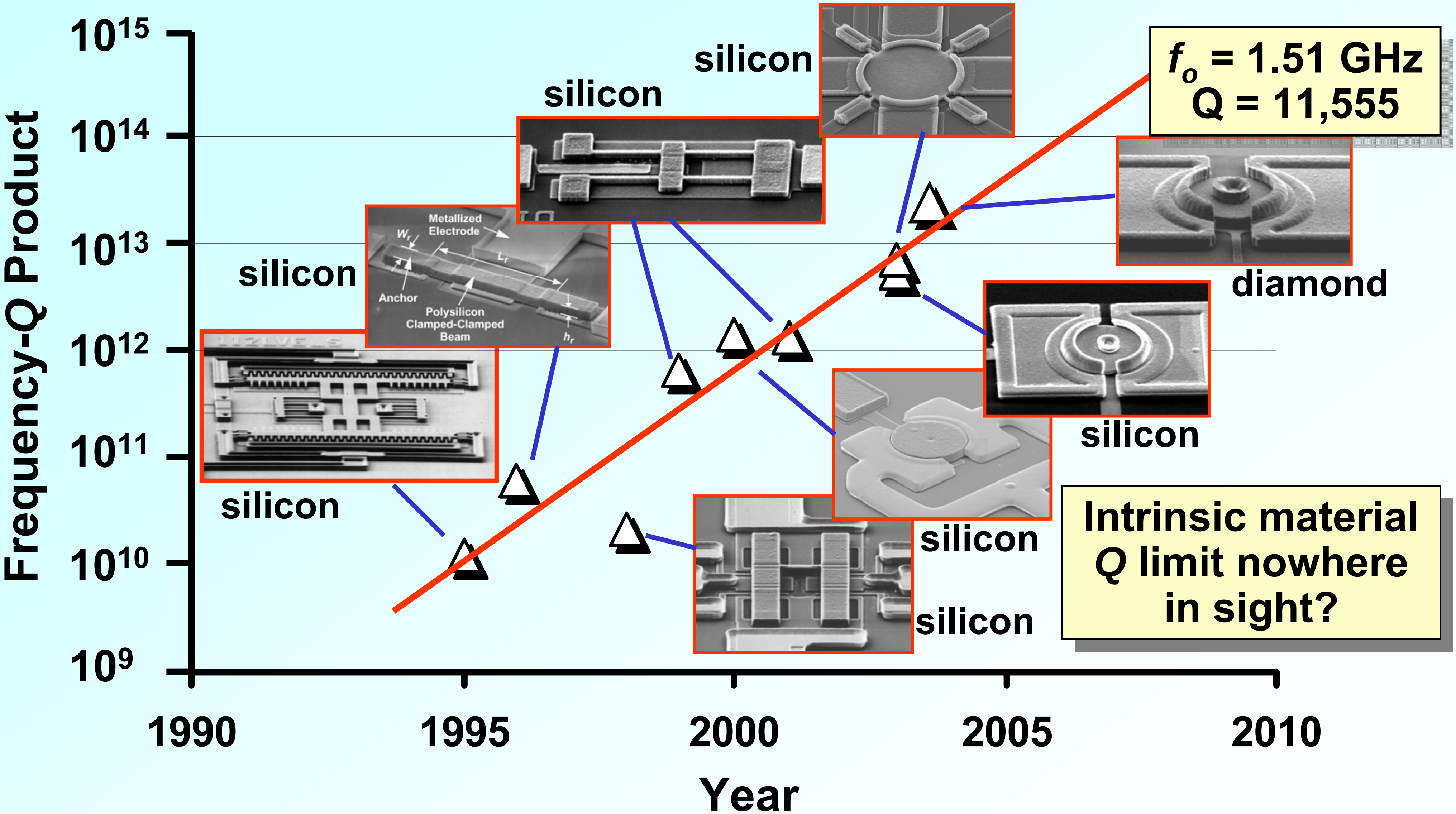
Tiny Lateral Transducer Gaps





- ***Right***: **zoom-in on the 80 nm gap achieved via the sacrificial sidewall spacer process**

μMechanical Resonator f_o-Q Product

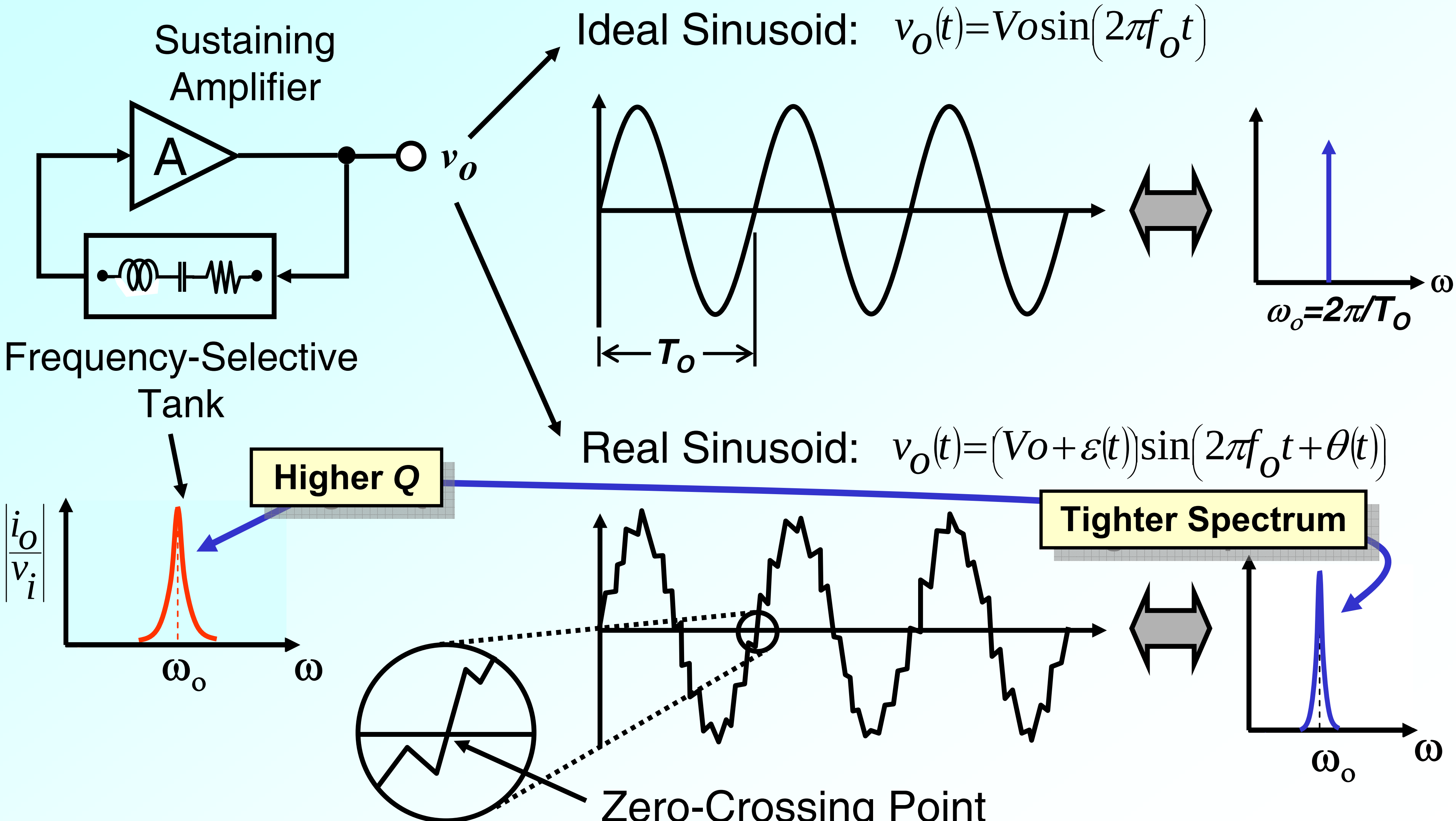


- Freq.-*Q* product rising exponentially over the past years

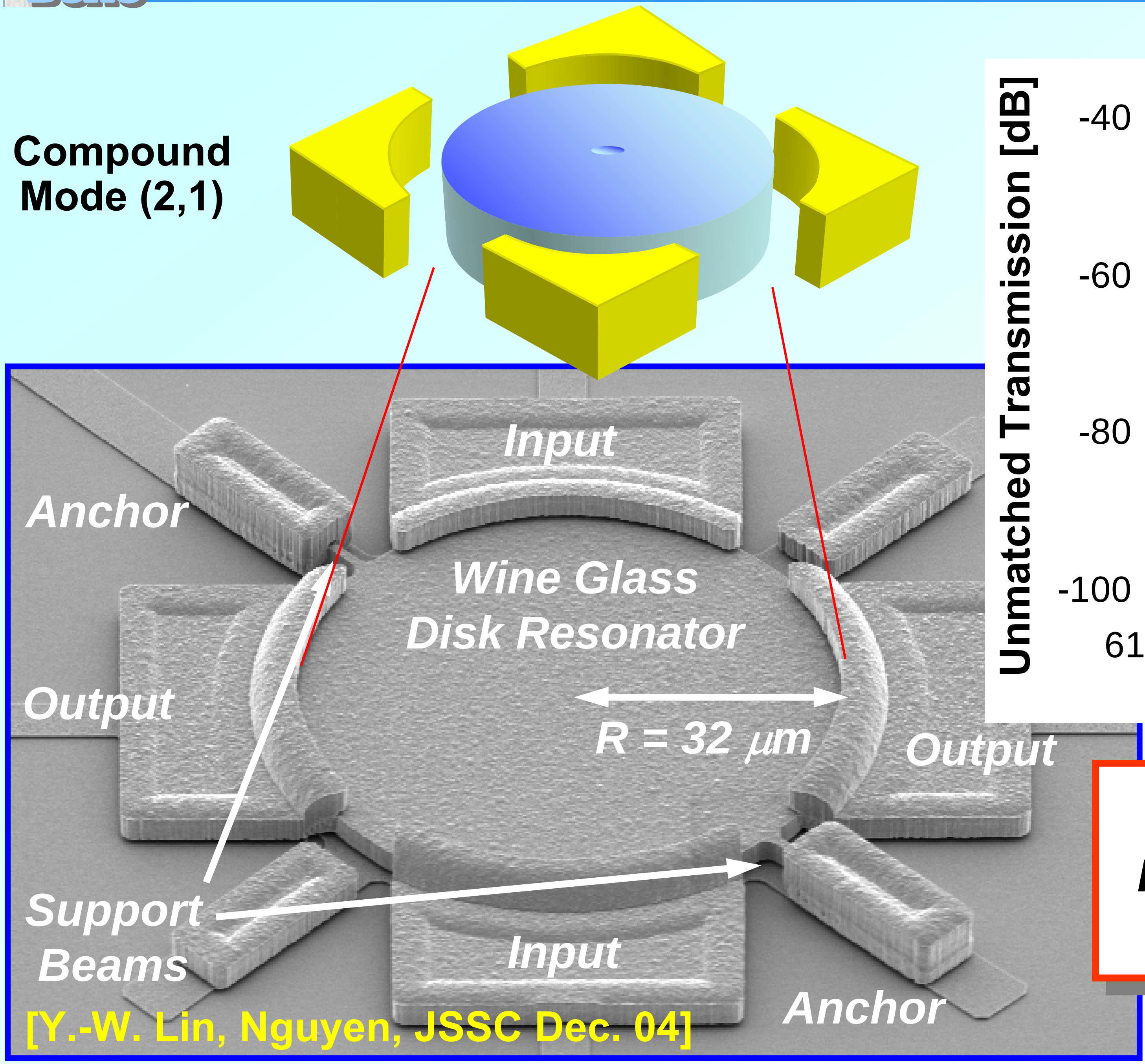
Micromechanical Resonator Oscillators

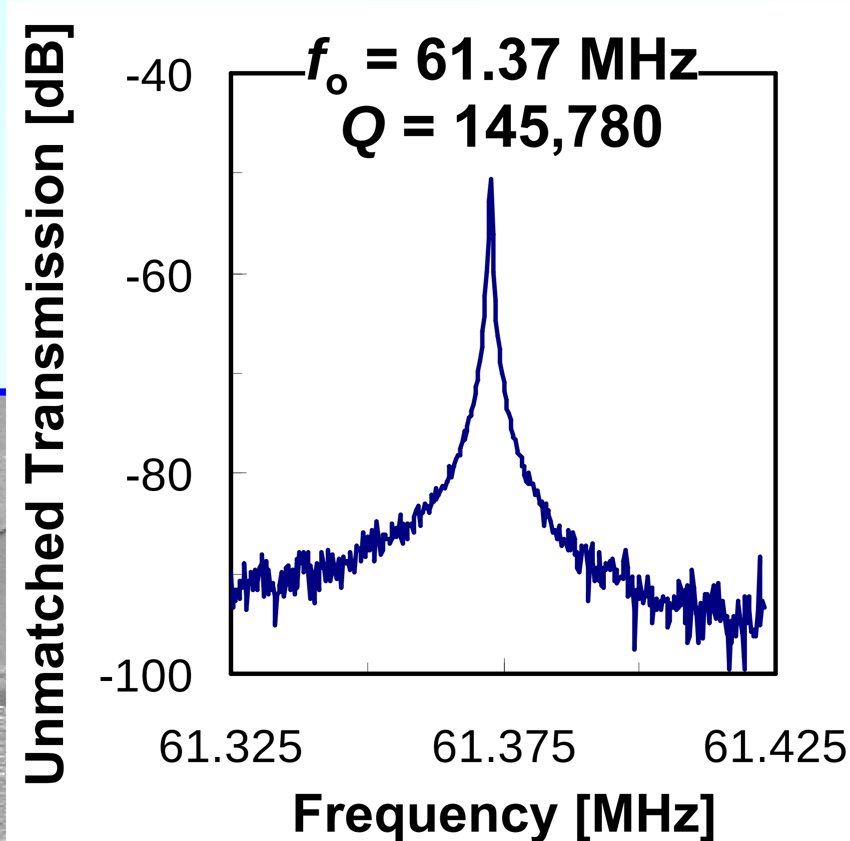
Oscillator: Need for High Q

- ***Main Function***: provide a stable output frequency
- ***Difficulty***: superposed noise degrades frequency stability



Polysilicon Wine-Glass Disk Resonator





Resonator Data

R **= 32 μm,** ***h*** **= 3 μm**

d **= 80 nm,** V_p **= 3 V**

Phase Noise in Oscillators

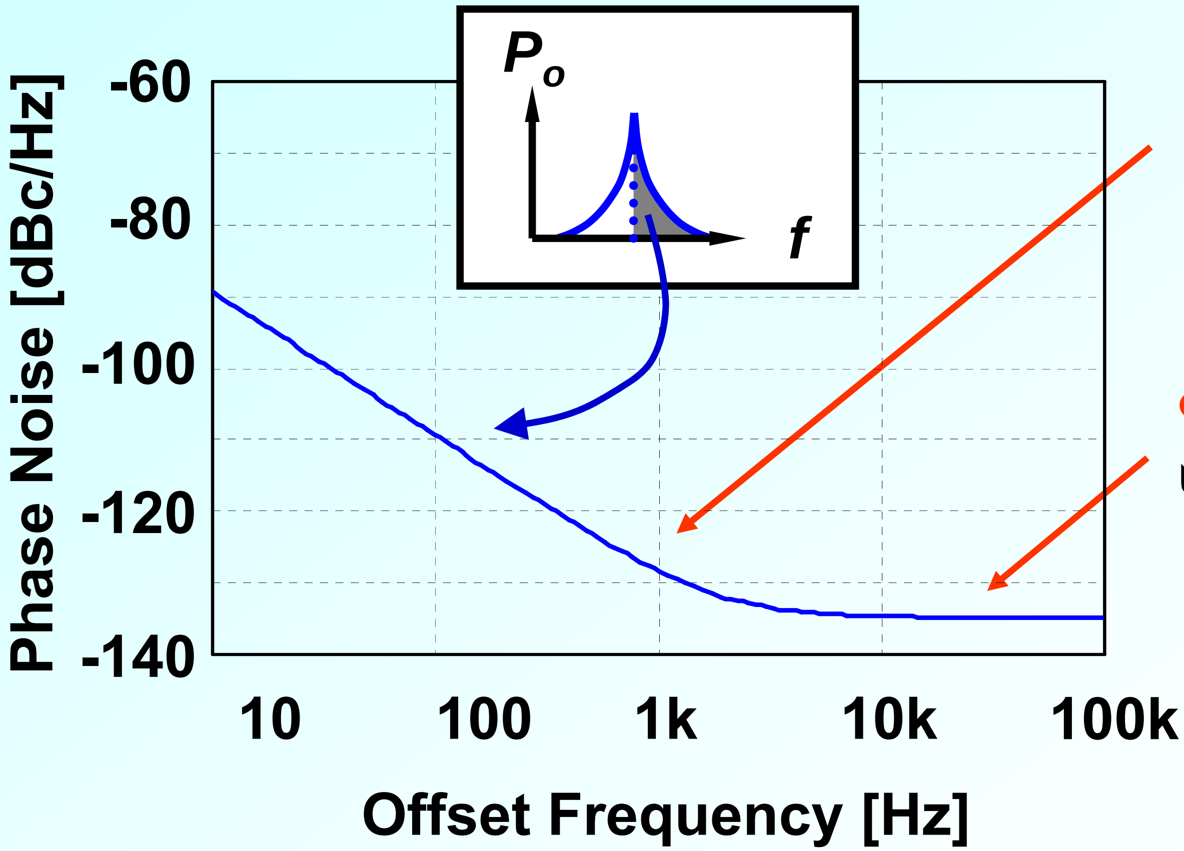
- Single Sideband Phase Noise Density to Carrier Power Ratio in Oscillator, $L\{f_m\}$

$$L\{f_m\} \propto \frac{kT}{P_o} \cdot \left(\frac{f_o}{Q \cdot f_m} \right)^2$$

$f_o \Rightarrow$ Carrier Frequency

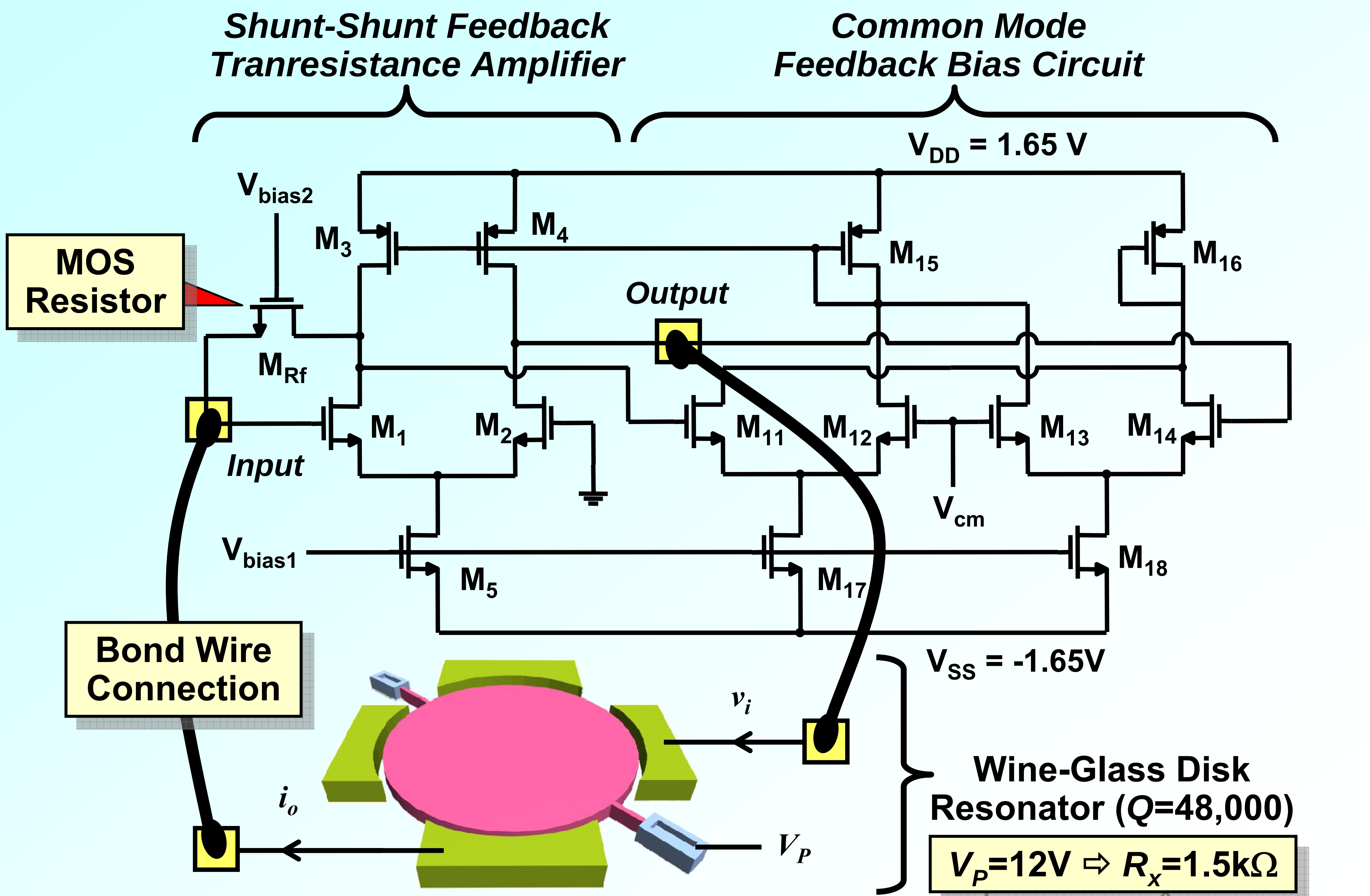
$f_m \Rightarrow$ Offset Frequency

$P_o \Rightarrow$ Signal Power

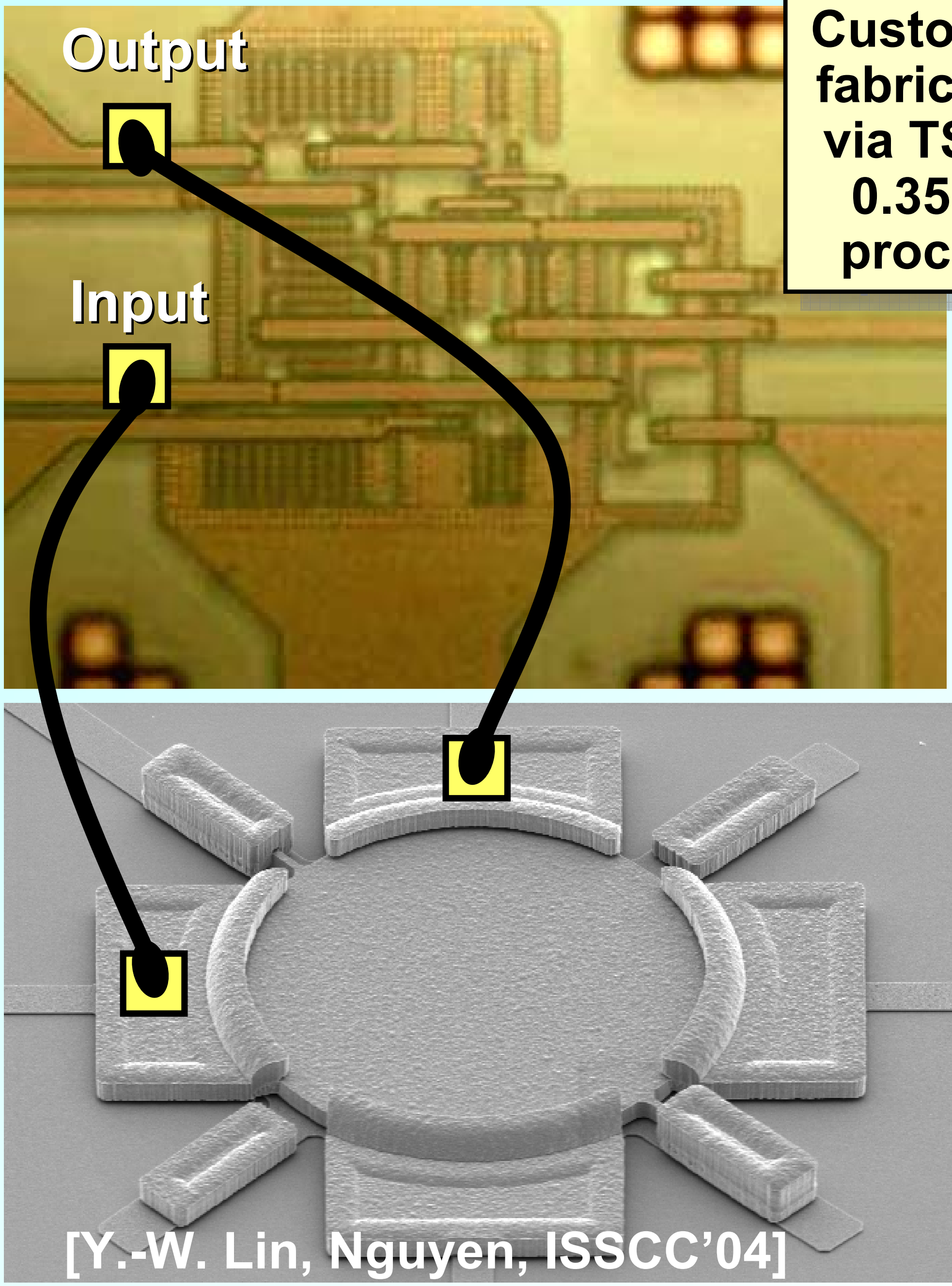


- **High *Q***
  ↳ reduces close-to-carrier phase noise
- **High P_o**
  ↳ reduces far-from-carrier phase noise

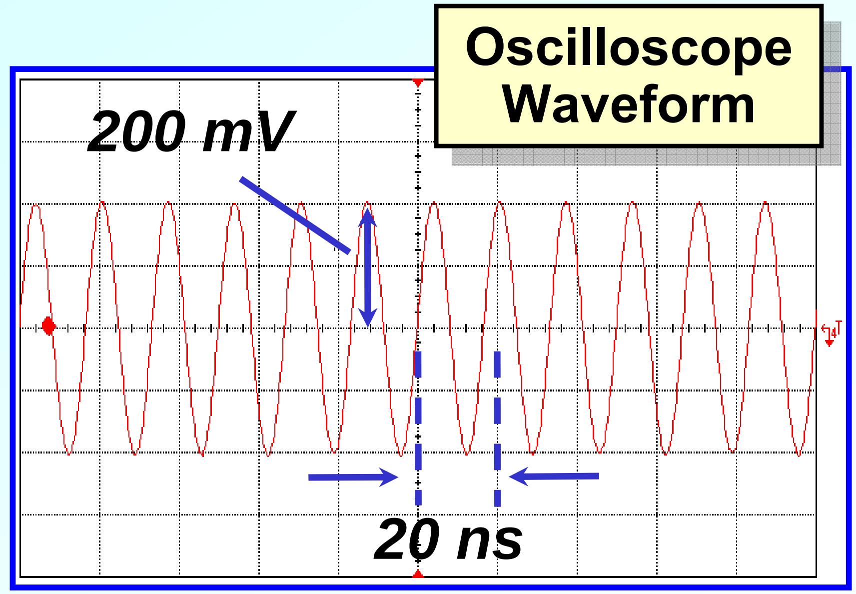
Wine Glass Disk Oscillator

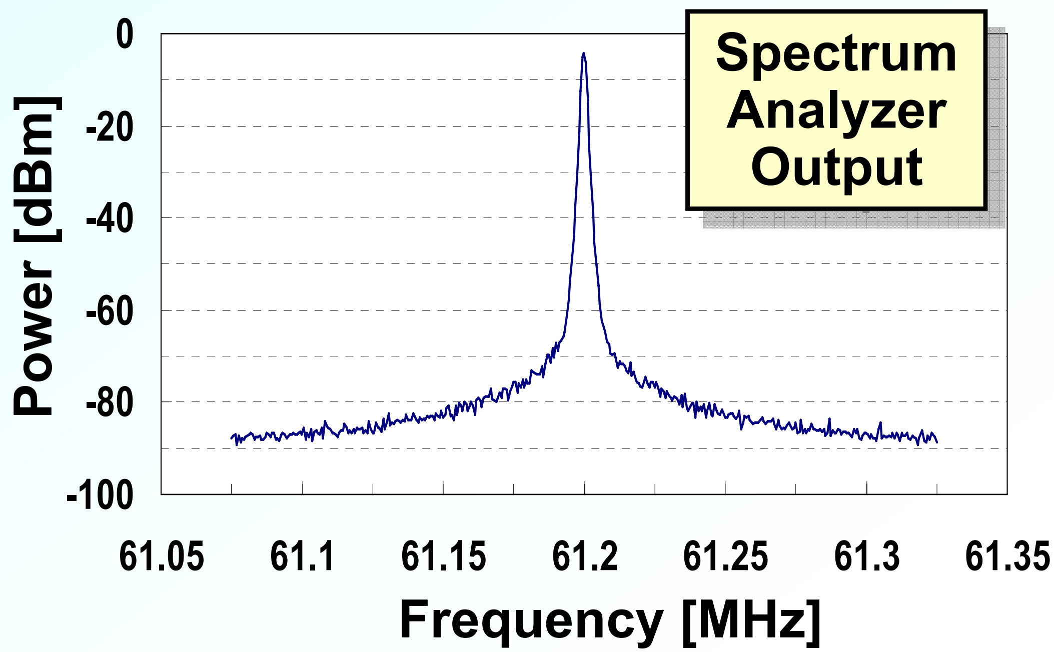


Time & Freq. Domain Performance

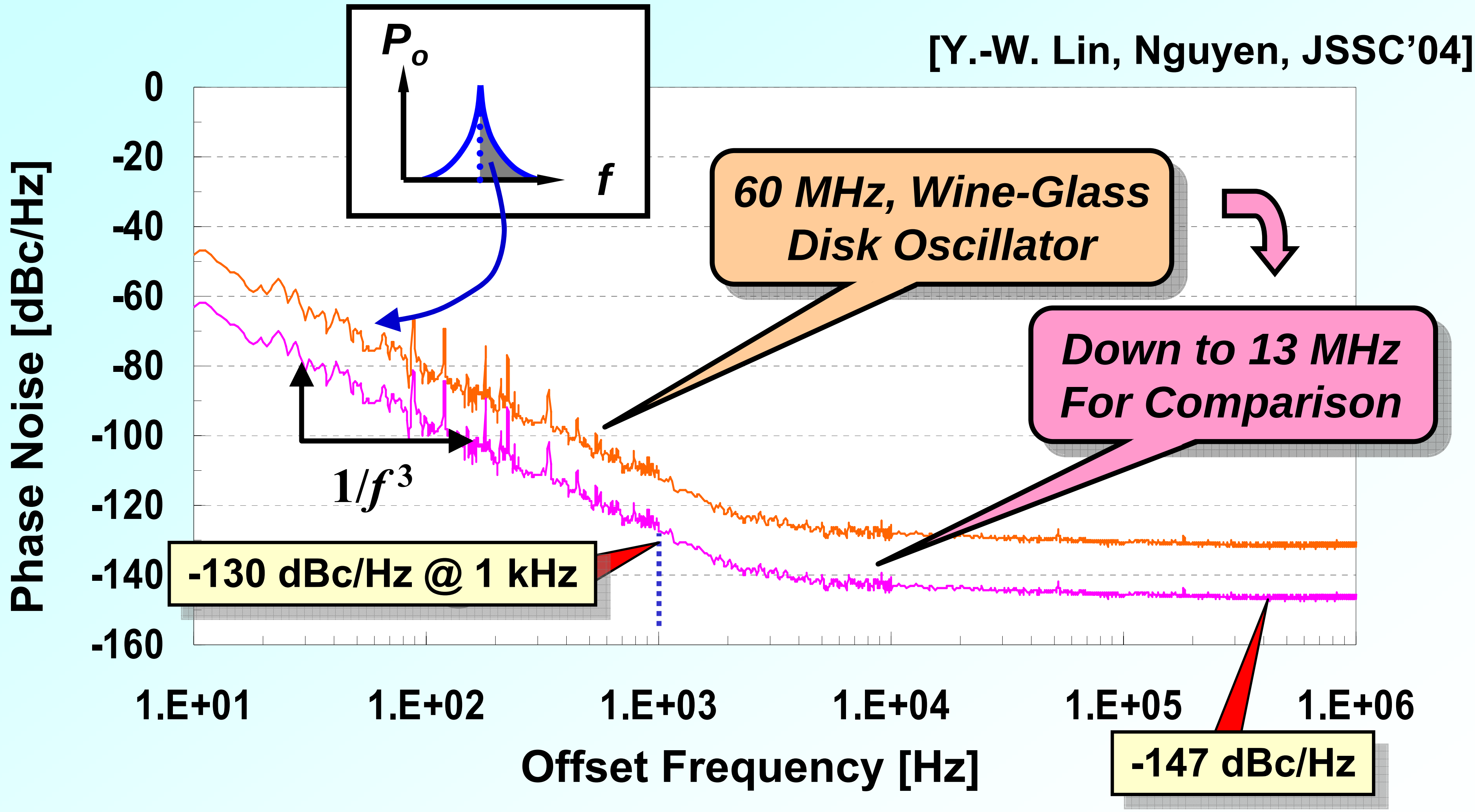


Custom IC fabricated via TSMC 0.35μm process





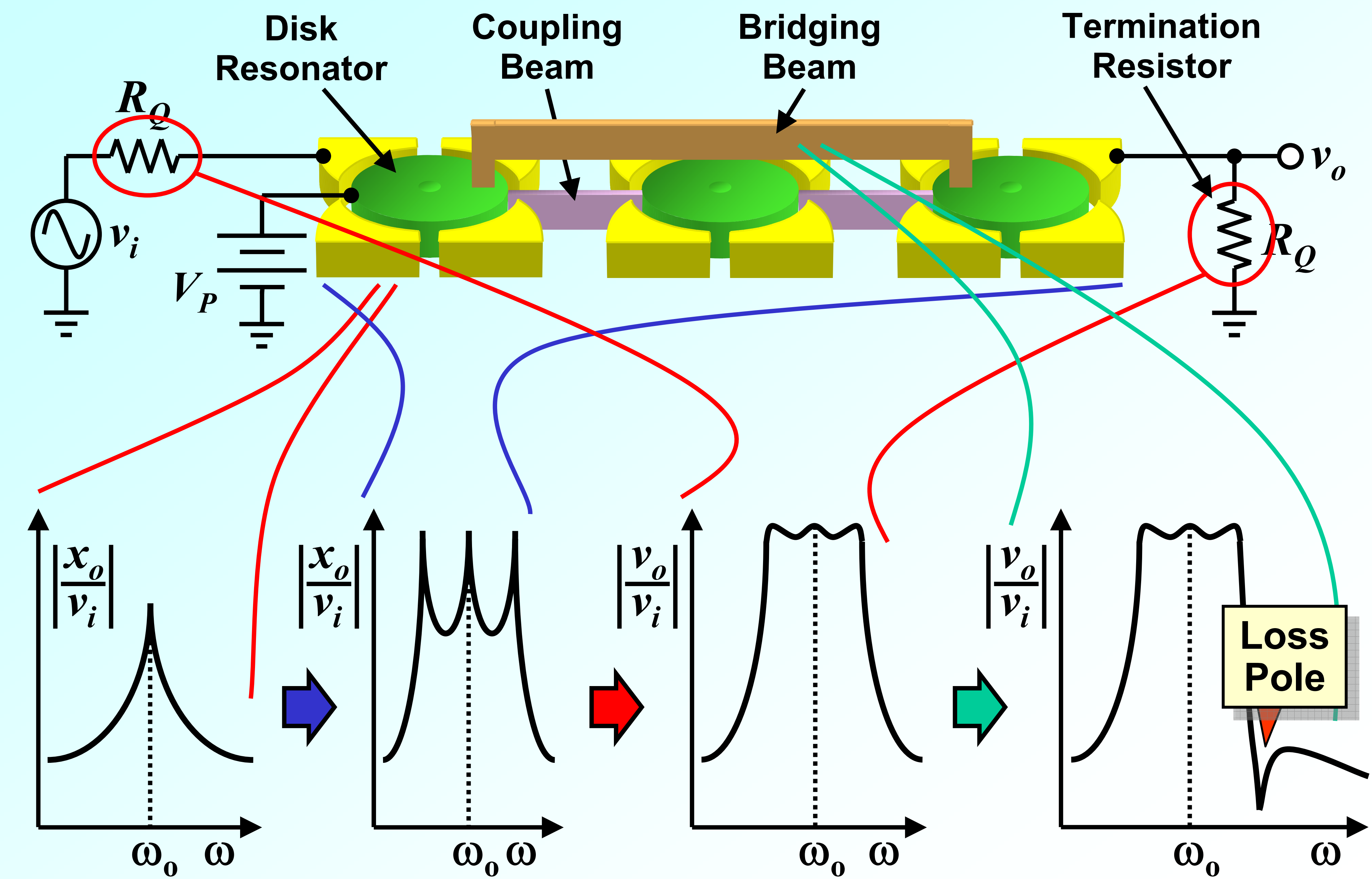
Phase Noise Measurement



Nearly satisfies Global System for Mobile Communications (GSM) phase noise specifications! → **Requires only 300 μW and 150 x 150 μm²!**

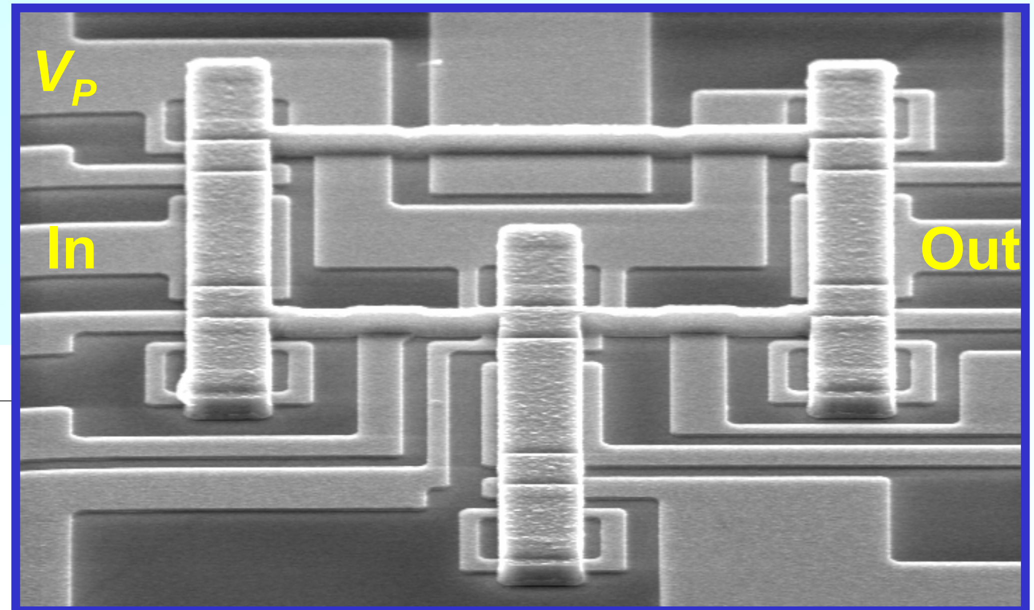
Integrated Micromechanical Circuits

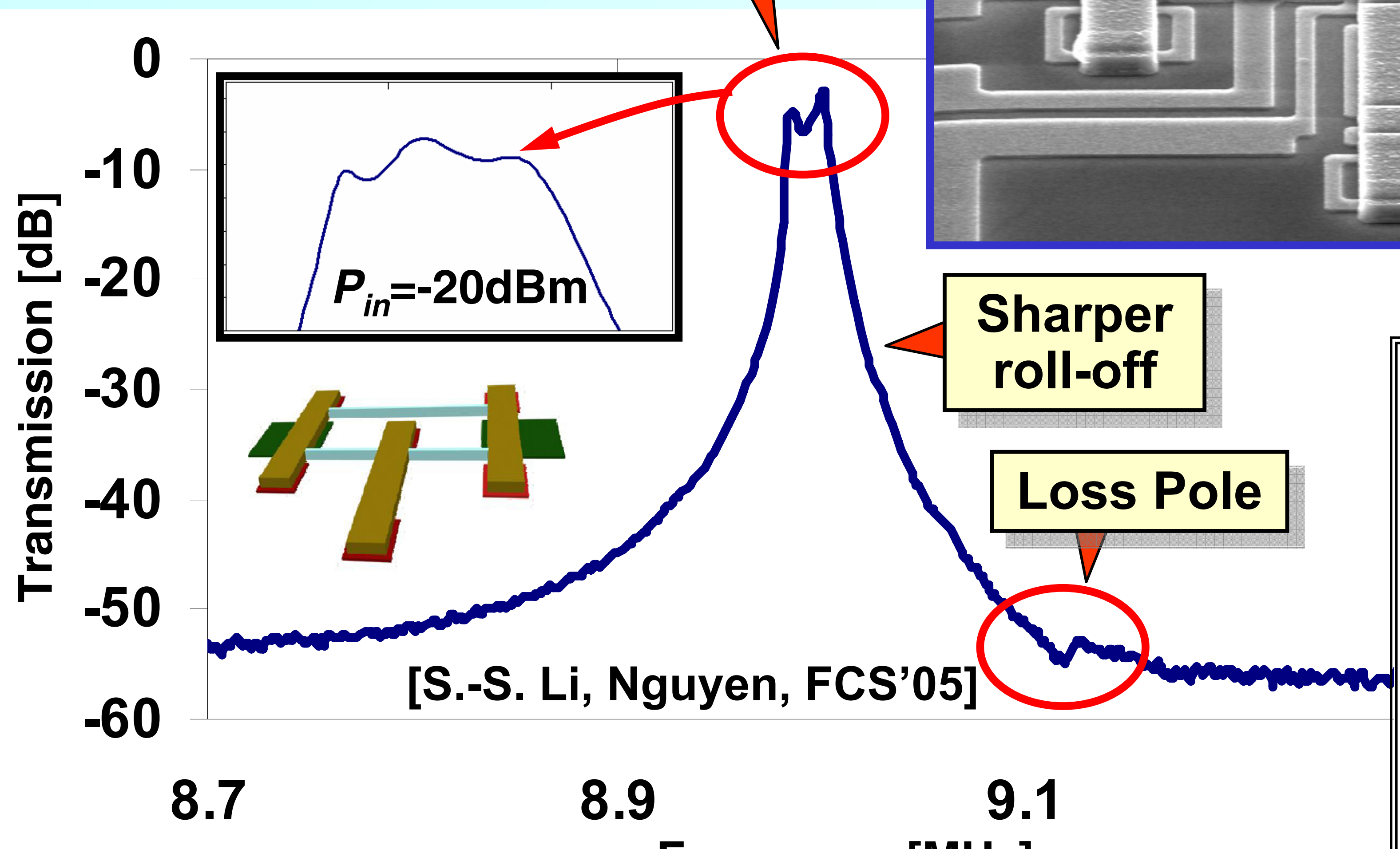
Micromechanical Filter Design Basics



3CC 3λ/4 Bridged μMechanical Filter

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

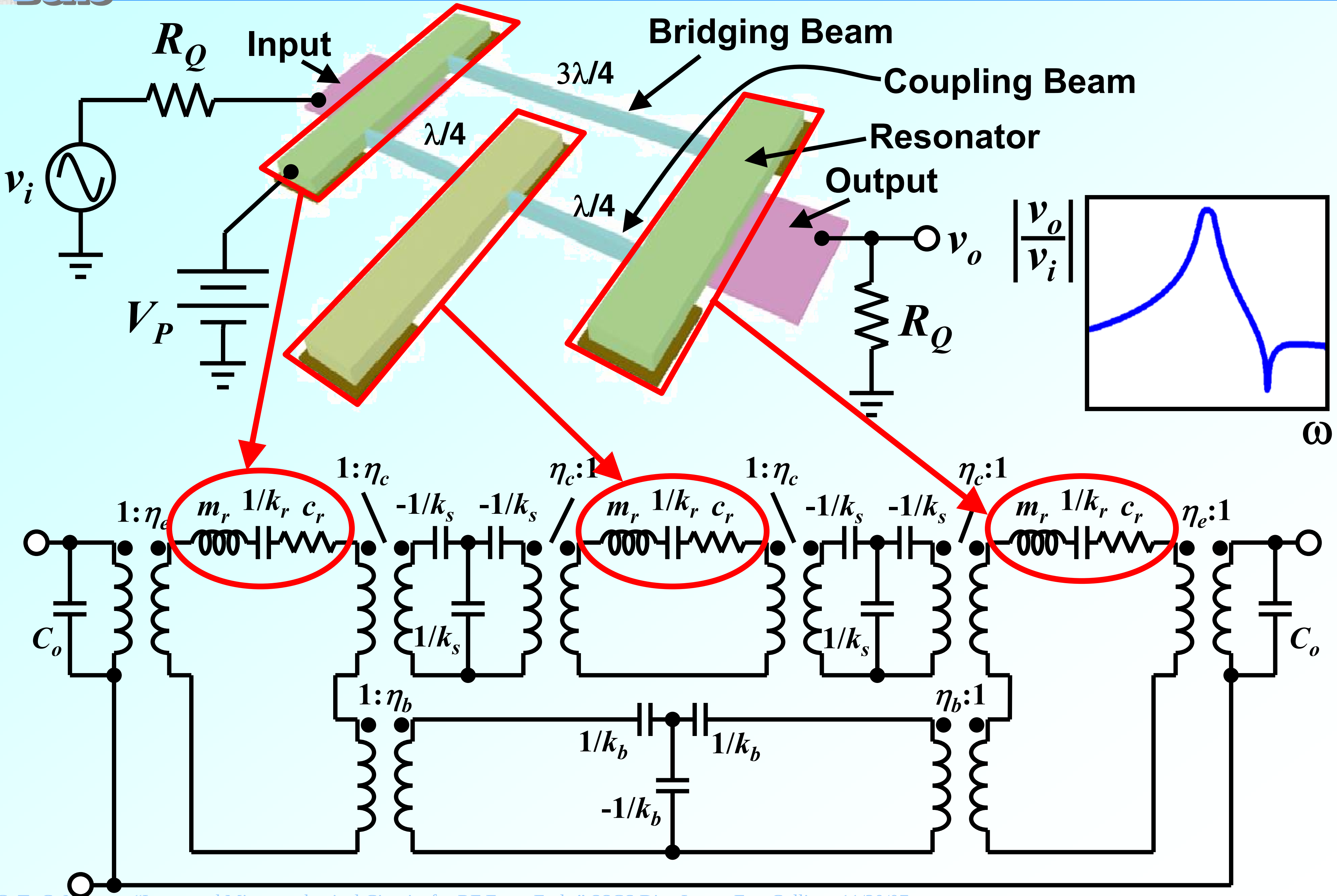




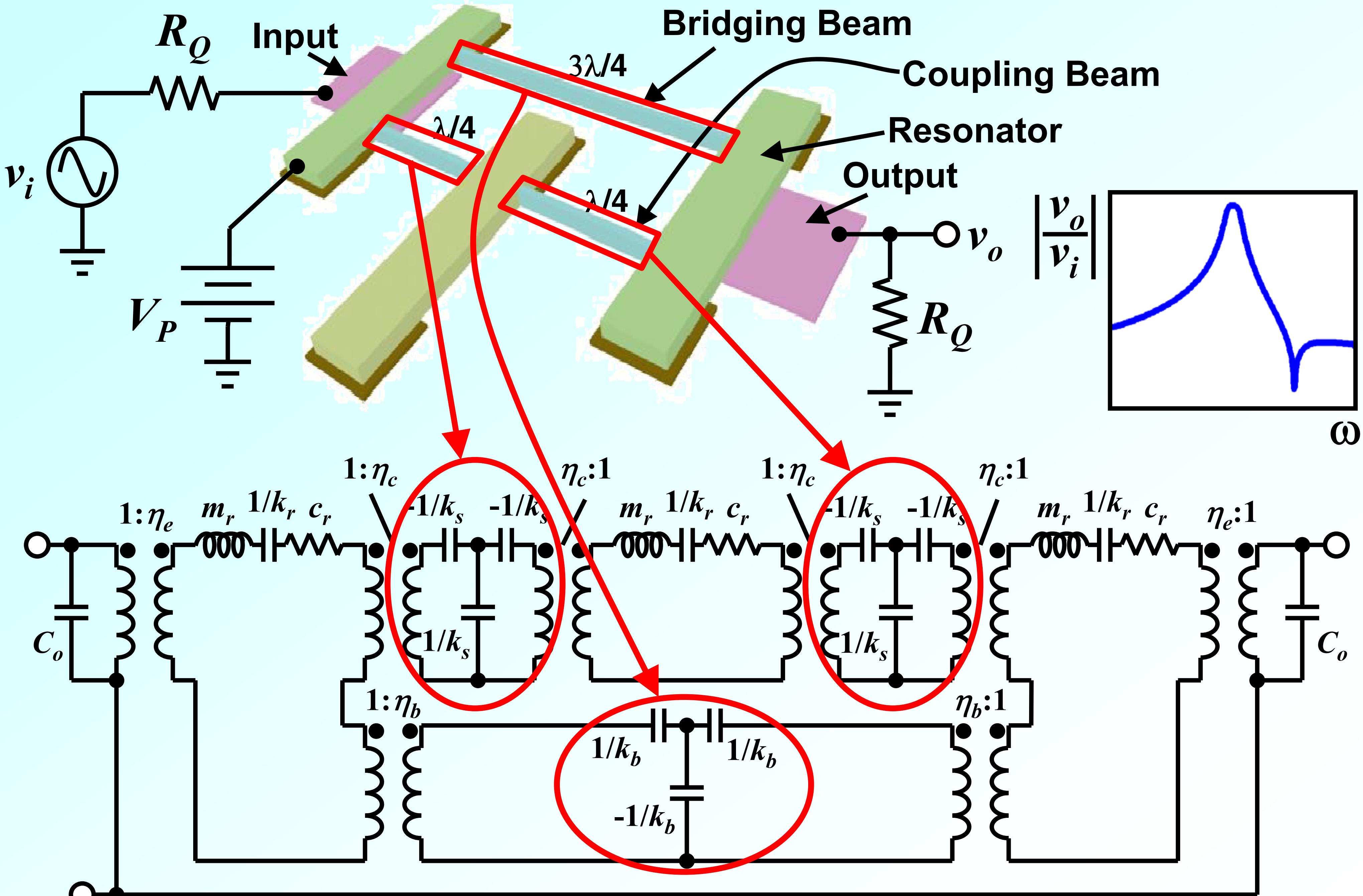
Design:
L_r=40μm
W_r=6.5μm
h_r=2μm
L_c=3.5μm
L_b=1.6μm
V_P=10.47V
P=-5dBm
R_{Qi}=R_{Qo}=12kΩ

[Li, *et al.*, UFFCS'04]

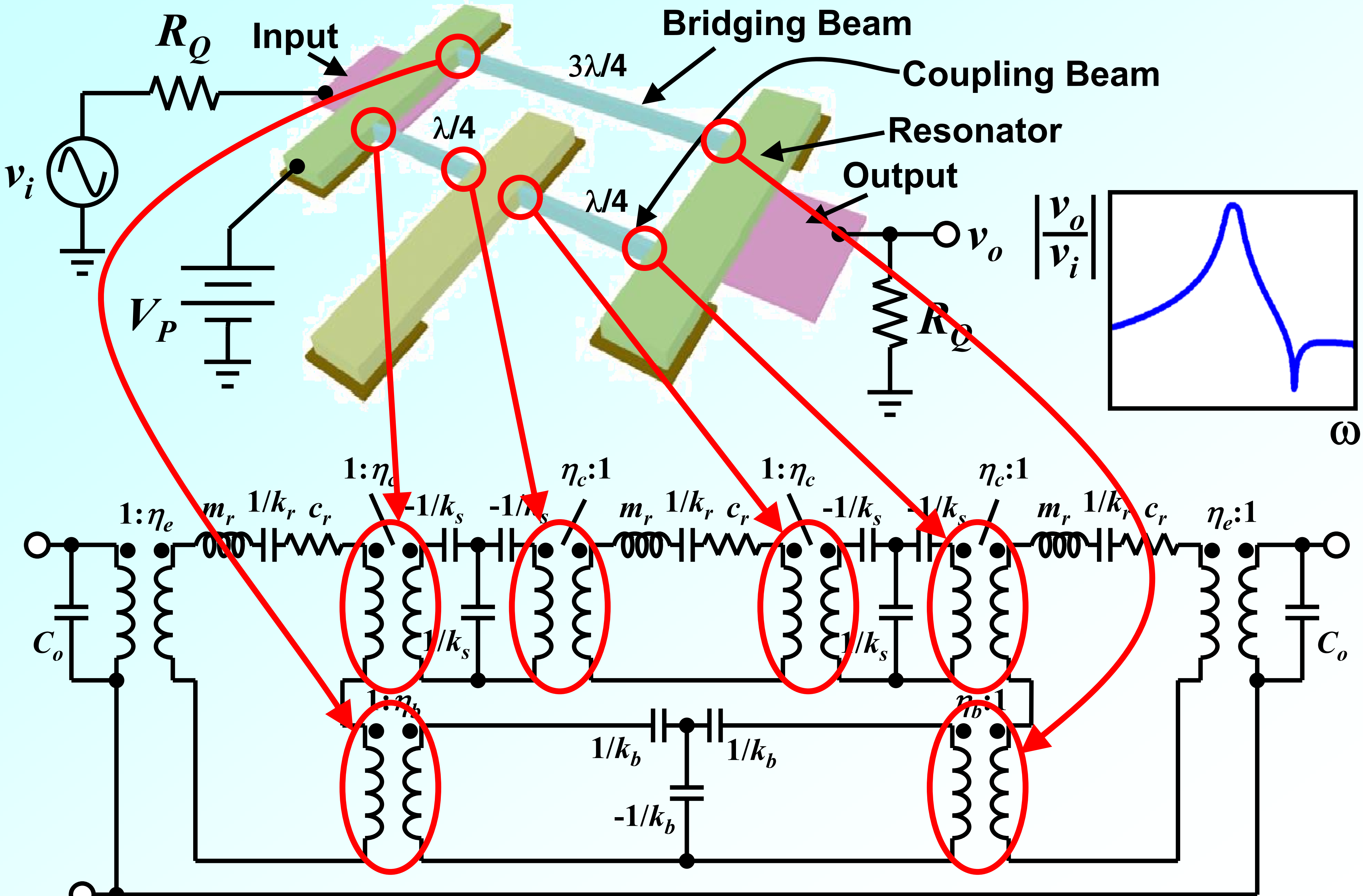
Micromechanical Filter Circuit



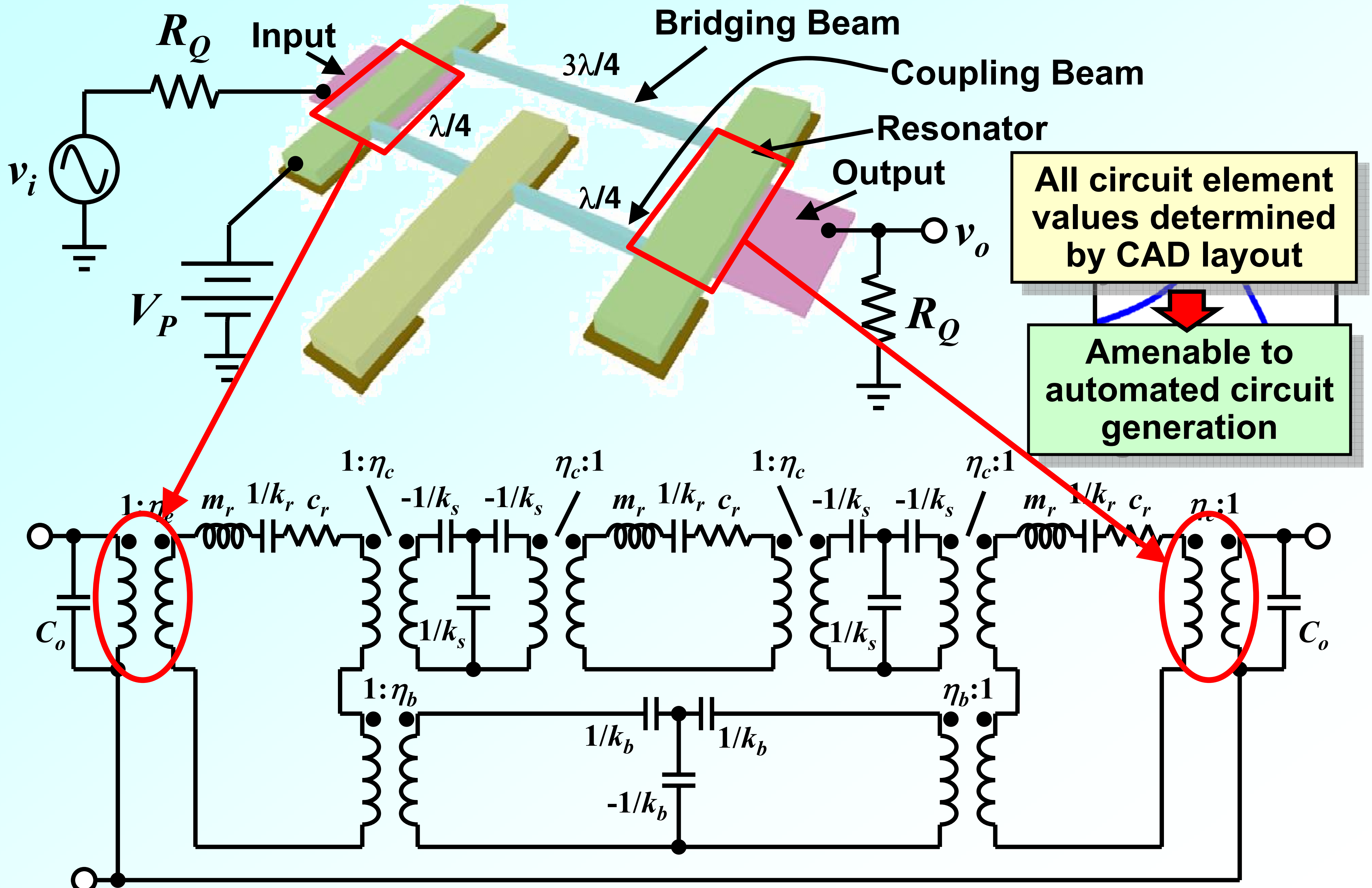
Micromechanical Filter Circuit



Micromechanical Filter Circuit



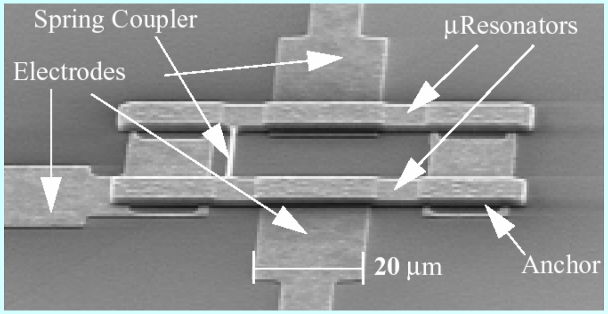
Micromechanical Filter Circuit

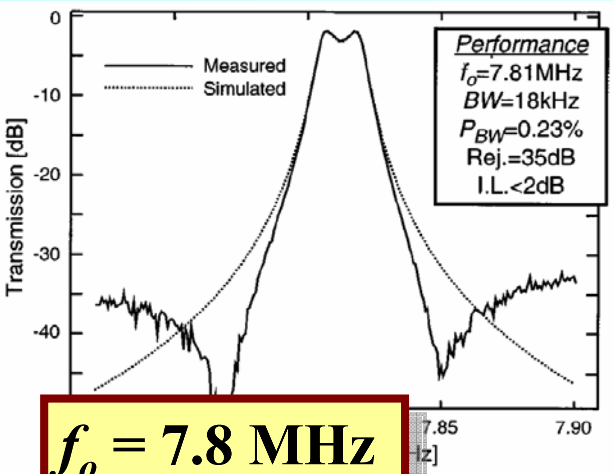


Demo'ed Micromechanical Filters

BSAC

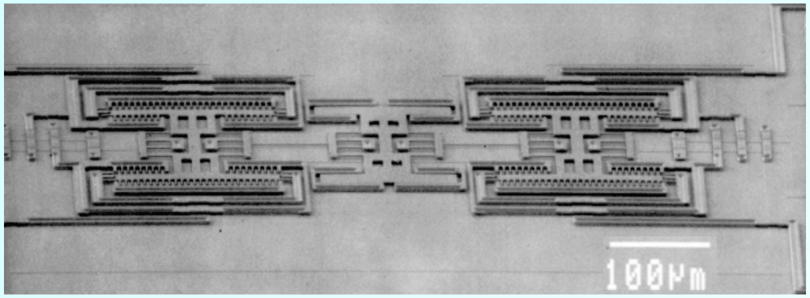
HF Micromech. Filter [Bannon, IEDM'96]

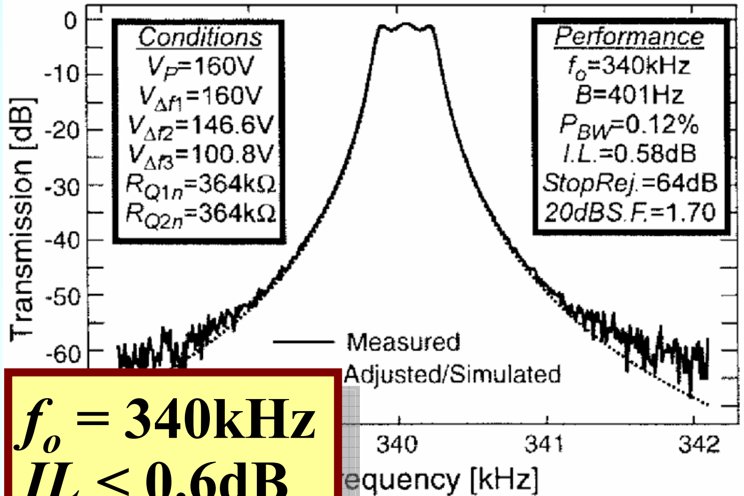




f_o = 7.8 MHz
IL < 2dB
R_Q = 14.7kΩ

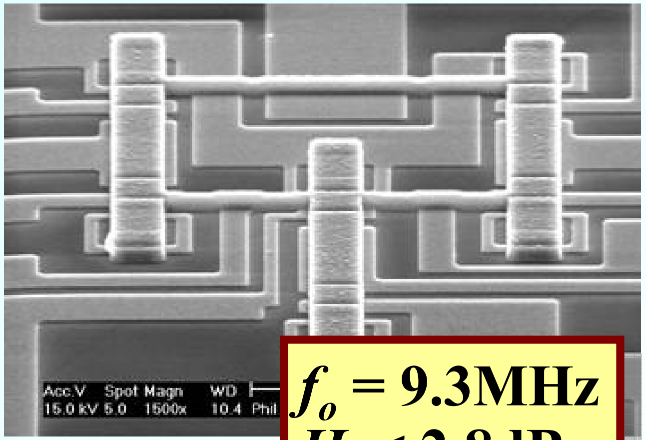
High-Order Micromechanical Filter [Wang, MEMS'97]



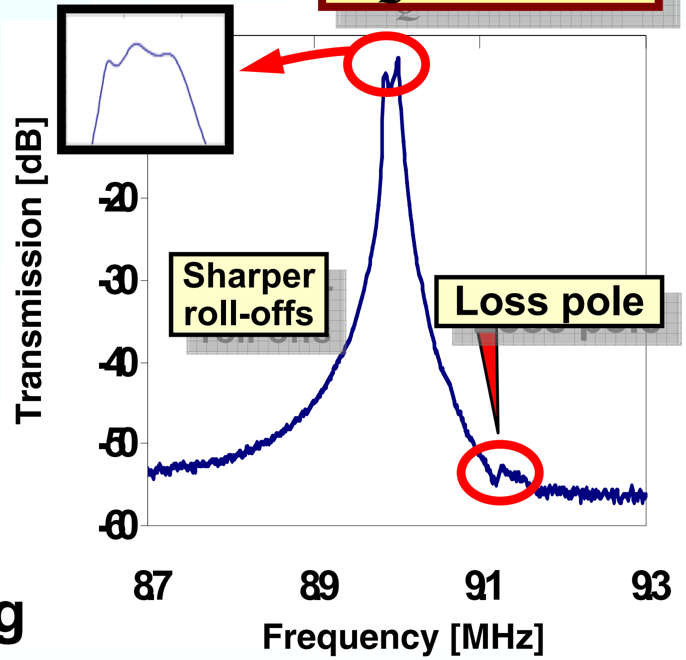


f_o = 340kHz
IL < 0.6dB
R_Q = 364kΩ

Bridged μMech. Filter [S.-S. Li, UFFCS'2004]



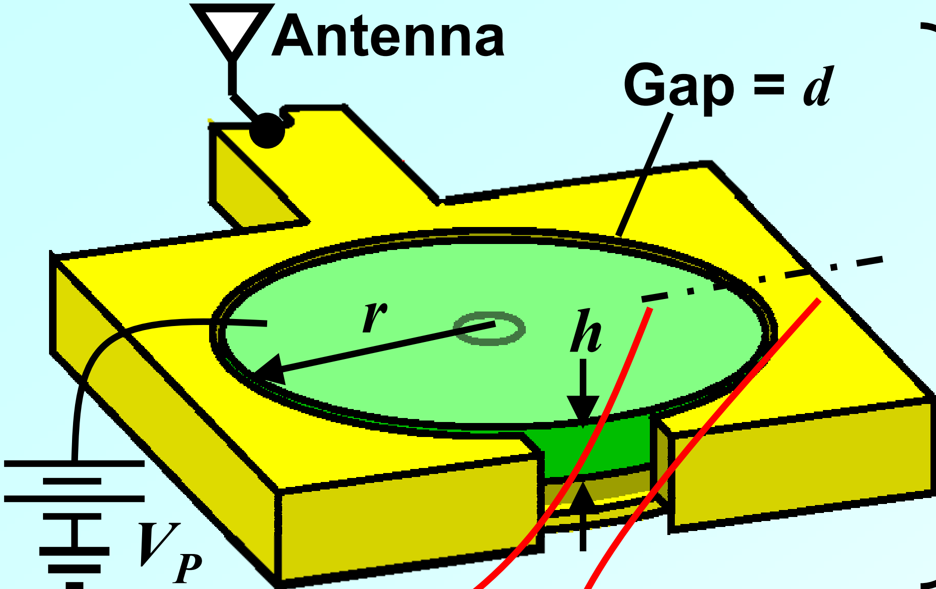
f_o = 9.3MHz
IL < 2.8dB
R_Q = 12kΩ

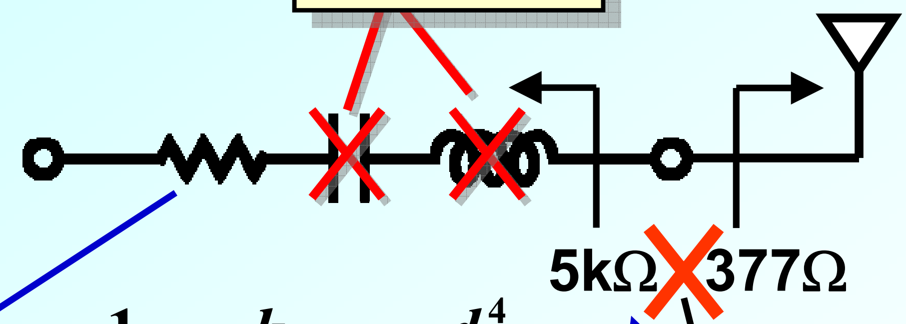


- MEMS Filters ⇨ excellent insertion loss
- ***Problem:*** high impedance & poor power handling

Impedance Matching
(Device Approach)

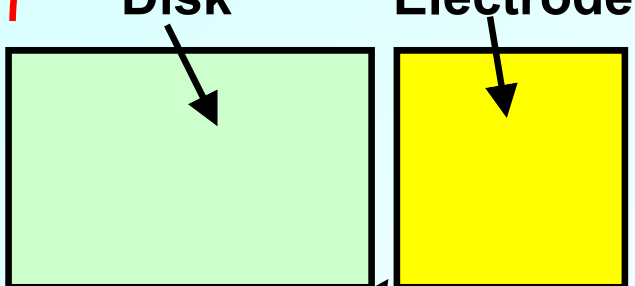
Solid Dielectric Capacitive Transducer





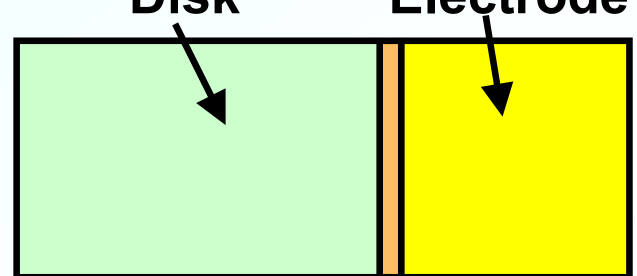
$$R_x = \frac{1}{(2\pi r)^2} \frac{k_r}{\omega_o Q} \cdot \frac{d^4}{\varepsilon^2 V_P^2 h^2}$$

Opportunity: **increase permittivity ε**
⇨ square law reduction in R_x



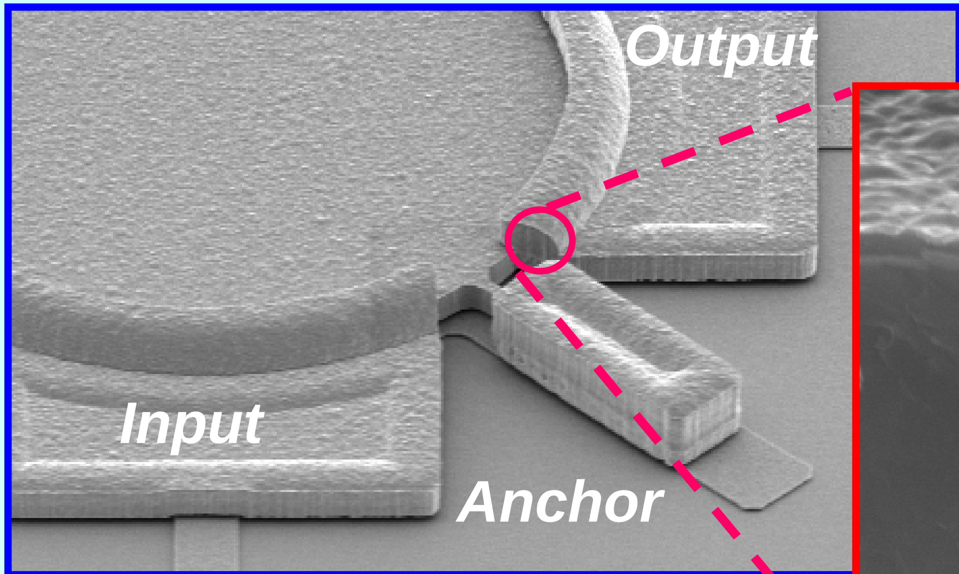
ΔGap ⇩ κ times
Permittivity ε ⇧ ε_r times

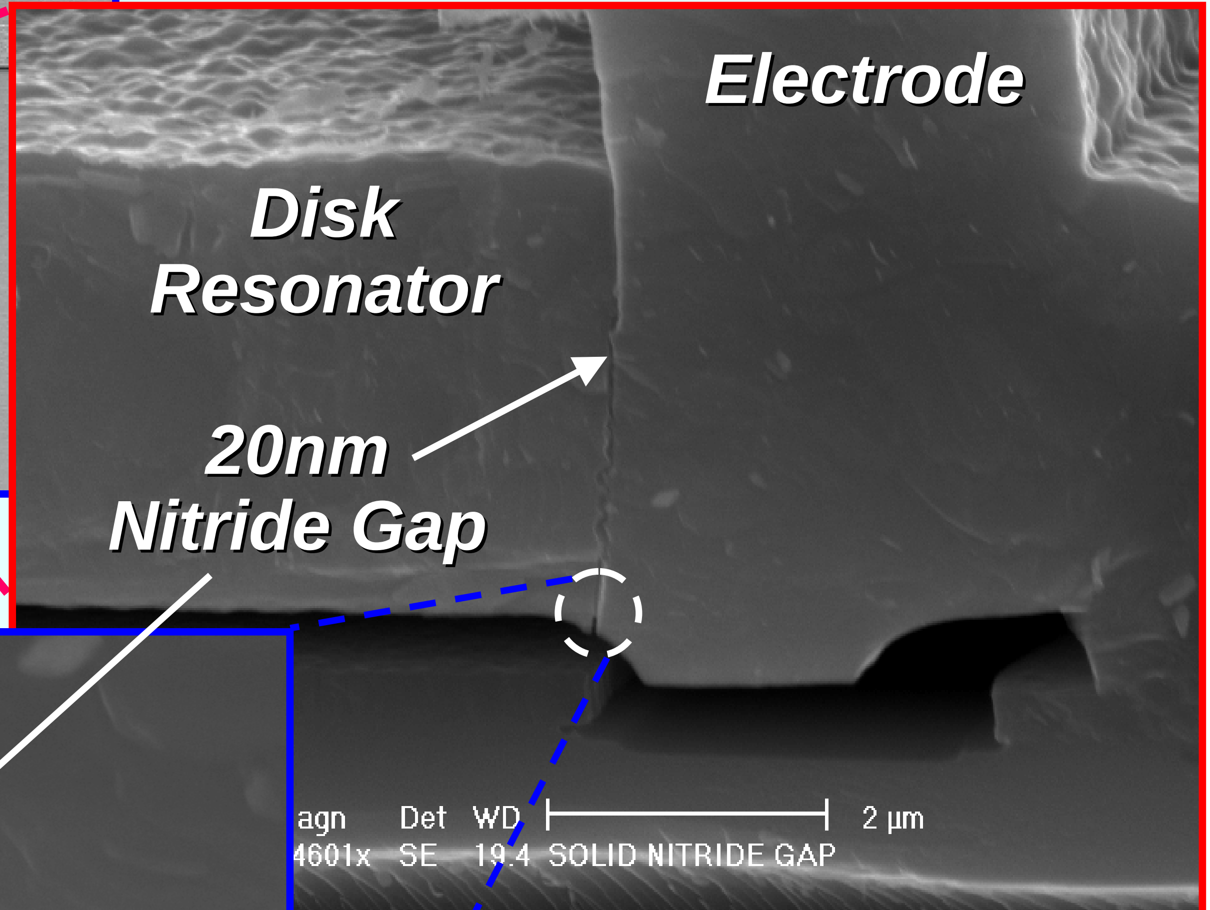
R_x ⇩ ε_r^2/κ times

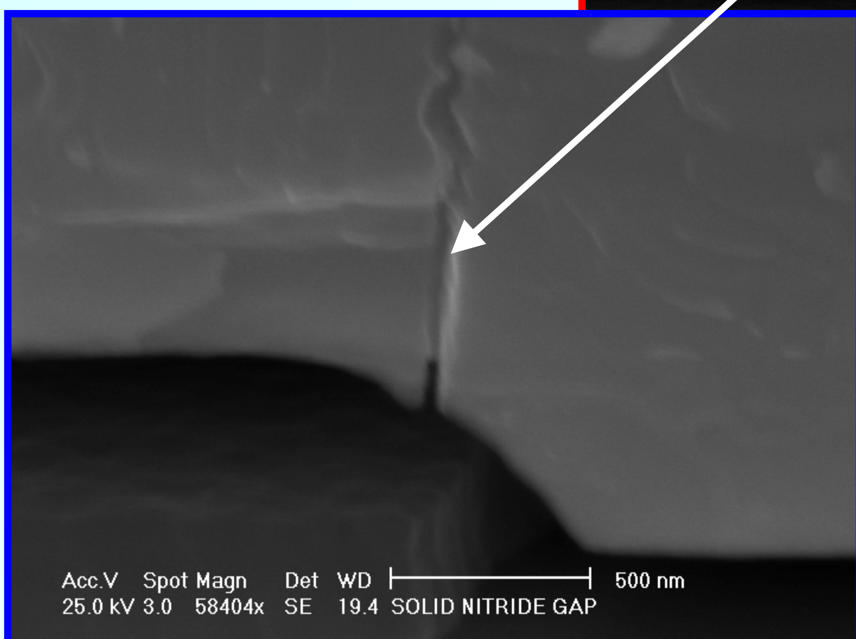


Tiny Lateral Solid-Dielectric Gaps

[Y.-W. Lin, C. Nguyen FCS'05]





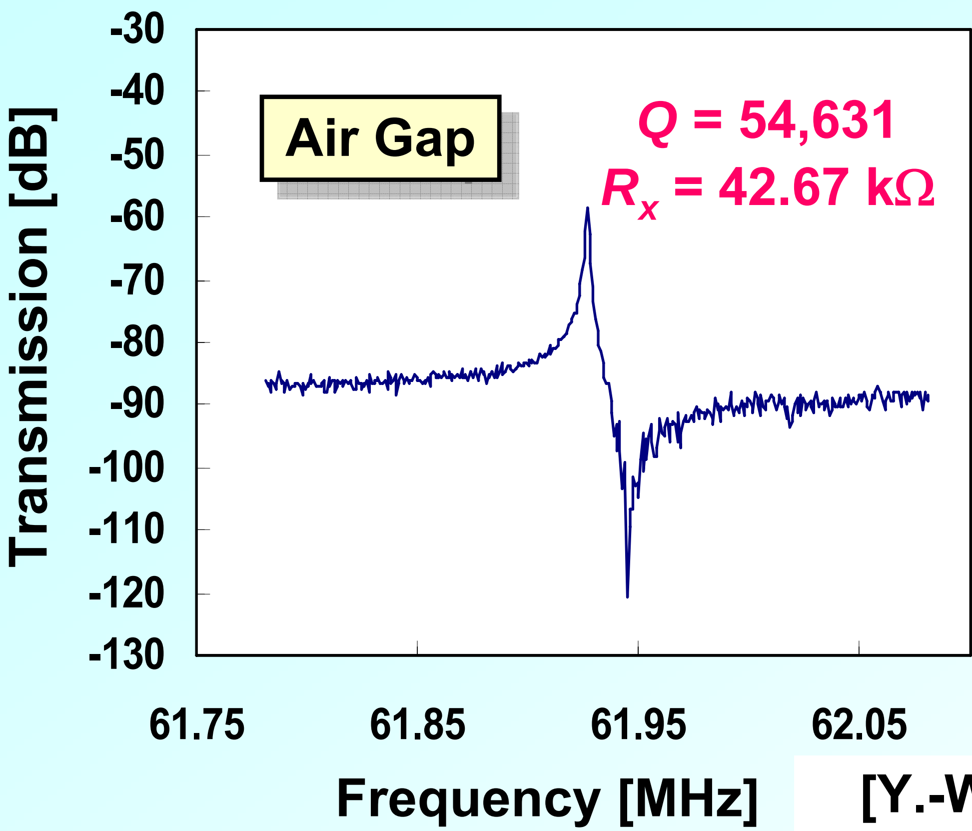


No small gap etch diffusion bottleneck ⇨ release step much faster than air gap case

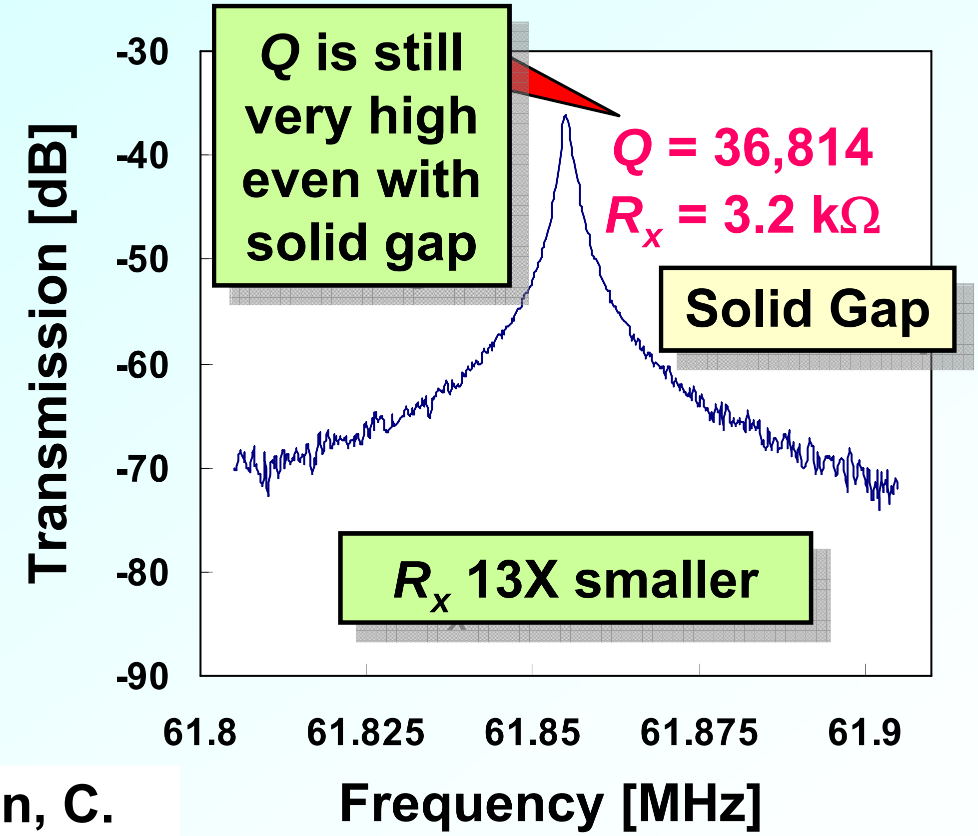
Air- vs. Solid-Gap Comparison

BSAC

60-MHz WG Disk w/ Air Gap



60-MHz WG Disk w/ Solid Gap



[Y.-W. Lin, C. Nguyen FCS'05]

60-MHz Wine-Glass Disk Data

In Vacuum, R = 32 μm, h = 3 μm

d_o = 80 nm (air gap)

V_P = 8 V, P_{in} = -10 dBm

f_o = 61.927 MHz

Resonance frequency remains virtually the same!

60-MHz Wine-Glass Disk Data

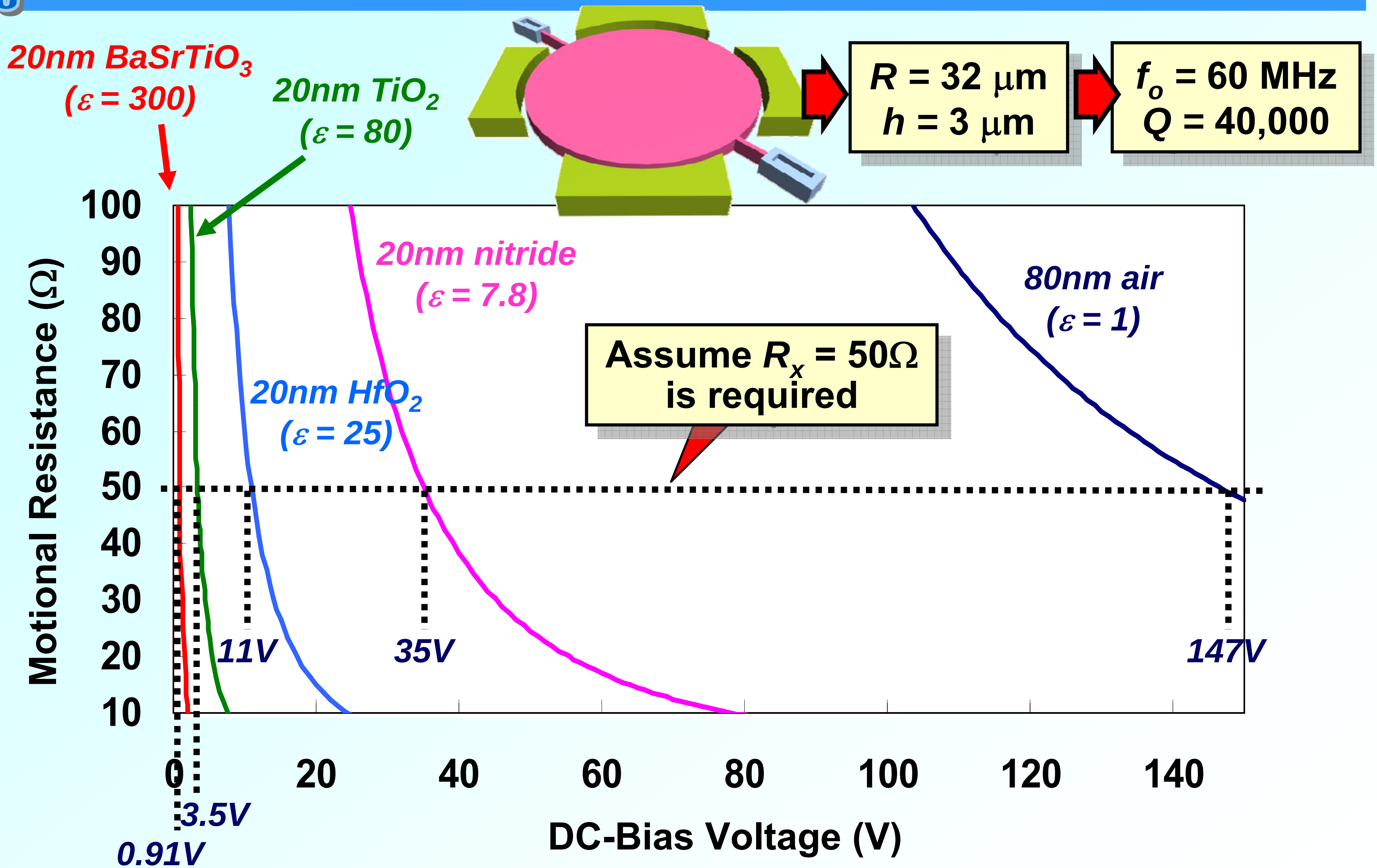
In Vacuum, = 32 μm, h = 3 μm

d_o = 20 nm (nitride gap)

V_P = 8 V, P_{in} = -30 dBm

f_o = 61.855 MHz

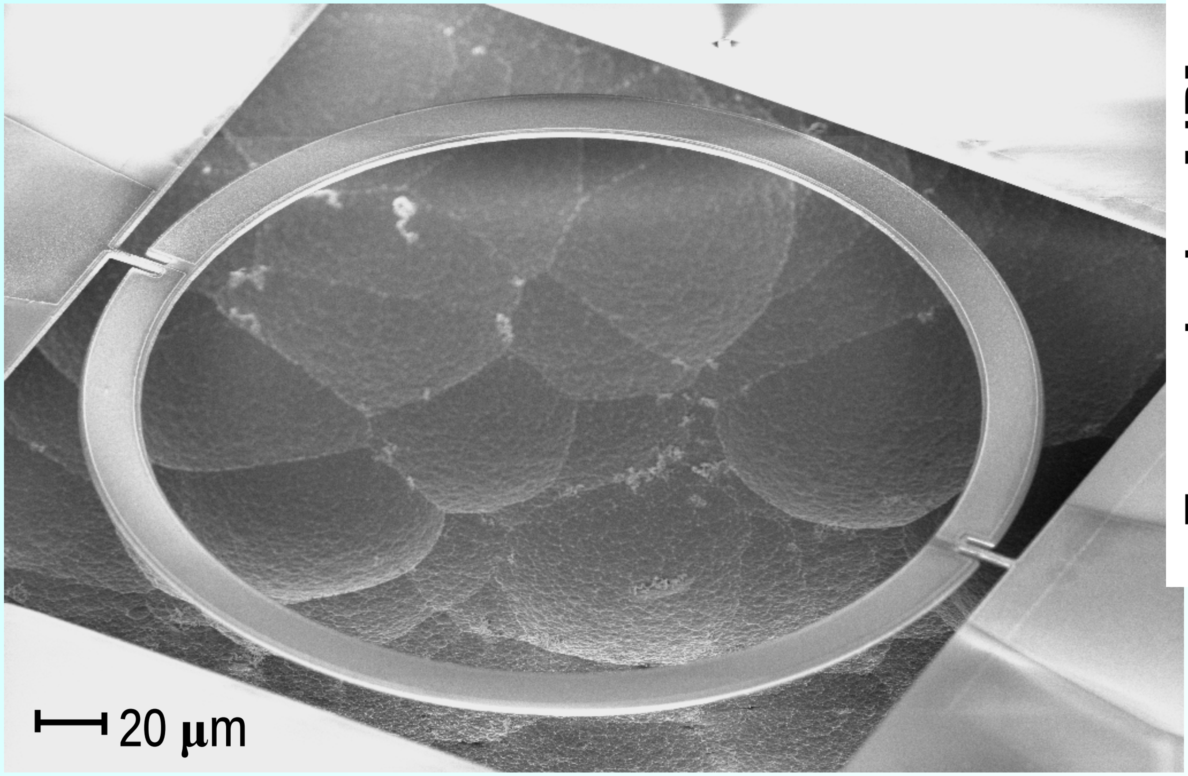
Benefit: Greatly Reduced DC-Bias



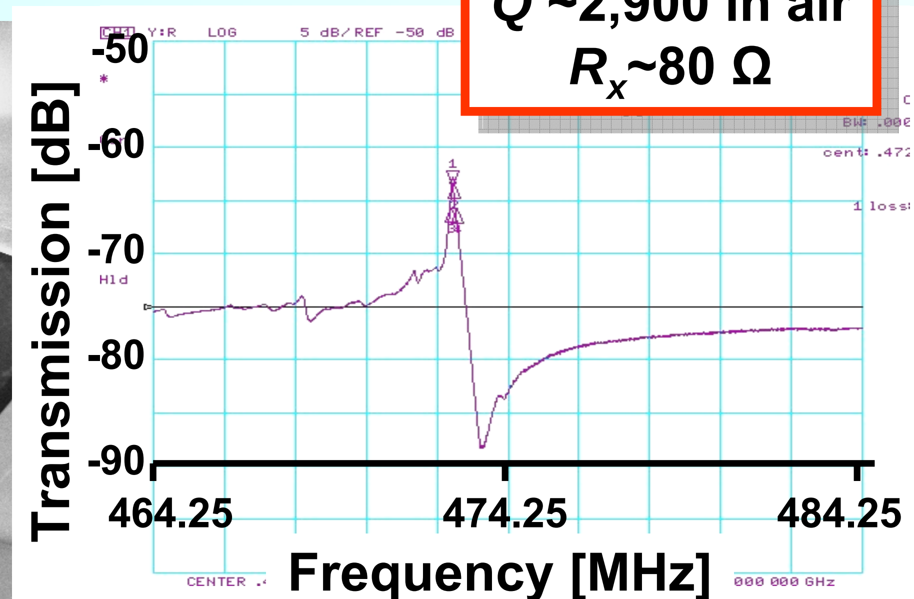
To achieve 50Ω impedance, the DC-Bias voltage can be reduced from 147V to 0.91V using solid gap technology

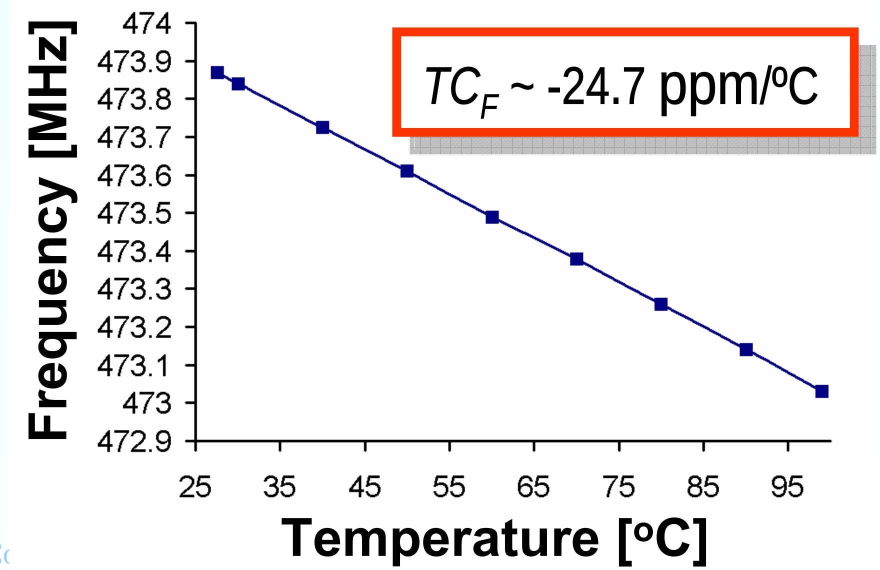
Piezoelectric μMechanical Resonators

- **Contour-mode, ring-shaped AlN Resonators**
- **Driven laterally via the d_{31} coefficient**



[Piazza, Pisano MEMS'05]

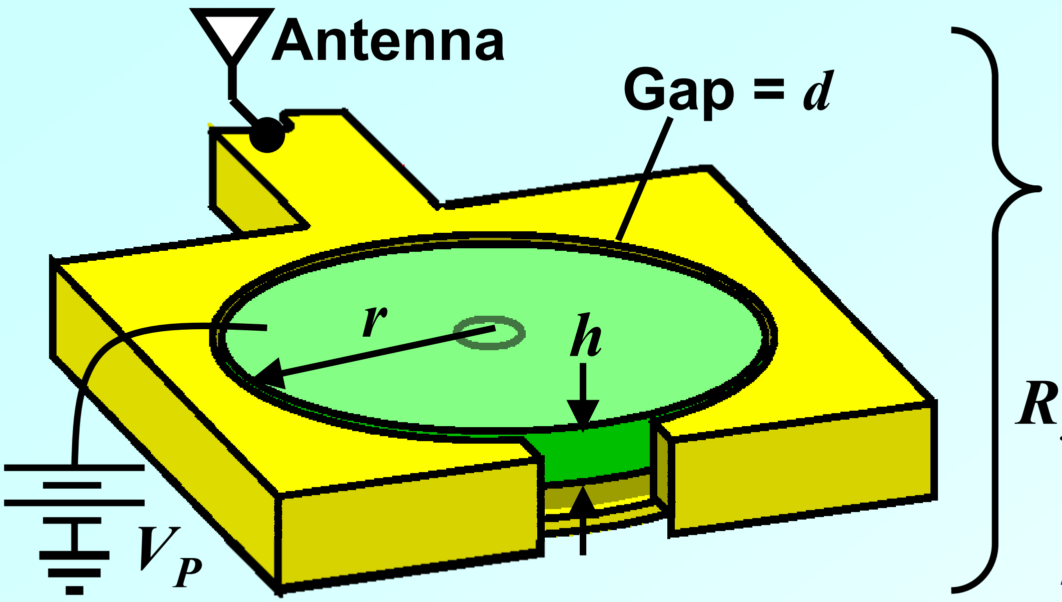




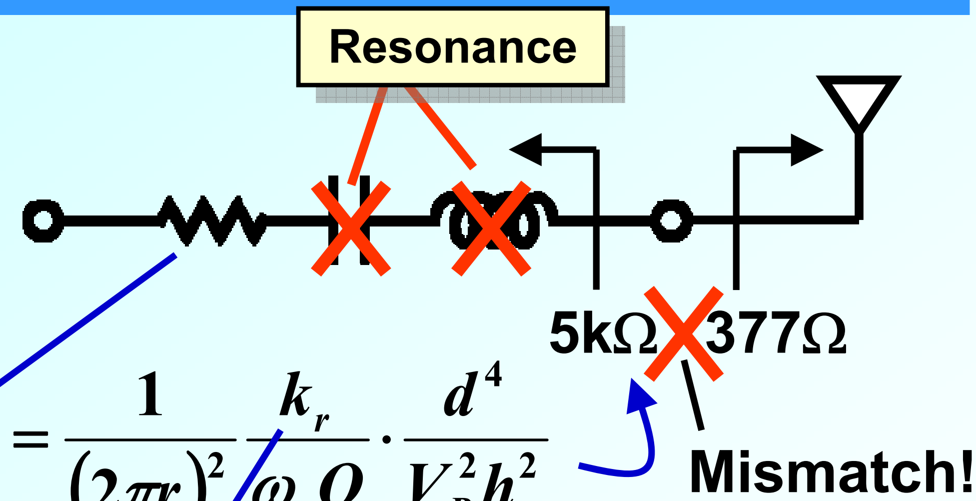
- **Freqs. up to 473 MHz (so far) determined by lateral dimensions!**
- ***Q*'s sufficient for pre-select filters**

Impedance Matching
(Mechanical Circuit Approach)

Issue: Impedance Matching



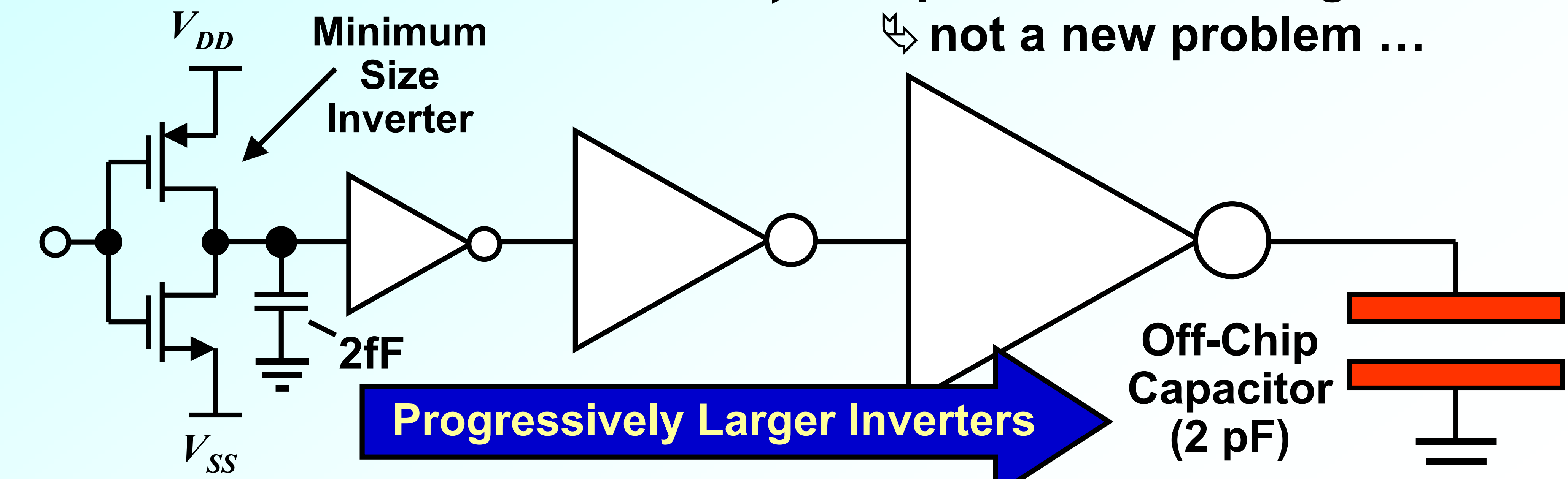
μMechanical Disk Resonator



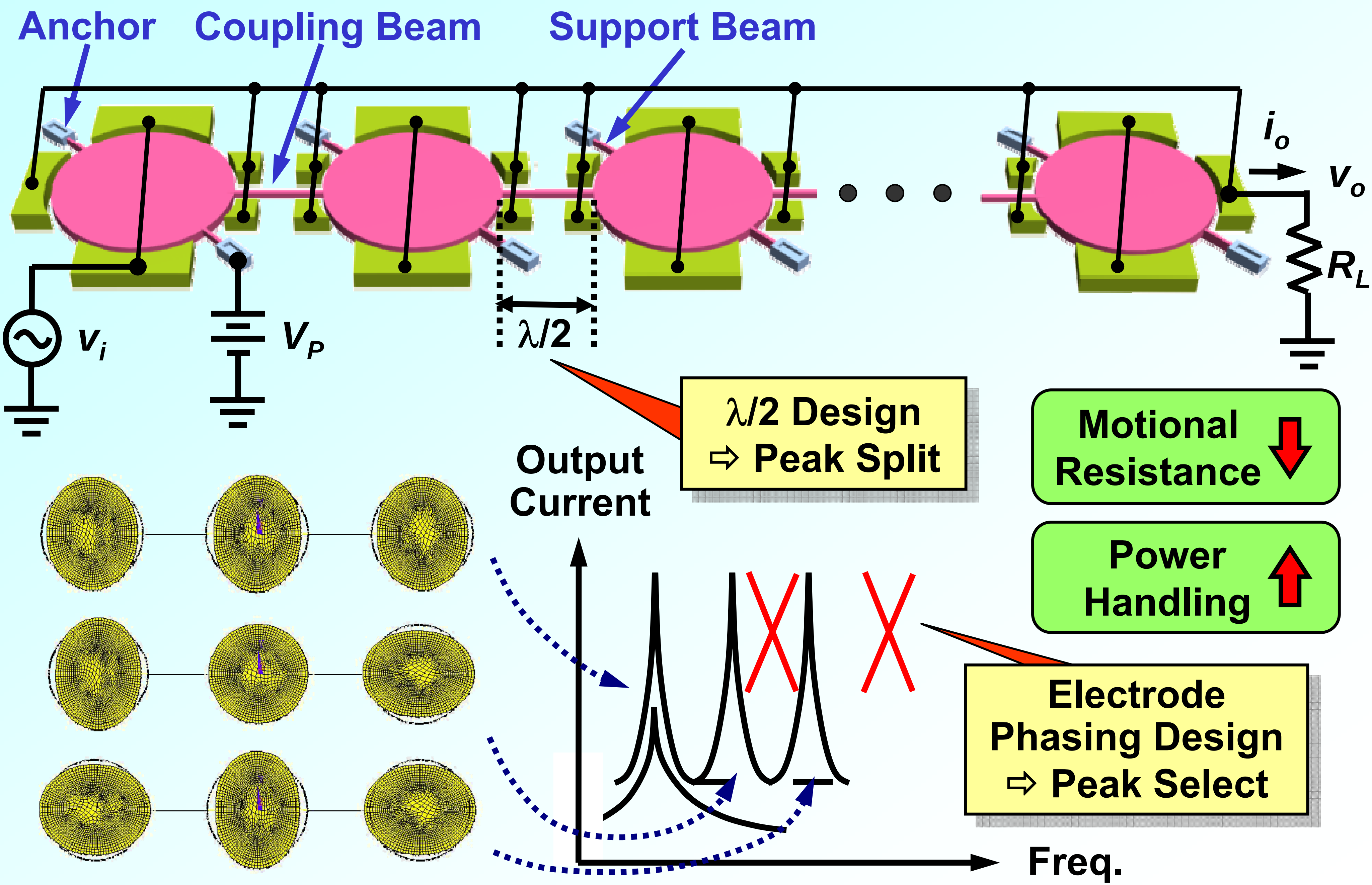
$$R_x = \frac{1}{(2\pi r)^2} \frac{k_r}{\omega_o Q} \cdot \frac{d^4}{V_P^2 h^2}$$

k_r = 7,350,000 N/m

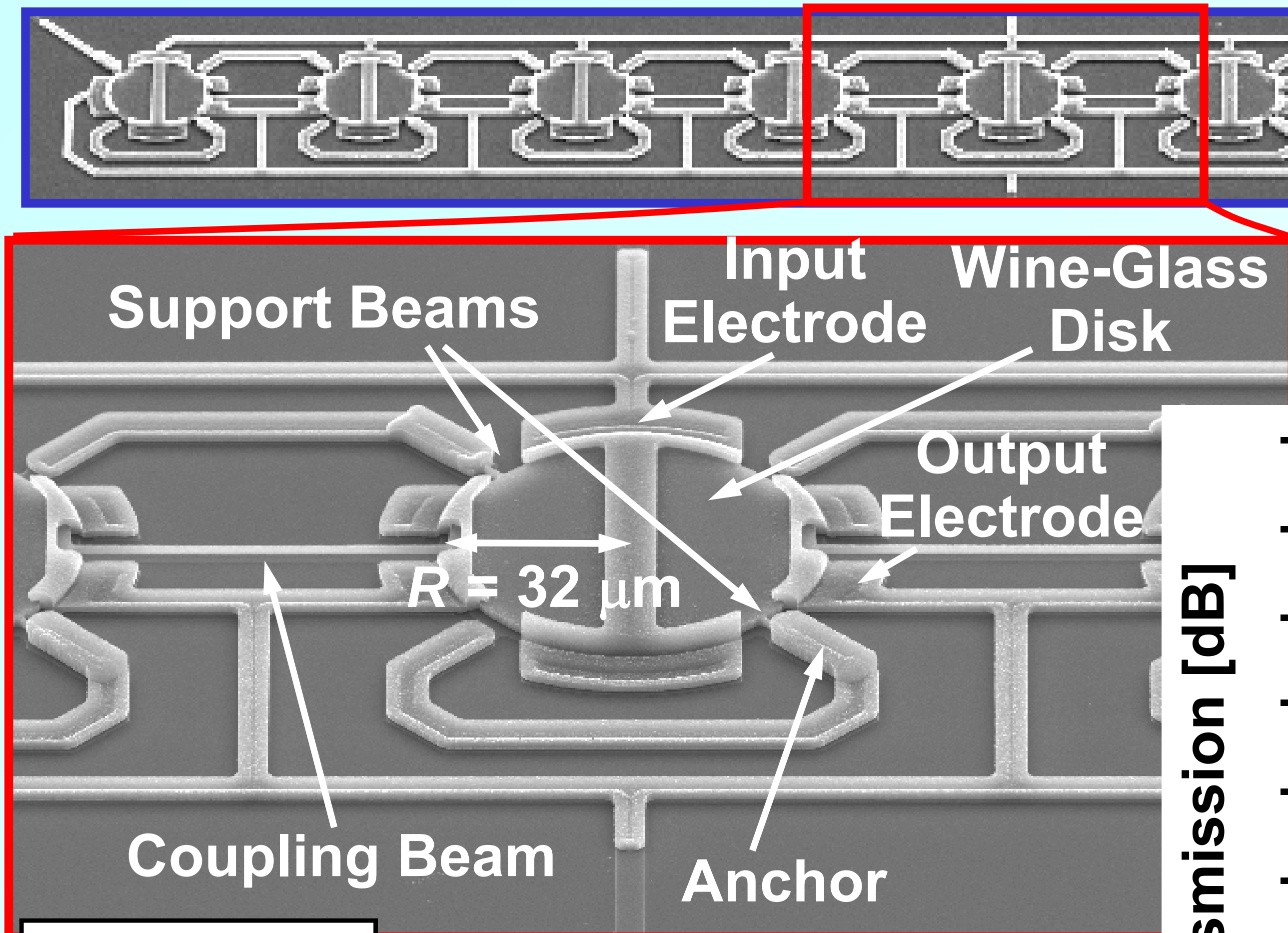
- Impedance matching needed
  - not a new problem …

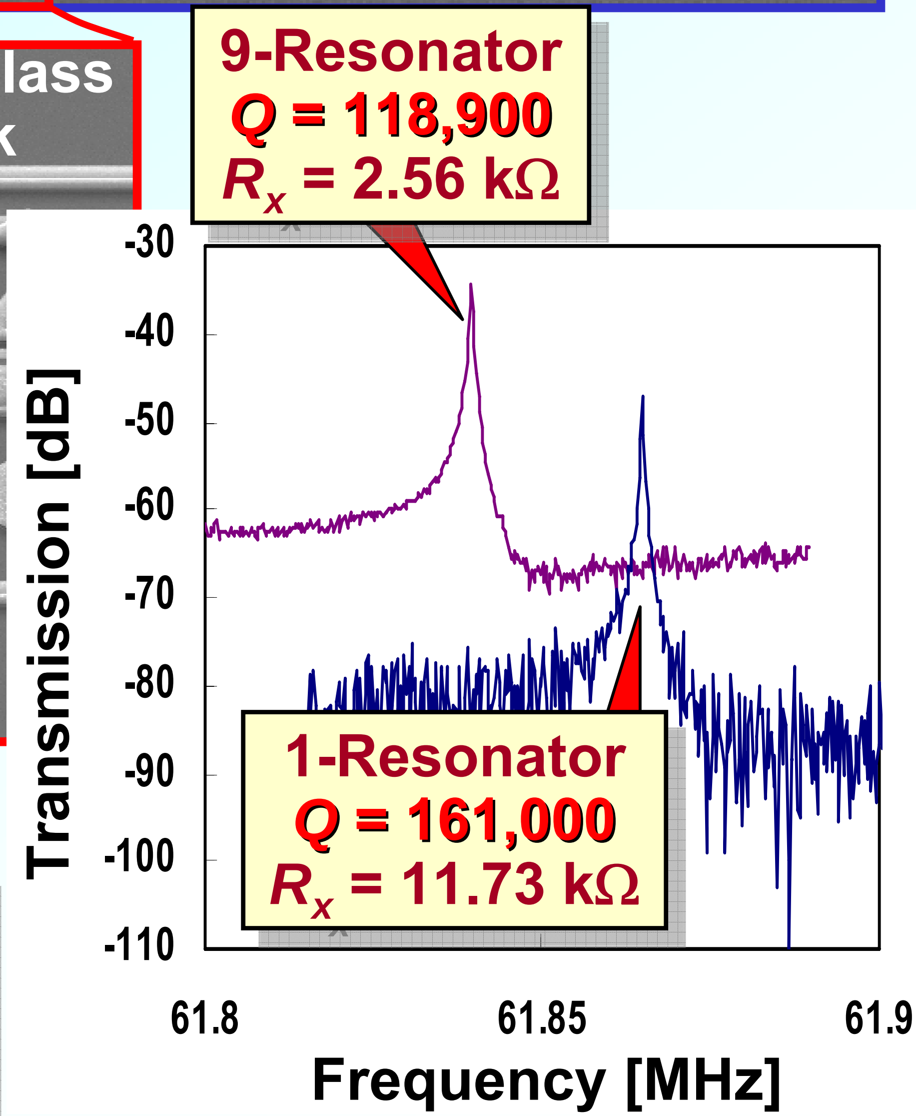


Impedance Reduction Via Arraying



9-Wine-Glass Disk Composite Array





Data

$R = 32\ \mu m$

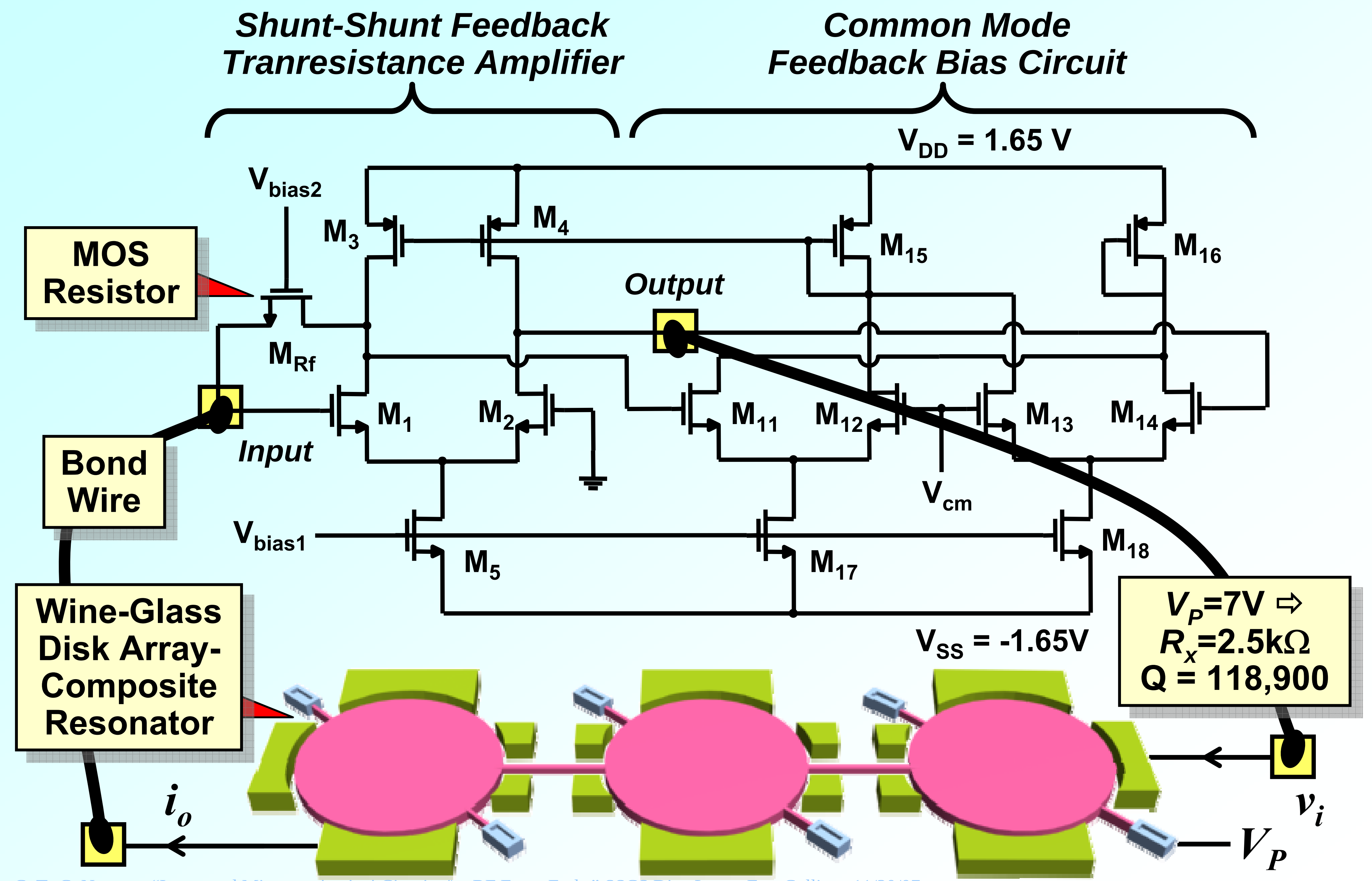
$h = 3\ \mu m$

$d = 80\ nm$

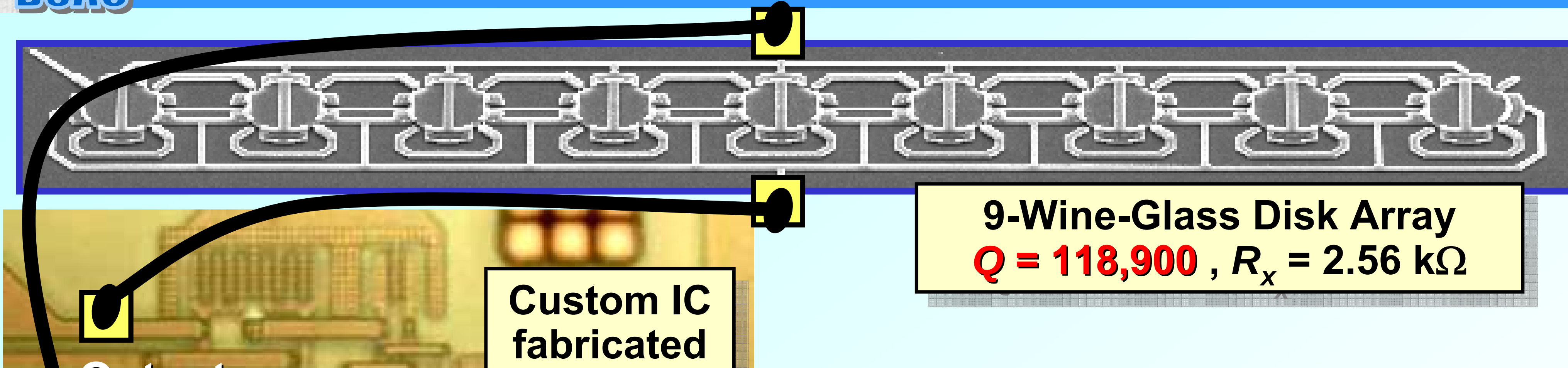
$V_P = 7\ V$

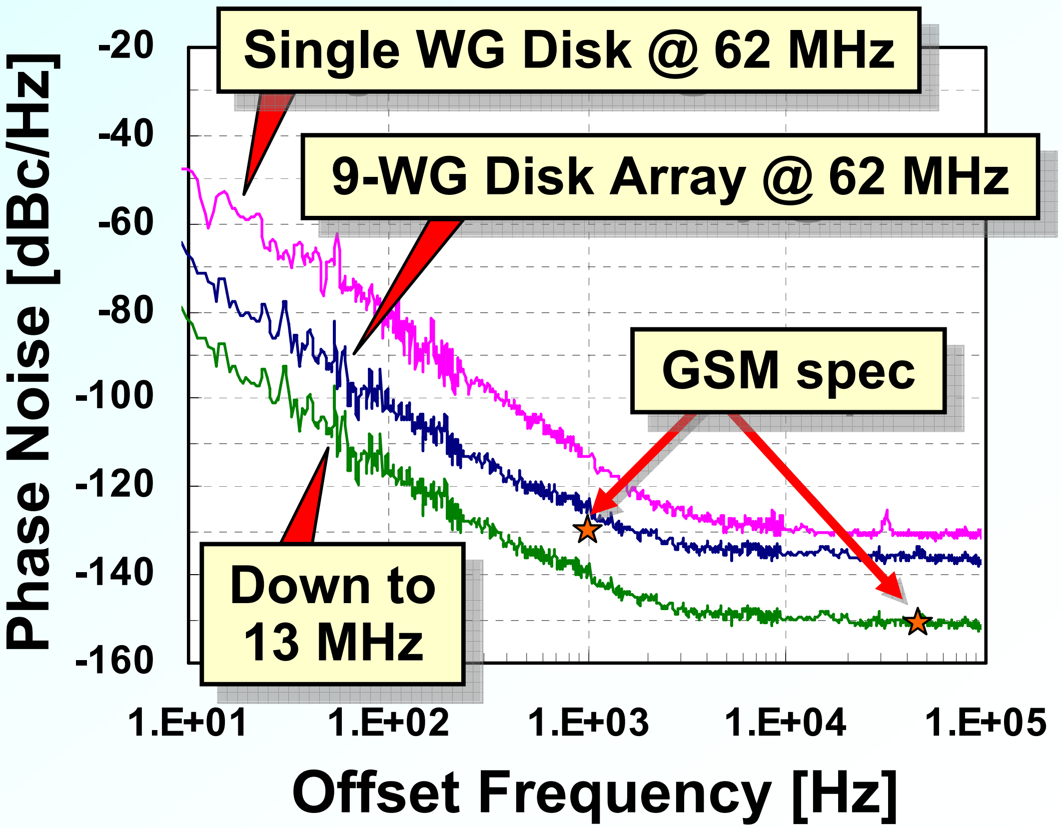
Wine-glass disks retain *Q*'s >100,000 even in large arrays!

Wine Glass Disk Array Oscillator



GSM-Compliant Oscillator

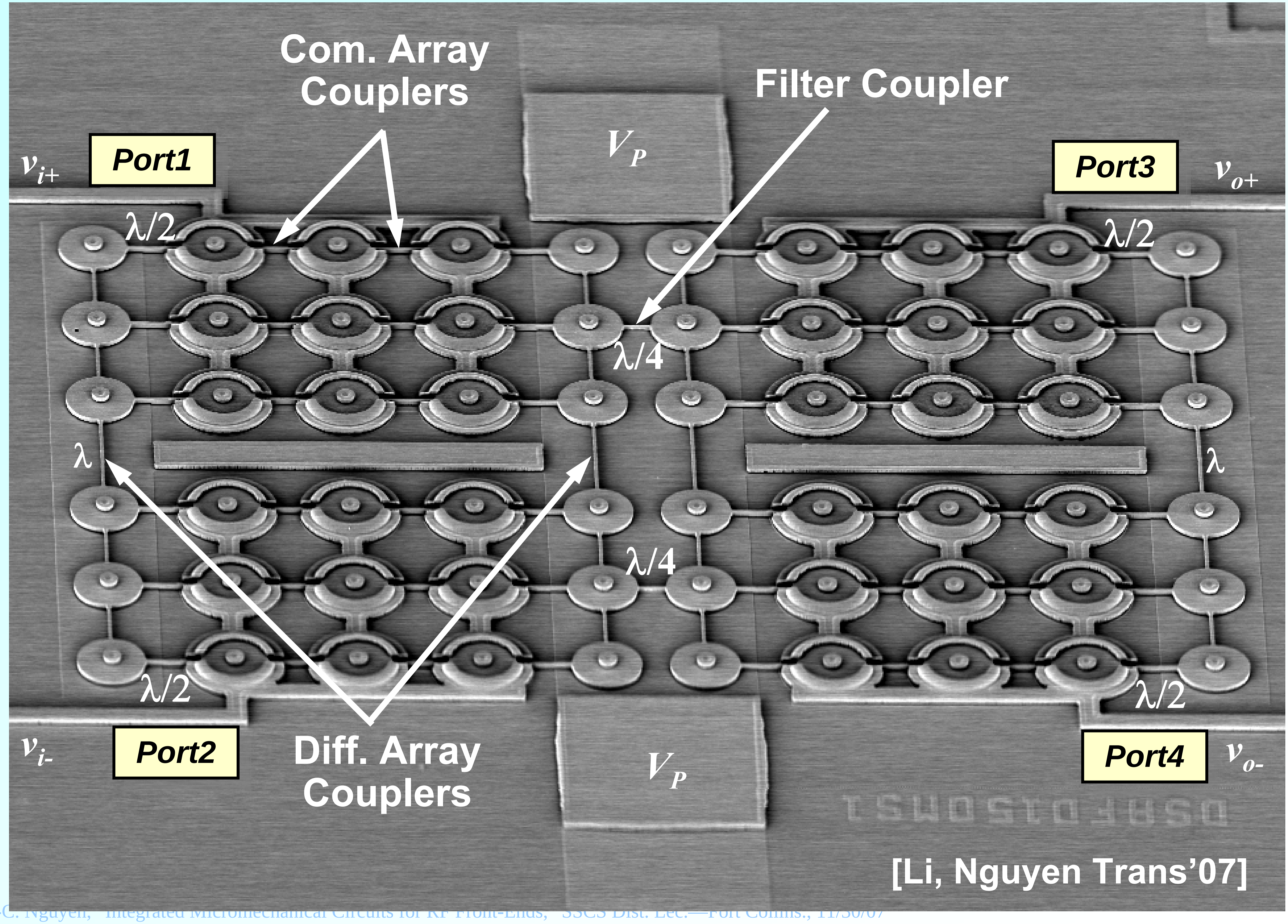




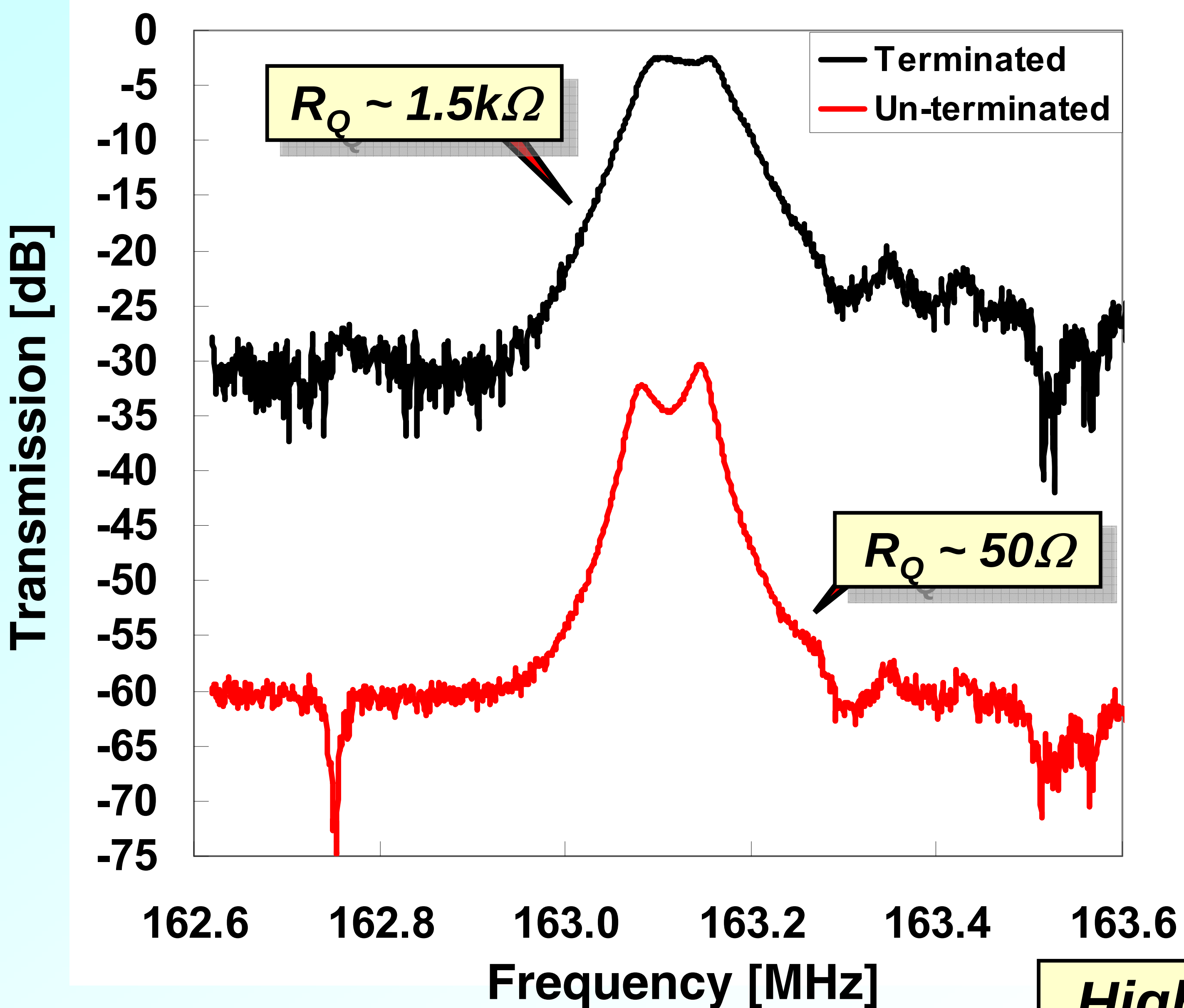
Satisfies Global System for Mobile Communications (GSM) phase noise specifications!

All made possible by *mechanical* circuit design!

163-MHz Differential Disk-Array Filter



Measured Filter Freq. Characteristics



Performance

r=17μm

h=3μm

d_o=80nm

V_P=14V

P=-15dBm

f_o=163.126MHz

Q_{res}=10,500

R_x=977Ω

BW=98.477kHz

P_{BW}=0.06%

I.L.=2.43dB

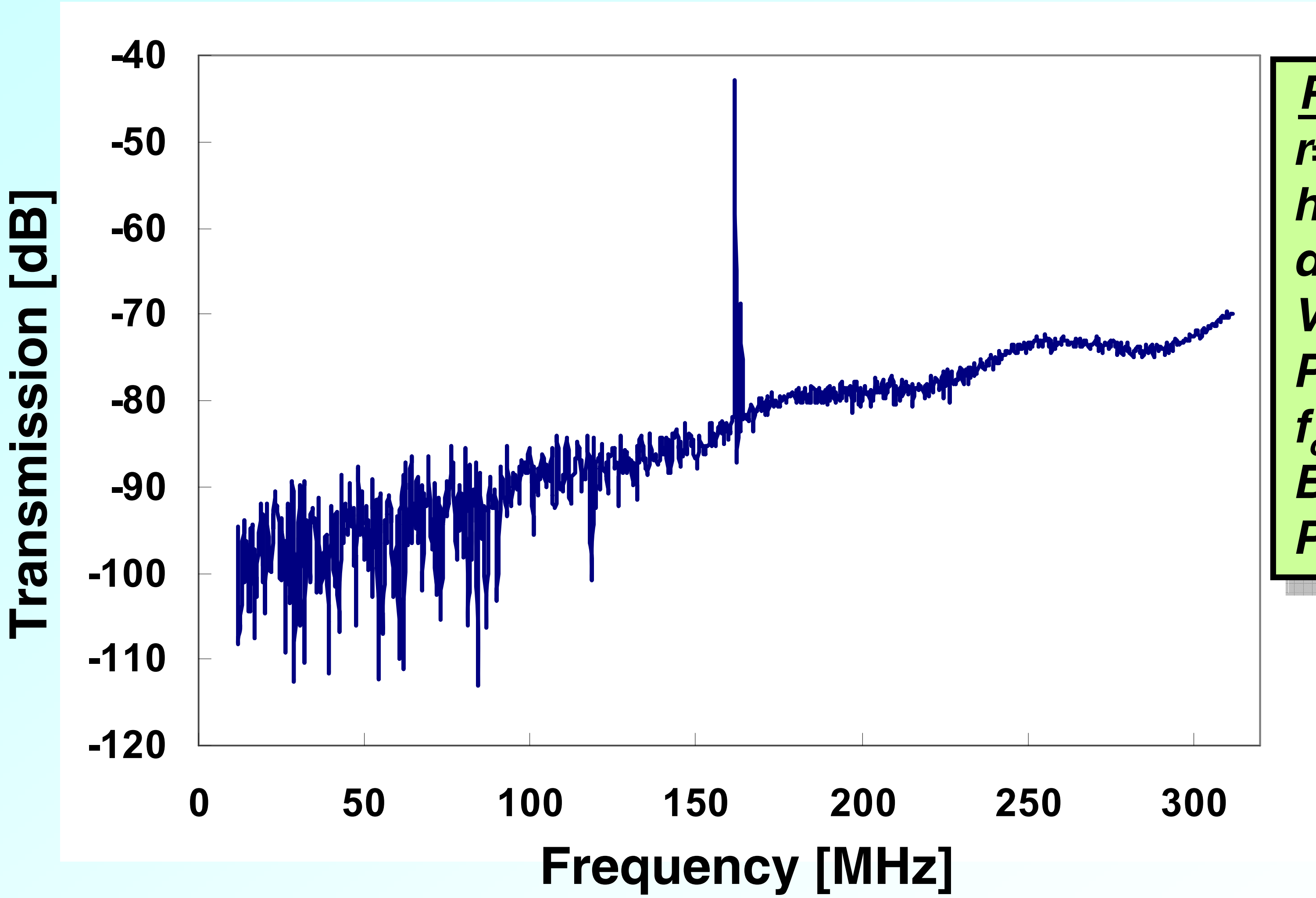
20dB S.F.=2.85

$R_{Q1}=R_{Q2}$=1.6kΩ

$R_{Q3}=R_{Q4}$=1.4kΩ

High Q & Low R_X

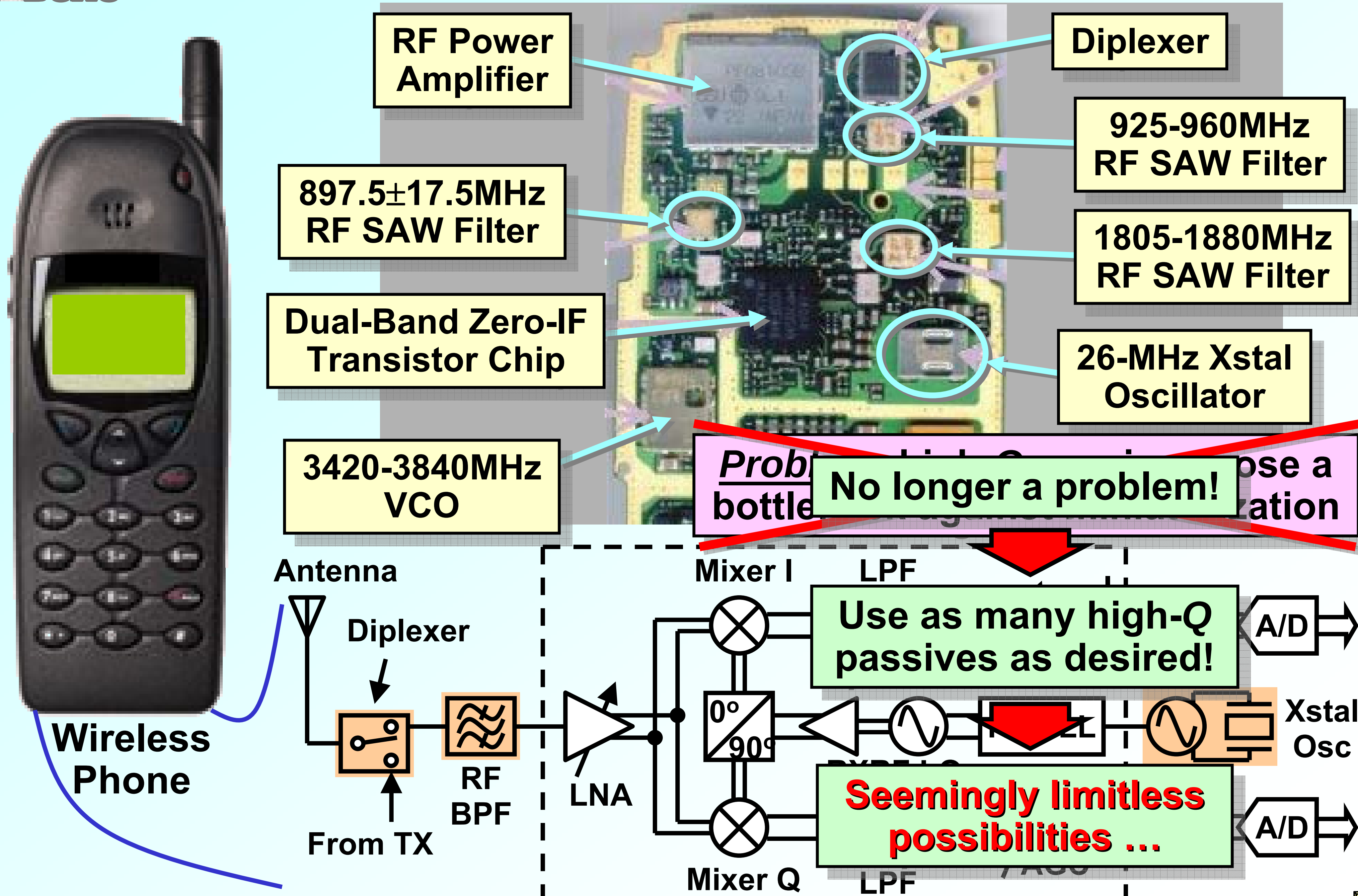
Filter Measurement Over 300MHz Span



Performance
r=17μm
h=3μm
d_o=80nm
V_P=8V
P=-15dBm
f_o=163.126MHz
BW=98.477kHz
P_{BW}=0.06%

No Spurious Modes

So Many Passive Components!

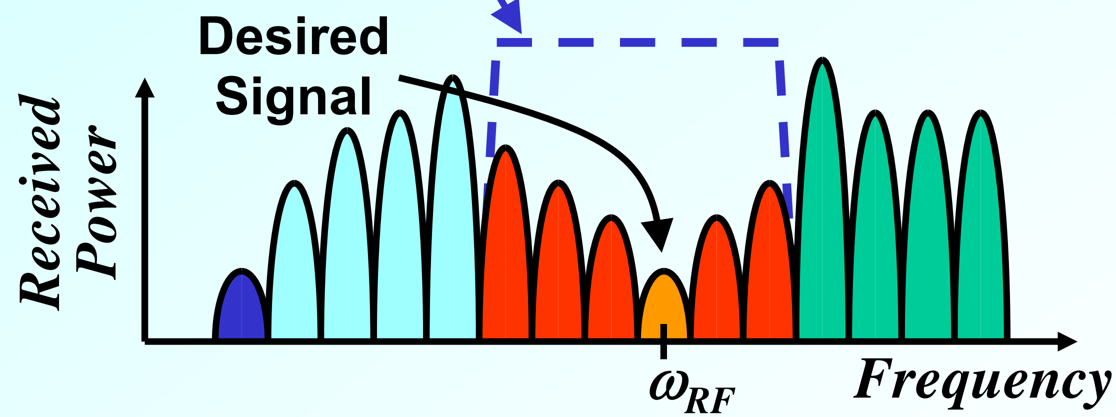


RF Channel Selection

Motivation: Need for High *Q*

The higher the *Q* of the Pre-Select Filter ⇨ the simpler the demodulation electronics

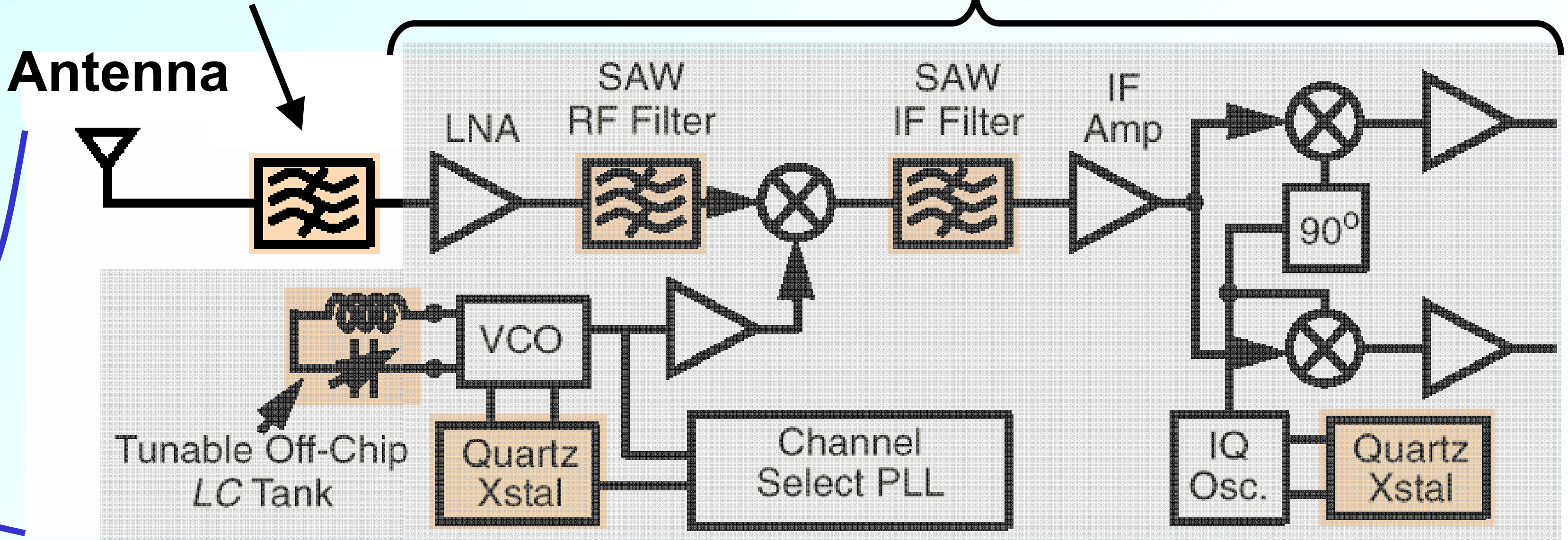
Presently use resonators with *Q*'s ~ 400



Wireless Phone

Pre-Select Filter in the GHz Range

Demodulation Electronics



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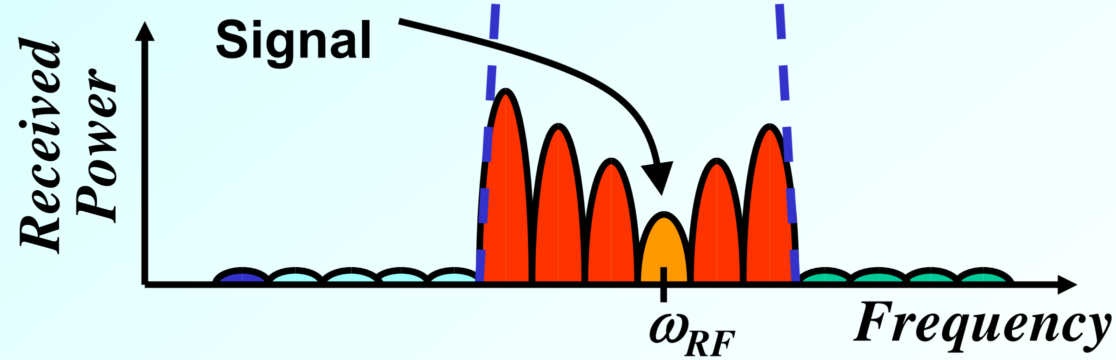
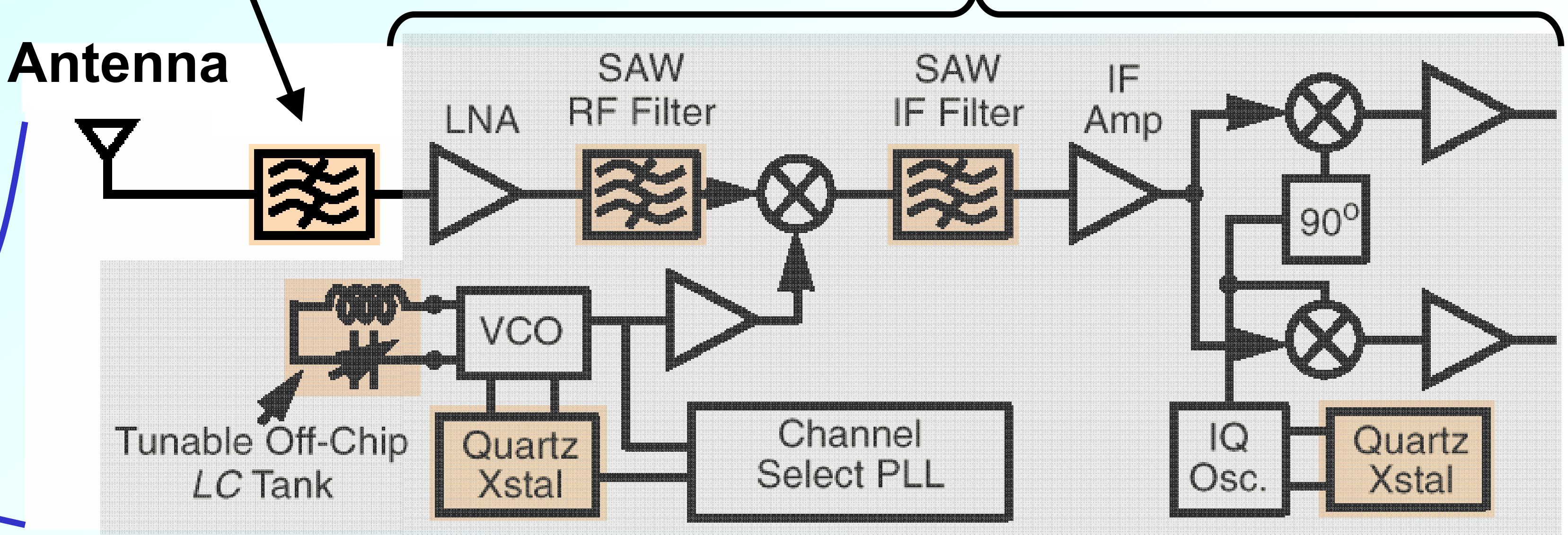


Wireless Phone

Pre-Select Filter in the GHz Range

Demodulation Electronics

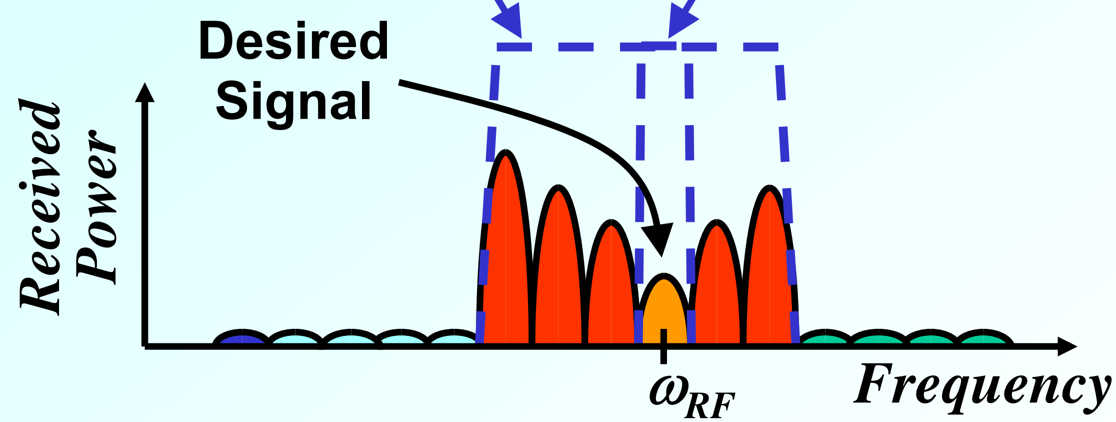


Motivation: Need for *Q*'s > 10,000

The higher the *Q* of the Pre-Select Filter ⇨ the simpler the demodulation electronics

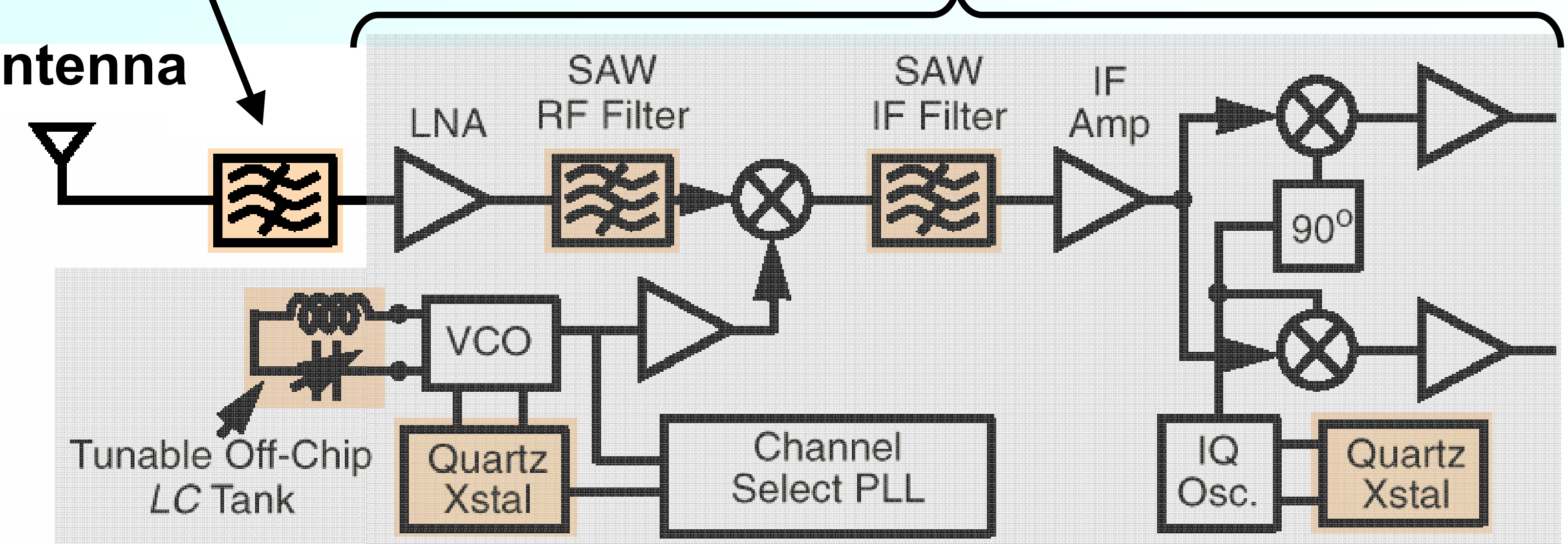
Presently use resonators with *Q*'s ~ 400

If can have resonator *Q*'s > 10,000



Pre-Select Filter in the GHz Range

Demodulation Electronics



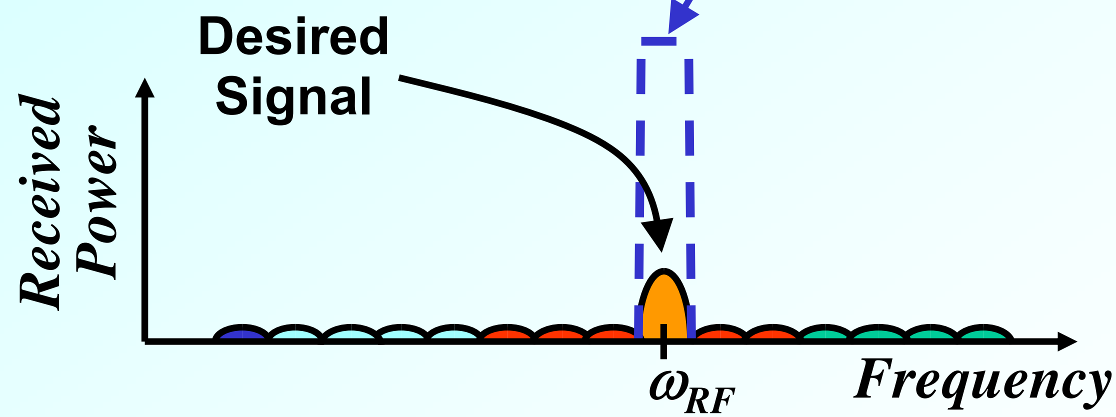
Wireless Phone

Motivation: Need for *Q*'s > 10,000

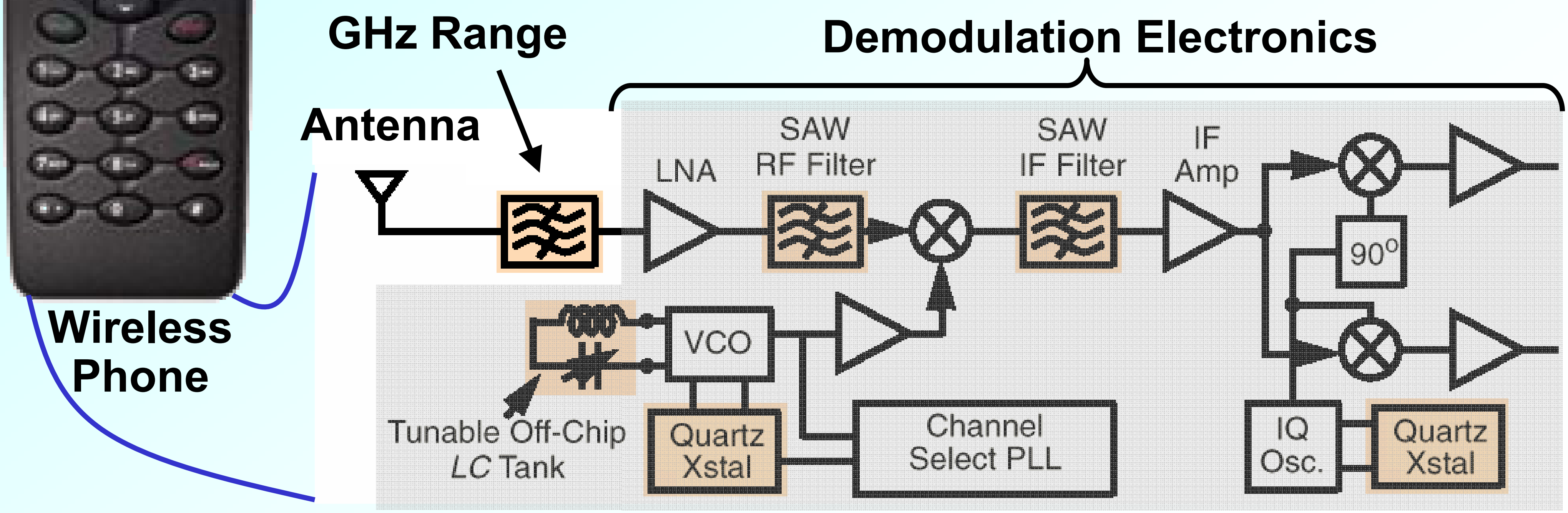
The higher the *Q* of the Pre-Select Filter ⇨ the simpler the demodulation electronics

Presently use resonators with *Q*'s ~ 400

If can have resonator *Q*'s > 10,000



Pre-Select Filter in the GHz Range



Motivation: Need for *Q*'s > 10,000

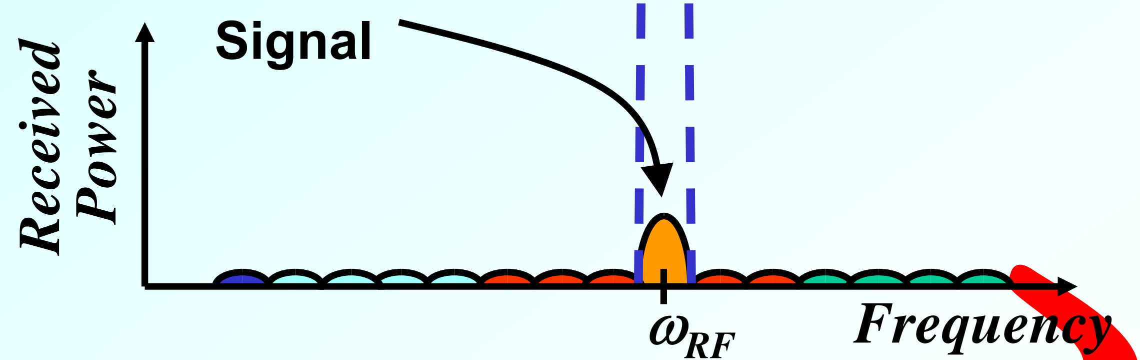
BSAC

Wireless Phone

The higher the *Q* of the Pre-Select Filter ⇨ the simpler the demodulation electronics

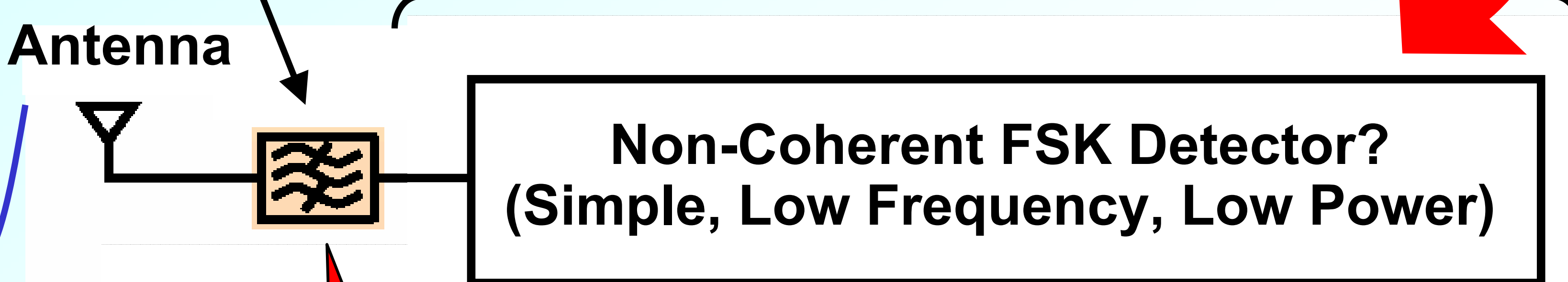
Presently use resonators with *Q*'s ~ 400

If can have resonator *Q*'s > 10,000



Pre-Select Filter in the GHz Range

Demodulation Electronics



Front-End RF Channel Selection

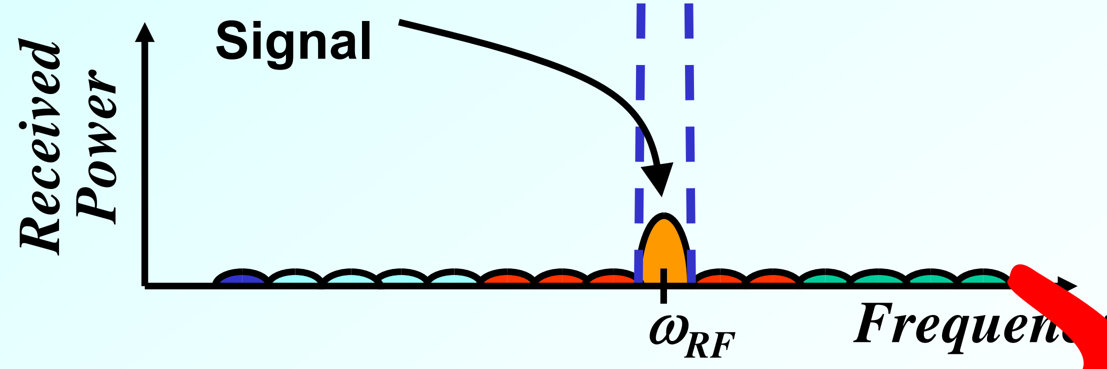
Substantial Savings in Cost and Battery Power

Motivation: Need for *Q*'s > 10,000

The higher the *Q* of the Pre-Select Filter ⇨ the simpler the demodulation electronics

Presently use resonators with *Q*'s ~ 400

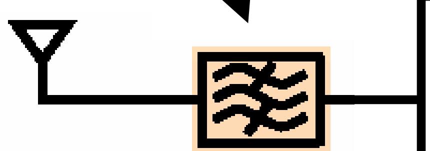
If can have resonator *Q*'s > 10,000



Demodulation Electronics

Pre-Select Filter in the GHz Range

Antenna

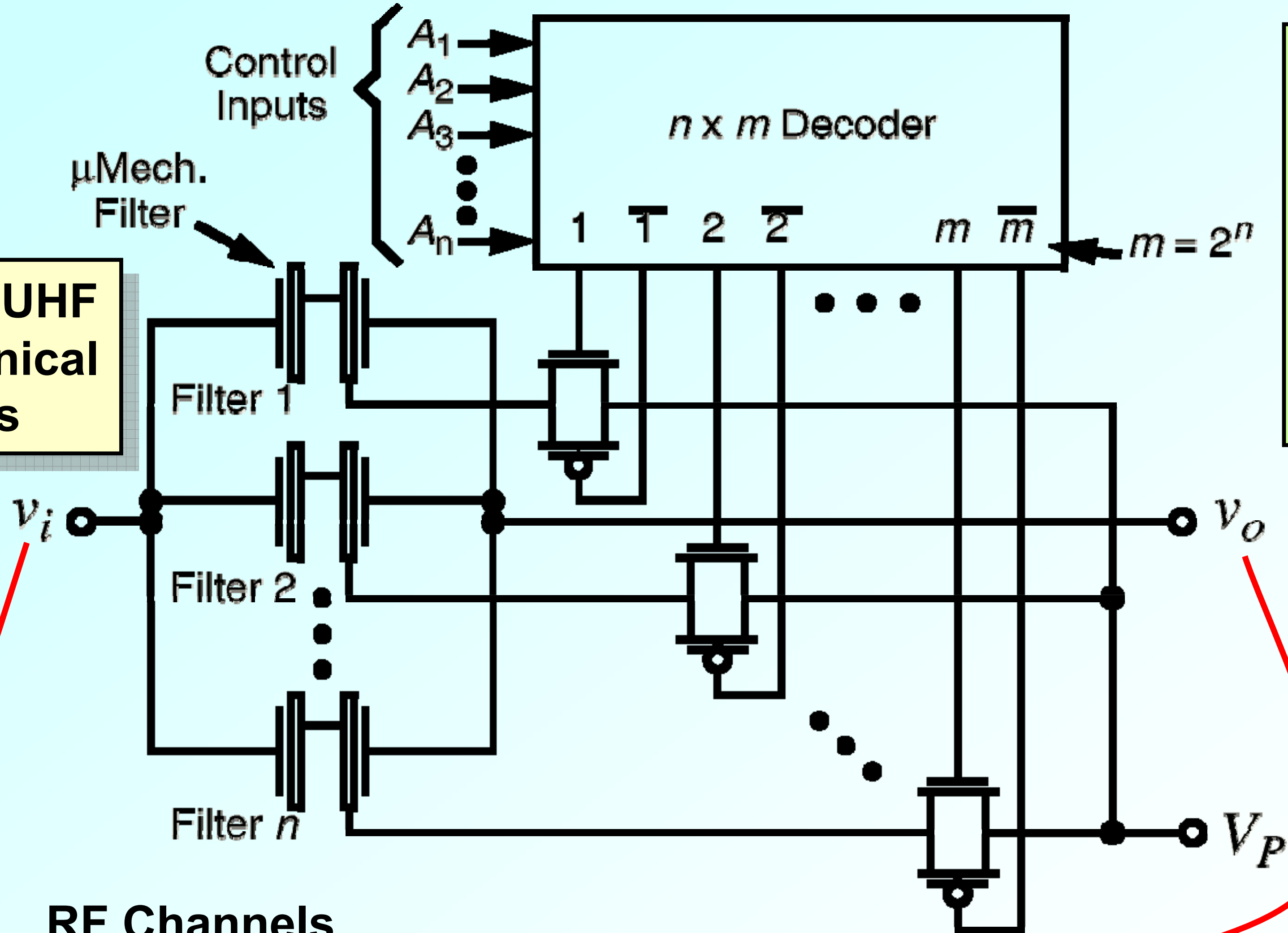


Direct-Sampling A/D Converter ⇨ Software-Defined Radio

Front-End RF Channel Selection

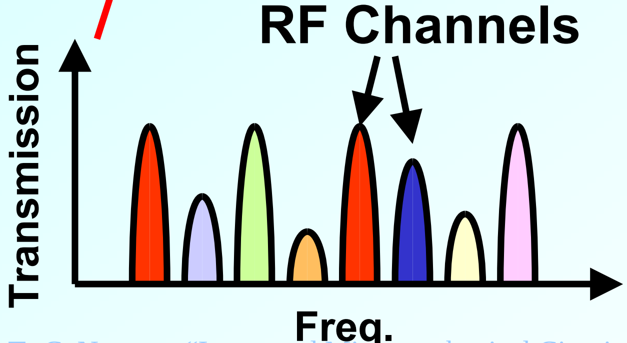
Maximum Flexibility ⇨ one circuit satisfies all comm. standards

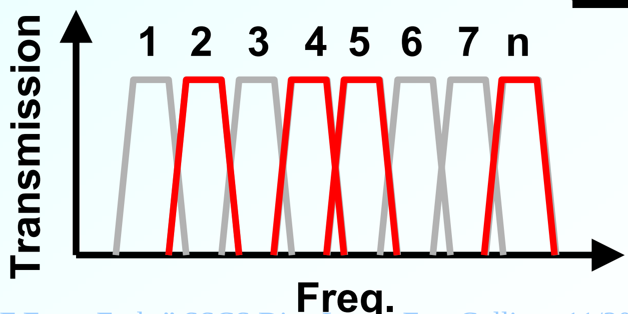
RF Channel-Select Filter Bank

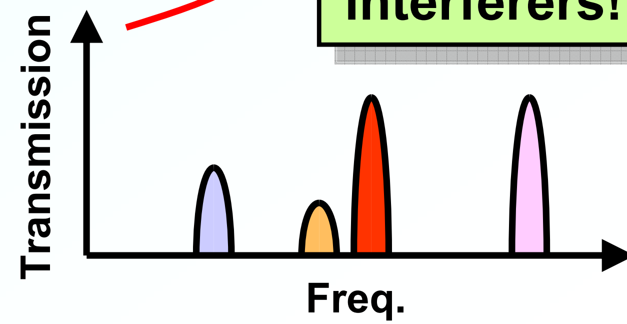


Bank of UHF µmechanical filters

Switch filters on/off via application and removal of dc-bias V_P, controlled by a decoder







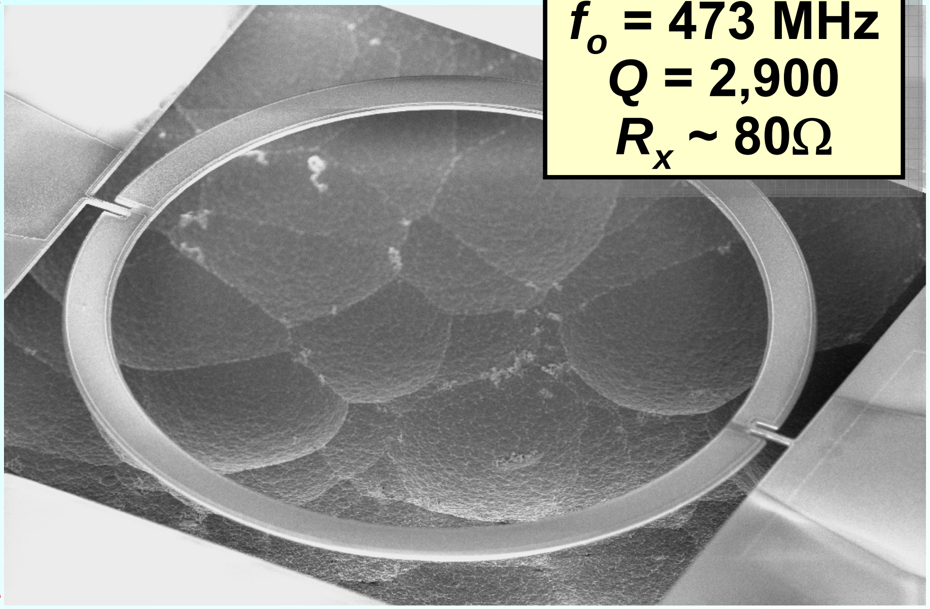
Remove all interferers!

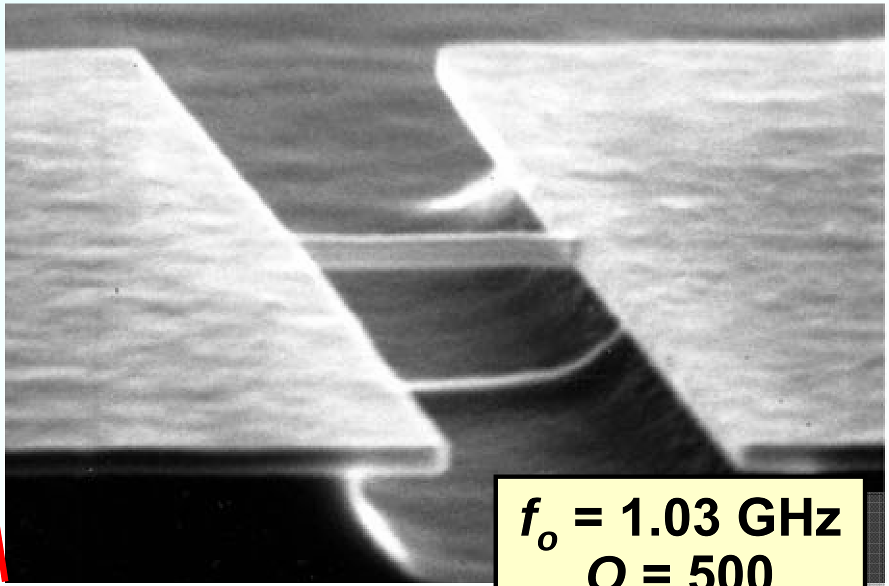
Conclusions

- **Vibrating RF MEMS have achieved**
  - Q's >10,000 at GHz frequencies in sizes less than 20 μm in diameter and w/o the need for vacuum encapsulation
  - TC_f's < -0.24 ppm/°C (better than quartz)
  - aging at least on par with quartz
  - circuit-amenable characteristics
  - VLSI potential
- **Time to turn our focus towards mechanical circuit design and mechanical integration**
  - maximize, rather than minimize, use of high-*Q* components
  - e.g., RF channelizer ⇨ paradigm-shift in wireless design
  - even deeper ⇨ frequency domain computation
- ***Need***:
  - automated design tools for LSI and higher
  - single-chip integrability with transistor circuits
  - methods for frequency positioning
  - continued scaling to nano-dimensions ⇨ >10 GHz …
- **Beginnings of a revolution reminiscent of the IC revolution?**

Growing Vibrating RF MEMS Research

- ***UC Berkeley***:
  - Clark Nguyen, Al Pisano
  - capacitive & AlN resonators
- ***Hughes Research***:
  - Randy Kubena
  - quartz resonators
- ***Cal Tech***:
  - Michael Roukes
  - nanomechanical resonators
- ***Georgia Tech***:
  - Farrokh Ayazi
  - SOI resonators
- ***Stanford***:
  - Tom Kenny, Roger Howe
  - epi/SOI, SiGe resonators





Acknowledgments

- Former graduate students, especially
  - Prof. Jing Wang, now at the Univ. of South Florida
  - Dr. Sheng-Shian Li, now at RF Microdevices
  - Dr. Yu-Wei Lin, now at Broadcom
- Much of the work shown was funded by grants from DARPA and by an NSF ERC in Wireless Integrated Microsystems