LESSON 5 – MEMS Resonators

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Advanced NEMS Lab (ANEMS)

EPFL-IGM NEMS

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Course content and schedule

Dates	Lectures	Lecturers	Mean
20.02	Introduction Transducers review: pre-recorded lectures	D. Briand / G. Villanueva	Live
27.02	Sensors part I Exercices	D. Briand	Live
05.03	Sensors part II Industrial seminar #1	D. Briand	Live
12.03	Students presentations	D. Briand / G. Villanueva	Live
19.03	Actuators and Optical MEMS Industrial seminar #2	D. Briand	Live
26.03	Acoustic and Ultrasonic MEMS Industrial seminar #3	G. Villanueva	Live
09.04	Acoustic and Ultrasonic MEMS	G. Villanueva	Live
16.04	RF-MEMS NEMS	G. Villanueva	Live
23.04	Interactive session	D. Briand / G. Villanueva	Live
30.04	Thermal and gas sensors Industrial seminar #4	D. Briand	Live
07.05	Packaging	D. Briand	Live
14.05	Packaging Industrial seminar #5	D. Briand	Live
21.05	PowerMEMS	D. Briand	Live
28.05	Quiz + oral exam instructions Evaluation of the course	All	Live

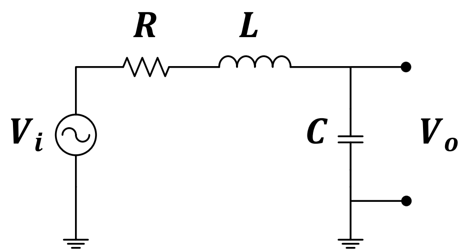
Contents

What is a Resonator?

- **Wikipedia says…**

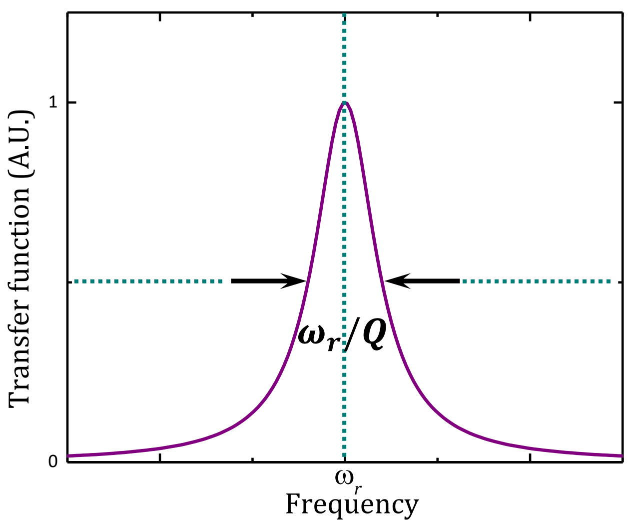
System that tends to oscillate with greater amplitude at some frequencies than at others

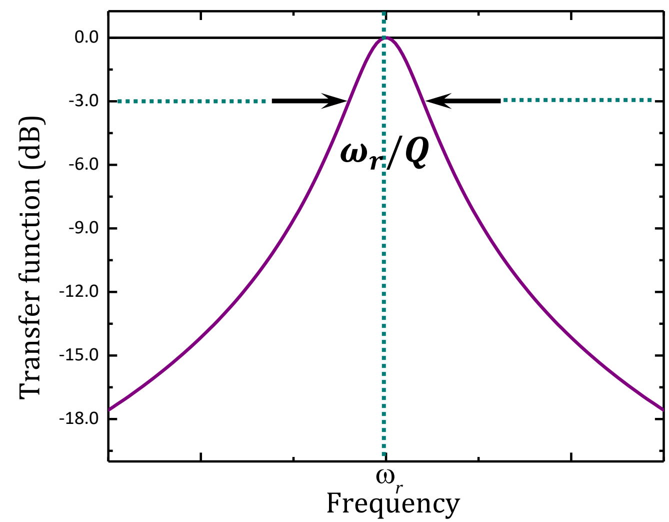
…and Wikipedia is usually right.



$$S_{21} = \left|\frac{V_o}{V_i}\right|^2 = \frac{1}{(1-(LC\omega)^2)^2 + (\omega RC)^2}$$

$$= \frac{1}{\left(1-\left(\frac{\omega}{\omega_r}\right)^2\right)^2 + \left(\frac{\omega}{\omega_r Q}\right)^2}$$





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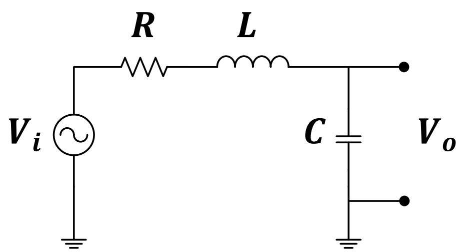

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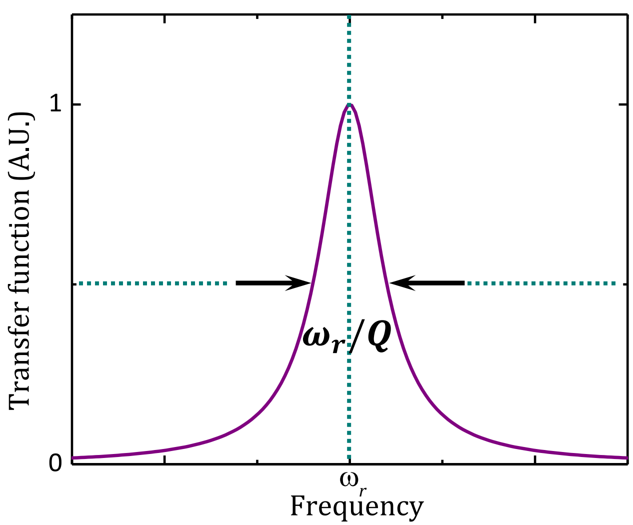
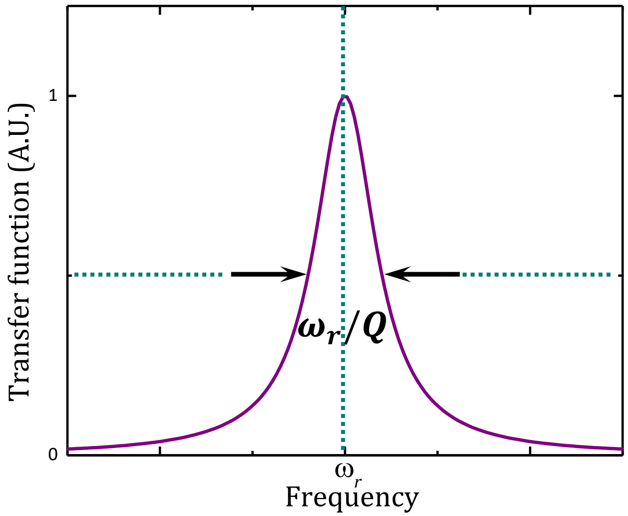


- Q **- Quality factor**
  - ***Measure of how good/bad a resonator is***
  - $Q = 2\pi \frac{E_{stored}}{E_{lost}}$; $Q = \frac{\omega_r}{FWHM}$; $Q = \frac{S_{21}(\omega_r)}{S_{21}(\omega=0)}$
  - ***Establishes level of interaction with the "outside"***

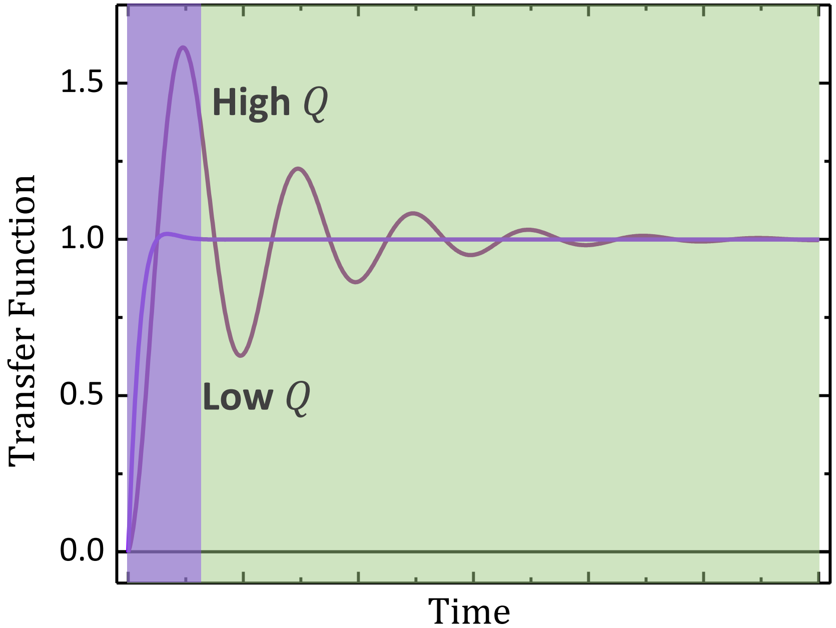
- **It depends on the application**
- **Trade-off**
  - Less influence from external noise
  - Time required to settle down the transients $\tau \sim 2\pi \frac{Q}{\omega_r}$
    - Every mechanical structure has resonances

If your application "resonates" – then better as high as possible

Resonator

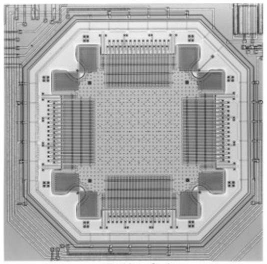


Response to a stepped stimulus



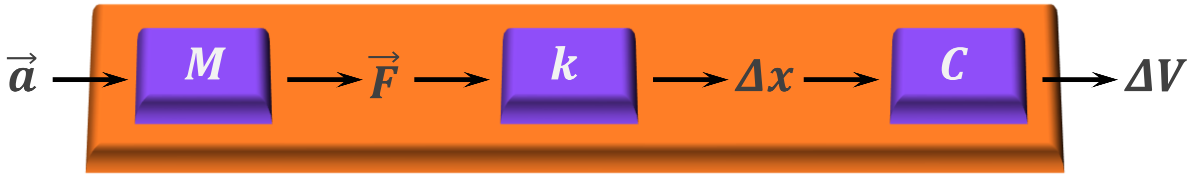
Difference between resonator and other systems

Accelerometer (DC)

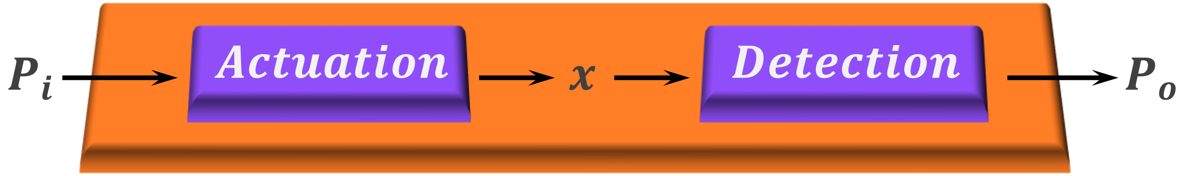


ADXL202 Sensor Structure

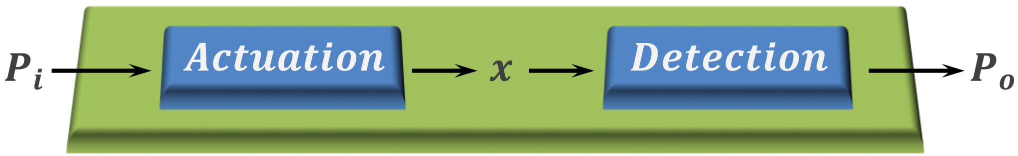
Courtesy of Analog Devices, Inc. Used with permission.



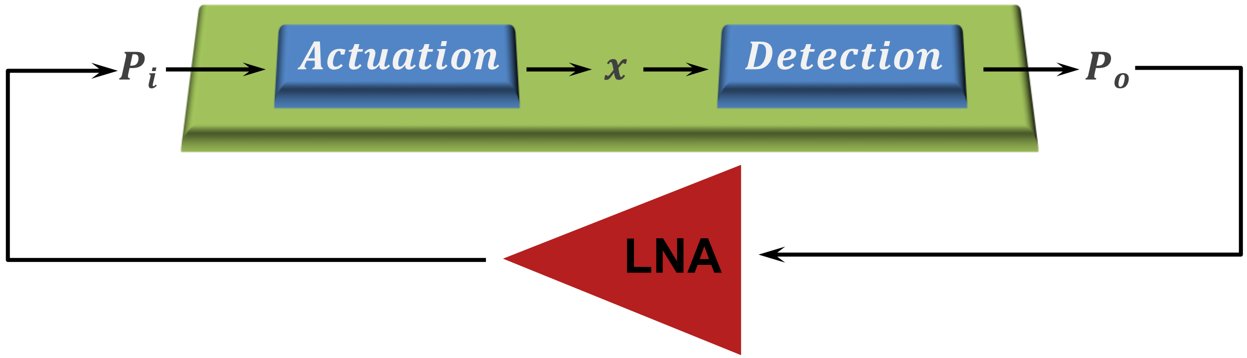
MEMS Resonator



RF Filter



Oscillator



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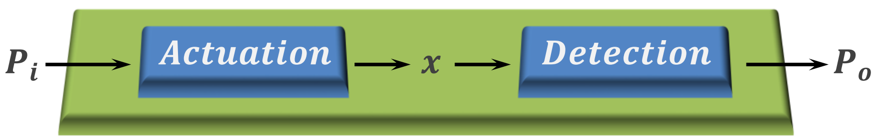

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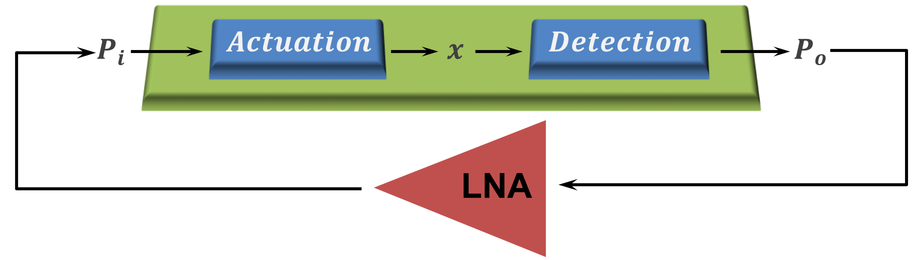
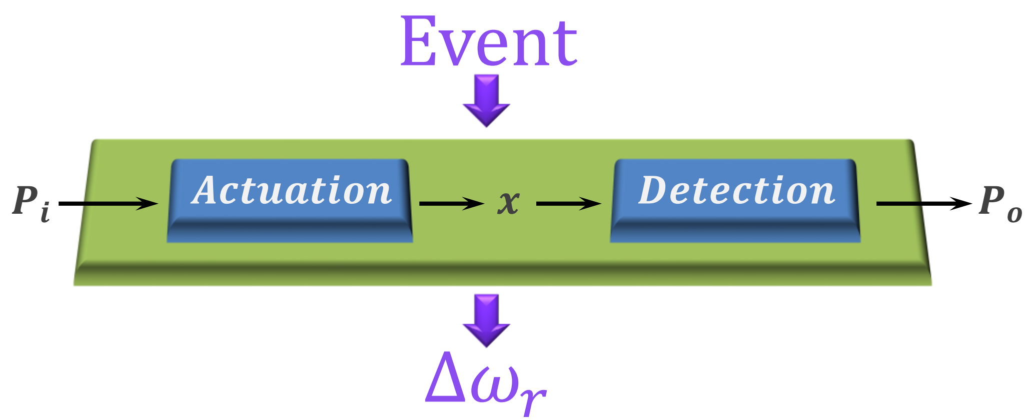
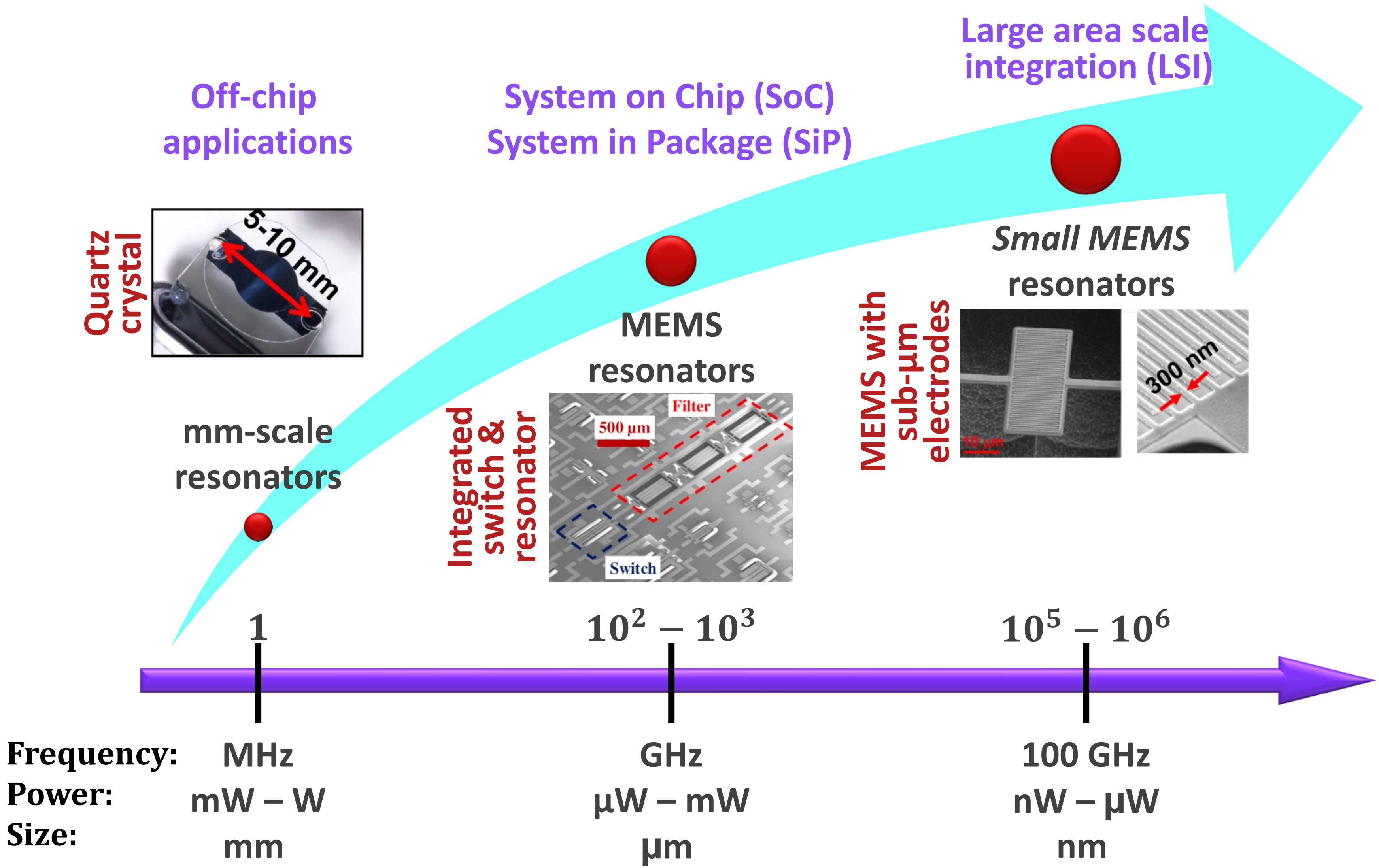


Resonant sensor



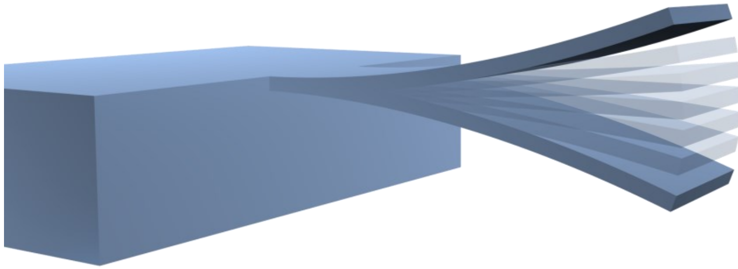
What kind of event could it be?

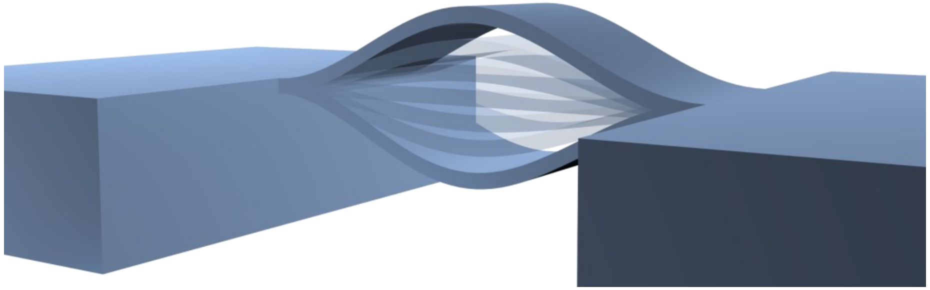


Source: Prof. G. Piazza

TYPES OF MEMS RESONATORS

Flexural



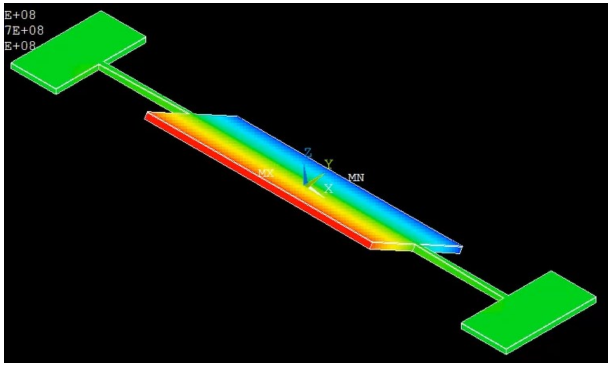


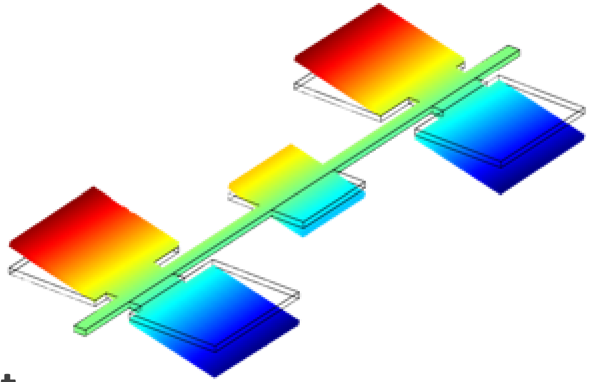
- Bending of mechanical structures is involved
- 1D: cantilevers (C-F), beams (C-C), free-free (F-F); 2D: membranes (CCCC), plates (CFFF)
- Equation of motion is a 4th order differential equation
  - Solution is a combination of trigonometric and hyperbolic functions

- *Typical frequencies:* 10kHz – 100MHz
- *Applications:* Low frequency oscillators, sensors
- *Advantages:*
  - Intuitive and clear understanding of motion
  - Low mass – preferred for sensing
- *Disadvantages:* gas or liquid damping is very important

$$f \propto \sqrt{\frac{E}{\rho}}\frac{t}{L^2}$$

Torsional



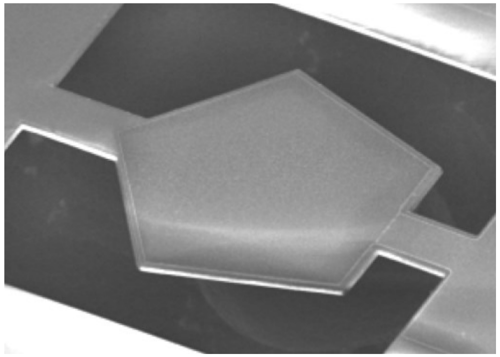


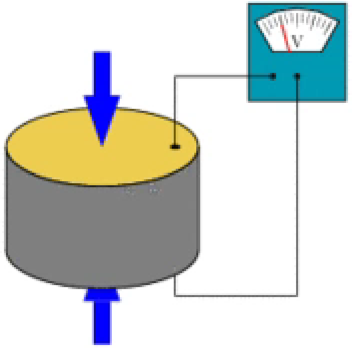
- **Motion based on torsion, torque-based movement**
- **Usually paddle-like structures**
- **Equation of motion is a 2nd order differential equation**
  - **Solution is a combination of trigonometric functions**

$$f \propto \sqrt{\frac{G}{\rho}}\sqrt{\frac{t^3}{L_r L_p W_p^3}}$$

- *Typical frequencies:* **10kHz – 10MHz**
- *Applications:* **Low frequency oscillators, sensors**
- *Advantages:*
  - **Intuitive and clear understanding of motion**
  - **Low interaction with substrate (thin supporting rods)**
- *Disadvantages:* **very fragile and costly to fabricate (very thin rods)**

Acoustic - Thickness



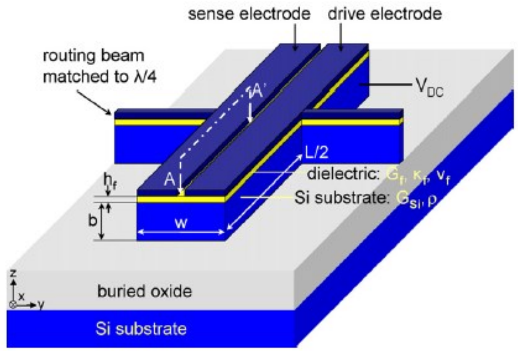


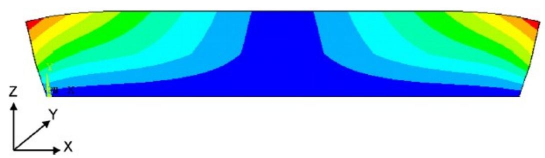
- **Acoustic waves constructive interaction**
- **Movement is 3D (due to Poison's ratio) – Reduced to 1D if $w > t$**
- **Equation of motion is a 2nd order differential equation – wave equation**
  - **Solution is a trigonometric function, Frequencies are multiples**

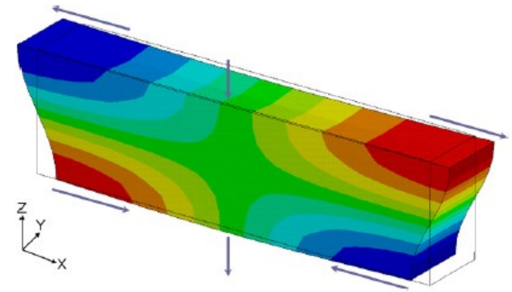
$$f \propto \sqrt{\frac{E}{\rho}\frac{n}{t}}$$

- *Typical frequencies:* **100MHz – 10GHz**
- *Applications:* **Filters, Oscillators**
- *Advantages:*
  - **High frequency, high Q**
  - **Easy electromechanical modelling**
- *Disadvantages:*
  - **Complicated design (to trim properties)**
  - **One frequency per wafer**

Acoustic - Shear







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- *Advantages:*
  - **High frequency, high Q**
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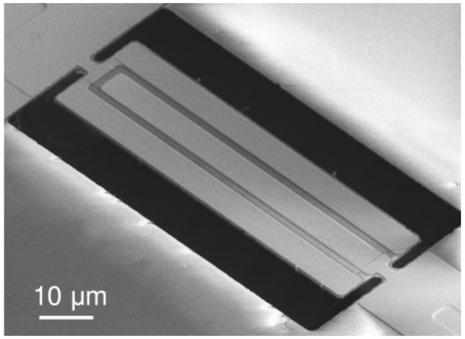
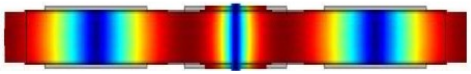
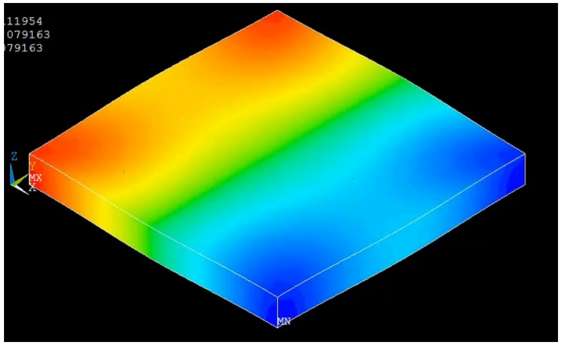
- *Disadvantages:*
  - **Complicated design (to trim properties)**
  - **Even less intuitive than previous one**

Acoustic - Lateral







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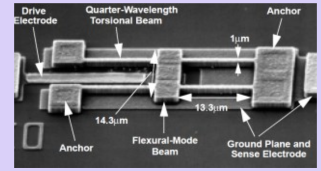
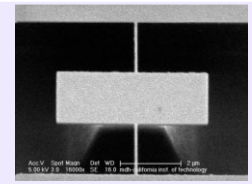
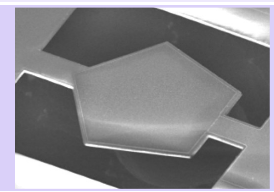
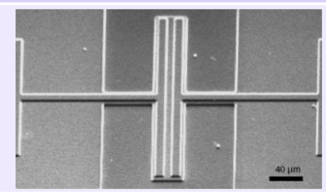
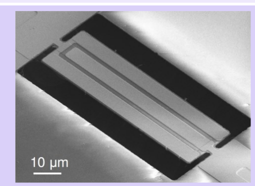
$$f \propto \sqrt{\frac{E}{\rho}\frac{n}{w}}$$

- *Typical frequencies:* **100MHz – 10GHz**
- *Applications:* **Filters, Oscillators**
- *Advantages:*
  - **Frequency defined by lithography, high frequency, high Q**
  - **Easy electromechanical modelling**
- *Disadvantages:*
  - **Complicated design (to trim properties)**

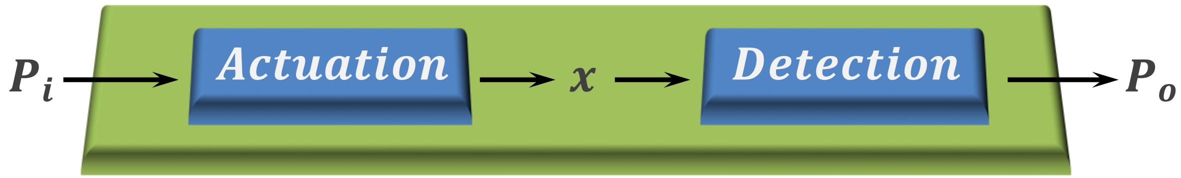
Types of MEMS Resonators

Type	Frequency		Example
Flexural	$f \propto \sqrt{\frac{E}{\rho}}\frac{t}{L^2}$	**100 kHz – 100 MHz**	
Torsional	$f \propto \sqrt{\frac{G}{\rho}}\sqrt{\frac{t^3}{L_r L_p W_p^3}}$	**10 kHz – 10 MHz**	
Thickness	$f \propto \sqrt{\frac{E}{\rho}}\frac{n}{t}$		
Shear	$f \propto \sqrt{\frac{G}{\rho}}\frac{n}{t}$	**100 MHz – 10 GHz**	
Lateral	$f \propto \sqrt{\frac{E}{\rho}}\frac{n}{w}$		

Damping/loss mechanisms?

$$Q = 2\pi \frac{E_{stored}}{E_{lost}}$$

- Viscous damping
  - Displacement of gas or liquid molecules
  - Pressure and mode-shape dependent
- Anchoring losses
  - Radiation of energy to the substrate
  - Minimized using phononic crystals (artificial mirror for acoustic energy)
- Material losses
  - Surface states
  - Volume losses
    - Defects motion
    - Thermo-elastic damping
    - Akhiezer effect (electro-phonon dissipative coupling)



- Capacitive/Electrostatic
- Thermal
- Piezoresistive
- Piezoelectric
- Electrostrictive
  - Polarizing a dielectric material – effectively turning it piezoelectric

- Non dissipative
- Based on material property
- No need for external DC
- Good scaling with frequency

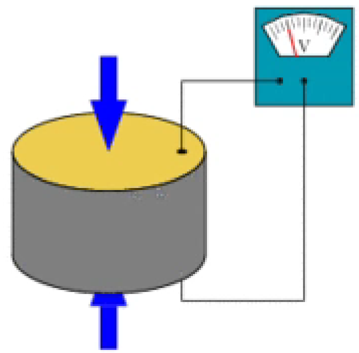
Comparing resonators

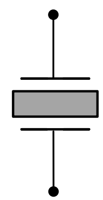
- It's difficult to compare "*apples and oranges*"
- Figures Of Merit (FOM)
  - Useful to get much information into a single parameter

- $\boldsymbol{FOM_1 = f_r \cdot Q}$
  - Determines which resonator would work better as an *oscillator*
  - It can be seen that there is kind-of a trade-off between $\boldsymbol{f_r}$ and $\boldsymbol{Q}$
- $\boldsymbol{FOM_2 = k_t^2 \cdot Q}$
  - $\boldsymbol{k_t^2}$ measures how much mechanical energy gets converted into electrical energy
  - This FOM determines which resonator would work better as a *filter*
  - Piezoelectric resonators have the highest values

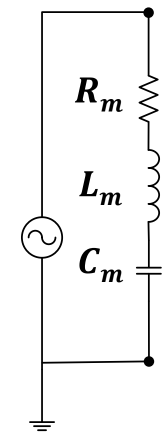
Modelling resonators – 1-port

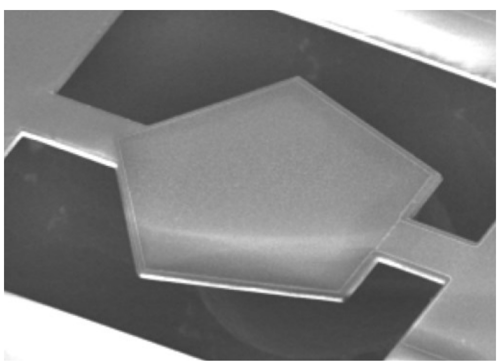
- Equivalent circuit
  - Allows to reproduce mechanical resonator behavior with circuit simulation tools
- Historically, the first one to be developed was a 1-port model for Quartz crystals

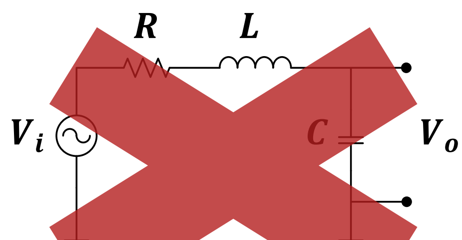




Resonator symbol

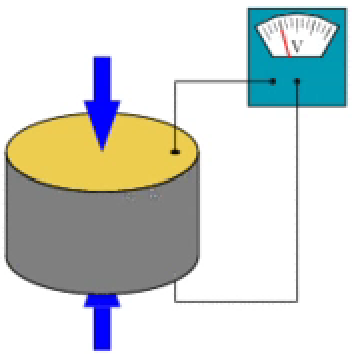


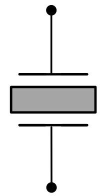




Electrical resonator

- **Equivalent circuit**
  - Allows to reproduce mechanical resonator behavior with circuit simulation tools
- **Historically, the first one to be developed was a 1-port model for Quartz crystals**





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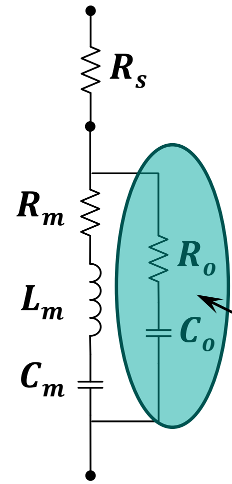
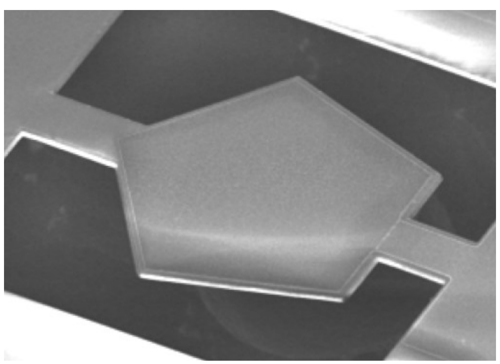
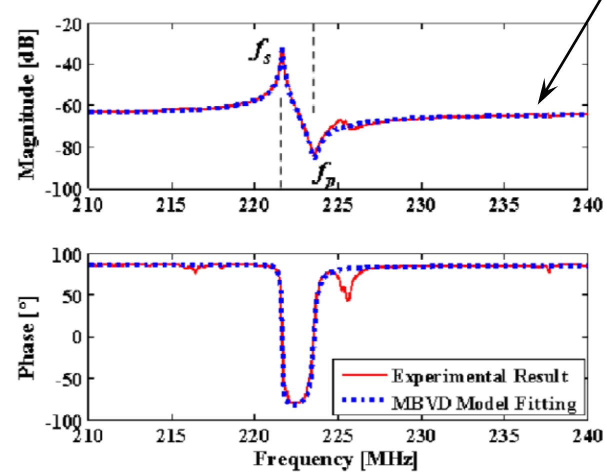
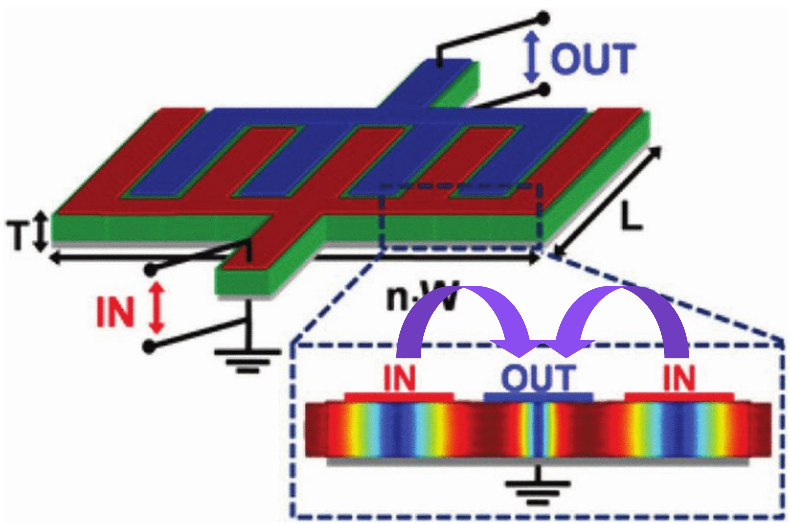


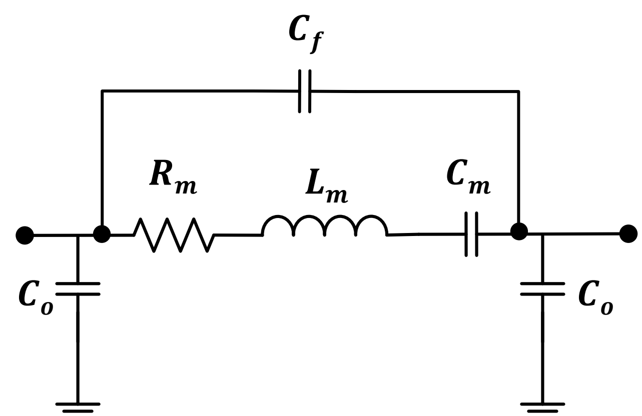
Parasitic impedance

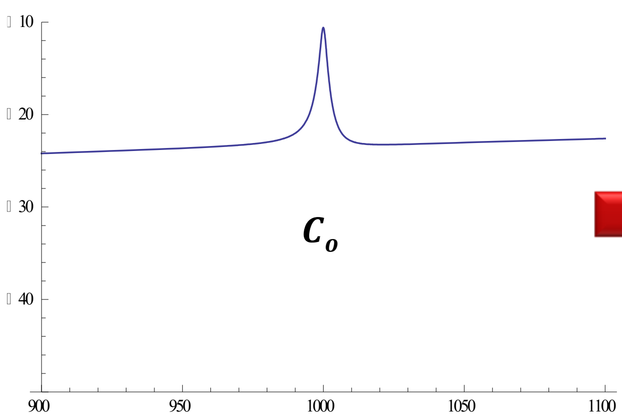


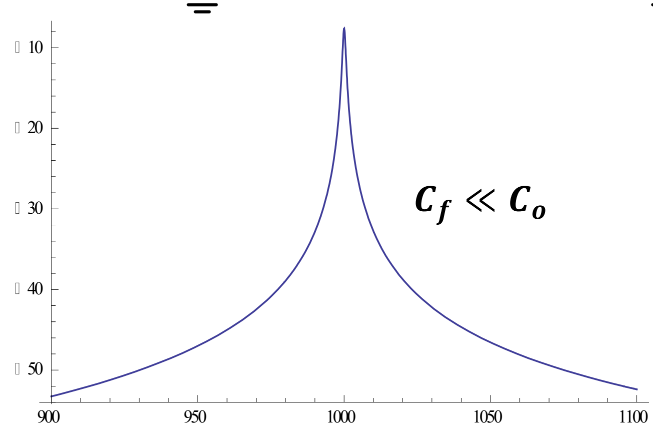


- **In order to reduce the effect of parasitics**
  - **Two separate ports for excitation and readout**



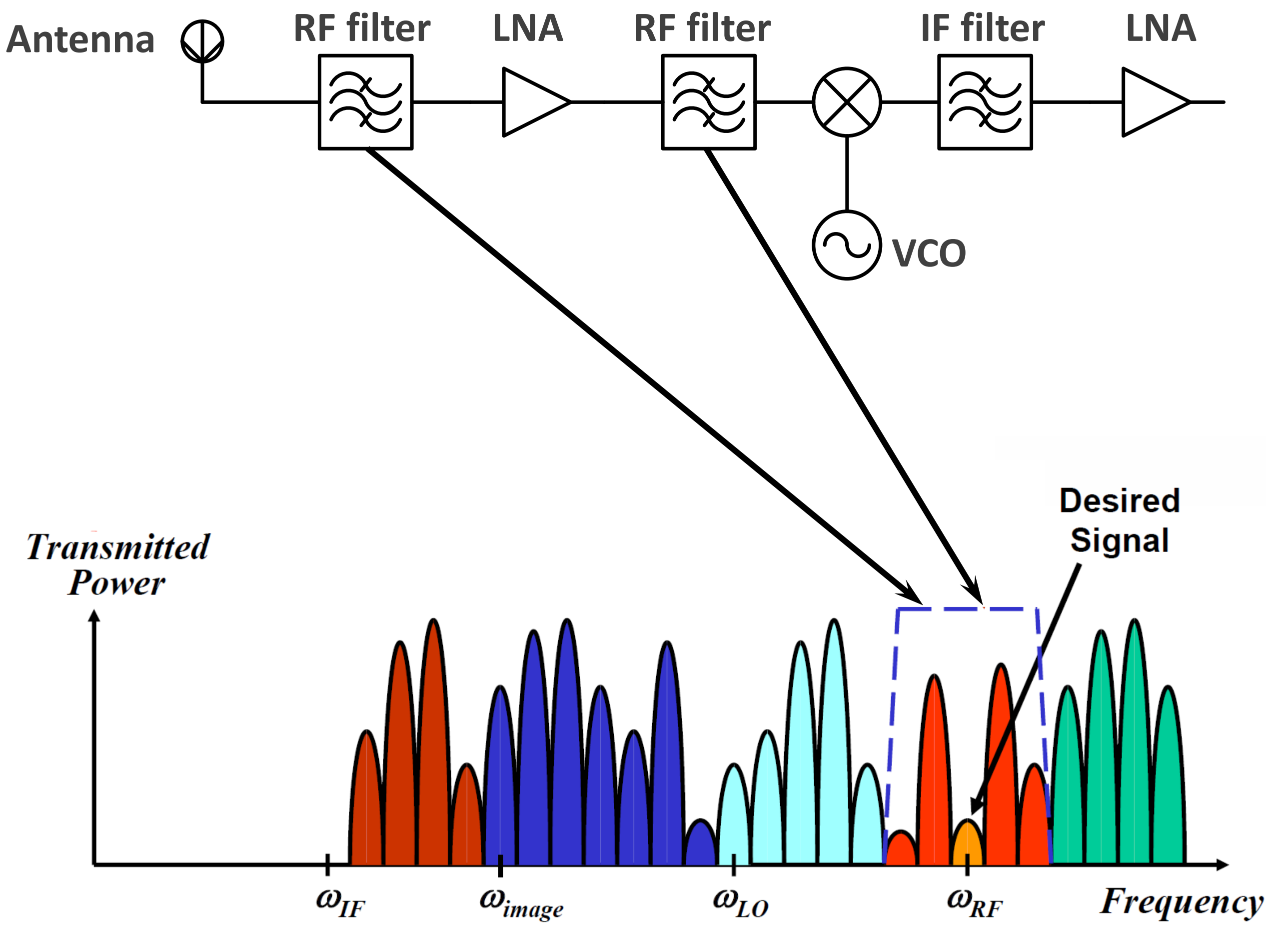






MEMS RF-FILTERS

- **Typically – Receivers work using heterodyne conversion**



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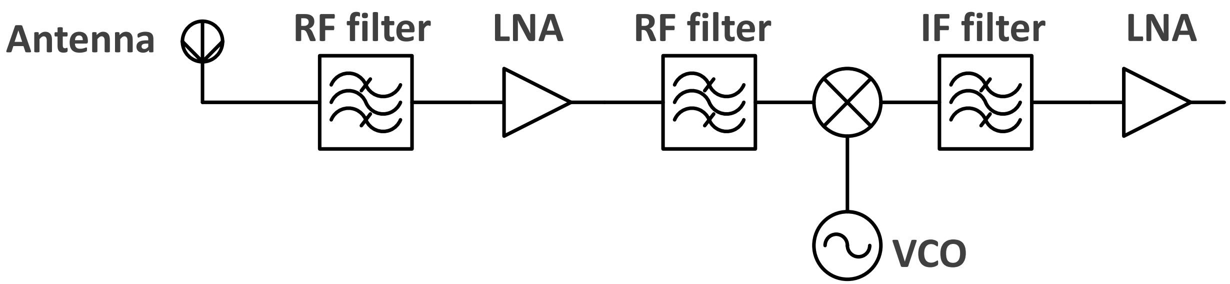

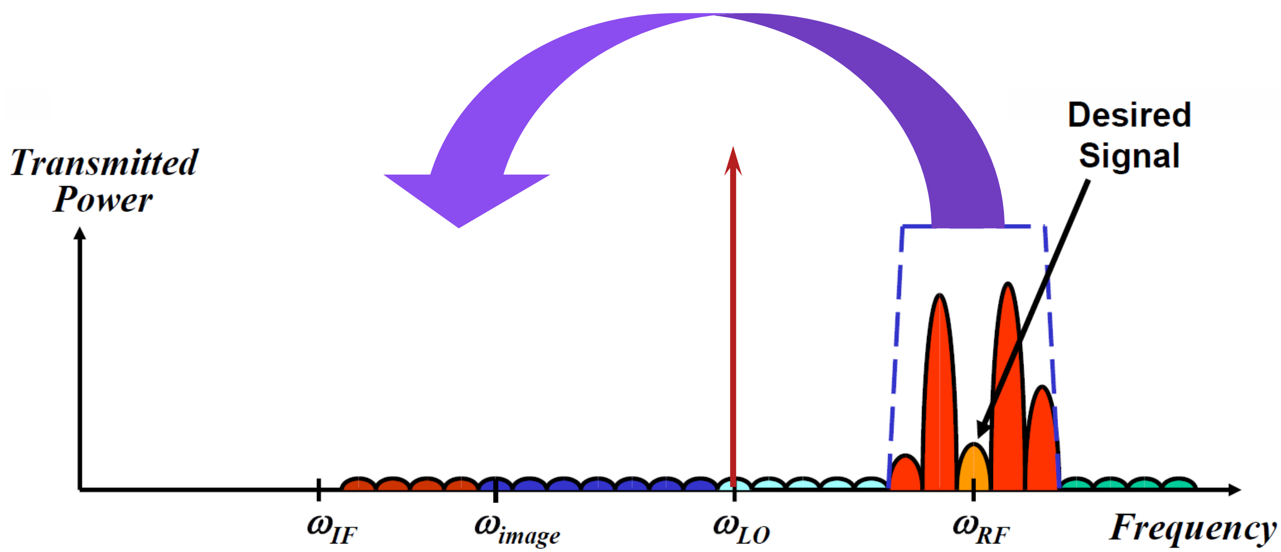

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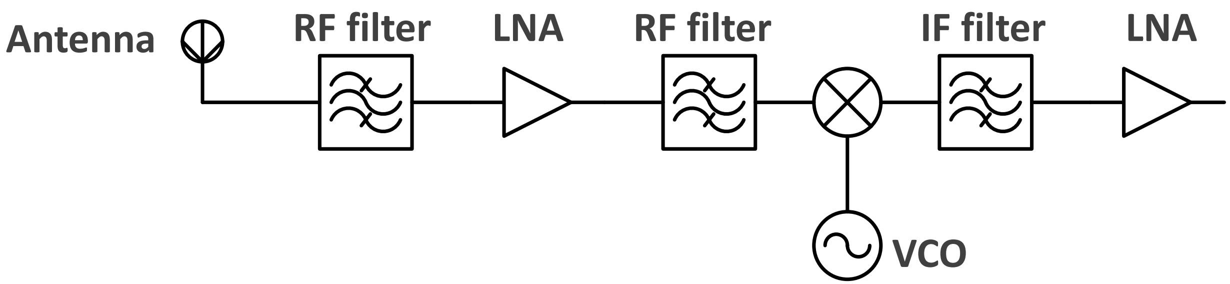
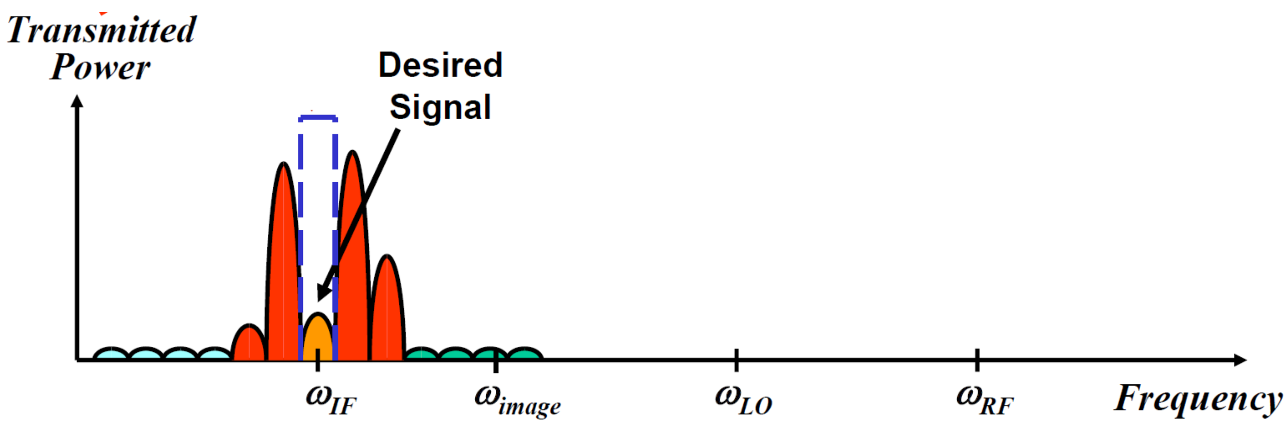
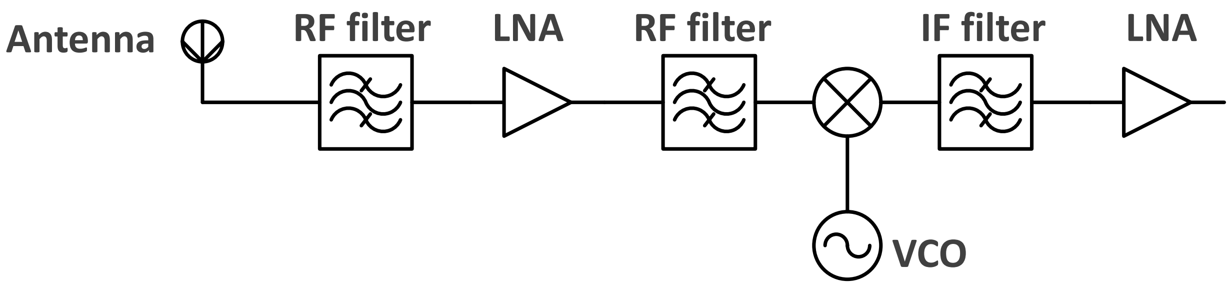
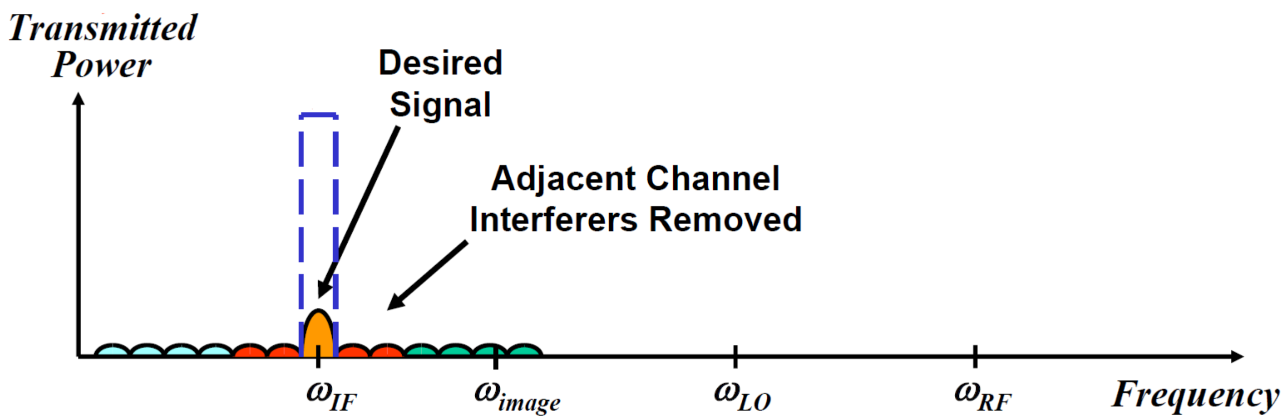




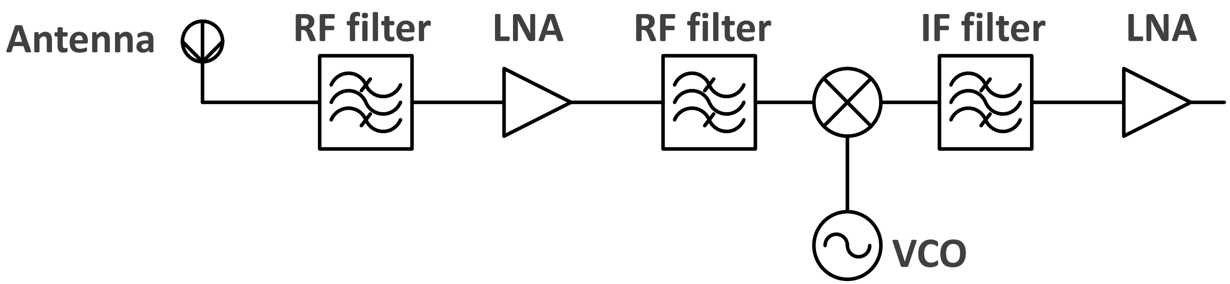
- **Typically – Receivers work using heterodyne conversion**





What for? Communications front-ends

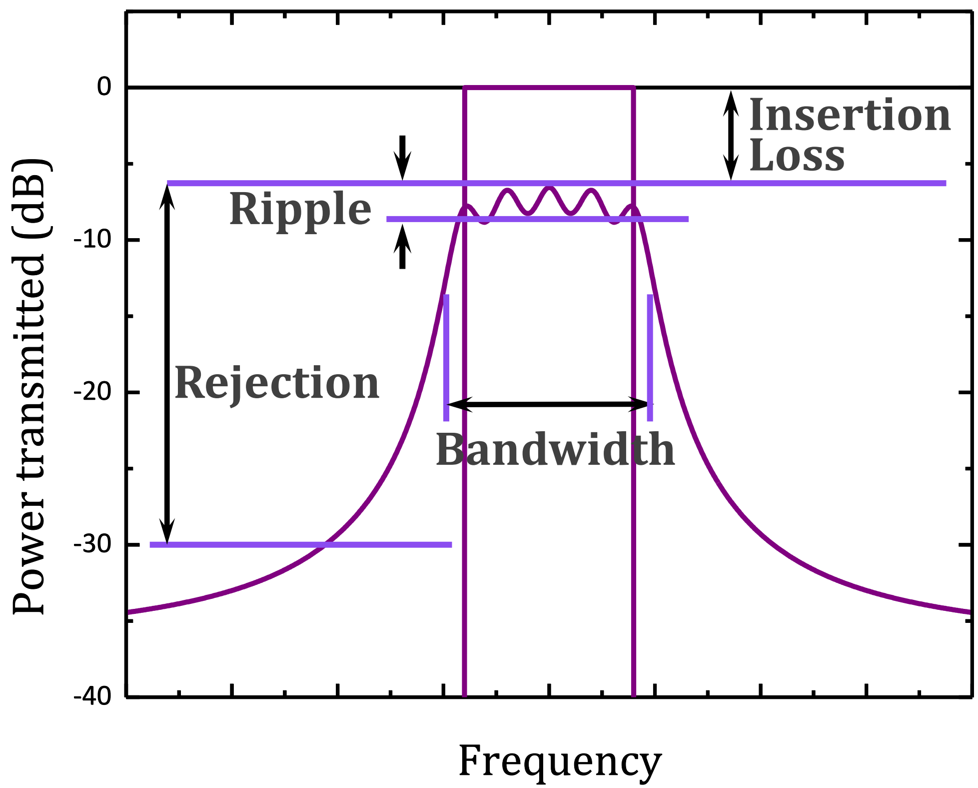
- Typically – Receivers work using heterodyne conversion



- It is necessary to do conversion down to IF because at RF, Qs are not good
- With RF-MEMS filters – Direct filtering is possible

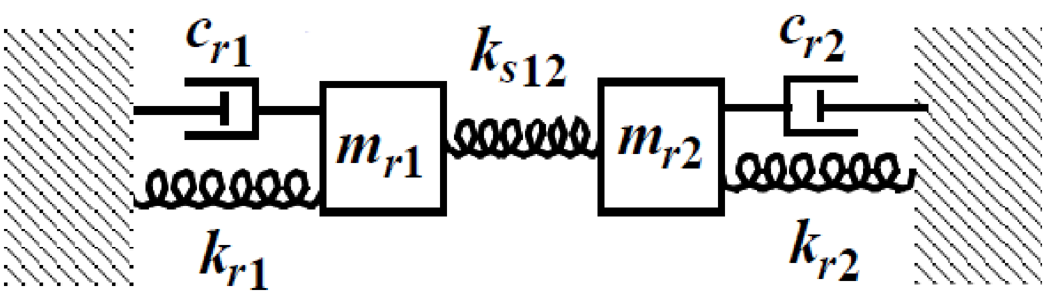
Filter Specifications

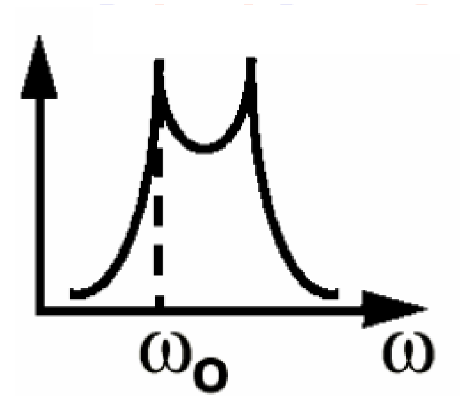
- Ideal is a rectangular filter
- Filter design focus is mainly on
  - Insertion loss (and ripple)
  - Bandwidth
  - Rejection
  - Impedance
- Arrays of coupled resonators
  - High Q = high rejection
  - Separation = Bandwidth
- Coupling can be
  - Electrical
  - Mechanical
  - Acoustical

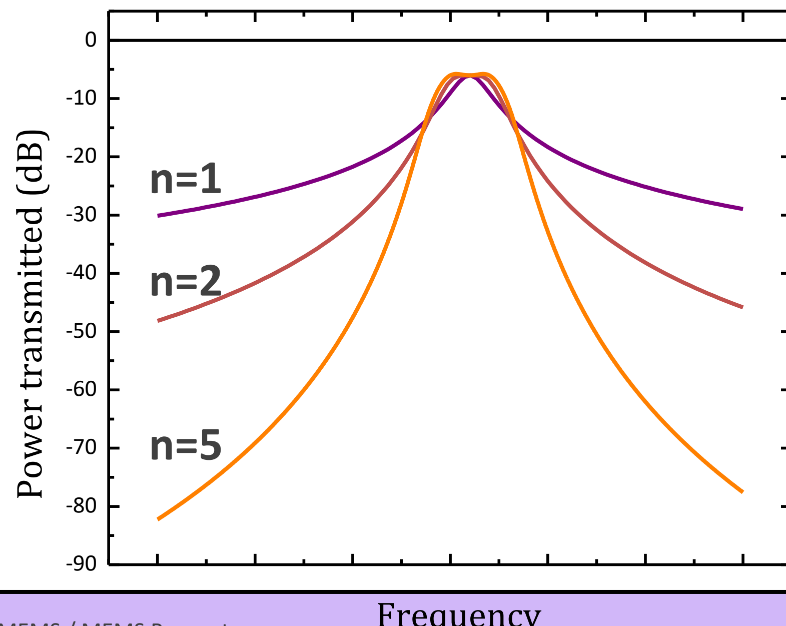


Coupled resonators

- **Basic idea**
  - 2 coupled resonators
  - Symmetric and Anti-Symmetric motion
  - New frequencies are defined by coupling factor



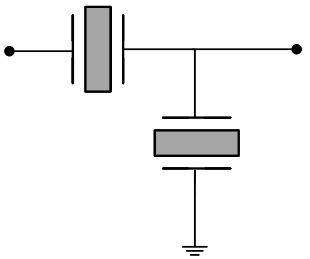




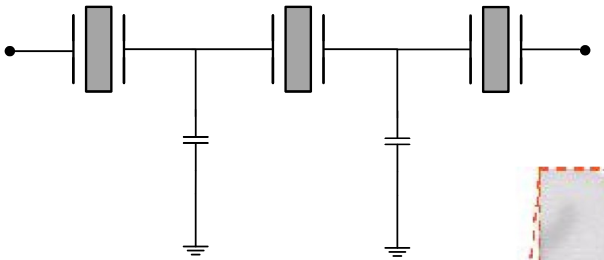
Sharper rejection for a larger Bandwidth with more coupled resonators

Coupling for filters

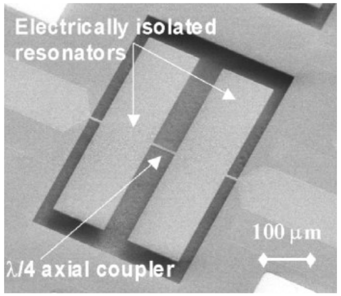
- Electrical
  - Ladder-like

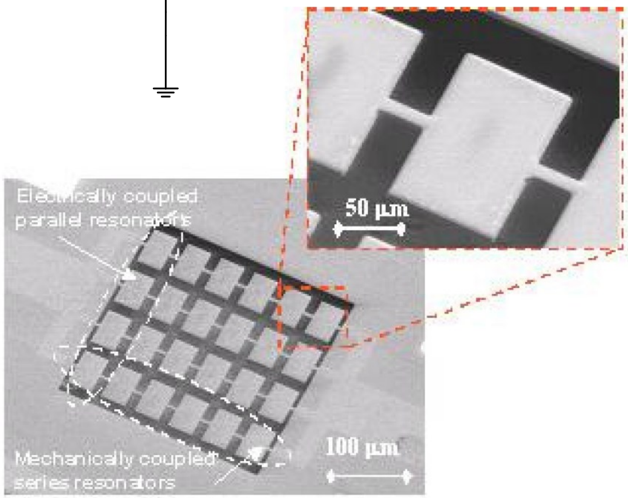


  - Series

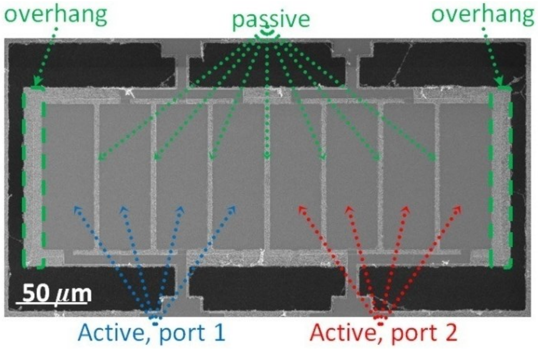


- Mechanical

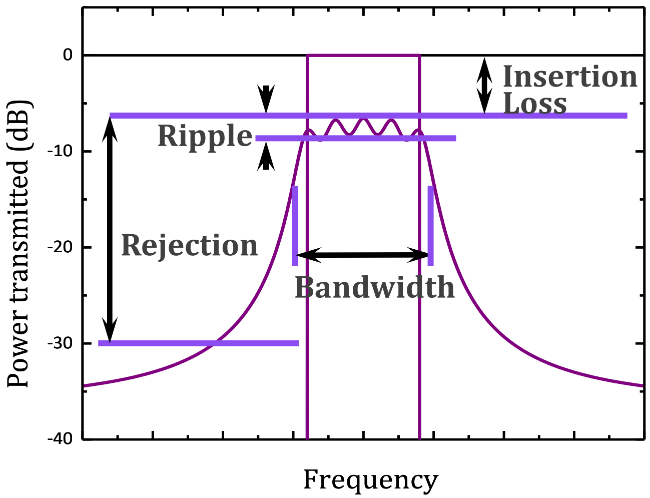




- Acoustic



Filter design



- Depends on transduction and geometry
- Piezoelectric contour-mode resonators:
  - Bandwidth
    - Set by the electromechanical coupling coefficient

$$BW \sim \frac{3}{\pi^2} k_t^2$$

  - Insertion Loss
    - Set by $FOM_2 = k_t^2 \cdot Q$

$$IL \sim -20 \log\left(\frac{4}{4 + (3\pi^2)/(k_t^2 Q)}\right)$$

  - Rejection
    - Controlled by parasitics (C_f)

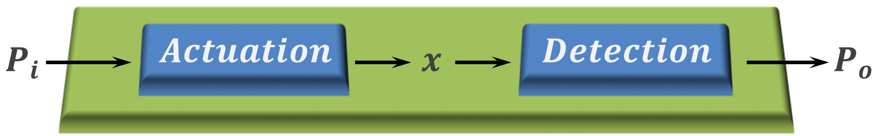
$$Reject \sim -20 \log\left(\frac{C_f}{C_o}\right) - IL$$

  - Impedance
    - Termination capacitance, can be tuned

$$IL \sim \left|\frac{1}{j\omega_c C_o}\right|$$

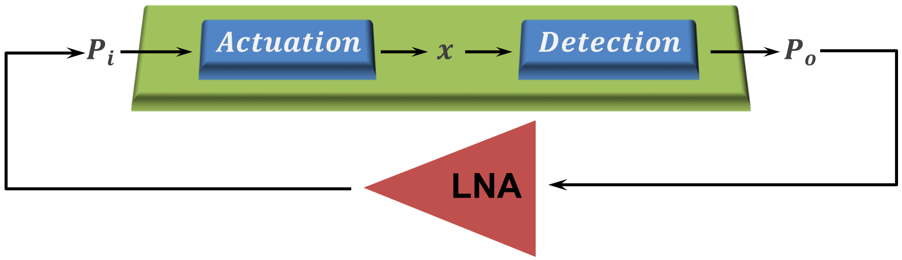
MEMS OSCILLATORS

Passive/Resonator



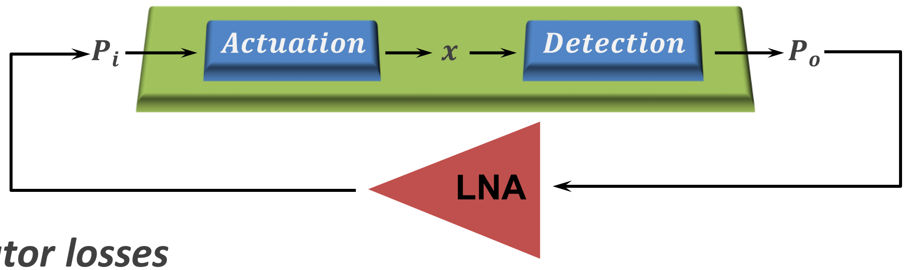
- Power output linearly depends on power input
- Requires a harmonic drive to have response

Active/Oscillator



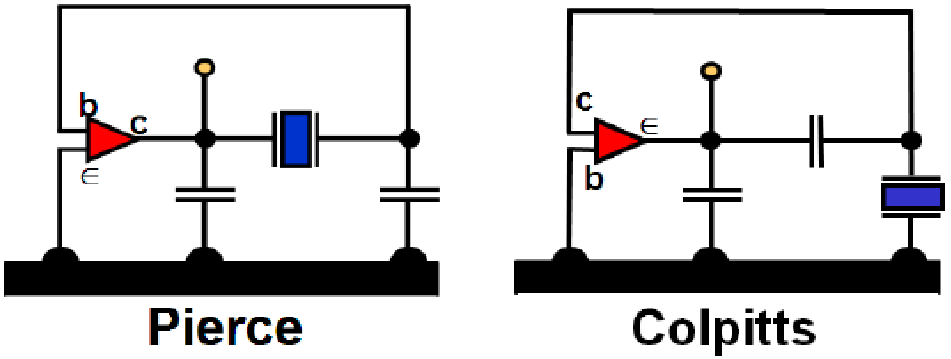
- Outputs a harmonic signal by only applying DC power

Basic implementation



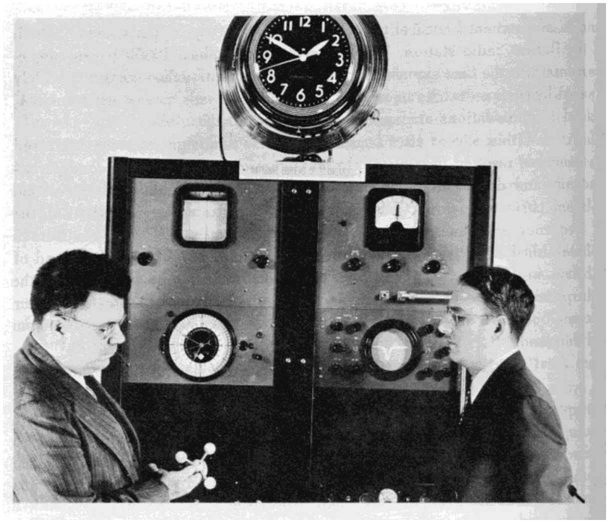
- Idea
  - Amplify P_o enough to *compensate resonator losses*
  - Feed it back to device with *appropriate phase*
  - *Barkhausen's criteria*

- Two simplest implementations
  - Pierce & Colpitts oscillators
  - 1 transistor, 2 capacitors – oscillator is running!

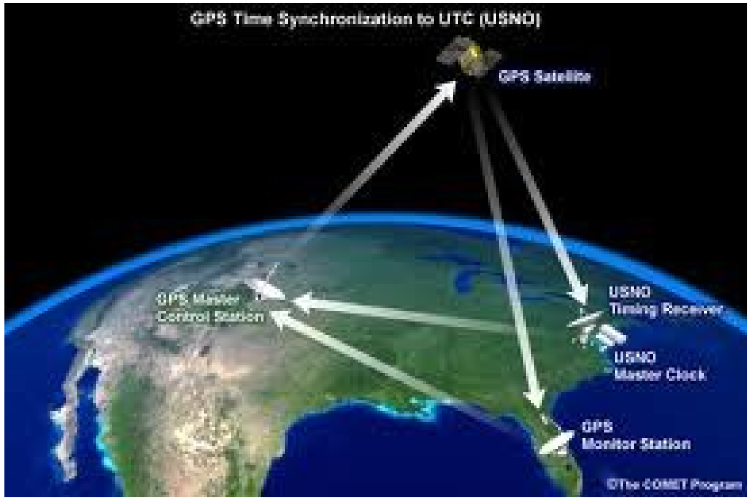


- Every watch has an oscillator inside – to keep track of time
- Oscillator’s beats are later translated into seconds (e.g. by a counter)
- For a precise watch – necessary a precise oscillator
- Precision is required in the long term (this is important)

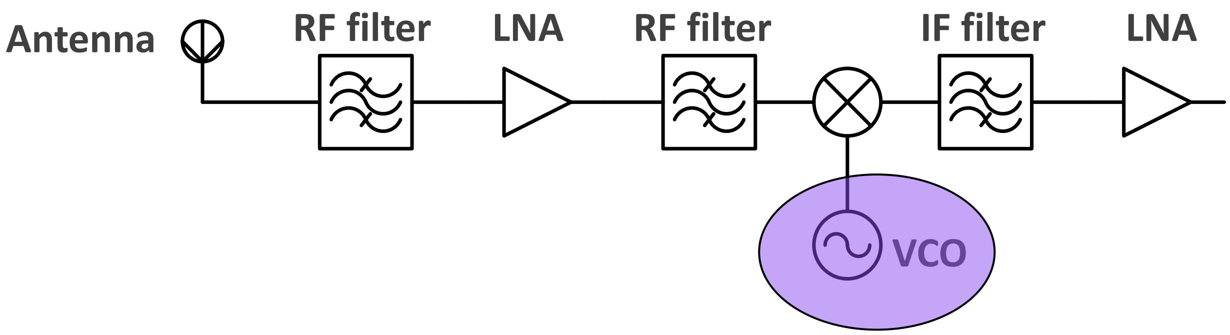
- **What is the most precise clock?**
  - **Atomic Clock – *30 fs error per day!!!!!***



- **Applications that require very high precision?**
  - **Geolocation (GPS, Galileo…)**
  - **Radar, LiDAR,…**



- Communications
  - Front-End/Receiver



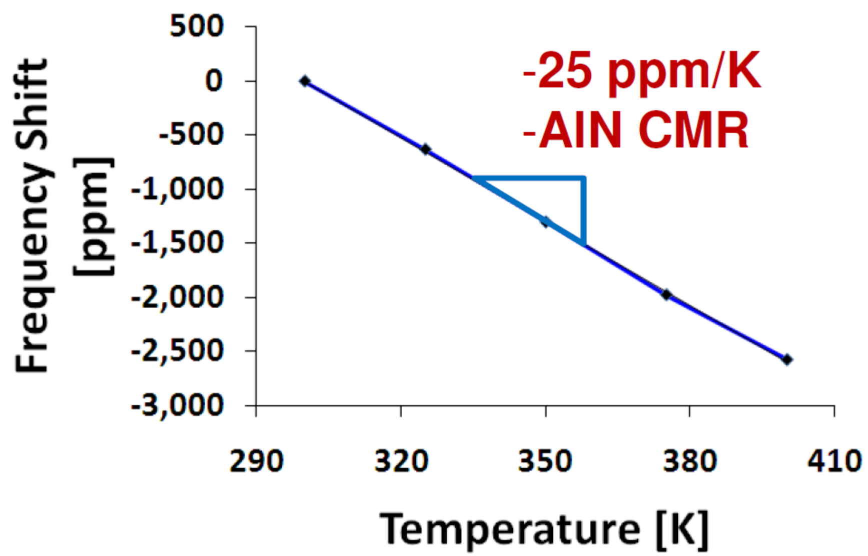
- Oscillator signal is used to encode and decode signals
- Clean communication needs a precise oscillator
- Precision is important at very short timescales, $< \ 1\,\mathrm{ms}$

"Performance" Metrics

- Phase noise
- Temperature stability
- Acceleration stability
  - Vibrations affect resonant frequency
  - $f = f_0(1 + \Gamma \cdot |\vec{a}|)$
  - $\Gamma \sim 10^{-5}\mathrm{g}^{-1}$ for most MEMS devices
- Power consumption
  - More autonomous devices
  - Stand-by and clocking applications
    - 32.768 kHz $(= 2^{15}\mathrm{Hz})$
    - $\sim 1\ \mu\mathrm{W}$
- Size
  - Smaller footprint = Cheaper

Temperature stability

- Frequency depends on temperature
  - $f = f_0(1 + \mathrm{TCF} \cdot \Delta\mathrm{T})$
- TCF can have different origins
  - Change in Young's modulus $\partial E/\partial T$
  - Change in volume/dimensions/density $\alpha = \partial L/\partial T$
  - Change in tension, surface stress, etc.
- Specification asks for $\sim 10\ \mathrm{ppm}$ over the whole operational range (e.g. -30 – 70ºC)
  - $\partial E/\partial T \sim \pm 10\ \mathrm{ppm/K!!!!!!!}$
- Solutions for compensation
  - Quartz crystals get special cuts



Temperature stability

- **Frequency depends on temperature**
  - $f = f_0(1 + \mathrm{TCF} \cdot \Delta\mathrm{T})$
- **TCF can have different origins**
  - **Change in Young's modulus $\partial E / \partial T$**
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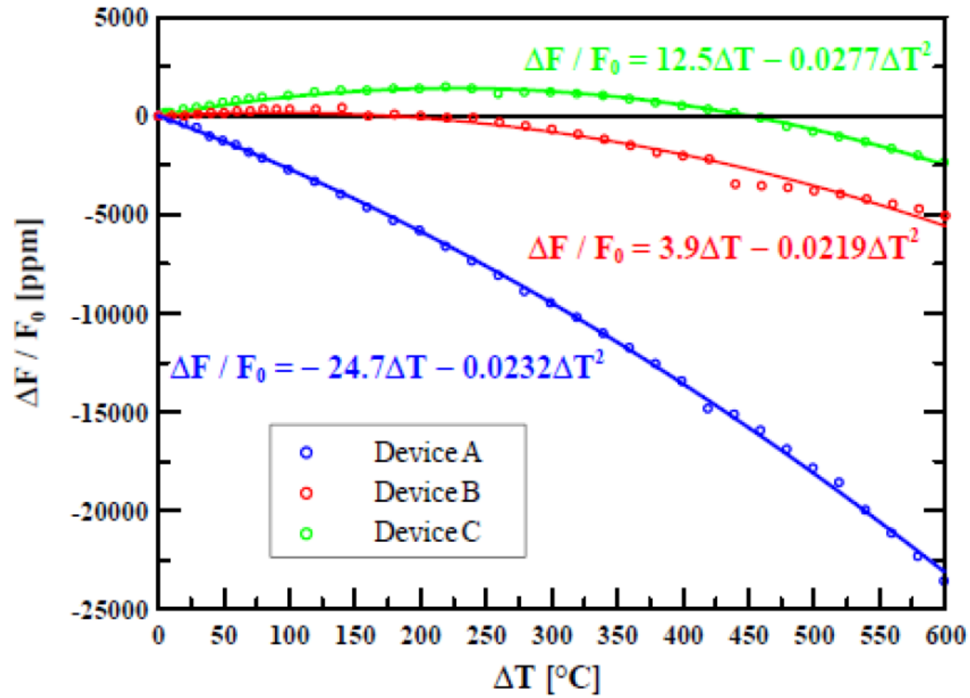
- **Specification asks for ~ 10 ppm over the whole operational range (e.g. -30 – 70ºC)**
  - $\partial E / \partial T \sim \pm 10$ ppm/K!!!!!!!
- **Solutions for compensation**
  - Quartz crystals get special cuts
  - MEMS – hybrid structures to balance (using positive and negative $\partial E / \partial T$)
    - Not linear over wide T range



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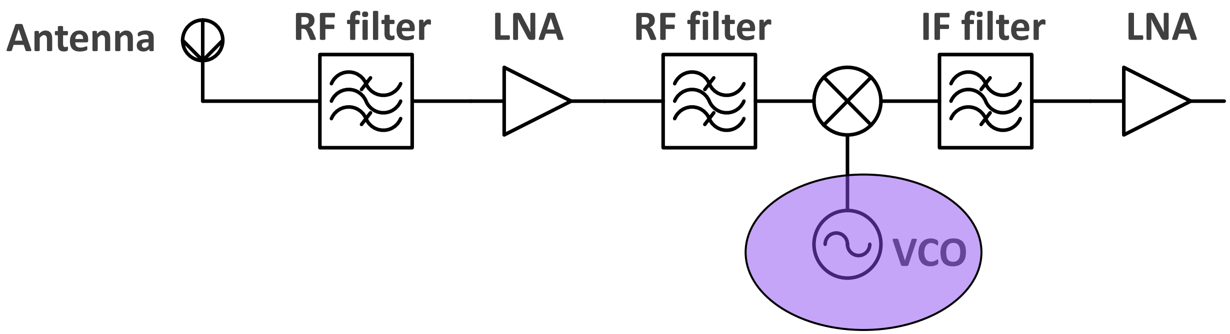
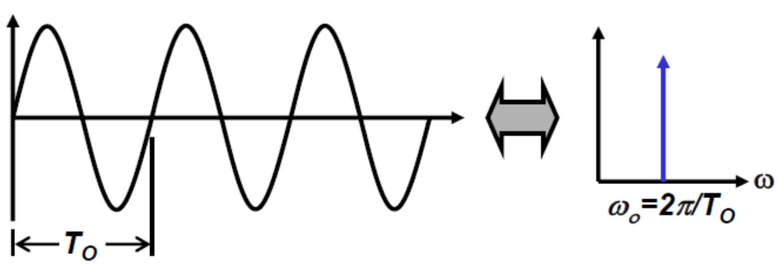
- Specification asks for ~ 10 ppm over the whole operational range (e.g. -30 – 70ºC)
  - $\partial E / \partial T \sim \pm 10$ ppm/K!!!!!!!
- Solutions for compensation
  - Quartz crystals get special cuts
  - MEMS – hybrid structures to balance (using positive and negative $\partial E / \partial T$)
    - Not linear over wide T range
  - Circuit compensation
    - Use external circuit to detect T and correct the frequency
    - Best results but causes Power consumption to increase
    - Cheaper resonators

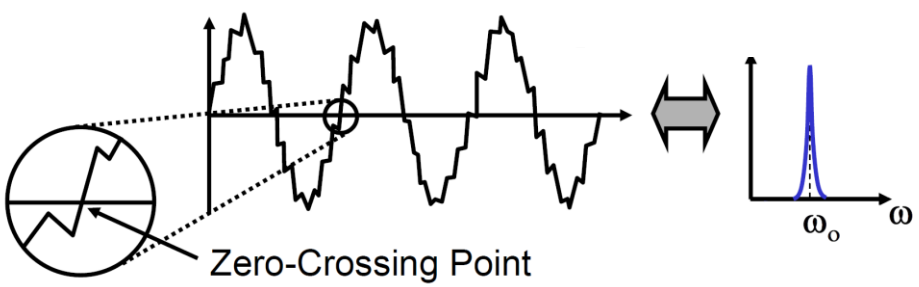
- Communications



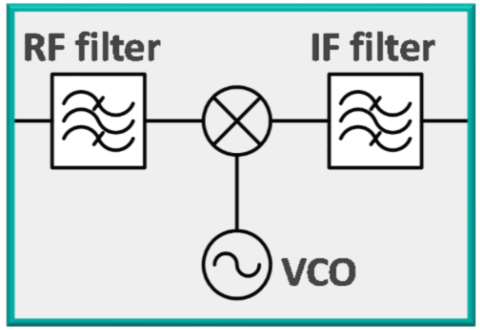
Ideal Frequency Source



Real Frequency Source



Phase Noise



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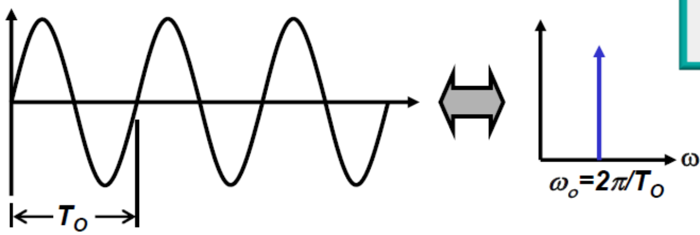
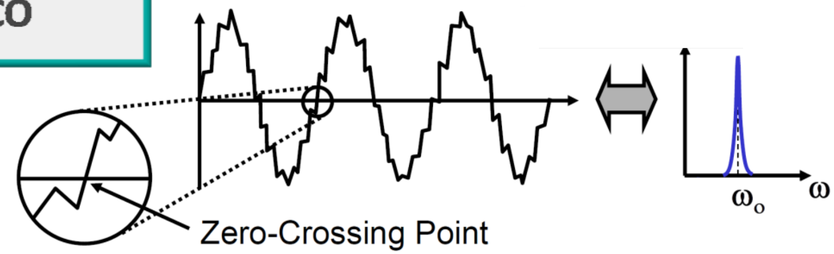
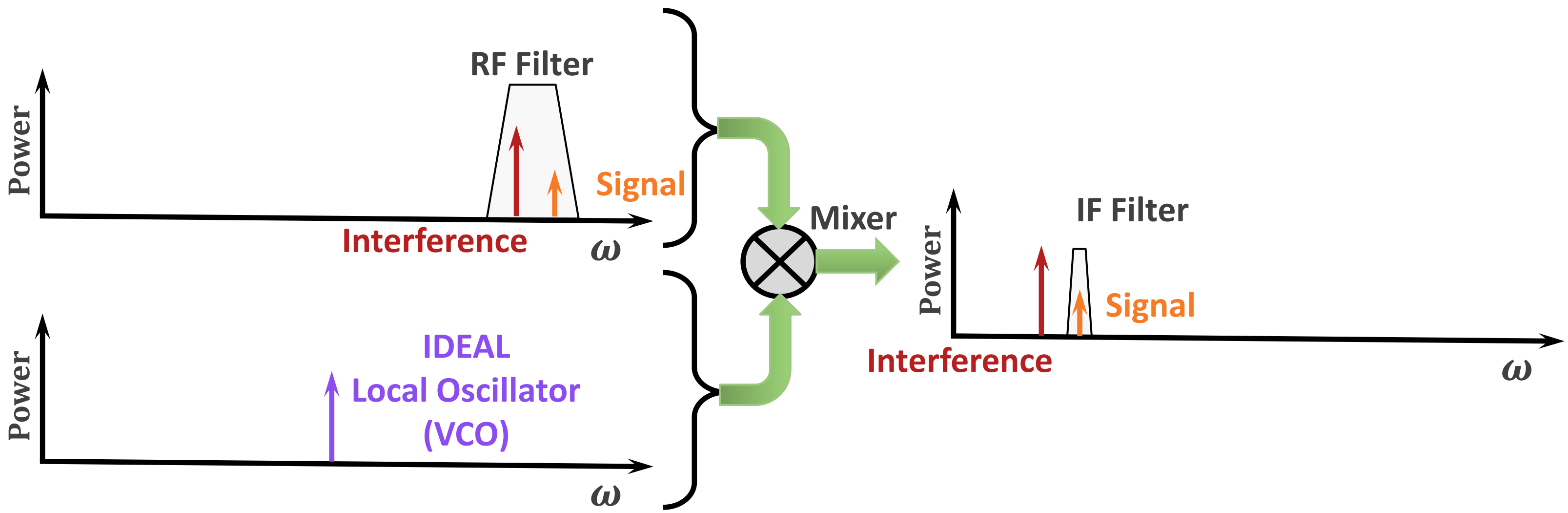


Real Frequency Source





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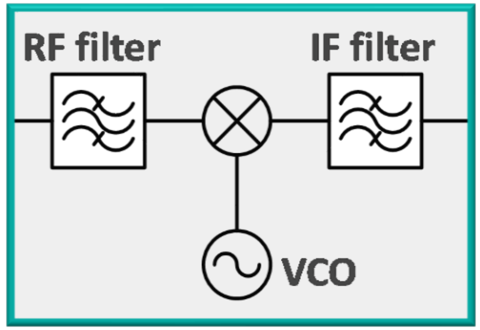

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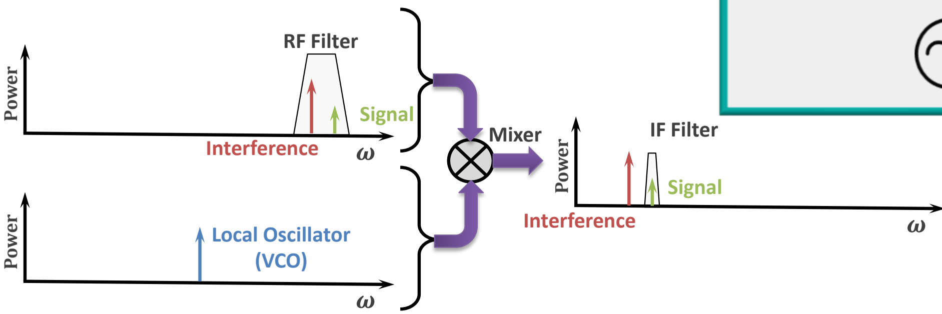
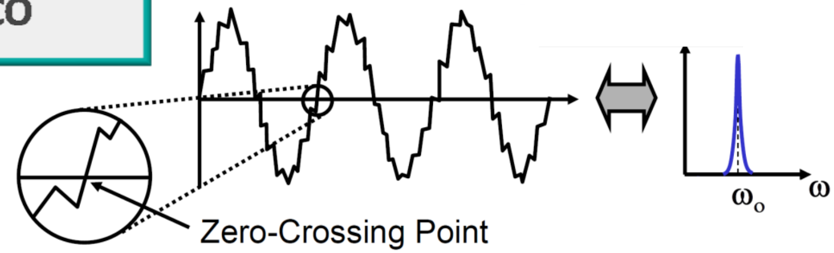
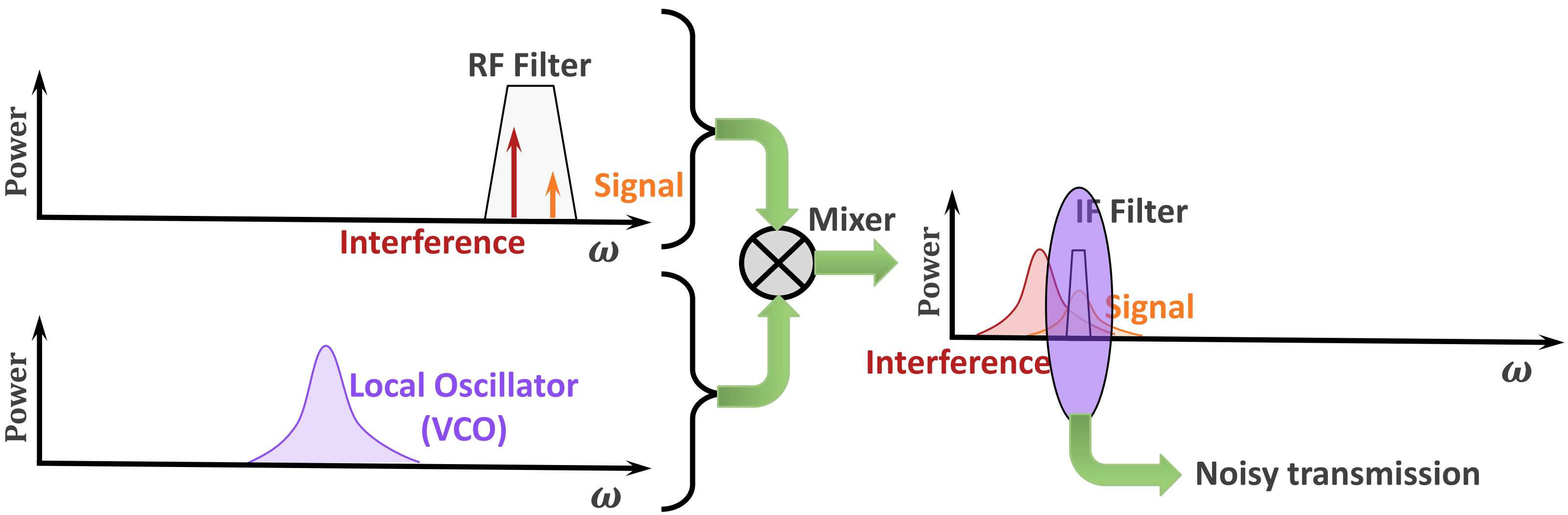
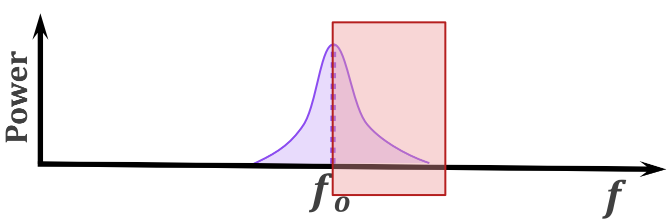


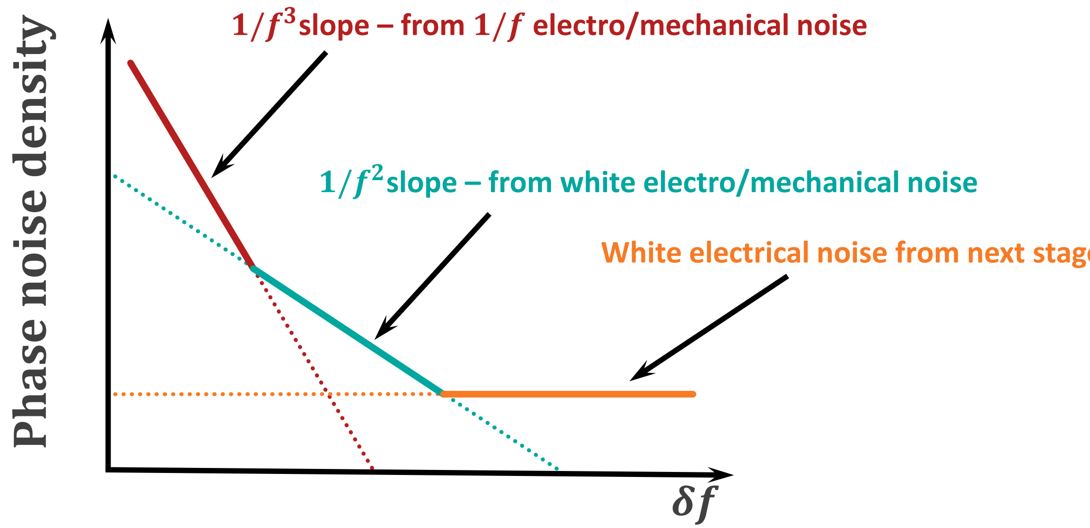
Real Frequency Source





- Phase noise determines the precision of the oscillator
  - How accurate the generated frequency signal is
- It is measured in relative power to the total carrier power per Hz
  - $\frac{dBc}{Hz}$
- Leeson's formula
  - $S_\phi(\delta f) = 10\ log\left(F\frac{k_B \cdot T \cdot f_0}{Q \cdot E}\frac{1}{\delta f^2}\right)$
  - Incomplete, needs some modifications/additions





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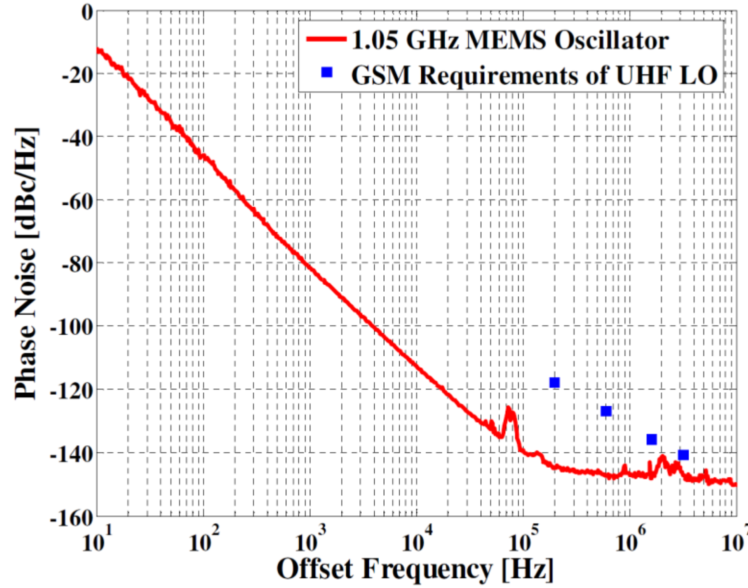
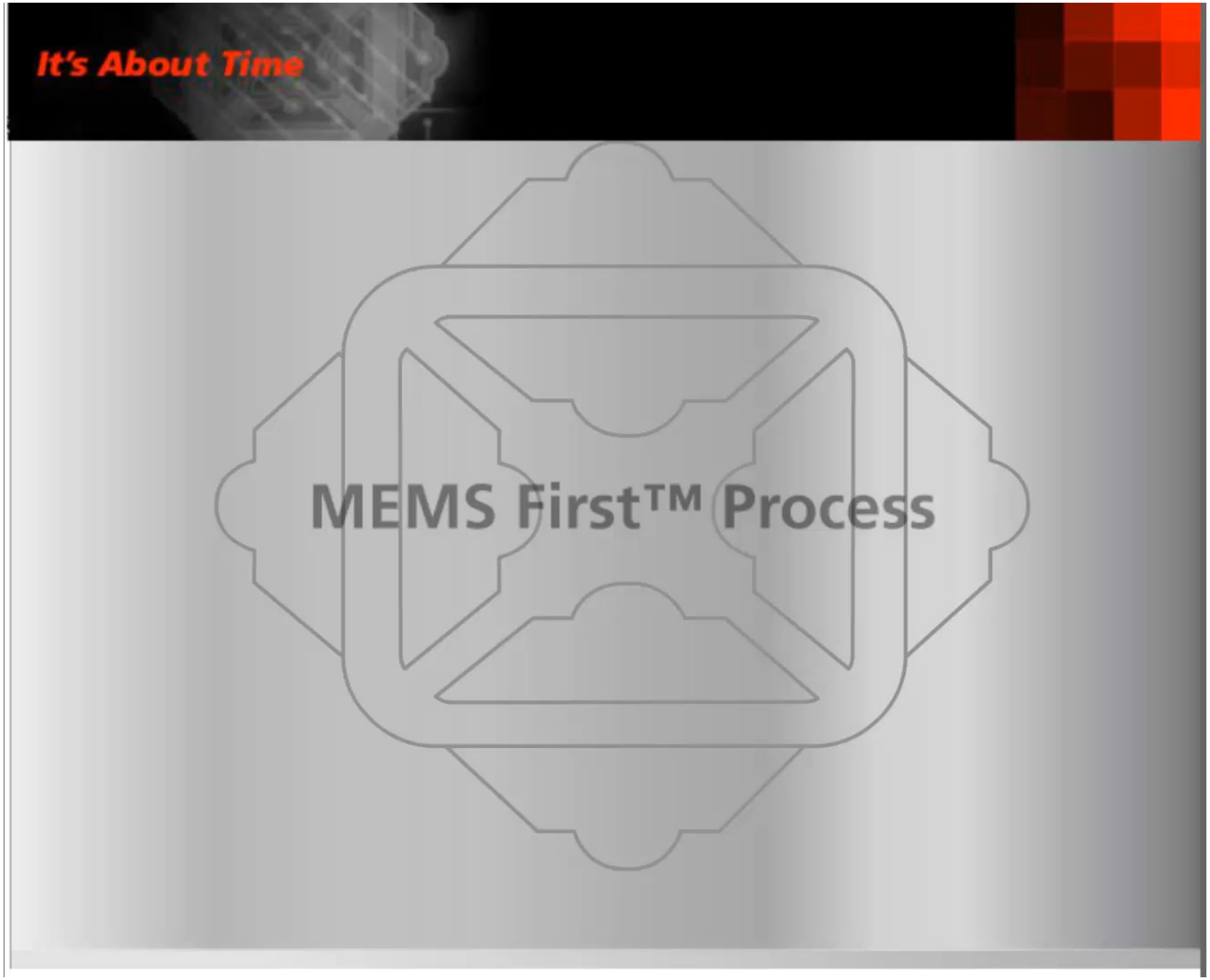
  - $S_\phi(\delta f) = 10\ log\left(F \frac{k_B \cdot T \cdot f_0}{Q \cdot E} \frac{1}{\delta f^2}\right)$
  - Incomplete, needs some modifications/additions
- Specifications/Requirements
  - Depend on the *carrier frequency*
    - High frequencies can be divided
    - "Averages" $1/f^2$ noise
  - Great advantage of MEMS
    - High $FOM_1 = f_r \cdot Q$
- Phase noise is a very critical parameter because it cannot be filtered out or adjusted externally

GSM Requirements	
f_m	*PN*
kHz	dBc/Hz
200	≤ -118
400	≤ -124
600	≤ -127
800	≤ -130
1600	≤ -136
> 3200	≤ -141

[Q. Gu, Springer 2005]



Packaging – SiTime MEMS-First process



Take home messages

- What is a Resonator?
- Quality factor
  - High or low?
  - What determines if it's high or low?

- Why MEMS resonators?
- Types of MEMS resonators
  - Frequency dependence on dimensions
  - Major application fields

- MEMS filters (passive)
  - What are the most important parameters to optimize?
- MEMS oscillators (active)
  - Why is phase noise important?
  - Why is T stability important and how is it achieved?

Lecture 6 – NEMS

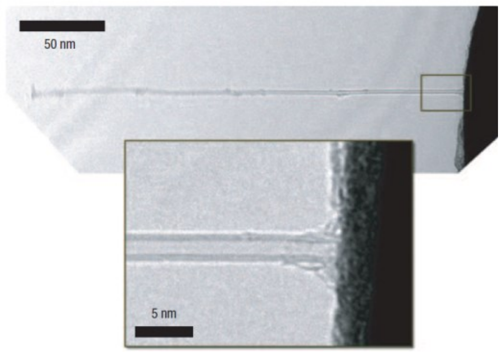
Prof. Guillermo Villanueva

Advanced NEMS Lab (ANEMS)

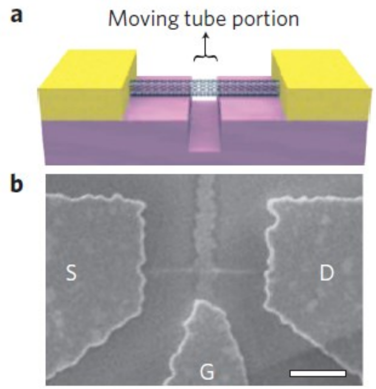
EPFL-IGM NEMS

Contents

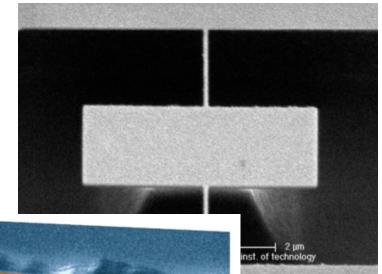
- **Introduction**
  - **NEMS examples**
  - **NEMS definition(s)**
  - **Why NEMS?**
  - **NEMS Fabrication**
  - **Main challenges**

a


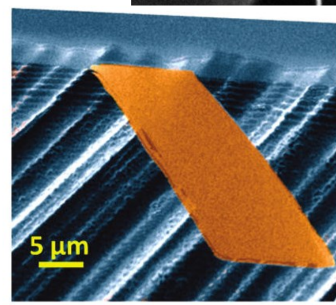
50 nm
5 nm



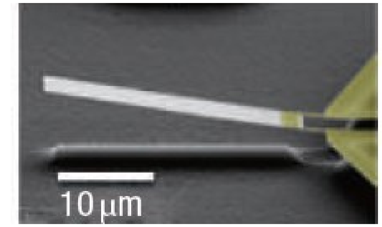
a
Moving tube portion
b
S
D
G



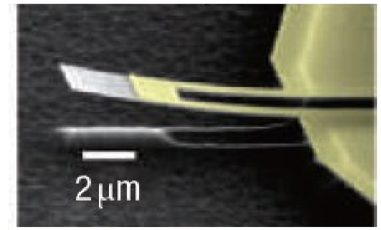
2 µm
inst. of technology



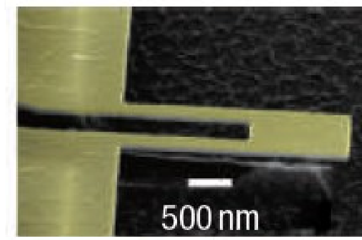
5 µm



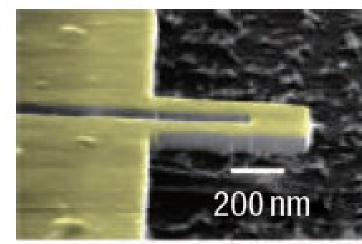
10 µm



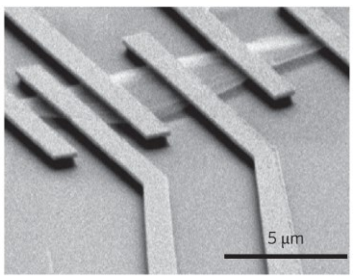
2 µm



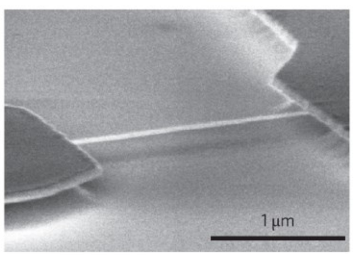
500 nm



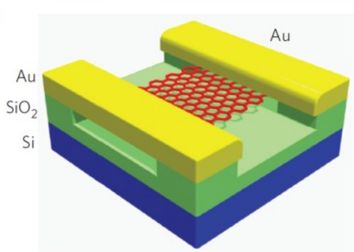
200 nm

a


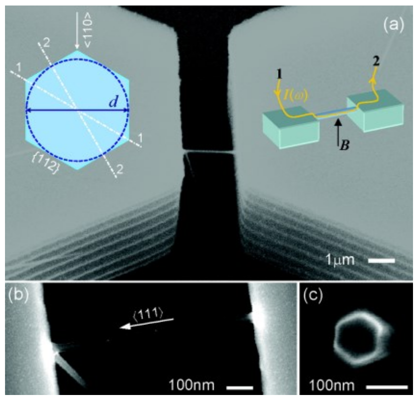
5 µm

b


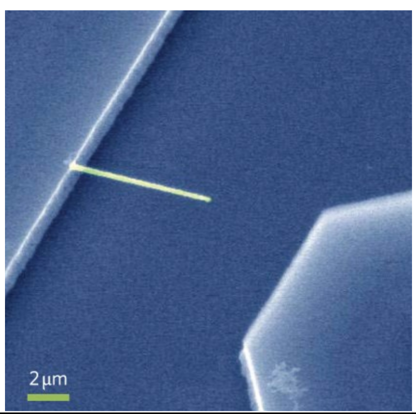
1 µm

c


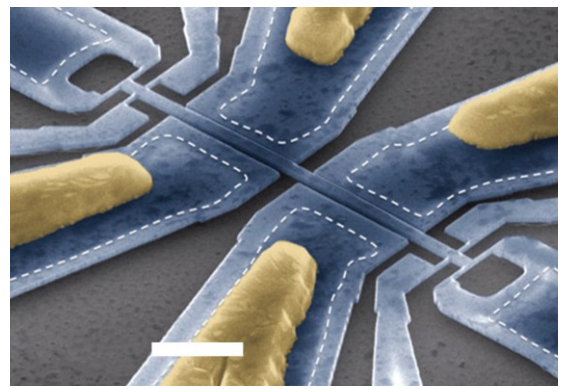
Au
Au
SiO2
Si

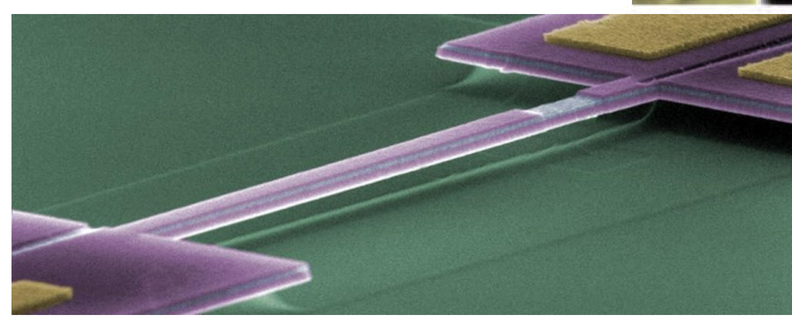


(a)
d
⟨112⟩
⟨110⟩
1
2
B
1µm
(b)
⟨111⟩
100nm
(c)
100nm



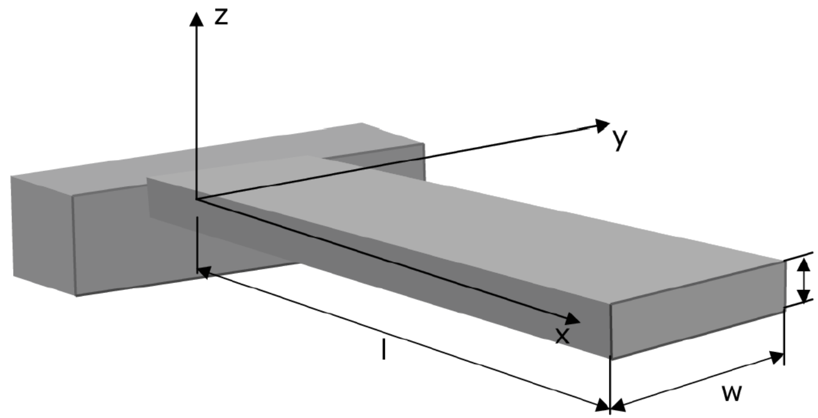
2µm





NEMS definition

- NEMS tends to include "small MEMS"
- 1 possible definition
  - 2 out of 3 dimensions $\leq 1\mu m$
- But then…
  - What about graphene resonators?
  - Or extremely thin MEMS?



- Another possible definition – "mesoscopic system"
  - Referring to number of atoms in the mechanical device
    - Golden Gate – $\sim 10^{34}$ atoms
    - Trampoline – $\sim 10^{28}$ atoms
    - Guitar string – $\sim 10^{23}$ atoms
    - MEMS accelerometer – $\sim 10^{16}$ atoms
    - Thin plate – $\sim 10^{12}$ atoms
    - Si-based NEMS – $\sim 10^{10}$ atoms
    - CNT – $\sim 10^{5}$ atoms

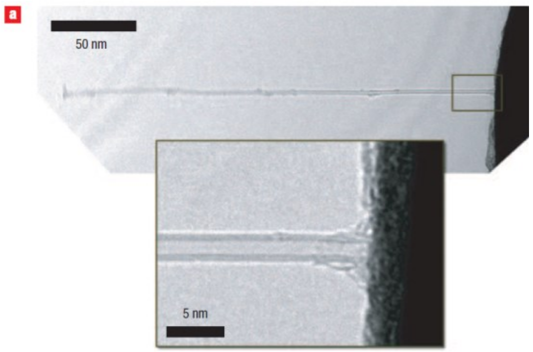
Macroscopic (Golden Gate, Trampoline, Guitar string)
Microscopic (MEMS accelerometer, Thin plate)
Mesoscopic (Si-based NEMS, CNT)

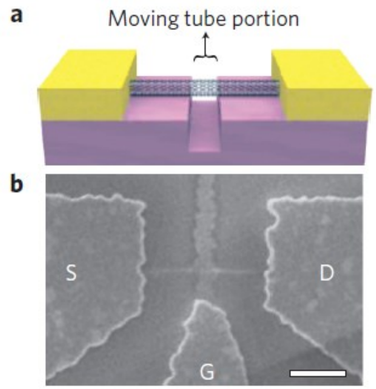
NEMS Fabrication

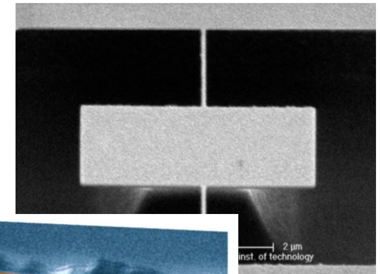
- Top-Down
  - Pushing down the dimensions of standard µfab tools
  - EBL, DUV, NIL, Stencil, FIB – To improve the resolution of UV Lithography
  - Finer tuning of etching and deposition recipes
    - Smooth edges
    - Accurate thicknesses
  - Easy integration and connection to “macro” world
  - Very high cost to reduce dimensions

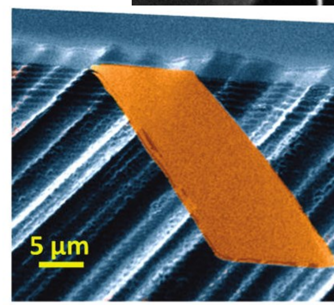
- Bottom-up
  - Direct growth/synthesis of structures
  - Highly based on chemical processes and reactions
    - CVD, VLS method, Arc-discharge…
  - Very cheap to produce millions of devices
  - Very difficult to integrate and connect them (eventually using top-down techniques)

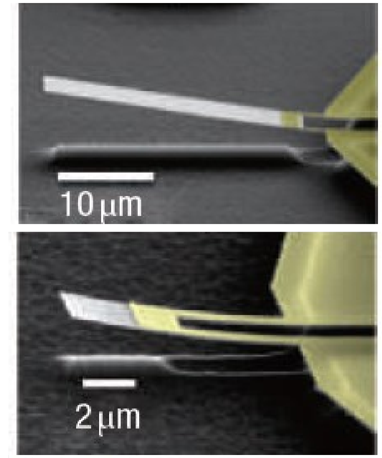
NEMS examples

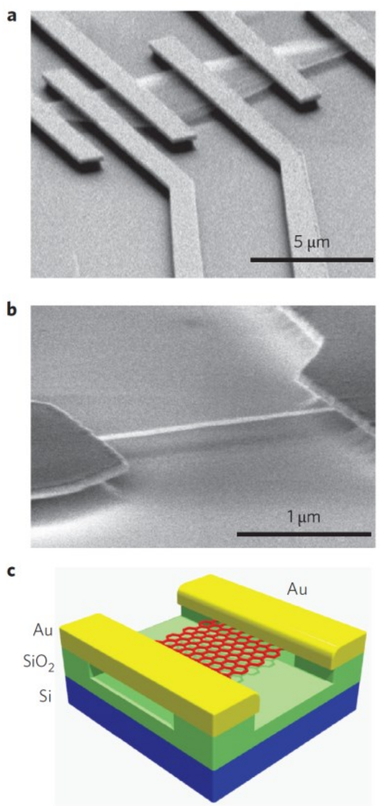


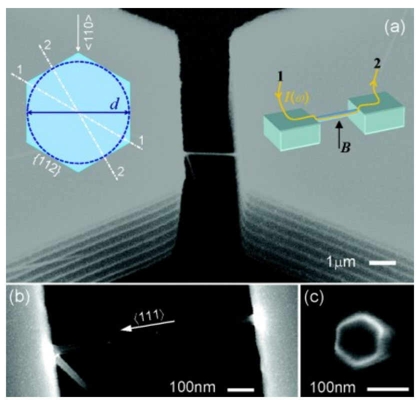


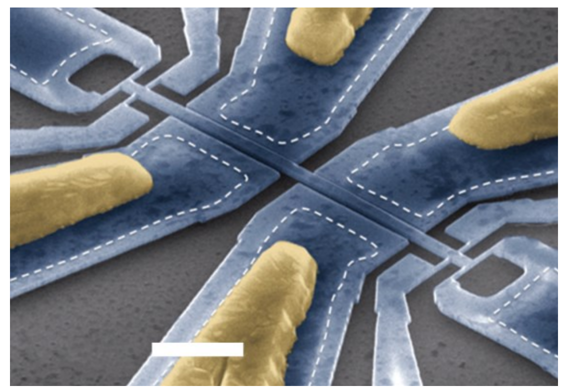


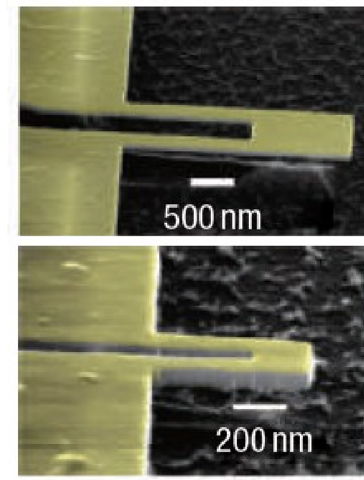


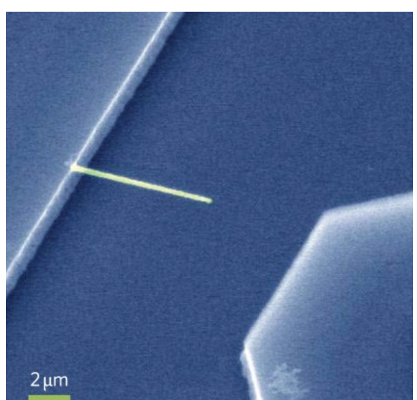


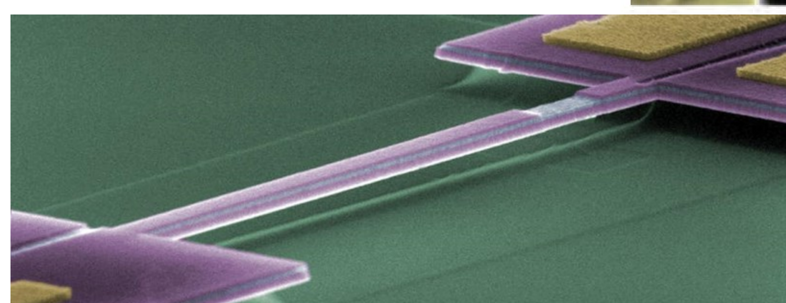


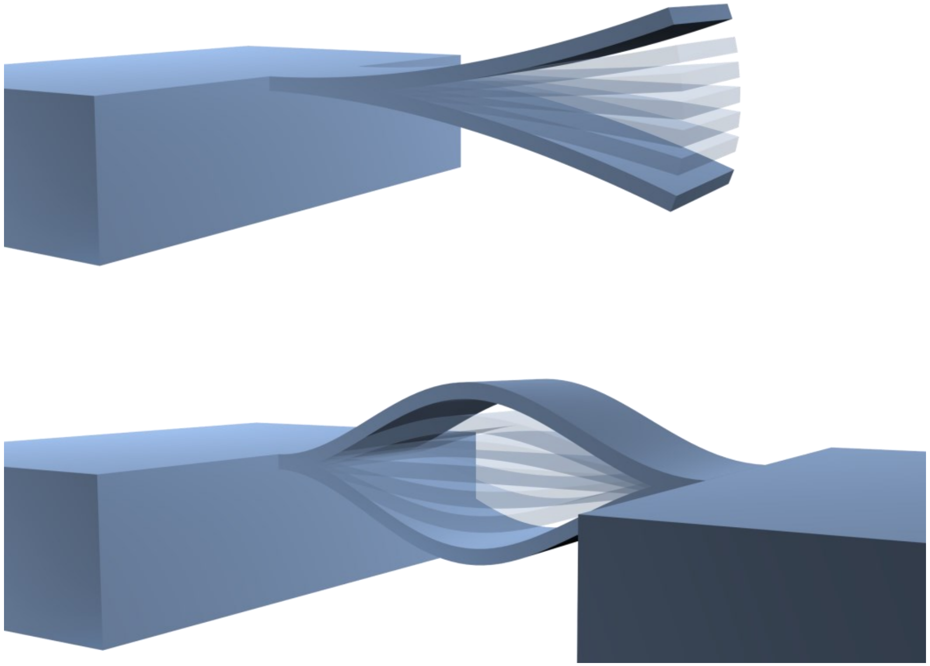


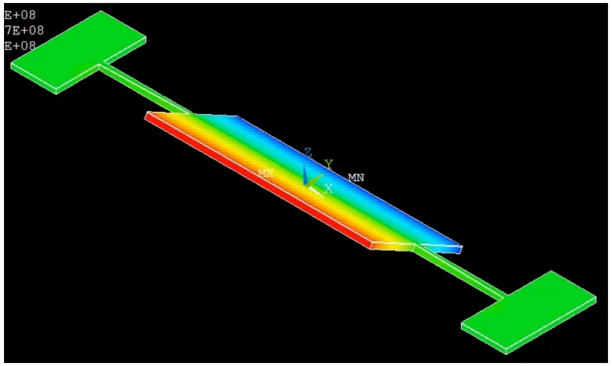












- Intuitive and clear understanding of motion
- Very low masses
- Very low stiffness

Why NEMS?

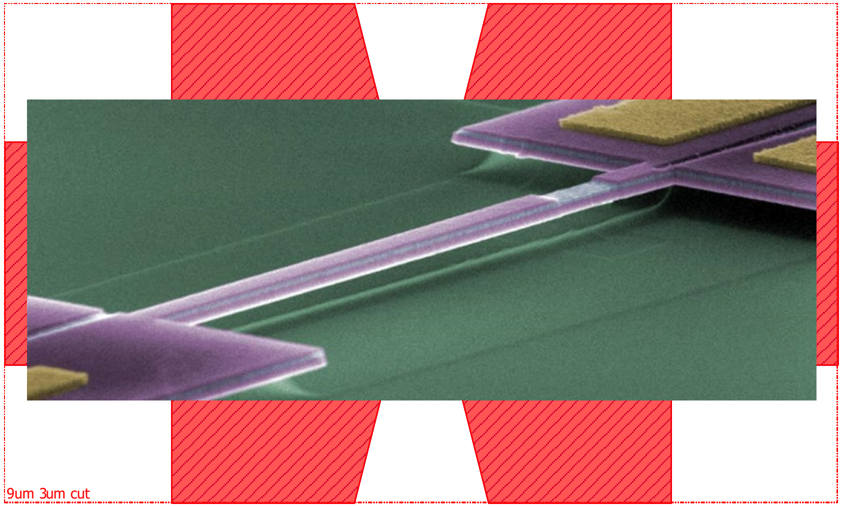
- **Size**
  - Higher level of integration
  - Very thin – good for stress-based sensing
- **Mass**
  - Low thermal mass – good for T or heat sensing
  - Low mass – good for detection of small mass landing
  - Gravity/Acceleration can be mostly neglected
- **Stiffness**
  - Low stiffness for a given frequency – good for Force sensing
- **Frequency**
  - High frequency – less influence from vibrations & faster measurement

Challenges

- Fabrication
  - Expensive (top-down)
  - Difficult to contact (bottom-up)
  - Imperfections become (relatively) too large
    - Surface roughness
    - Surface contaminants
    - Material defects
    - Grain boundaries

- Low reproducibility
- Mechanical properties deteriorate
- Lower Q factors

- Measurement
  - Connection to "macro" world unavoidable
  - Motional signal is "buried" in parasitics
  - Very challenging to
    - Match impedance
    - Remove background
    - Amplify signal



STATIC DETECTION

Static detection

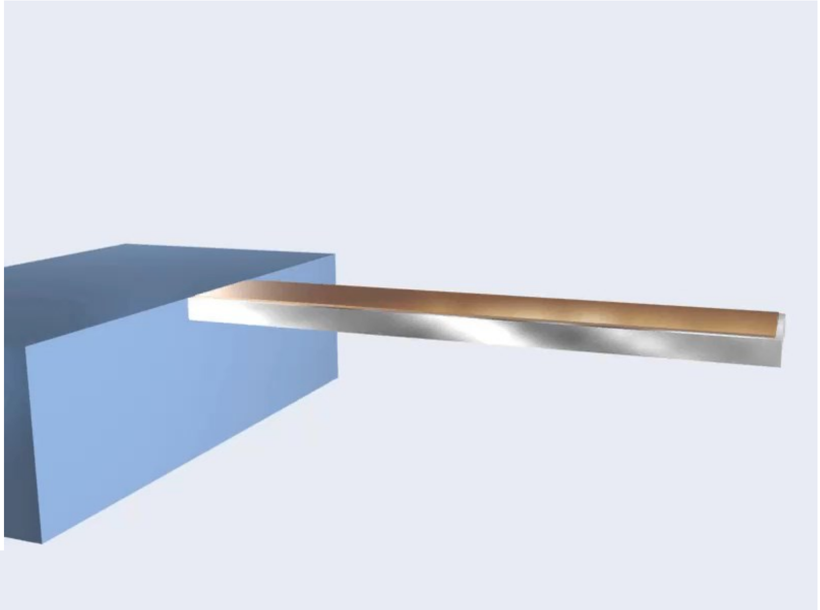
- **Mechanical system is not moving at first**
- **Event happens and mechanical device responds**

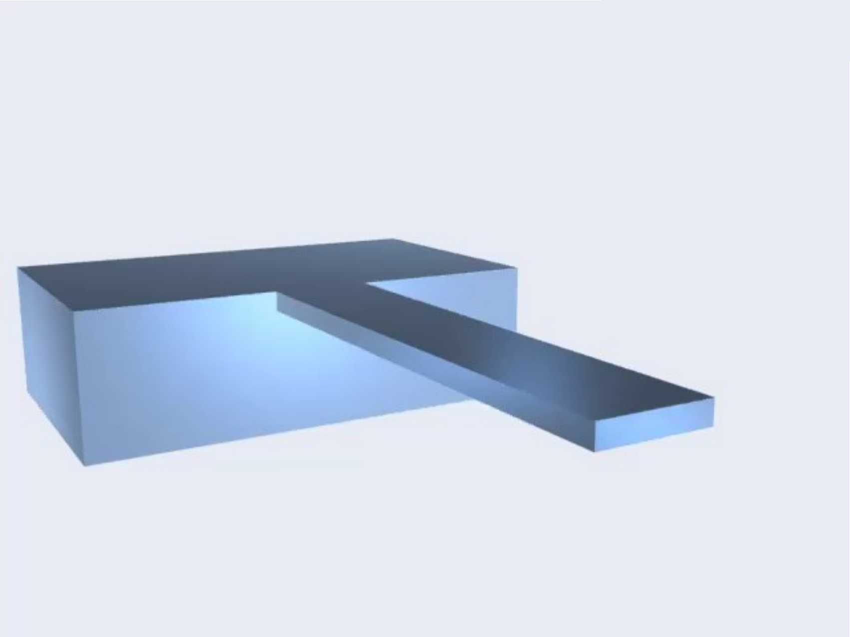
Static detection

- Mechanical system is not moving at first
- Event happens and mechanical device responds

- Temperature
  - Thermal expansion gradient

- Gas sensor
  - T based



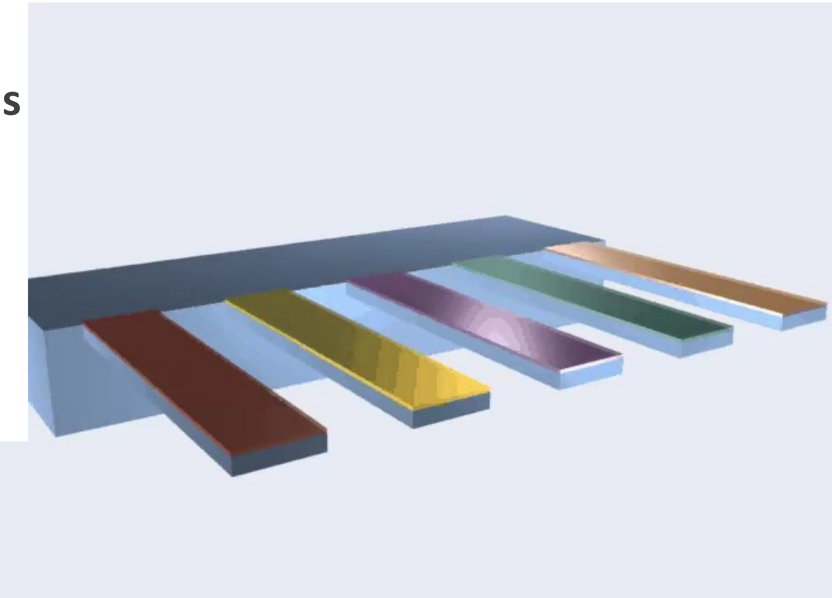


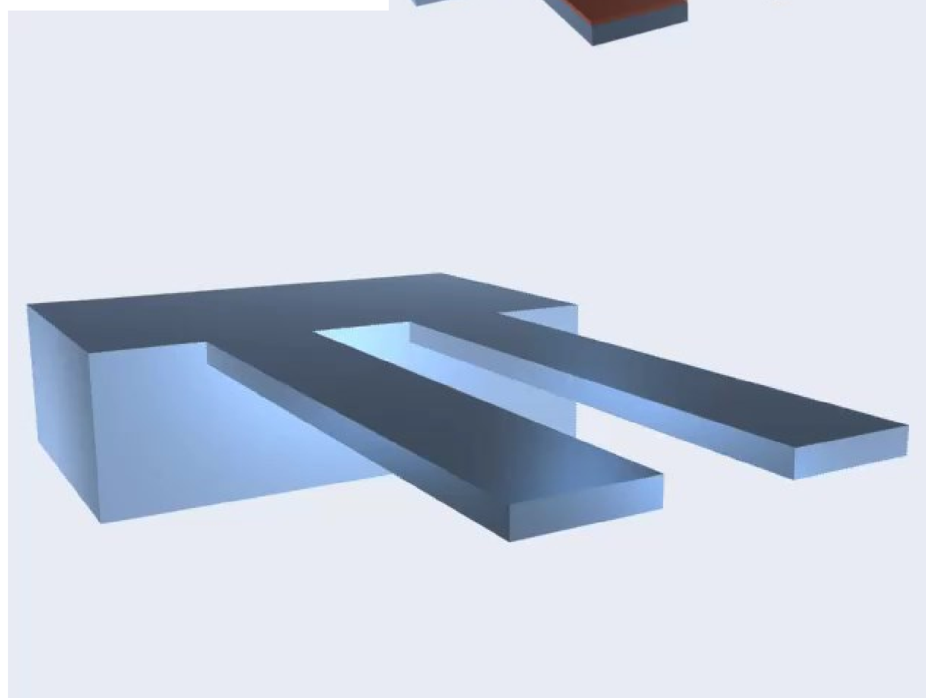
- Mechanical system is not moving at first
- Event happens and mechanical device responds

- Temperature
  - Thermal expansion gradient

- Gas sensor
  - T based
  - Surface stressed based

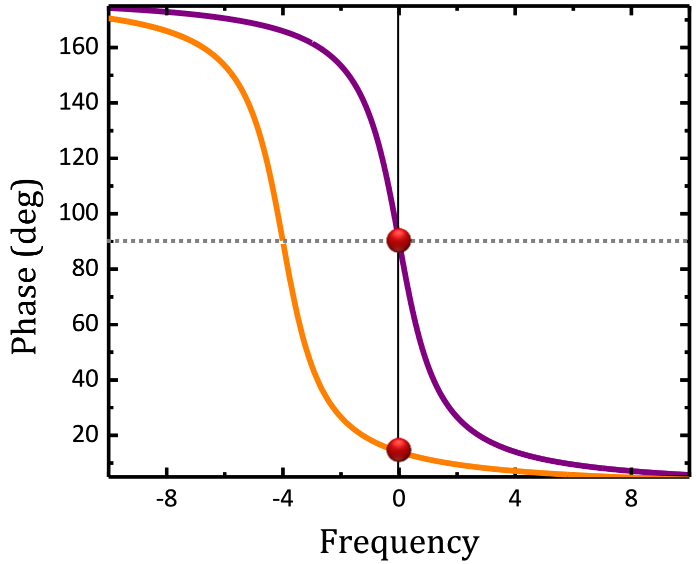
- Reference always needed

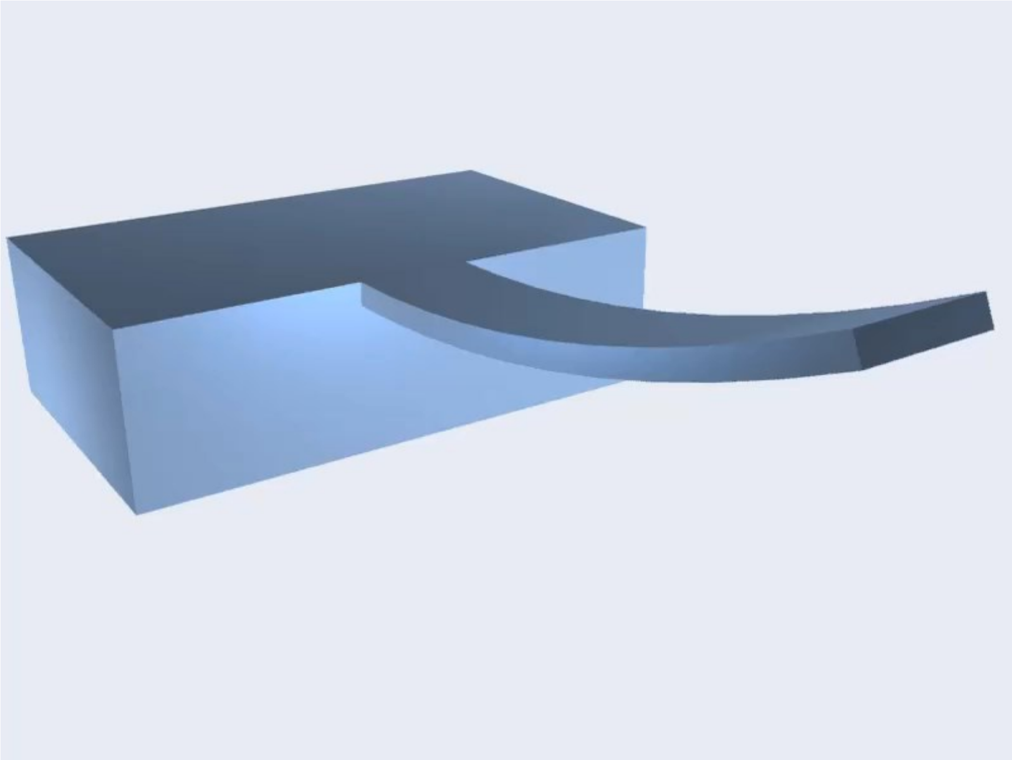




DYNAMIC DETECTION

- **Mechanical system moving constantly**
  - At or close to the resonance frequency
- **Event happens and mechanical device responds**
  - By changing its resonance frequency
- **Frequency is the magnitude that is tracked**
  - PLL or oscillator
  - Frequency counter



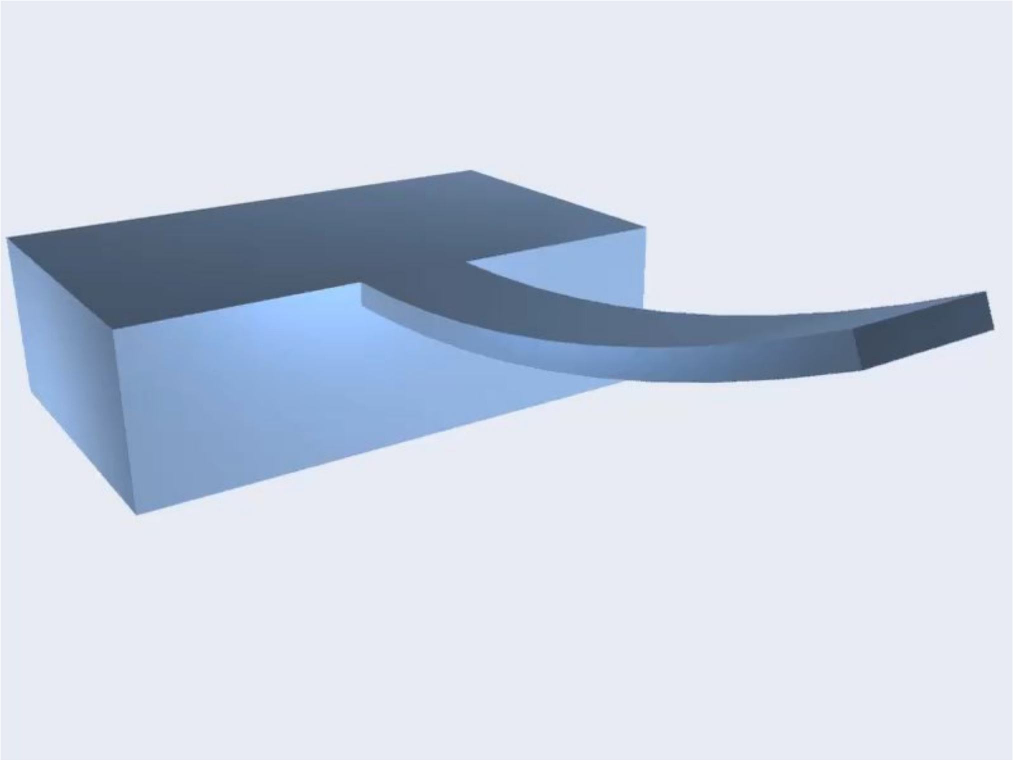


Dynamic detection

- Mechanical system moving constantly
  - At or close to the resonance frequency
- Event happens and mechanical device responds
  - By changing its resonance frequency
- Frequency is the magnitude that is tracked
  - PLL or oscillator
  - Frequency counter

Noise in frequency determines device performance

- Mass
  - Deposition or removal of material
  - Gases, mass spectrometry
- Material properties
- Temperature
- Stiffness
- Stress



Take home messages/Possible questions

- **Why NEMS?**

- **Static & dynamic sensing**
  - **How do they work in general?**
  - **What are the main differences between NEMS and MEMS?**
  - **Why is it interesting to go to NEMS?**
  - **Examples**
  - **What is most important?**
  - **How to build a better sensor?**