Bandwitdh limit and sensitivity of a multi-mode opto-electomechanical transducer

Nicola Malossi
Sezione di Fisica, Scuola di Scienze e Tecnologie
Università di Camerino

06/10/2017 Pisa

Outlook

1. About the quantum optics and cryogenic group in Camerino
2. Electro-opto mechanics: motivations
3. Designing an Electro-opto-mechanics device
4. Single mode and multi mode RF-optical transducer
5. Proof of principle device and experimental result
6. Conclusion and outlook

Quantum optics and cryogenic group in Camerino

Theoretical tradition in quantum optics and recently in opto-mechanics (Tombesi, D.Vitali)

Experimental tradition in Cryogenics (superconduction) (R. Natali, “russian school”) 1994

Experimental quantum optics activity 2008 (quantum cryptography) (G. Di Giuseppe, R. Natali)

Experimental opto-mechanics (G. Di Giuseppe, R. Natali, D. Vitali) 2010

Experimental electro-opto-mechanics (G. Di Giuseppe, R. Natali, N. Malossi D. Vitali) 2013

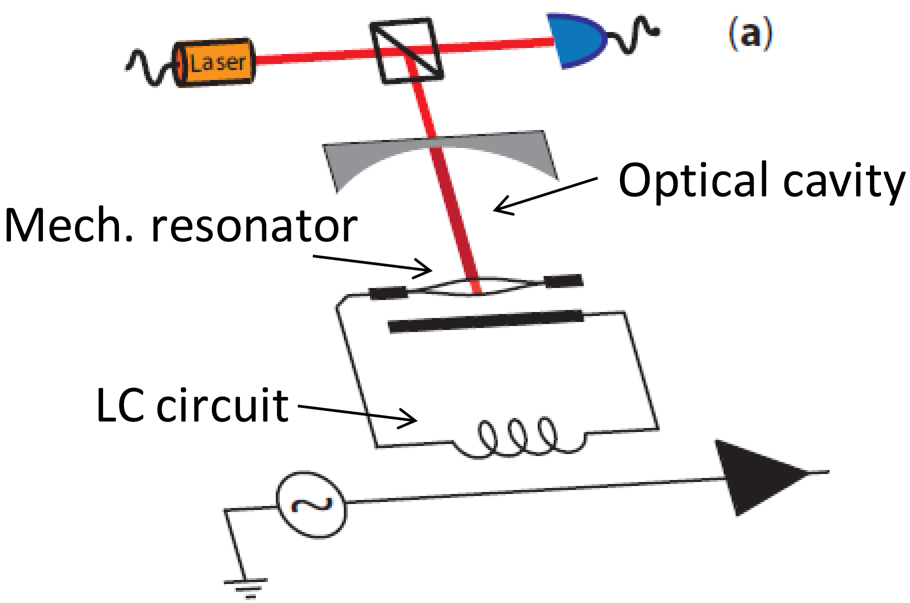
Group:
Theory: D.Vitali, F.Zippilli
Experiment: G. Di Giuseppe, R. Natali, N. Malossi, M. Bawai

Projects: HUMOR INFN group 2
ITN-Marie Curie cQOM
FP7 iQuoems
H2020-FETPROACT: HOT

Why Electro-opto-mechanics?

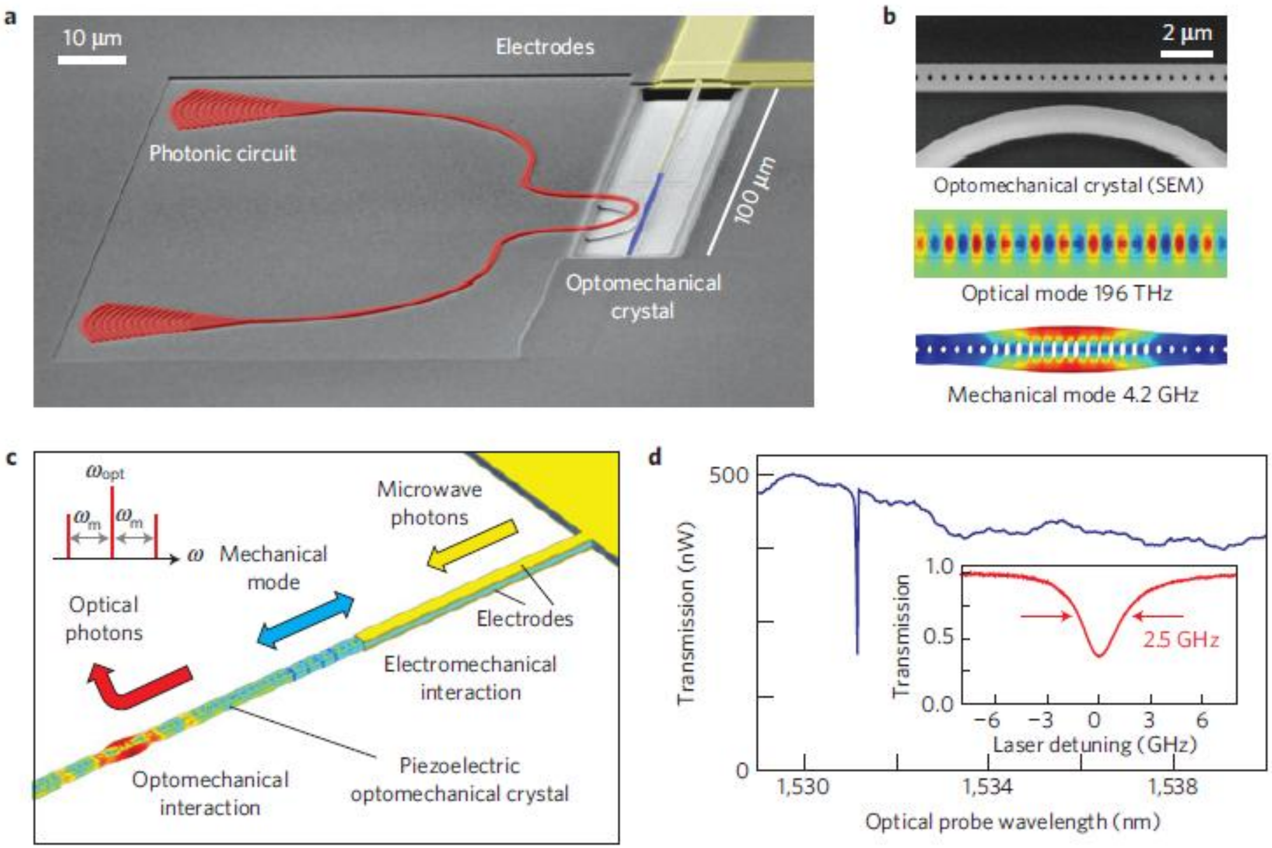
Light is optimal for quantum communications between nodes, while **microwaves/RF** are used for manipulating solid state quantum processors

⇒ **a quantum interface between optical and microwave photons would be extremely useful**

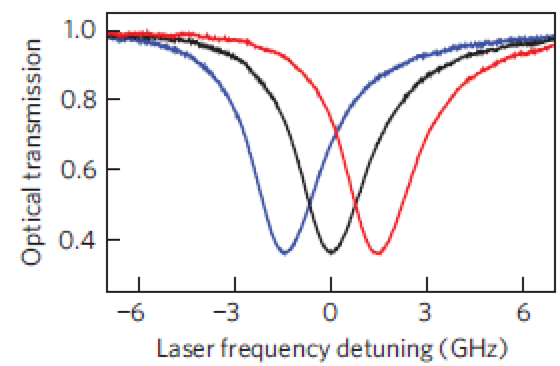


Quantum interface between optical and microwave photons based on a **nanomechanical resonator in a superconducting circuit, simultaneously interacting with the two fields**

VARIOUS RECENT EXAMPLES

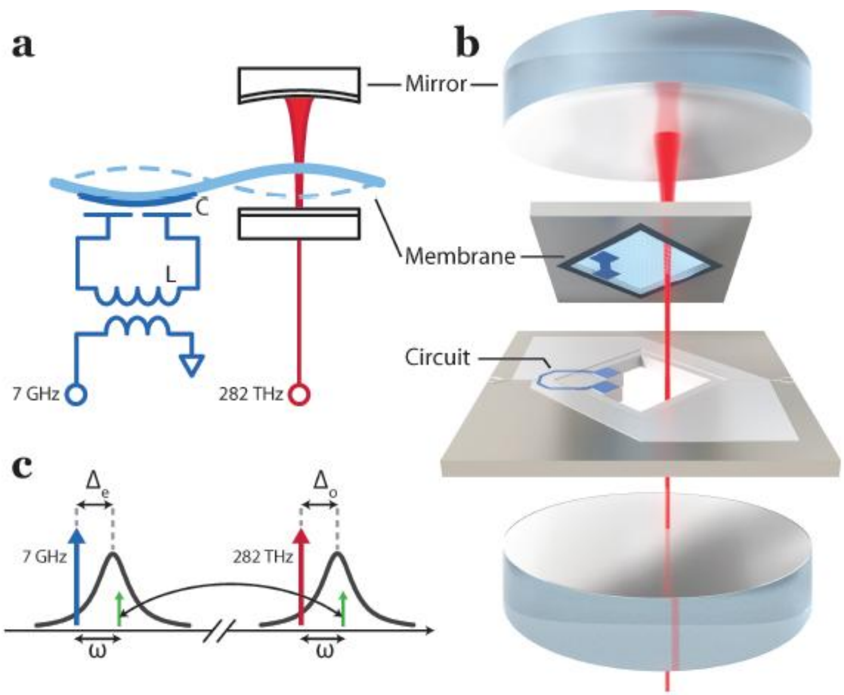


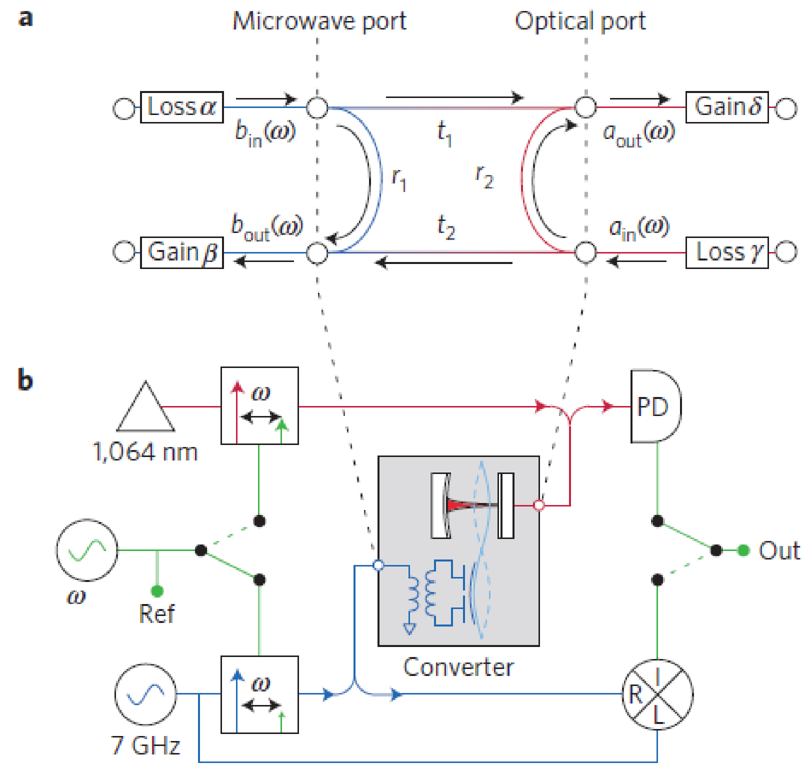
Cleland group, UCSB, NatPhys 2013



Piezoelectrically controlled optomechanical crystal

MEMBRANE-OPTICAL-TO-MICROWAVE CONVERTER





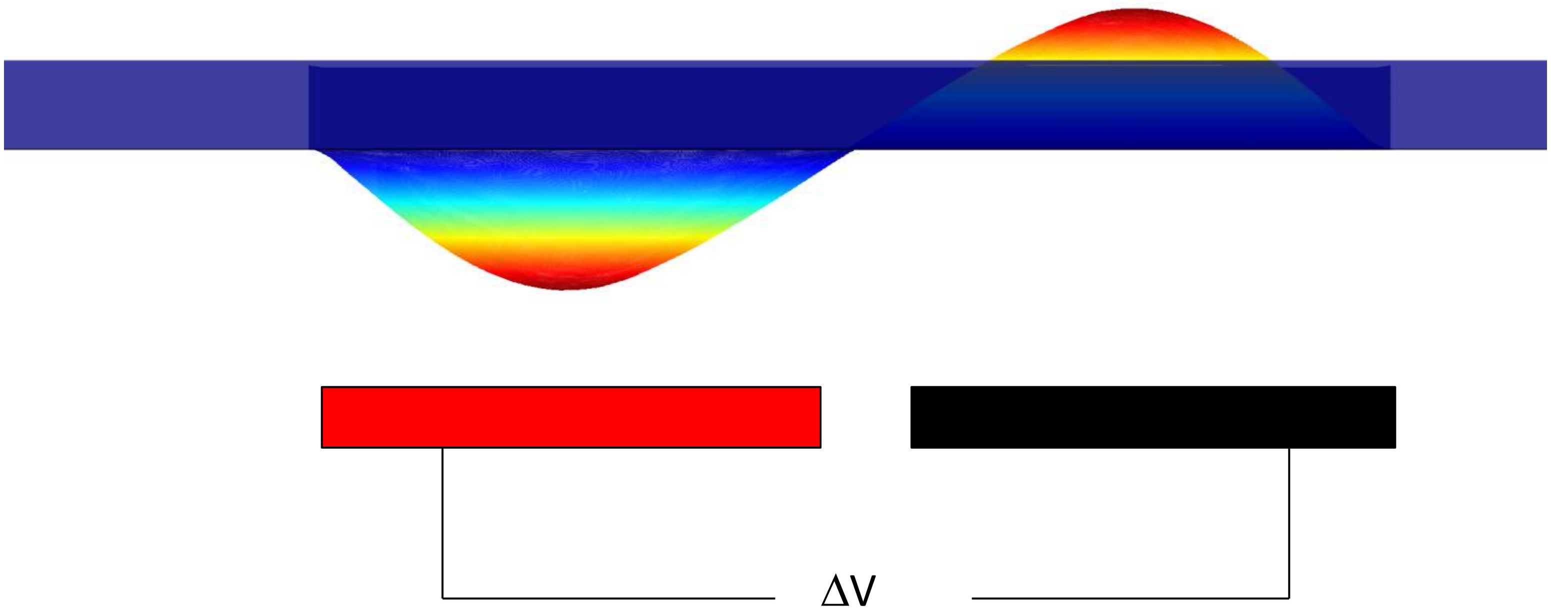
Adding a LC circuit to the membrane-in-the-middle setup, R.W. Andrews et al., Nature Physics 10, 321–326 (2014)

Electro-opto-mechanics in Camerino: The plan.

1. Realizing an electro-mechanical (High-Q mechanical) device in the RF domain with optical properties.
2. Characterization of the electro-mechanical device by optical and electrical means at room temperature and at cryogenic temperature.
3. Realization of a "RF to optical" transducer at room temperature and cryogenic temperature.
4. Study and developing strategies to increase transducer bandwidth.
5. Realization of a "two-ways RF-optical" transducer, exploiting opto-mechanical interaction (cavity-optomechanics)
6. The asymptotic limit: developing a quantum transducer (cryogenic temperature)

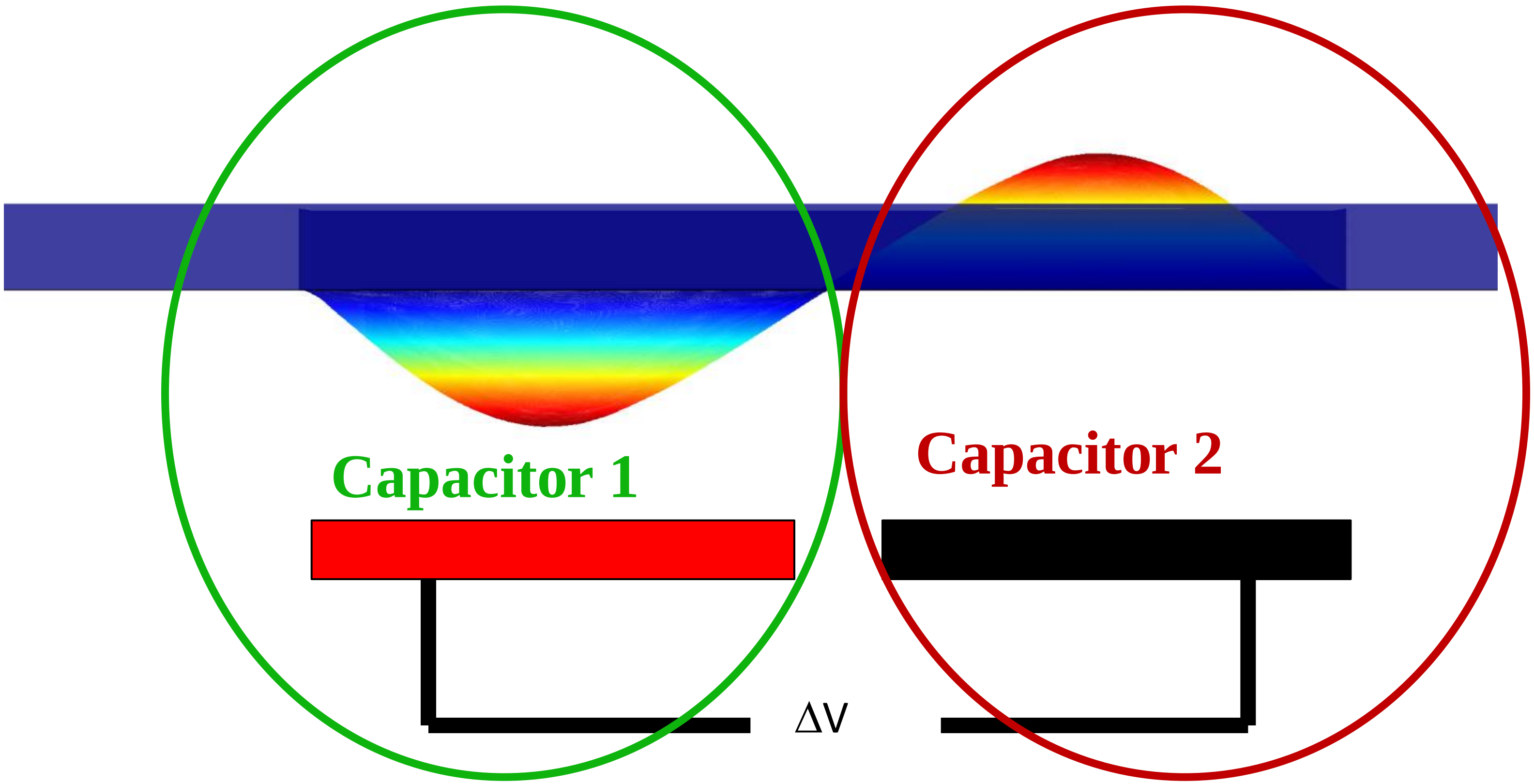
Capacitive coupling: no-contacts capacitor

High-Q Mechanical Oscillator (SiN 50nm thick) with metal on top



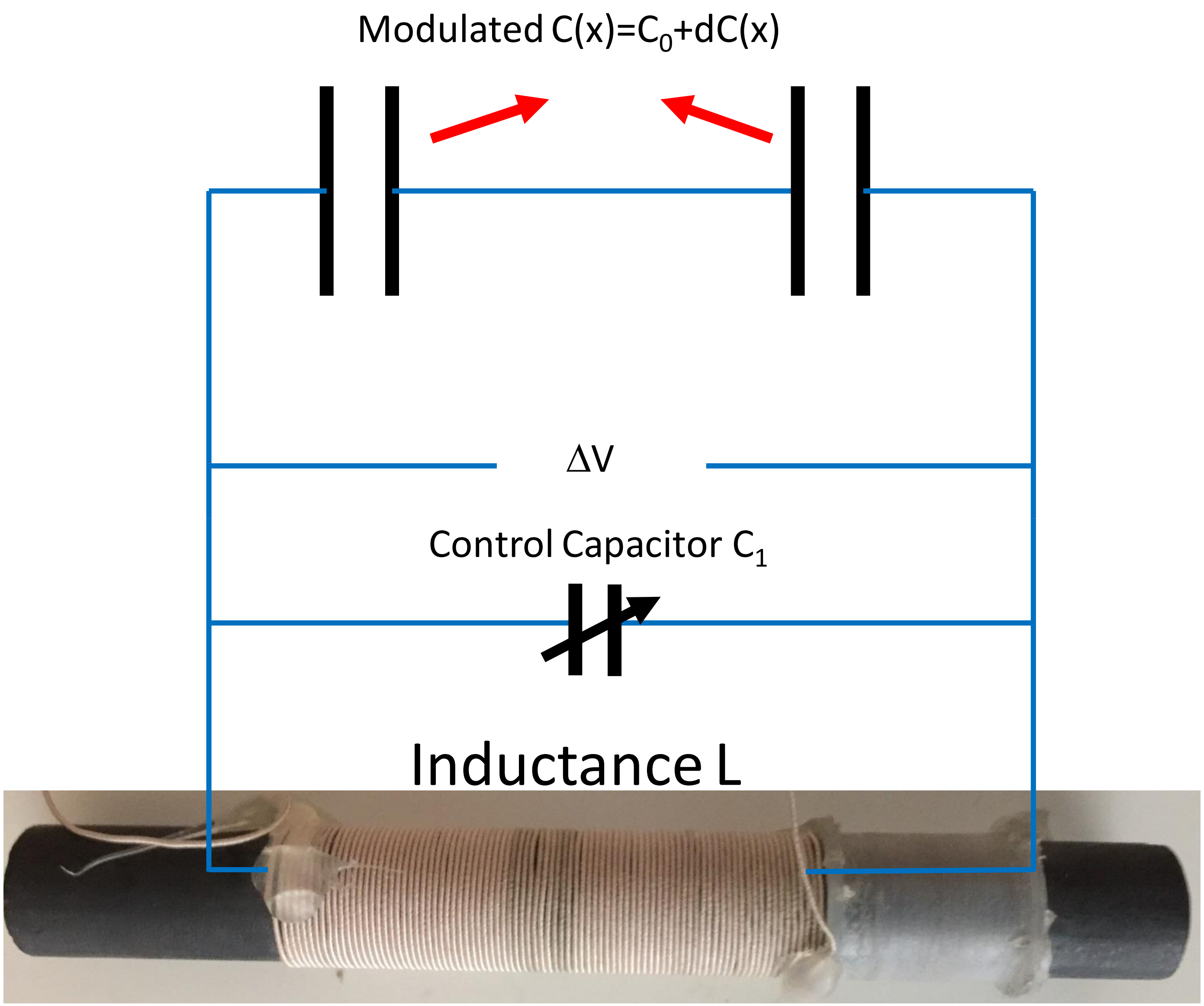
Electrodes

How do we build a elettro-mechanical oscillator?



Like having two capacitors in series whose capacitance is modulated by the mechanical motion

Coupling with L



Coupling

Designing and building an eletromechanical Oscillator:

1. Frequency
2. Quality Factor

Designing and building an LC Oscillator (Electrical)

1. Frequency
2. Quality Factor

Designing the eletromechanical oscillator: limits

Metalization of the membrane

Restrictions:

1. Optical access
2. No contact on the membrane
3. Quality factor behavior?
4. Decouplig from the frame

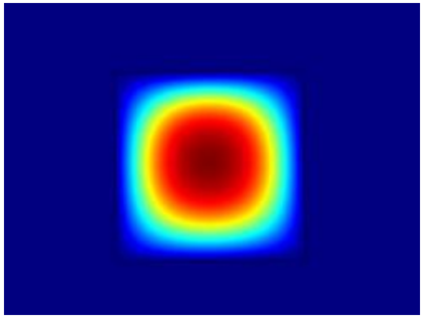
Designing of the electrodes

Restrictions:

1. Optical access
2. Coupling optimization to the mechanical modes
3. Distance from the membrane

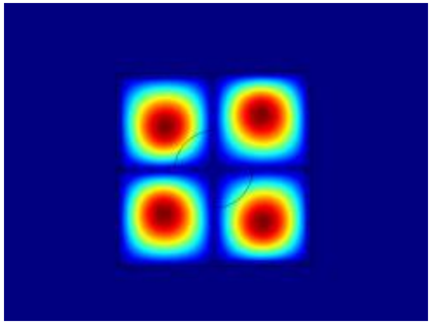
Mechanical Mode:

Most important choosing the "best" mechanical mode



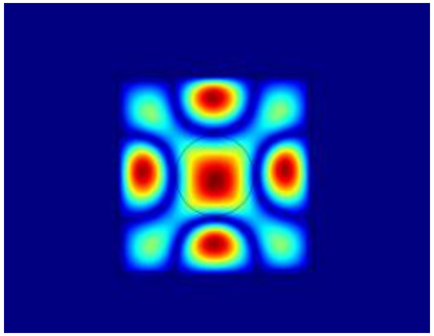
1. Coupling with light cavity mode: maximal

2. Eletromechanics: Maximum displacment is exactly where non metal can be placed2.



1. Coupling with light cavity mode: hard

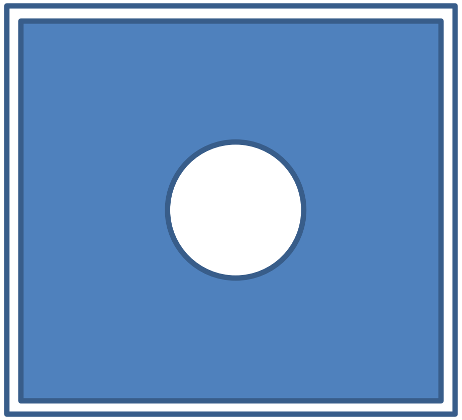
2. Eletromechanics: Maximum displacment is exactly where metal can be placed.



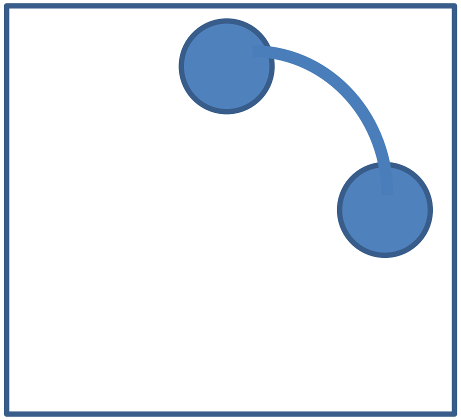
1. Coupling with light cavity mode: good

2. Eletromechanics: Maximum displacment is exactly where metal can be placed.

The metalized membrane:



Maximal Area (max coupling)

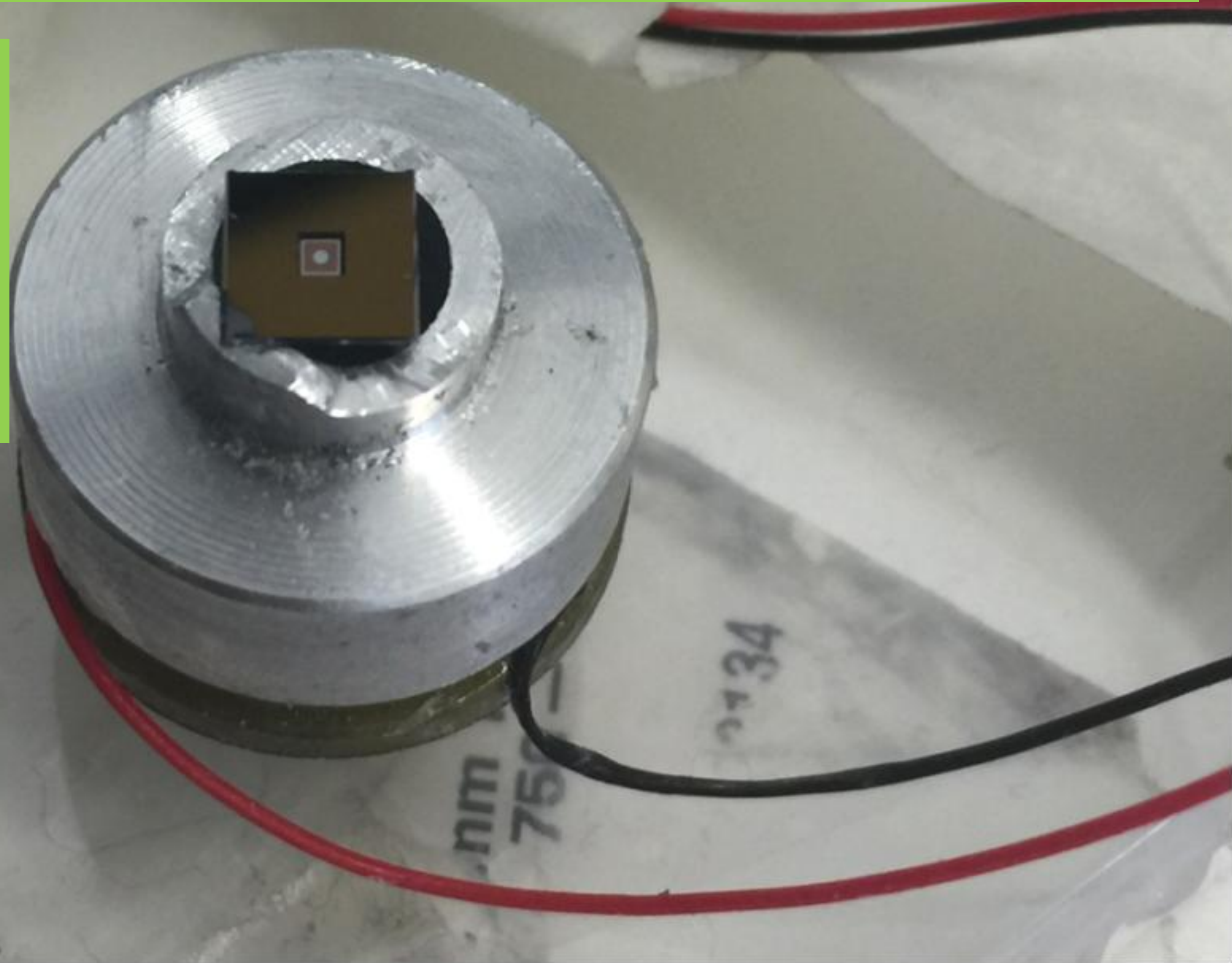


Minimal Mass
(min mode perturbation)

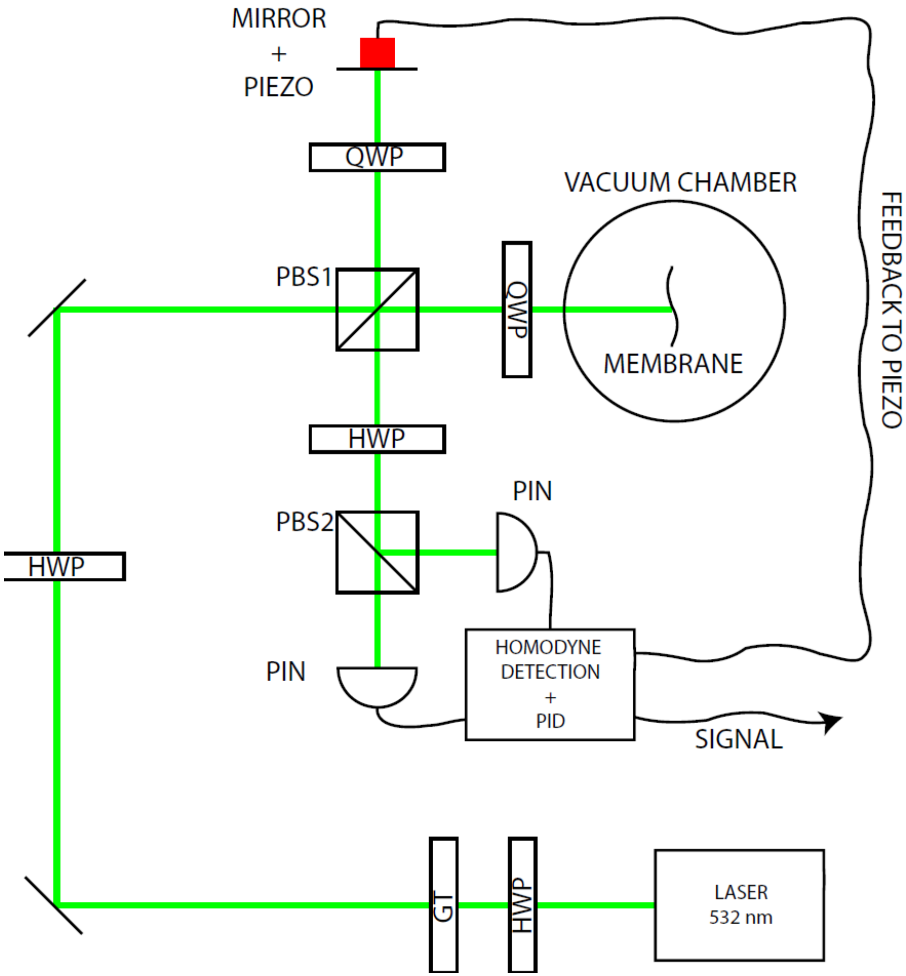
The mechanical oscillator

Mechanical oscillator: (made by NORCADA)
Silicon Nitride membrane: 1mm x1mm, thickness 50nm

Frequency foundamental mode: around 370 kHz (no metal)
Quality factor >10^5



Mechanical oscillator characterization



Noise spectrum:

Standard Interformetry

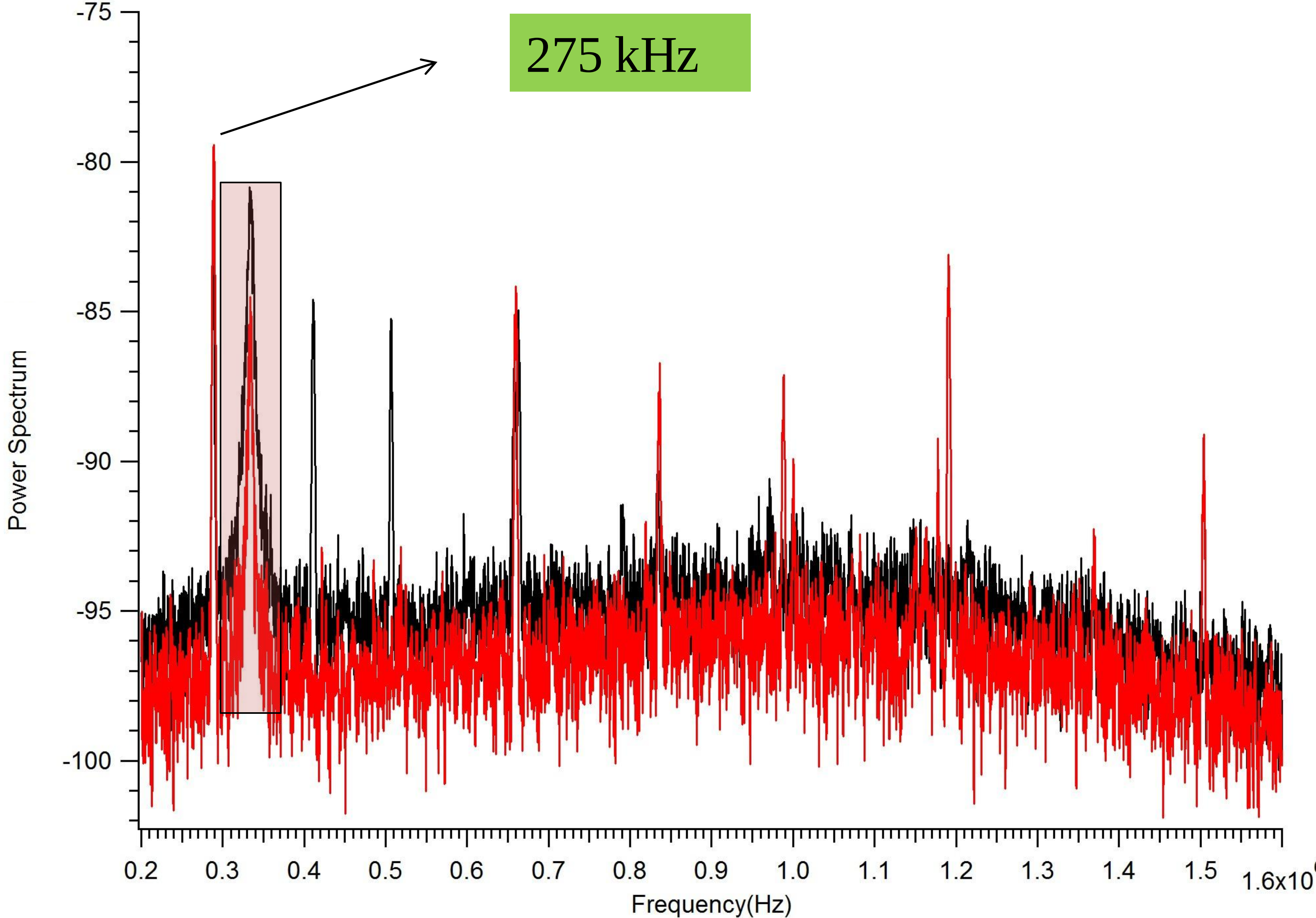
Shot noise limeted Homodyne Detection

Q factor (Lifetime):

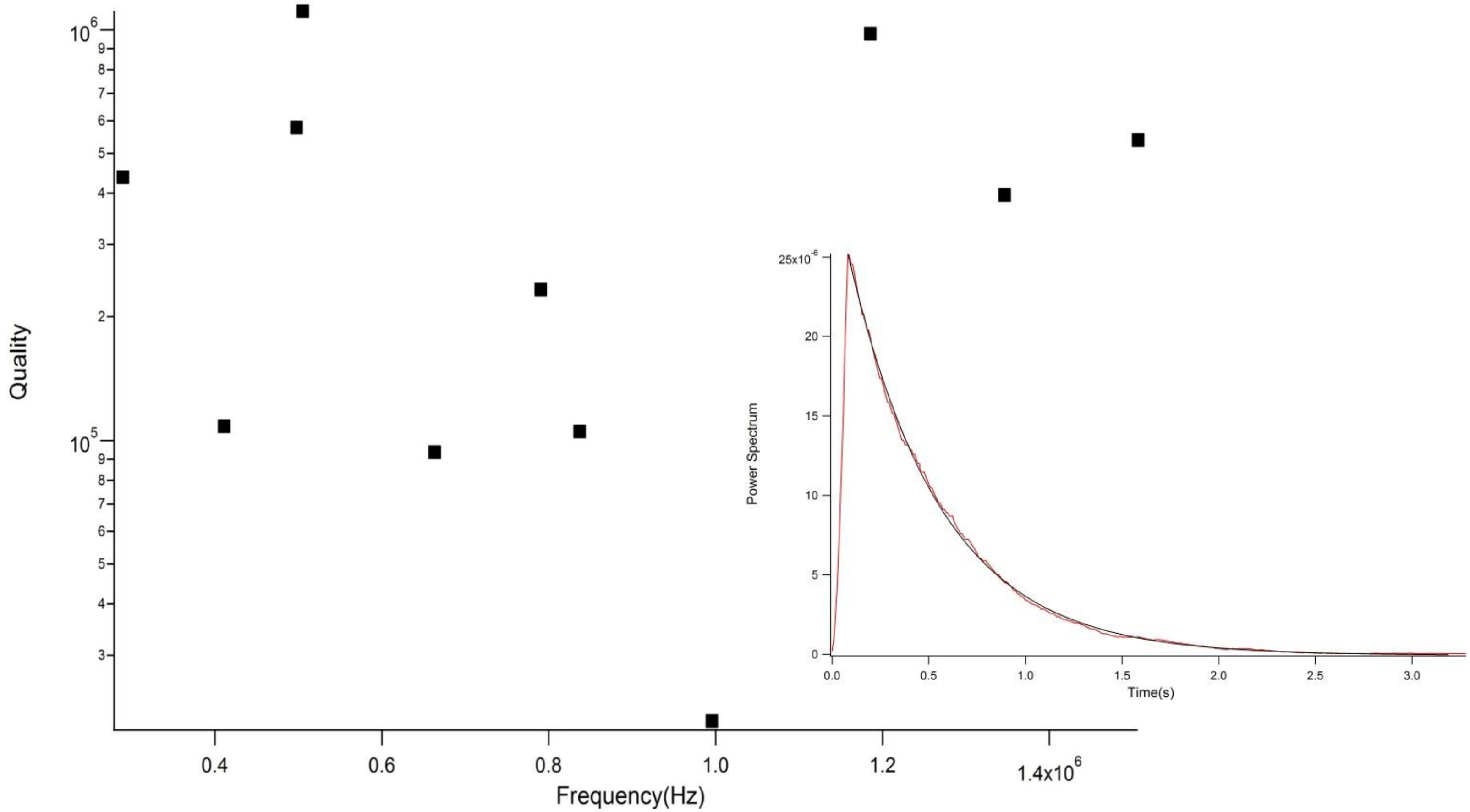
Ring down

Mechanical oscillator properties

Noise power spectrum: interferometry+homodyne detection

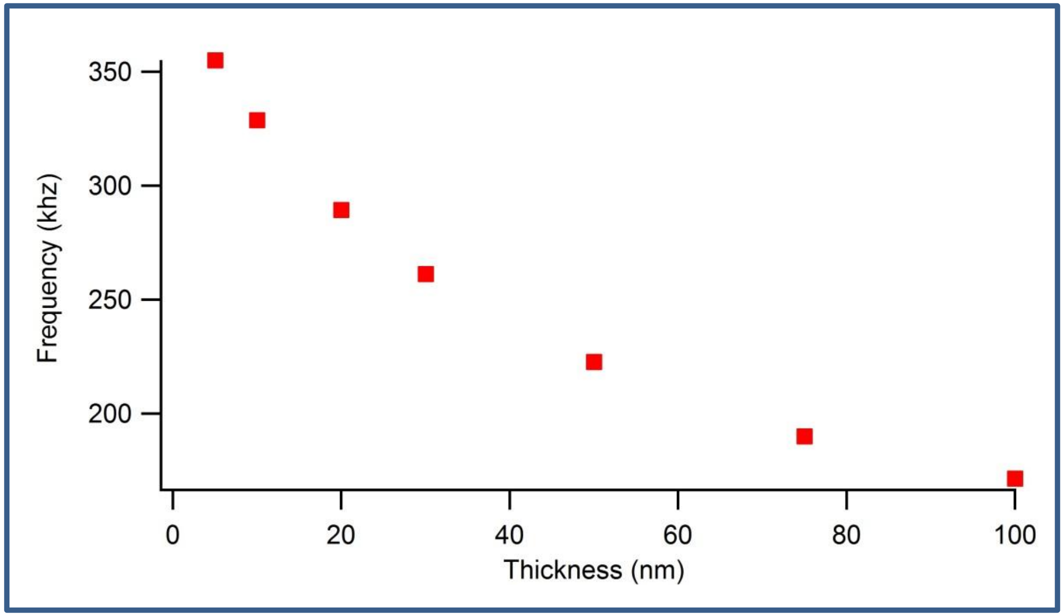


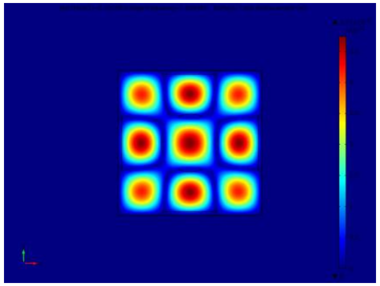
Oscillator quality factor



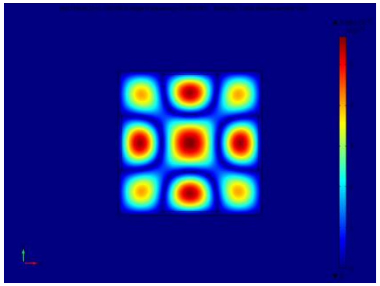
Q>100000

Problem: identify the modes.
Solved by Finite elements Simulation with Comsol

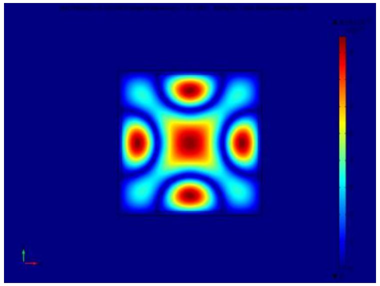




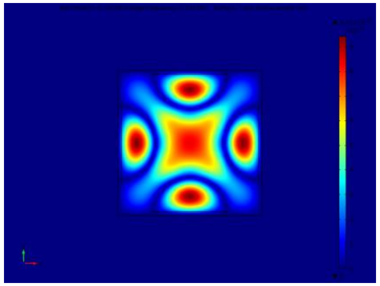
5nm



10 nm

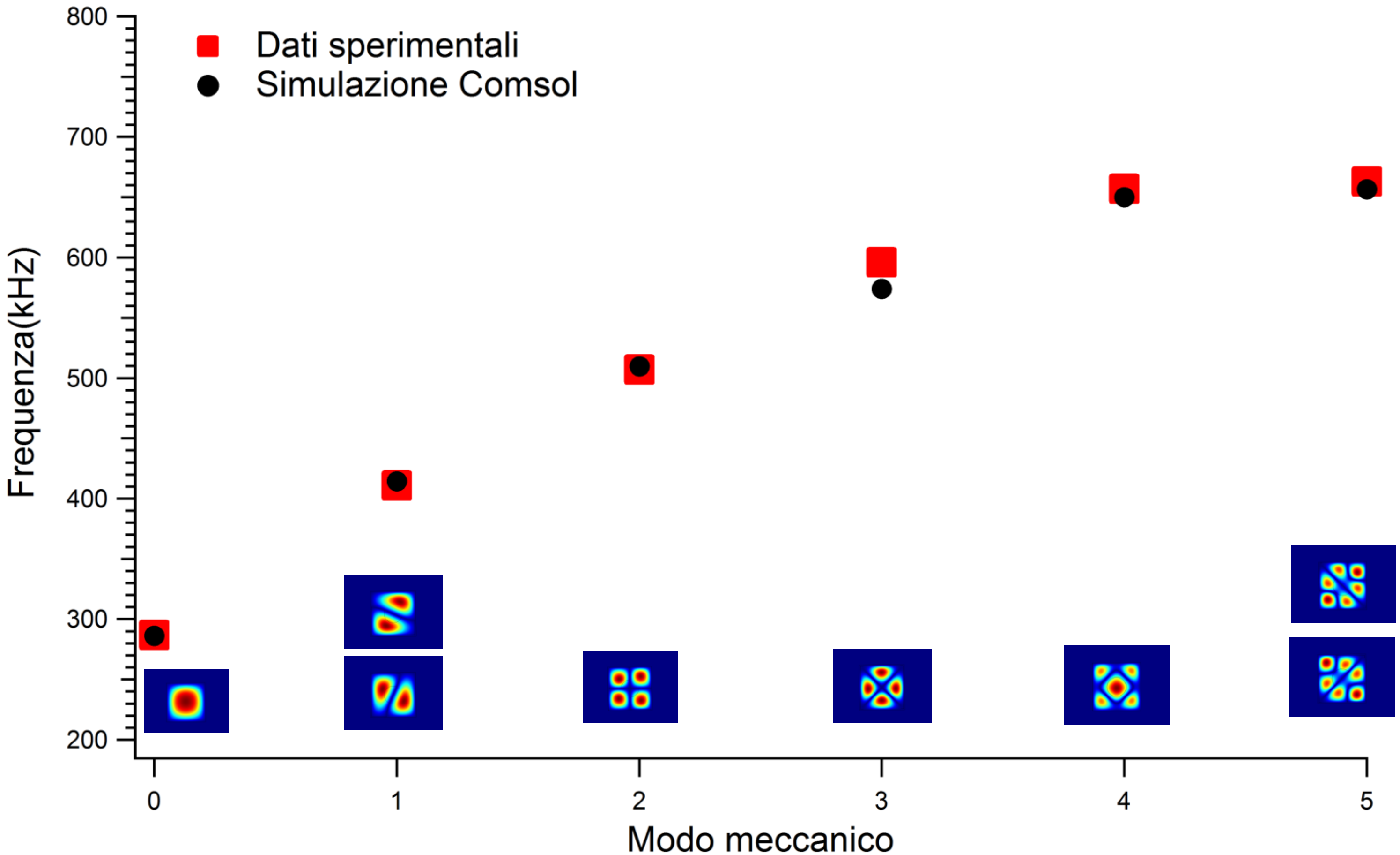


30 nm



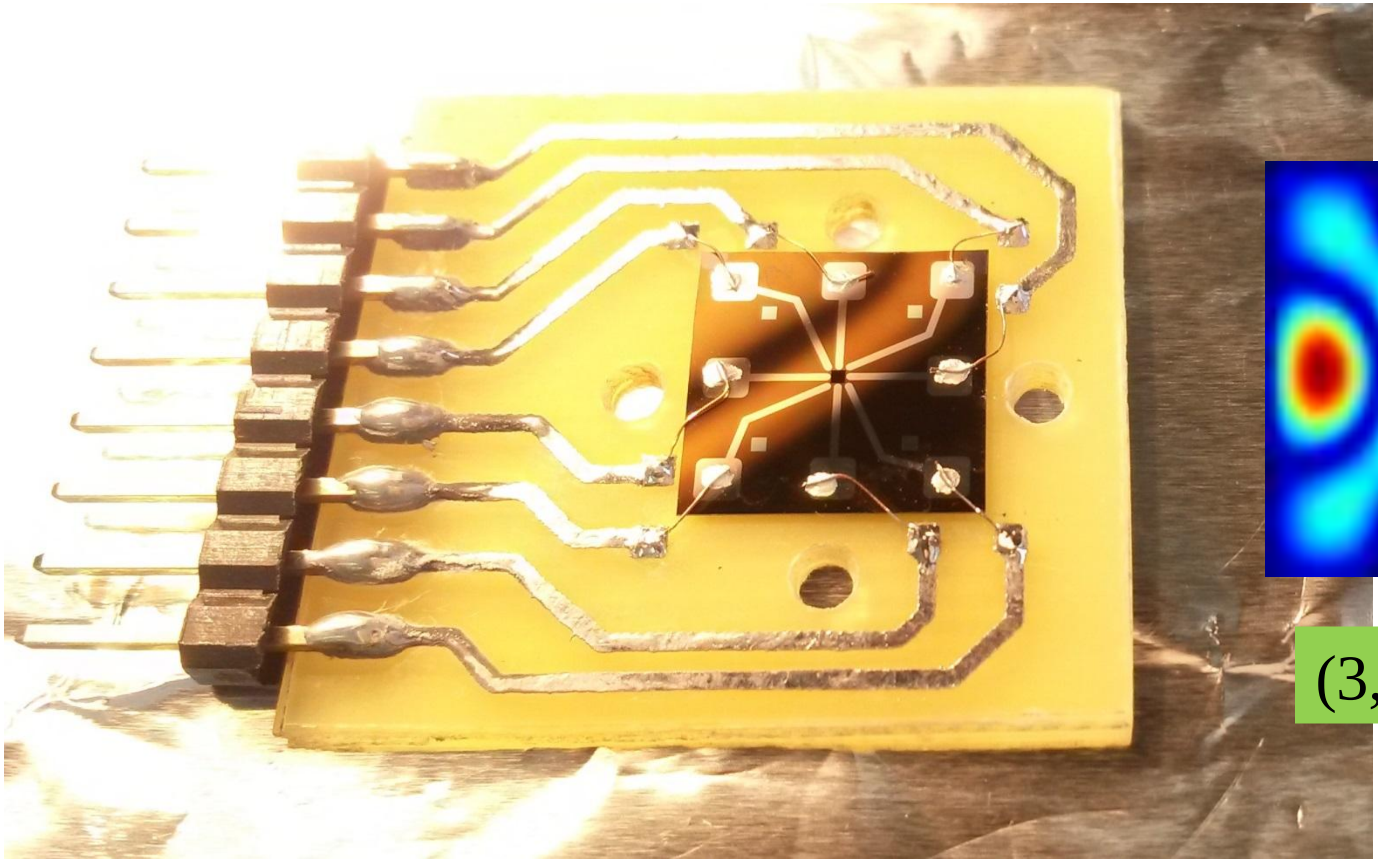
50 nm

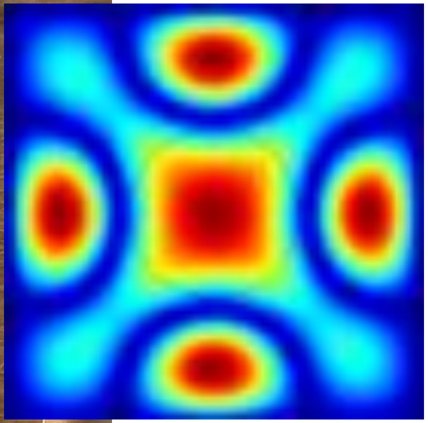
Modes identification with finite elements simulation



Simulation with 21nm metal layer

Electrode 1

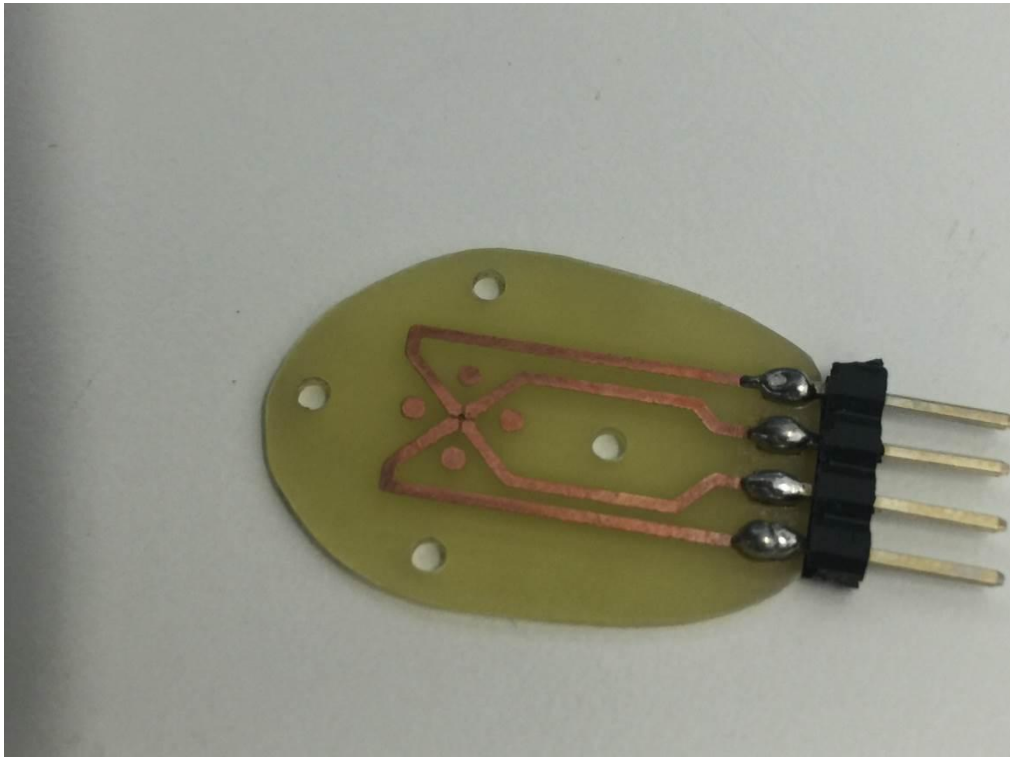




(3,3) mode

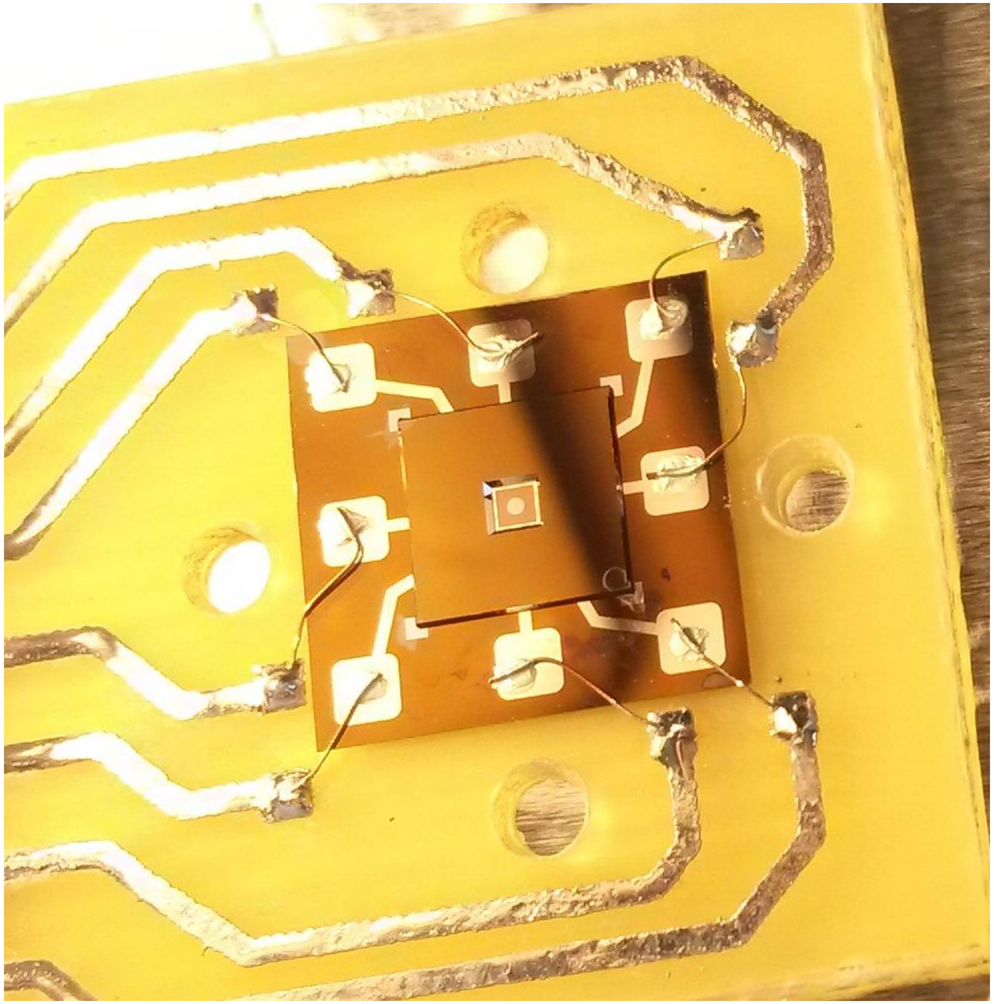
10x10 mm silicon frame

Electrode 2 «home made electrodes»



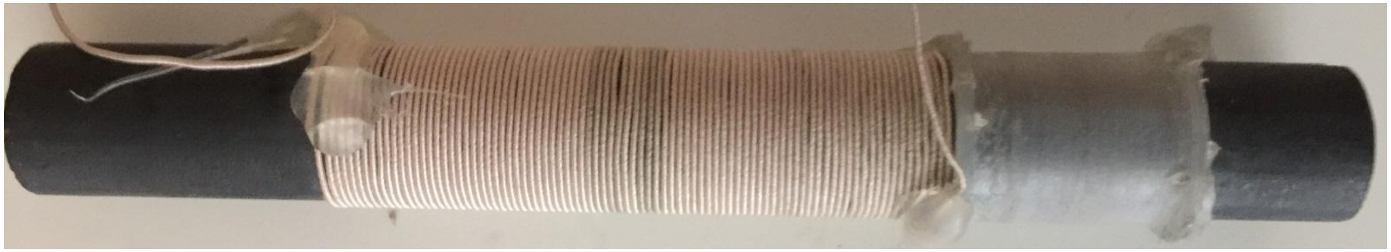
Experiment at room temperature.

“Sandwich”: electro-mechanical device



Did it work? Let’s talk about the LC oscillator before

LC oscillator

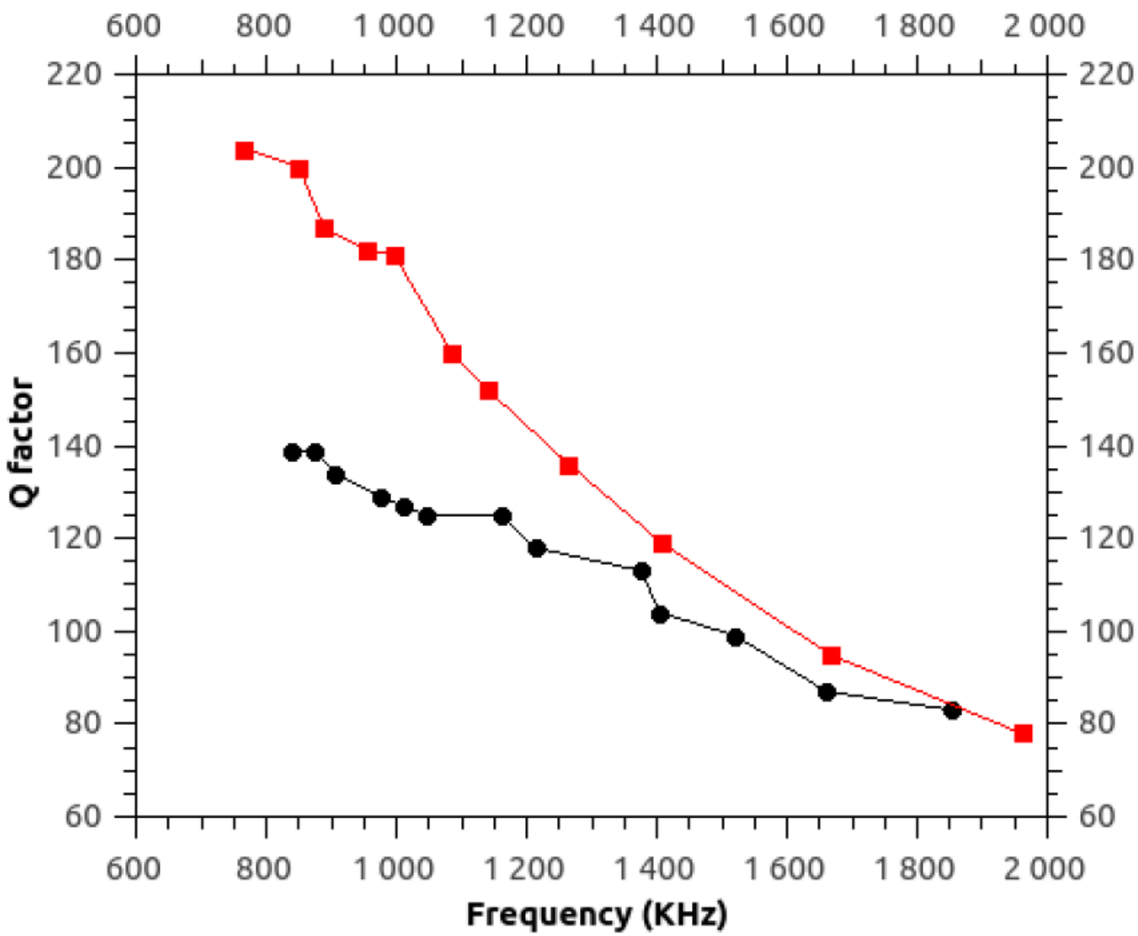


Frequency: tunable from 200 khz to Mhz

Quality as high as possible

Litz wires and ferrite rods

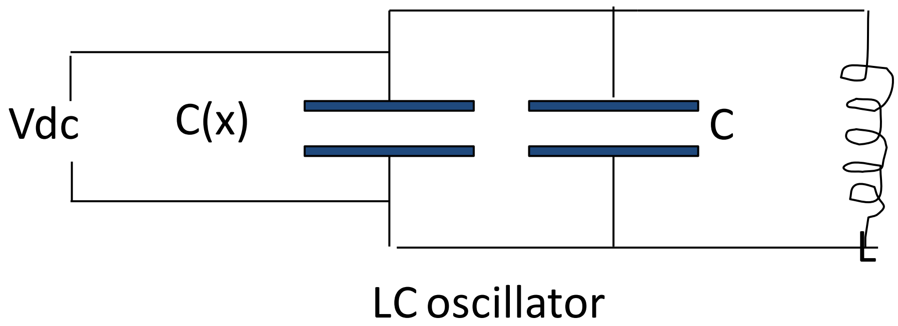
Q factor vs frequency



Red -> Room Temperature

Black-> Nitrogen Temperature

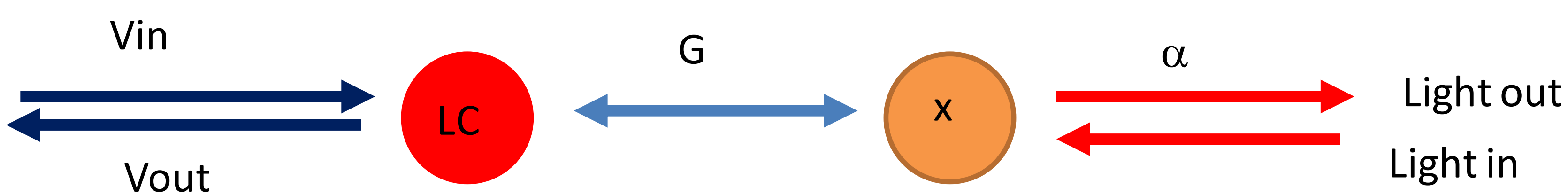
Electro-mechanical oscillator



Than… the Hamiltonian (we stay classical)

$$H = \sum_i \frac{p_i^2}{2m_i} + \frac{m_i \omega_i^2 x_i^2}{2} + \frac{\phi^2}{2L} + \frac{q^2}{2C(\{x_i\})} - qV$$

RF to Opto Transducer: one mode



Leading to Langevin Equation

$$\dot{x}_i = \frac{p_i}{m_i}$$

$$\dot{p}_i = -m_i \omega_i^2 x_i - \frac{q^2}{2} \frac{\partial}{\partial x_i} \left(\frac{1}{C(\{x_i\})} \right) - \gamma_i p_i + F_i$$

$$\dot{q} = \frac{\phi}{L}$$

$$\dot{\phi} = -\frac{q}{C(x)} - \Gamma_{\mathrm{LC}} \phi + V$$

1) Restricting to one mechanical mode
2) linearizing around an equilibrium state by writing each parameter as a sum of a constant + a modulating term (DC+AC terms)

Shot of relations

$$\dot{\delta x_i}(t) = \frac{\delta p_i(t)}{m_i}$$

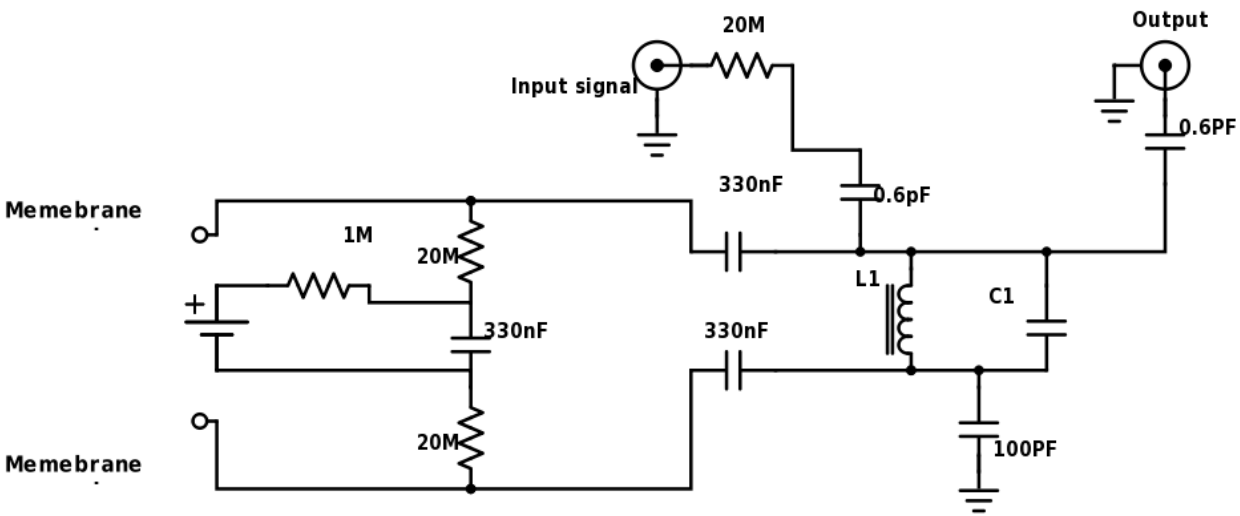
$$\dot{\delta p_i}(t) = -m_i\omega_i^2\delta x_i(t) - \underbrace{\frac{\bar{q}^2}{2}\,\frac{\partial^2}{\partial^2 x_i}\left(\frac{1}{C(\{x_i\})}\right)\bigg|_{x_i=\bar{x}_i}}_{2m\omega_i\,\Delta\omega_i}\delta x_i(t)$$

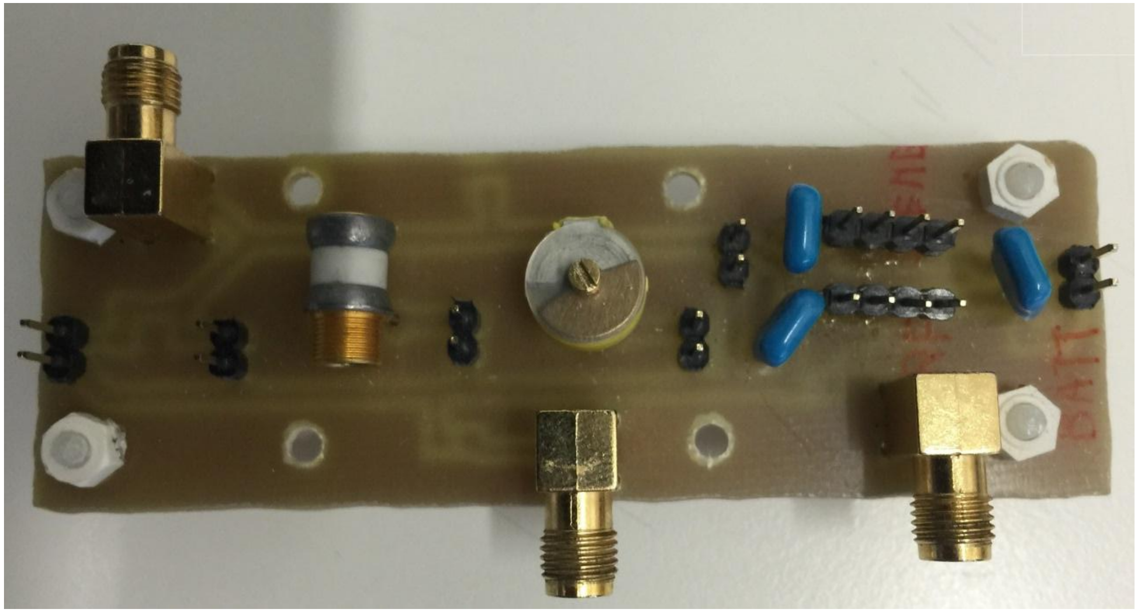
$$- \gamma_i\delta p_i - \underbrace{\bar{q}\,\frac{\partial}{\partial x_i}\left(\frac{1}{C(\{x_i\})}\right)\bigg|_{x_i=\bar{x}_i}}_{G_i}\delta q(t) + F_i$$

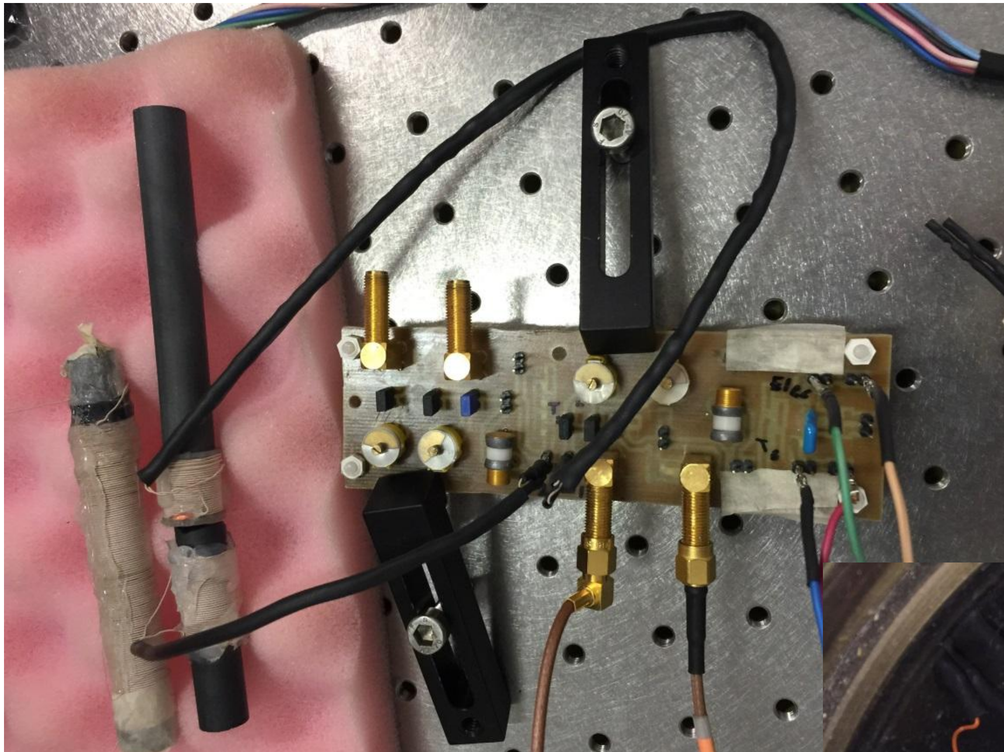
$$\dot{\delta q}(t) = \frac{\delta\phi(t)}{L}$$

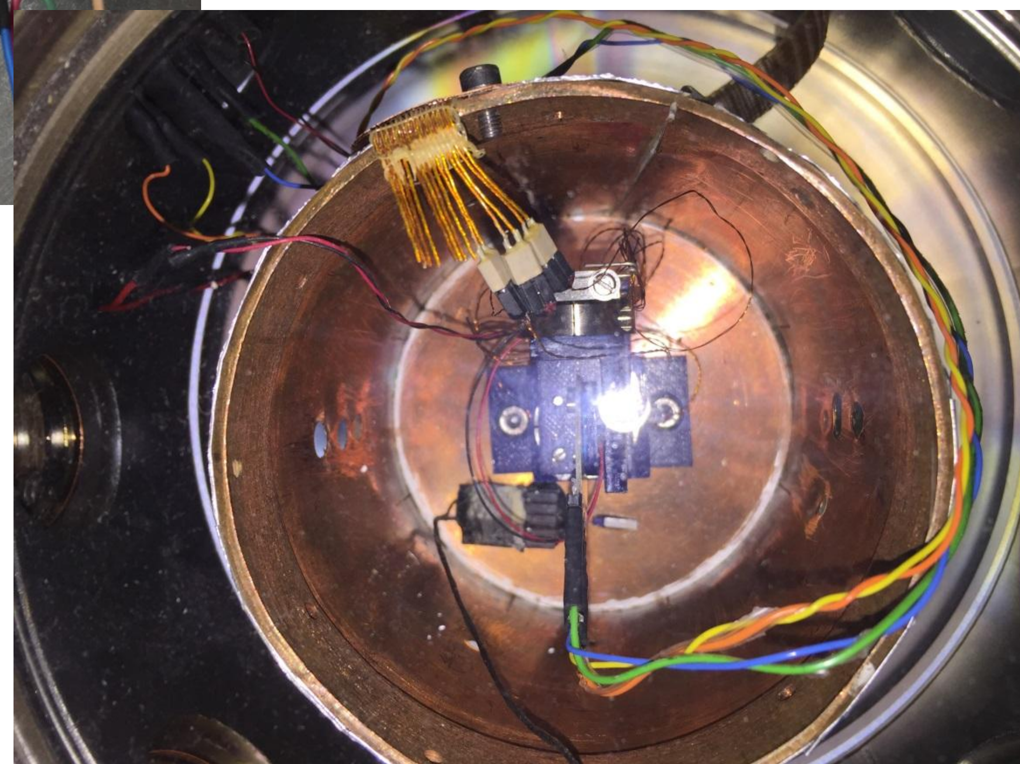
$$\dot{\delta\phi}(t) = -\frac{\delta q(t)}{C(\{\bar{x}_i\})} - \sum_j \underbrace{\bar{q}\,\frac{\partial}{\partial x_j}\left(\frac{1}{C(\{x_i\})}\right)\bigg|_{x_i=\bar{x}_i}}_{G_j}\delta x_j(t) - \Gamma_{\mathrm{LC}}\delta\phi(t) + \delta V(t)$$

How it looks in the lab…









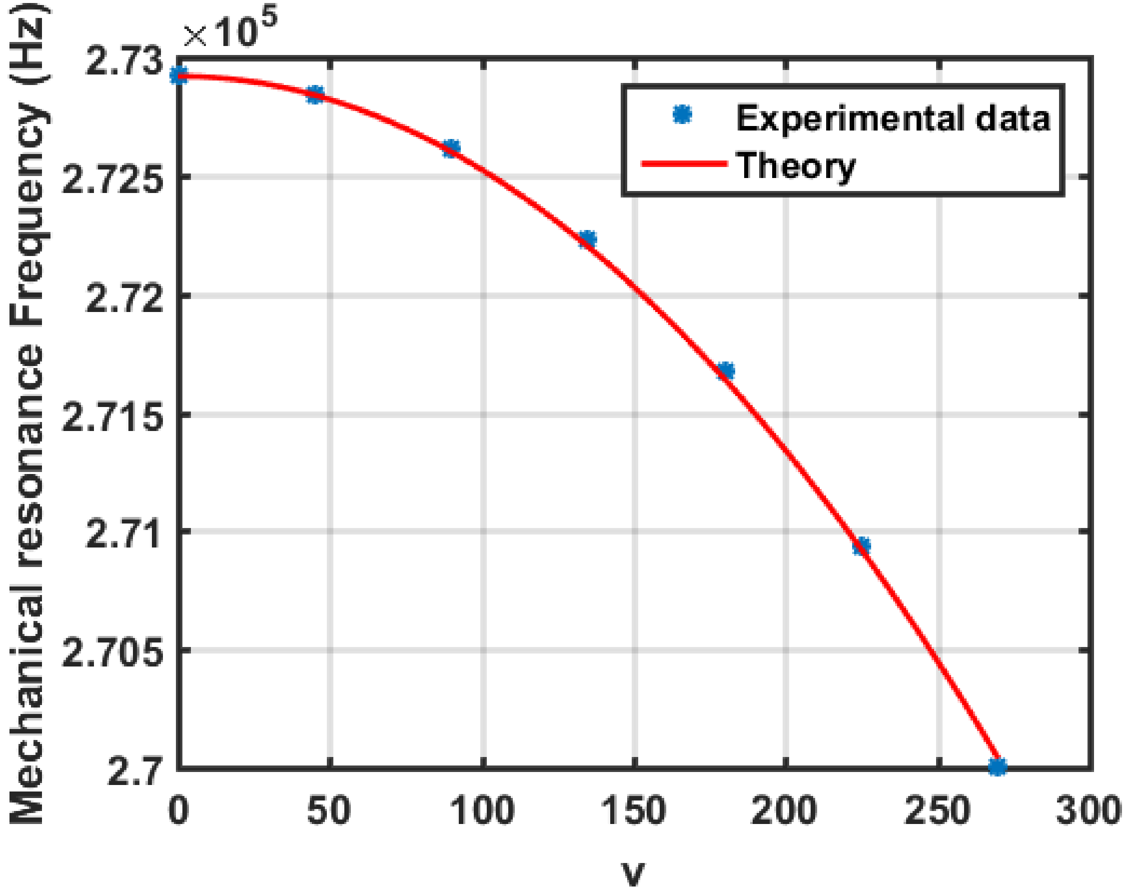
Looking for smoking guns: «static» result

Electrostatic force change equilibrium point and effective spring constant of the mechanical oscillator

$$\Delta\omega_i = \frac{\bar{q}^2}{4m_i\omega_i}\,\frac{\partial^2}{\partial x_i^2}\left(\frac{1}{C(\{x_i\})}\right)\Bigg|_{x_i=\bar{x}_i}.$$

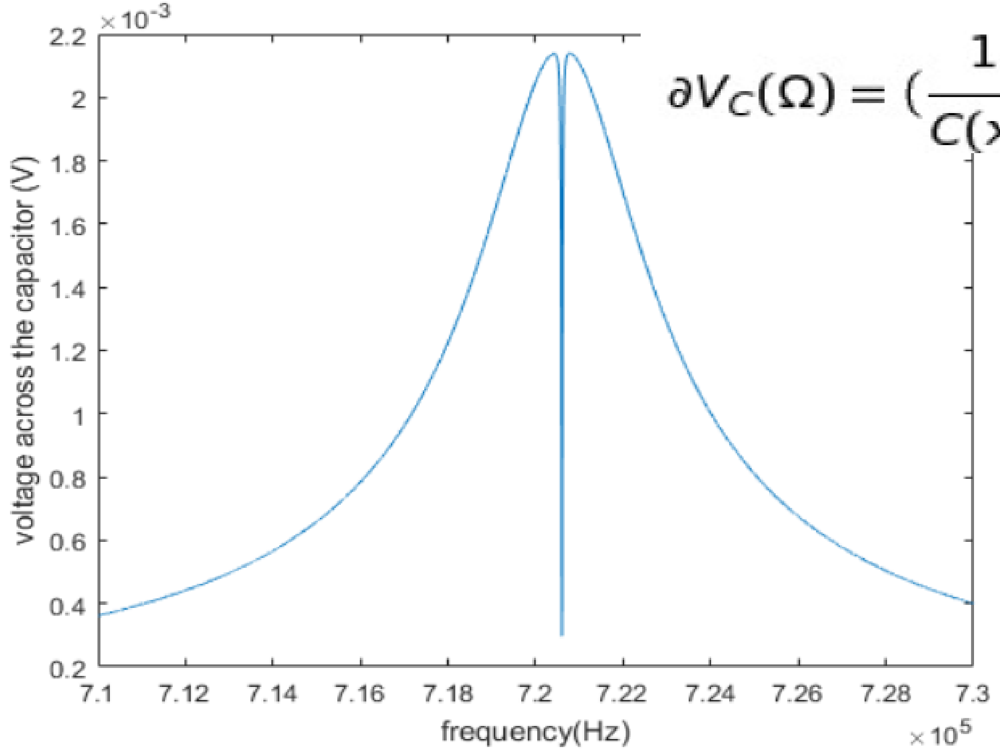
1. At first order it is quadratic in Vdc
2. It scales with 1/d^3 where d is the distance between the plate.

Mechanical oscillator frequency shift



Extimating the spacing: d around 30μm (interferometric measurament)

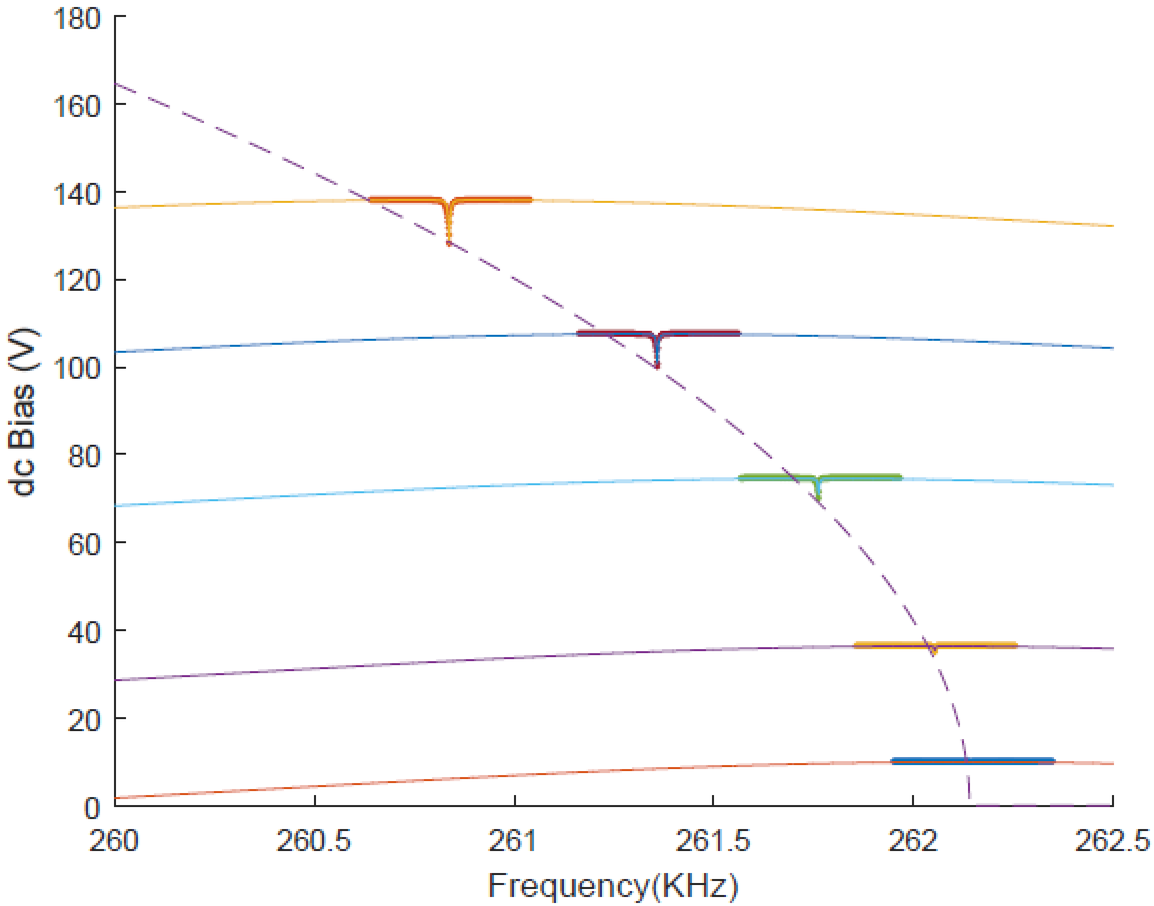
Electro-mechanical induced transparency: Resonant case. Single mechanical mode



$$\partial V_C(\Omega) = \left(\frac{1}{C(x)} - \chi_m(\Omega) G^2\right) \chi_{LC}(\Omega) \partial V_s(\Omega)$$

When the LC-oscillator frequency and the mechanical oscillator frequency are in resonance, the two oscillator interfers destructevely due to the coupling which can be observed in the electrical signal.

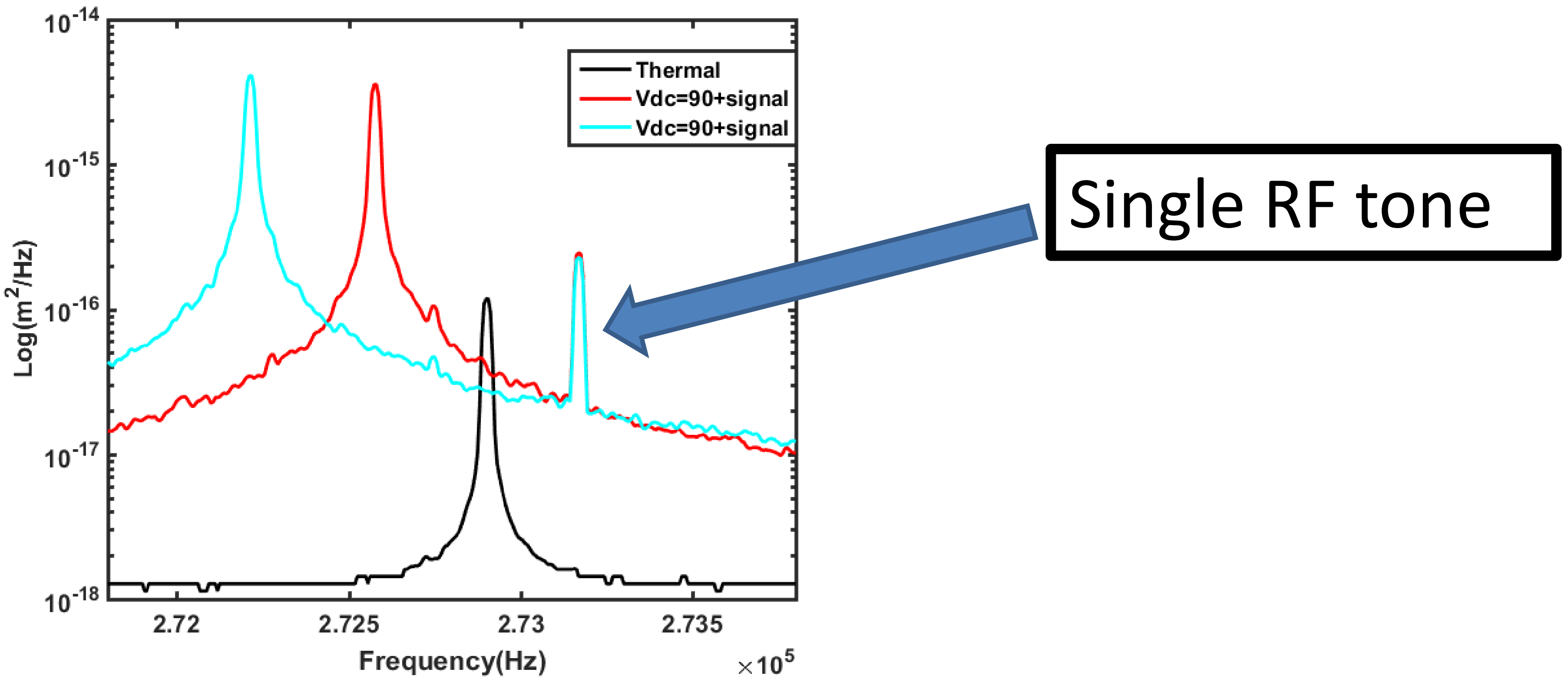
Electrical-mechanical Induced transparency:



LC is driven by an external source and the electrical signal is detected on the plate of the capacitor after decoupling the continuos Voltage, seeded on Network analyzer

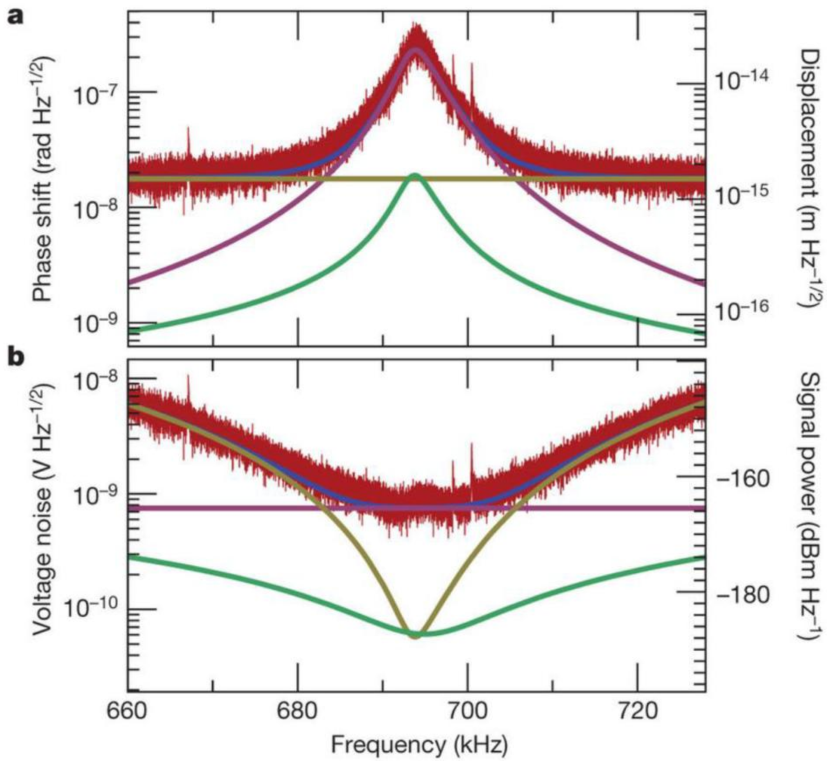
G= 240 V/m at Vdc=138V compatible with plates distance around 30 micron

Detecting an RF signal with light



Optimal transducer: Strong coupling regime

Question: How much is the voltage sensitivity of the transducer?



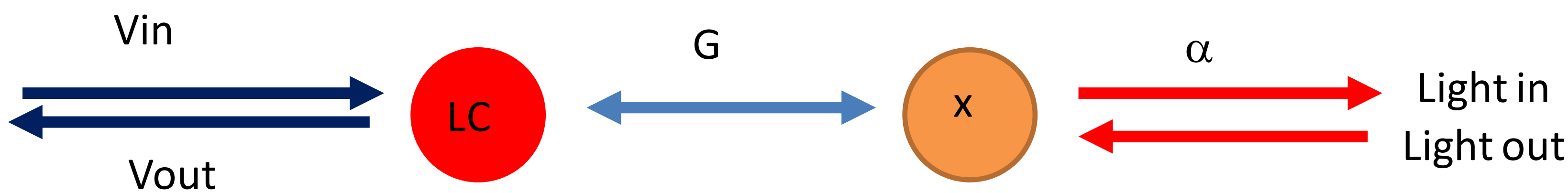
Results from: T.Bagci Nature 507, 81–85

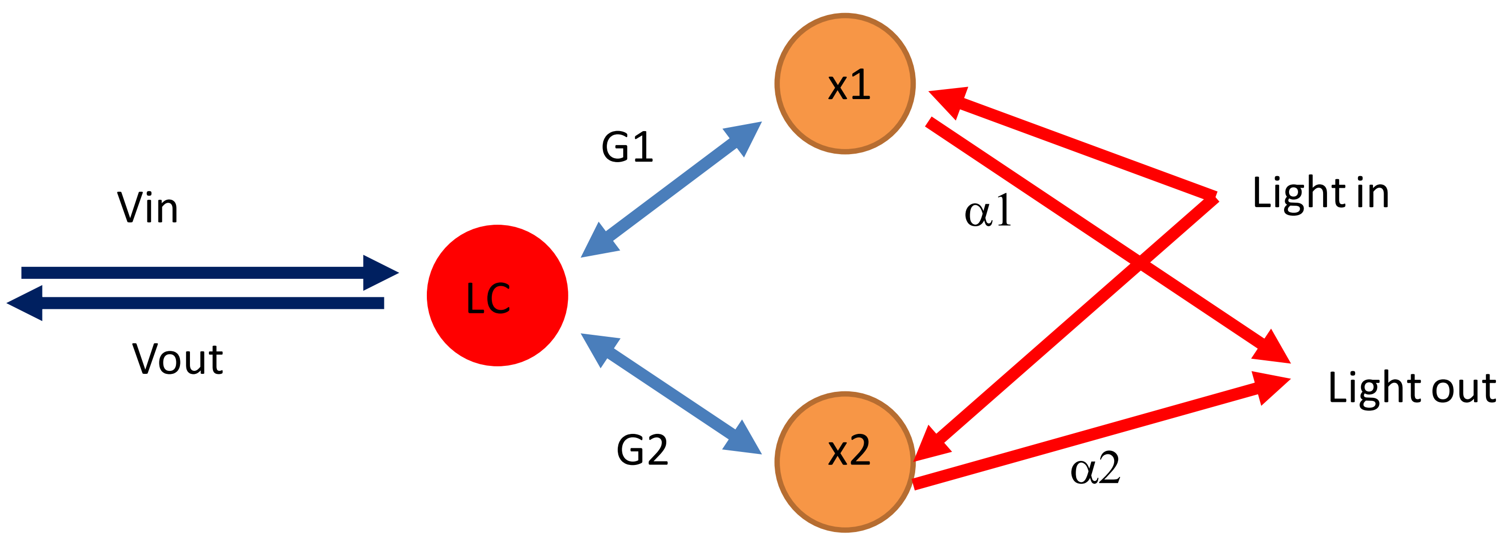
1) Close to Strong coupling regime
2) d= 1 micron (20 Vdc) (almost the limit)
3) Sensitivity 10^9 V/Hz^(-1/2), Bandwitdh 10 khz
   S=10^8 V/(Hz^(-1/2) 60khz

$$S_{\phi\phi}^{\mathrm{tot}}(\Omega) = (2k)^2 \left|\chi_{\mathrm{m,eff}}(\Omega)\right|^2 \left(\left|G\chi_{LC}(\Omega)\right|^2 S_{VV}(\Omega) + S_{FF}^{\mathrm{th}}(\Omega)\right)$$

$$S_{VV}^{\mathrm{im}}(\Omega) = \frac{S_{\phi\phi}^{\mathrm{im}}(\Omega)}{\left|2k\chi_{\mathrm{m,eff}}(\Omega)G\chi_{LC}(\Omega)\right|^2} = \frac{S_{xx}^{\mathrm{im}}(\Omega)}{\left|\chi_{\mathrm{m,eff}}(\Omega)G\chi_{LC}(\Omega)\right|^2}$$

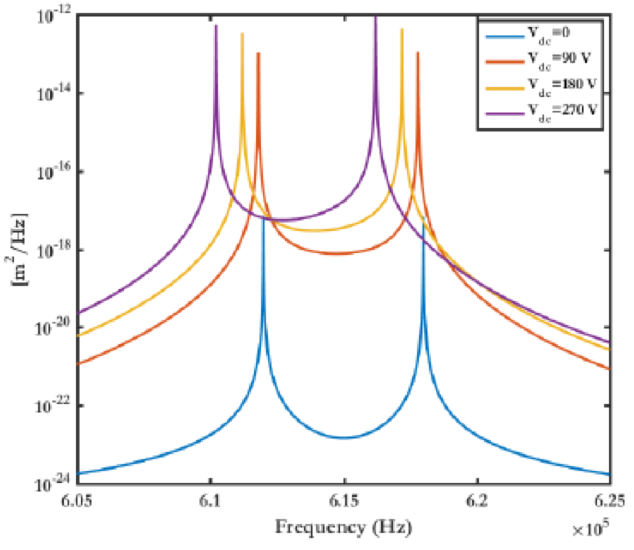
Transducers



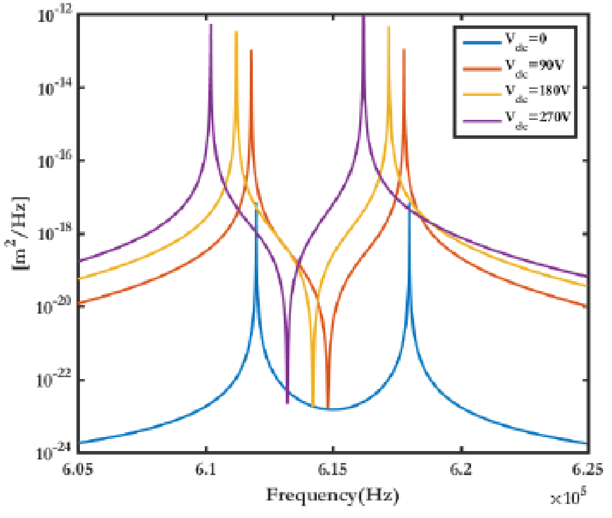


$$
\begin{aligned}
S_{\rm out}(\Omega) \;=\; & |\alpha_1|^2 \, |\chi_1(\Omega)|^2 \; S_{F1}(\Omega) + |\alpha_2|^2 \, |\chi_2(\Omega)|^2 \; S_{F2}(\Omega) \\
& + |\alpha_1 G_1 \chi_1(\Omega) + \alpha_2 G_2 \chi_2(\Omega)|^2 \, |\chi_{LC}(\Omega)|^2 \, S_{\delta V}(\Omega) + S_{\rm in}(\Omega)\,.
\end{aligned}
$$

Theory

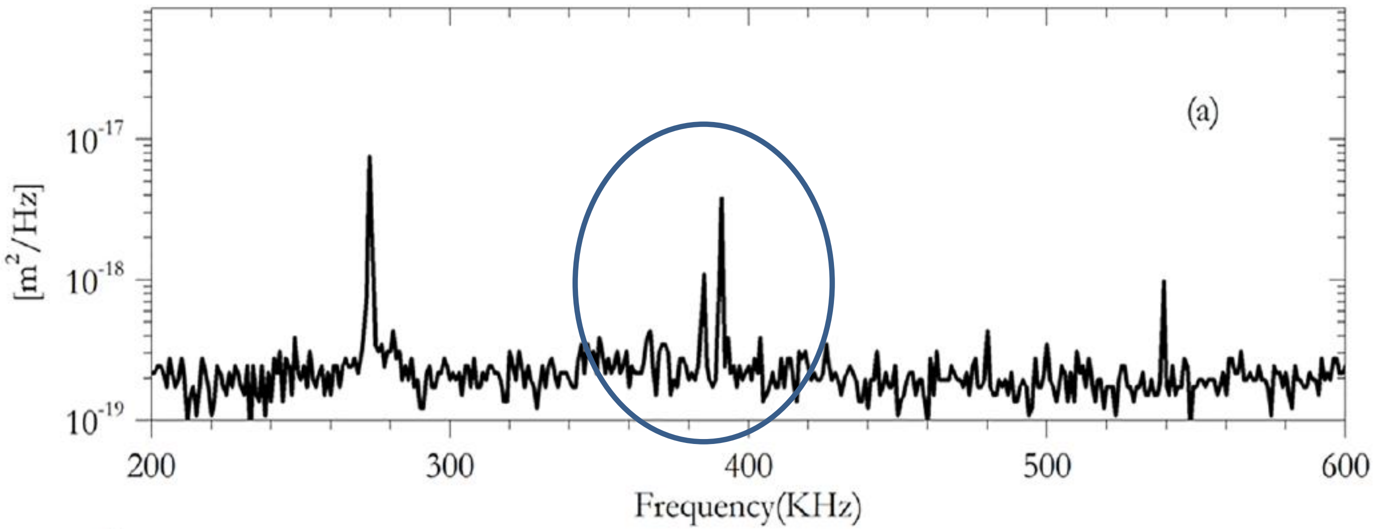


Costructive interference
Increasing bandwitdh
between the two modes

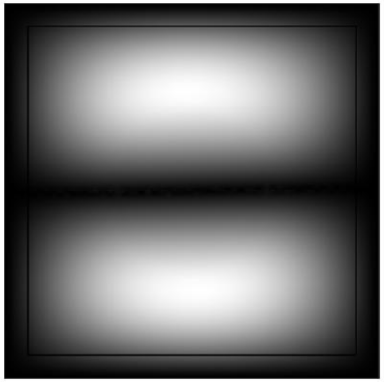


Destructive resonance
Antiresonance
cancellation regime

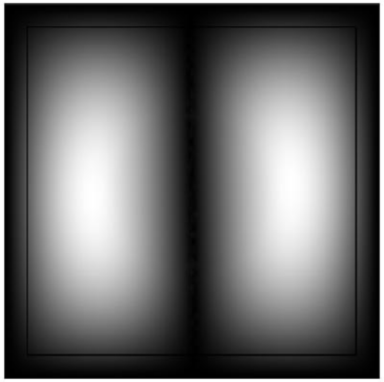
Degenerate modes



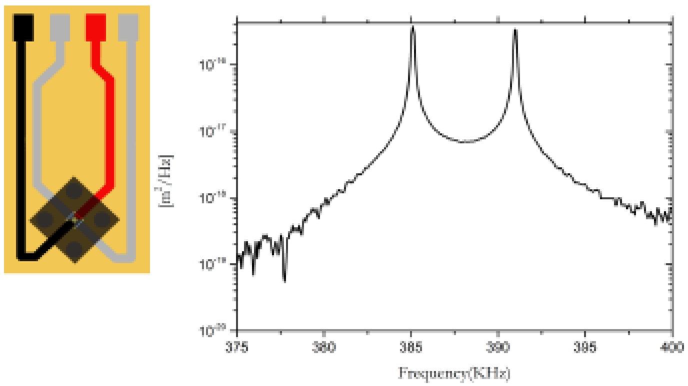
(1,2)



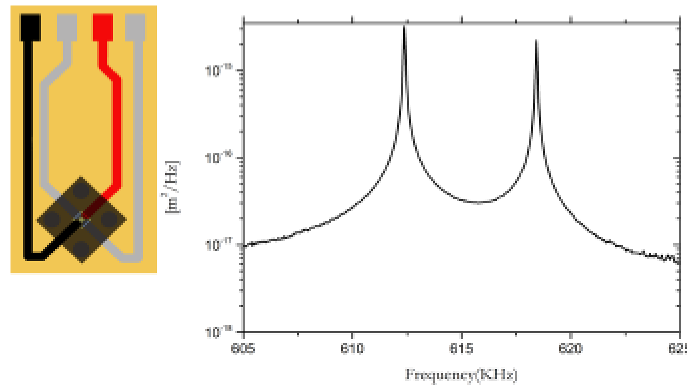
(2,1)



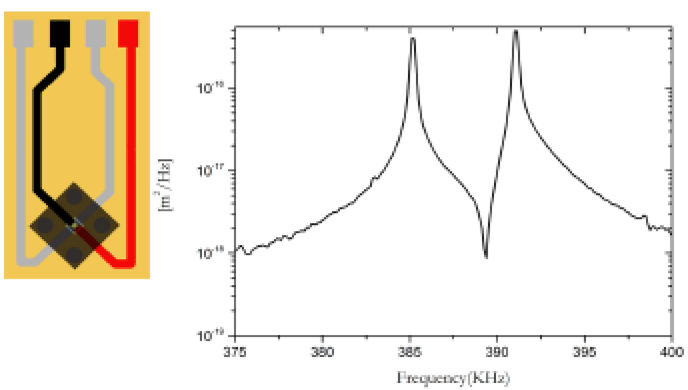
Experiments: changing G1 and G2 signs

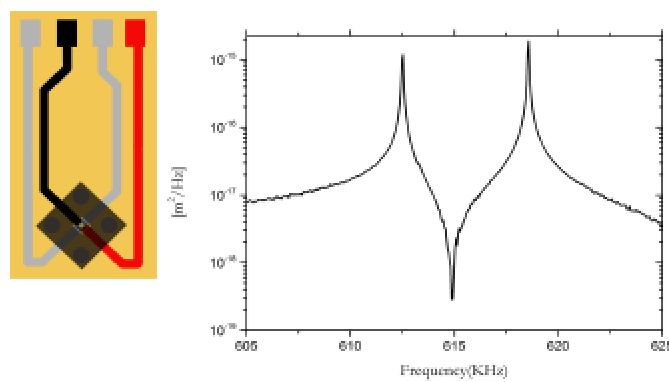


(a)

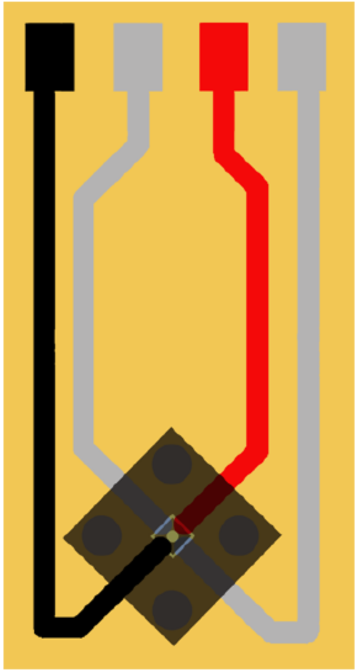


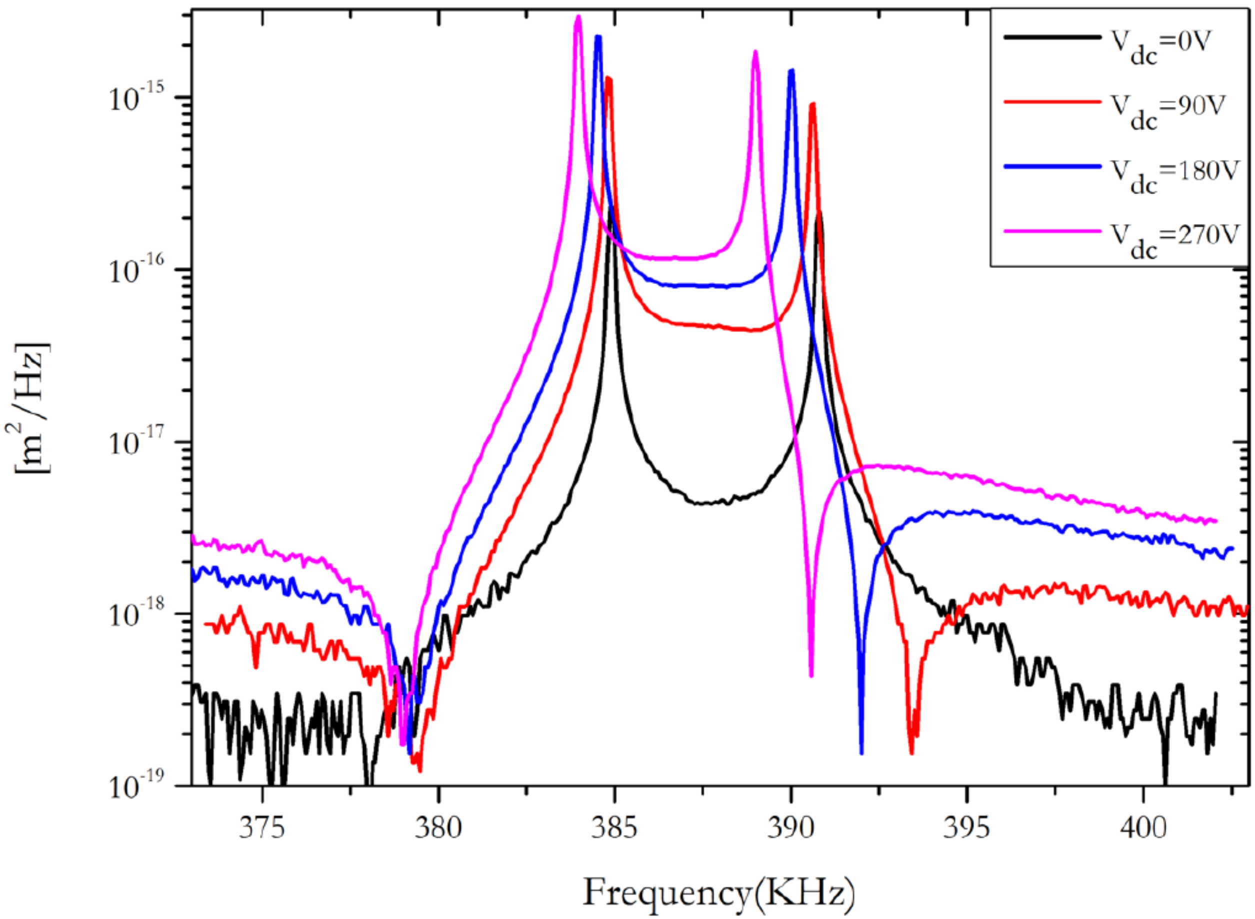
(b)



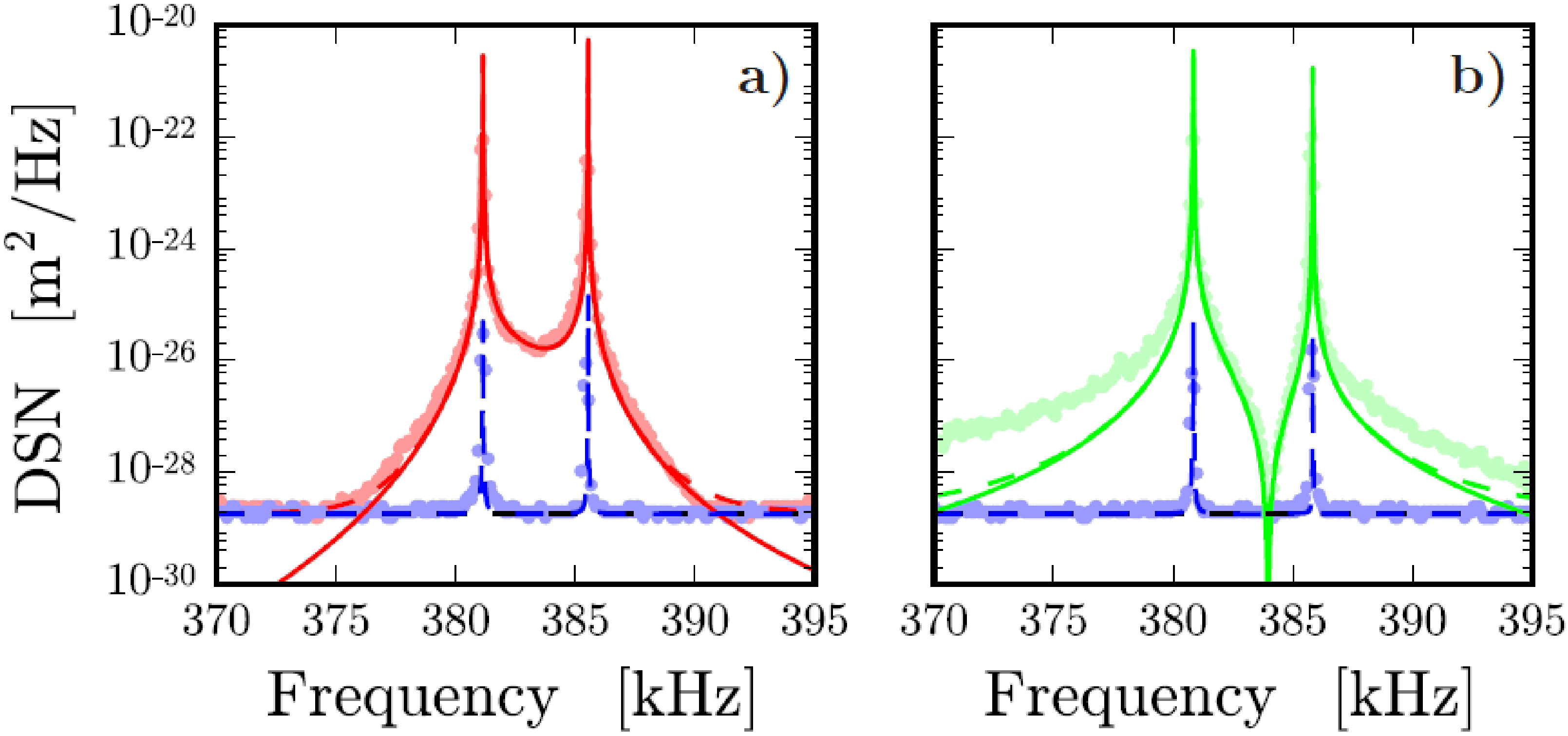


Dependence over the coupling (Vdc)



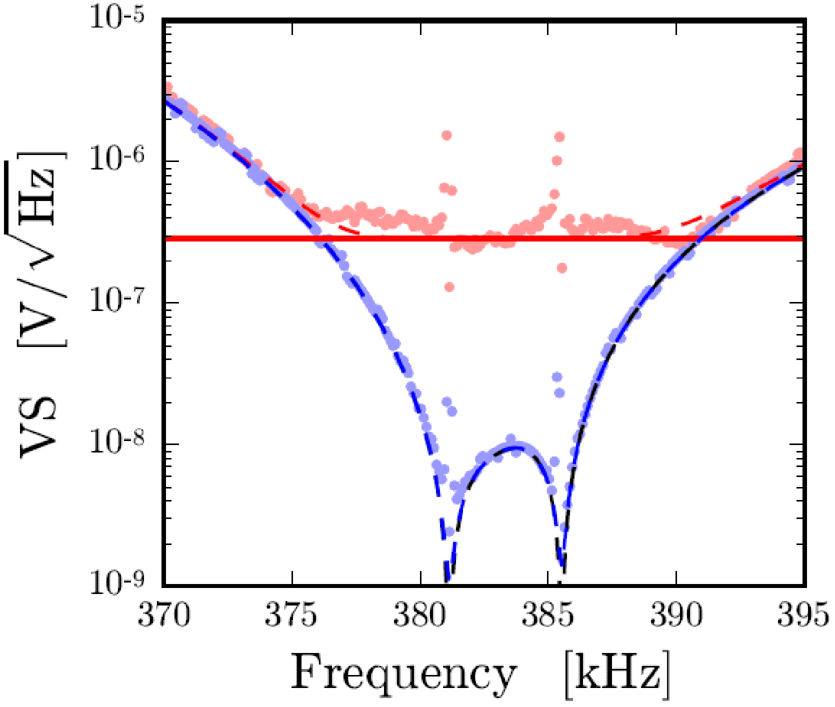


Sensitivity and bandwidth



Seeding gaussian RF noise 30 Mhz bandwitdh

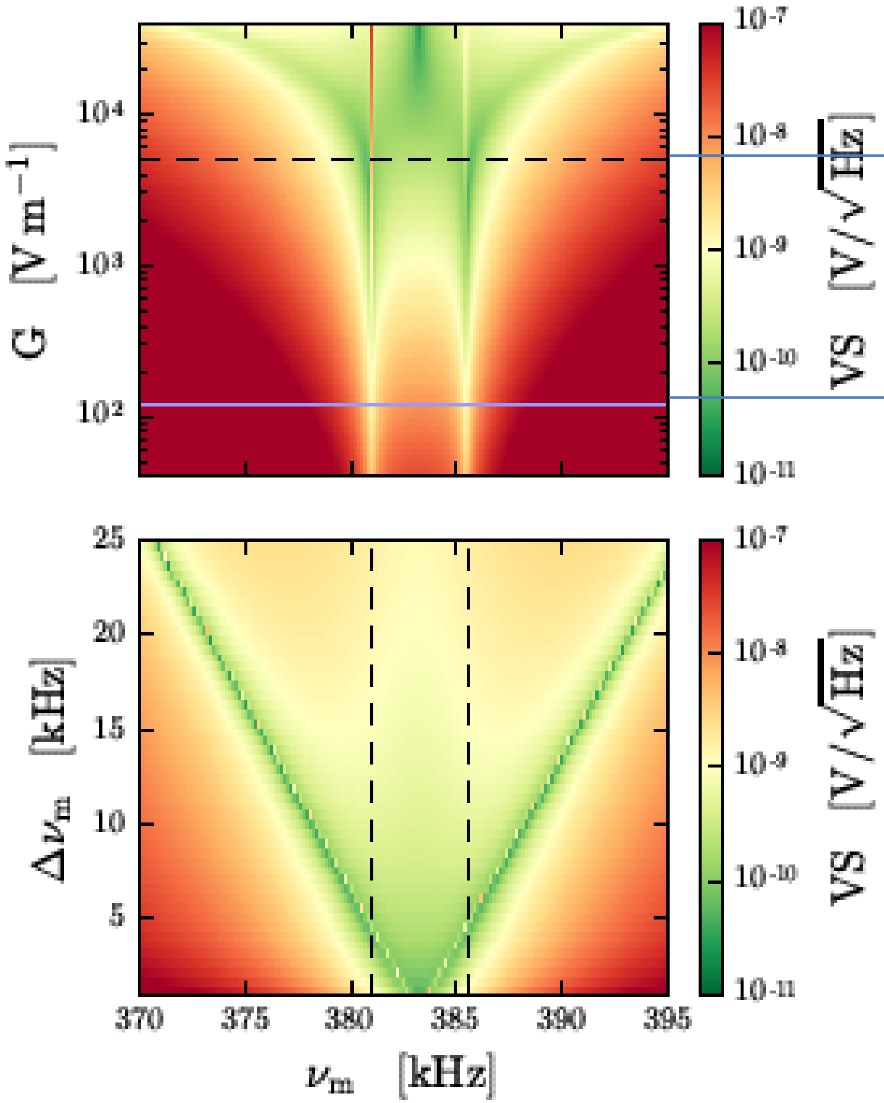
Sensitivity and bandwidth



G1=G2=110 V m^(-1) (d=30 micron)
Faraway from strong coupling regime

Sensitivity 10^(-8) V/Hz^(1/2)
Bandwitdh around 5 Khz (modes distance)

better bandwitdh?



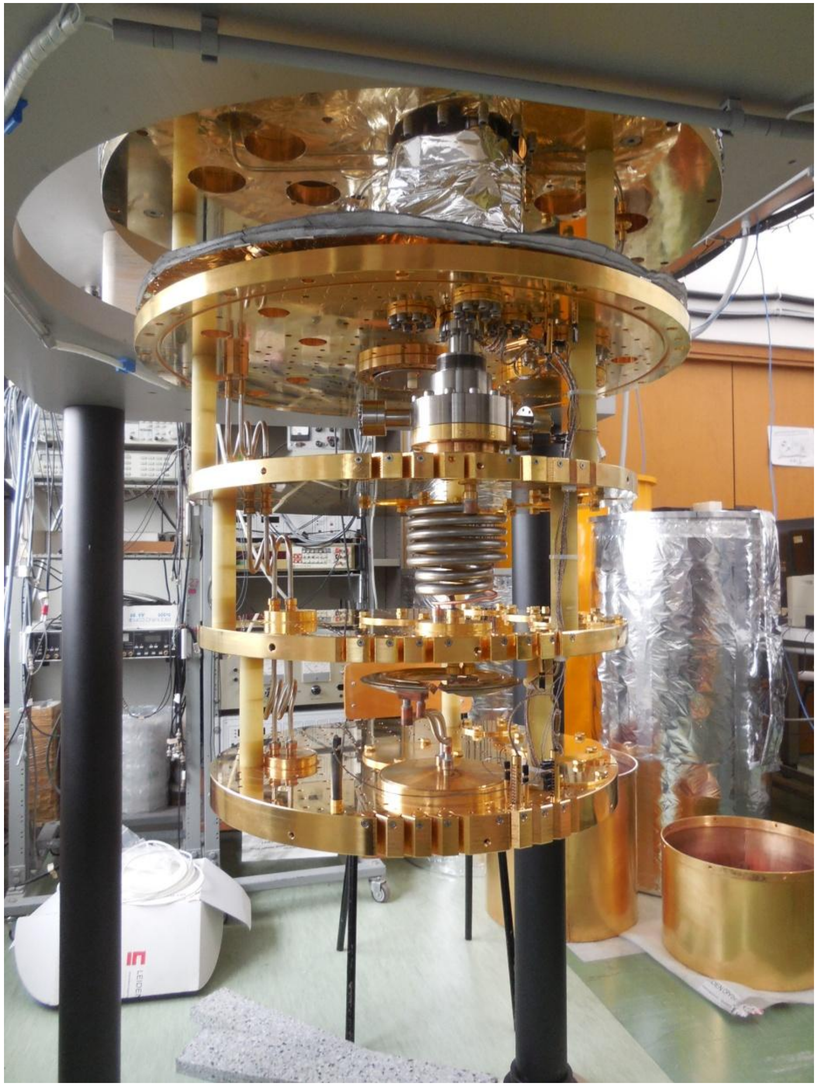
G=14000 V m^(-1) (d=3 micron)

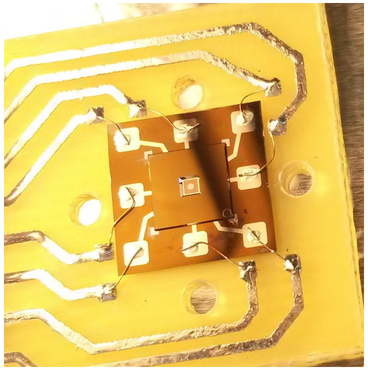
Proof of principle device: now

Increasing bandwitdh by increasing mode splitting. Retangular membrane

... future

1. Testing in cryogenic enviroment… 8 mK

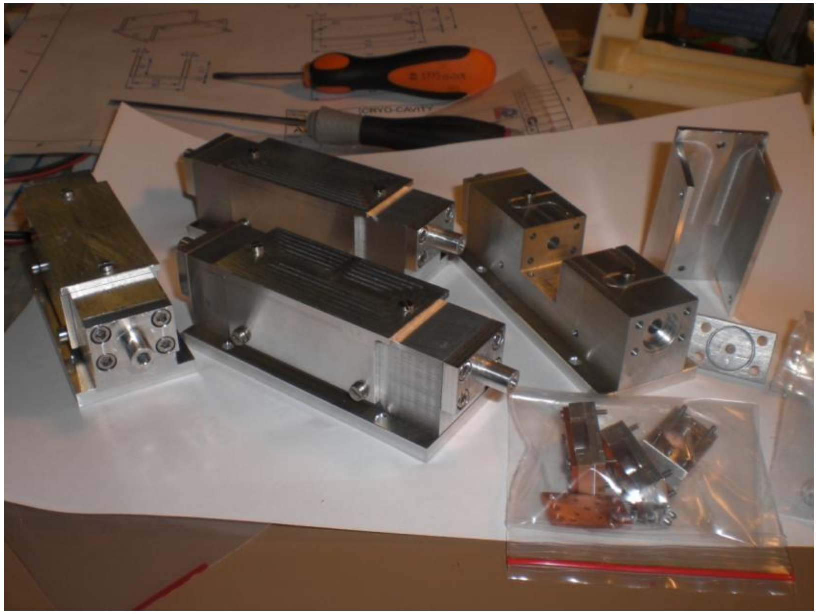




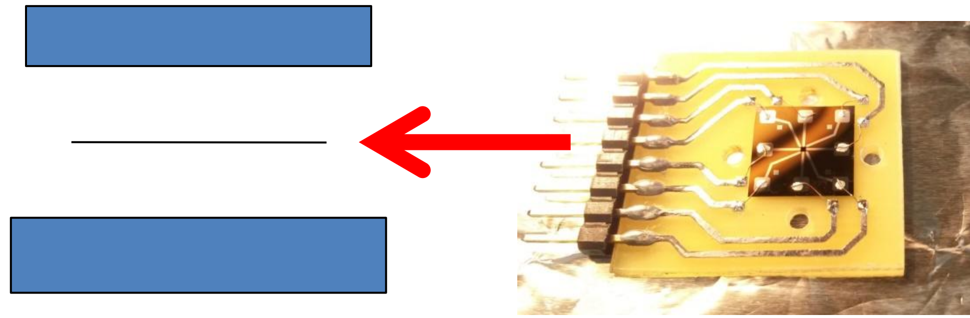
1. Preliminary results indicate 4 micron distance

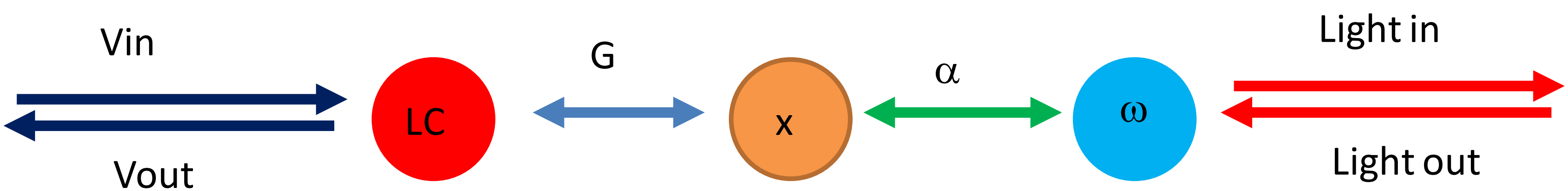
2. Designing supercunducting coils for inductance in cryogenics

2. Going to cavity: RF-opt opt-RF transducer



Membrane in the middle set-up inside in an high finesse optical cavity.





Conclusions

1. We start and set-up an electro-opto-mechanics experiment in Camerino.
2. We investigate the electro-mechanical coupling for different homemade designed oscillator
3. We study the increasing of bandwidth detection exploiting constructive interference between multimode mechanical oscillator.

Thank you