tHEEOM-RD

technology for High Efficiency Electro-Optical Modulator

CSN5 – 19 Luglio 2023 - Sezione INFN Perugia

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Unità partecipanti: Trento, Perugia (+Firenze)

Responsabile locale: David Vitali INFN-PG

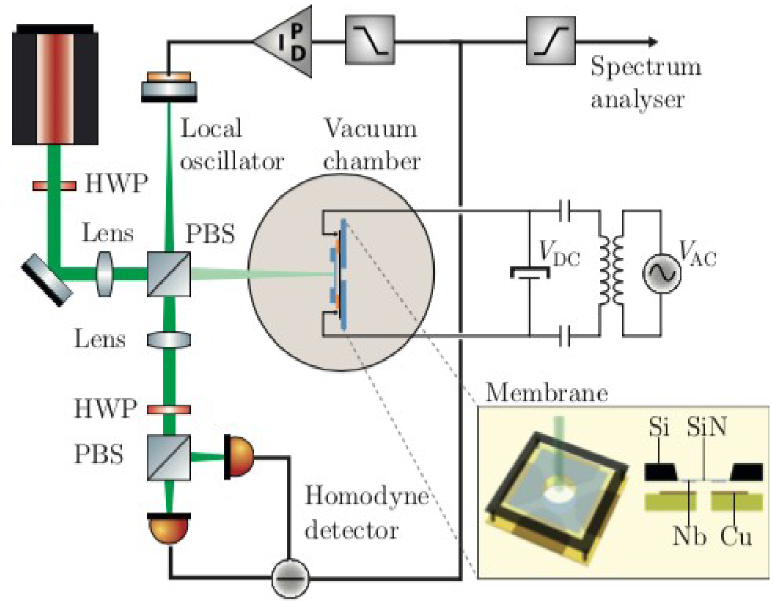
Electro-Optical mechanical modulators exploiting the electro-opto-mechanical interaction for transduction of weak rf signals

Quantum networks

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

Quantum interface between optical and microwave photons would be extremely useful: **optimal solid state qubits – optical photon transducer (Opto- electro-mechanical systems)**

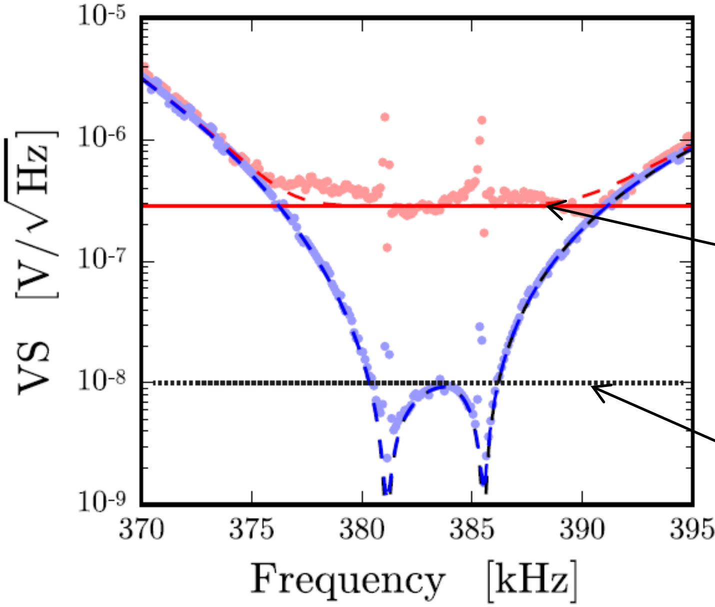
High-sensitive optical detection of an rf signal:



Applications (classical domain):

- RF high efficiency sensors in NMR - KAZUYUKI TAKEDA et al. Electro-mechano-optical detection of nuclear magnetic resonance - Optica 2018
- RF EOM could integrate non-reciprocal devices (without the use of magneto-optic effect) RF-isolators/RF circulators X. W. Xu et al., Nonreciprocal conversion between microwave and optical photons in electro- optomechanical systems, Phys. Rev. A 93, 023827 (2016).

High-sensitive optical detection of a weak rf signal



Voltage sensitivity = 300 nV/√Hz over a 15 kHz bandwidth with rf-noise added

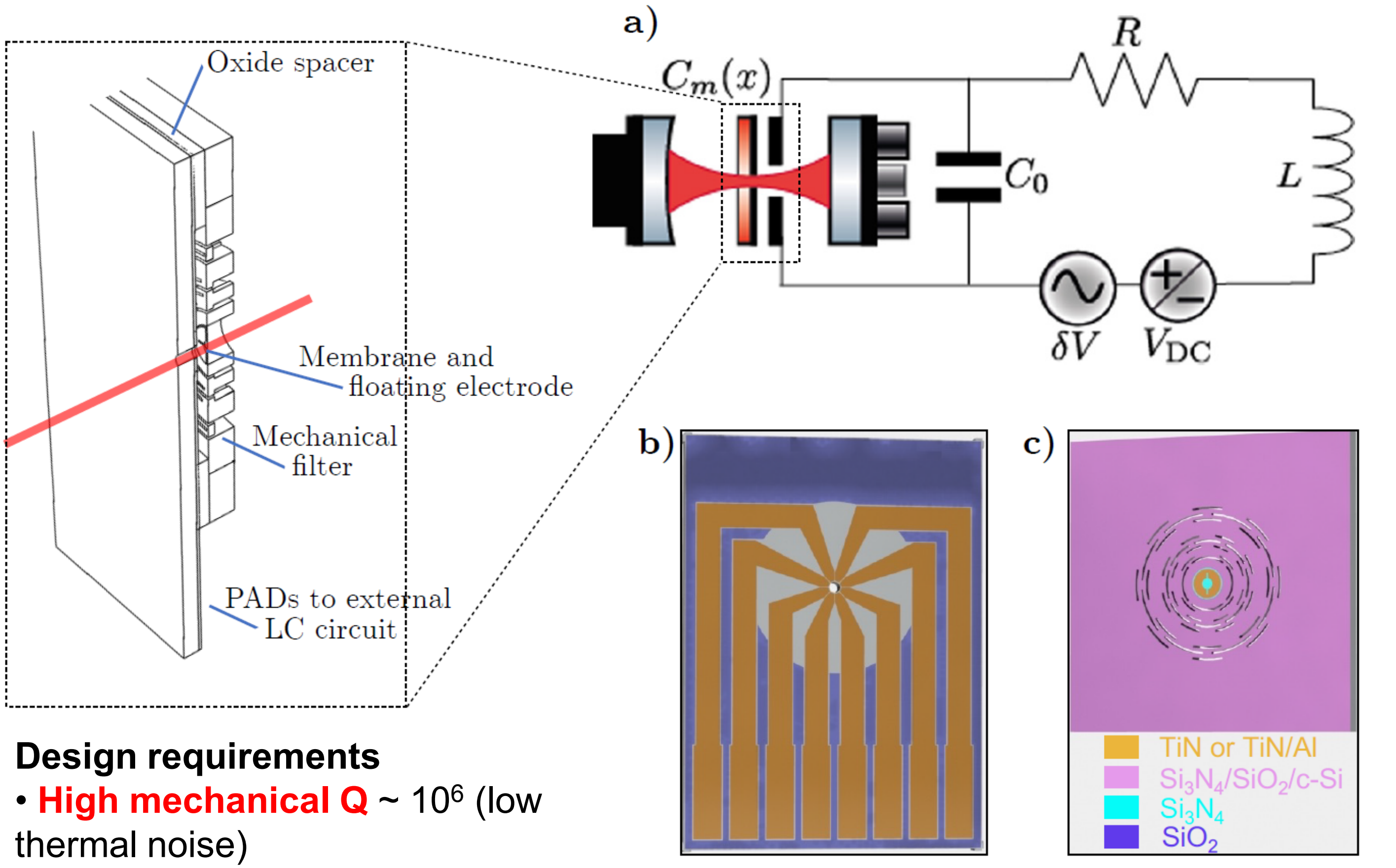
Optimal shot-noise limited sensitivity = 10 nV/√Hz over a 5 kHz bandwidth (negligible rf noise)

I. Moaddel Haghighi, N. Malossi, R. Natali, G. Di Giuseppe, and D. Vitali, Phys. Rev. Applied **9**, 034031 (2018)

Theeom_RD aims at improving the device: **better membrane capacitor** ⇒

- improved transduction efficiency
- reduced added noise
- increased bandwidth
- possibility to operate in the quantum regime at ultracryogenic temperatures

SCHEME OF THE OPTO-ELECTRO-MECHANICAL MODULATOR



Electrode connected to the LC circuit

Floating electrode on the SiN membrane

Design requirements

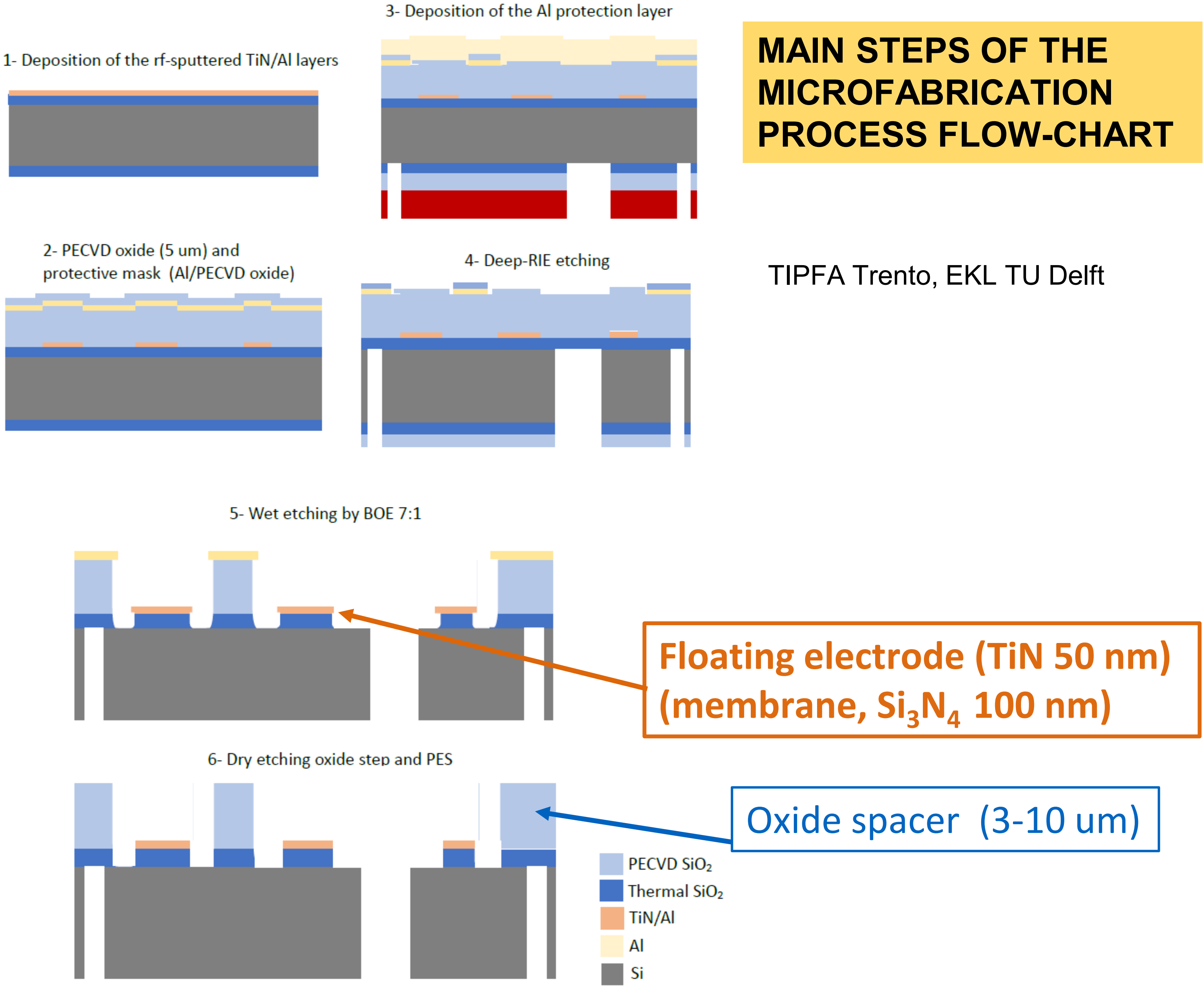
- **High mechanical Q** ~ 10^6 (low thermal noise)
- **Small gap d between** capacitor electrodes and large effective capacitor area A_{eff} for strong enough electromechanical coupling

$$C(\hat{x}) = C_0 + C_m(\hat{x}) = C_0 + \frac{\varepsilon_0 A_{\text{eff}}}{h_0 + \hat{x}},$$

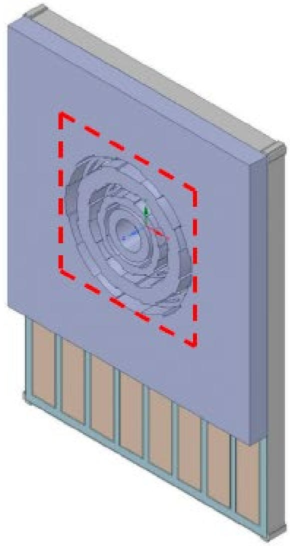
M. Bonaldi, A. Borrielli, G. Di Giuseppe, N. Malossi, B. Morana, R. Natali, P. Piergentili, P. M. Sarro, E. Serra, D. Vitali, in print on Entropy, 2023, Special Issue "Lectures on Recent Experimental Achievements in Quantum-Enhanced Technologies". N. Malossi et al., Phys. Rev. A 103, 033516 (2021)

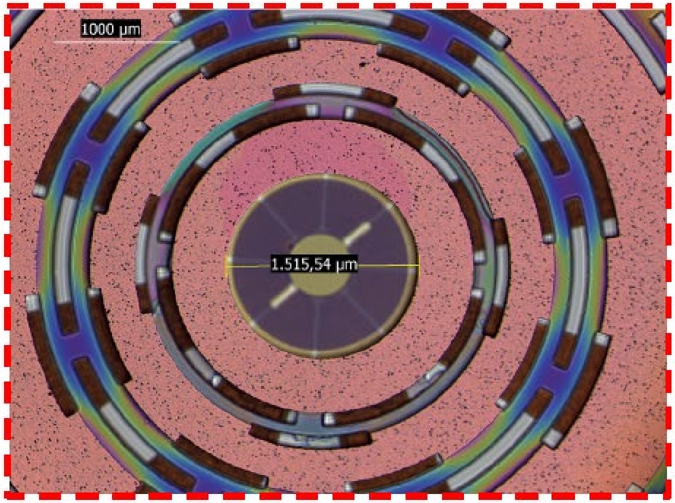
MAIN STEPS OF THE MICROFABRICATION PROCESS FLOW-CHART

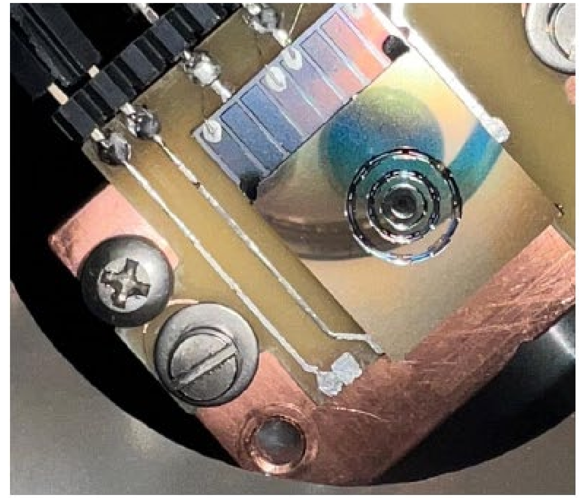
TIPFA Trento, EKL TU Delft

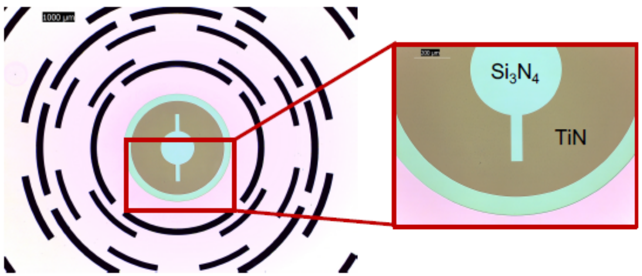


ASSEMBLED DEVICE





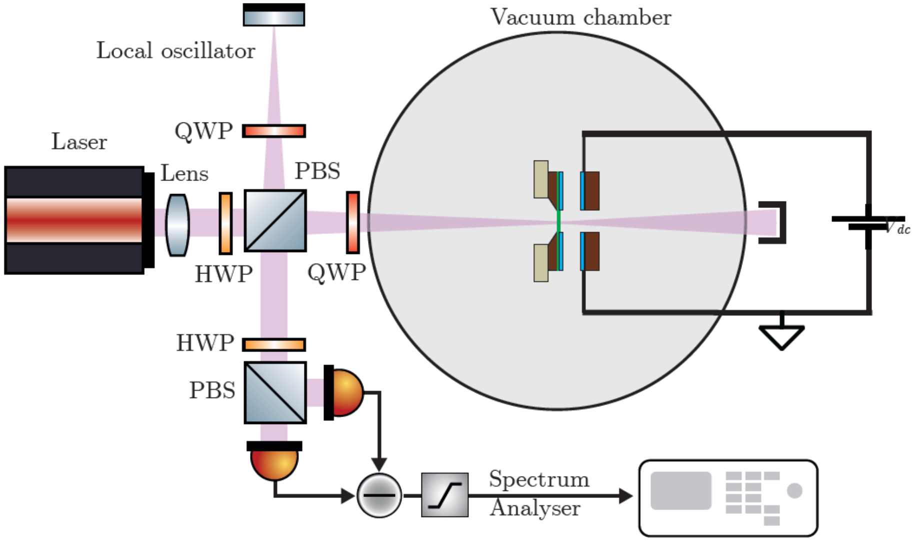




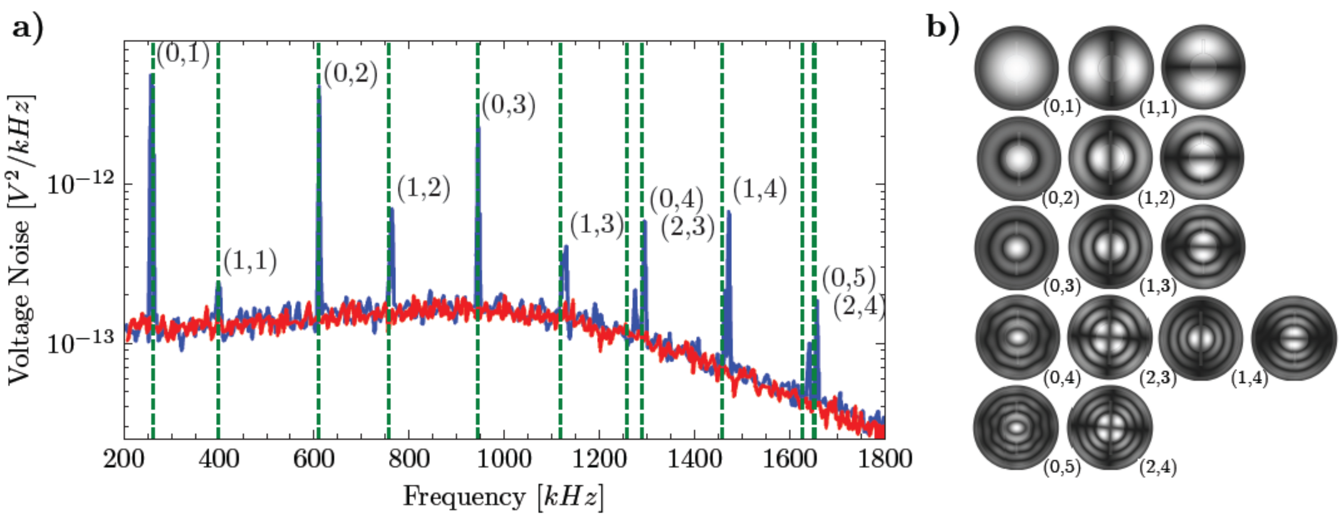
Optical image of the SiN stoichiometric nanomembrane (light blue) with the TiN layer (brown). The membrane is endowed with the on-chip shield for recoil losses (right). Detailed view of the TiN notch in the membrane electrode used for the mode identification and the component assembly

Left: Detailed view of the interaction region in the OEMM assembled device.
Right: The device clamped to the OFHC copper block, and the diving PCB board used in the optical setup

Mechanical modes characterization via optical homodyne detection

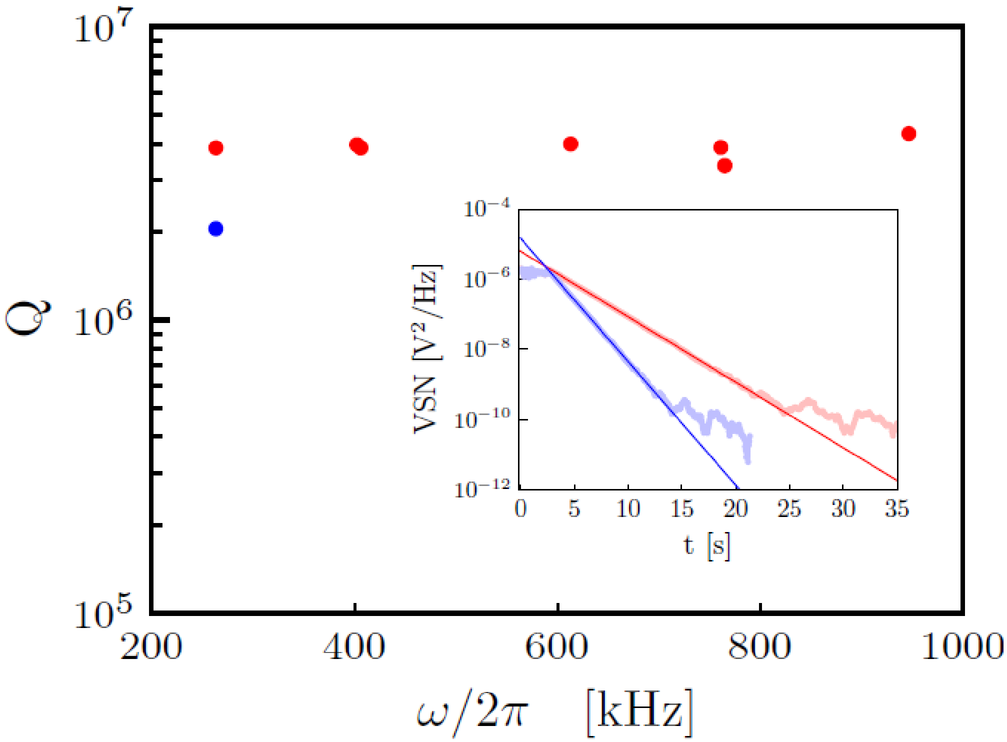


Michelson interferometer with shot noise limited homodyne detection

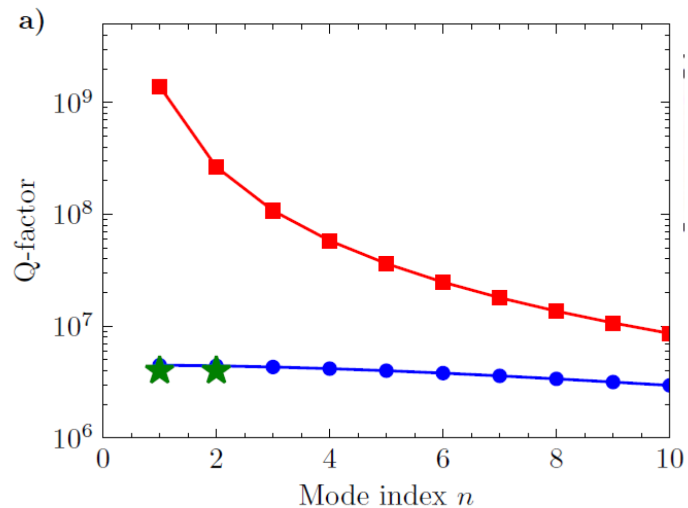


a) Voltage spectral noise of the homodyne signal (blue) and the shot-noise contribution (red). The green dashed lines are the calculated frequencies from the FEM simulation.
b) Calculated mode shapes by FEM simulation, corresponding to the calculated mode frequencies present in the spectrum.

MEASUREMENT OF THE QUALITY FACTOR: TARGET VALUE ACHIEVED



Agreement with theory (blue dots and green stars)
Red dots: Q without edge losses of the SiN layer (theory)



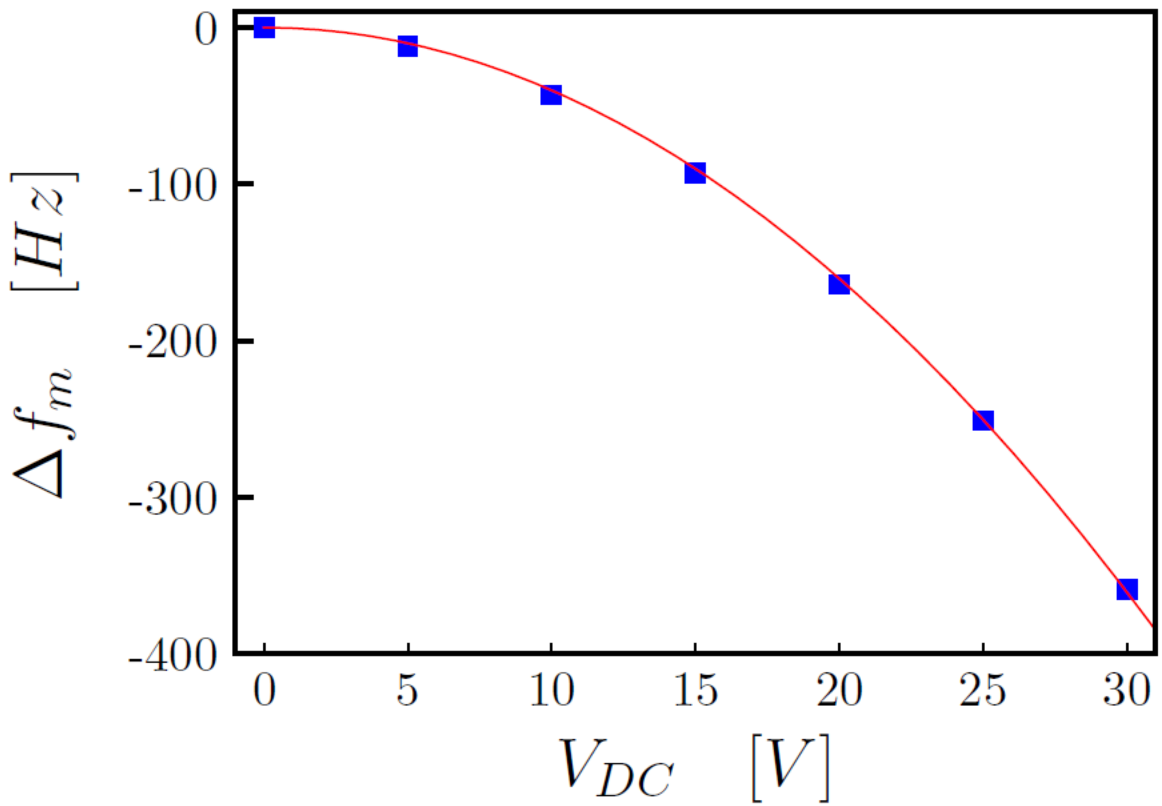
Measurement of the mechanical Q-factor for different modes after the final assembling of the device. Red points correspond to measurements at V_{DC}=0V, the blue point corresponds to the measurement at V_{DC}=30V.

Inset: voltage spectral noise (VSN) density of the homodyne signal during the ring-down measurement of the fundamental mode (0,1)

Losses are dominated by edge losses of the SiN layer

⇒ Thickness and shape of the metal coating on a stressed membrane can be arbitrary **if patterning starts from a few microns of the membrane's edge**.

Electro–mechanical characterization of the device



Measurement of the frequency shift of the (1,1) mode as a function of the DC voltage bias. The red line is the fit of the data, ⇒
average distance between the electrodes and the membrane d = 5.12 μm, (using the parameters: effective area A_{eff}= 0.075 mm^2; membrane mass m_{eff}= 420 ng; unperturbed mode frequency $f_0 = f_{11}$ = 399587 Hz.

$$\Delta f_m = -\frac{\epsilon_0}{8\pi^2}\frac{A_{eff}}{m_{eff} d^3 f_0} V_{DC}^2$$

FUTURE ACTIVITIES AND PERSPECTIVES

Research keeps on going via
PRIN 2022 "**Quantum transduction and sensing with opto-electro-mechanical systems" (PI: Unicam + INFN TIPFA + CNR-IMEM Trento)**

TECHNICAL IMPROVEMENTS

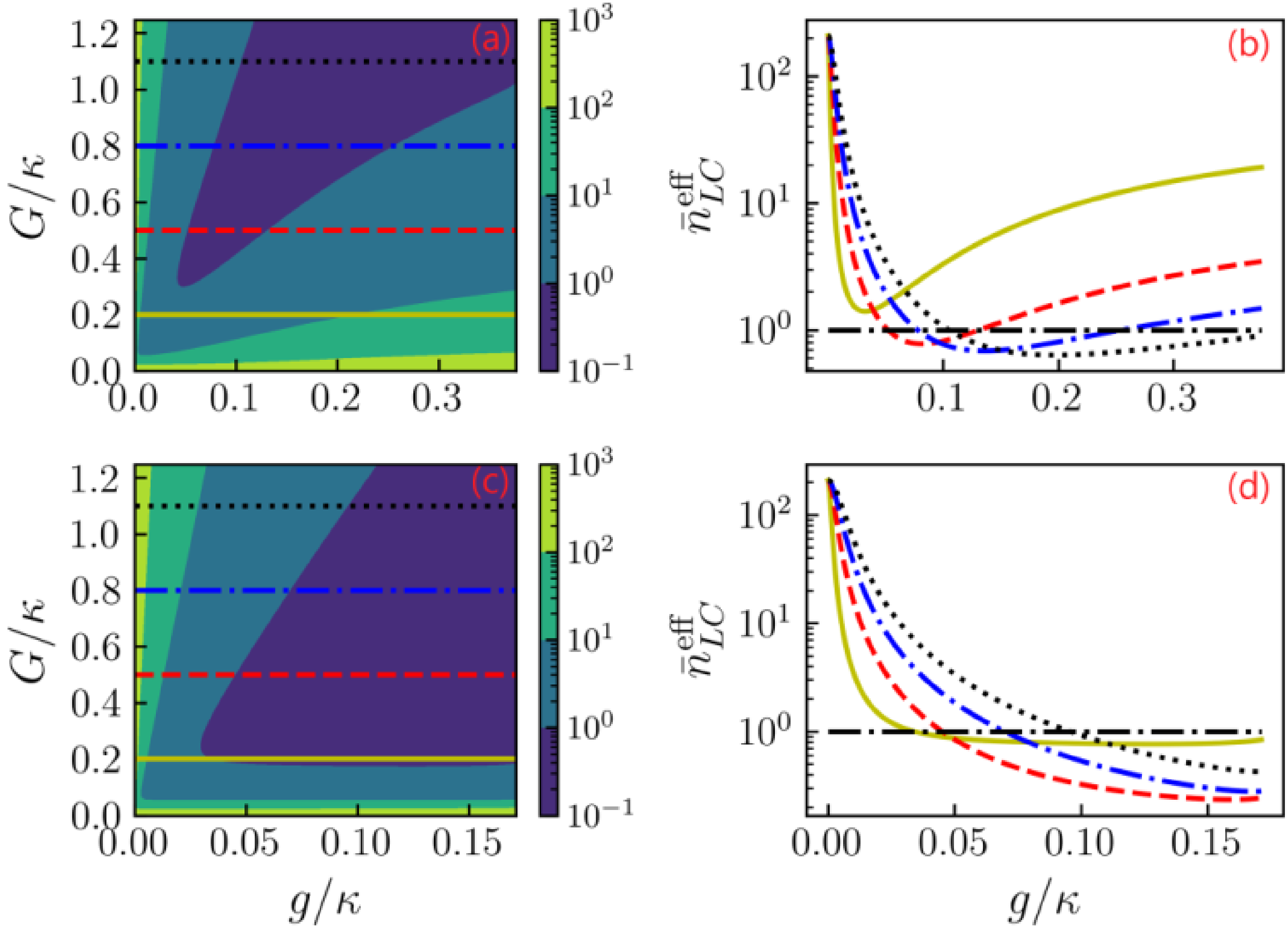
- Improving devices yield and reproducibility;
- Avoid electrical cross-talk between the membrane capacitor and the electrode (oxide passivation) for a large span of voltage biases
- Better control of the capacitor plate distance

PHYSICS AND DEVICES

1. **"Sympathetic" cooling to the quantum ground state of an LC resonator**: laser cooling of the SiN membrane which then sympathetically cools the coupled quasi-resonat LC rf-circuit

2. **Nonreciprocal rf-optical transduction** via interference

Ground state sympathetic cooling of the LC is possible



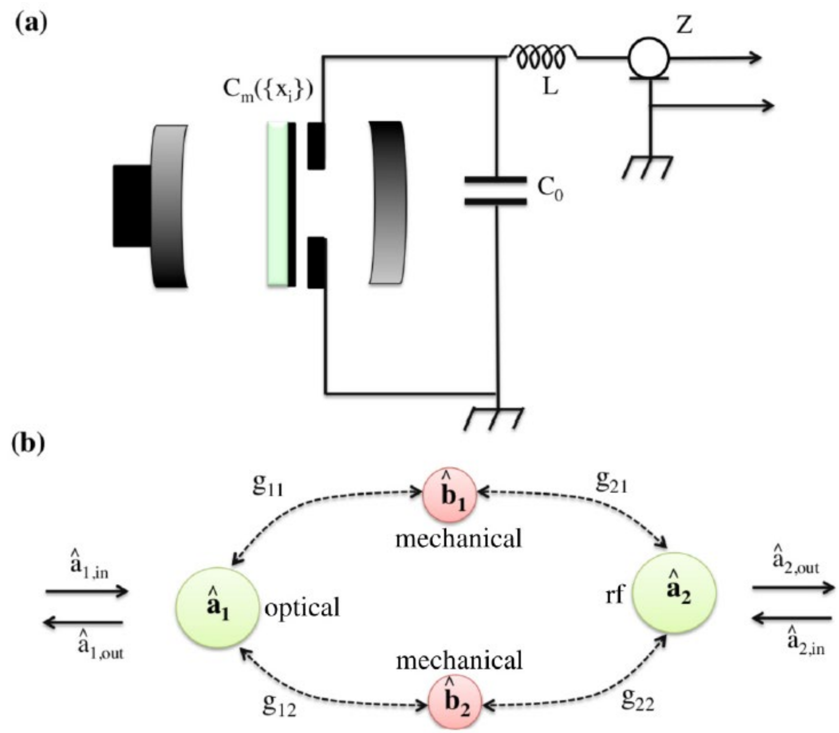
Exact results for the stationary LC circuit occupancy n_{eff}^{LC}

LC-mechanical are always kept on resonance by adjusting parameters

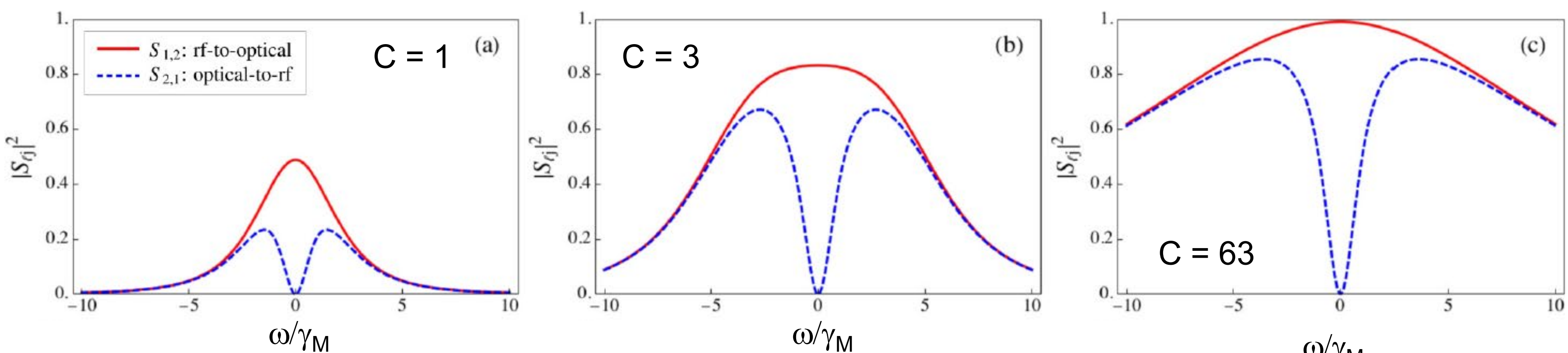
$$Q_{LC} = 4 \times 10^4 \quad T = 10\ \mathrm{mK}$$

N. Malossi et al., Phys. Rev. A **103,** 033516 (2021)

Nonreciprocal conversion between radio-frequency and optical photons with an optoelectromechanical system



N. Eshaqi-Sani et al, Phys. Rev. A 106, 032606 (2022)



Equal electromechanical and optomechanical cooperativities C