A Chip-scale Optomechanical Accelerometer for Inertial Navigation Suitable for Small Satellites

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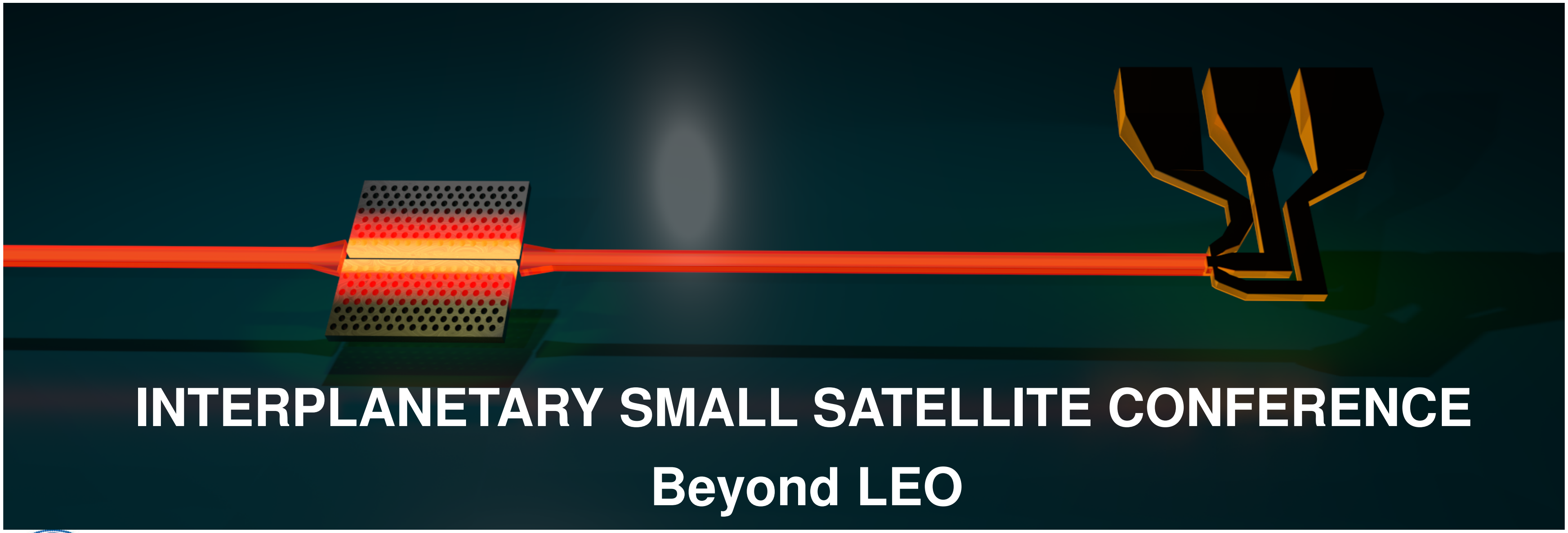


INTERPLANETARY SMALL SATELLITE CONFERENCE

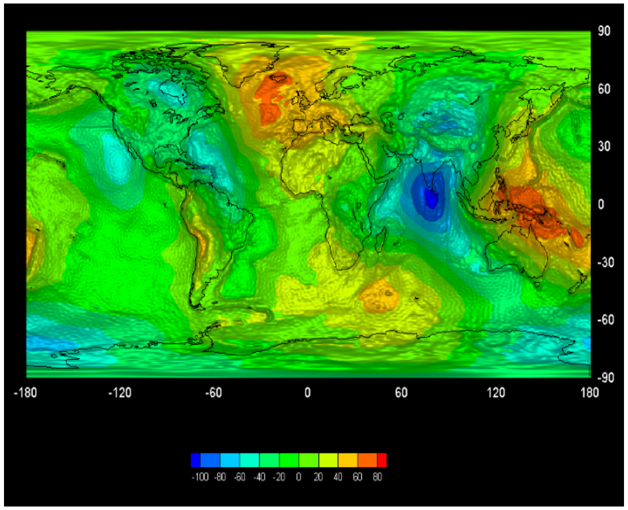
Beyond LEO

Accelerometer's Applications

I. Inertial Navigation

II. Earthquake prediction

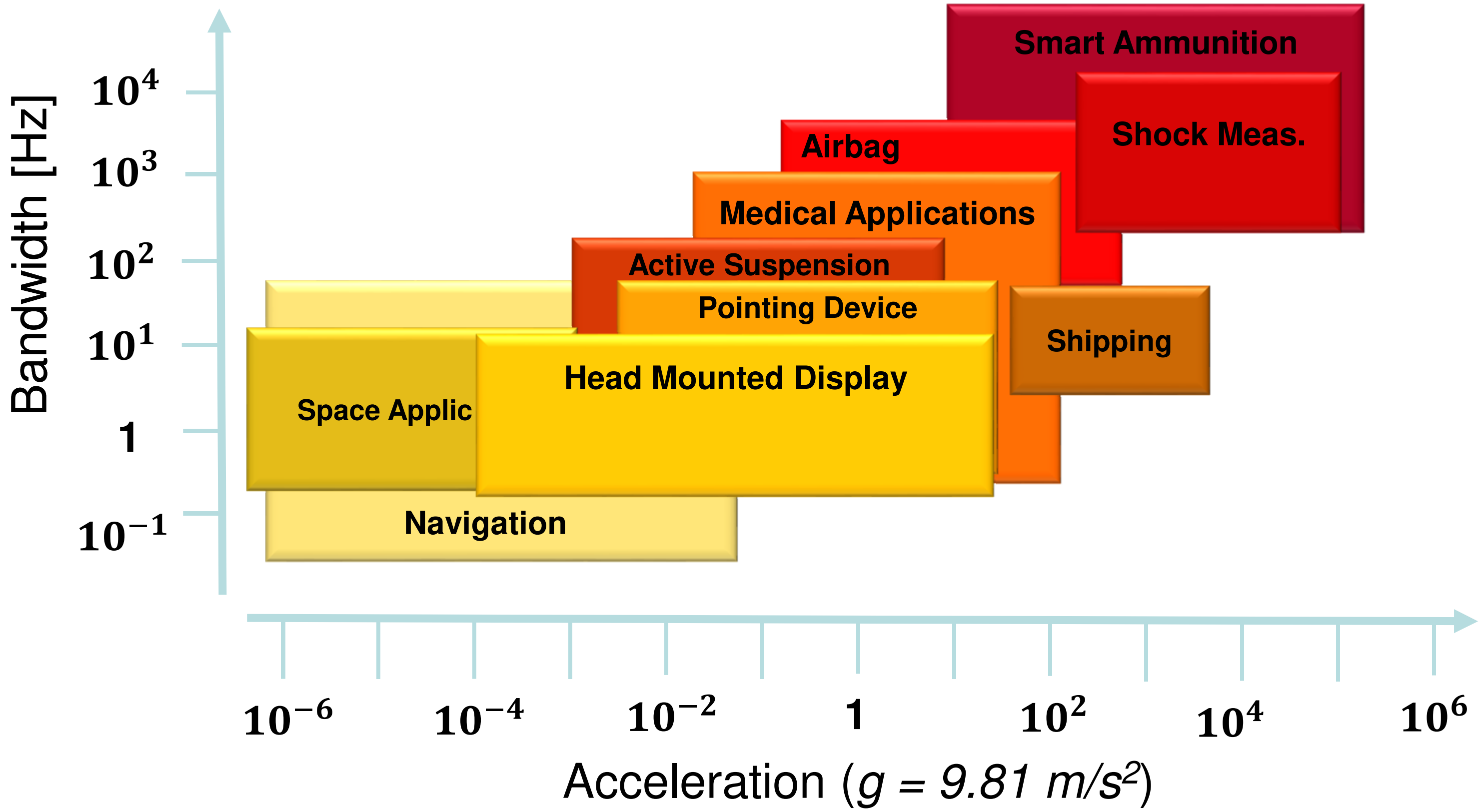
III. Obstacle avoidance



IV. Gravimetry

V. Oil field exploration

Accelerometer performance according to application



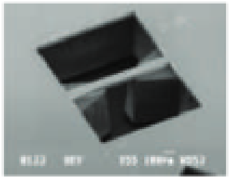
Source: Adapted from: Kraft Michael, Micromachined inertial sensors state of the art and a look into the future. Measurement+Control **33**., (2000)

Cavity optomechanics: light forces at the nanoscale

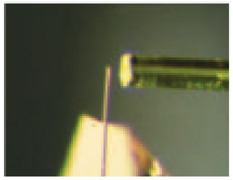
Gram-scale mirror

Silicon nitride membrane

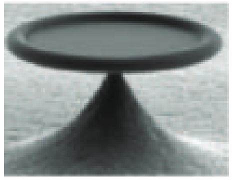
Sub-millimeter mirror



AFM cantilever mirror



Silica micro-toroid cavity



50 µm micro-mirror

2 µm dwarf mirror

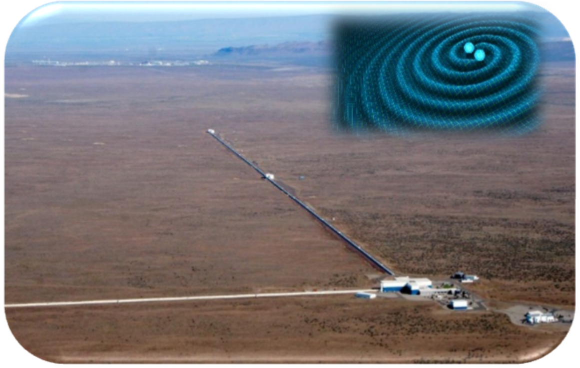
Nano-resonator

Sub-diffraction limit

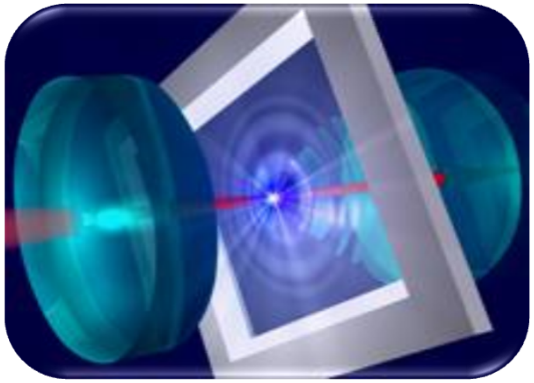
1 cm

100 nm

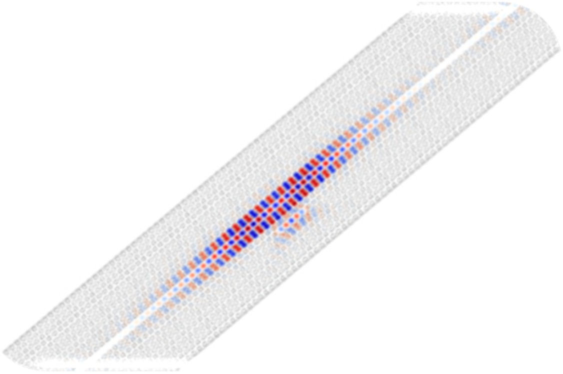
LIGO



Radiation Pressure



Optical Gradient Force



kilometers

centimeters

micrometers

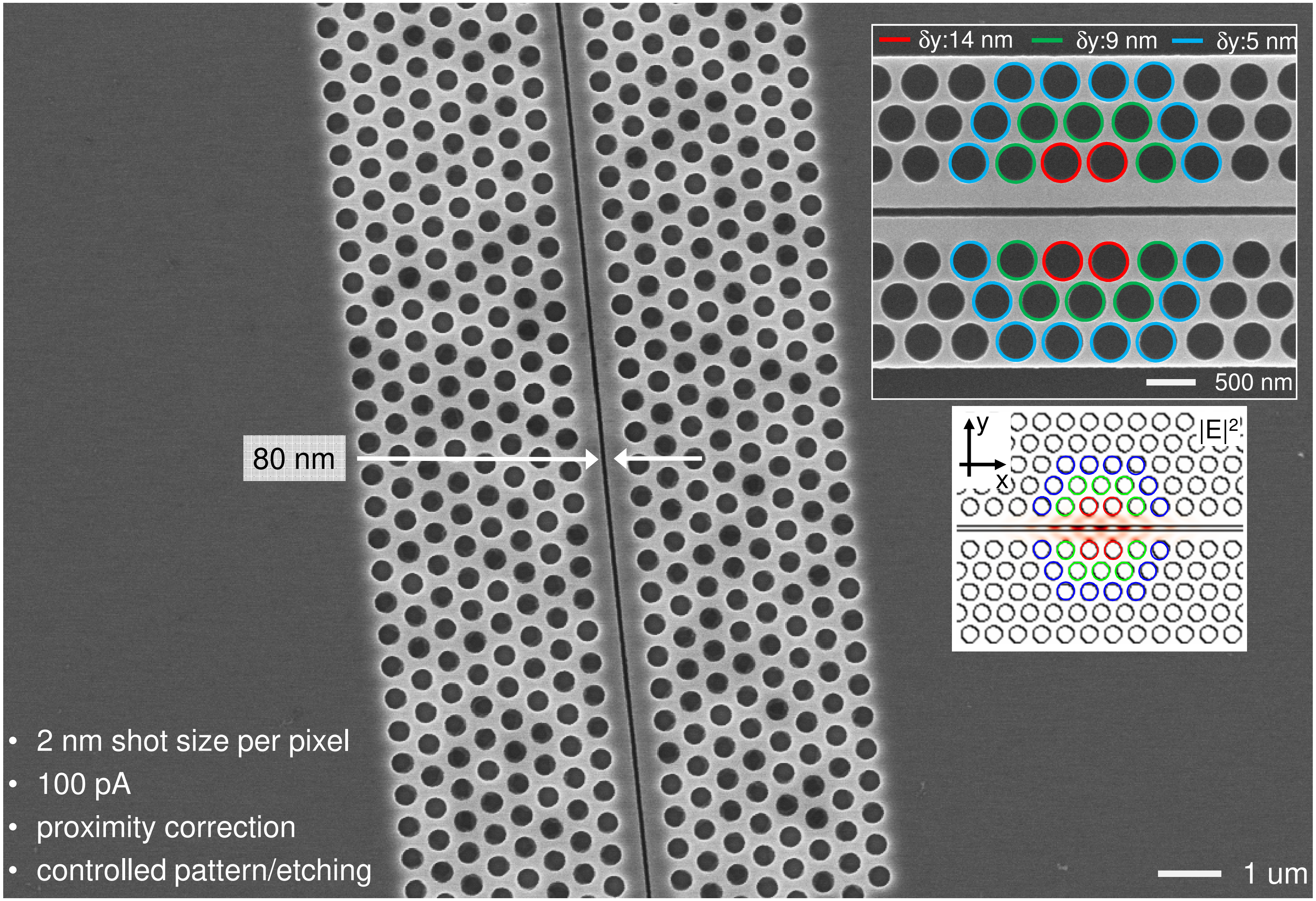
Gravity wave observatory
Livingston, LA & Hanford, WA

Harris et al. *Nature* **452**, 06715 (2008)
Harris and Wong et al.

Wong group, Columbia and UCLA

Favero and Karrai, *Nature Photonics* **3**, 201 (2009).

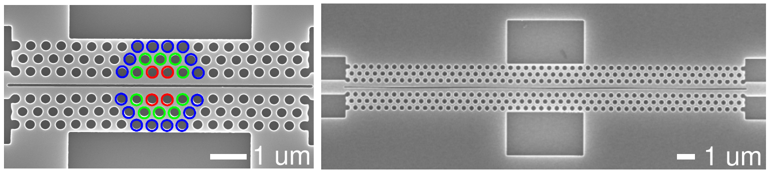
Optimized slot-cavity nanofabrication



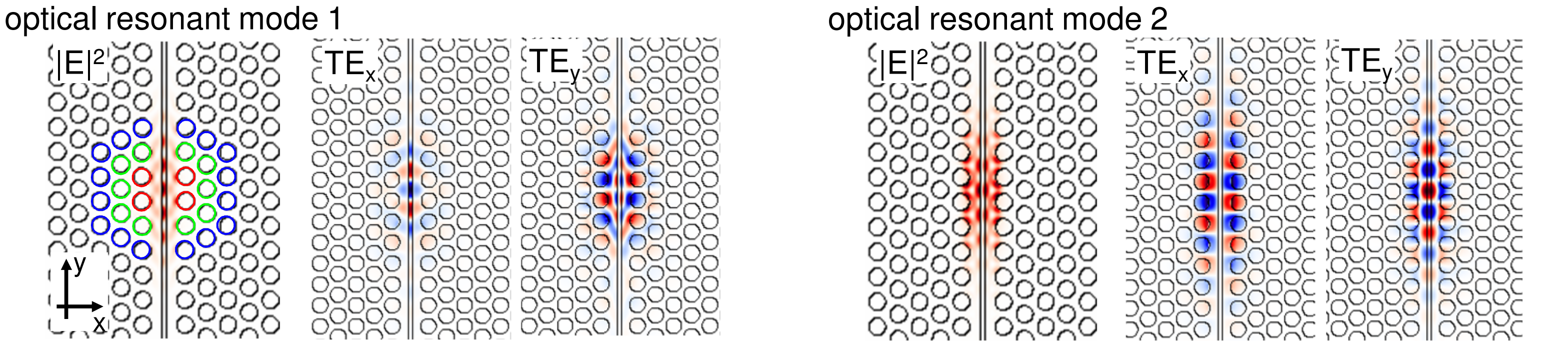
- 2 nm shot size per pixel
- 100 pA
- proximity correction
- controlled pattern/etching

D. Wang and M. Dadgar (Wong) et al.

Chip-scale cavity optomechanics: 2D slot cavities



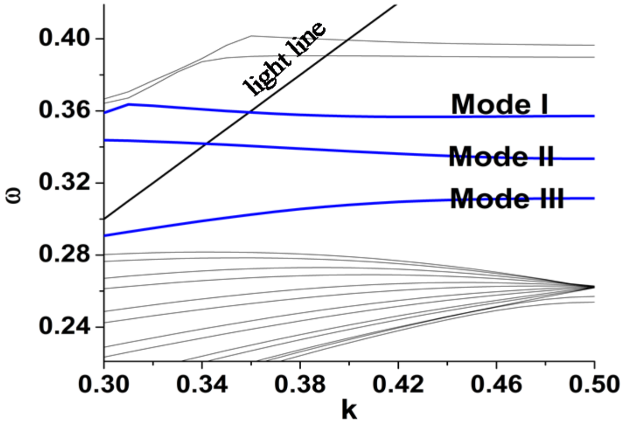
- first two eigenmode *E*- and *H*-fields



- finite-difference time-domain
- Q_{theory} ~ 4,000,000 (Q_{expt} ~ 200,000 to 1e6)
- mode volume V ~ $0.02(\lambda/n_{air})^3$

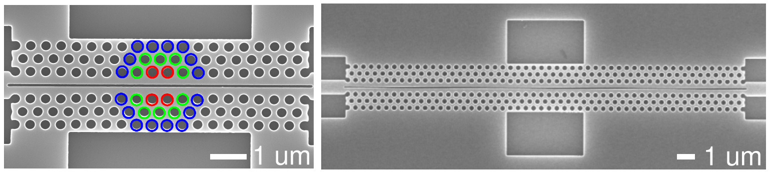
  - a = 490nm, r = 0.34a, t = 0.449a,
  - n_{si}=3.48;
  - d_A=0.0286a, d_B=0.019a and d_C=0.0095a
  - *s*=80nm

modeled band structure

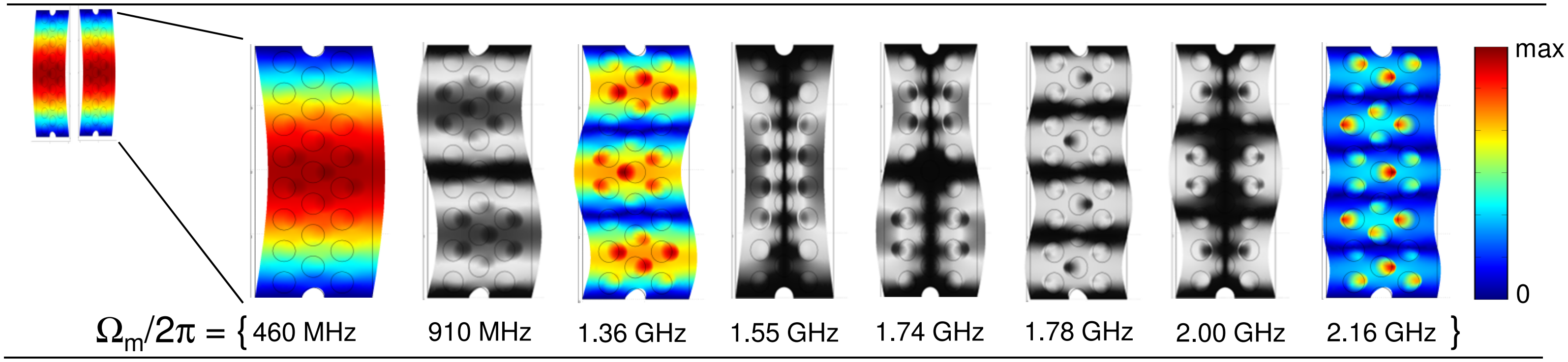


Gao (Wong) et al., *Appl. Phys. Lett.* **96**, 051123 (2010).

Chip-scale cavity optomechanics: mechanical modes

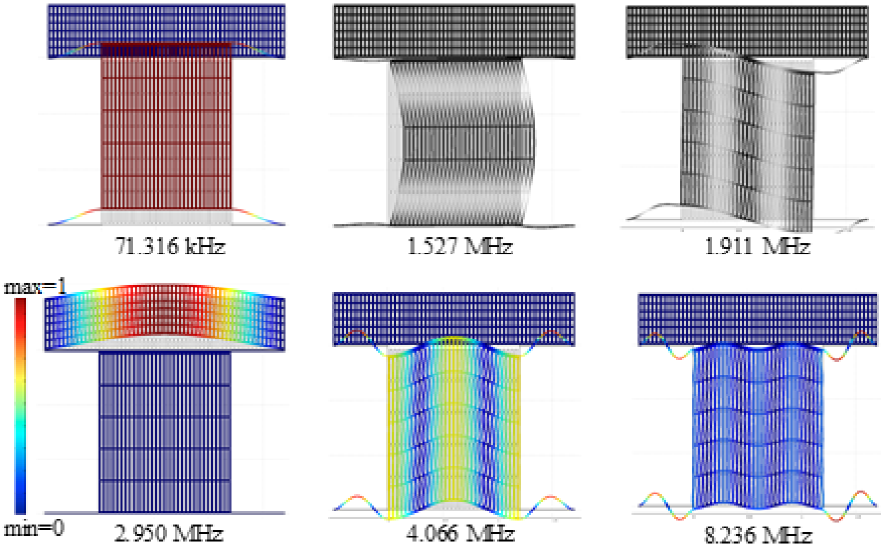


- first eight eigenmode displacement fields



$\Omega_m/2\pi = \{$460 MHz 910 MHz 1.36 GHz 1.55 GHz 1.74 GHz 1.78 GHz 2.00 GHz 2.16 GHz$\}$

- comsol finite-element: common, differential, compression, twisting, in/out-of-plane modes
- selection by symmetry (modes in color are allowed; modes in grey are forbidden)



Li (Wong) et al., *Optics Express* **18**, 23844 (2010) and Safavi-Naeini (Painter) et al., *Appl. Phys. Lett.* **97**, 181106 (2010).

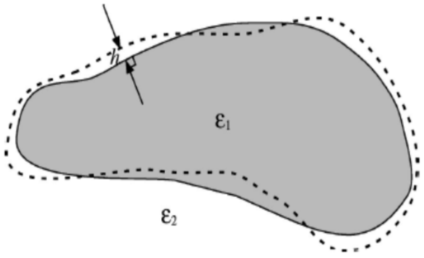
Coupled mode and first-order perturbation theory

$$\boxed{\begin{aligned} &\frac{da}{dt} = i\Delta(x)a - \left(\frac{1}{2\tau_0}+\frac{1}{2\tau_{ex}}\right)a + i\sqrt{\frac{1}{2\tau_{ex}}}\,s \qquad\qquad \Delta(x) = \Delta + g_{OM}x = (\omega-\omega_o) + g_{OM}x \\ &\frac{d^2x}{dt^2} + \frac{\Omega_m}{2Q_m}\frac{dx}{dt} + \Omega_m^2 x = \frac{F_o}{m_{eff}} + \frac{F_{th}}{m_{eff}} = -\frac{|a|^2 g_{OM}}{m_{eff}\omega_0} + \frac{F_{th}}{m_{eff}} \end{aligned}}$$

- optomechanical coupling

$$g_{om} = \frac{d\omega}{dx} \qquad\qquad L_{om}^{-1} = \frac{1}{\omega}\frac{d\omega}{dx}$$

- first-order perturbation theory for Maxwell’s equations with shifting material boundaries



$$\frac{d\omega}{dx} = -\frac{\omega^{(0)}}{2}\frac{\left\langle E^{(0)}\left|\frac{d\varepsilon}{dx}\right|E^{(0)}\right\rangle}{\left\langle E^{(0)}\left|\varepsilon\right|E^{(0)}\right\rangle}$$

$$\left\langle E^{(0)}\left|\frac{d\varepsilon}{dx}\right|E^{(0)}\right\rangle = \int dA\frac{dh}{dx}\left[\Delta\varepsilon|E|^2 - \Delta\left(\varepsilon^{-1}\right)|D|^2\right]$$

↔ with anisotropic smoothening

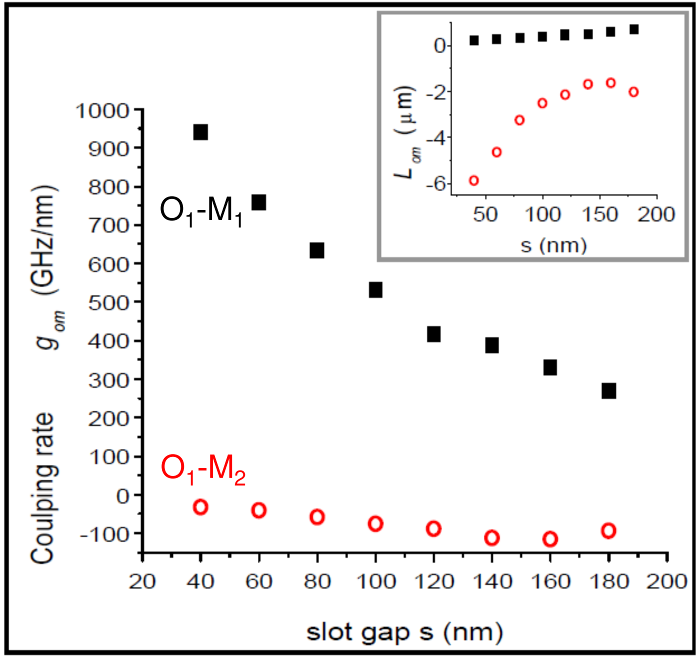
$$\boxed{g_{om} = \frac{1}{2\omega}\frac{\int dA\left(\vec{q}\cdot\hat{\vec{n}}\right)\left[\Delta\varepsilon|E|^2 - \Delta\left(\varepsilon^{-1}\right)|D|^2\right]}{\int dV\varepsilon\,|E(r)|^2}}$$

H. A. Haus, *Waves and Fields in Optoelectronics*.
C. W. Wong et al. *Appl. Phys. Lett.* **84**, 1242 (2004).
S. G. Johnson et al. *Phys. Rev. E* **65**,066611(2002).
M. Eichenfield et al. *Optics Express* **17**, 20078 (2009).

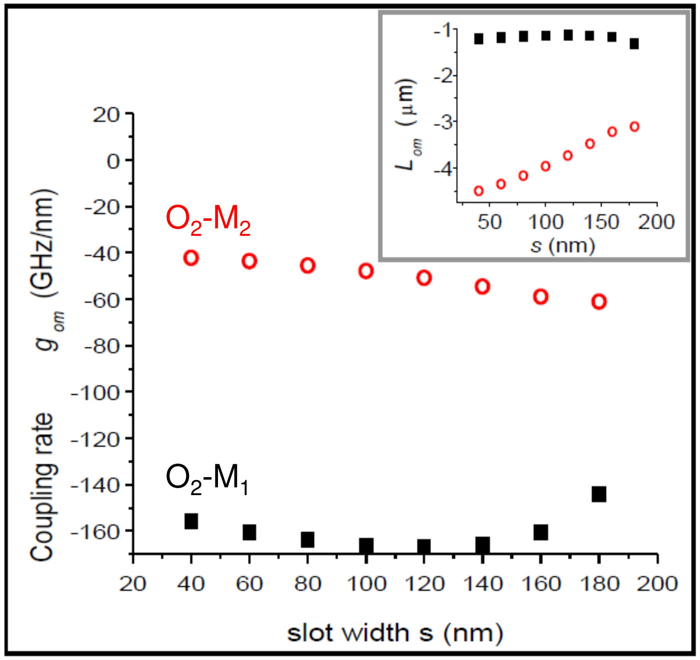
Multi-modal optomechanical coupling rates

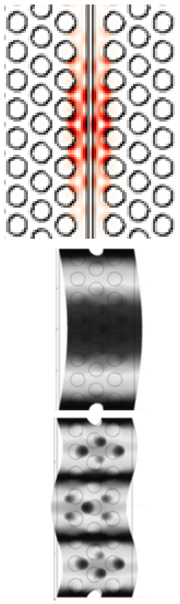
- from first-order perturbation theory

optical mode 1 ←→ {mechanical 1,2}



optical mode 2 ←→ {mechanical 1,2}



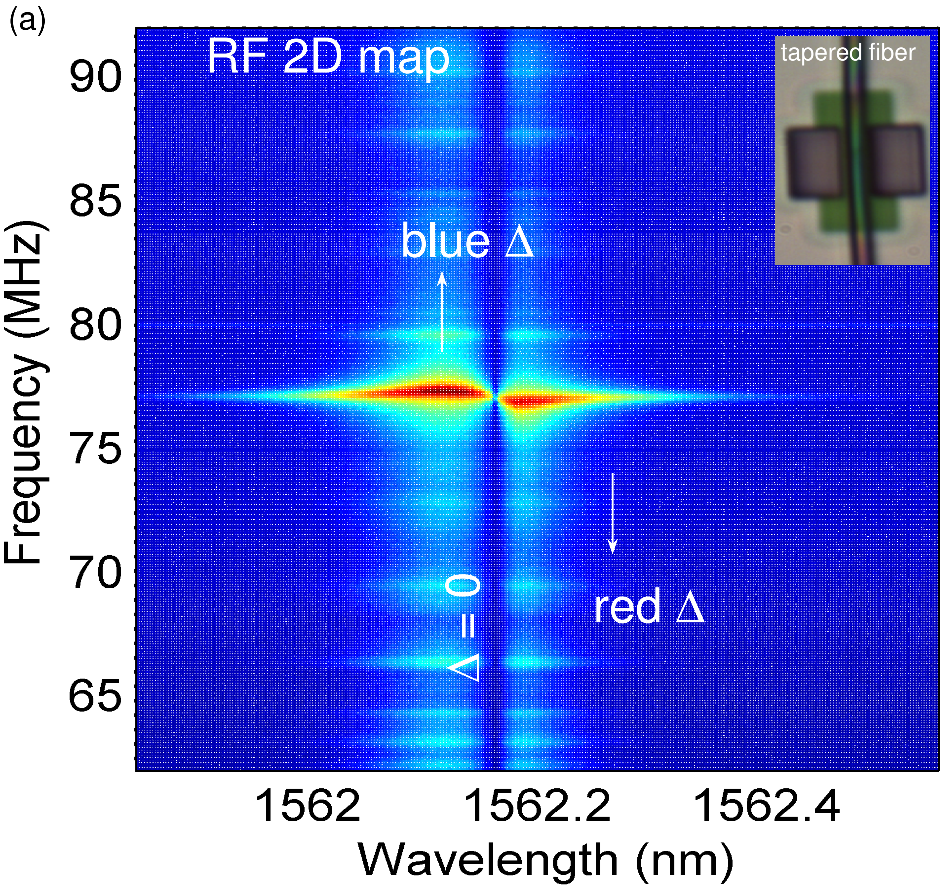


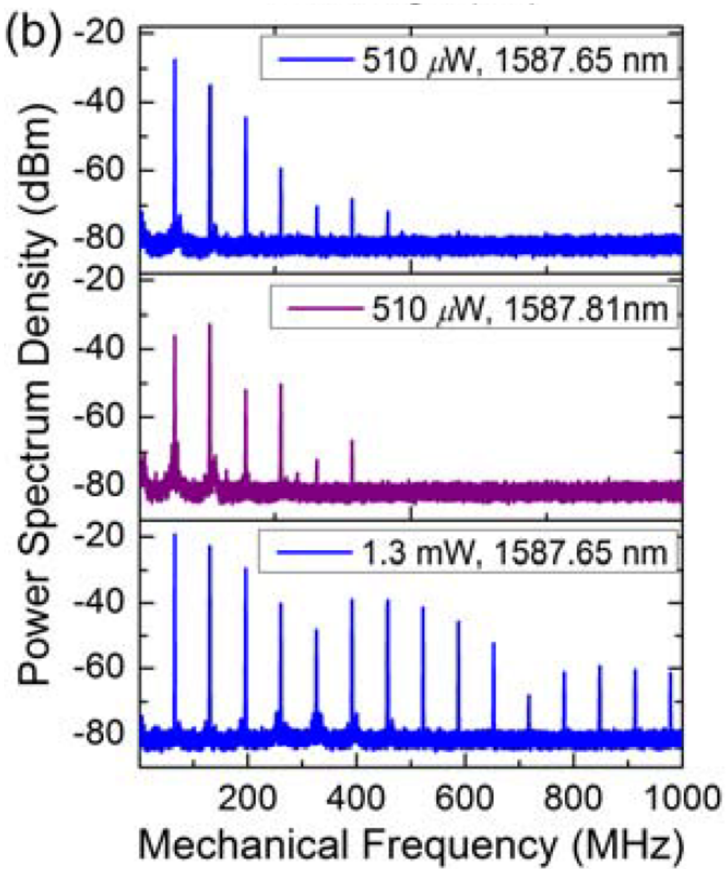
- **$g_{om}/2\pi$ = 940 GHz/nm** **$g^*/2\pi$ = 2 MHz (vacuum – zero-point motion)**
  (several times larger than earlier cavity optomechanical interactions)

- m_{eff} ~ 2 pg, $\Omega_m/2\pi$ ~ 100 MHz, Q_o = 500,000; λ = 1550 nm

Li (Wong) et al., *Optics Express* **18**, 23844 (2010).

Optomechanical oscillator: regenerative oscillations

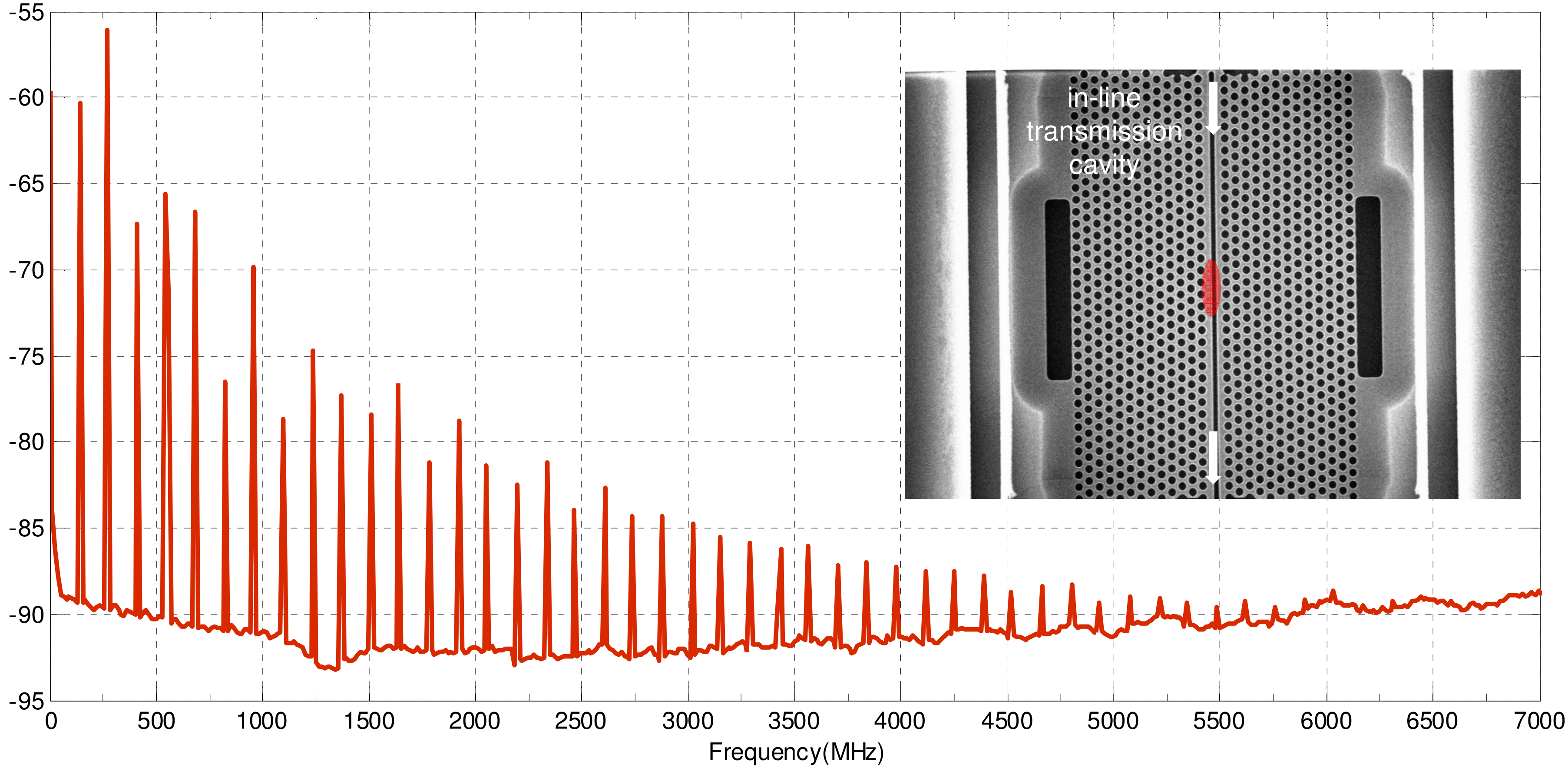




- **strong $g_{om}/2\pi$** (154 GHz/nm; g*/2 π ~ 330-kHz)
- **15+ harmonic (detector limited) for locking**
- **higher-harmonic of GHz fundamental possible**

Optomechanical oscillator: regenerative oscillations

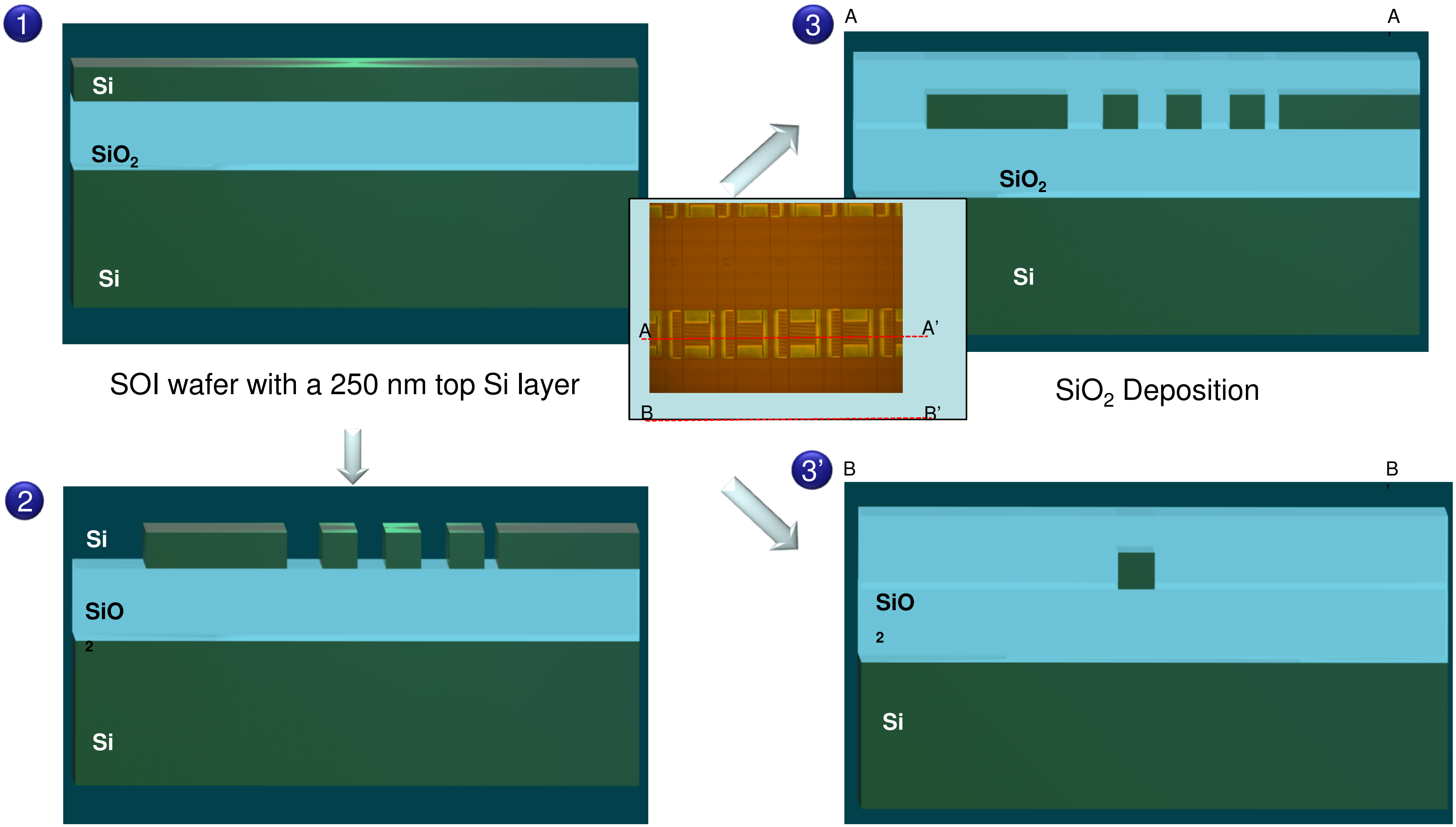
- developed under DARPA ORCHID
- CW-pumped RF oscillator/clock



- here up to 44th harmonic observed, for ~ 5.5 GHz RF tone
- More than 100 harmonics (CLEO 2016)

- Y. Huang, J.G. Flor Flores, C.W. Wong, et al., *Wide optical force-induced RF dynamic range and 100+ high-order stable mechanics in chip-scale optomechanical cavities*, CLEO (2016).

Accelerometer Fabrication Process (I)



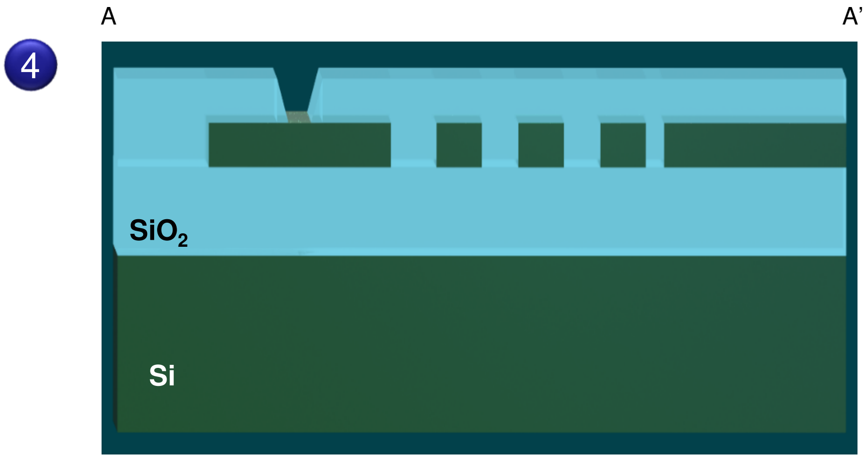
SOI wafer with a 250 nm top Si layer

Top Si etching

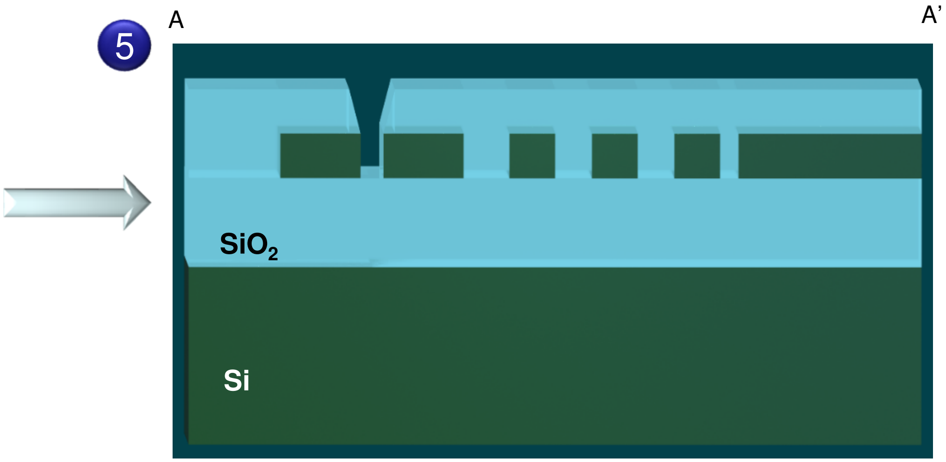
SiO_2 Deposition

SiO_2 Deposition (Waveguide view)

Accelerometer Fabrication Process (II)



(30 nm to 100 nm) slot cavity: SiO_2 Etching



(30 nm to 100 nm) slot cavity: SiO_2 Etching

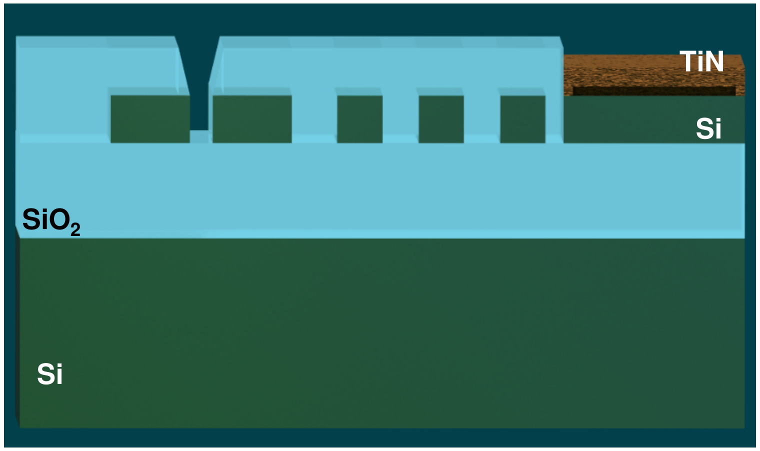
RIE SiO_2 Etching (waveguide)

Accelerometer Fabrication Process (III)

⑥

SiO_2 etching for metallization

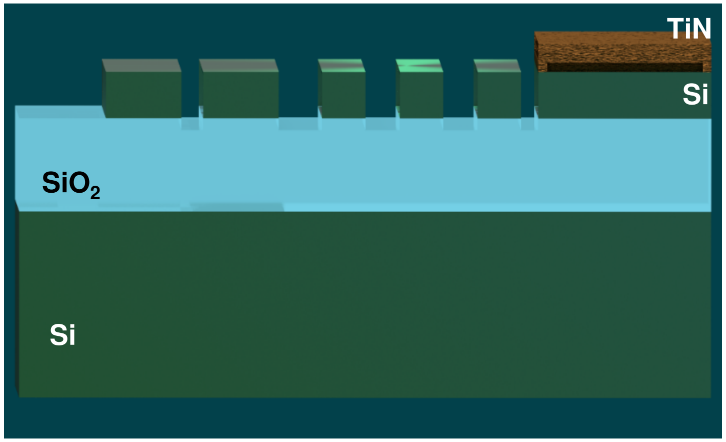
⑦



Metallization TiN

No oxide between the Si and metal layer, since this might cause problems during the final release.

⑧

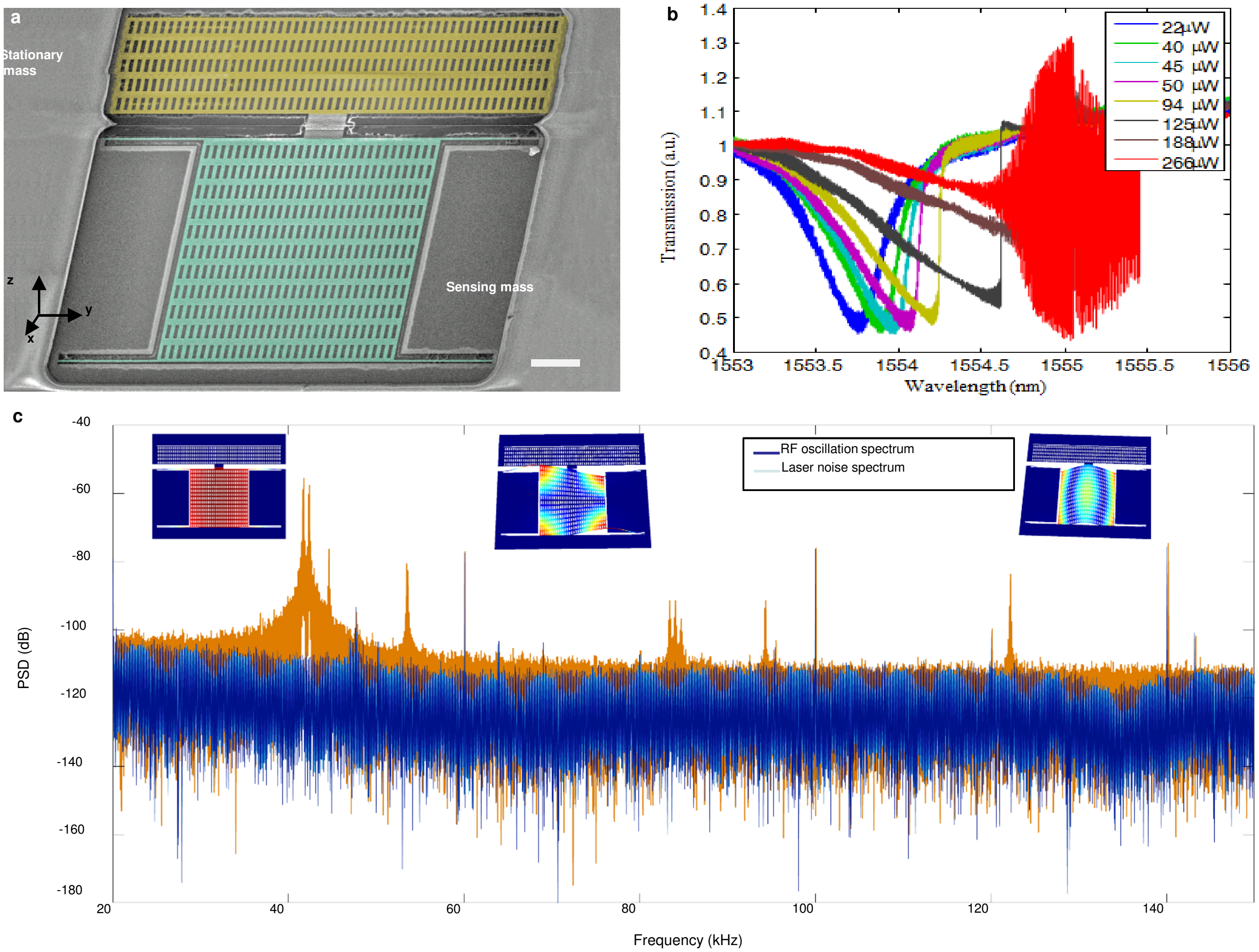


Top oxide etching

⑨

Underneath oxide etching - Oscillator release

Optomechanical oscillator: high dynamic range and precision force sensing



- •RF mode of the optomechanical accelerometer with integrated waveguides
- •as the transmission spectra is monitored for cavity coupling, the main measurements are done in parallel by RF optical readout.

Calculated Power Dependence in oscillation mode

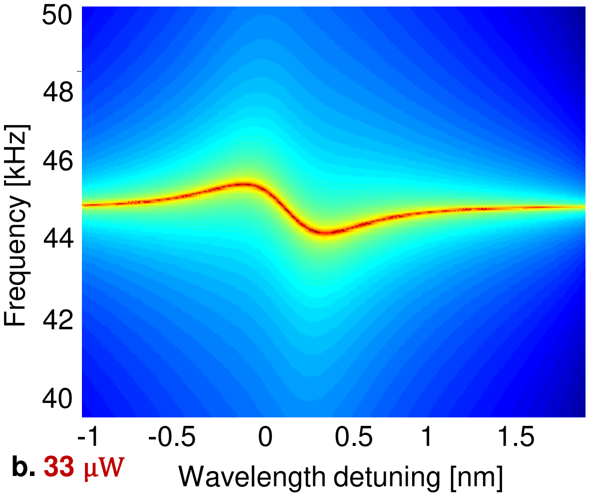
Power spectral dependence

$$S_x(\Omega) = \frac{2\Gamma_m k_B T/m_x}{\left(\Omega_m^2 - \Omega^2\right) + (\Omega\Gamma_m)}$$

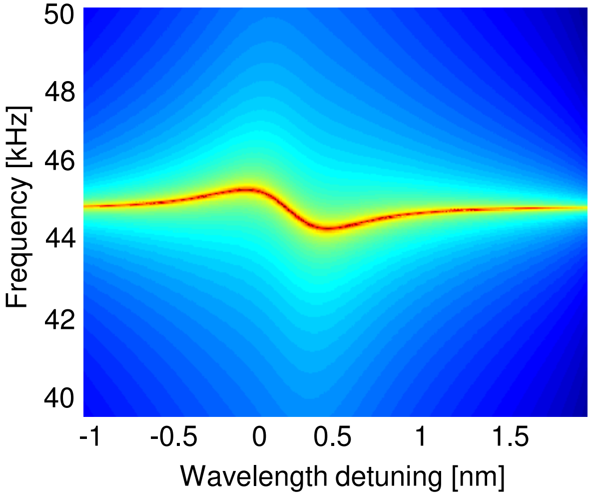
Mechanical Frequency dependence

$$\Omega'_m = \sqrt{\Omega_m^2 + \left(\frac{2|\hat{a}|^2 g_{om}^2}{\left((\omega_l - \omega_c + g_{om}x_s)^2 + (1/2\tau)^2\omega_c m_x\right)}\right)(\omega_l - \omega_c + g_{om}x_s)}$$

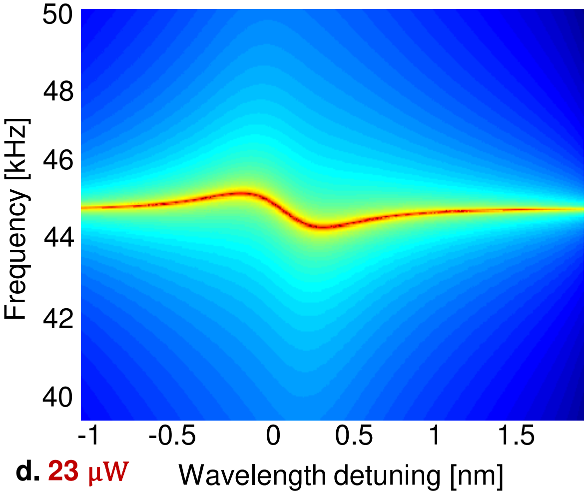
a. 42 µW



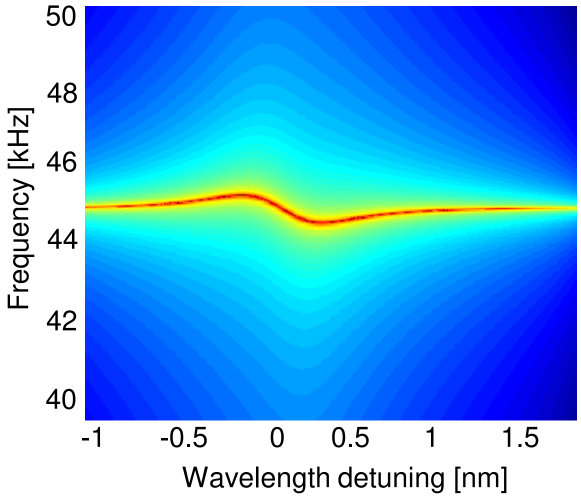
b. 33 µW



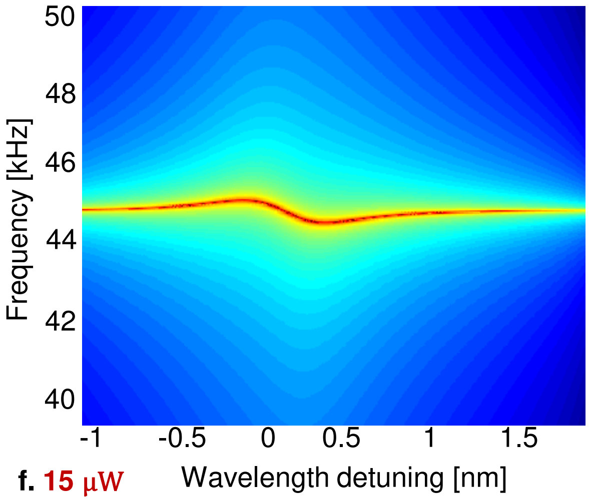
c. 29 µW



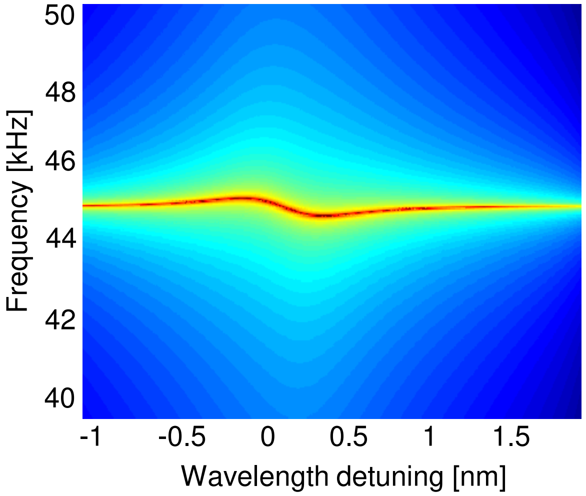
d. 23 µW



e. 19 µW



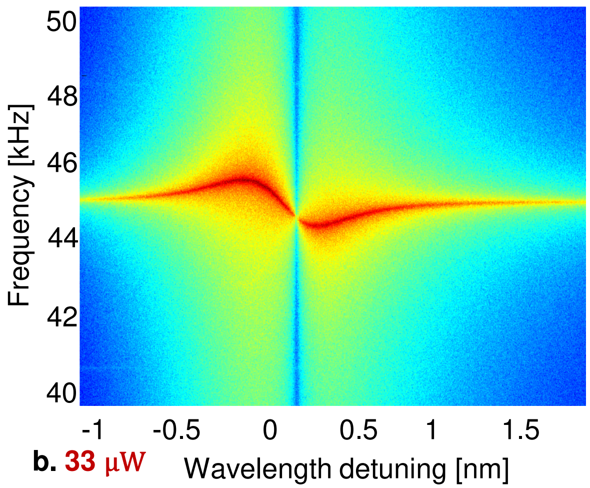
f. 15 µW



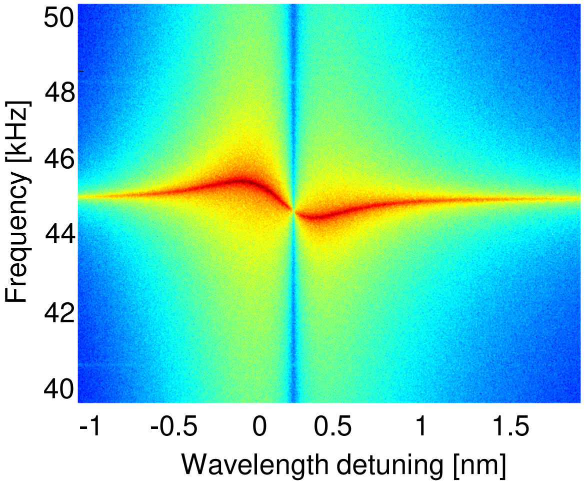
Flor Flores, Huang, Li, Wong et al., P*ower-dependence of high-Q optomechanical oscillators.*,CLEO (2017).

Power Dependence in oscillation mode

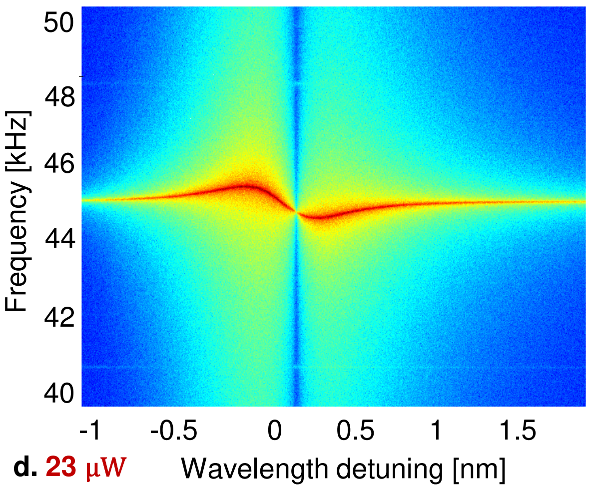
a. 42 μW



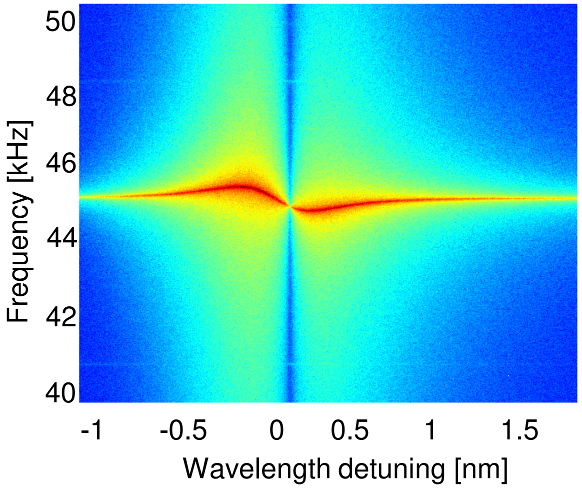
b. 33 μW



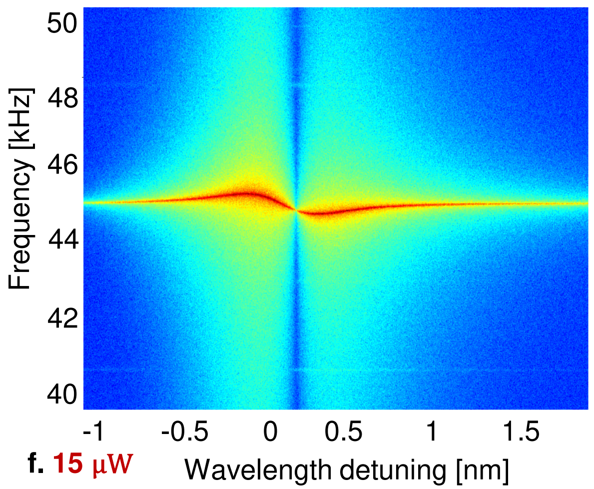
c. 29 μW



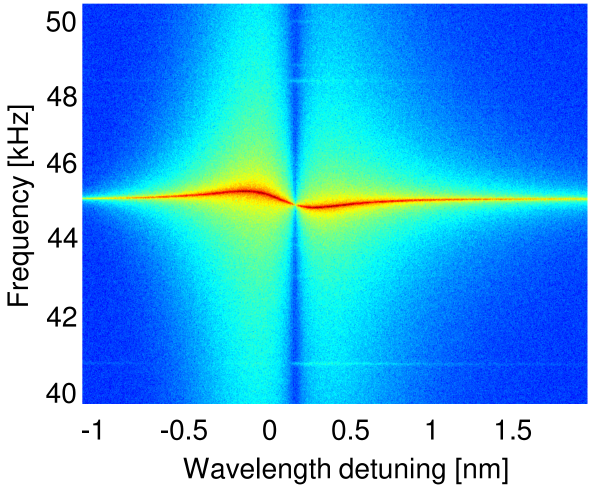
d. 23 μW



e. 19 μW



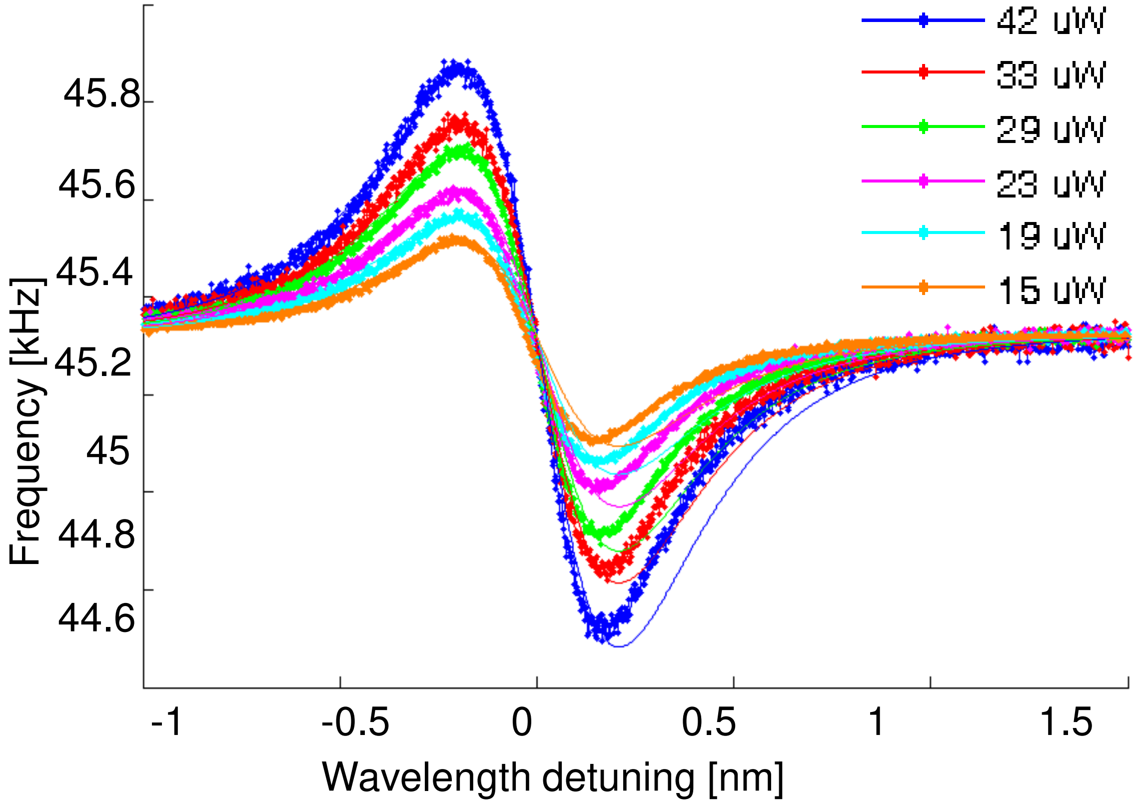
f. 15 μW



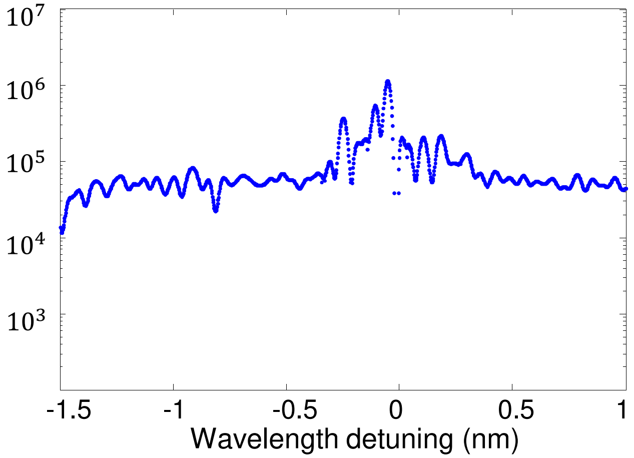
Flor Flores, Huang, Li, Wong et al., P*ower-dependence of high-Q optomechanical oscillators.,*CLEO (2017).

OMO experimental performance

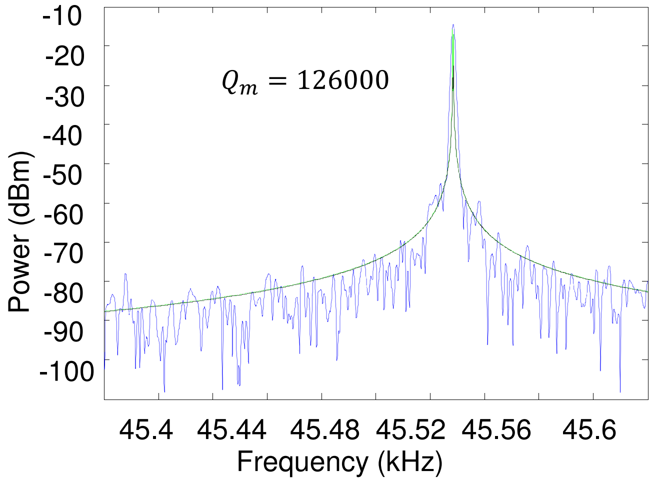
- Very high mechanical quality factor
- Linear region fit



Mechanical Quality Factor as a function of detuning

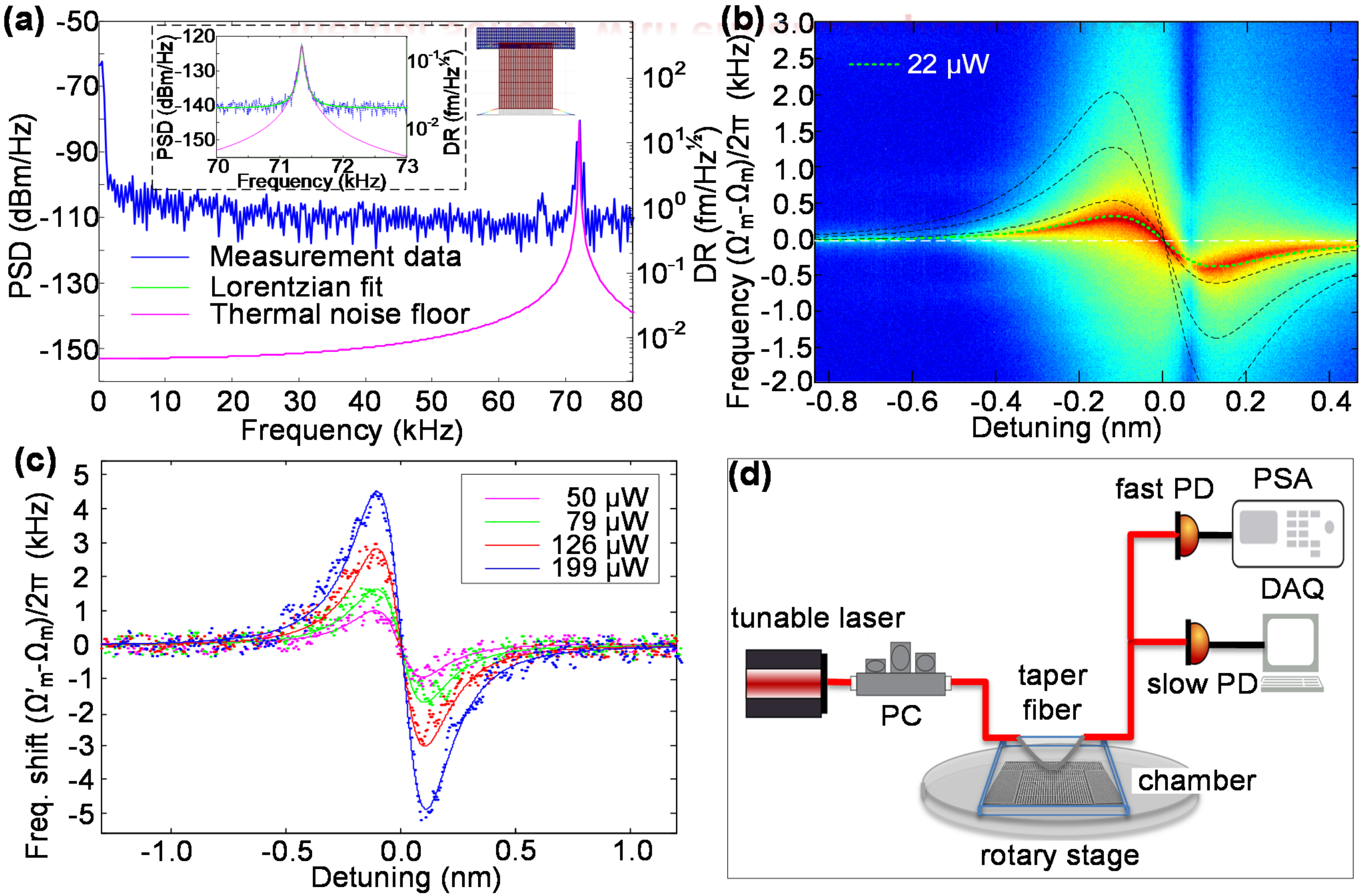


Mechanical Response



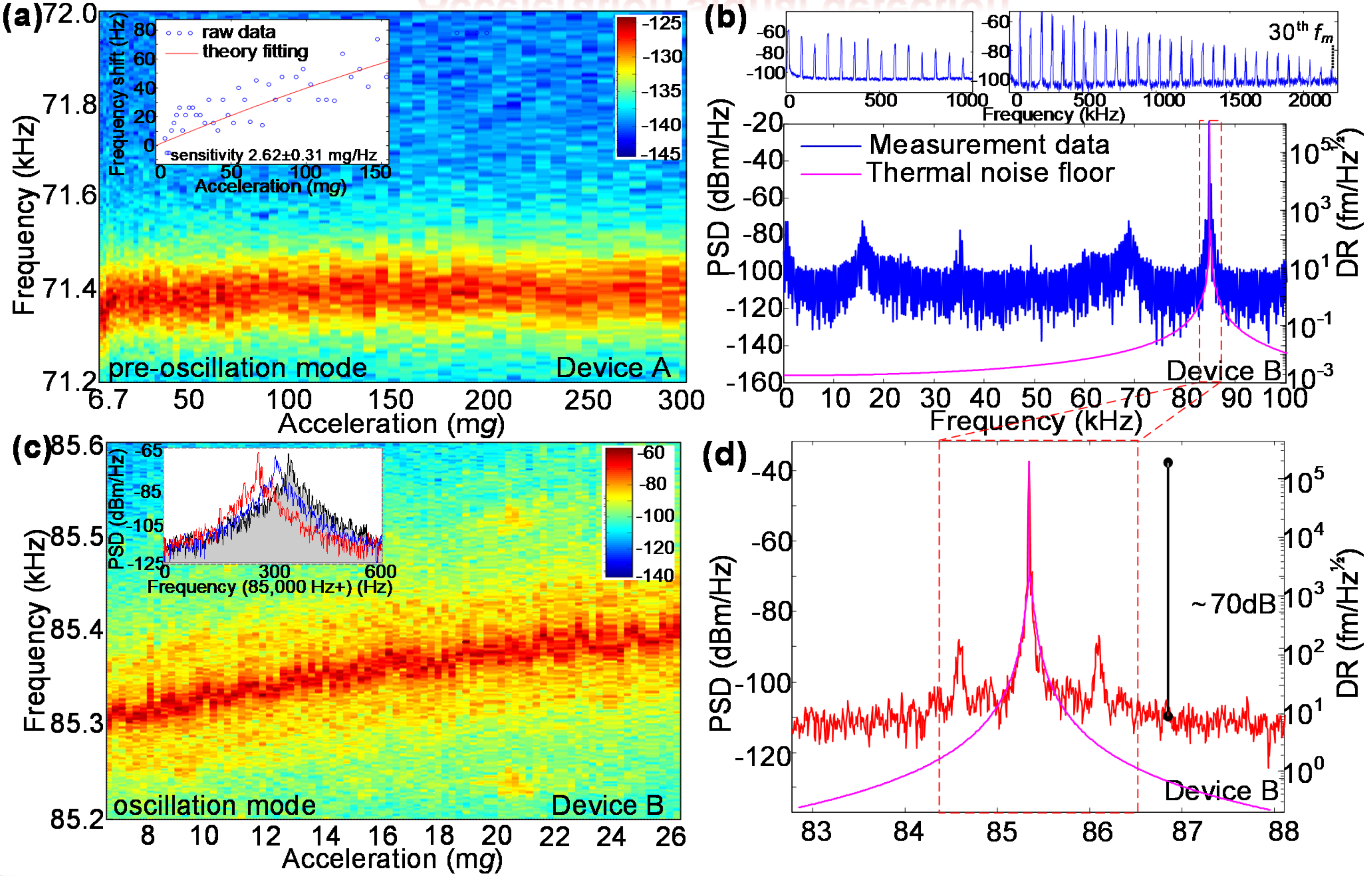
Flor Flores, Huang, Li, Wong et al., P*ower-dependence of high-Q optomechanical oscillators.,*CLEO (2017).

Inertial sensor with enhanced performance



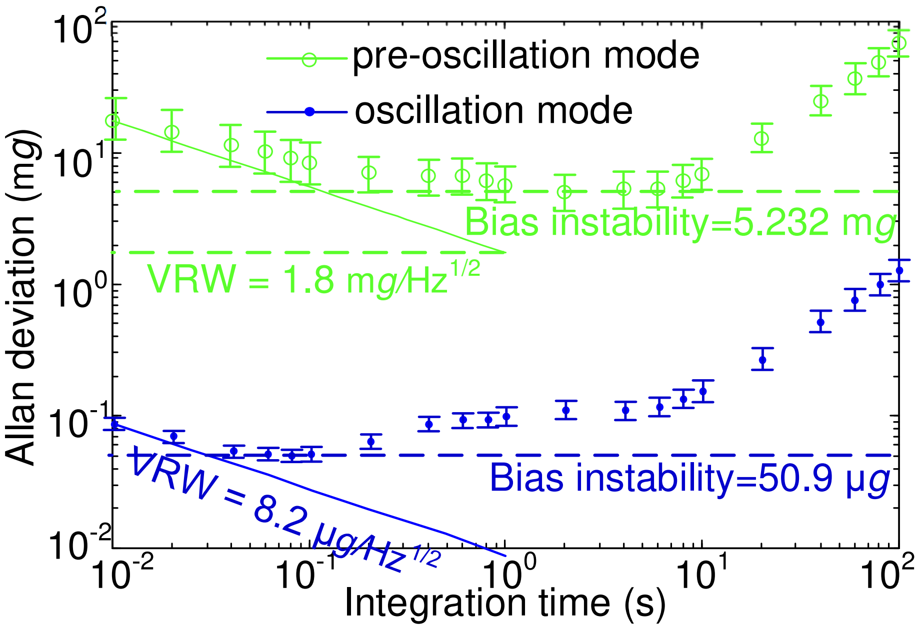
Y. Huang, J. G. Flor Flores, Y. Li, W. Wang, D. Wang, N. Goldberg, J. Zheng et al., "A Chip-Scale Oscillation-Mode Optomechanical Inertial Sensor Near the Thermodynamical Limits," *Laser & Photonics Reviews* 14, no. 5 (2020): 1800329

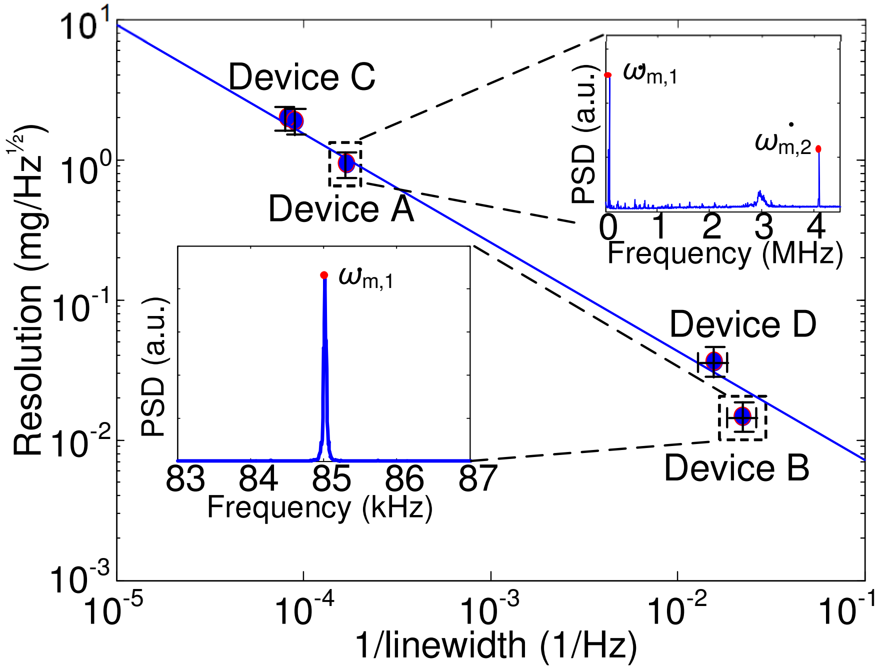
Acceleration signal detection



Y. Huang, J. G. Flor Flores, Y. Li, W. Wang, D. Wang, N. Goldberg, J. Zheng et al., "A Chip-Scale Oscillation-Mode Optomechanical Inertial Sensor Near the Thermodynamical Limits," *Laser & Photonics Reviews* 14, no. 5 (2020): 1800329

Oscillation and pre-oscillation modes performance

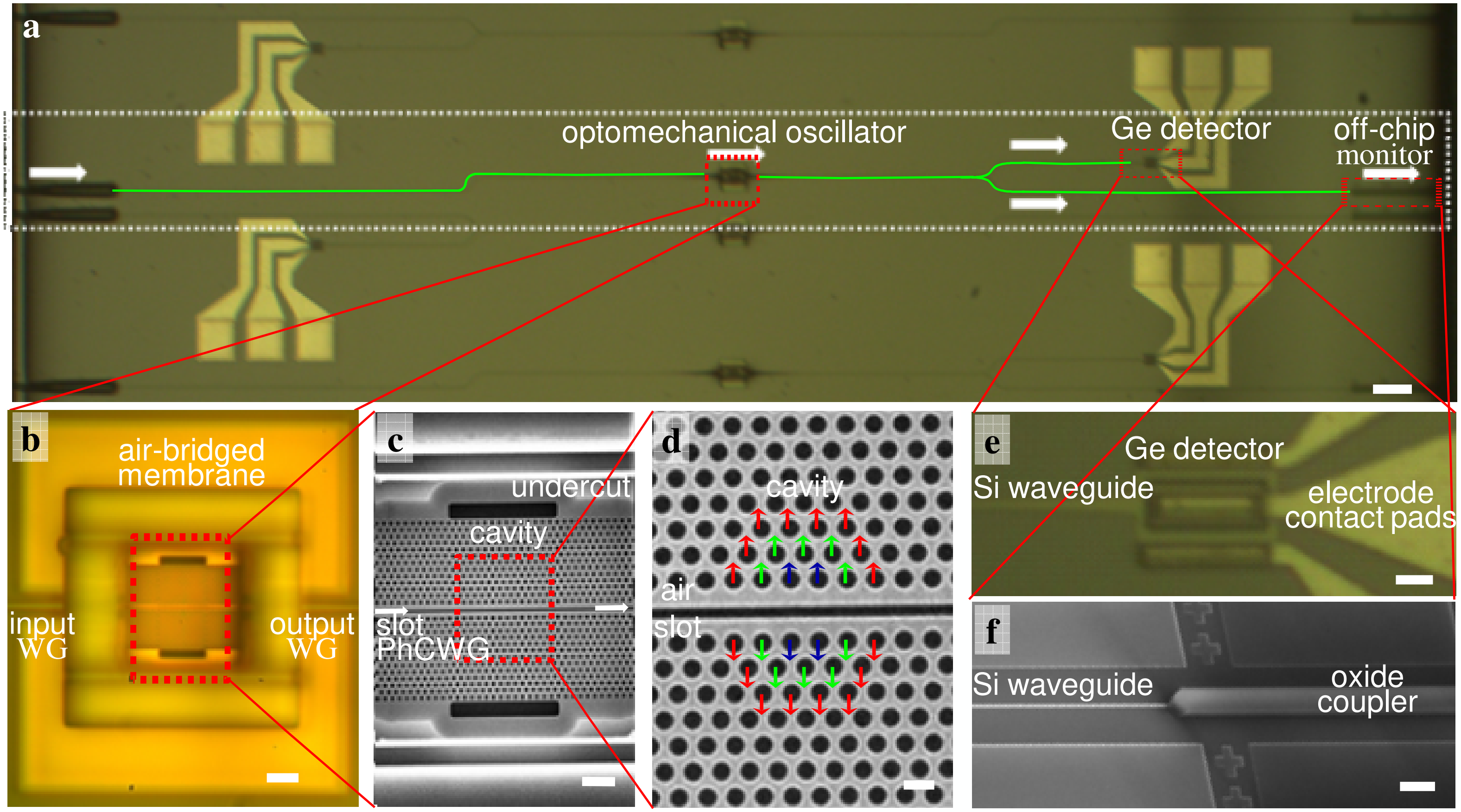




- ➢ Allan deviation measured at the pre-oscillation and oscillation modes.
- ➢ x220 Improvement in the oscillation mode compare to pre-oscillation.
- ➢ Optomechanical coupling rate of 37.1 GHz/nm
- ➢ Further stability can be improved with laser stabilization.

Y. Huang, J. G. Flor Flores, Y. Li, W. Wang, D. Wang, N. Goldberg, J. Zheng et al., "A Chip-Scale Oscillation-Mode Optomechanical Inertial Sensor Near the Thermodynamical Limits," *Laser & Photonics Reviews* 14, no. 5 (2020): 1800329

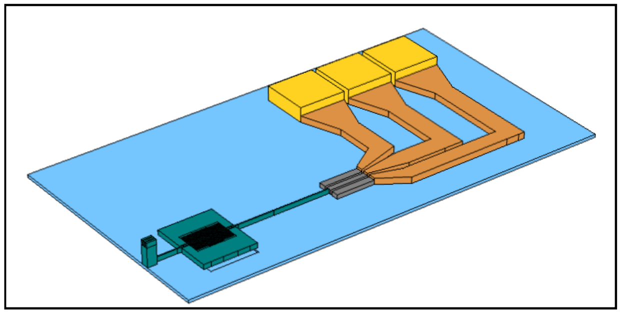
DARPA ORCHID: A monolithic optomechanical photonic crystal oscillator chipset



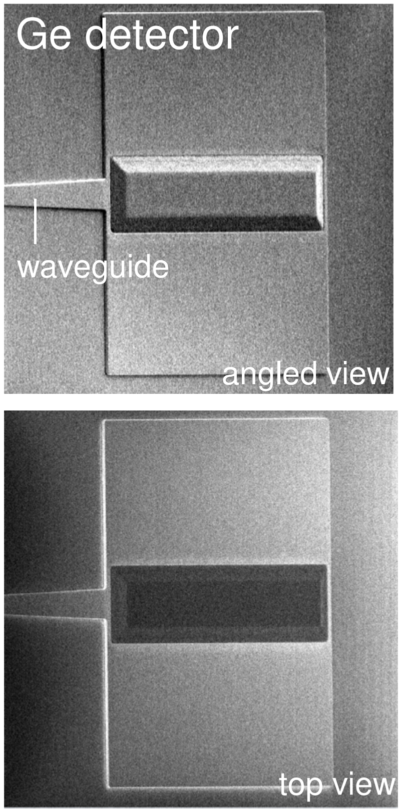
- photonic crystal resonator nanomembranes with Ge detectors
  – challenging fabrication and integration, yet high-yield in fabrication

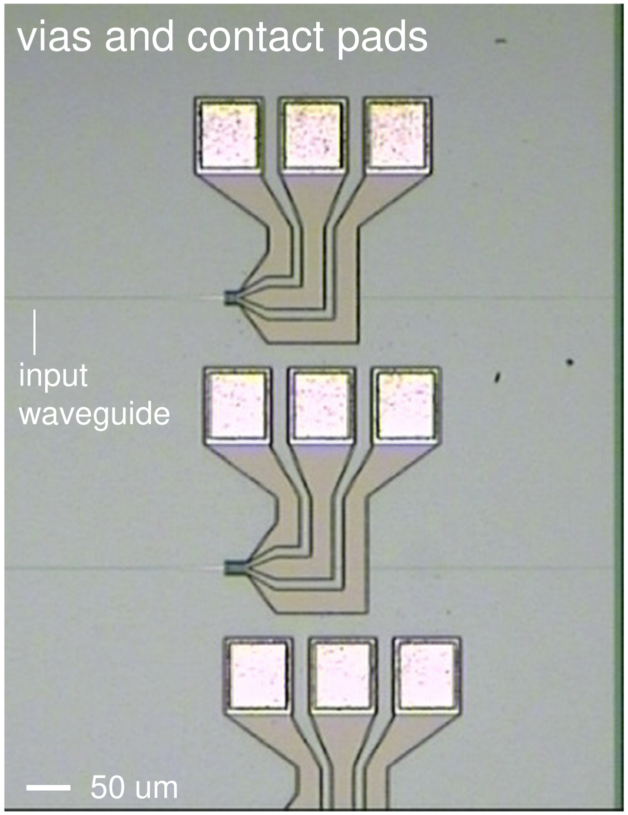
Luan X., Y. Huang, C.W. Wong, et al., *An integrated low-phase noise radiation-pressure-driven optomechanical oscillator chipset*, Scientific Reports.

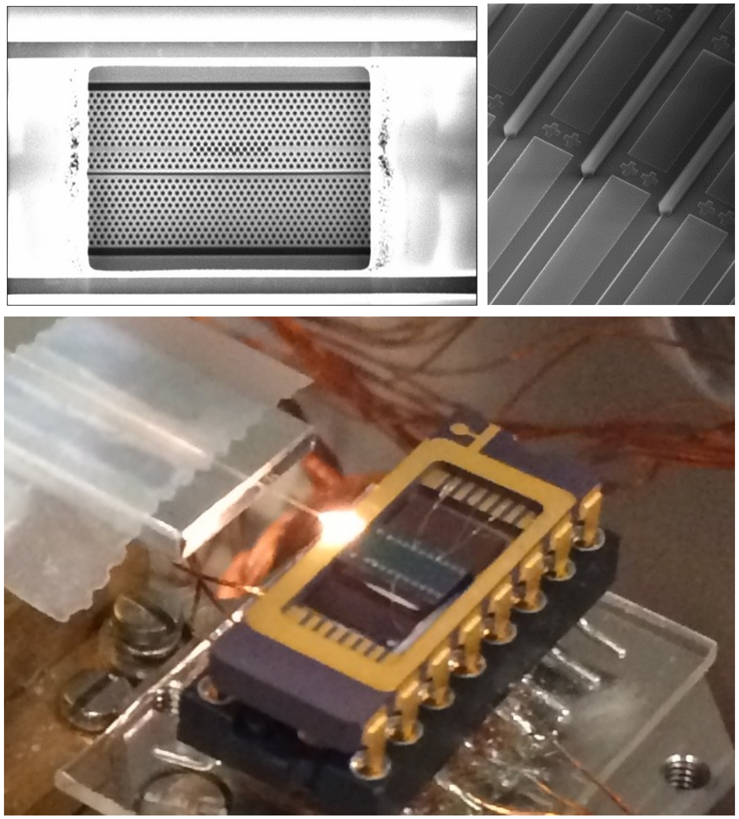
An integrated OMO chipset



- CMOS front-end Ge detector
- molecular-beam epitaxy growth and contacts
- with alignment marks for OMO process
- near-unity coupling from waveguide to detector



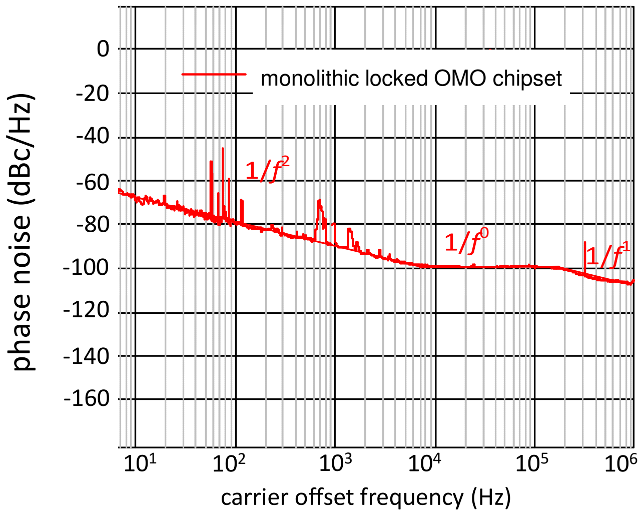




Luan X., Y. Huang, C.W. Wong, et al., *An integrated low-phase noise radiation-pressure-driven optomechanical oscillator chipset*, Scientific Reports.

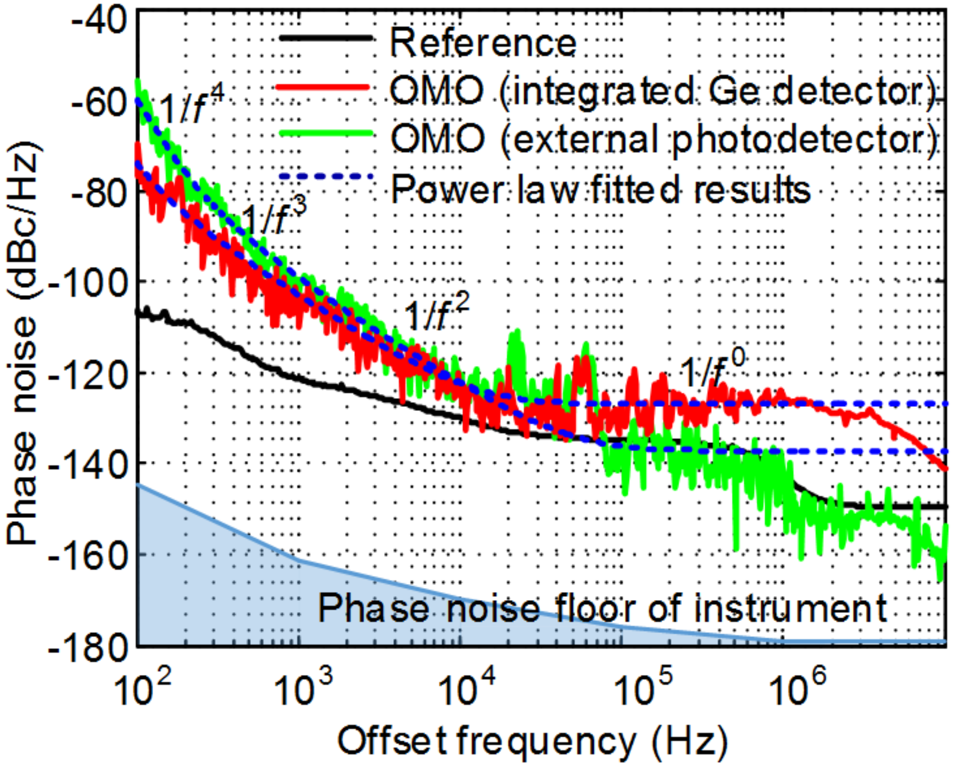
An integrated OMO chipset: single sideband phase noise

Previously



- SSB L(f) ~ -100 dBc/Hz at 10 kHz offset

Currently



- at -125 dBc/Hz at 10-kHz offset for ~ 100 MHz carrier at 400 uW intracavity power
- with 6.9 GHz harmonic
- operating in ambient (non-vacuum)

- Allan deviation at ~ 5×10^{-9} at 1-ms integration

See also Zheng, Hati, Howe and Wong et al., *Appl. Phys. Lett.* **102**, 141117 (2013).

Components and monolithic oscillator development

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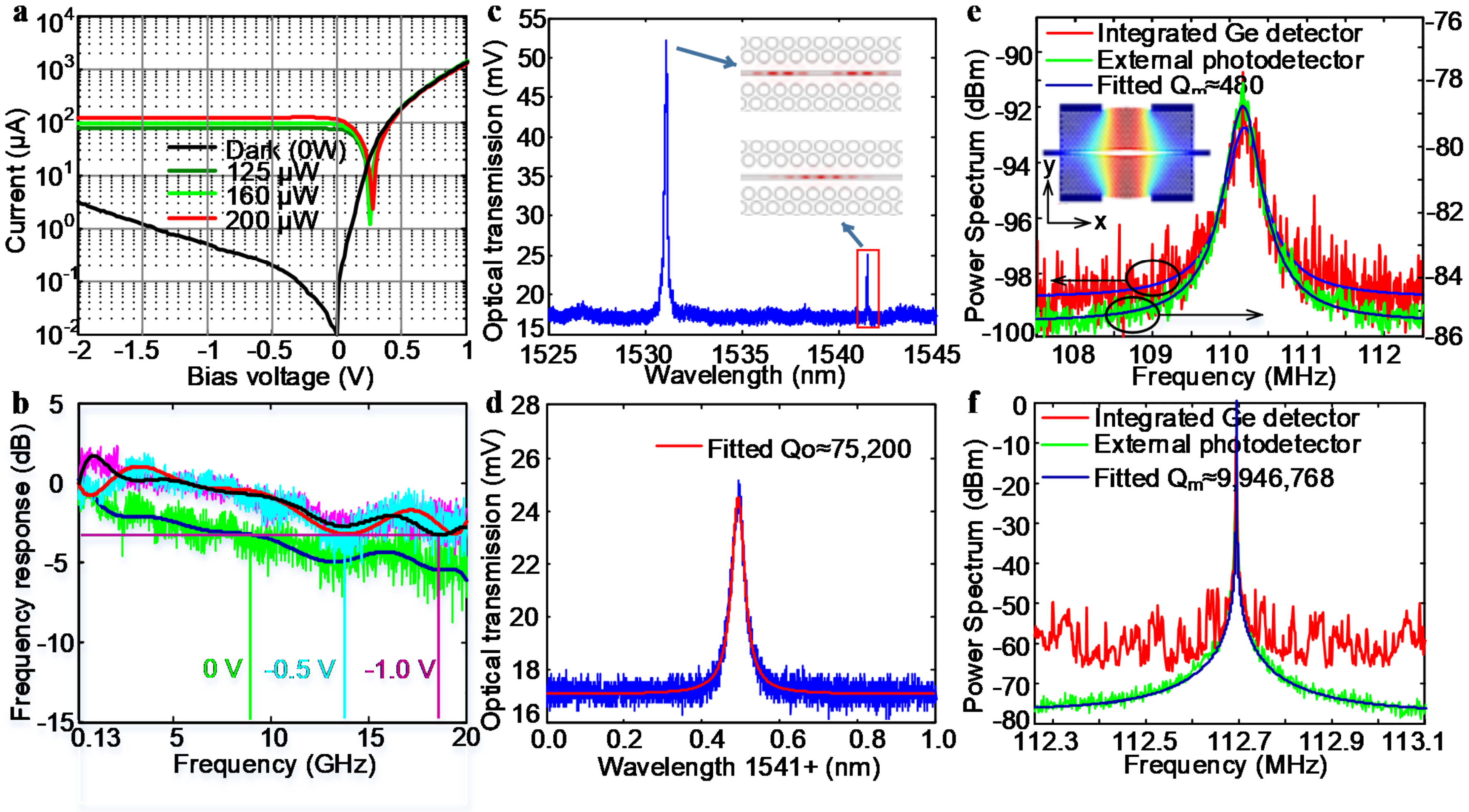

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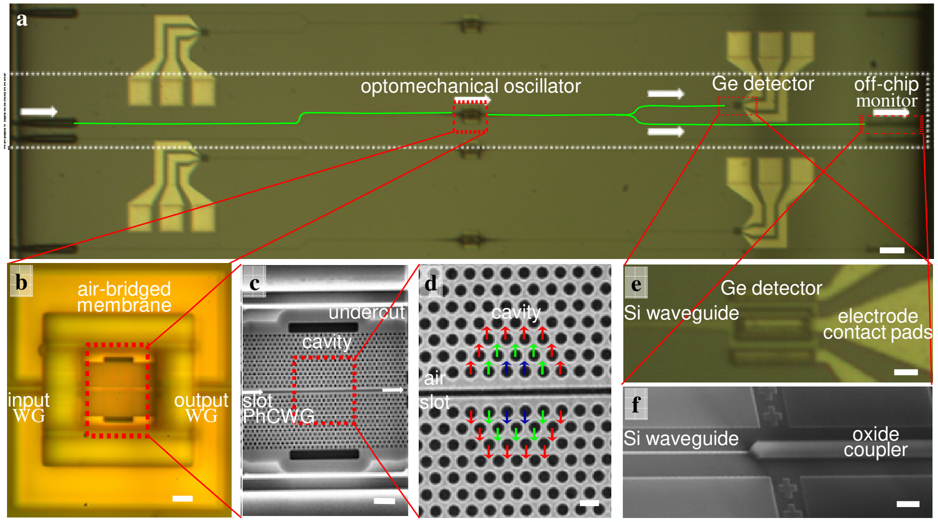
Acknowledgments

Collaborators

- A. Matsko, V. Iltchenko, W. Zhang et al. (JPL)
- E. Hudson, K. Wang, M. Jarrahi, B. Jalali, D. Huffaker, W. Campbell et al. (UCLA)
- F. Wong, Shapiro, Englund, Berggren, Barbastathis et al. (MIT)
- Heinz, Bergman, Osgood, Hone, Weinstein (Columbia)
- L. Maleki, (OEwaves)
- Thales Research Group (France)
- M. Sfeir, M. Cotlet, M. Lu, A. Stein (Brookhaven)
- Institute of Microelectronics Singapore
- IBM
- GE Global Research Center
- etc



Funding Support

- NASA Small Spacecraft Technology Program (SSTP)
- DARPA Young Faculty Award
- DARPA DODOS / InPho / ORCHID / EPIC
- NSF CAREER Award
- NSF IGERT Optics and Quantum Electronics
- NSF DMR, ECCS, and CBET
- DOE Energy Frontier Research Center
- 3M Faculty Award
- Intel
- New York State (NYSTAR)

A Chip-scale Optomechanical Accelerometer for Inertial Navigation Suitable for Small Satellites

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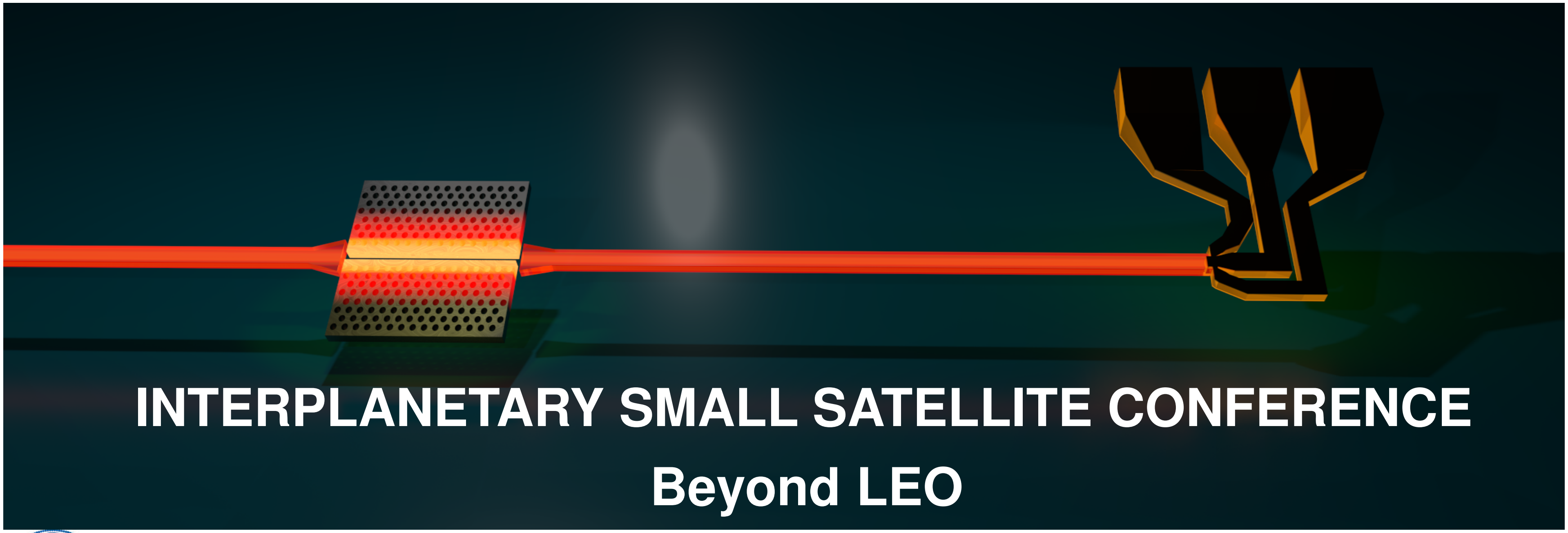

INTERPLANETARY SMALL SATELLITE CONFERENCE

Beyond LEO