Thesis Defense
Christopher Baker

On-chip nano-optomechanical whispering gallery mode resonators

Under the direction of Ivan Favero and Giuseppe Leo

Outline

1. Introduction
2. Whispering gallery mode resonators
3. Nanofabrication
4. Experimental guided optics
5. Mechanics of nanoresonators
6. Optomechanical coupling
7. Experimental optomechanics
8. Conclusions/perspectives

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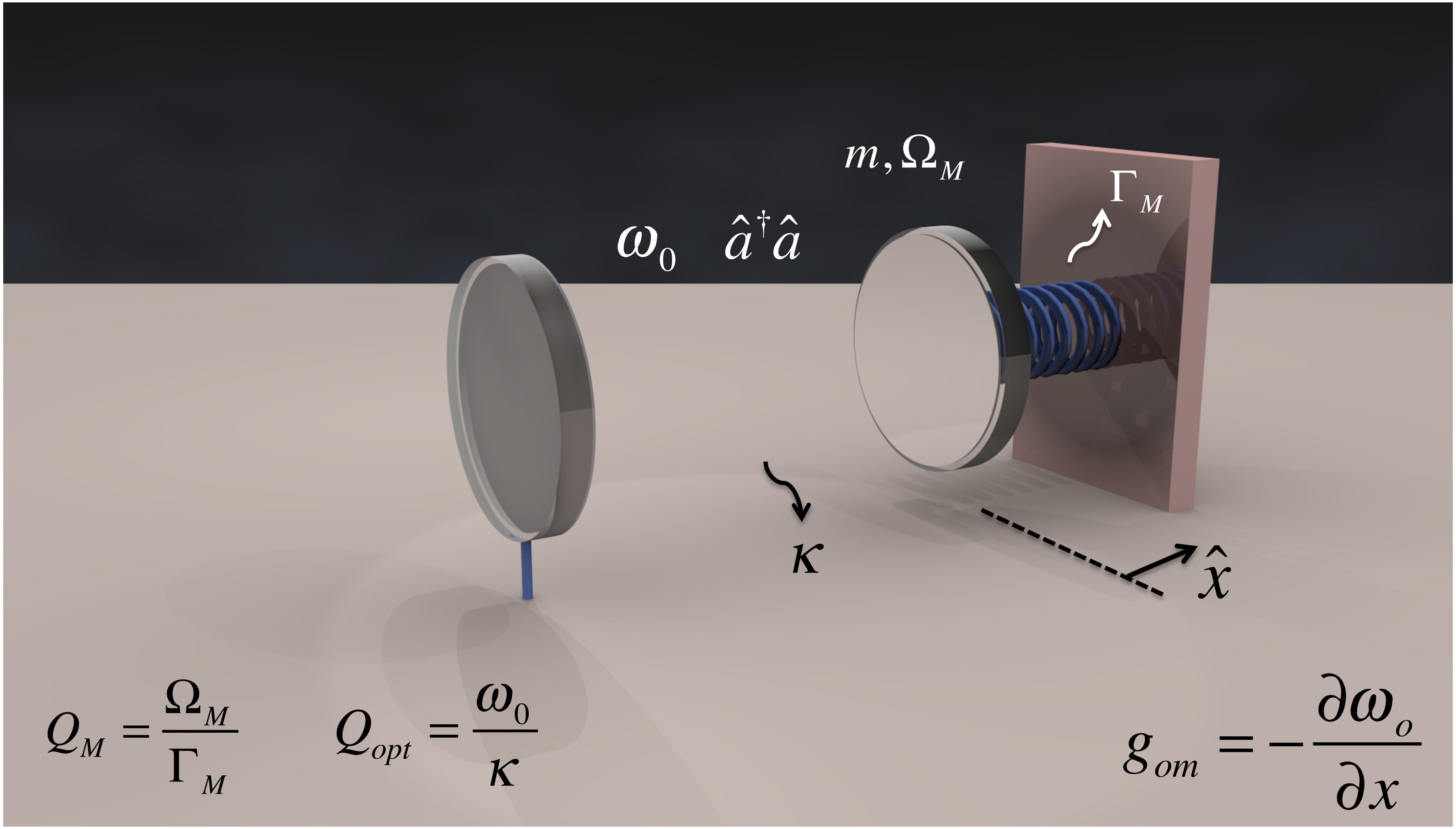
Optomechanics

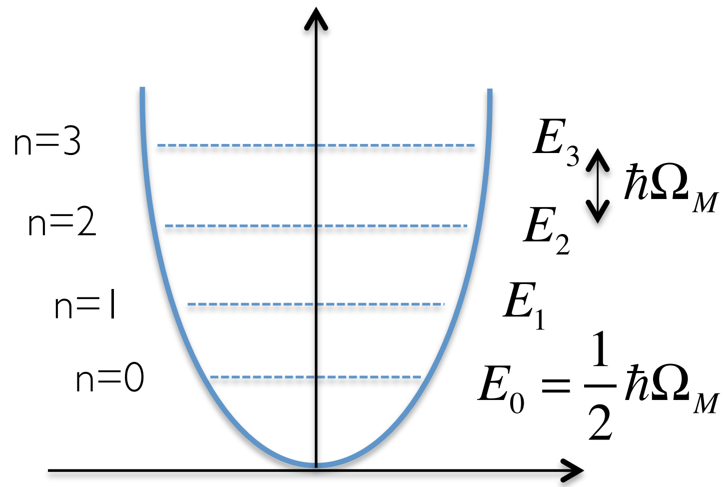


Hamiltonian optomechanics

$$\hat{H} = \underbrace{\hbar\omega_0(\hat{x})\hat{a}^\dagger\hat{a}}_{\text{Optical energy}} + \underbrace{\hbar\Omega_M\hat{b}^\dagger\hat{b}}_{\text{Mechanical energy}}$$

$$\omega_0(\hat{x}) \approx \omega_0 - g_{om}\hat{x}$$

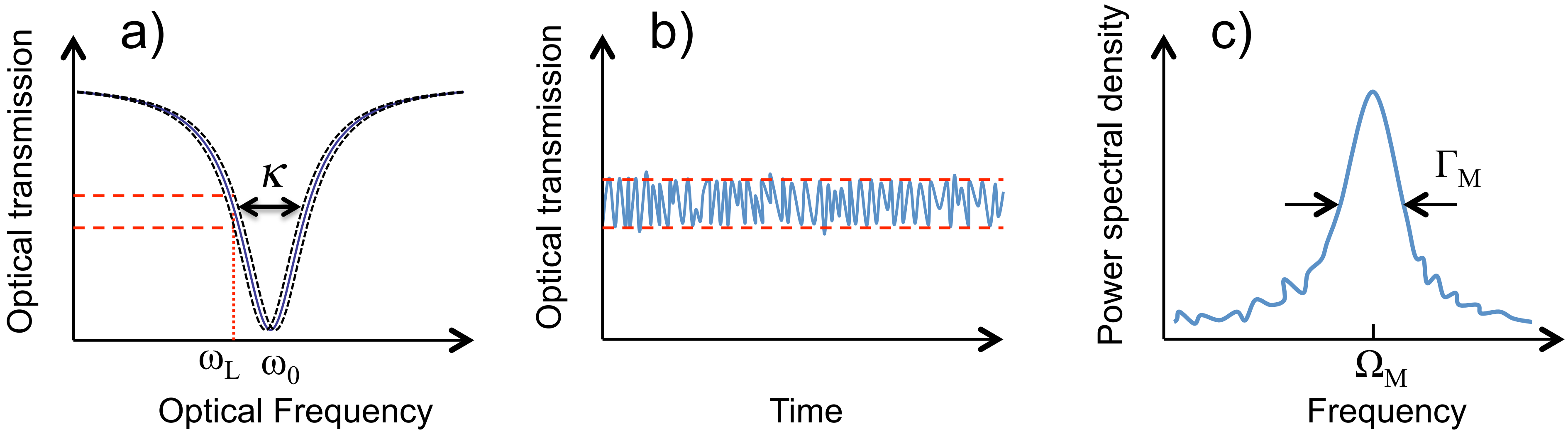
$$\hat{x} = x_{\mathrm{ZPF}}\left(\hat{b}+\hat{b}^\dagger\right)$$



$$\hat{H} = \hbar\omega_0\hat{a}^\dagger\hat{a} + \hbar\Omega_M\hat{b}^\dagger\hat{b} - \hbar\underbrace{g_{om}x_{ZPF}}_{g0}\hat{a}^\dagger\hat{a}\left(\hat{b}^\dagger+\hat{b}\right) \qquad x_{ZPF} = \sqrt{\frac{\hbar}{2m_{eff}\Omega_M}}$$

$$\boxed{\hat{H} = \hbar\omega_0\hat{a}^\dagger\hat{a} + \hbar\Omega_M\hat{b}^\dagger\hat{b} - \hbar g_0\hat{a}^\dagger\hat{a}\left(\hat{b}^\dagger+\hat{b}\right)}$$

High sensitivity displacement readout

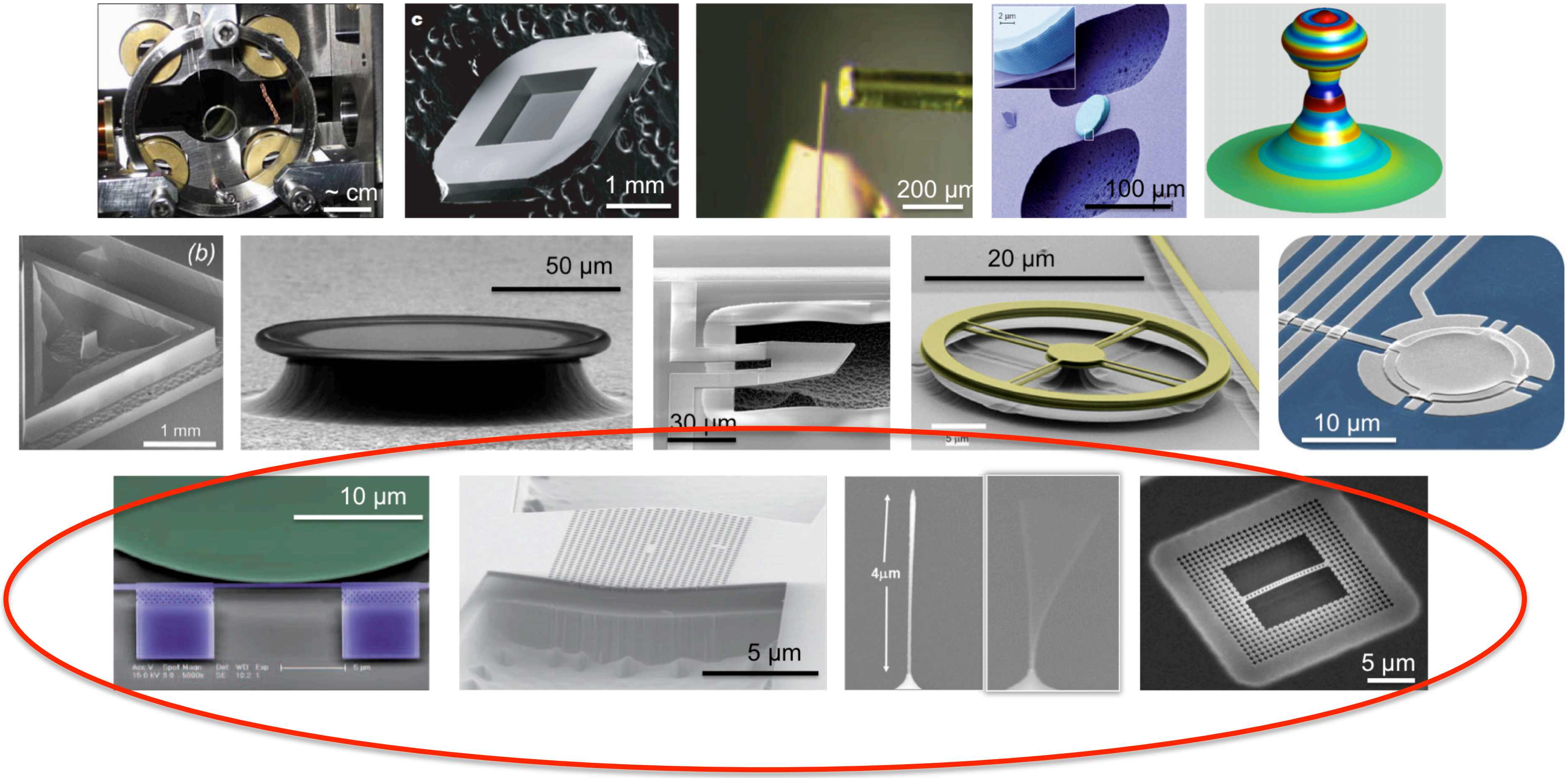


Ultra-high sensitivity optical readout of the mechanical displacement

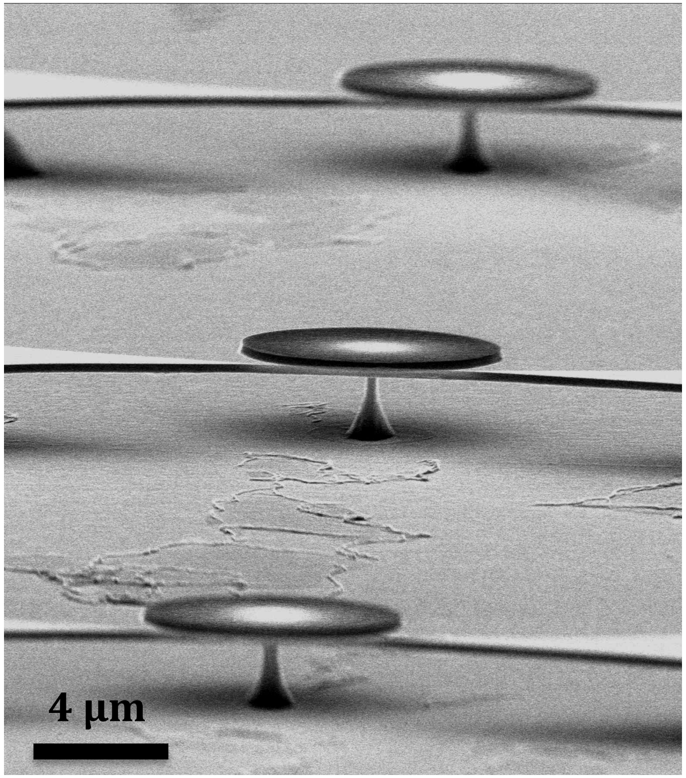
Optical cooling and amplification of mechanical motion

Towards quantum effects of light and mechanics

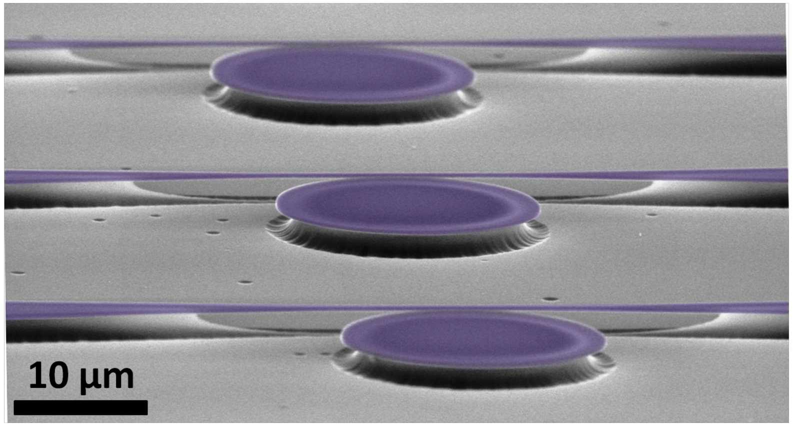
Optomechanical setups



Our systems



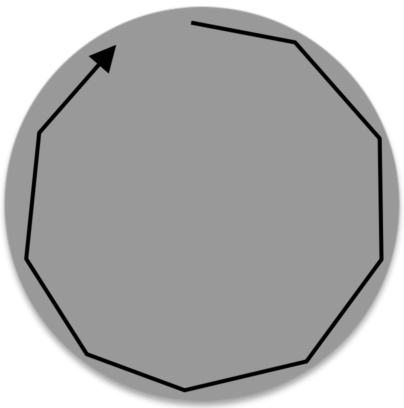
Gallium Arsenide (GaAs) disk
optomechanical resonators



Silicon nitride (SiN)
optomechanical resonators

Outline

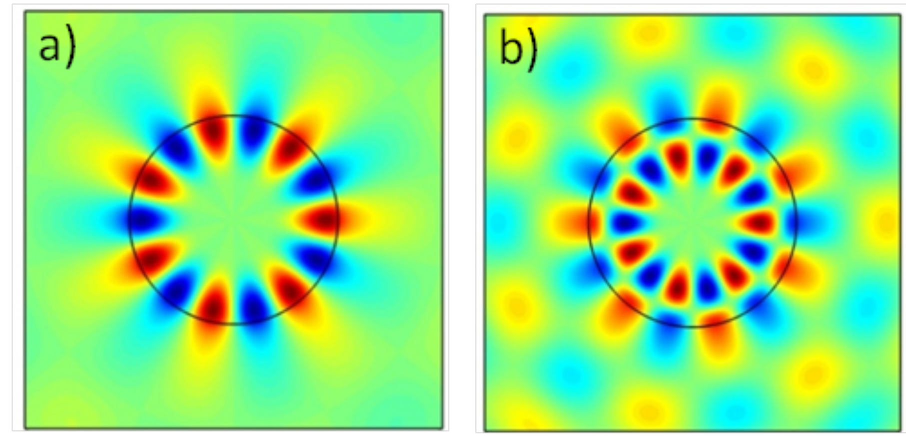
Optical WGM resonator



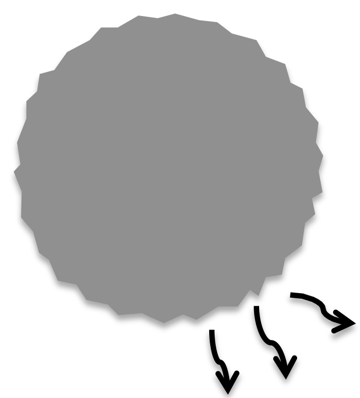
Resonance condition

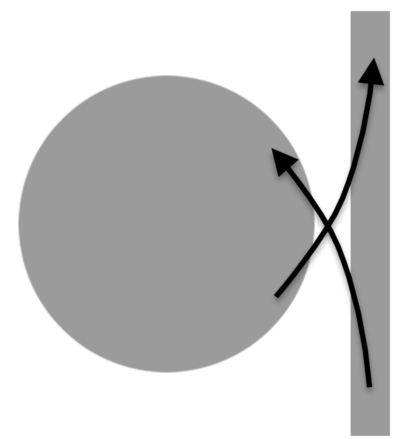
$$2\pi n R \approx m\lambda_0$$

$$Q_{\mathrm{opt}} = \frac{\omega_0}{\kappa}$$

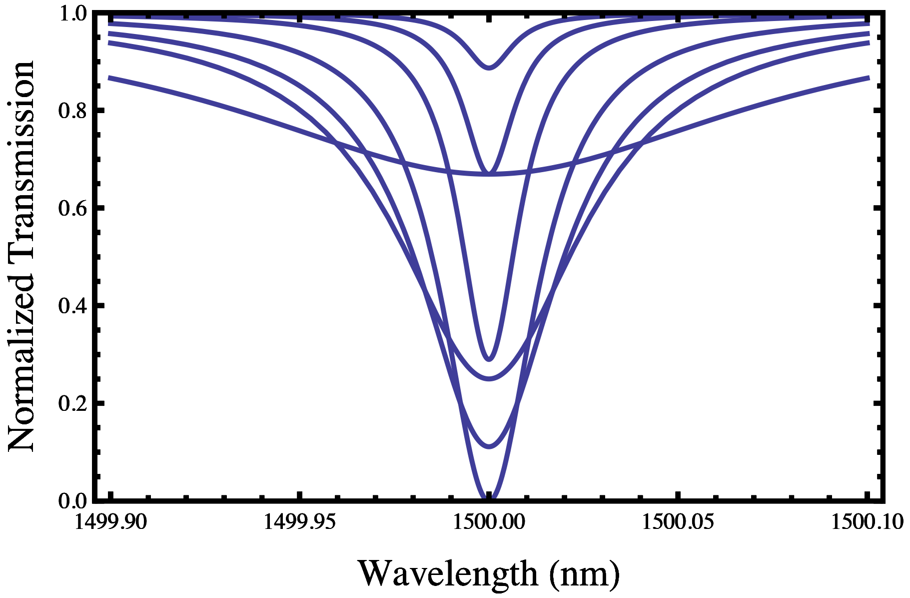


•High optical Q (> 10^5) → Large field enhancement
•High refractive index, Small mode volume (sub-μm^3)
•Evanescent coupling via bus waveguide



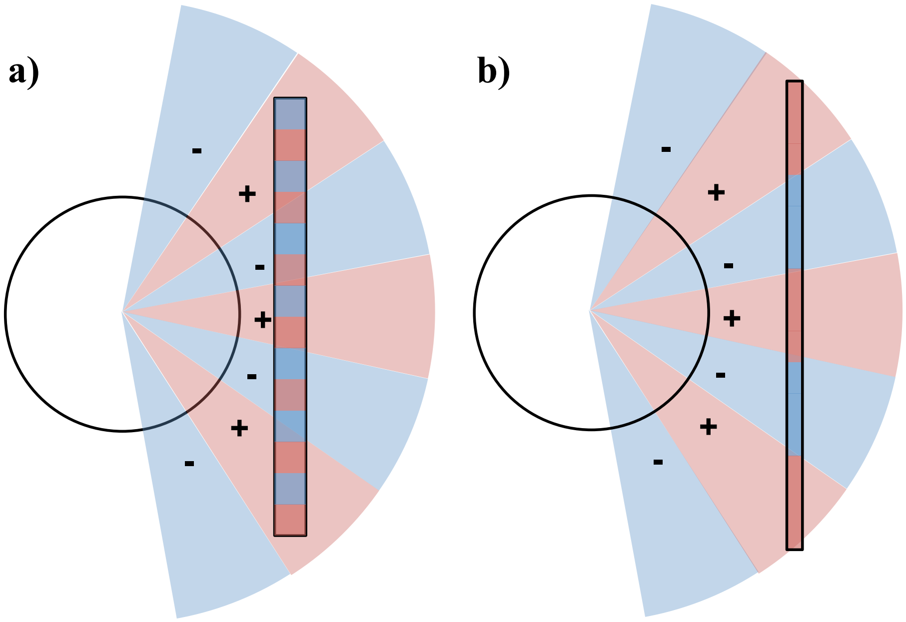


Evanescent coupling



Critical coupling regime T_{on}=0, maximum field in the cavity.

➔ Need to precisely tune the coupling strength



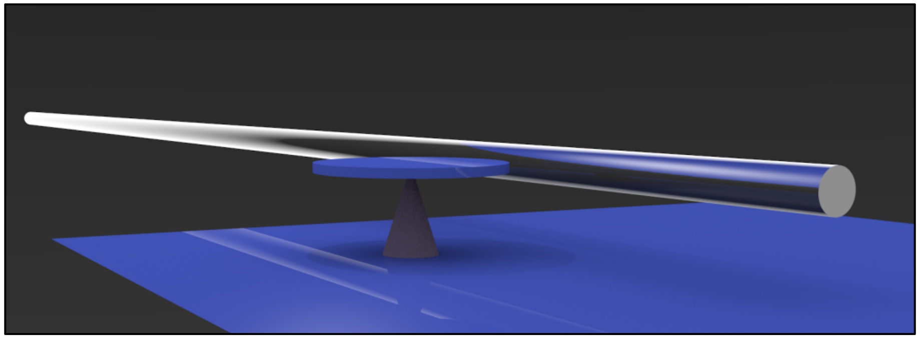
Adjust the coupling strength

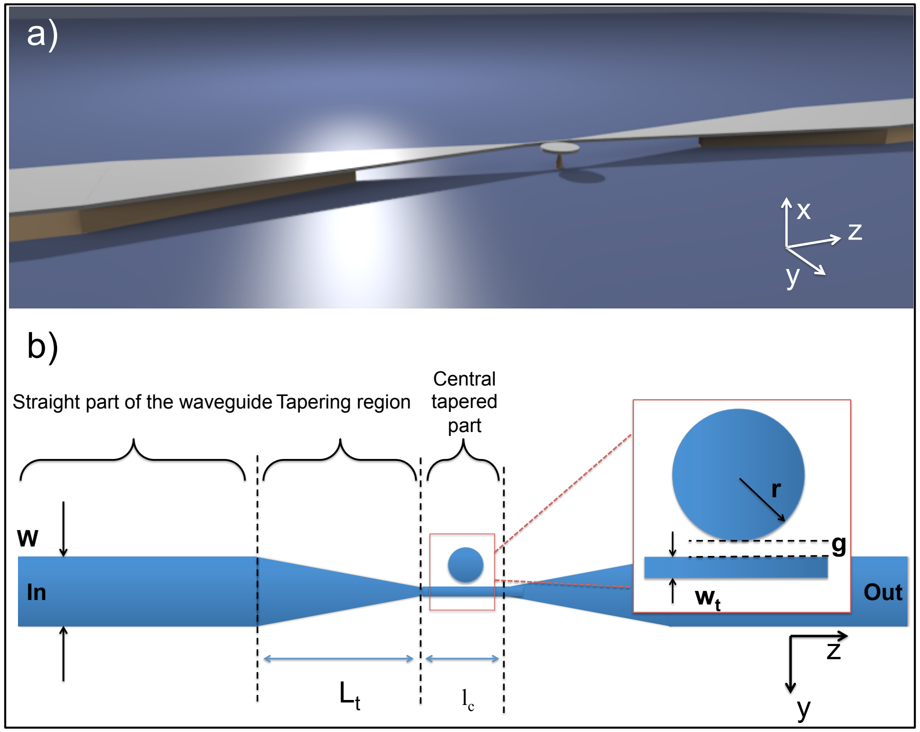
-Gap distance

-Waveguide width

Described by Coupled Mode Theory (CMT) formalism.

Optical coupling scheme





Two different coupling schemes:

- Fiber taper

+ adjustable coupling strength
+ high power
- fragile
- mechanical stability
- bulky

- Integrated waveguide

+ compact
+ stable
- non adjustable

Lu Ding, et al. Applied Optics, 49(13):2441-2445, 2010.
C. Baker et al. Applied Physics Letters, 99:151117, 2011.

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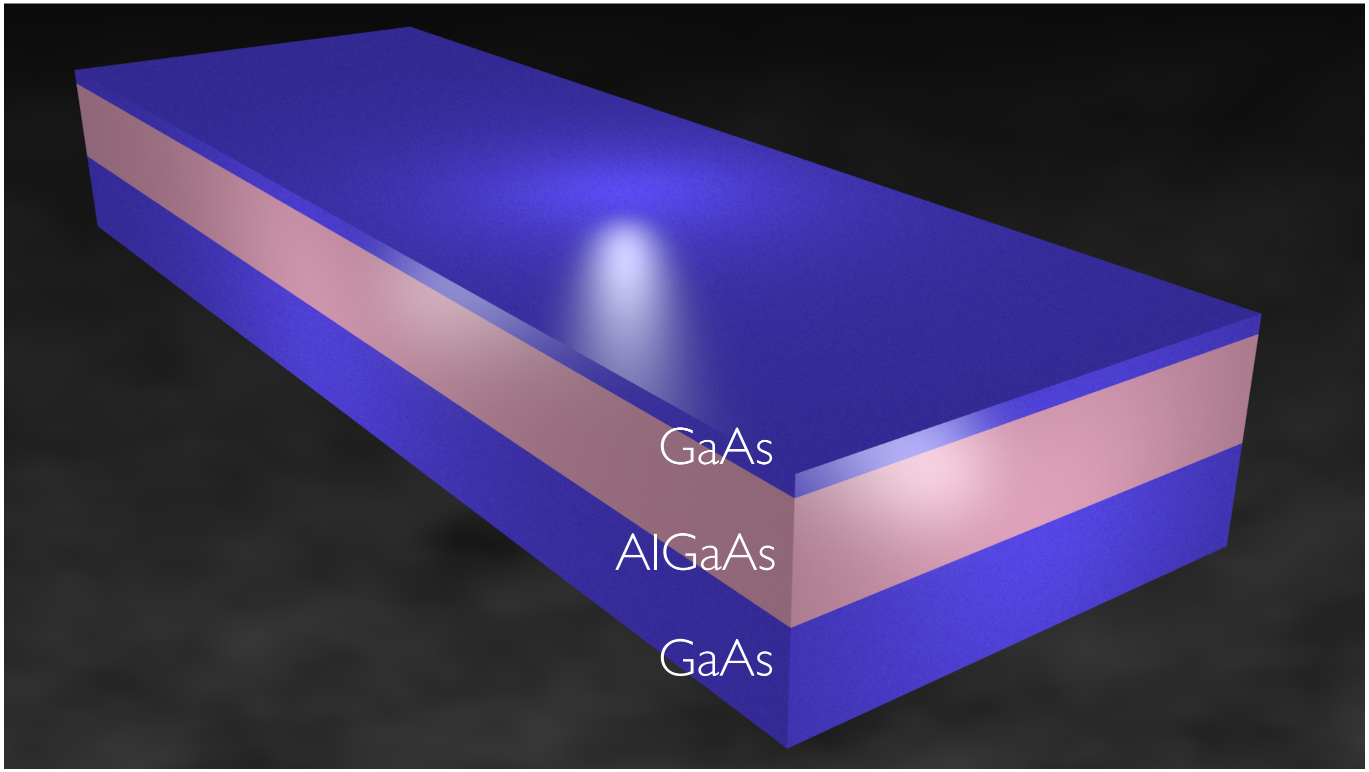
GaAs nano-fabrication steps



1) Clean wafer

2) E-beam resist and exposure

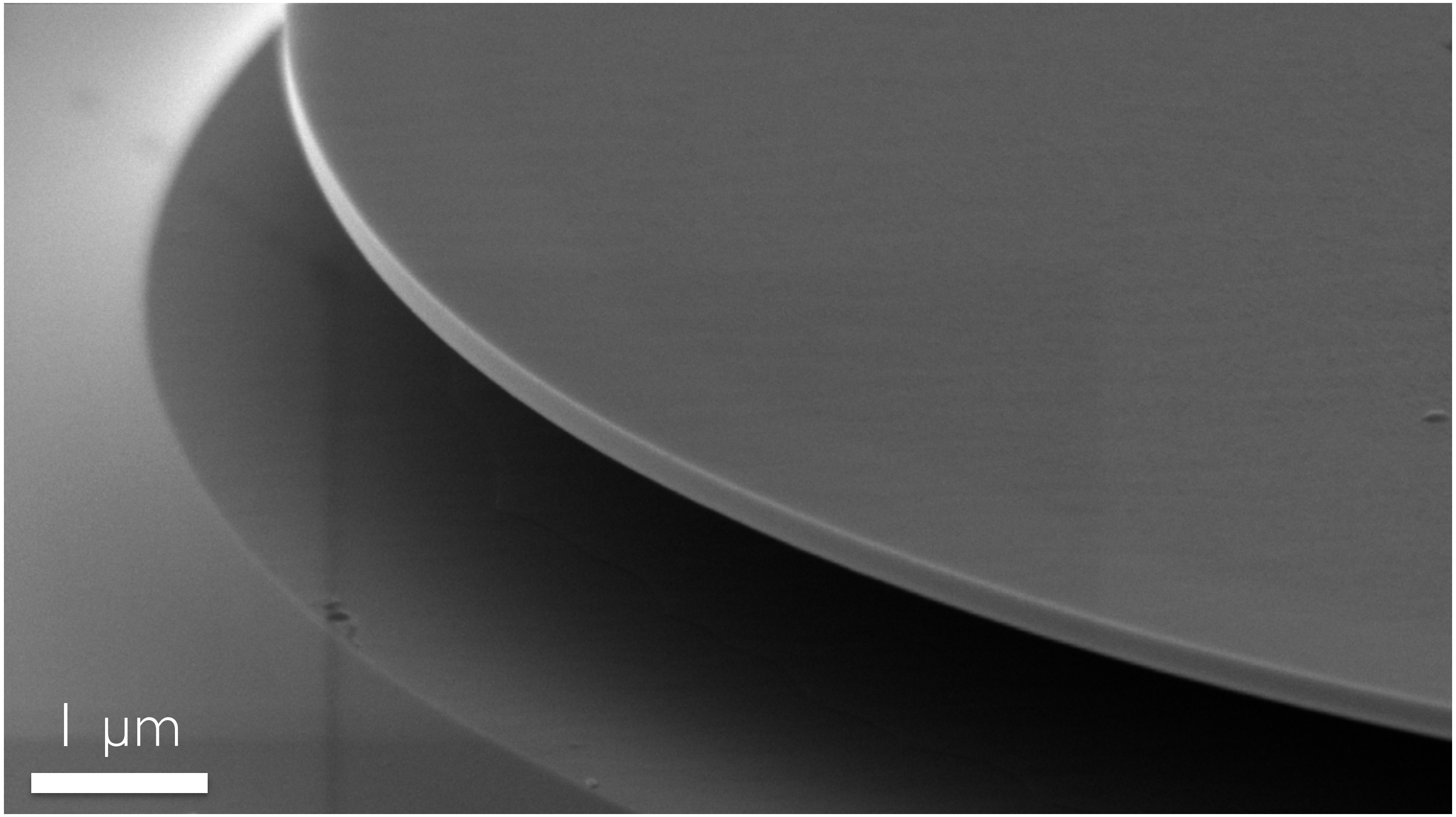
3) Development

4) Non selective ICP etch *or* wet etch

5) Selective HF under-etch

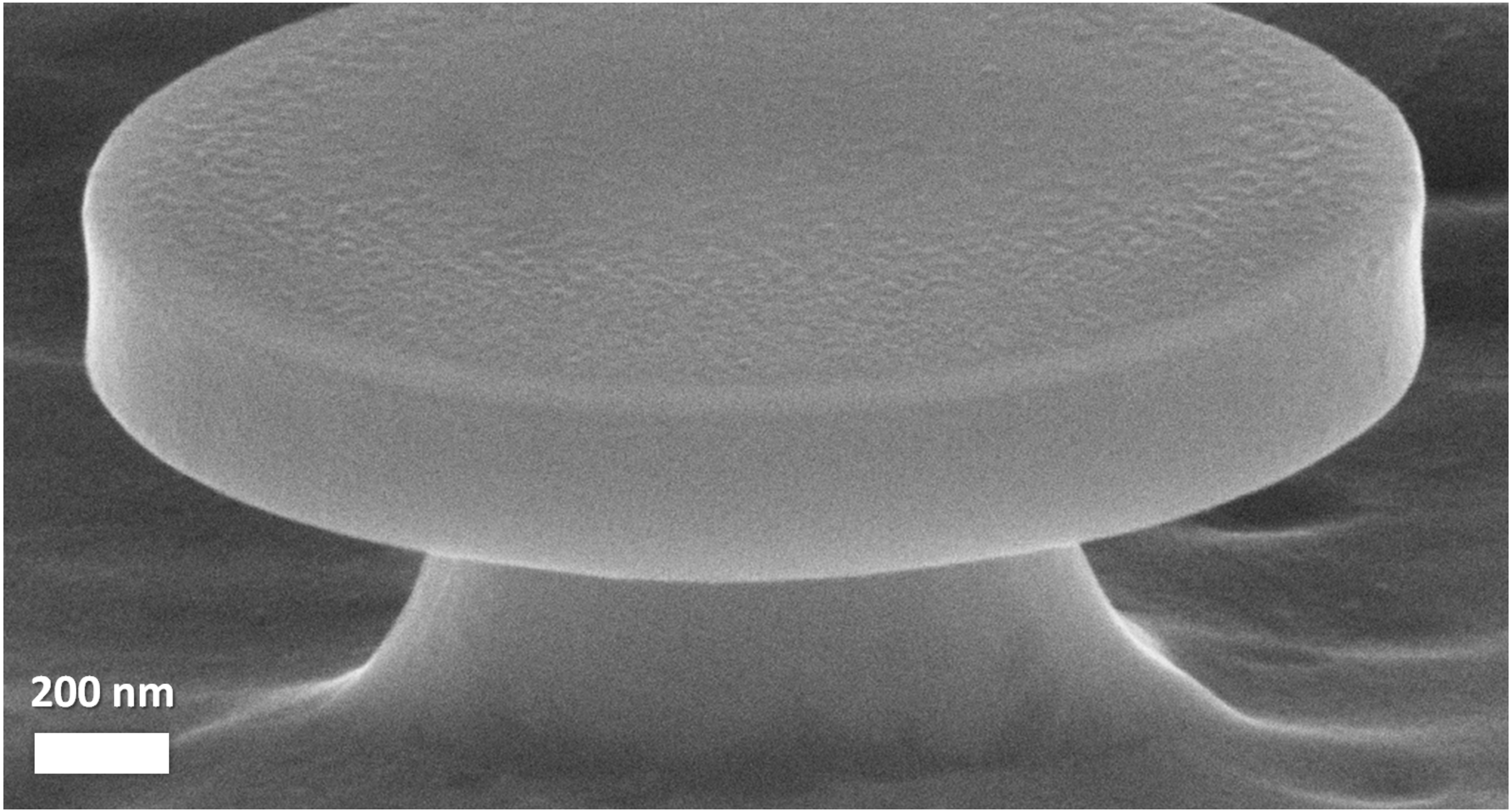
6) Cleaning – finished sample

GaAs non selective wet etch



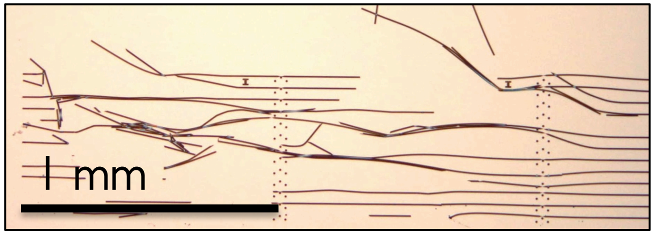
+ Smooth etch
- Poor verticality and gap distance control not adapted for small on-chip resonators

Optimized ICP etch



- Ar and $SiCl_4$ plasma chemistry
- Small sidewall roughness

GaAs nanofabrication potential problems

1


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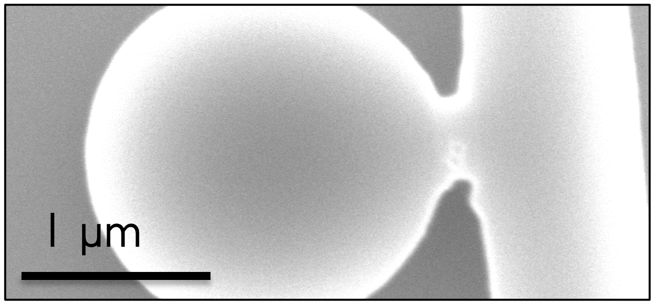

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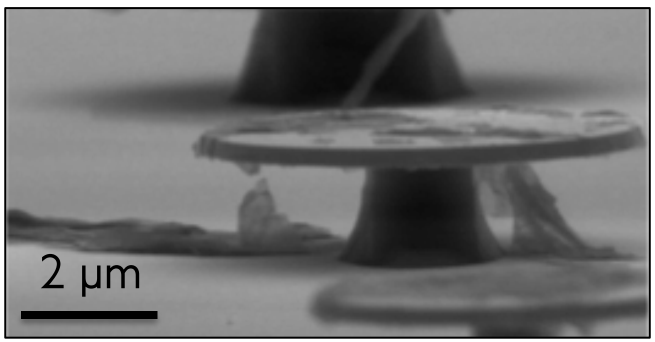

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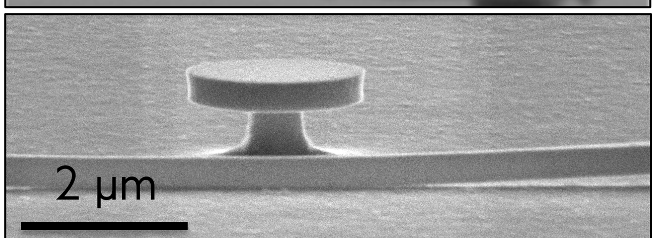
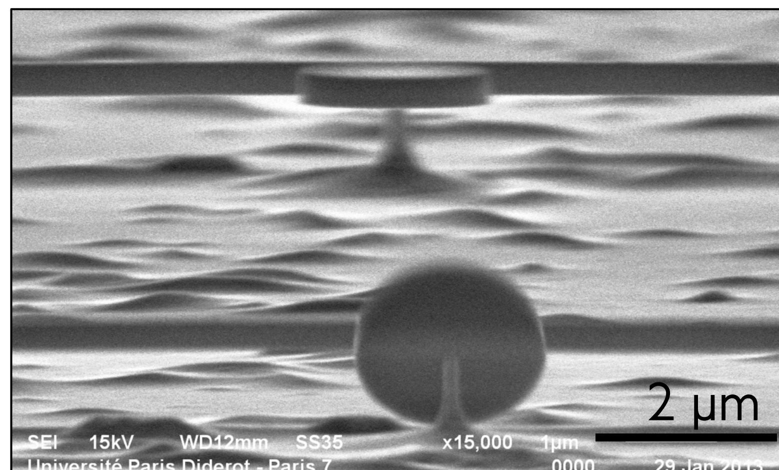
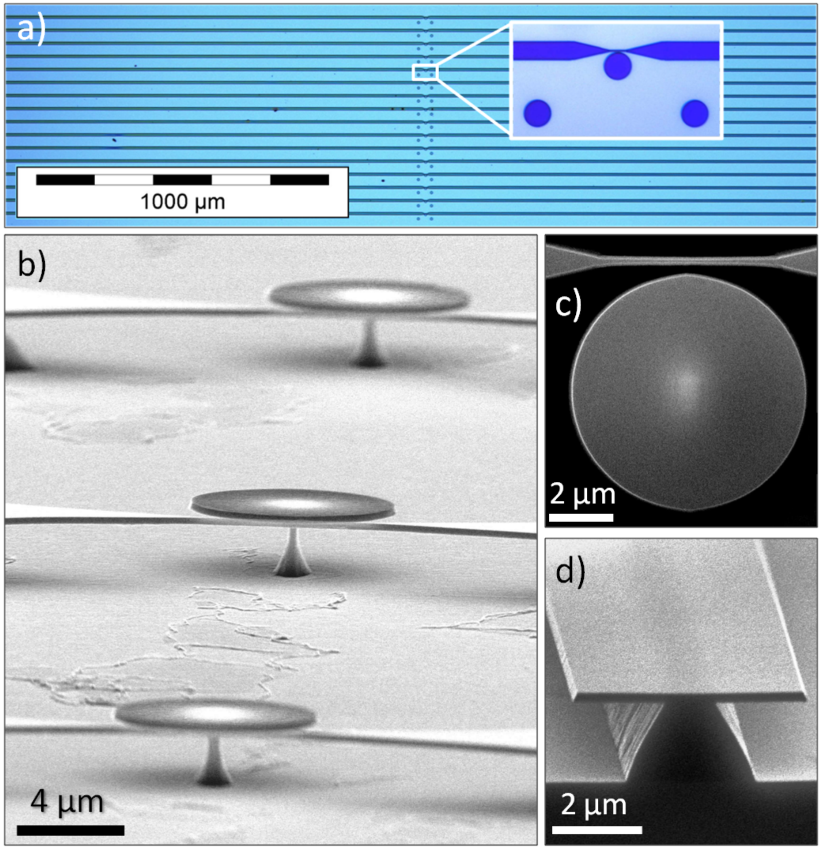
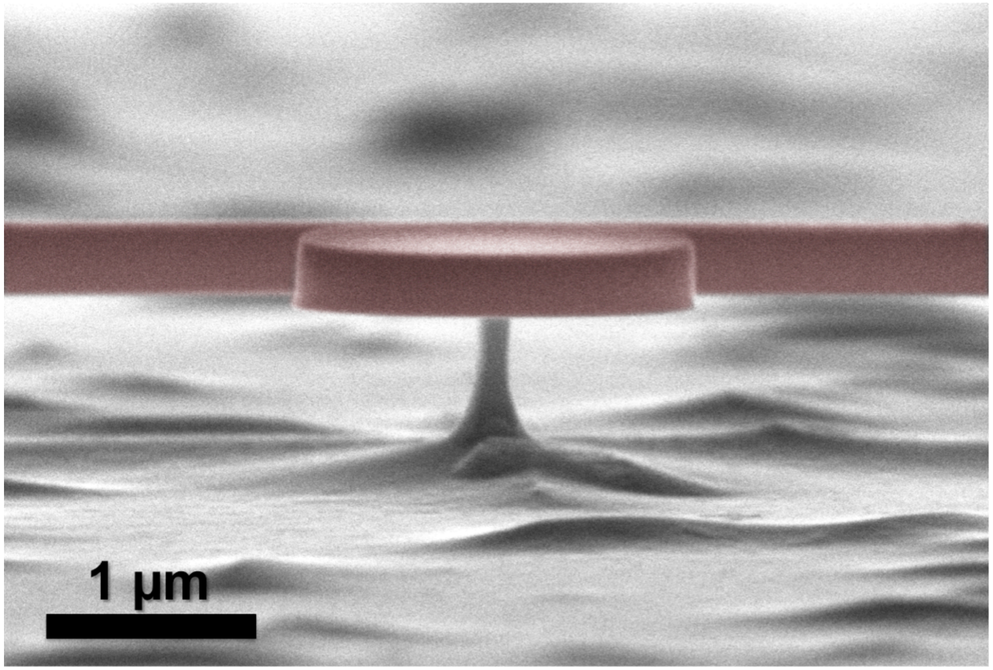


1. Resist delamination
2. Proximity effect
3. Problematic oxidation
4. Collapsing waveguide
5. Pedestal dimension control

5


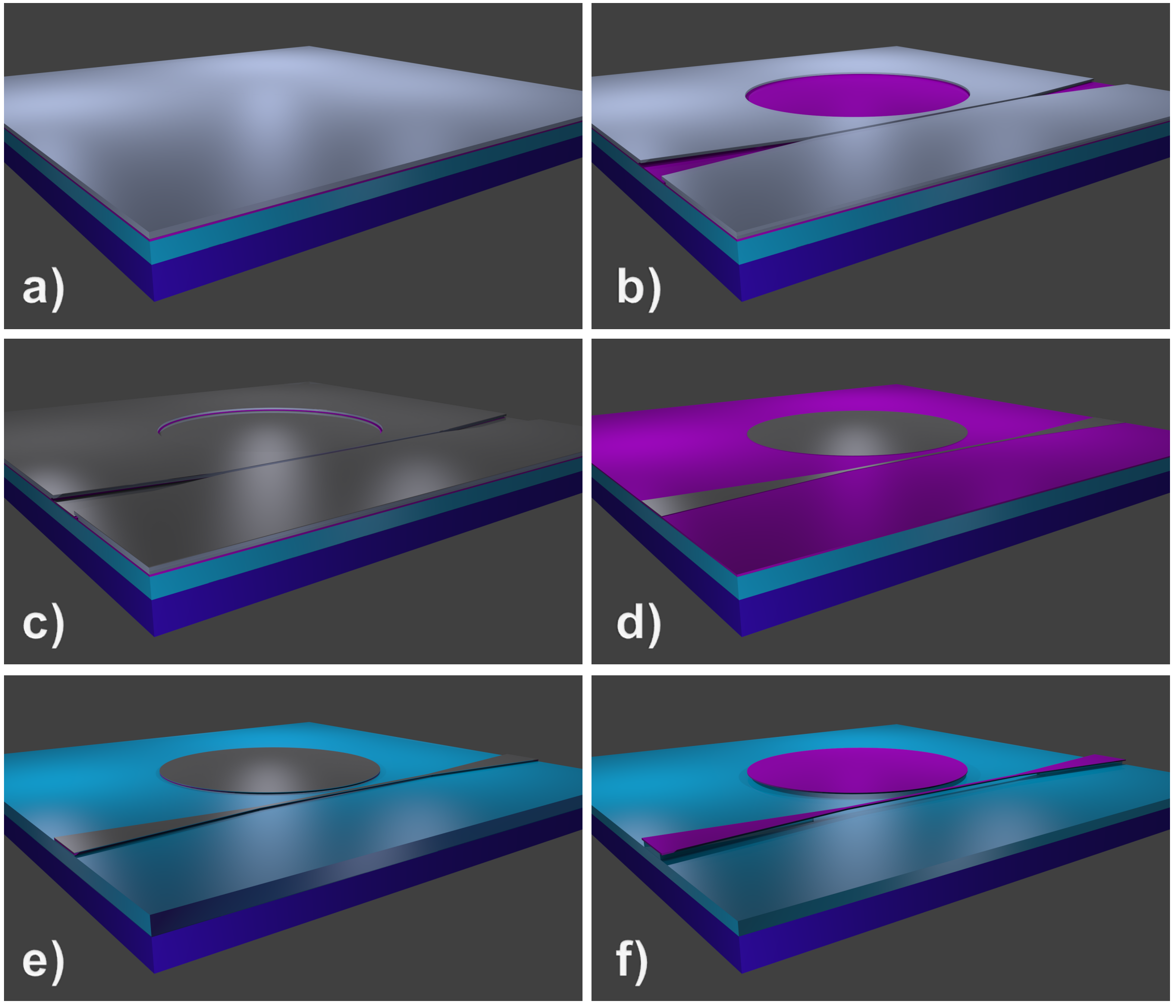
GaAs nano-fabrication results



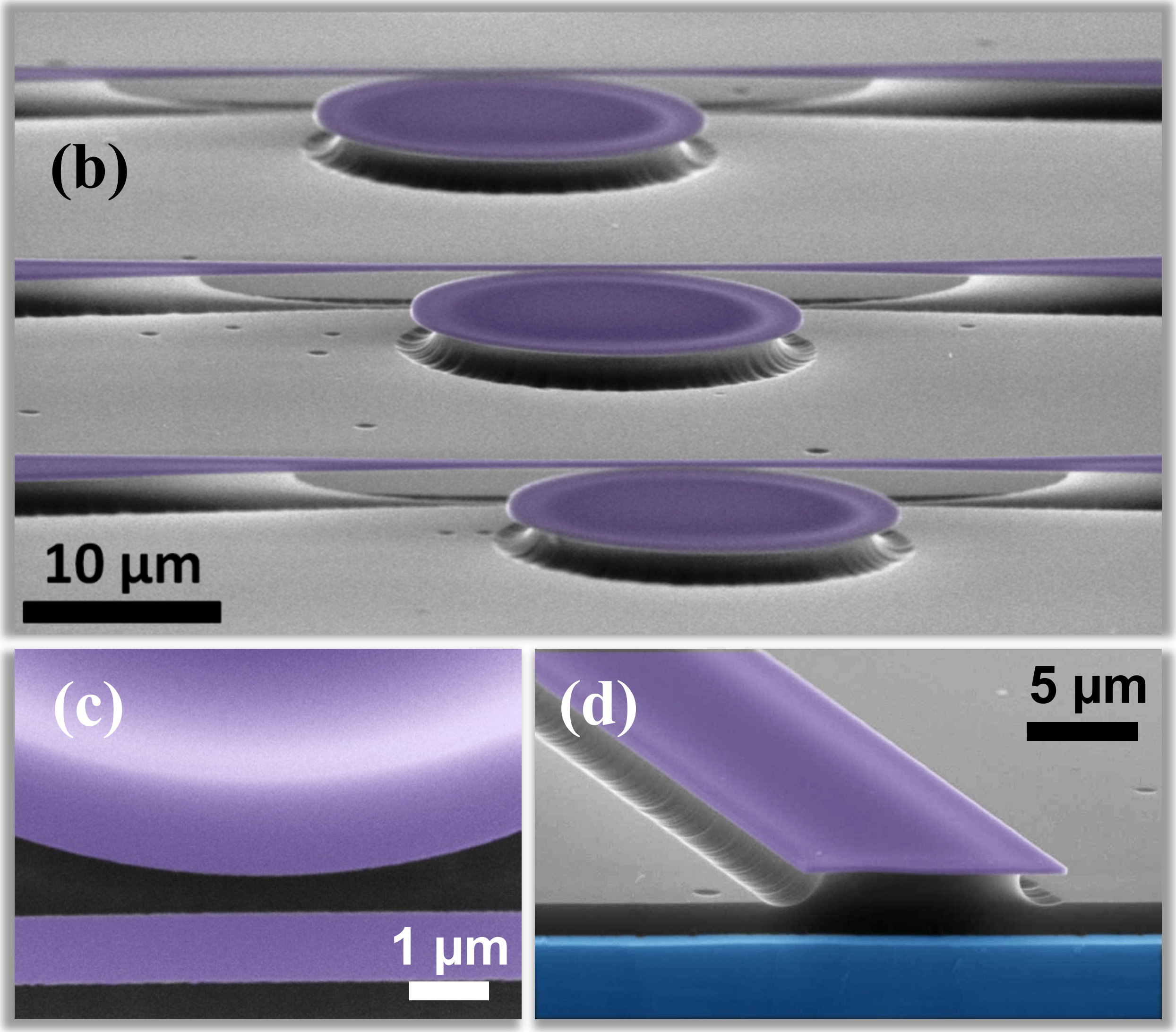


	DISK	PEDESTAL	WAVEGUIDE
1st Gen	3.5 µm radius 200 nm thickness	>100 nm radius 1.8 µm height	300 nm width 300 nm gap
2nd Gen	1 µm radius 320 nm thickness	80 nm radius 1 µm height	200 nm width 400 nm gap

SiN resonators fabrication steps

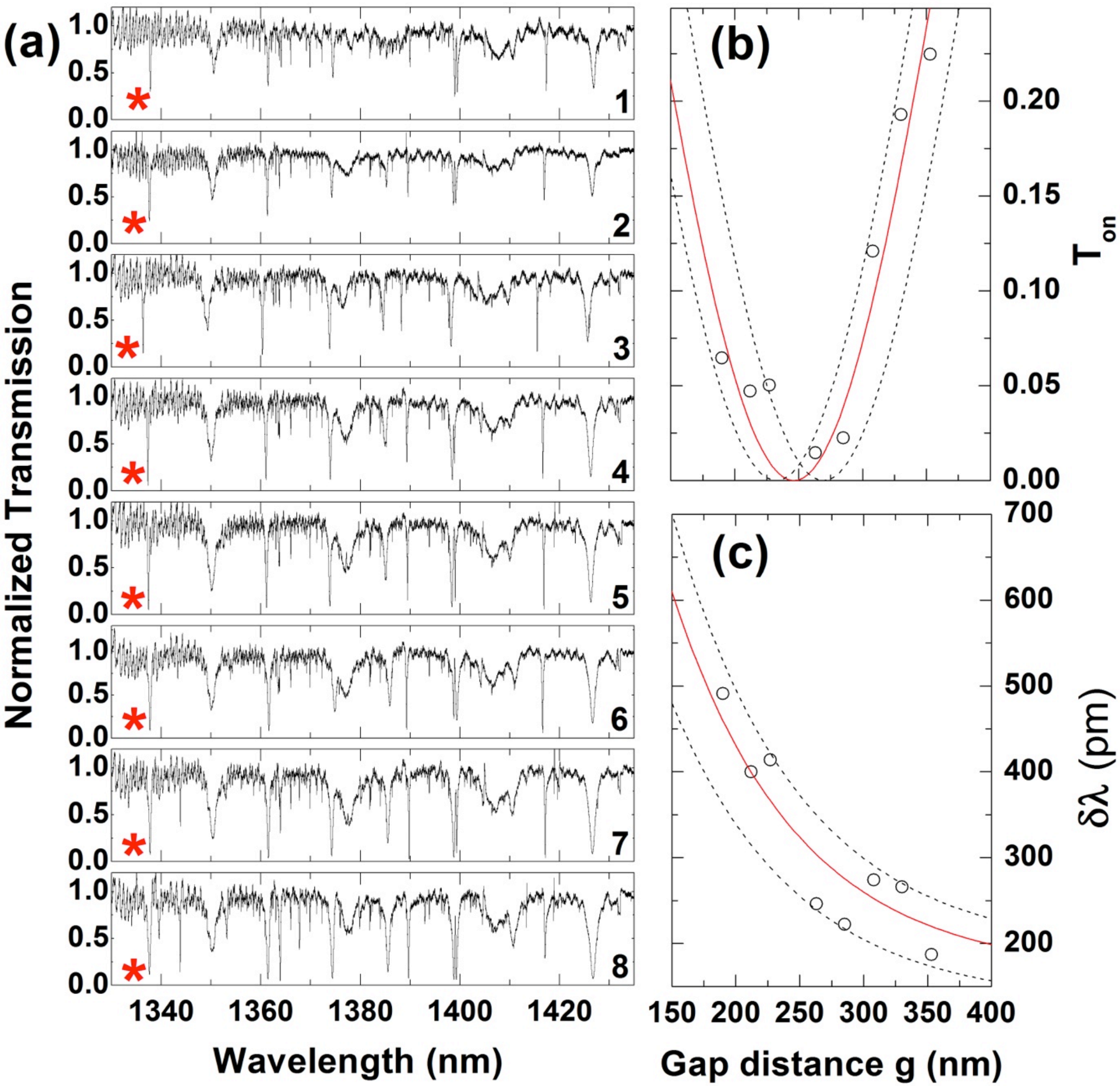


On-chip silicon nitride resonators



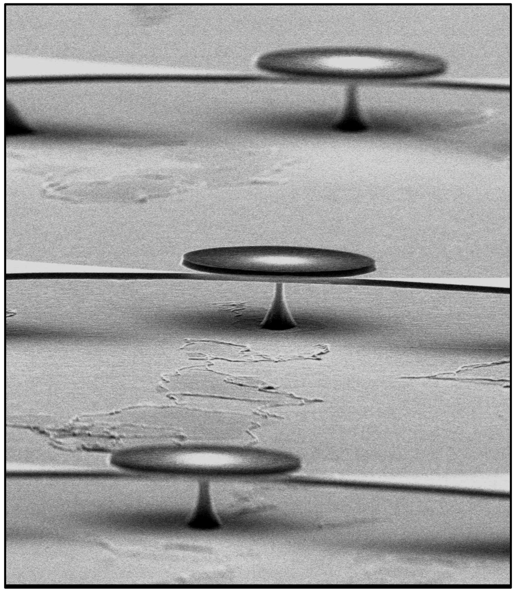
Outline

GaAs on-chip photonics



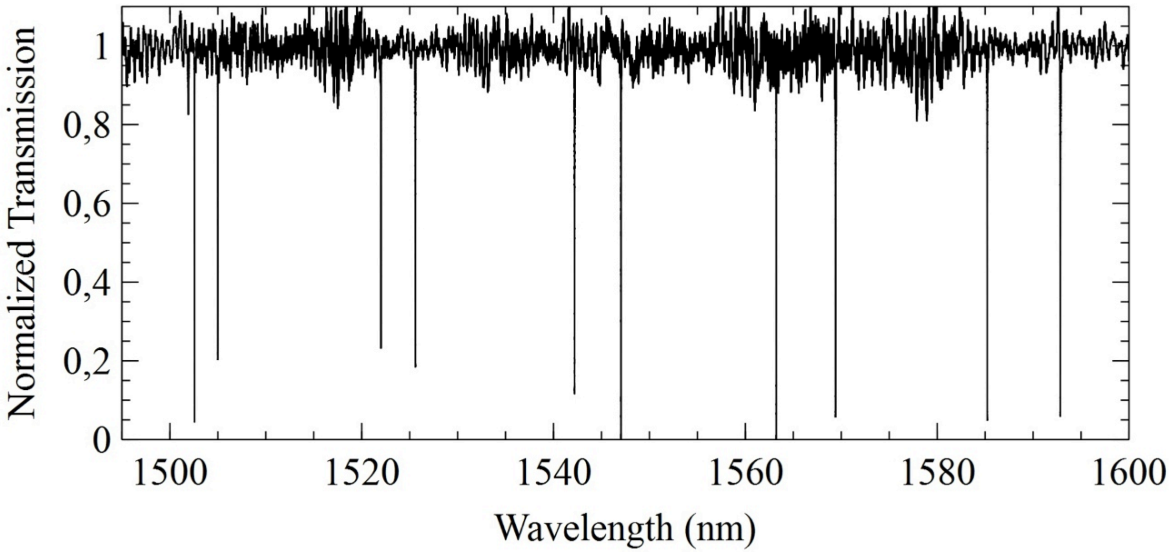
Observation of critical coupling, Q_{opt}= few 10^4

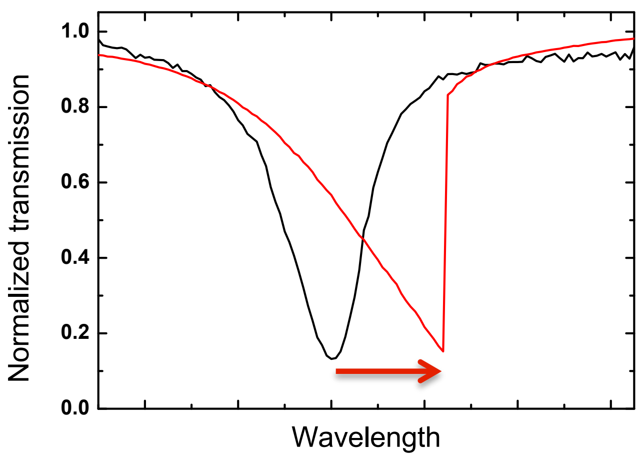
Since 2011 enhancements:
×100 optical transmission
×10 optical Q
(Q_{opt} now limited by optical absorption)



C. Baker et al.. *Applied Physics Letters*, 99:151117, 2011.

Silicon nitride on-chip WGM resonators





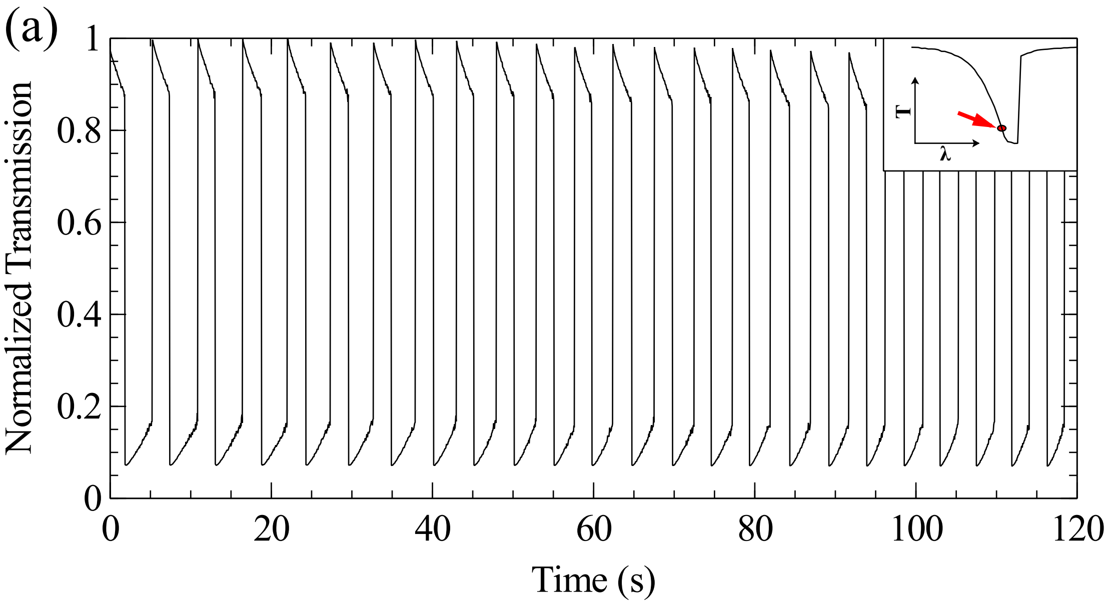
Several high Q high contrast optical resonances

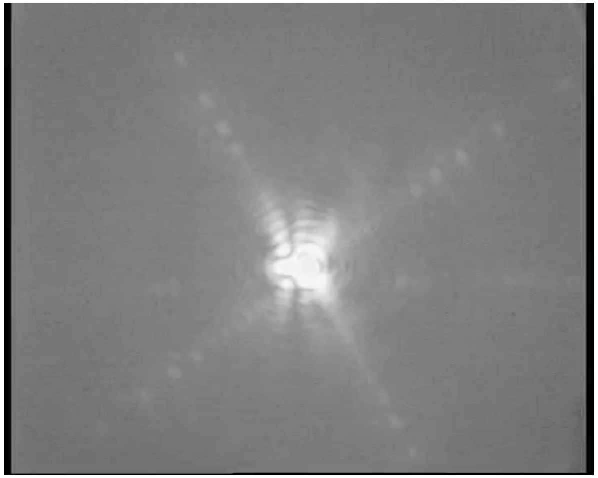
Highest optical Q~400 000

$(dn/dT)_{SiN} \sim 2\times10^{-5}\ K^{-1}$

Thermo-optic distortion

Optical instability and self-pulsing in SiN

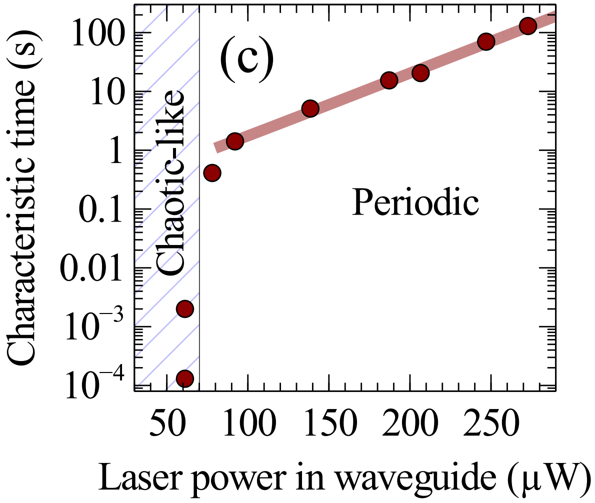




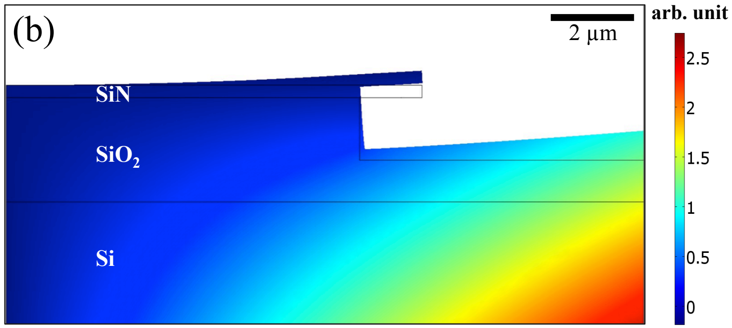
For constant laser power and wavelength light injection chaotic or periodic optical output.

Behavior depends upon:

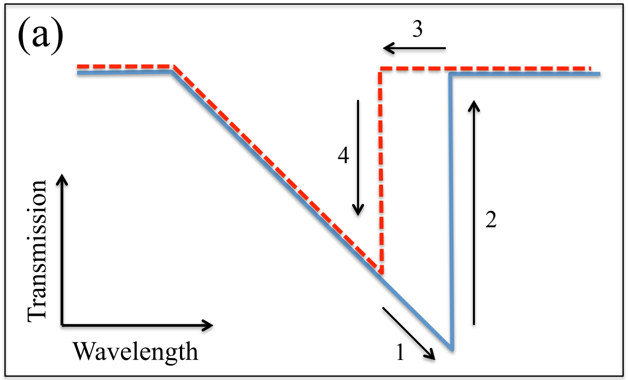
- laser power
- laser detuning

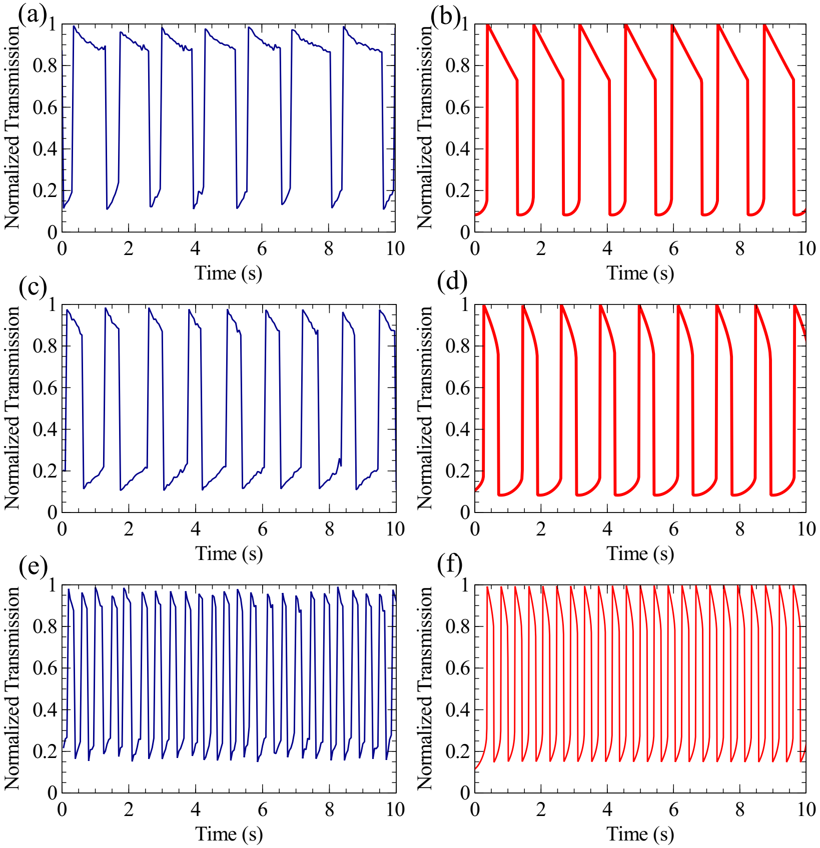


Optical instability and self-pulsing in SiN



Interaction between fast thermo-optic and slow thermo-mechanical nonlinearity





Blue: experimental data
Red: numerical model

C. Baker et al. *Optics Express*, 20(27):29076–29089, 2012.

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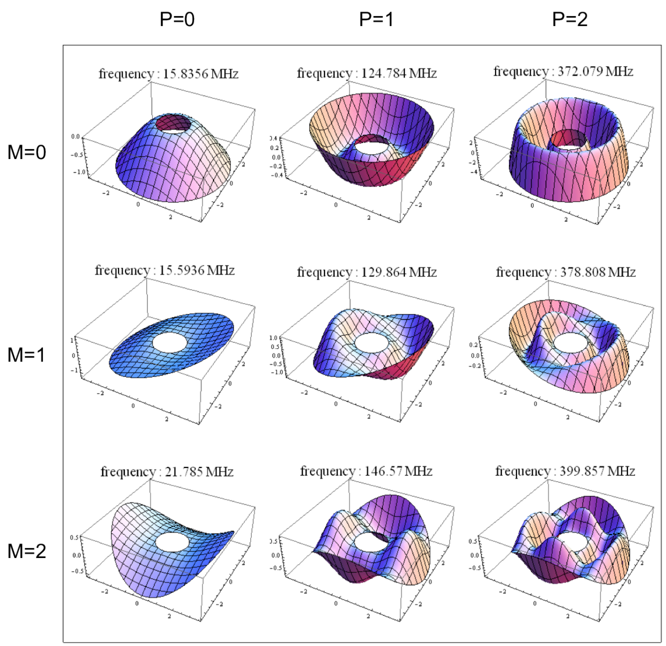
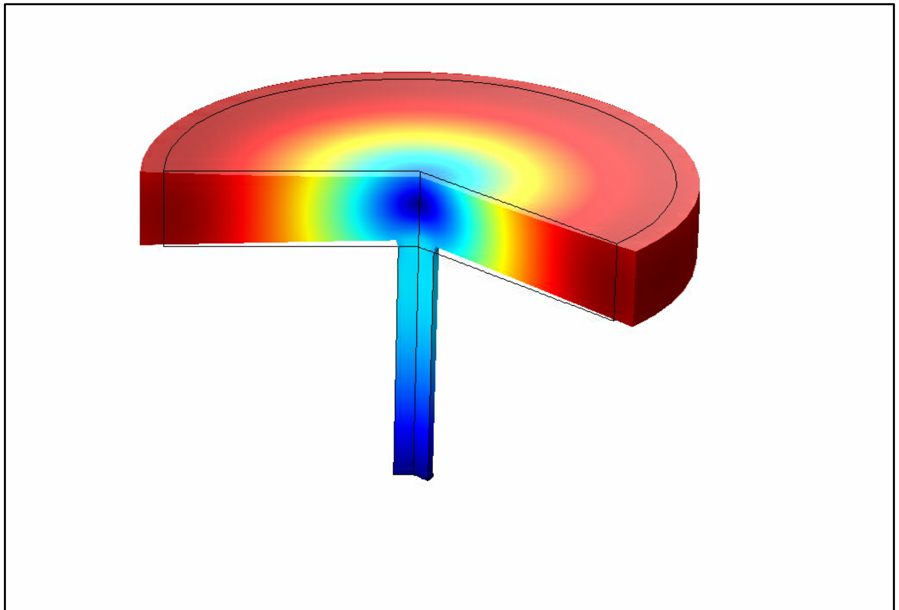
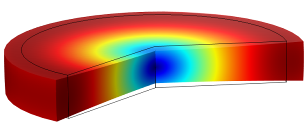
GaAs disk mechanics

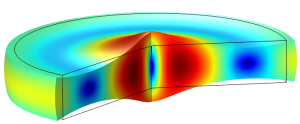


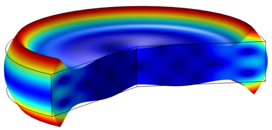
Out-of-plane mechanical modes



Colormap: total displacement







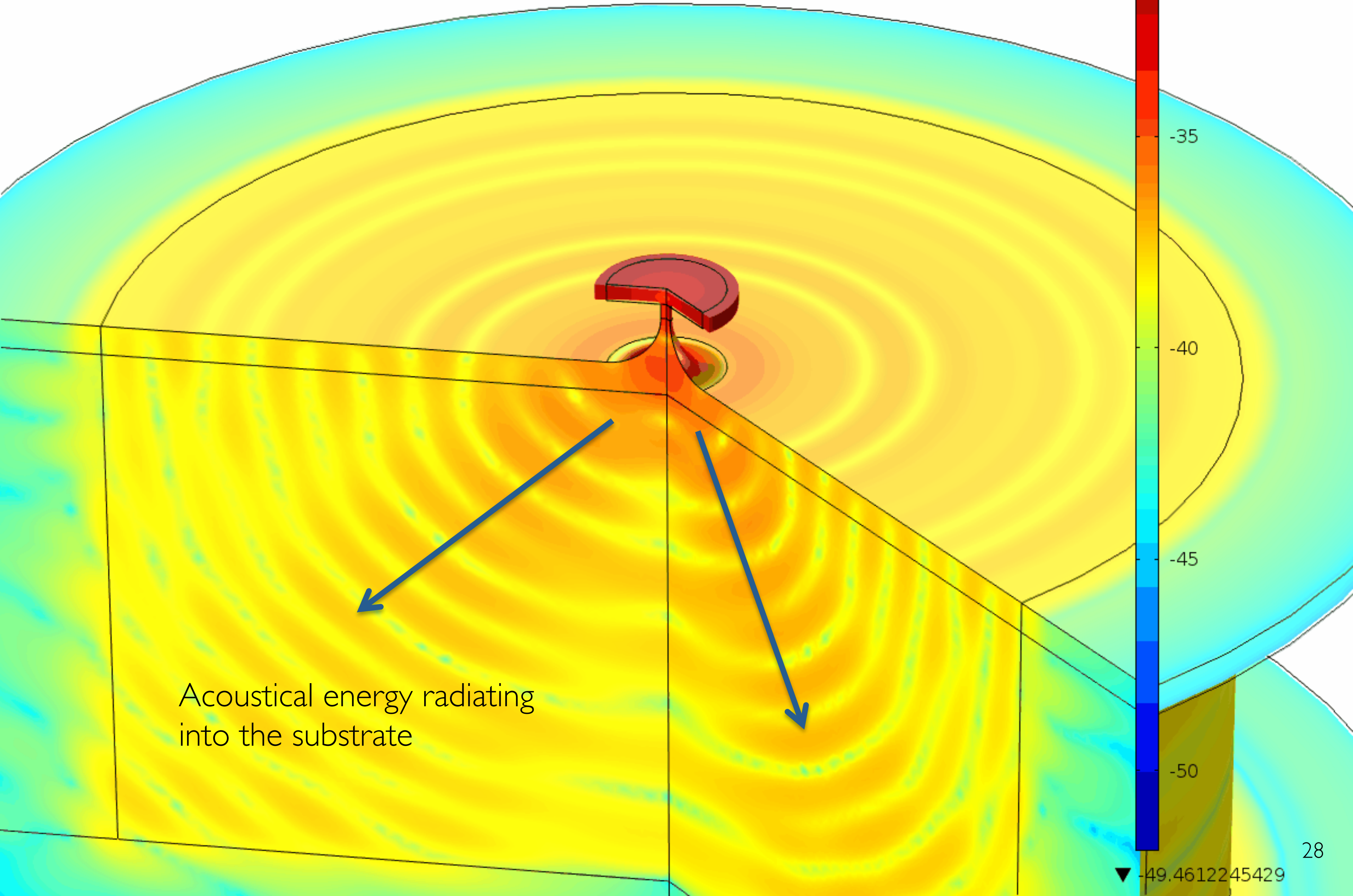
In-plane mechanical modes

+ **Small mass:** picogram range
+ **High frequency:** > 1GHz range

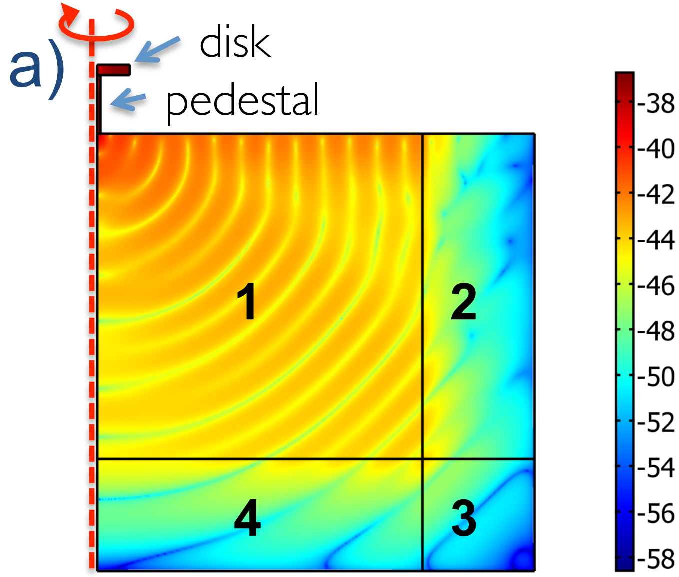
In plane/out-of-plane coupling ➔ losses via pedestal

Mechanical dissipation through clamping losses in GaAs disks

Colormap: log(total displacement)

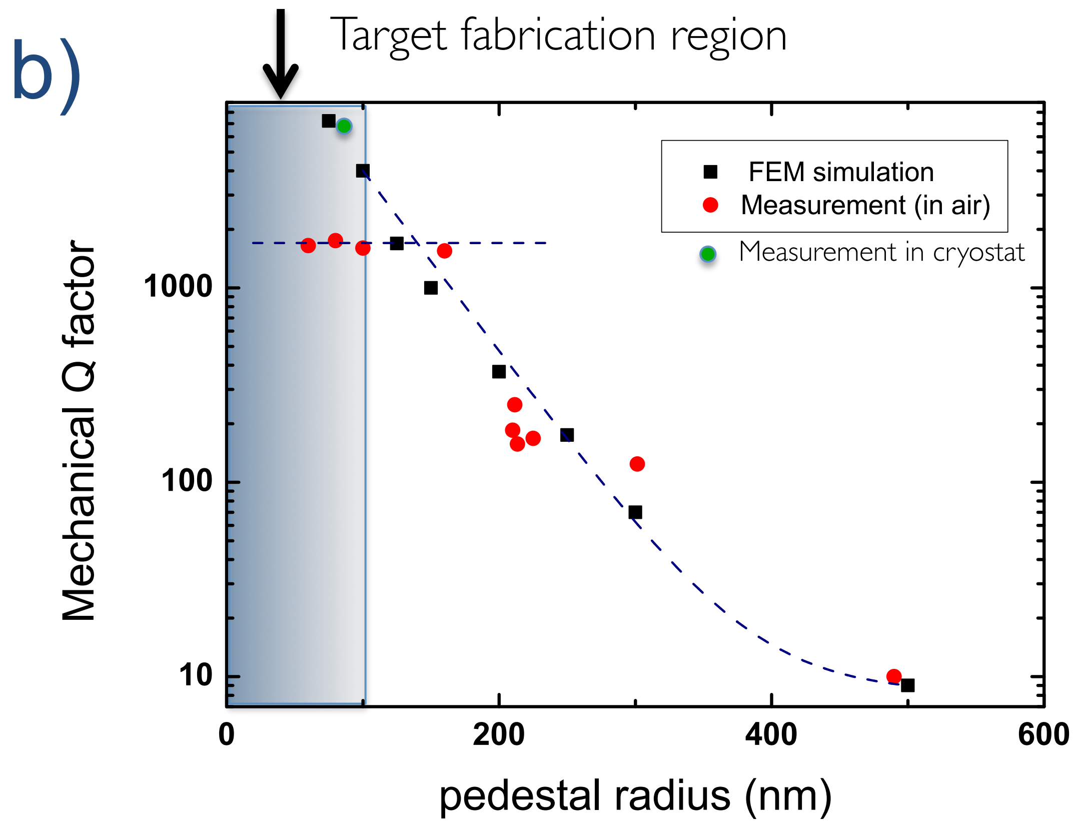


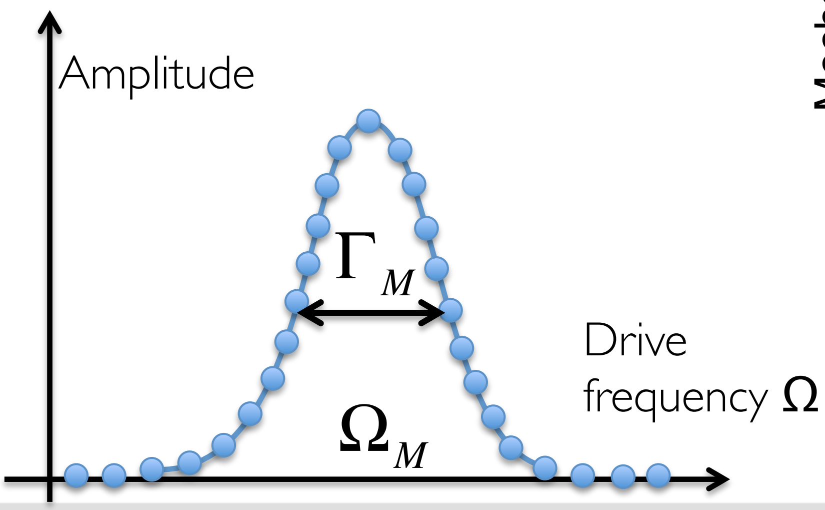
Mechanical clamping losses in GaAs disks



2,3,4 Perfectly matched layers

$$F = F_0 \times \cos(\Omega t)$$





$$Q \times f_M$$

DT. NGuyen, C. Baker et al. arXiv:1309.4971, 2013.

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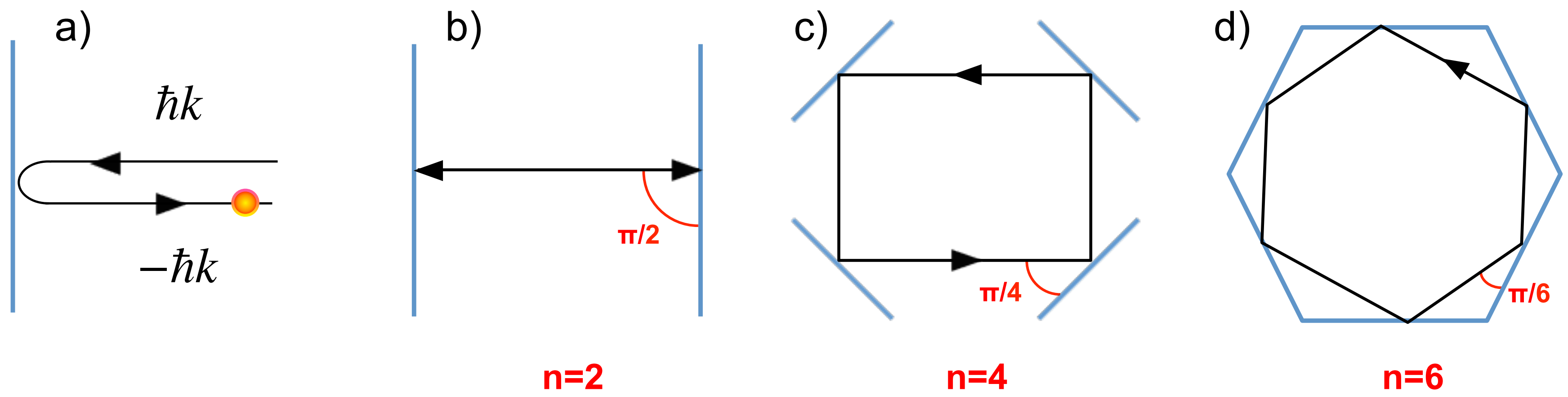
Radiation pressure in a GaAs disk resonator



Momentum transfer per round trip in a circular cavity:

$$2\hbar k \lim_{n\to\infty} n \sin(\pi / n) = 2\pi\hbar k$$

$$F = \frac{dP}{dt} = \frac{2\pi\hbar k}{2\pi R n_{eff} / c} = \frac{\hbar\omega_0}{R} \approx 1.5\times 10^{-13} N$$

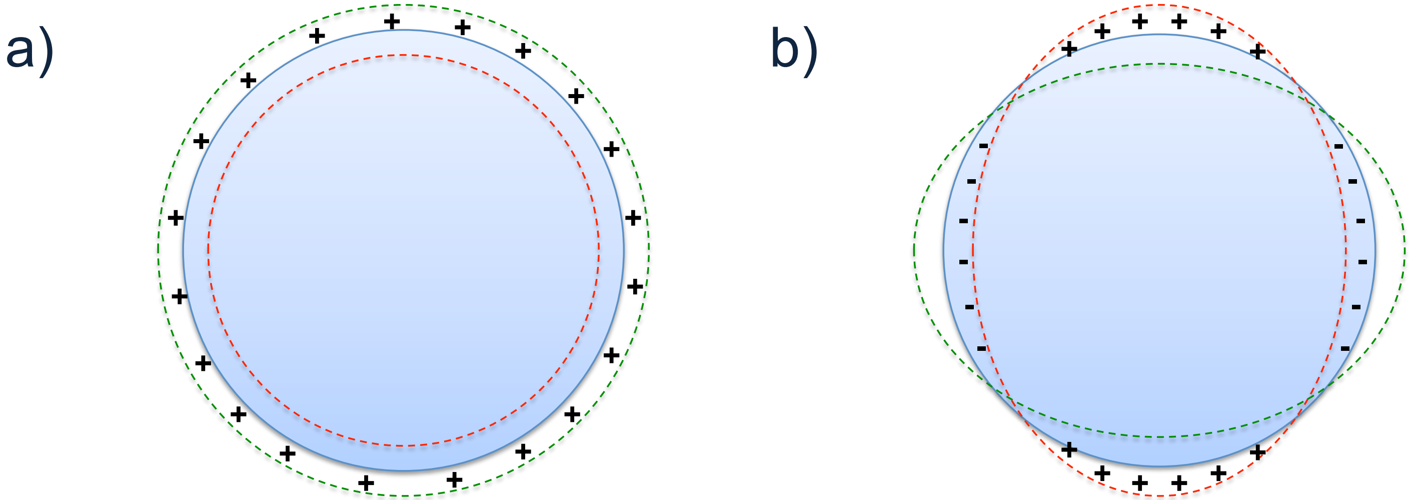
$$P = mg = 5.2\times 10^{-14} N$$

Radiation pressure force due to a single photon larger than the disk's weight !

Geometric optomechanical coupling in GaAs disks

$$2\pi n R \simeq m\lambda_0$$

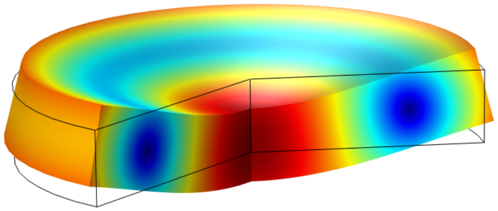
Mechanical deformation → Change in cavity size → shift in optical resonance frequency



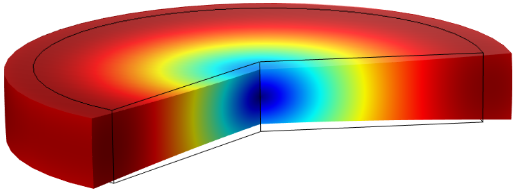
Selection rule: largest optomechanical coupling for modes with highest rotational symmetry

Calculations of g_0^{geo} in GaAs disks

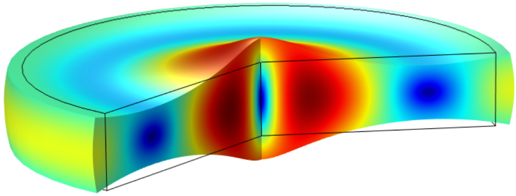
For a 1 μm radius GaAs disk:



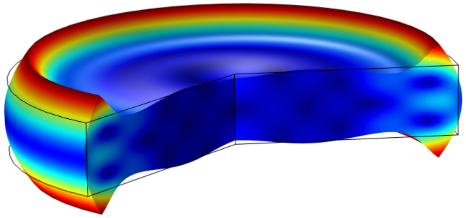
Ω_M=0.5 GHz,
g_0^{geo}=0.32 kHz



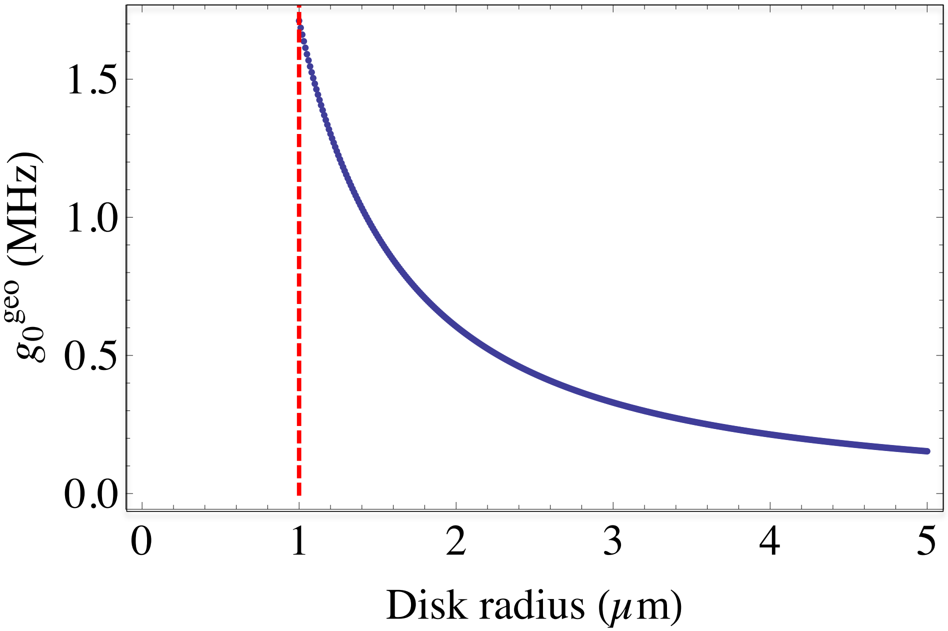
Ω_M=1.37 GHz,
g_0^{geo}=1.3 MHz



Ω_M=3.5 GHz,
g_0^{geo}=0.5 MHz

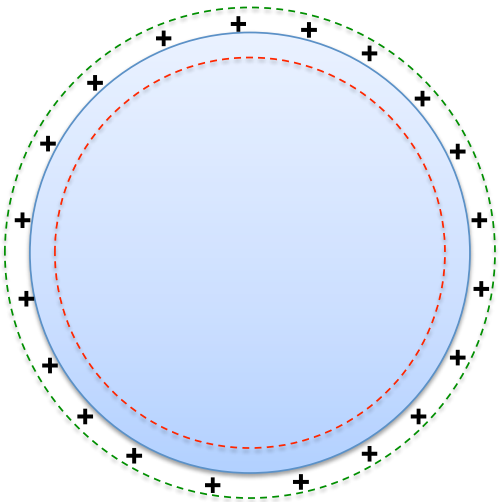


Ω_M=5.7 GHz,
g_0^{geo}=0.18 MHz



Semi-analytical derivation of g_0^{geo}

Photoelastic optomechanical coupling in GaAs disks



$$2\pi nR \simeq m\lambda_0$$

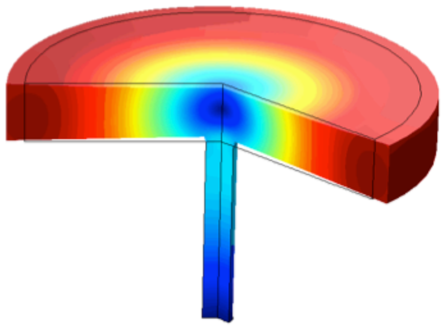
$$\begin{pmatrix} \Delta(\varepsilon_1^{-1}) \\ \Delta(\varepsilon_2^{-1}) \\ \Delta(\varepsilon_3^{-1}) \\ \Delta(\varepsilon_4^{-1}) \\ \Delta(\varepsilon_5^{-1}) \\ \Delta(\varepsilon_6^{-1}) \end{pmatrix} = \underbrace{\begin{pmatrix} p_{11} & p_{12} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{11} & p_{12} & 0 & 0 & 0 \\ p_{12} & p_{12} & p_{11} & 0 & 0 & 0 \\ 0 & 0 & 0 & p_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & p_{44} & 0 \\ 0 & 0 & 0 & 0 & 0 & p_{44} \end{pmatrix}}_{\text{photoelastic tensor}} \begin{pmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{pmatrix}$$

Mechanical deformation → deformed crystal lattice → anisotropic *and* inhomogeneous dielectric permittivity

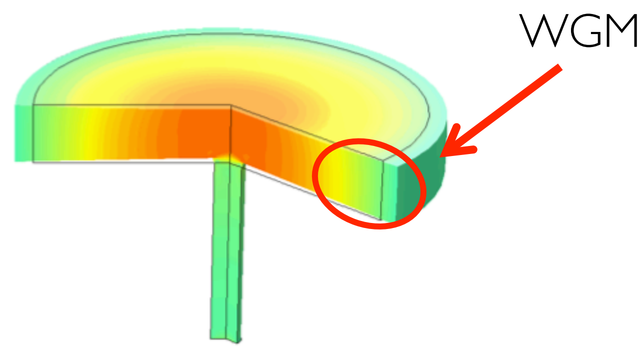
The p_{ij} are negative in GaAs ➔ geometric and photoelastic optomechanical coupling add constructively ☺

Strong photoelastic coupling in GaAs disks, $g_0^{pe} \sim 1$ MHz for the first RBM, comparable to g_0^{geo}

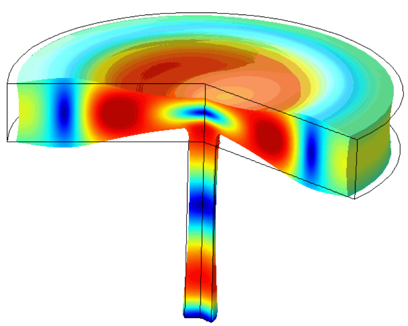
1st and 2nd RBM strain profile



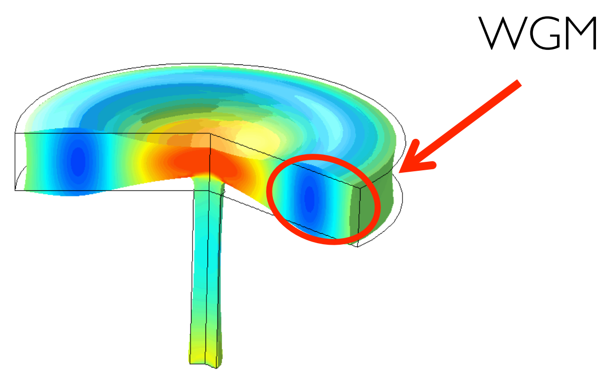
1st RBM displacement



1st RBM radial strain



2nd RBM displacement



2nd RBM radial strain

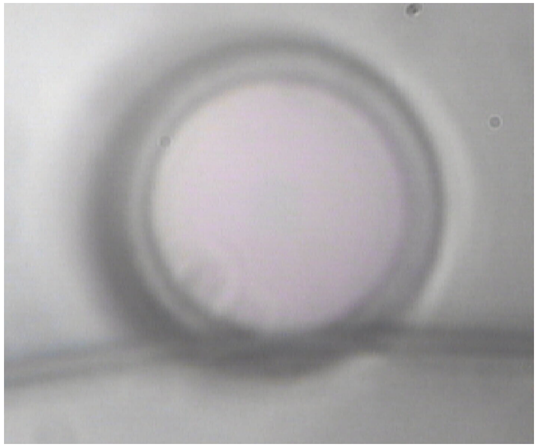
g_0^{pe} ~**2MHz**, at 3.5 GHz

C. Baker et al. *In preparation*

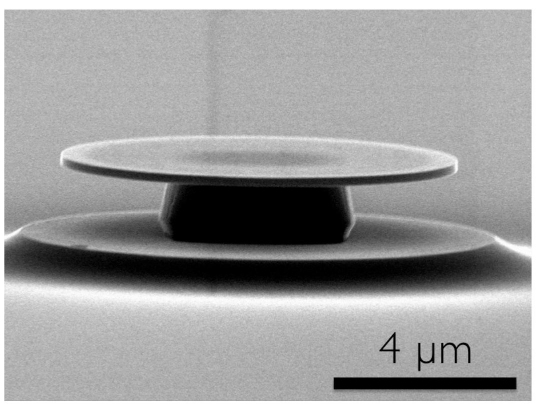
Outline

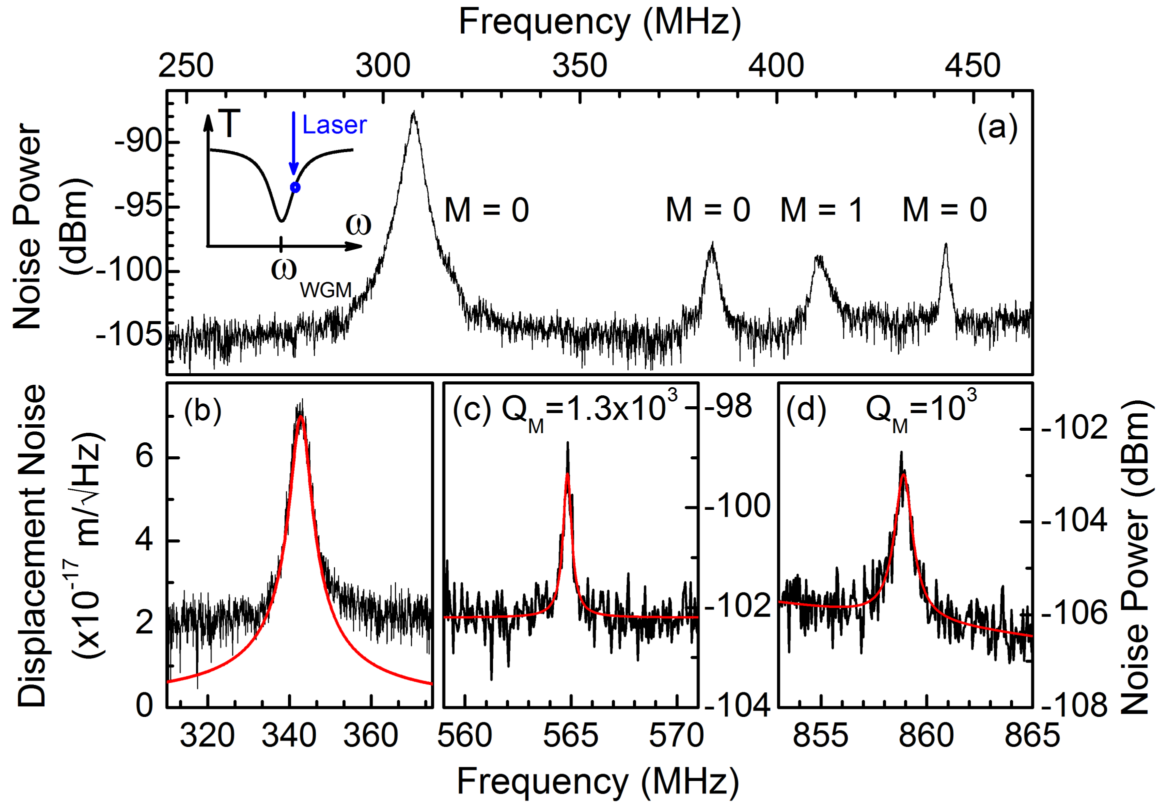
1. Introduction
2. Whispering gallery mode resonators
3. Nanofabrication
4. Experimental guided optics
5. Mechanics of nanoresonators
6. Optomechanical coupling
7. Experimental optomechanics
8. Conclusions/perspectives

Ultra-sensitive optical measurement of GaAs disk motion



Fiber-coupled freestanding GaAs disk resonator

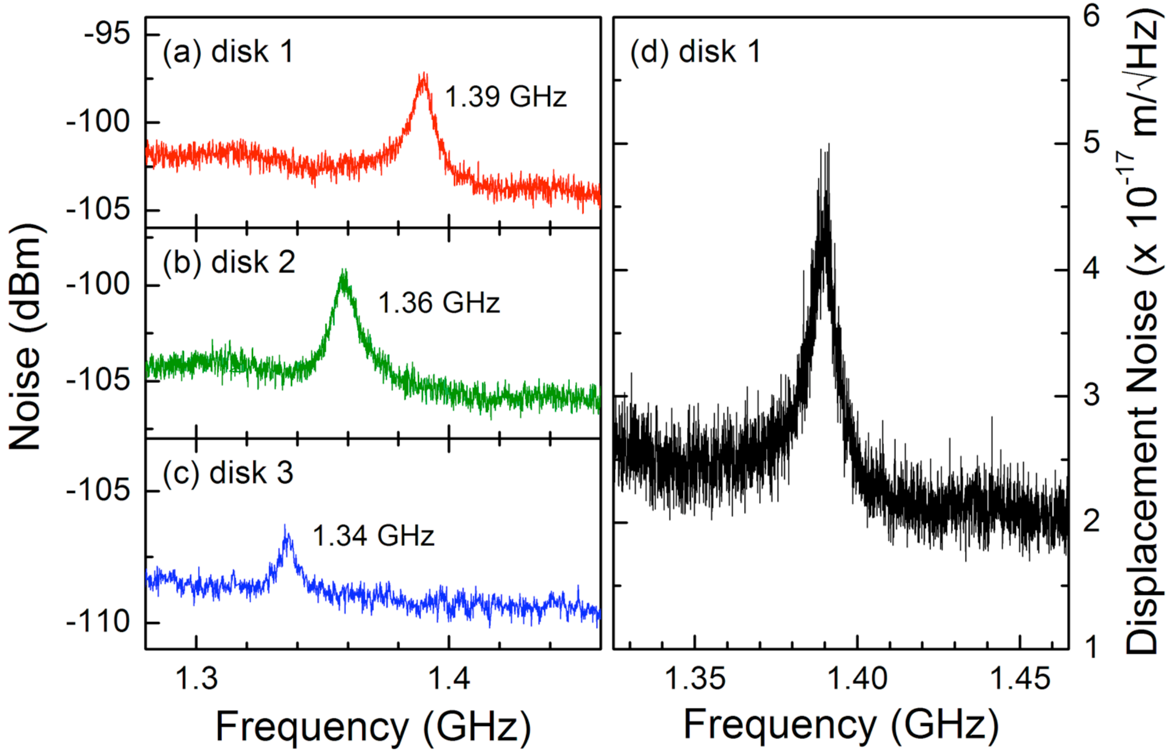


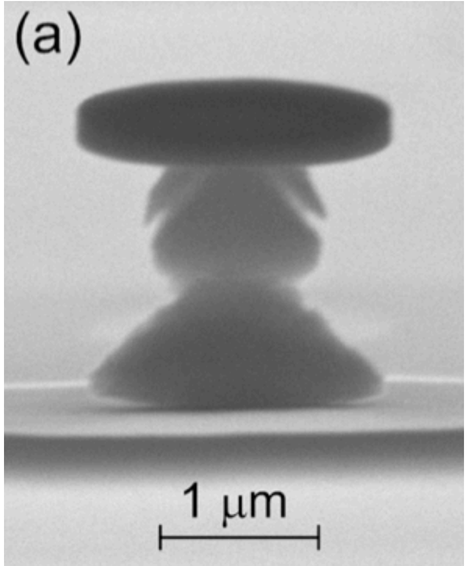


- Frequency of mechanical modes up to GHz
- In air, mechanical Q factor 50 to 10^3 ($Q \times f_M \sim 10^{11}$ in air)
- Sensitivity 10^{-17} m/√Hz (approaching the quantum limit)
- Optomechanical coupling $g_0 \sim 100$ kHz

L. Ding, C. Baker et al. *Physical Review Letters*, 105(26):263903, 2010.

GaAs Disk Mechanical modes above the GHz

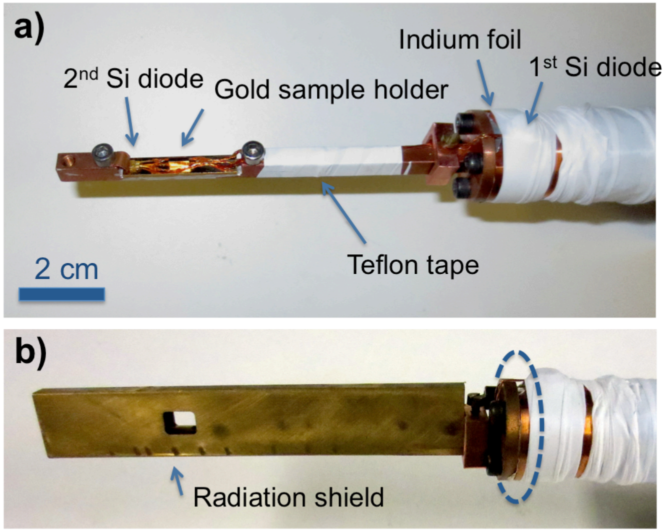


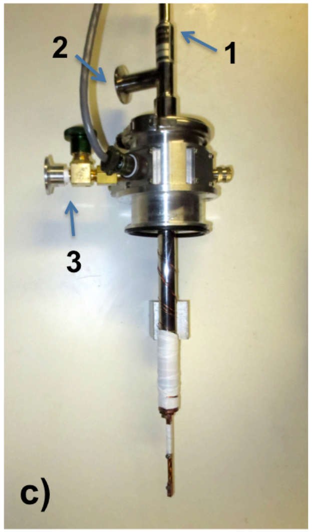


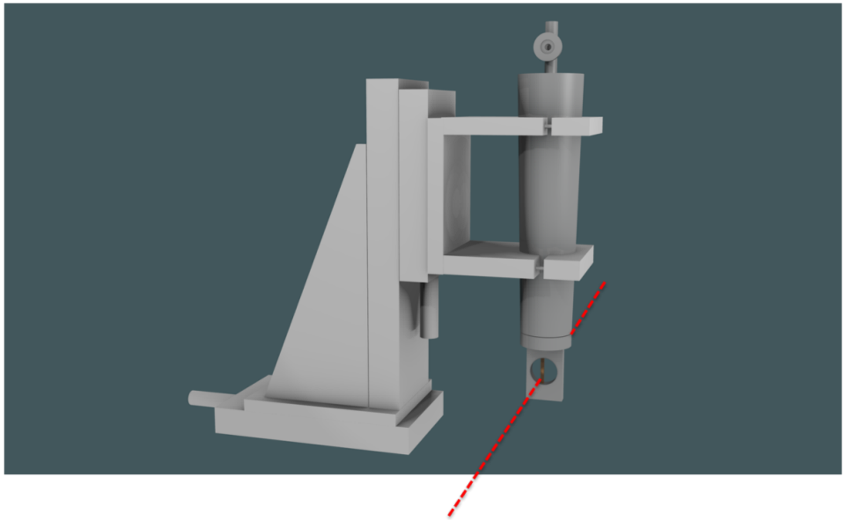
Radius = 1 μm, $Q \times f_M \sim 10^{11}$, $g_o \approx 1$ MHz

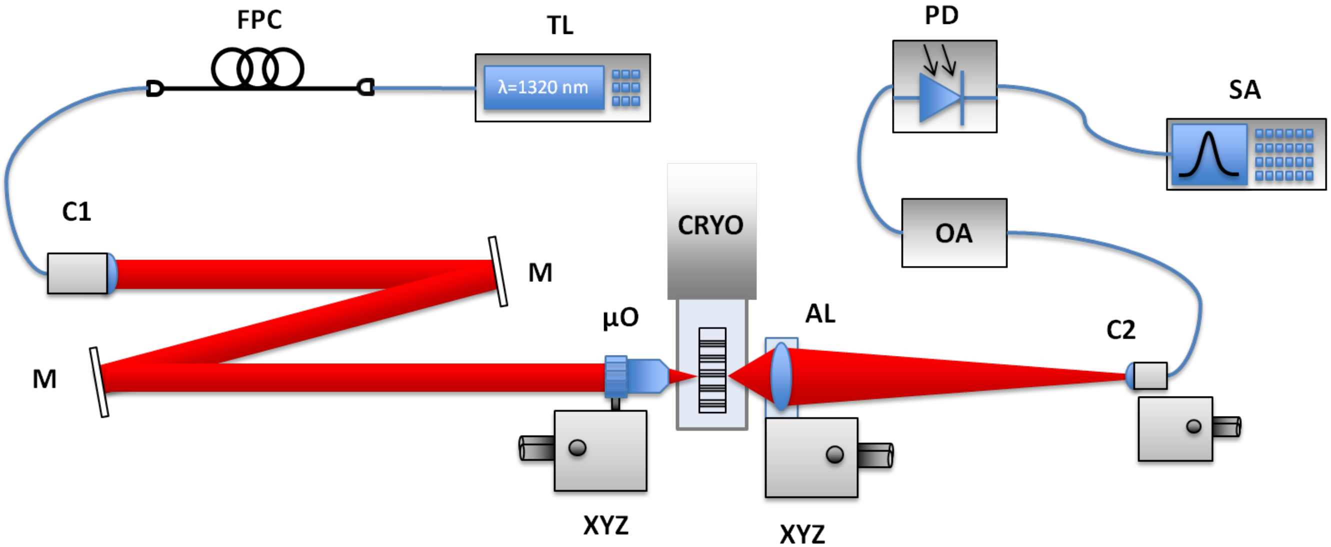
L. Ding, C. Baker et al. *Applied Physics Letters*, 98:113108, 2011.

Cryostat setup

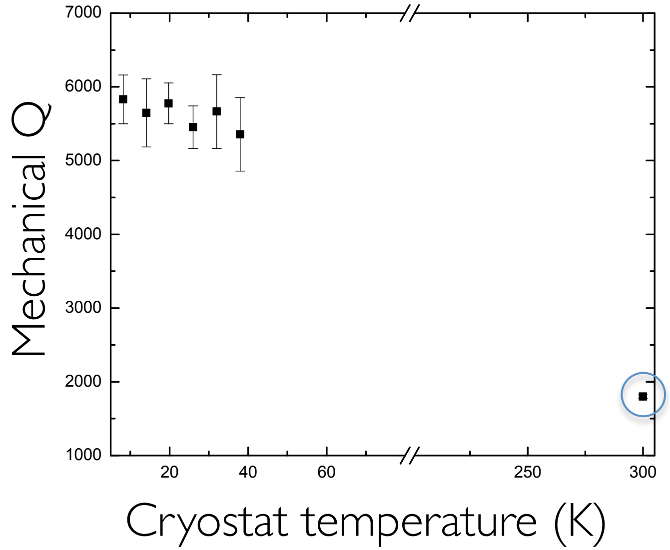


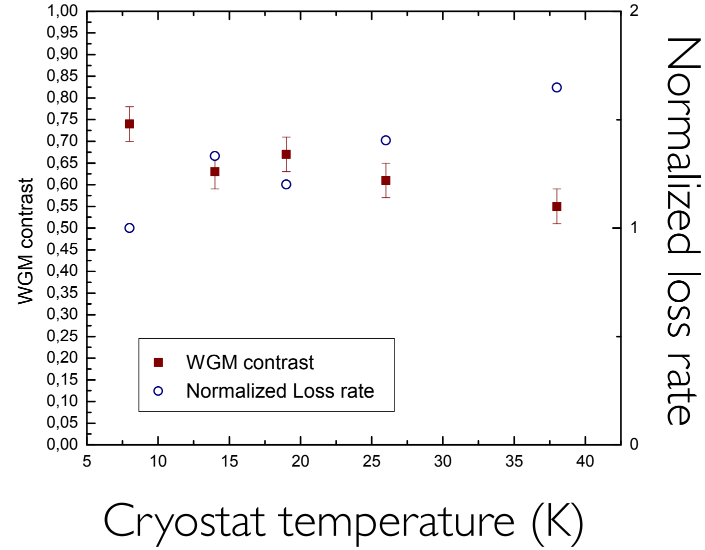


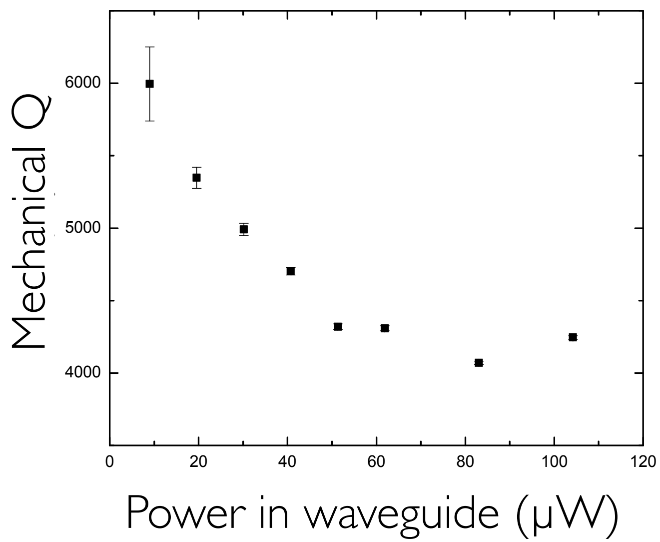


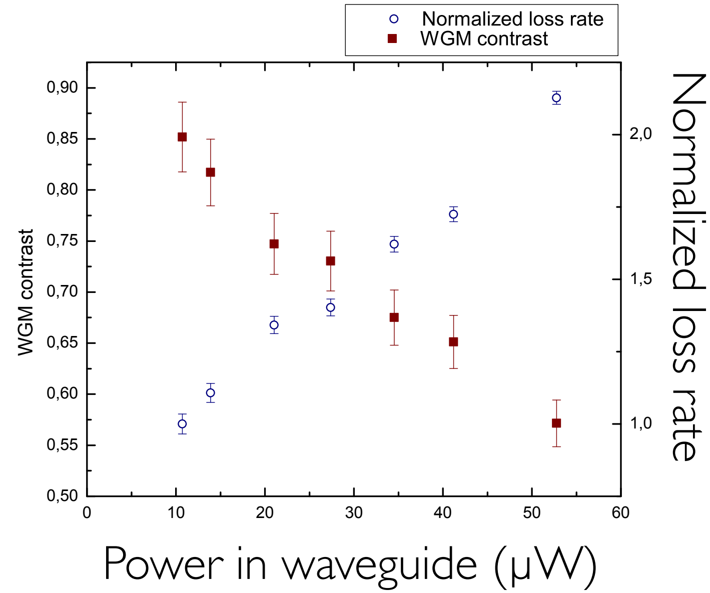


Measurements in cryostat

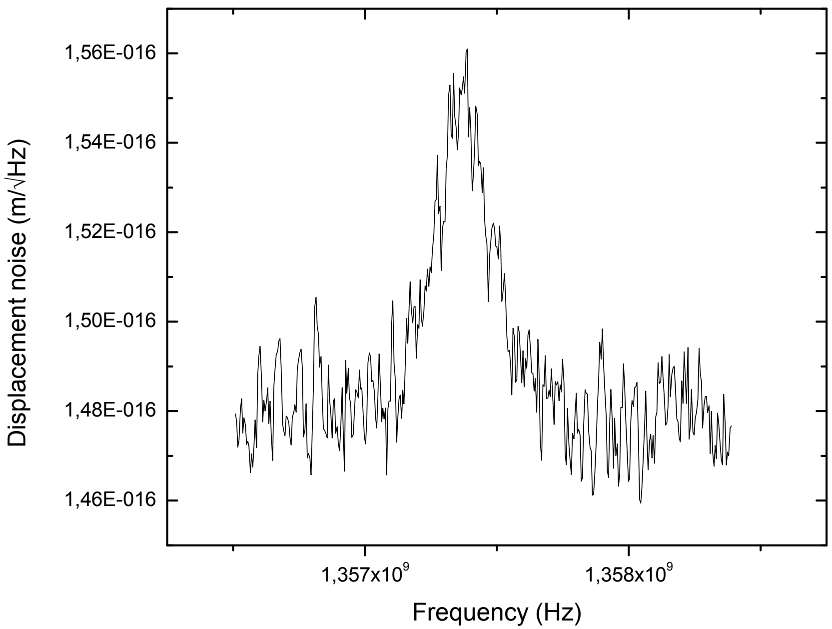








Experimental perspectives: towards quantum effects



Measurement of mechanical mode thermalized at 12K:

$$n_{\mathrm{th}} = \frac{k_B T}{\hbar \Omega_M} \sim 180 \text{ phonons}$$

$$\frac{4 g_0^2 N_{cav}}{\kappa \Gamma_M}$$

- At 4K, thermal occupation n_{th}~60 phonons

With current parameters, expect to cool by a factor ~100

Optomechanical cooling to quantum ground state feasible

Thanks

DON

I. Favero, G. Leo, S. Ducci, D. Parrain, D.-T. Nguyen, W. Hease, B. Guha, E. Gil-Santos, A. Andronico, A. Delga, M. Savanier, A. Orieux, S. Mariani, C. Ozanam, G. Boucher, A. Eckstein, F. Boitier, C. Autebert

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MPQ

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