Quantum Science Generation Trento 2025 – May 7

Dissipative and dispersive cavity optomechanics with a suspended frequency-dependent mirror

Juliette Monsel

Experiment S. K. Manjeshwar, A. Ciers, J. Monsel, H. Pfeifer, C. Peralle, S. M. Wang, P. Tassin, W. Wieczorek *Opt. Express* **31** 30212 (2023)

Theory J. Monsel, A. Ciers, S. K. Manjeshwar, W. Wieczorek, J. Splettstoesser *Phys. Rev. A* **109** 043532 (2024)
L. Du, J. Monsel, W. Wieczorek, J. Splettstoesser *Phys. Rev. A* **111** 013506 (2025)

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Swedish Research Council
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CHALMERS UNIVERSITY OF TECHNOLOGY Area of Advance NANO
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Researcher in Janine Splettstoesser's group

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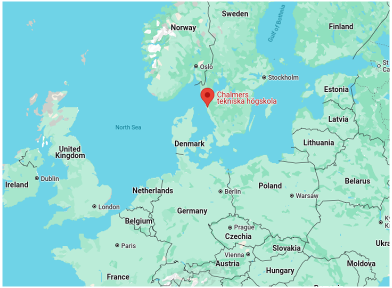
Dynamics and thermodynamics of nanoscale devices:

- Optomechanics
- Quantum transport
- Noise, fluctuations, bounds ...
- Nonthermal thermodynamic resources



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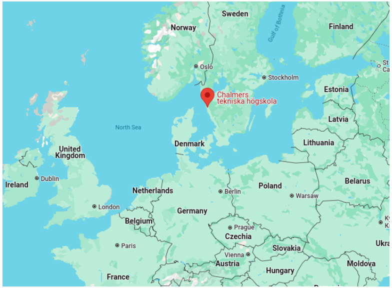

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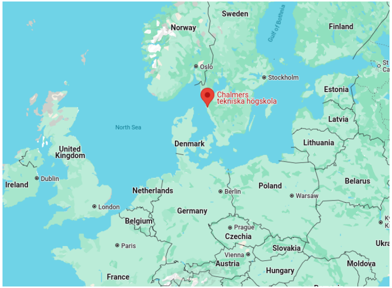


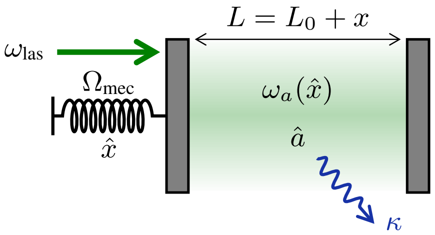
Outline

1. Standard dispersive cavity optomechanics
2. Modeling the experiment: optomechanics with a frequency-dependent mirror
   - Dispersive optomechanics with a frequency-dependent mirror
   - Additional dissipative optomechanical effects
3. Strategies to reach the resolved-sideband regime
   - Fano mirror engineering
   - Coherent feedback scheme

Outline

Standard dispersive cavity optomechanics

Optical cavity with one moving-end mirror:



Cavity mode coupled to mechanical mode

Standard dispersive cavity optomechanics

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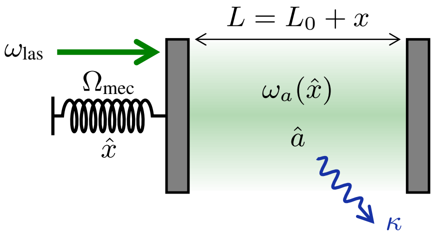

- Resonator motion ⇒ change in cavity resonance frequency
  $\omega_a(x) = n\frac{\pi c}{L(x)} \simeq \omega_a(0) + x\left(\frac{\partial \omega_a}{\partial x}\right)_{x=0}$ ⇒ coupling $g^\omega \propto -\left(\frac{\partial \omega_a}{\partial x}\right)_{x=0}$

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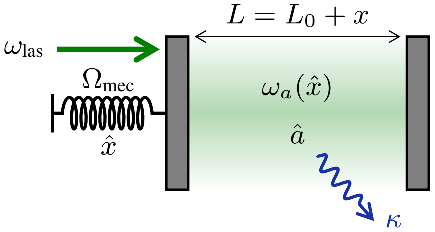


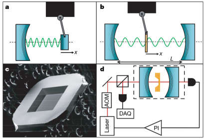
- Resonator motion $\Rightarrow$ change in cavity resonance frequency
  $\omega_a(x) = n\frac{\pi c}{L(x)} \simeq \omega_a(0) + x\left(\frac{\partial \omega_a}{\partial x}\right)_{x=0} \Rightarrow$ coupling $g^\omega \propto -\left(\frac{\partial \omega_a}{\partial x}\right)_{x=0}$
- Photons in the cavity $\Rightarrow$ radiation pressure on the mirror
  $\Rightarrow$ change rest position of resonator

Cavity mode coupled to mechanical mode

Experimental platforms

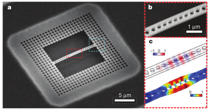
Many different implementations, for instance:

- Membrane in the middle



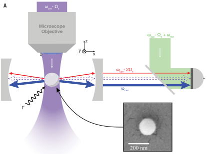
J. D. Thompson et al.
Nature **452**, 72 (2008)

- Integrated system



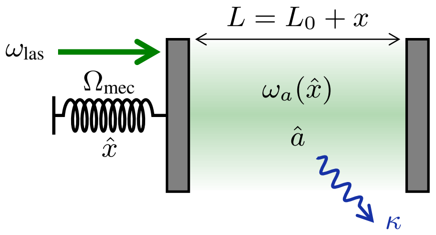
J. Chan et al.
Nature **478**, 89 (2011)

- Levitated particle



U. Delić et al.
Science **367**, 892 (2020)

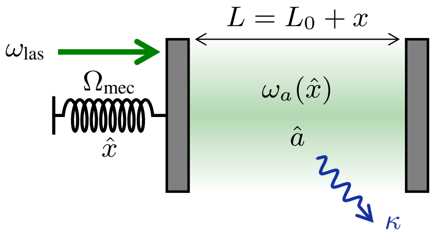
Applications

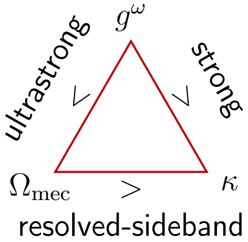


Single-photon optomechanical coupling: $\omega_a(x) = n\frac{\pi c}{L(x)}$ and $g^\omega = -\left(\frac{\partial \omega_a}{\partial x}\right)_{x=0} x_{\text{ZPF}}$

- Ground-state cooling of the mechanical resonator
- Sensing: force sensor, gravitational waves ...
- Quantum manipulation of nanomechanical resonators

Applications





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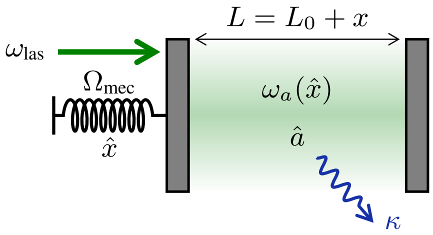

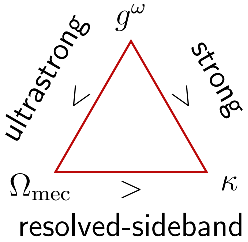

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Issue: g^ω typically very small

How to improve the coupling strength?

- Make cavity shorter → microcavity $L_0 = \lambda_\mathrm{a}/2$ $(n = 1)$
  Issue: larger loss rate κ

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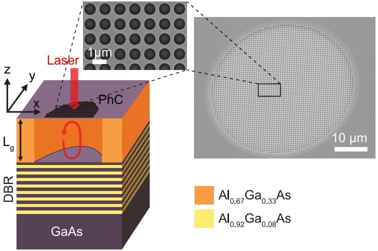
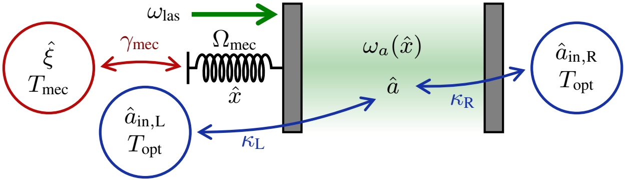
Experimental device



- Free-space microcavity
- On-chip integration
- Suspended photonic crystal mirror
  → frequency dependence

How to model this system?

Standard dispersive cavity optomechanics



M. Aspelmeyer, T. J. Kippenberg, F. Marquardt *Rev. Mod. Phys.* **86**, 1391 (2014)

$$\hat{H} = \frac{\hat{p}^2}{2m} + \frac{1}{2}m\Omega_{mec}^2\hat{x}^2 + \hbar\omega_a\hat{a}^\dagger\hat{a} + \hbar(\epsilon\hat{a}^\dagger e^{-i\omega_{las}t} + \epsilon^*\hat{a}e^{i\omega_{las}t}) - \hbar g_a^\omega\hat{a}^\dagger\hat{a}\frac{\hat{x}}{x_{ZPF}}$$

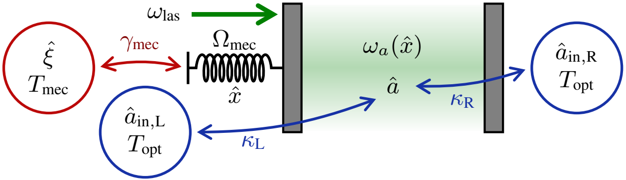
Resonator frequency Ω_{mec}, position $\hat{x}$, momentum $\hat{p}$, damping rate γ_{mec}

Cavity frequency ω_a, annihilation operator $\hat{a}$, loss rate $\kappa = \kappa_L + \kappa_R$

Laser drive frequency ω_{las}, amplitude ϵ

Coupling single-photon optomechanical coupling strength

Standard dispersive cavity optomechanics



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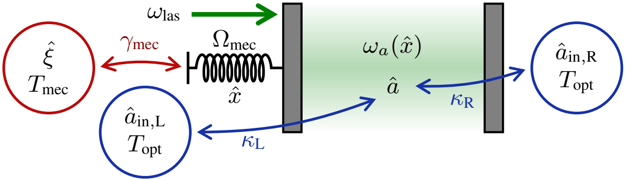

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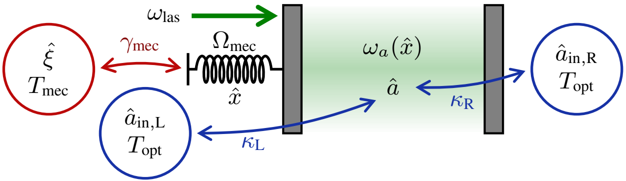

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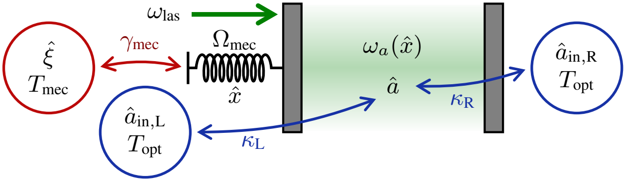

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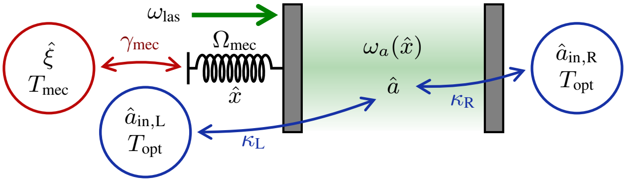
Coupling single-photon optomechanical coupling strength

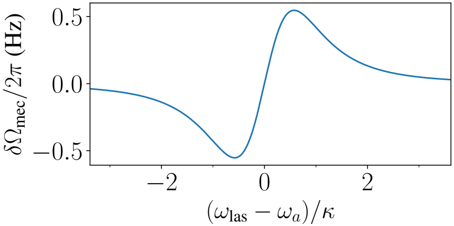
$\Rightarrow$ Solved with typical input-output framework in the **linearized** regime

$$\hat{H}_{\rm int}^{\rm lin} = -\hbar g_a^\omega\sqrt{n_a}(\delta\hat{a}^\dagger + \delta\hat{a})\frac{\delta\hat{x}}{x_{\rm ZPF}}$$

Optical spring effect



Frequency shift induced by the light field: $\Omega_{\rm mec}^{\rm eff} = \Omega_{\rm mec} + \delta\Omega_{\rm mec}$

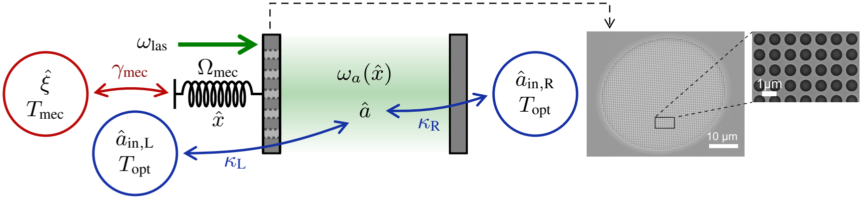


Linearized limit and $\kappa \gg \Omega_{\rm mec}$ (nonresolved sideband)

Outline

Frequency-dependent (Fano) mirror

Strongly frequency-dependent left mirror (e.g. photonic crystal)



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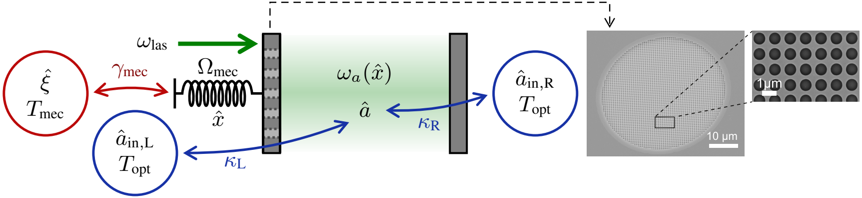
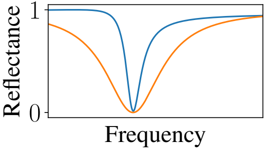


- Fano profile, reduced losses



O. Černotík, A. Dantan, C. Genes, *Phys. Rev. Lett.* **122**, 243601 (2019)

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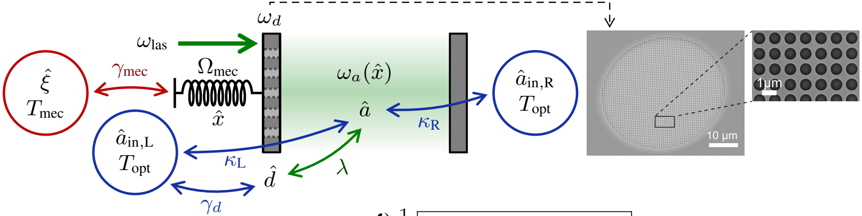

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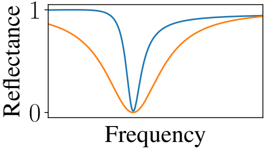
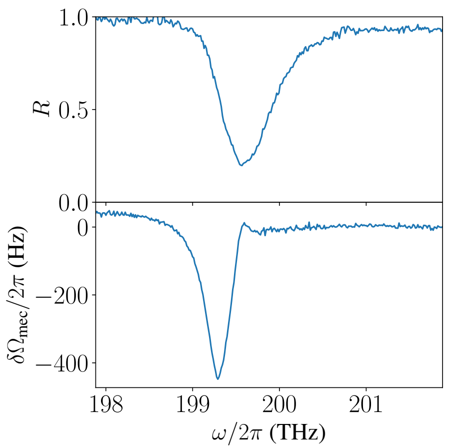


O. Černotík, A. Dantan, C. Genes, *Phys. Rev. Lett.* **122**, 243601 (2019)

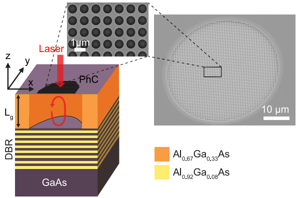
- Coupled-mode model: mirror mode ω_d, $\hat{d}$, γ_d

  Coupling to the cavity mode $\hat{H}_{\text{Fano}} = \hbar\lambda(\hat{d}^\dagger\hat{a} + \hat{a}^\dagger\hat{d})$

Comparison to the experiment



Experiment



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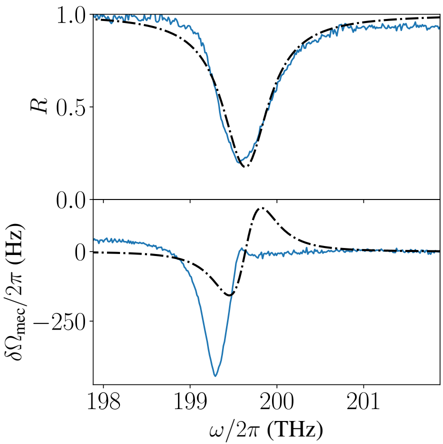

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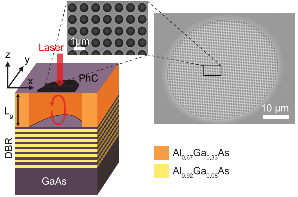

Standard dispersive optomechanics

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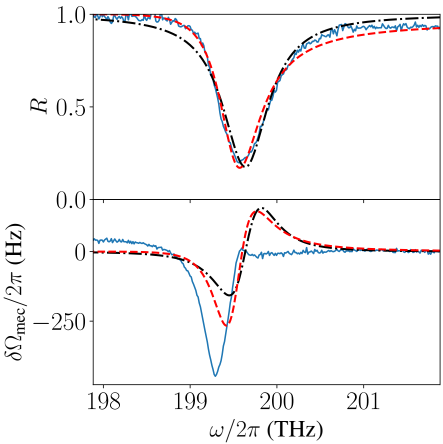
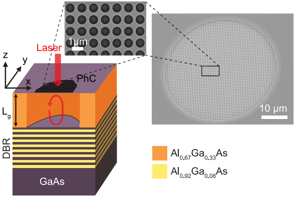
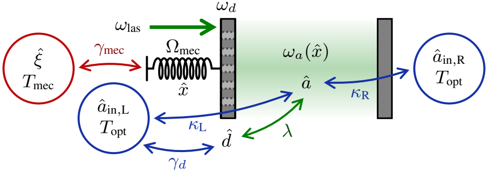


— Experiment



-·-· Standard dispersive optomechanics

- - - Dispersive optomechanics + Fano mirror



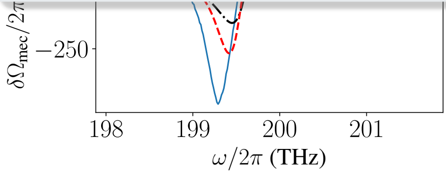
Dispersive optomechanics + Fano mirror: Optics ✔ – Mechanics ✘

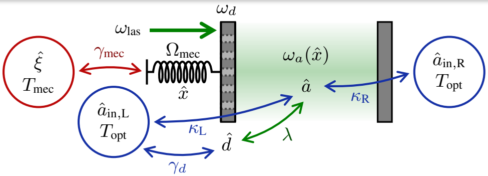
Comparison to the experiment

What are we missing?

- Dissipative optomechanics: $\kappa_{\mathrm{L}}(\hat{x})$

  F. Elste, S. M. Girvin, A. A. Clerk, *Phys. Rev. Lett.* **102**, 207209 (2009)





Dispersive optomechanics + Fano mirror: Optics ✔ – Mechanics ✘

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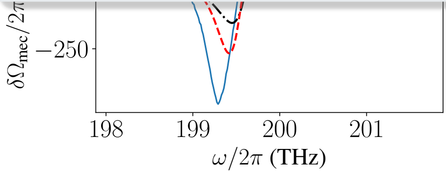
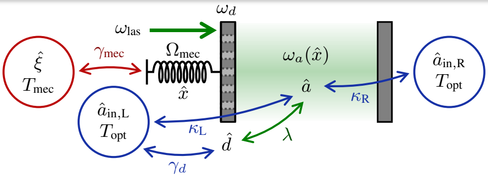
- Optomechanical effects on the mirror mode:
  $\omega_d(\hat{x})$ (dispersive) and $\gamma_d(\hat{x})$ (dissipative)

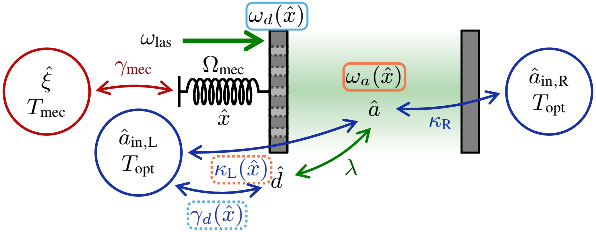
  J. Monsel, A. Ciers, S. K. Manjeshwar, W. Wieczorek, J. Splettstoesser *Phys. Rev. A* **109** 043532 (2024)





Dispersive optomechanics + Fano mirror: Optics ✔ – Mechanics ✘

Dissipative optomechanics with a Fano mirror

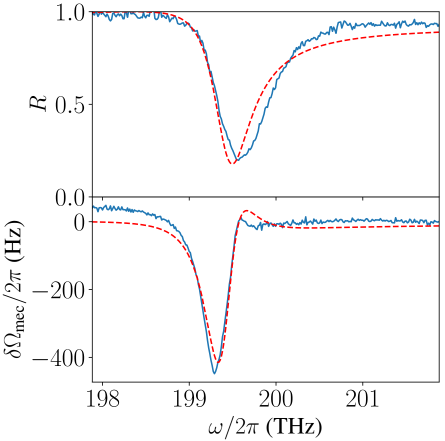


4 optomechanical couplings needed:

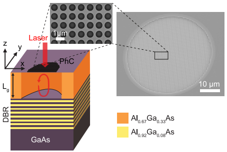
	Dispersive	Dissipative
Cavity mode, $\hat{a}$	$g_a^\omega = -\left(\frac{\partial \omega_a}{\partial x}\right)_0 x_{\text{ZPF}}$	$g_a^\kappa = \left(\frac{\partial \kappa_{\text{L}}}{\partial x}\right)_0 x_{\text{ZPF}}$
Mirror mode, $\hat{d}$	$g_d^\omega = -\left(\frac{\partial \omega_d}{\partial x}\right)_0 x_{\text{ZPF}}$	$g_d^\kappa = \left(\frac{\partial \gamma_d}{\partial x}\right)_0 x_{\text{ZPF}}$

Dissipative optomechanics with a Fano mirror

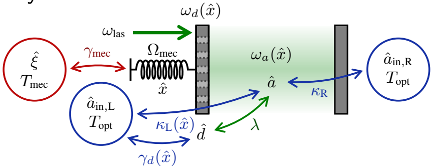
Comparison to the experiment



Experiment



Dissipative & dispersive optomechanics for cavity and mirror modes

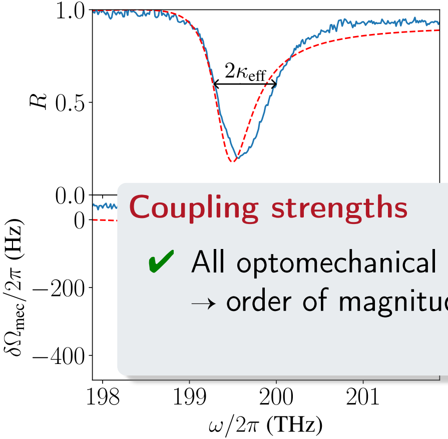


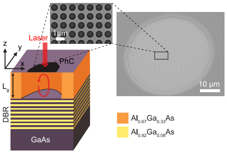
$g_a^\omega/\Omega_{\rm mec} \simeq 4.5$, $g_a^\kappa/\Omega_{\rm mec} \simeq 8.7$, $g_d^\omega/\Omega_{\rm mec} \simeq -3.0$, $g_d^\kappa/\Omega_{\rm mec} \simeq 2.2$

Optics ✔ – Mechanics ✔

Dissipative optomechanics with a Fano mirror

Comparison to the experiment





Coupling strengths

✔ All optomechanical couplings are in the **ultrastrong** regime
→ order of magnitude confirmed by FEM simulations

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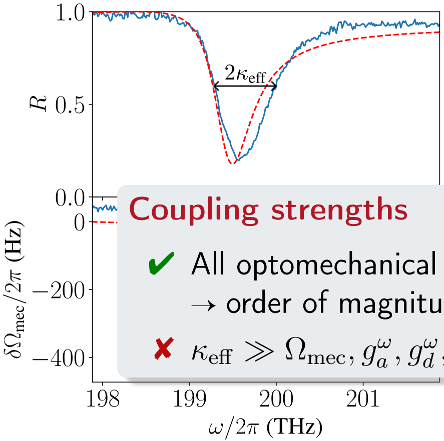
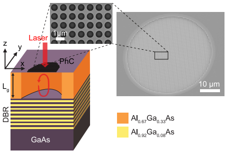




Coupling strengths

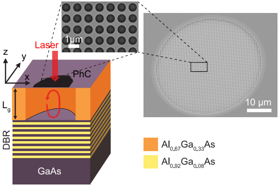
- ✔ All optomechanical couplings are in the **ultrastrong** regime → order of magnitude confirmed by FEM simulations
- ✘ $\kappa_{\mathrm{eff}} \gg \Omega_{\mathrm{mec}}, g_a^\omega, g_d^\omega, g_a^\kappa, g_d^\kappa$ → far from strong coupling regime

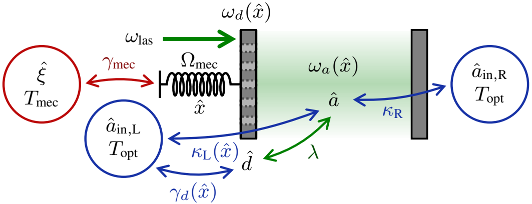
$\gamma_d(\hat{x})$

$g_a^\omega/\Omega_{\mathrm{mec}} \simeq 4.5$, $g_a^\kappa/\Omega_{\mathrm{mec}} \simeq 8.7$, $g_d^\omega/\Omega_{\mathrm{mec}} \simeq -3.0$, $g_d^\kappa/\Omega_{\mathrm{mec}} \simeq 2.2$

Optics ✔ – Mechanics ✔

Experiment – Summary





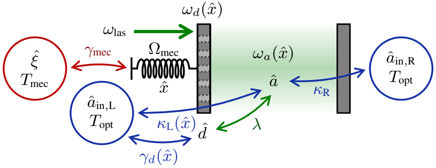
- On-chip free-space microcavity of sub-μm length
- Non-standard optomechanical effects, captured by *versatile* coupled-mode model: cavity + Fano mirror + mechanics with **dispersive** and **dissipative** optomechanical effects
- Single-photon ultrastrong coupling but very large optical losses

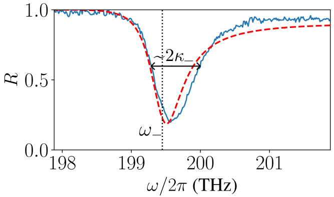
S. K. Manjeshwar, A. Ciers, J. Monsel, H. Pfeifer, C. Peralle, S. M. Wang, P. Tassin, W. Wieczorek *Opt. Express* **31** 30212 (2023)

Outline

Fano mirror engineering

How to further decrease the optical losses?





Fano mirror engineering

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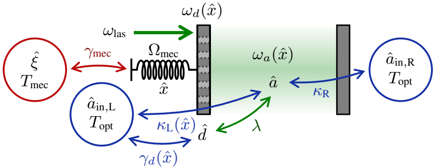

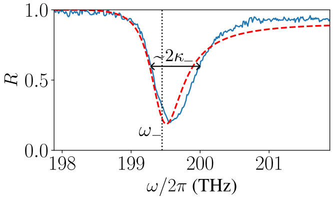

Optics only:

$$\begin{bmatrix}\dot{\hat{a}}\\ \dot{\hat{d}}\end{bmatrix} = -i\begin{bmatrix}\omega_a - i\kappa & \lambda - i\sqrt{\kappa_{\rm L}\gamma_d}\\ \lambda - i\sqrt{\kappa_{\rm L}\gamma_d} & \omega_d - i\gamma_d\end{bmatrix}\begin{bmatrix}\hat{a}\\ \hat{d}\end{bmatrix} + \begin{matrix}\text{input}\\ \text{fluct.}\end{matrix}$$

J. Monsel, A. Ciers, S. K. Manjeshwar, W. Wieczorek, J. Splettstoesser *Phys. Rev. A* **109** 043532 (2024)

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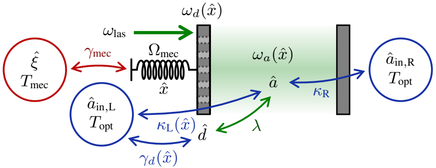

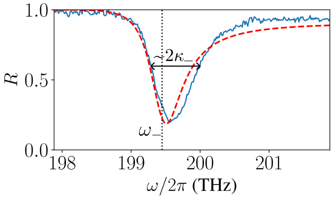

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  Normal modes: frequencies $\omega_\pm = \text{Re}(\Omega_\pm)$, loss rates $\kappa_\pm = -\text{Im}(\Omega_\pm)$

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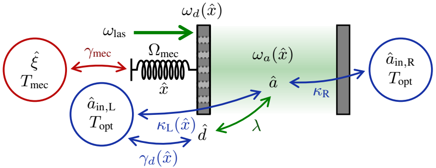

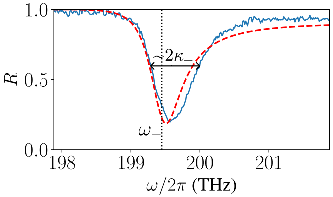

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J. Monsel, A. Ciers, S. K. Manjeshwar, W. Wieczorek, J. Splettstoesser *Phys. Rev. A* **109** 043532 (2024)

Fano mirror engineering

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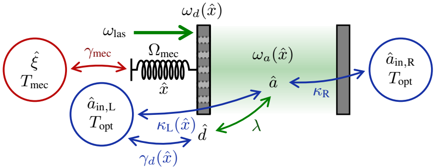

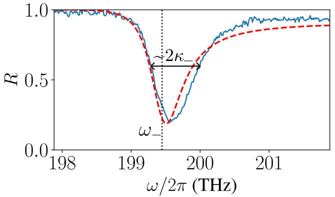

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- Dissipative optical coupling $-i\sqrt{\kappa_{\rm L}\gamma_d}$
- Fano mirror engineering (ω_d, γ_d) + small $\kappa_{\rm R} \Rightarrow$ $\kappa_- \lesssim \Omega_{\rm mec}$

J. Monsel, A. Ciers, S. K. Manjeshwar, W. Wieczorek, J. Splettstoesser *Phys. Rev. A* **109** 043532 (2024)

Effective resolved-sideband regime

Effective sideband resolution: $\kappa_- \lesssim \Omega_{\rm mec}$ but $\kappa, \gamma_d \gg \Omega_{\rm mec}$

$\Rightarrow$ Behaves like a standard resolved-sideband device for $\omega_{\rm las} \simeq \omega_- \pm \Omega_{\rm mec}$

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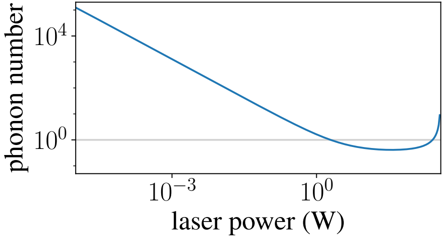

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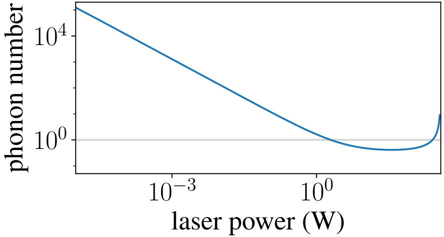

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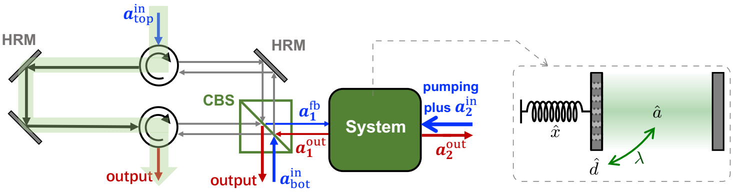
Challenging parameters + fabrication imprecision

Fano mirror and coherent feedback scheme

Add coherent feedback loop:



- No measurement

L. Du, J. Monsel, W. Wieczorek, and J. Splettstoesser, *Phys. Rev. A* **111** 013506 (2025)

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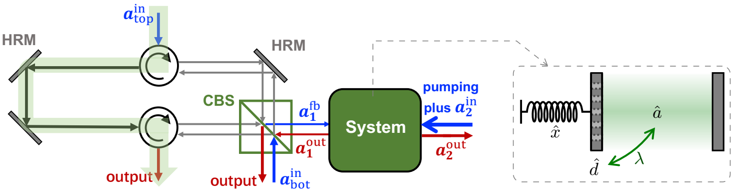
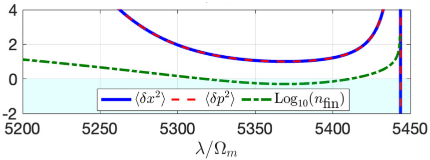


- No measurement
- Compensate for imperfect device parameters



L. Du, J. Monsel, W. Wieczorek, and J. Splettstoesser, *Phys. Rev. A* **111** 013506 (2025)

Conclusion

- Versatile coupled-mode model in good agreement with experiment

  S. K. Manjeshwar, A. Ciers, J. Monsel, H. Pfeifer, C. Peralle, S. M. Wang, P. Tassin, W. Wieczorek *Opt. Express* **31** 30212 (2023)

- Harness coupling between two optical modes to reach the effective resolved-sideband regime

  J. Monsel, A. Ciers, S. K. Manjeshwar, W. Wieczorek, J. Splettstoesser *Phys. Rev. A* **109** 043532 (2024)

- Add coherent feedback loop to compensate for parameter limitations and imperfections

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Outlook

- Model parameters $\xrightarrow{?}$ device geometry
- Nonlinear regime