Enhancing the optomechanical interaction with coupled cavities

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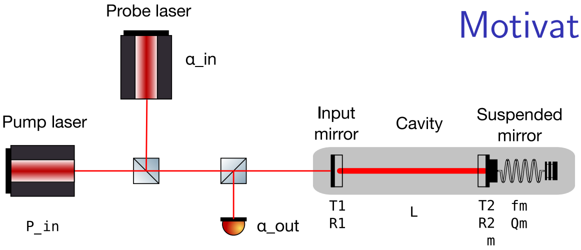
May 23, 2019

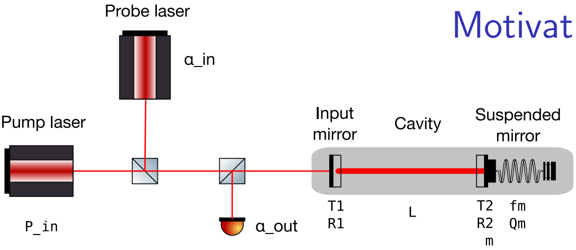
Motivation

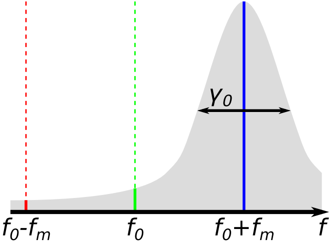


- Many applications, including ground state cooling and unstable filters, rely on retardation effects
- These effects become significant when optical dynamics is comparable to or slower than the mechanical motion, i.e. the system operates in the **resolved sideband regime**:

  Cavity bandwidth $\gamma_0 << $ *mechanical resonant frequency* f_m.
- Mechanical motion creates sidebands of the EM field.
- If the pump is detuned from cavity resonance by f_m, then (only!) one of the sidebands is resonantly enhanced.

Motivation



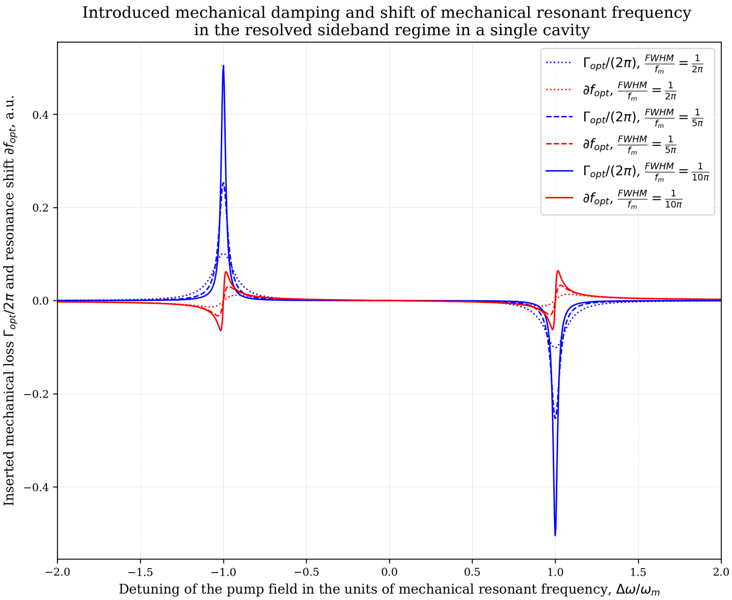


Maximal insertion loss:

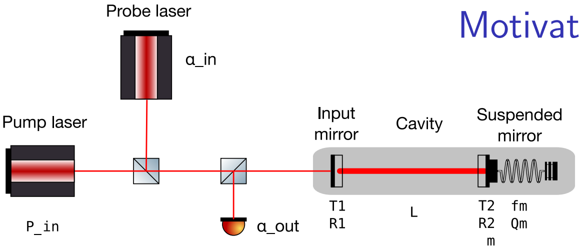
$$\frac{\Gamma_{opt}}{2\pi} = \frac{1}{2\pi}\frac{R_2}{T_1 + T_2}\frac{8P_{IC}}{mc\lambda_0 f_m}, \quad \text{where}$$

$$P_{IC} \approx P_0 \frac{T_1}{1 + R_1 R_2 - 2\sqrt{R_1 R_2}\cos 2\pi \frac{f_m}{f_F}}$$

Motivation

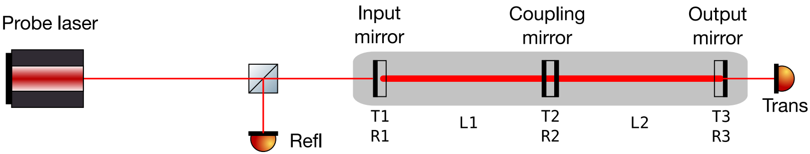

Introduced mechanical damping and shift of mechanical resonant frequency
in the resolved sideband regime in a single cavity
$\Gamma_{opt}/(2\pi)$, $\frac{FWHM}{f_m} = \frac{1}{2\pi}$
∂f_{opt}, $\frac{FWHM}{f_m} = \frac{1}{2\pi}$
$\Gamma_{opt}/(2\pi)$, $\frac{FWHM}{f_m} = \frac{1}{5\pi}$
∂f_{opt}, $\frac{FWHM}{f_m} = \frac{1}{5\pi}$
$\Gamma_{opt}/(2\pi)$, $\frac{FWHM}{f_m} = \frac{1}{10\pi}$
∂f_{opt}, $\frac{FWHM}{f_m} = \frac{1}{10\pi}$
Inserted mechanical loss $\Gamma_{opt}/2\pi$ and resonance shift ∂f_{opt}, a.u.
0.4
0.2
0.0
−0.2
−0.4
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
Detuning of the pump field in the units of mechanical resonant frequency, $\Delta\omega/\omega_m$

Motivation

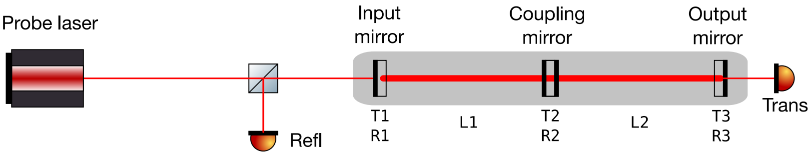


- Narrow cavity bandwidth in the resolved sideband limit suppresses not only the opposite sideband but the carrier itself too.
- If we could avoid this suppression, then the effects such as optomechanical cooling would be greatly enhanced.
- What if we had another optical resonance at the carrier frequency?

Coupled optical cavities



Coupled optical cavities



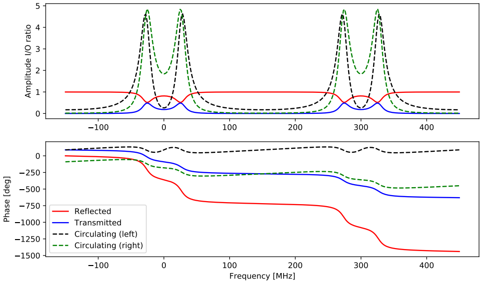
Resonance splitting

if $L_1 = L_2 = L_0$:

$$\Delta f = \frac{c}{2\pi L_0} \arctan \sqrt{\frac{4 r_1 r_3}{r_2^2 (r_1 + r_3)^2} - 1}$$

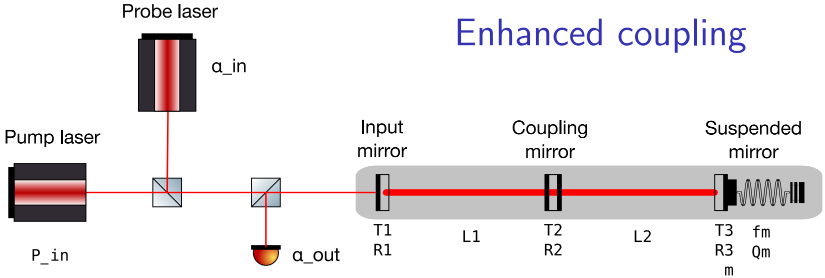
if $T_{1,2,3} << 1$:

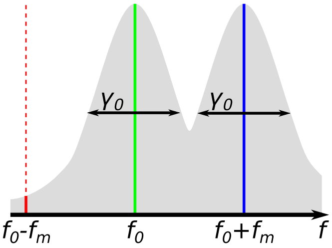
$$\Delta f \approx \frac{c\sqrt{T_2}}{2\pi L_0}$$



$L_1 = L_2 = 50$ cm, $T_1 = 0.5$, $T_2 = 0.3$, $T_3 = 0.1$

Enhanced coupling

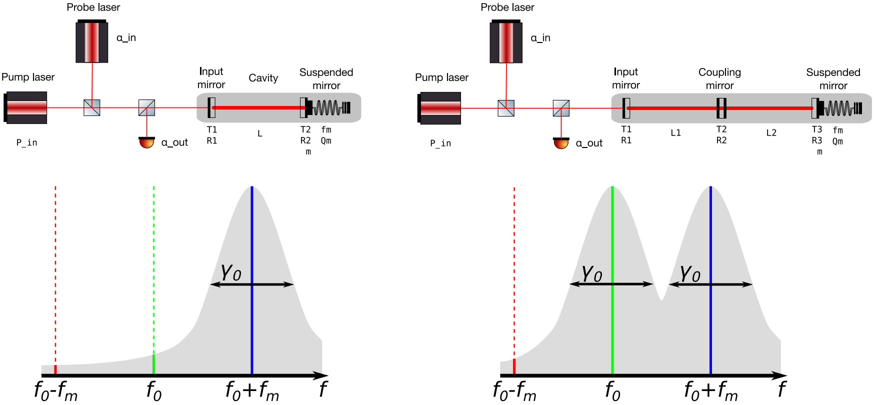




- Resonant frequency splitting can be tuned to the mechanical resonant frequency
- Optical pump and one of the sidebands are *both* resonantly enhanced
- Enhanced maximal insertion loss:

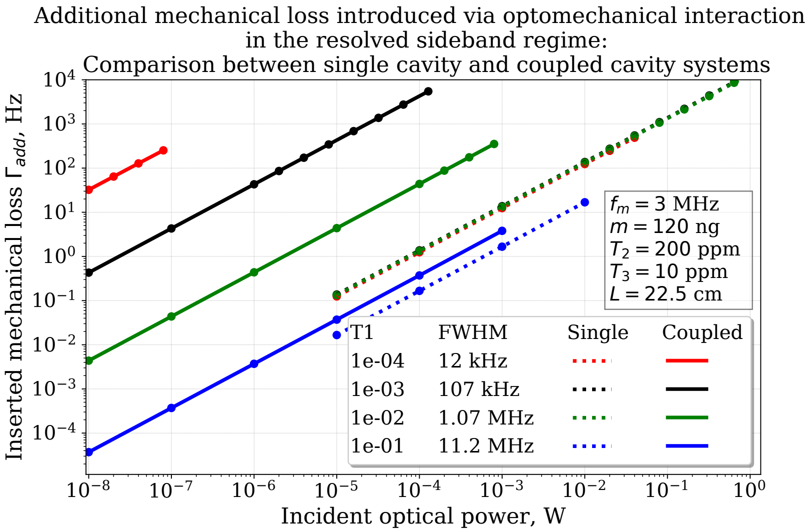
$$\Gamma_{opt}^{coupled} = \Gamma_{opt}^{single} \left(\frac{2f_m}{\gamma_0}\right)^2 .$$

Enhanced coupling

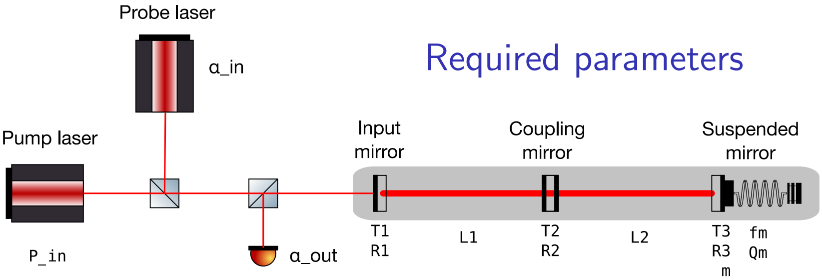


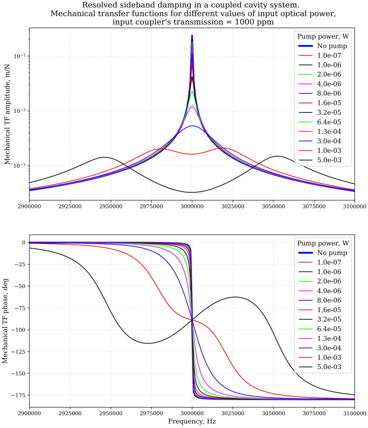
$$\Gamma_{opt}^{coupled} = \Gamma_{opt}^{single}\left(\frac{2f_m}{\gamma_0}\right)^2 .$$

Insertion mechanical loss



Required parameters





$$f_m = 3 \text{ MHz}$$

$$m = 120 \text{ ng}$$

$$P_{in} = 500 \ \mu\text{W}$$

$$w_0 = 8 \ \mu\text{m}$$

$$T_1 = 1000 \text{ ppm}$$

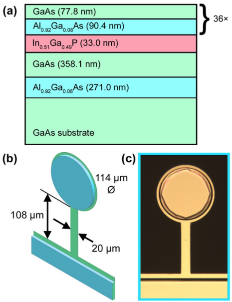
$$T_2 = 200 \text{ ppm}$$

$$T_3 = 10 \text{ ppm}$$

$$L_1 = L_2 = 22.5 \text{ cm}$$

Mirror design

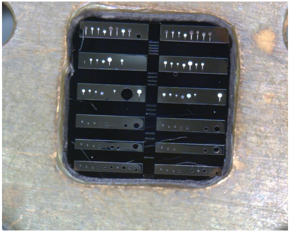
I. GaAs/AlGaAs stack mirrors on GaAs cantilevers

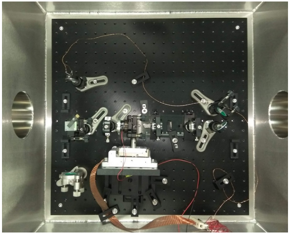


Robinjeet Singh et al. (2016). "Stable optical trap from a single optical field utilizing birefringence". In: *Physical review letters* 117.21, p. 213604

- f_m below 1 kHz
- $Q_m \sim 10^4$ at 300 K

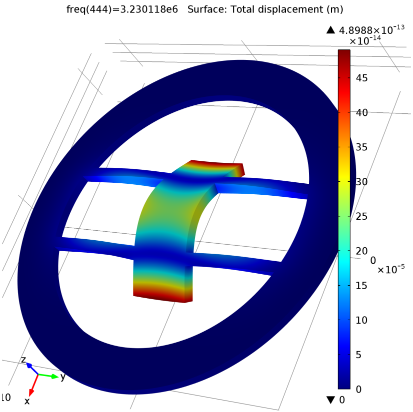
We borrowed one chip from LSU (thanks Thomas)

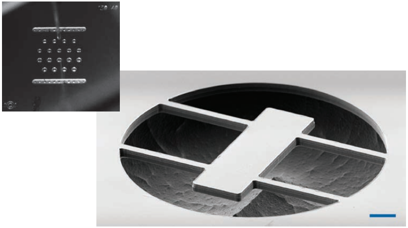




Mirror design

II. GaAs/AlGaAs free-free beams





Garrett D. Cole et al. (2011). "Phonon-tunnelling dissipation in mechanical resonators". In: *Nature Communications* 2.1, p. 231

- free-free resonator geometry
- $Q_m \approx 5 \times 10^3$ at 300 K
- $Q_m \approx 10^5$ at 4 K
- $f_m = 3$ MHz for $(6.67 \times 40 \times 100)\ \mu\text{m}^3$

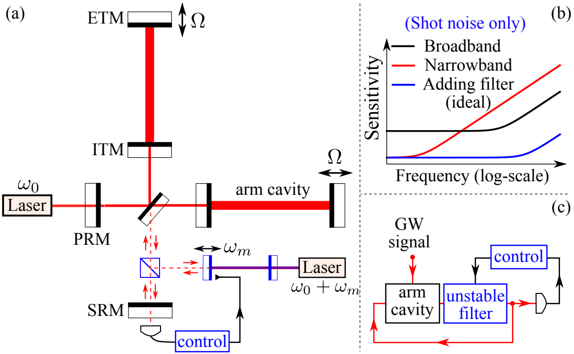
Current status

- Chip design being finalised
- Ongoing study on coupled cavity control (modelling+experiment)
- First aLIGO CDS standalone rack built in Birmingham
- Practising optomechanics with the existing chip
- Design of the experimental layout ongoing

Applications

- Resolved sideband cooling
- Unstable optomechanical filter
- Elimination of backaction
- Triple resonant transducer
- Optomechanically induced transparency
- Ponderomotive squeezing
- etc.

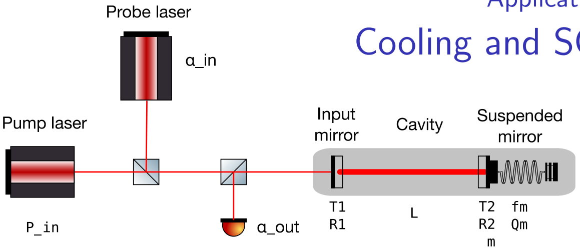
Optomechanical filter

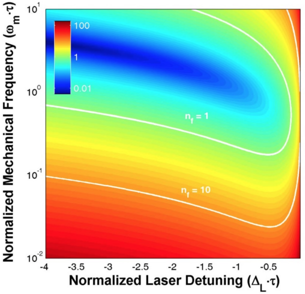


Haixing Miao et al. (2015). "Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters". In: *Physical review letters* 115.21, p. 211104

$$\hat{a}_{out} \approx e^{2i\Omega/\gamma_0}\,\hat{a}_{in}.$$

Cooling and SQL





Ignacio Wilson-Rae et al. (2007). "Theory of ground state cooling of a mechanical oscillator using dynamical backaction". In: *Physical Review Letters* 99.9, p. 093901

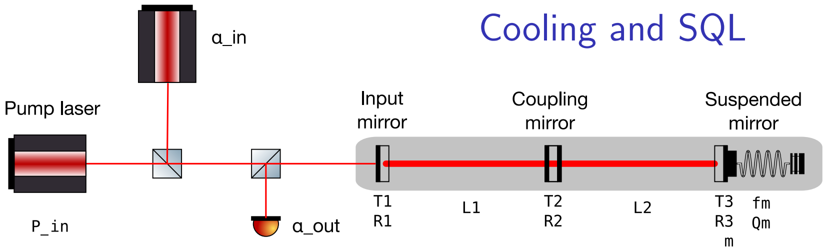
- if $\omega_m << \gamma$:

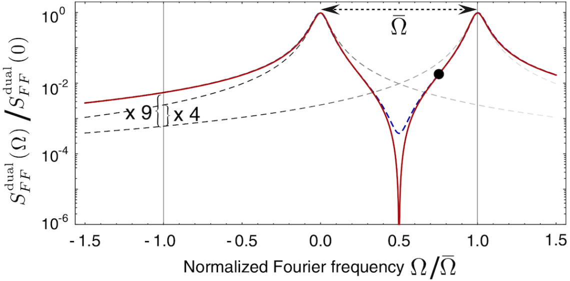
$$\langle n\rangle \approx \frac{\gamma}{4\omega_m} >> 1, \quad T \approx \frac{\hbar}{k_B}\gamma.$$

- if $\omega_m >> \gamma$:

$$\langle n\rangle \approx \frac{\gamma^2}{16\omega_m^2} << 1.$$

Cooling and SQL





- SQL increases by a factor of 9:

$$\langle n \rangle \approx 9 \frac{\gamma^2}{16\omega_m^2}.$$

- Quantum noise is "cancelled" at $\omega = \omega_m/2$.

Jens M Dobrindt and Tobias J Kippenberg (2010). "Theoretical analysis of mechanical displacement measurement using a multiple cavity mode transducer". In: *Physical review letters* 104.3, p. 033901

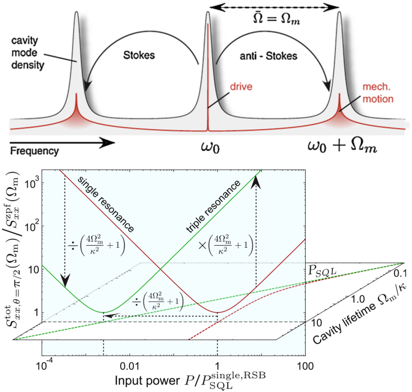
Three resonances

- Three equally spaced resonances
- Carrier and *both* sidebands are enhanced
- Perfect transducer, sensitivity is enhanced by

$$S_{xx}^{\text{triple}}(\omega_m)/S_{xx}^{\text{single}}(\omega_m) = \left(1 + \frac{4\omega_m^2}{\gamma_0^2}\right)^{-1}$$

- SQL is unchanged (as compared to the single resonance case) at obtained at lower power

$$P_{SQL}^{\text{triple}}/P_{SQL}^{\text{single}} = \frac{\gamma_0^2}{4\omega_m^2}$$



Jens M Dobrindt and Tobias J Kippenberg (2010). "Theoretical analysis of mechanical displacement measurement using a multiple cavity mode transducer". In: *Physical review letters* 104.3, p. 033901

Thank you for your attention!