Enhancing the optomechanical interaction with coupled cavities

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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:
  \[ \text{Cavity bandwidth } \gamma_0 \ll \text{mechanical resonant frequency } f_m. \]
- 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:

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

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

Introduced mechanical damping and shift of mechanical resonant frequency in the resolved sideband regime in a single cavity.

- $\Gamma_{opt}(2\pi)$, \[ \text{FWHM} = \frac{1}{2\pi} \]
- $\partial f_{opt}$, \[ \text{FWHM} = \frac{1}{2\pi} \]
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• 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

\[ \Delta f = \frac{c^2}{2\pi L_0} \arctan\sqrt{\frac{r_1r_2}{r_1r_3}} \left(\frac{r_1 + r_3}{2}\right)^2 - 1 \]

if \( T_1, T_2, T_3 << 1 \):

\[ \Delta f \approx \frac{c}{2\pi L_0} \sqrt{T_2^2} \]
Coupled optical cavities

Resonance splitting

if \( L_1 = L_2 = L_0 \):

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

if \( T_{1,2,3} \ll 1 \):

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

\( L_1 = L_2 = 50 \text{ cm}, \ T_1 = 0.5, \ T_2 = 0.3, \ T_3 = 0.1 \)
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:
  \[
  \Gamma_{\text{opt}}^{\text{coupled}} = \Gamma_{\text{opt}}^{\text{single}} \left( \frac{2f_m}{\gamma_0} \right)^2.
  \]
Enhanced coupling

\[ \Gamma_{\text{opt \ coupled}} = \Gamma_{\text{opt \ single}} \left( \frac{2f_m}{\gamma_0} \right)^2. \]
Insertion mechanical loss

Additional mechanical loss introduced via optomechanical interaction in the resolved sideband regime:

Comparison between single cavity and coupled cavity systems

- \( f_m = 3 \text{ MHz} \)
- \( m = 120 \text{ ng} \)
- \( T_2 = 200 \text{ ppm} \)
- \( T_3 = 10 \text{ ppm} \)
- \( L = 22.5 \text{ cm} \)

<table>
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<th>T1</th>
<th>FWHM</th>
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<th>Coupled</th>
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<td>1e-01</td>
<td>11.2 MHz</td>
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</table>
**Required parameters**

- $f_m = 3$ MHz
- $m = 120$ ng
- $P_{in} = 500$ $\mu$W
- $w_0 = 8$ $\mu$m
- $T_1 = 1000$ ppm
- $T_2 = 200$ ppm
- $T_3 = 10$ ppm
- $L_1 = L_2 = 22.5$ cm

Resolved sideband damping in a coupled cavity system.
Mechanical transfer functions for different values of input optical power, input coupler's transmission = 1000 ppm.
Mirror design

I. GaAs/AlGaAs stack mirrors on GaAs cantilevers

We borrowed one chip from LSU (thanks Thomas)

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
II. GaAs/AlGaAs free-free beams

- 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 \((6.67 \times 40 \times 100) \) \( \mu \)m\(^3\)

Garrett D. Cole et al. (2011). “Phonon-tunnelling dissipation in mechanical resonators”. In: Nature Communications 2.1, p. 231
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.
Haixing Miao et al. (2015). “Enhancing the bandwidth of gravitational-wave detectors with unstable optomechanical filters”. In: Physical review letters 115.21, p. 211104

\[ \hat{a}_{out} \approx e^{2i\Omega/\gamma_0} \hat{a}_{in}. \]
Applications

Cooling and SQL


- if $\omega_m \ll \gamma$:

  $\langle n \rangle \approx \frac{\gamma}{4\omega_m} \gg 1$, \hspace{1cm} T \approx \frac{\hbar}{k_B} \gamma.$

- if $\omega_m \gg \gamma$:

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

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
  \[ \omega = \omega_m/2 \]
Applications

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

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

Thank you for your attention!