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Influence of thermo-optic effect on the optomechanical coupling rate in acousto-optic cavities

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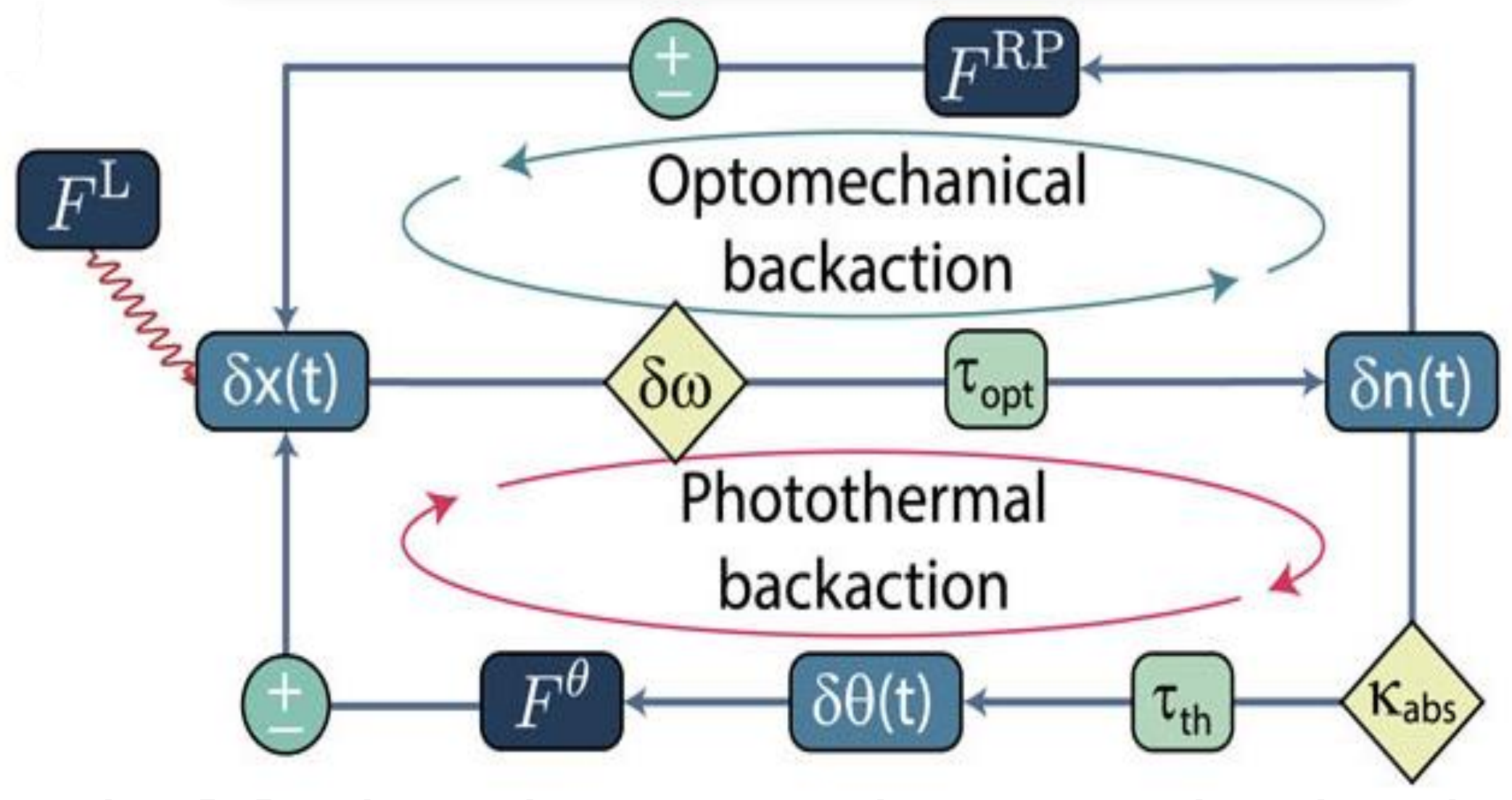
ABSTRACT

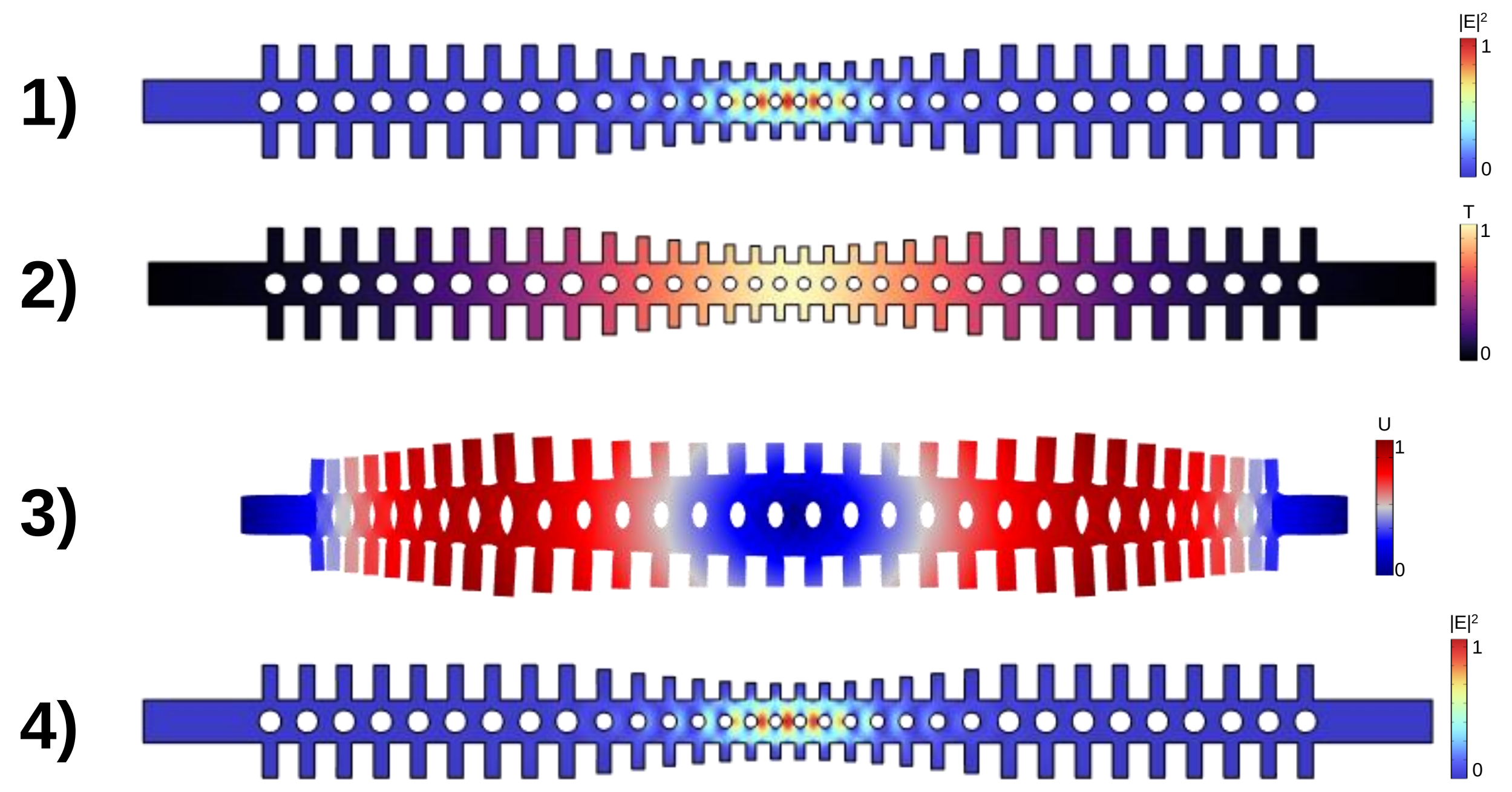
Optomechanical (OM) cavities are devices that enhance the interaction between photons and phonons through the radiation-pressure force [1]. To quantify that interaction, the OM coupling parameter g_0 is generally defined by the optical frequency shift due to mechanical oscillations. So far, only photoelastic and moving boundaries effects have been considered to contribute to the calculation of g_0 i.e., only mechanical-optical effects have been taken into account. In this work, thermal effects are considered to determine how they affect the canonical optomechanical coupling parameter.

PREVIOUS WORK



In this model [2], photothermal and optomechanical backaction were simultaneously introduced in the model, leading to dynamical equations mediated by thermal Langevin, radiation-pressure, and photothermal forces, but the thermal effect on the optomechanical coupling rate was not studied.

SIMULATIONS



1) Optical mode at 1550 nm.
2) Thermal distribution generated by optical mode heating.
3) Mechanical deformation due to 2.
4) Optical mode after thermo-optic effect

Calculation steps: $\boxed{\left(\frac{\partial\omega}{\partial T}\right)_\alpha : \mathbf{1)} \rightarrow \mathbf{2)} \rightarrow \mathbf{4)}}$; $\boxed{\frac{dT}{d\alpha} : \mathbf{1)} \rightarrow \mathbf{2)} \rightarrow \mathbf{3)}}$

THEORETICAL BACKGROUND

$$\omega = \omega(\alpha, T) \longrightarrow \frac{d\omega(\alpha,T)}{d\alpha} = \left(\frac{\partial\omega}{\partial\alpha}\right)_T + \left(\frac{\partial\omega}{\partial T}\right)_\alpha \frac{dT}{d\alpha}$$

$$G_{OM} = G_{PE} + G_{MB} + G_{TO}$$

- G_{TO} is added as a corrective term to the canonical optomechanical pull parameter.
- Thermo-optic $\left(\frac{\partial\omega}{\partial T}\right)_\alpha$ and thermal expansion $\frac{dT}{d\alpha}$ effects contribute to G_{TO}.

METHODS

Three different methods have been considered to calculate the thermo-optic contribution to the optomechanical coupling rate g_{TO}.

1 Empirical

$$\frac{dT}{d\alpha} = \frac{1}{\boxed{\alpha_L} L_{eff}} \qquad \alpha_L(T) = s + a\left(\frac{685}{T}\right)^2 \cdot \left(\frac{e^{\frac{685}{T}}}{\left(e^{\frac{685}{T}} - 1\right)^2}\right) + \frac{b\left(\frac{T}{395} - 1\right)^2}{1 + \frac{hT}{395}}$$

$$\left(\frac{\partial\omega}{\partial T}\right)_\alpha = -\frac{\omega}{n} k \qquad \boxed{\frac{g_{Emp}}{2\pi} = \frac{g_{PE}}{2\pi} + \frac{g_{MB}}{2\pi} - \frac{\omega}{2\pi n} k \frac{x_{ZPF}}{\alpha_L L_{eff}}}$$

2 Perturbation theory

$$\left(\frac{\partial\omega}{\partial T}\right)_\alpha = -\omega_c \frac{\int |\vec{e}|^2 n \frac{dn}{dT} \delta T dV}{\int |\vec{e}|^2 \varepsilon dV}$$

$$\boxed{\frac{g_{Pert}}{2\pi} = \frac{g_{PE}}{2\pi} + \frac{g_{MB}}{2\pi} - \frac{\omega_c}{2\pi} \frac{\int |\vec{e}|^2 n \frac{dn}{dT} \delta T dV}{\int |\vec{e}|^2 \varepsilon dV} \frac{x_{ZPF}}{\alpha_L L_{eff}}}$$

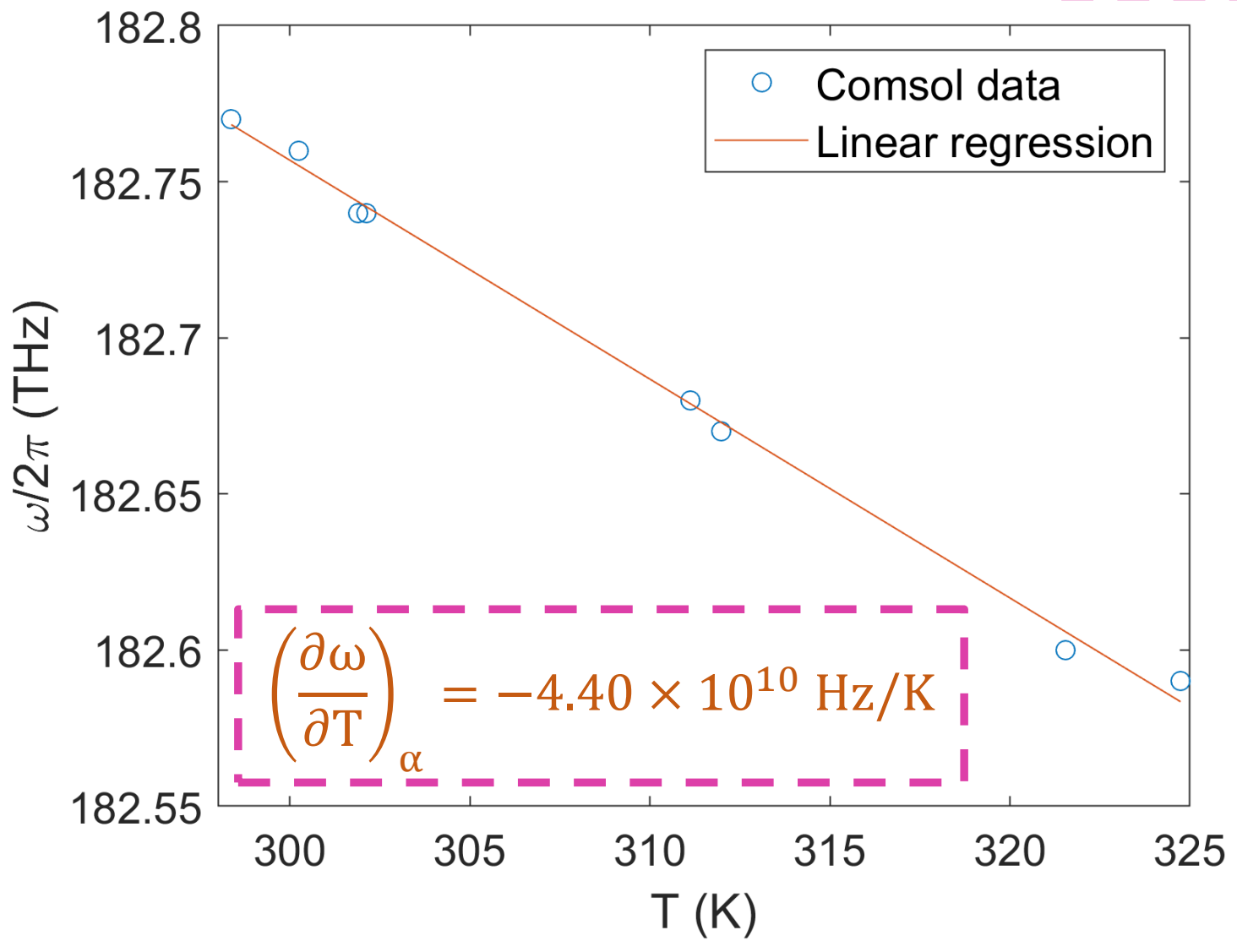
3 Numerical (Comsol)

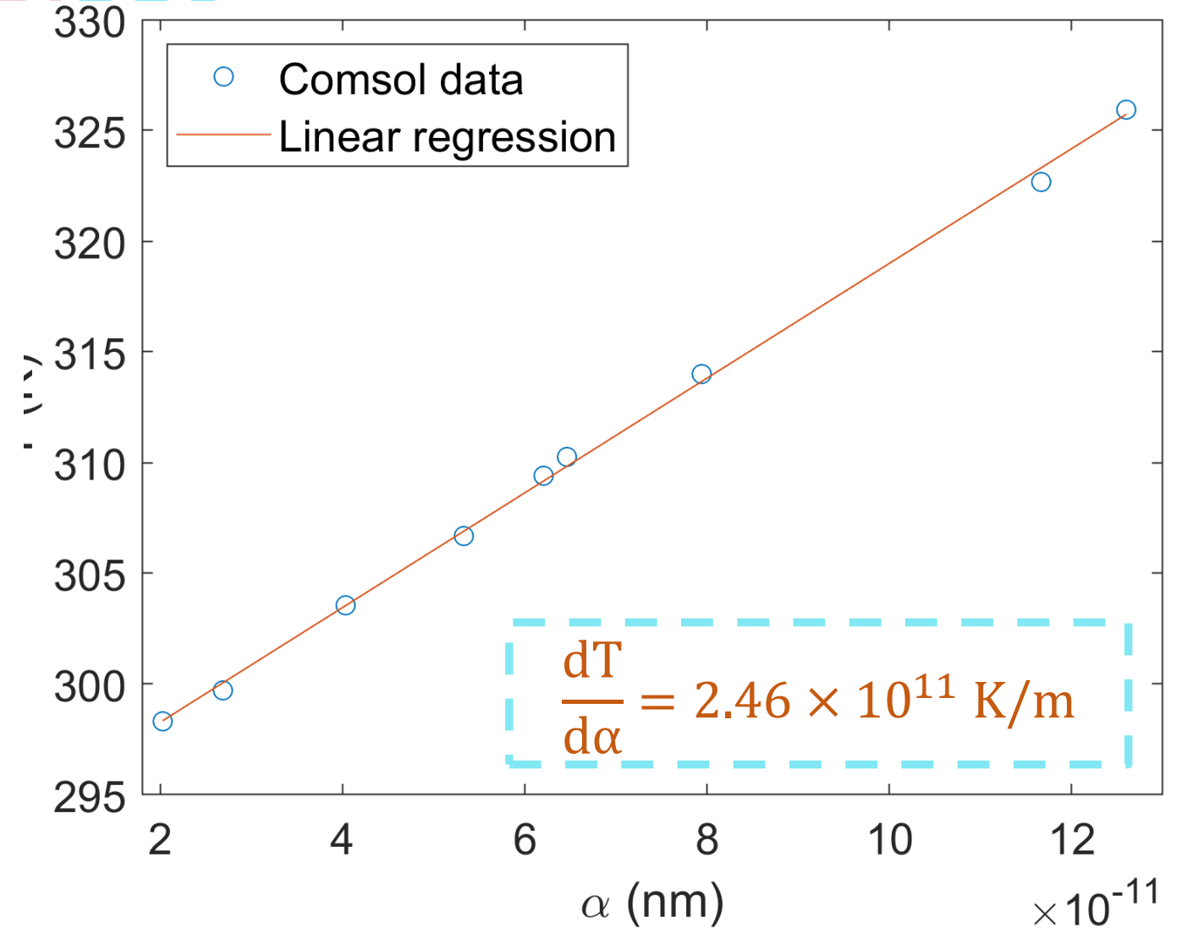
1. Simulate thermo-optic effect in the cavity for several temperatures to obtain $\left(\frac{\partial\omega}{\partial T}\right)_\alpha$.
2. Simulate photo-elastic effect in the cavity for several temperatures to obtain $\frac{dT}{d\alpha}$.
3. Graph ω-T and T-α curves using the simulated data and obtain their derivatives.

$$\boxed{\frac{g_{Num}}{2\pi} = \frac{g_{PE}}{2\pi} + \frac{g_{MB}}{2\pi} + \frac{x_{ZPF}}{2\pi} \left(\frac{\partial\omega}{\partial T}\right)_\alpha \frac{dT}{d\alpha}}$$

RESULTS

a) $$\boxed{\frac{g_{Num}^{TO}}{2\pi} = \frac{x_{zpf}}{2\pi} \left(\frac{\partial\omega}{\partial T}\right)_\alpha \frac{dT}{d\alpha} = -4634 \text{ kHz}}$$



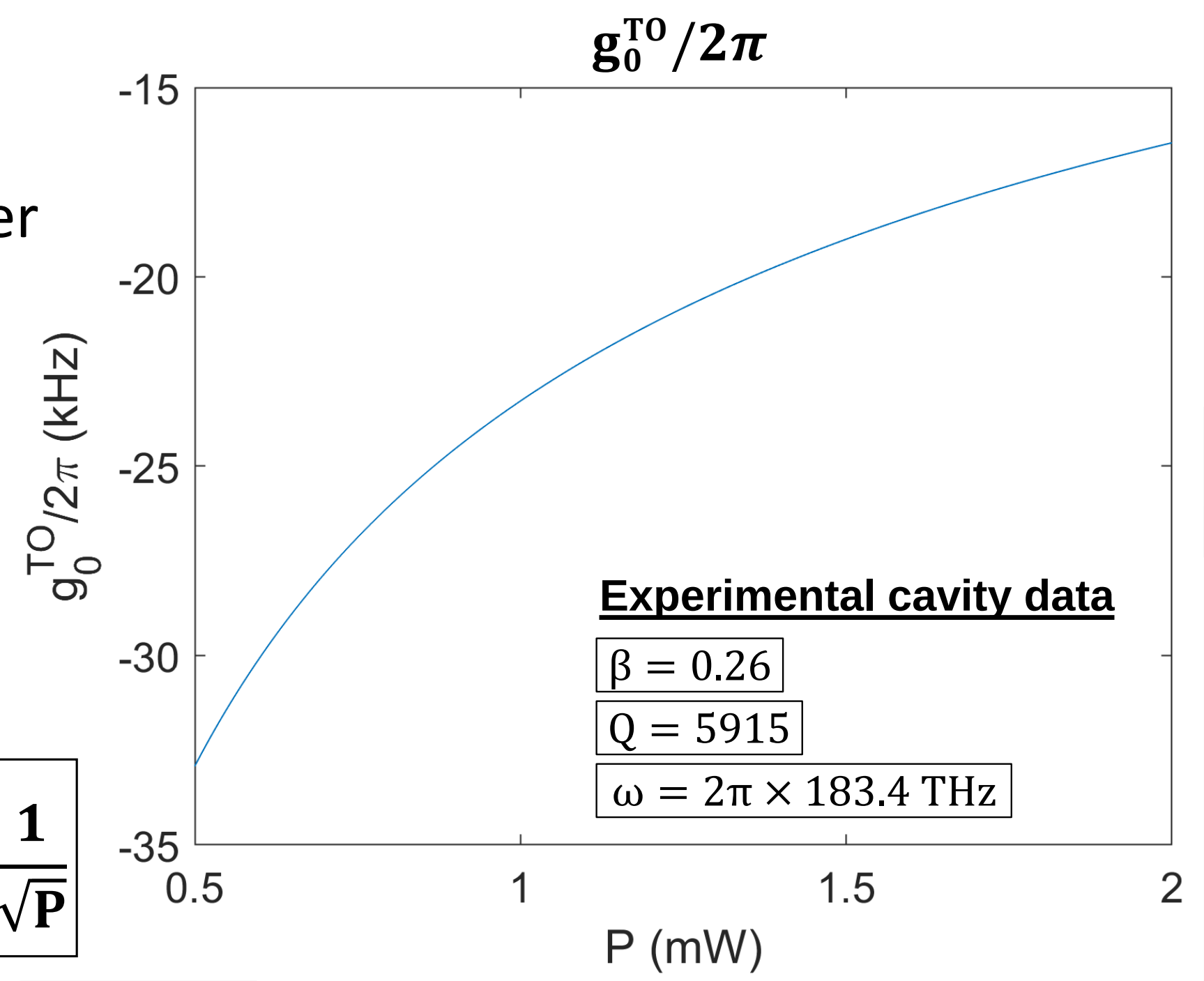


- In order to calculate g_0^{TO} we may consider the number of photons in the cavity $\bar{n}_{cav}$. → c) $\boxed{g = g_0 \sqrt{\bar{n}_{cav}}}$

b) $$\boxed{\bar{n}_{cav} = \frac{\kappa_{ex}}{\Delta^2 + (\kappa/2)^2} \frac{P}{\hbar\omega_L} = \frac{4\beta Q P}{\omega^2 \hbar}}$$

$\kappa_{ex} \rightarrow \boxed{\beta\kappa}$; $\Delta \rightarrow \boxed{0}$; $\kappa \rightarrow \boxed{\omega/Q}$; $\boxed{\omega \approx \omega_L}$

Substituting a) and b) in c) → $$\boxed{\frac{g_0^{TO}}{2\pi} = \frac{X_{zpf}}{2\pi} \left(\frac{\partial\omega}{\partial T}\right)_\alpha \frac{dT}{d\alpha} \omega \sqrt{\frac{\hbar}{4\beta Q}} \frac{1}{\sqrt{P}}}$$



CONCLUSIONS

Thermal effects play a significant role in the calculation of the optomechanical coupling rate. Although the thermal contribution is almost negligible for a silicon photonic crystal cavity ($\frac{g_0^{TO}}{2\pi} \approx -25$ kHz for $P = 1$ mW), it may become significant for some other optomechanical cavities or resonators at higher powers. This theoretical model is still under development, and experimental measurements will be conducted to validate the theoretical results.

REFERENCES & ACKNOLEDGEMENTS

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