Phonon Pumping by Modulating the Ultrastrong Vacuum

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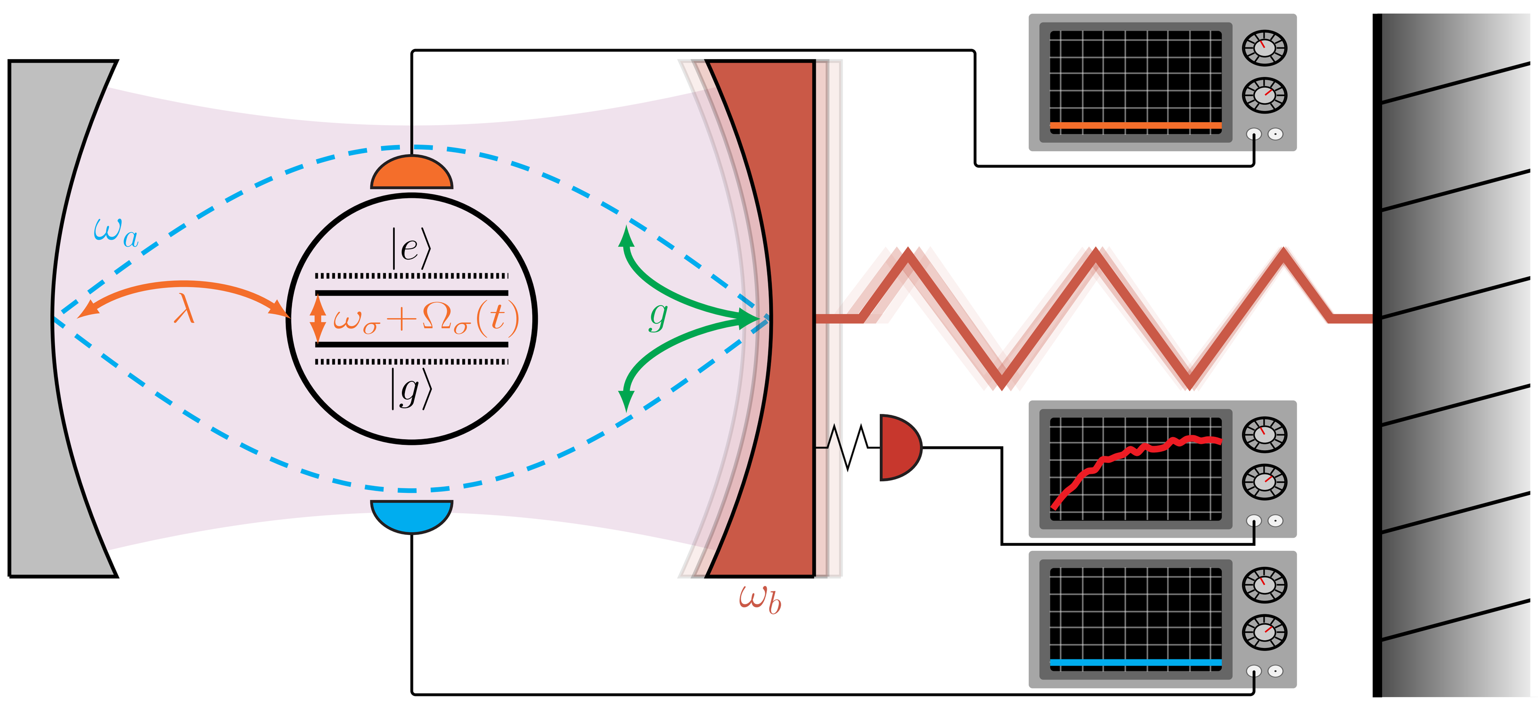
The System



A cavity is ultrastrongly coupled to a qubit. The cavity also interacts with a vibrating mirror. The frequency of the qubit is adiabatically modulated, and the USC virtual photon population oscillations cause the exchitation of the mirror.

The Model

$$\hat{H}(t) = \hat{H}_{\mathrm{R}} + \hat{H}_{\mathrm{opt}} + \hat{H}_{\mathrm{M}}(t)$$

$$\hat{H}_{\mathrm{R}} = \omega_a \hat{a}^\dagger \hat{a} + \omega_\sigma \hat{\sigma}_+ \hat{\sigma}_- + \lambda(\hat{a} + \hat{a}^\dagger)(\hat{\sigma}_- + \hat{\sigma}_+),$$

$$\hat{H}_{\mathrm{opt}} = \omega_b \hat{b}^\dagger \hat{b} + \frac{g}{2}(\hat{a} + \hat{a}^\dagger)^2(\hat{b}^\dagger + \hat{b})$$

$$\hat{H}_{\mathrm{M}}(t) = \frac{1}{2}\Delta_\omega \left[1 + \cos(\omega_d t)\right] \hat{\sigma}_+ \hat{\sigma}_- = \Omega_\sigma(t) \hat{\sigma}_+ \hat{\sigma}_-$$

The system evolves according to the Lindblad master equation

$$\dot{\hat{\rho}} = -i\left[\hat{H}(t), \hat{\rho}\right] + (1 + n_{\mathrm{th}})\gamma_b \mathcal{D}\left[\hat{b}\right]\hat{\rho} + n_{\mathrm{th}}\gamma_b \mathcal{D}\left[\hat{b}^\dagger\right]\hat{\rho} + \gamma_{\mathrm{D}} \mathcal{D}\left[\hat{b}^\dagger \hat{b}\right]\hat{\rho}$$

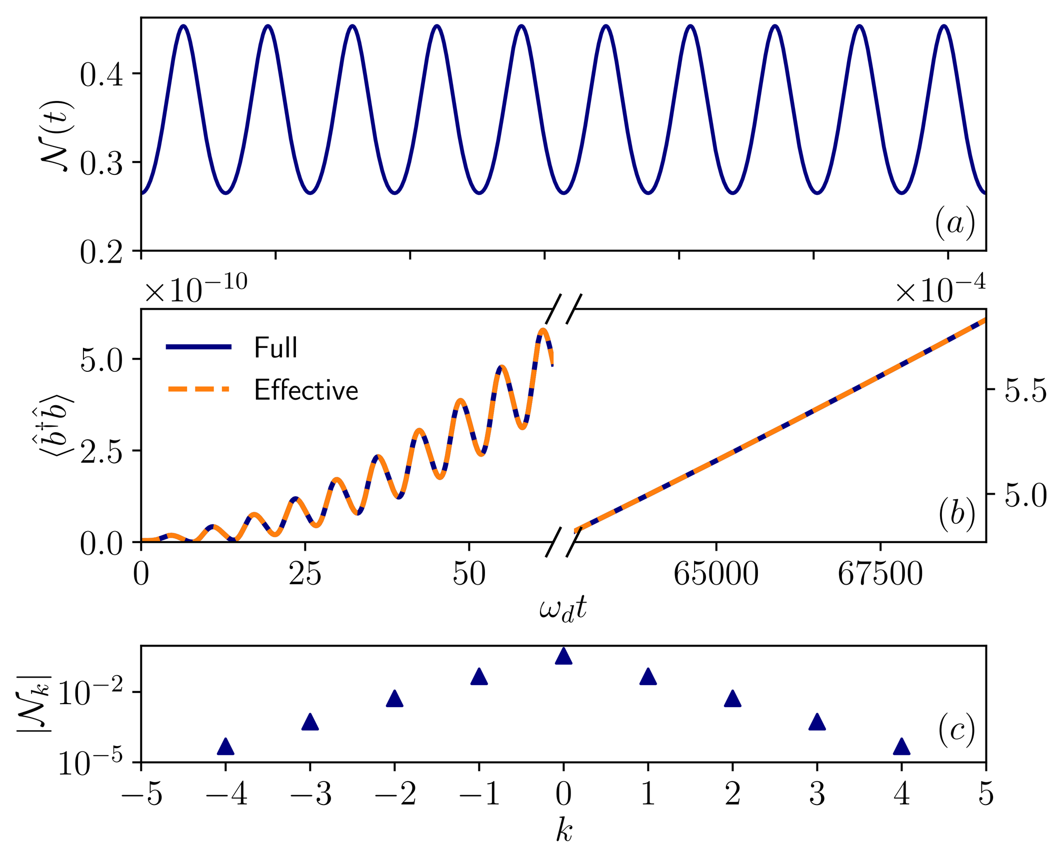
Dispersive Approximation

In the regime $g \ll \omega_d \simeq \omega_b \ll \omega_a \simeq \omega_\sigma$, the entanglement between the mechanical motion and the USC subsystem is negligible, and the state of the system can be factored as $|\Psi(t)\rangle \simeq |\psi(t)\rangle \otimes |\phi_b(t)\rangle$, where $|\psi(t)\rangle$ and $|\phi_b(t)\rangle$ are the USC and mirror states, respectively.

$$\hat{H}_b(t) = \langle \psi_0(t) | \hat{H}_{\mathrm{opt}} | \psi_0(t) \rangle = \omega_b \hat{b}^\dagger \hat{b} + \frac{g}{2}\mathcal{N}(t)\left(\hat{b} + \hat{b}^\dagger\right),$$

with $\mathcal{N}(t) = \langle \psi_0(t) | 2\hat{a}^\dagger \hat{a} + \hat{a}^2 + \hat{a}^{\dagger 2} | \psi_0(t) \rangle$

Results

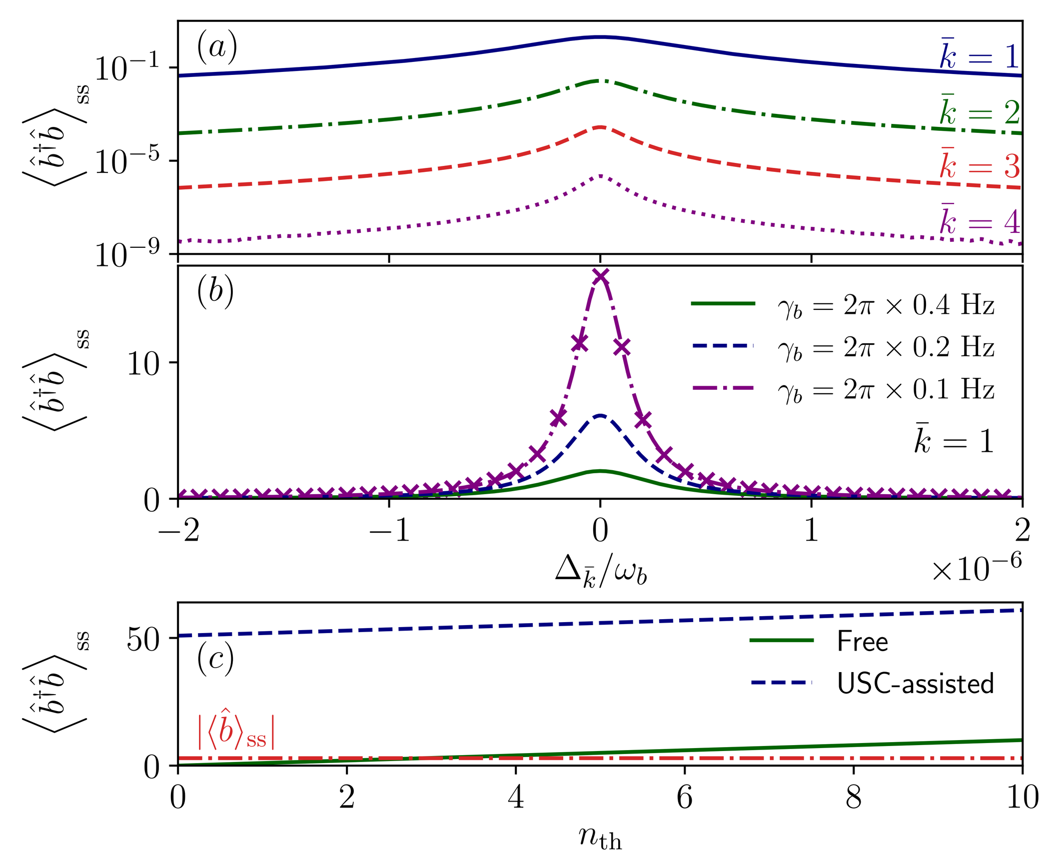


$$\mathcal{N}(t) = \sum_{k=-\infty}^{+\infty} \mathcal{N}_k e^{ik\omega_d t}$$

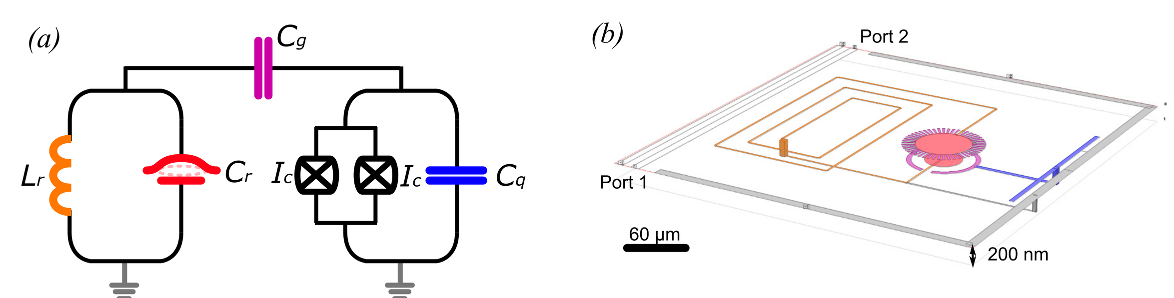
$$\langle \hat{b}^\dagger \hat{b} \rangle_{\mathrm{ss}} = \frac{\gamma + \gamma_{\mathrm{D}}}{\gamma} \left| \langle \hat{b} \rangle_{\mathrm{ss}} \right|^2 + n_{\mathrm{th}}$$

with

$$\langle \hat{b} \rangle_{\mathrm{ss}} = (g\mathcal{N}_{\bar{k}})/[2\Delta_{\bar{k}} + i(\gamma + \gamma_D)]$$



Experimental Proposal



(a) Lumped element circuit of a resonator containing a mechanical capacitor, capacitively coupled to a frequency tunable transmon qubit. (b) Design of a 60 μm mechanical drum with 200 nm vacuum gap to the bottom electrode.

References

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[2] Aspelmeyer, Markus, et al., Rev. Mod. Phys. 86.4 (2014): 1391-1452.

[3] Minganti, Fabrizio, et al., SciPost Phys. 17.1 (2024): 027.

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