Pulsed CV Transducer Based on The Geometric Phase Effect

Andrey Rakhubovsky, Nikita Vostrosablin and Radim Filip

Department of Optics, Palacký University, 17. Listopadu 12, 771 46 Olomouc, Czech Republic

andrey.rakhubovsky@gmail.com

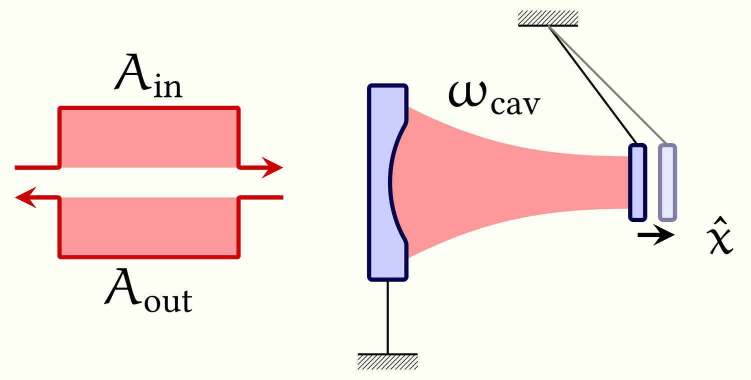
Palacký University Olomouc

Abstract

We propose a transducer that uses a sequence of pulsed quantum nondemolition (QND) interactions of the two modes of radiation with a mechanical oscillator to effectively induce a QND coupling between the modes. The properly engineered sequence of interactions drives the mechanical oscillator around a closed path in a phase space and thereby allows to trace the mechanical mode out of the interaction of the radiation modes, leaving the latter coupled. Importantly, the coupling can be achieved regardless of the temperature of the noisy mechanical mode.

Pulsed QND Optomechanics

Cavity Optomechanics [1] studies coupling of light (microwaves) to a movable mirror via radiation pressure.

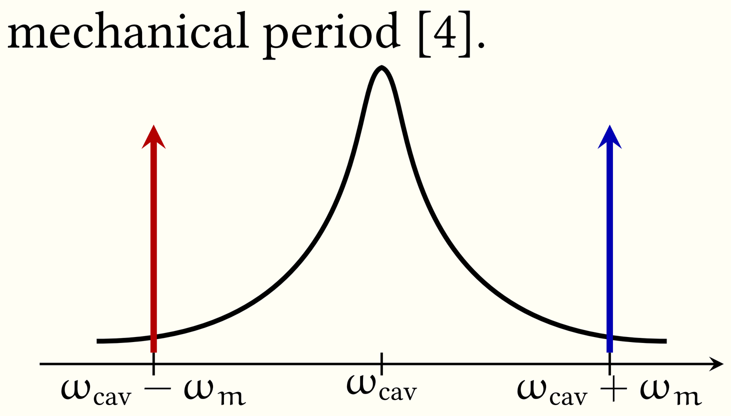


Hamiltonian is position dependent

$$\hat H = \hbar\omega_{cav}(\hat x)\hat a^\dagger \hat a \approx \hbar\left[\omega_{cav} + \hat x\frac{\partial \omega_{cav}}{\partial x}\right]\hat a^\dagger \hat a$$

$$\xrightarrow{\text{Linearization}} \hat H_{int} = -\hbar g_0\sqrt{\langle n_{cav}\rangle}\hat X\hat x$$

To achieve a pure non-demolition (QND) coupling, we assume modulation of pump at the mechanical frequency ω_m [2, 3] or using pulses much shorter than the mechanical period [4].



The resulting coupling is (for long pulses)

$$H_{int} = \hbar(g_1 qY + g_2 pX).$$

where $\hat x / x_{zpf} = q\cos\omega_m t + p\sin\omega_m t$.

$$\dot q = -\frac{\gamma}{2}q + \sqrt{\gamma}q_{th} + g_2 X;$$

$$\dot p = -\frac{\gamma}{2}p + \sqrt{\gamma}p_{th} - g_1 Y;$$

$$\dot X = -\kappa X + \sqrt{2\kappa}X^{in} + g_1 q;$$

$$\dot Y = -\kappa Y + \sqrt{2\kappa}Y^{in} - g_2 p;$$

Or (for short pulses):

$$H_{int} = \hbar g x (X\cos\theta + Y\sin\theta).$$

Quantum states of propagating light are defined in pulses [4, 5].

$$A^{in} = \frac{1}{\sqrt{\tau}}\int_0^\tau ds\, a^{in}(s); \quad A^{out} = \frac{1}{\sqrt{\tau}}\int_0^\tau ds\, a^{out}(s).$$

References

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[2] V. B. Braginsky, Y. I. Vorontsov, and K. S. Thorne, Science **209**, 547 (1980).

[3] A. A. Clerk, F. Marquardt, and K. Jacobs, New Journal of Physics **10**, 095010 (2008).

[4] M. R. Vanner, I. Pikovski, G. D. Cole, M. S. Kim, Č. Brukner, K. Hammerer, G. J. Milburn, and M. Aspelmeyer, Proceedings of the National Academy of Sciences **108**, 16182 (2011).

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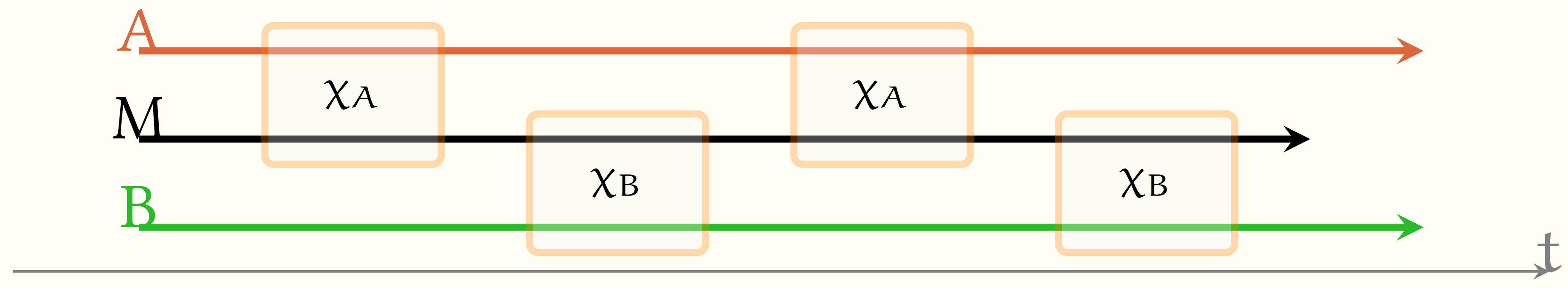
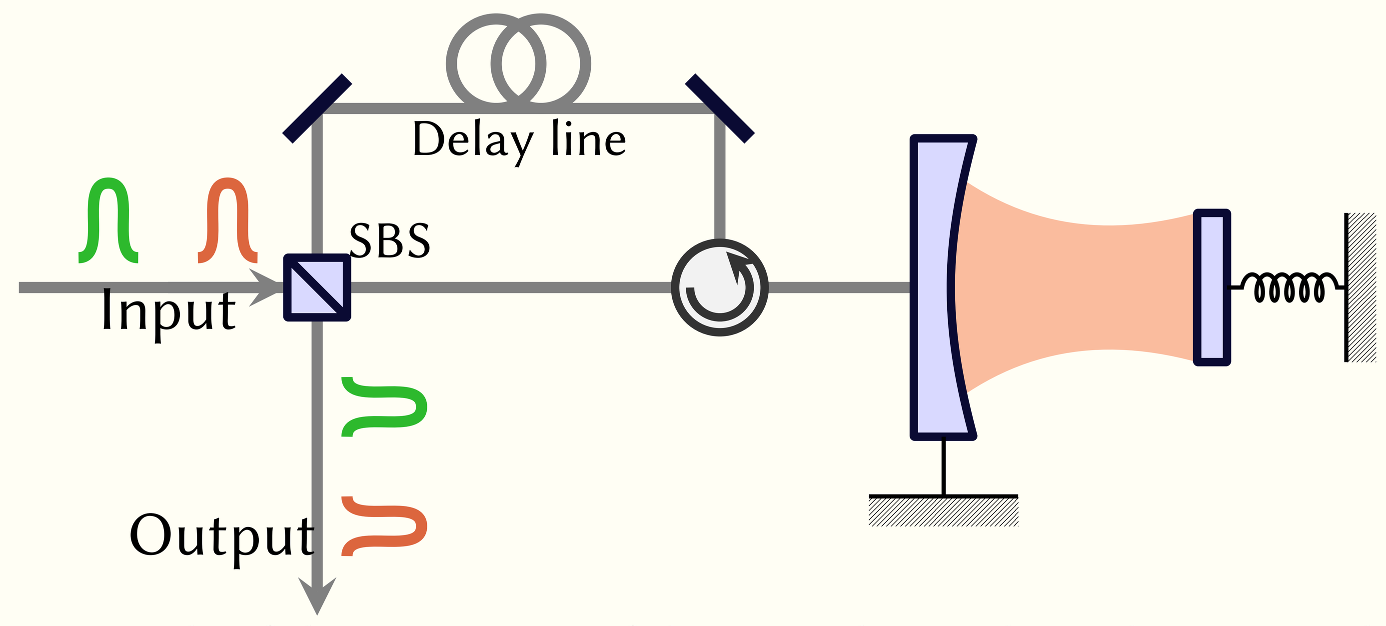
Basic Principles Of Operation

The transducer connects two radiation modes A and B which may be both optical as well as optical and microwave fields. The first pulse A (red) is sent to the cavity to interact with mechanical mode M. After the interaction is complete the pulse is sent to the delay line and the second pulse B (green) interacts with M within the cavity. The interactions of the two pulses are then repeated one more time and both pulses are released to the outputs. The pulses do not overlap during the protocol.

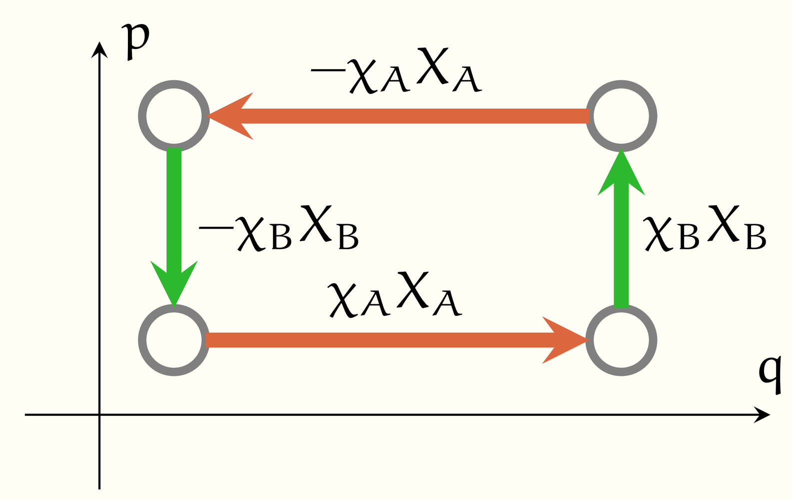
Block-Scheme Of Interactions



Principal Scheme



Mechanical Phase Space

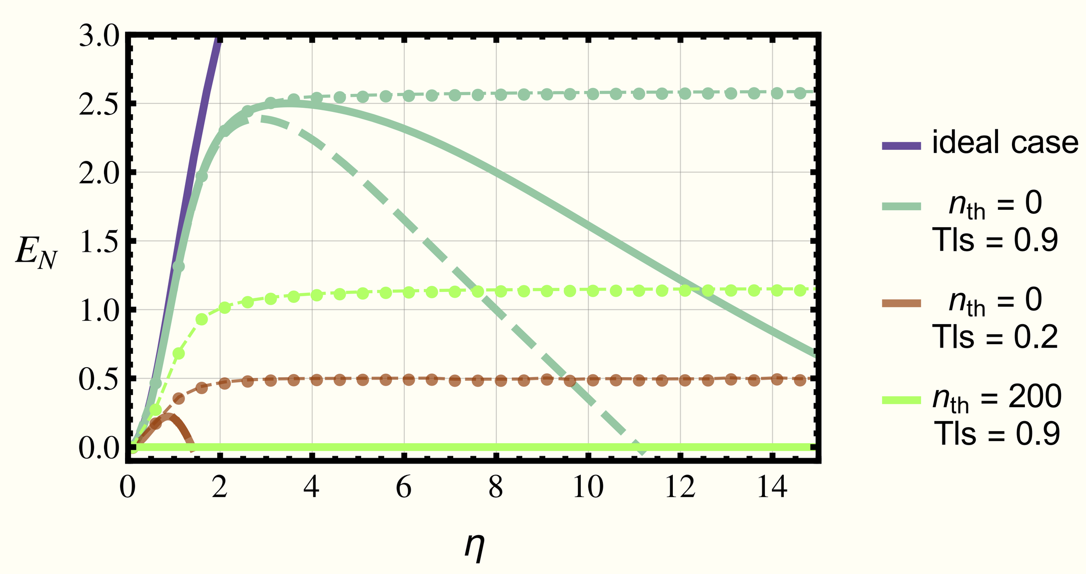


As a result of the operation of the transducer, the radiation modes appear to be coupled via QND interaction $H_{QND} \propto \eta^2 Y_A X_B$, with the gain $\eta^2 = \chi_A\chi_B$.

Performance and Robustness

The transducer helps to establish a QND gate between the two modes. To evaluate the efficiency, we estimate the Gaussian entanglement between them.

Entanglement Of Long Pulses

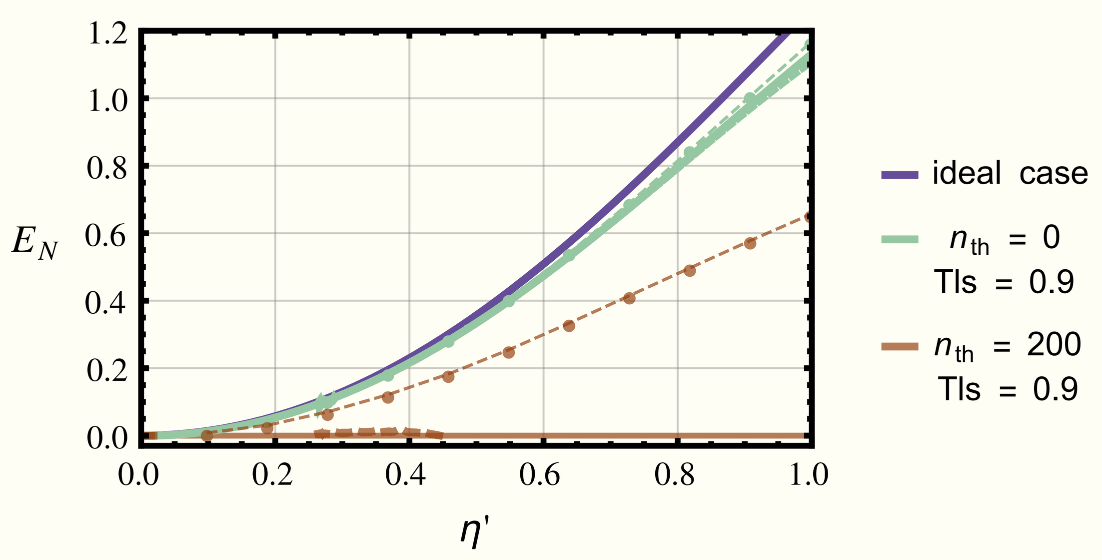


The desired ideal performance is degraded in a real setup by optical losses (losses in the delay line, modes mismatch, imperfect coupling etc.) and thermal losses from the mechanical environment.

Partially the degradation comes from the deviation from the closed path in the mechanical phase space. Proper adjustment of the interaction gains allows to partially compensate the imbalance.

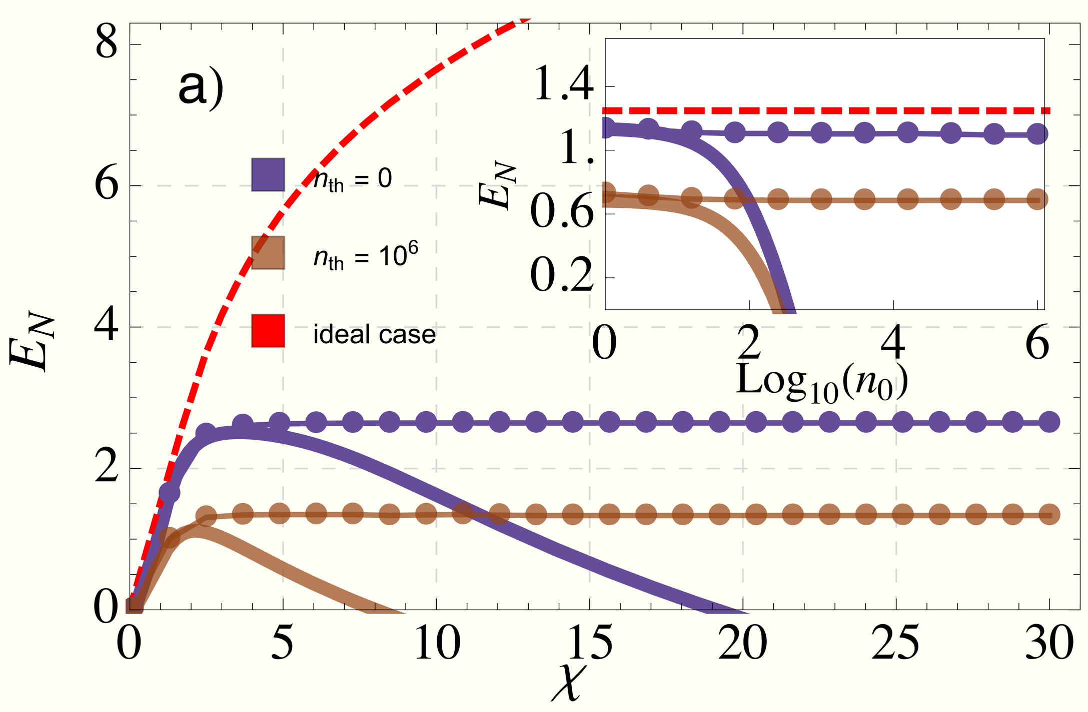
Optoelectromechanical Transducer

The system operating with long pulses is capable of entangling an optical pulse with a microwave one at reasonably high occupations of mechanical mode, provided the gains of individual interactions are properly optimized.

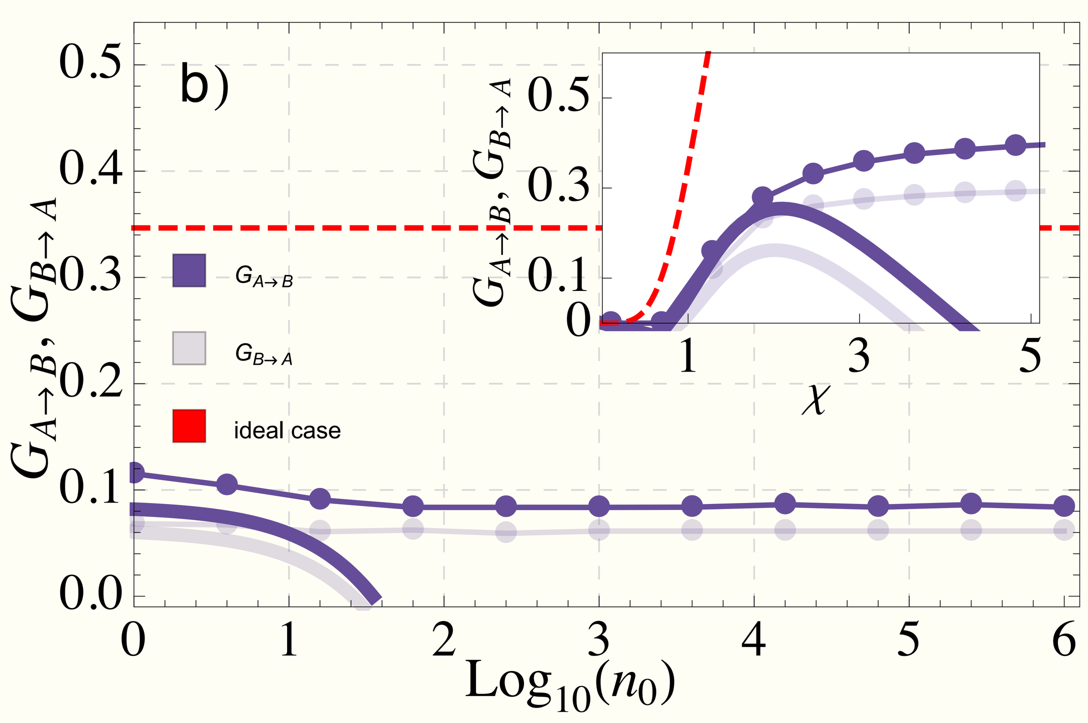


Entanglement And Steering With Short Pulses

The optomechanical system operating with pulses much shorter than the period of the mechanical oscillations is capable of entangling two distinct optical modes interacting with a shared mediator.



The optimization of the individual gains helps to achieve entanglement and quantum steering almost regardless of the initial occupation of the mechanical mode.



Conclusion

The transducer based on the geometric phase effect can operate within as well as beyond the resolved sideband regime. It is robust to the losses of radiation and noises of the mechanical system. It is capable of inducing QND gate between the modes of radiation and entangling the latter.