

Correlated noise can be beneficial to quantum transducers

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Quantum systems are inherently susceptible to noise—a notorious factor that induces decoherence and limits the performance of quantum applications. To mitigate its detrimental effects, various techniques have been developed, including cryogenic cooling, bath engineering, and quantum error correction. In this Letter, we demonstrate that by exploiting noise correlations in coupled quantum systems, the overall impact of noise can be significantly suppressed. Specifically, in a piezo-optomechanical-based microwave-optical quantum transducer, correlations between the noise affecting the acoustic and electrical modes can lead to substantial noise reduction, thereby enhancing the performance of quantum transduction. This reduction is primarily governed by the phase of the piezomechanical coupling and is also influenced by system parameters such as the coupling ratio and mode cooperativity. Since these parameters simultaneously affect the signal transmissivity, they must be optimized to achieve the transducer's optimal performance. Our work provides a systematic framework for this optimization, offering a guidance for practical designs.

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Introduction. Cooling a quantum system—such as a hybrid quantum transducer with coupled bosonic modes [1–8]—close to its ground state is crucial for its applications in the quantum regime. At finite temperature, the bosonic modes may exhibit high thermal occupation, which would induce detrimental decoherence to the system, thereby hindering the execution of any quantum tasks. Cryogenic condition is typically achieved using dilute refrigerators capable of reaching temperatures of several millikelvin (or even microkelvin), albeit with limited cooling power [9]. However, to have a better power-handling capability, these refrigerators generally operate more efficiently at slightly higher temperatures [10]. In addition, to maintain a strong bosonic mode coupling strength or to have an effective quantum operation, the slightly hot environment is sometimes unavoidable since controlled laser pumps have to be used that cause laser heating [11–13]. This indicates that the bosonic modes would have to frequently operate in a non-negligible thermal environment in practical situations.

Thus, it is often necessary for the system to maintain low thermal excitation of its modes while residing in a higher-temperature environment. Radiative cooling is one technique to achieve this, and has been discussed in various contexts, including the setting of a superconducting resonator [14], cavity piezomechanics [11,15], and spin ensembles [16,17]. Radiative cooling is based on a very simple idea—by coupling

the system to an extra cold reservoir, the thermal occupation of specific modes can be radiatively cooled near their ground state, even when its surrounding remains relatively hot [14]. In this Letter, we propose a scheme that goes beyond conventional radiative cooling by further suppressing thermal noise through the exploitation of noise correlation for different modes. Specifically, in quantum transducers, cross-correlations between different modes can naturally emerge due to their interaction with a common phononic bath, which is inevitably influenced by pump-induced heating of the device substrate. Noise correlation has been used to enhance quantum applications, such as force sensing, which rely on additional entanglement, squeezing, or feedforward correction schemes [18–21]. To the best of our knowledge, we propose a protocol, for the first time of its kind, that by tuning the bosonic mode coupling phase, the noise correlation can contribute to the reduction of overall thermal noise in the quantum transducer, thereby enhancing the signal conversion capability. It is worth mentioning that these correlations need not be quantum in nature; they can be classical, yet still provide a mechanism for coherent noise cancellation when coupling phases are properly tuned. Moreover, by avoiding feedforward control, our approach offers a structurally simpler and potentially more scalable solution for quantum transduction.

Quantum transduction model. Quantum transducer aims to convert quantum information encoded in microwave (ω_c) and optical (ω_o) frequencies. Due to the large energy difference, the conversion is generally realized by nonlinear couplings between microwave and optical bosonic modes, e.g., the scattering pressure-induced optomechanical coupling [22]. With certain approximations, the coupling can be linearized to a beam-splitter or two-mode squeezing interaction, which further enables the state transduction in a coherent manner [5]. Without loss of generality, we take a piezo-optomechanical-system-based transducer for demonstration as shown in Fig.

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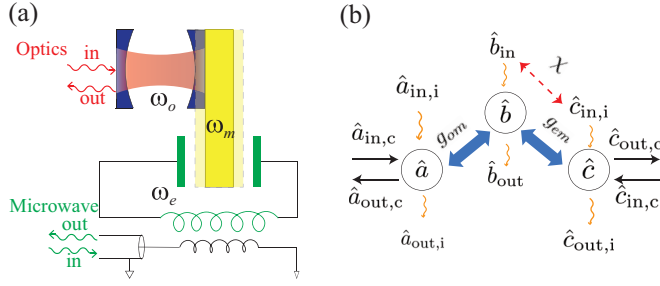


FIG. 1. (a) Schematic figure of a piezo-optomechanical system used for direct quantum transduction. (b) Illustration for the input-output relations with correlated intrinsic dissipation between the microwave and acoustic modes.

1(a), where the system's beam-splitter-type Hamiltonian can be written in the rotating frame as [11,23]

$$\frac{\hat{H}}{\hbar} = g_{om}(\hat{a}^\dagger \hat{b} + \hat{a} \hat{b}^\dagger) + (g_{em} \hat{b}^\dagger \hat{c} + g_{em}^* \hat{b} \hat{c}^\dagger). \quad (1)$$

We denote $\hat{a}$ and $\hat{c}$ as the bosonic operators for optical and electrical modes, respectively. $\hat{b}$ is an intermediate acoustic mode with frequency $\omega_m \sim \omega_e$. g_{om} ($|g_{em}|$) is the optomechanical (piezomechanical) coupling strength. We keep g_{em} as complex since the coupling phase would be important and the reason will become clear in the next section. The conversion between the optical and microwave photons can be understood as mode swaps enabled by the two beam-splitter interactions. In the experiment, the optical (electrical) mode is further coupled to an optical fiber (a microwave transmission line) that carries the input and output signals with coupling rates $\kappa_{o,c}$ and $\kappa_{e,c}$, respectively. In practice, all modes also intrinsically couple to their bath with the corresponding rates given by $\kappa_{o,i}$, $\kappa_{e,i}$, and κ_m .

To quantify the optical-microwave transduction, we first write down the Heisenberg-Langevin equations for each mode and the corresponding input-output formula as

$$\dot{\mathbf{a}} = \mathbf{A}\mathbf{a} + \mathbf{B}\mathbf{a}_{in}, \quad \mathbf{a}_{out} = \mathbf{B}^T \mathbf{a} - \mathbf{a}_{in}, \quad (2)$$

where we label the vectors $\mathbf{a} = \{\hat{a}, \hat{c}, \hat{b}\}^T$, $\mathbf{a}_{in} = \{\hat{a}_{in,c}, \hat{a}_{in,i}, \hat{c}_{in,c}, \hat{c}_{in,i}, \hat{b}_{in}\}^T$, and $\mathbf{a}_{out} = \{\hat{a}_{out,c}, \hat{a}_{out,i}, \hat{c}_{out,c}, \hat{c}_{out,i}, \hat{b}_{out}\}^T$. The lower indexes “in/out” are used to indicate the input and output traveling modes, while “c/i” represents the coupling and intrinsic loss ports. The matrices

$$\mathbf{A} = \begin{pmatrix} -\frac{\kappa_o}{2} & 0 & -ig_{om} \\ 0 & -\frac{\kappa_e}{2} & -ig_{em}^* \\ -ig_{om} & -ig_{em} & -\frac{\kappa_m}{2} \end{pmatrix} \quad (3)$$

and

$$\mathbf{B} = \begin{pmatrix} \sqrt{\kappa_{o,c}} & \sqrt{\kappa_{o,i}} & 0 & 0 & 0 \\ 0 & 0 & \sqrt{\kappa_{e,c}} & \sqrt{\kappa_{e,i}} & 0 \\ 0 & 0 & 0 & 0 & \sqrt{\kappa_m} \end{pmatrix}. \quad (4)$$

Equation (2) is usually solved in the frequency domain, where one can obtain the connection between the input and output modes as the scattering relation,

$$\mathbf{a}_{out}[\omega] = \mathbf{S}[\omega] \cdot \mathbf{a}_{in}[\omega], \quad (5)$$

where $\mathbf{S}[\omega] = \mathbf{B}^T(-i\omega\mathbf{I}_3 - \mathbf{A})^{-1}\mathbf{B} - \mathbf{I}_3$ is the scattering matrix. Based on the matrix, we can identify the quantum transduction channel in both directions; e.g., in the narrow bandwidth limit ($\omega = 0$), the microwave-to-optical conversion channel can be written as

$$\hat{a}_{out,c} = \sqrt{\eta}\hat{c}_{in,c} + \sqrt{1-\eta}\hat{e}. \quad (6)$$

It is a beam-splitter interaction mixing the microwave signal and noisy inputs. η is the transmissivity, which can be expressed as $\eta = 4C_{om}C_{em}\zeta_o\zeta_e/(1+C_{om}+C_{em})^2$, where $\zeta_o = \kappa_{o,c}/\kappa_o$ and $\zeta_e = \kappa_{e,c}/\kappa_e$ are the extraction ratios, and $C_{om} = 4g_{om}^2/\kappa_o\kappa_m$ and $C_{em} = 4|g_{em}|^2/\kappa_e\kappa_m$ are the system cooperativities. $\hat{e}$ collects the noisy influences from all other input modes,

$$\hat{e} = \frac{1}{\sqrt{1-\eta}}(S_{11}\hat{a}_{in,c} + S_{12}\hat{a}_{in,i} + S_{14}\hat{c}_{in,i} + S_{15}\hat{b}_{in}), \quad (7)$$

where S_{ij} are the corresponding scattering matrix elements. Obviously, the microwave-optical conversion defines a bosonic thermal loss channel with transmissivity η and thermal noise $n_e = \langle \hat{e}^\dagger \hat{e} \rangle$. We denote it as $\mathcal{N}(\eta, n_e)$. It is known that this channel is a Gaussian channel, which maps an input Gaussian state with covariance matrix $\mathbf{V}$ into $\mathbf{T}\mathbf{V}\mathbf{T}^T + \mathbf{N}$, where $\mathbf{T} = \sqrt{\eta}\mathbf{I}_2$ and $\mathbf{N} = (1-\eta)(2n_e+1)\mathbf{I}_2$ [24].

A quantum channel is capable of transmitting quantum information, and the transmission rate is quantified by quantum capacity. For many quantum channels, including the thermal loss channel, determining the exact quantum capacity is hard. As a result, lower bounds—being more tractable—are often used to analyze and understand channel properties. As mentioned, the quantum transducer is modeled as a bosonic thermal loss channel $\mathcal{N}(\eta, n_e)$, and a commonly used lower bound on the quantum capacity of such a channel is given by [24]

$$Q_{LB}^{\mathcal{N}} = \max \left\{ 0, \log_2 \frac{\eta}{1-\eta} - g(n_e) \right\}, \quad (8)$$

where $g(x) \equiv (x+1)\log_2(x+1) - x\log_2 x$ and it is a monotonically increasing function. This bound is tight for so-called pure loss channel ($n_e = 0$). For a pure loss channel, it is easy to get that $\eta = 1/2$ is the threshold to have a positive channel capacity. For a general thermal loss channel, it is necessary to have $\eta > 1/2$ in order to get a positive quantum capacity. The negative sign in front of $g(n_e)$ highlights the detrimental effect of thermal noise: as n_e increases, the channel's quantum capacity decreases. Therefore, identifying effective strategies for suppressing thermal noise is of critical importance.

Independent noise model. Typically, the noise terms originate from different physical processes and are thus independent. For the piezo-optomechanical transducer, all modes are intrinsically coupled to their thermal environment. Assuming the temperature is T , the average noise can be estimated by $n_{th}^{o,m,e} \equiv (e^{\hbar\omega_{o,m,e}/k_B T} - 1)^{-1}$. The optical mode is well known for its insensitivity to the environment since it has a relatively large mode frequency (several hundreds of THz) and $n_{th}^o = \langle \hat{a}_{in}^\dagger \hat{a}_{in} \rangle$ is very small even at room temperature. For temperature in the range of mK, the electrical and acoustic modes with much lower frequencies (generally $\omega_{e,m}$ are around several GHz) have a non-negligible thermal noise. If we safely ignore

the optical noise, the average input noise photon is written as

$$n_e = \langle \hat{e}^\dagger \hat{e} \rangle = \frac{1}{1 - \eta} (|S_{14}|^2 n_{th}^e + |S_{15}|^2 n_{th}^m), \quad (9)$$

where $|S_{14}|^2 = 4C_{em}C_{om}\zeta_o(1 - \zeta_e)/(1 + C_{om} + C_{em})^2$ and $|S_{15}|^2 = 4C_{om}\zeta_o/(1 + C_{om} + C_{em})^2$. $n_{th}^e = \langle \hat{c}_{in,i}^\dagger \hat{c}_{in,i} \rangle$ and $n_{th}^m = \langle \hat{b}_{in}^\dagger \hat{b}_{in} \rangle$ are the electrical and acoustic thermal noise, respectively. In experimental design [11,15], the acoustic and microwave modes are coupled to the same bath; thus, we denote $n_{th}^e = n_{th}^m \equiv n_{th}$, which simplifies the input noise expression as

$$n_e = \frac{1}{1 - \eta} (|S_{14}|^2 + |S_{15}|^2) n_{th}. \quad (10)$$

Correlated noise model. As mentioned earlier, the noise n_e in the transduction channel will degrade its performance. In this section, we show that this noise can be reduced if $\hat{b}_{in}$ and $\hat{c}_{in,i}$ are correlated. Importantly, we emphasize that this noise reduction is not limited to a specific platform—it exists in principle for any system with correlated noise inputs. Therefore, the protocol we propose below is broadly applicable and of potential interest across a wide range of quantum technologies. In this Letter, we take the practical setting of a piezo-optomechanical transducer, for example, where the electrical and acoustic modes are intrinsically coupled to the same bath, which is locally affected by the same laser heating as schematically shown in Fig. 1(b). Explicitly, we assume that their correlation formula can be written as

$$\langle \hat{c}_{in,i}^\dagger \hat{b}_{in} \rangle \equiv n_{th} \cdot \chi, \quad (11)$$

where χ is usually a complex number satisfying $0 \leq |\chi| \leq 1$, and it can be understood as a measure of the degree of correlations. Without losing any physical meaning, we take χ as a real positive number in the following discussions. As a result, the average input noise in Eq. (9) is modified as

$$n_e = \frac{1}{1 - \eta} (|S_{14}|^2 + |S_{15}|^2 + S_{14}^* S_{15} \chi + S_{15}^* S_{14} \chi) n_{th}. \quad (12)$$

We see that there are two extra terms added in the average noise, and their summation is obviously real. If it is negative in the meantime, the average noise n_e can be reduced. Interestingly, it is shown that the sign of the summation is controlled by the piezomechanical coupling phase. This can be understood intuitively—the correlated noise is injected into the acoustic and the electrical modes, so the phase of their coupling becomes important since it determines the way the correlated noise interacts in a coherent manner. Specifically, we write out the piezomechanical coupling as $g_{em} = |g_{em}|e^{i\theta}$, with θ the coupling phase. The scattering elements S_{14} and S_{15} take the form

$$S_{14} = \frac{-2e^{i\theta}\sqrt{C_{em}C_{om}(1 - \zeta_e)\zeta_o}}{1 + C_{om} + C_{em}}, \quad S_{15} = \frac{-2i\sqrt{C_{om}\zeta_o}}{1 + C_{om} + C_{em}}. \quad (13)$$

Thus, we have

$$S_{14}^* S_{15} + S_{15}^* S_{14} = \frac{8\sqrt{C_{em}(1 - \zeta_e)C_{om}\zeta_o}}{(1 + C_{om} + C_{em})^2} \sin \theta, \quad (14)$$

which is negative if the phase satisfies $\pi < \theta < 2\pi$, thus contributing to the noise suppression. It is worth mentioning

when $\theta \in (0, \pi)$, the average noise will increase due to the noise correlation. Specifically, when $\theta = 0$ or π , the noise correlation does not contribute to the overall noise, which is effectively the same as the independent noise model.

Numerical results. Assuming the transducer is in $T = 1$ K environment, the thermal noise $n_{th} \simeq 1.6$ for the modes with frequency $\omega_{m,e} = 10$ GHz. We first calculate the average noise in terms of the coupling phase. As shown in Fig. 2(a), for different degrees of noise correlation χ , the average noise $n_e(\theta)$ can almost be suppressed to below one half, which is critical for achieving single-photon-level quantum transduction. This technique has the potential to significantly reduce the reliance on cryogenic cooling, alleviating one of the major hardware constraints in quantum device operation.

Figures 2(b) and 2(c) depict the quantum capacity lower bound of the transduction channel according to Eq. (8). In Fig. 2(b), the contour lines on the upper-right corner show the parameter regime of positive capacity lower bound, where the system cooperativities C_{om} and C_{em} are scanned. The dashed black line encloses the upper-right corner where the system parameters fulfill $\eta > 1/2$ —a potential regime for $Q_{LB} > 0$ depending on the channel noise. We see that the orange area almost occupies all the enclosure for $\theta = 3\pi/2$, indicating a significant noise suppression. For slightly smaller coupling phase $\theta = 5\pi/4$, the orange area shrinks quickly since the average noise increases, matching the results in Fig. 2(a). In fact, if we keep decreasing the coupling phase, e.g., $\theta = \pi$, the yellow blob disappears totally in the same scanned parameter regime, indicating a zerotransduction capacity without the assistance from noise correlations.

Due to the noise correlation, the transduction capacity exhibits a nontrivial dependence on the electrical extraction ratio. On the one hand, the channel transmissivity η is proportional to ζ_e , which means a larger ζ_e generally benefits quantum transduction. However, according to Eq. (14), increasing ζ_e will lead to a smaller contribution from the correlated noise, thereby diminishing the potential gain in quantum capacity. This aligns with the intuition that a large ζ_e means less influence from the intrinsic noise $\hat{c}_{in,i}$, while this intrinsic noise is exactly what we need to cancel part of the noise from $\hat{b}_{in}$. In Fig. 2(d), we show this trade-off for varied system cooperativities. The blue, orange, and green curves represent the capacity lower bound as ζ_e is tuned. All of them rise in the beginning and quickly go down as we keep tuning up ζ_e , with a peak around $\zeta_e = 0.9$. In experiments, optimizing ζ_e is critical to achieving the best transduction performance.

Discussion. Correlated noise is present in many practical systems and has been investigated across a variety of platforms for different applications [18,21,25–29]. For instance, it has been widely recognized that quantum error correction schemes based on independent noise models are often insufficient in realistic scenarios, prompting the development of error correction techniques that explicitly incorporate correlated noise [27,28,30]. In Ref. [21], Y. Xia demonstrated noise reduction in a joint force sensing task involving two optomechanical systems. By injecting entangled laser beams, the shot noise between the two systems became correlated, leading to an overall suppression of measurement noise. More relevantly, Higginbotham *et al.* [18] studied electro-optic noise correlations in a hybrid transducer. The mechanical mode effectively

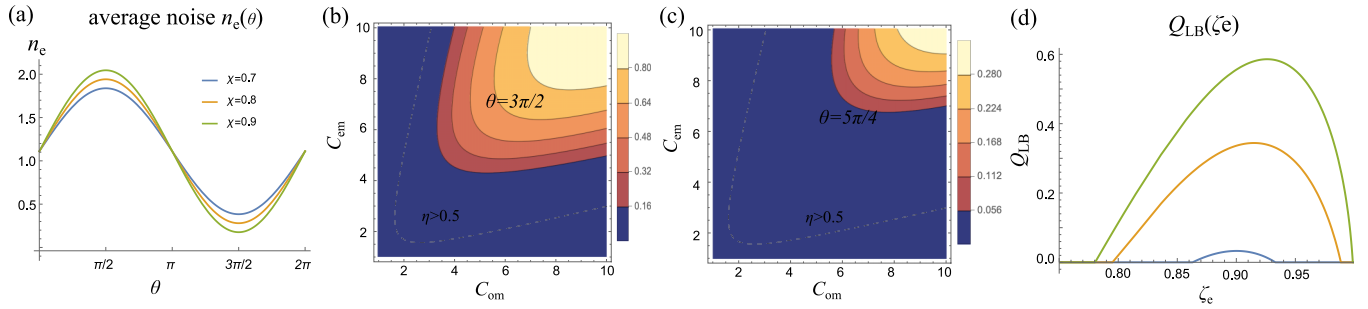


FIG. 2. (a) The average noise coupled to the transduction channel with respect to the piezomechanical coupling phase θ . The three curves correspond to varied degrees of noise correlations $\chi = \{0.7, 0.8, 0.9\}$. $C_{om} = C_{em} = 4$ and $\zeta_o = \zeta_e = 0, 9$ are used for all three curves. The contour plots in panels (b) and (c) show the channel's quantum capacity lower bound by scanning the system parameters C_{om} and C_{em} with $\theta = 5\pi/4$ and $\theta = 3\pi/2$, respectively. The degree of noise correlation $\chi = 0.9$ is used for both panels (b) and (d). The dashed lines delineate the regime where the channel's transmissivity $\eta > 0.5$ (the threshold). (d) The quantum capacity lower bound in terms of the electrical mode extraction ratio. The blue, orange, and green lines differ in the parameters $\{C_{om}, C_{em}\} = \{4, 4\}$, $\{5, 5\}$, and $\{6, 6\}$, respectively. For demonstration, the optical mode extraction ratio $\zeta_o = 0.9$ and the bath temperature $T = 1$ K are used for all plots.

served as a common thermal bath coupling both the electrical and optical modes. The resulting signal and idler outputs showed correlated noise, which the authors exploited using a feedforward cancellation scheme, significantly improving the signal-to-noise ratio.

In this work, we developed and demonstrated a strategy to enhance the performance of a quantum transducer by harnessing noise correlations and simple phase control. Properly tuning the mode coupling phase is able to suppress the overall noise to subphoton level, even the environment temperature is set to 1 K, effectively achieving system cooling. Compared to those previous works that rely on entanglement or active feedforward control [18,19,21], our protocol achieves noise suppression through passive noise correlation and phase control alone, providing a simpler and potentially more robust design.

When combined with other cooling methods, such as radiative cooling [13,14], this technique has the potential to achieve even greater noise suppression, thereby further improving quantum transduction performance. It is important to note, however, that noise correlations can also amplify the overall noise under certain conditions. Specifically, when the coupling phase $\theta \in (0, \pi)$ and the noise correlation coefficient χ remains positive, it would lead to increased overall noise.

In contrast, if $\chi < 0$, the noise can be suppressed within the same phase range. Therefore, in practical transducer design, the coupling phase should be carefully chosen based on the specific characteristics of the noise environment.

It is also worth noting that noise correlations may not remain stable over time due to fluctuations in the environment or system parameters. A key advantage of the proposed protocol is its robustness—even in the absence of beneficial noise correlations, it performs at least as well as conventional approaches that do not exploit correlation. This ensures that the protocol does not introduce additional vulnerability and remains effective across a range of practical conditions.

Beyond direct applications in quantum transduction, we believe that the exploration of noise correlations and the protocol proposed in this work could benefit a much broader range of quantum technologies. For example, it may prove useful in enhancing entanglement generation in parametrically coupled systems, where the noise is typically an issue of degrading the entanglement fidelity [31–33]. We leave further exploration of these possibilities to future work.

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Data availability. No data were created or analyzed in this study.

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