

Bipartite and tripartite output entanglement in three-mode optomechanical systems

Ying-Dan Wang,^{1,2} Stefano Chesi,³ and Aashish A. Clerk²

¹*State Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, China*

²*Department of Physics, McGill University, 3600 rue University, Montreal, Quebec, Canada H3A 2T8*

³*Beijing Computational Science Research Center, Beijing 100084, China*

(Received 5 July 2014; revised manuscript received 8 December 2014; published 5 January 2015)

We provide analytic insight into the generation of stationary itinerant photon entanglement in a three-mode optomechanical system. We identify the parameter regime of maximal entanglement and show that strong entanglement is possible even for weak many-photon optomechanical couplings. We also show that strong tripartite entanglement is generated between the photonic and phononic output fields; unlike the bipartite photon-photon entanglement, this tripartite entanglement diverges as one approaches the boundary of system stability.

DOI: [10.1103/PhysRevA.91.013807](https://doi.org/10.1103/PhysRevA.91.013807)

PACS number(s): 42.50.Wk, 07.10.Cm, 42.50.Ex

I. INTRODUCTION

Entanglement is one of the most fascinating and potentially useful aspects of quantum systems. Of particular interest is the generation of entangled itinerant quanta (which can be easily spatially separated) and of true multipartite entanglement (involving irreducible correlations between three or more subsystems). These goals have been the subject of considerable theoretical and experimental work in a variety of systems spanning quantum optics setups [1,2], cold atoms [3], superconducting circuits [4–6], and spin qubits [7]. Optomechanical systems [8], where mechanical motion interacts with electromagnetic fields, could be another powerful platform to realize these goals. A key advantage here is the potential to use mechanical motion to entangle disparate subsystems (e.g., microwave and optical photons). A number of schemes to generate entangled photons in optomechanics have been studied theoretically [9–15]. Recent experiments have also demonstrated mechanically mediated entanglement between two microwave pulses [16].

Here, we analyze theoretically both itinerant and multipartite entanglement in a three-mode optomechanical system in which two cavities are coupled to a single mode of a mechanical resonator. Such a setup has been realized in several recent experiments [17–19]. Previous theory work, largely numerical, examined bipartite output entanglement in this system [11,13–15] but mostly focused on transient [15] or experimentally -challenging strong-coupling regimes [13,14]. In contrast, we focus here on identifying the optimal conditions to generate stationary output entanglement with *weak* many-photon optomechanical couplings. We find that maximum entanglement is achieved through a simple matching condition of optomechanical cooperativities. Surprisingly, this operation point coincides with the least favorable regime for the generation of intracavity entanglement. We provide a complete yet simple analytic understanding of the physics, which also allows us to illustrate the trade-off between large entanglement and thermal resilience and to uncover a sensitive dependence of entanglement on the time delay between emitted wave packets.

We also address the generation of tripartite entanglement in such a hybrid three-mode system, considering correlations between both output photons and phonons. While usually ignored, the mechanical output field could be accessed experimentally, using, for example, optomechanical crystal

geometries with phonon waveguides [20] or by having the mechanical dissipation be dominated by a third auxiliary cavity used for cooling. We find that true hybrid tripartite entanglement is indeed created: the output state corresponds to a “twice-squeezed vacuum,” involving two two-mode squeezing operations. We also quantify this entanglement using the Gaussian Rényi-2 measure [21]. Besides being of fundamental interest, such tripartite entangled states have application to a variety of quantum information processing tasks such as teleportation, telecloning, and dense coding [22,23]. The present setup is especially suited to the continuous generation of nonlocal multipartite entanglement, as the phonons and photons from the two cavities are all emitted into spatially separated outputs. Note that Genes *et al.* [10] also studied tripartite entanglement in an optomechanical system, although in a setting where the entangled subsystems were not all spatially separated or itinerant.

It also worth noting that, while our emphasis here is on optomechanics, the physical features uncovered here apply generally to other bosonic three-mode systems (e.g., realized with superconducting circuits [24,25]).

Our paper is organized as follows: in Sec. II, we describe the physical system and its stability conditions. In Sec. III we obtain the optimal condition for bipartite output entanglement based on an analytical solution. In Sec. IV, we analyze in detail various imperfections such as thermal noise, non-rotating-wave-approximation corrections, internal losses, and finite bandwidth. In Sec. V, we describe how to achieve nonlocal tripartite output, which we quantify with the “residual Gaussian-Rényi-2” (GR2) entanglement measure. Section VI summarizes our results.

II. PHYSICAL SYSTEM

We consider a three-mode optomechanical system in which two cavities are coupled to a single mode of a mechanical resonator (see Fig. 1).

The standard optomechanical interacting Hamiltonian

$$\hat{H} = \omega_m \hat{b}^\dagger \hat{b} + \sum_{i=1,2} [\omega_i \hat{a}_i^\dagger \hat{a}_i + g_i (\hat{b}^\dagger + \hat{b}) \hat{a}_i^\dagger \hat{a}_i] \quad (1)$$

governs the system’s dynamics, where \hat{a}_i is the annihilation operator for cavity i (frequency ω_i), \hat{b} is the annihilation operator of the mechanical mode (frequency ω_m), and g_i is

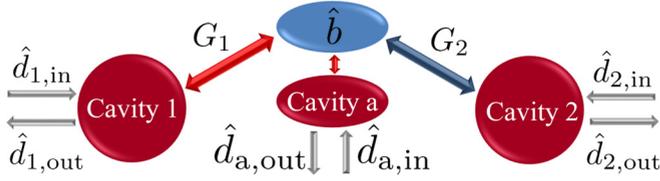


FIG. 1. (Color online) System schematics. Two driven cavities (cavities 1 and 2) interact with a common mechanical resonator (mode \hat{b}). This can generate entanglement in the optical outputs. An auxiliary third cavity (cavity a) can be used to cavity cool the mechanics and to make the mechanical output mode accessible.

the optomechanical coupling strengths. In order to generate steady-state entanglement, cavity 1 (2) is driven at the red (blue) sideband associated with the mechanical resonator: $\omega_{d1} = \omega_1 - \omega_m$ and $\omega_{d2} = \omega_2 + \omega_m$. By working in an interaction picture with respect to the free Hamiltonian and following the usual linearization procedure [8], we have $\hat{H}^R = \hat{H}_{\text{int}} + \hat{H}_{\text{CR}}(t)$, with

$$\hat{H}_{\text{int}} = (G_1 \hat{b}^\dagger \hat{d}_1 + G_2 \hat{b} \hat{d}_2) + \text{H.c.} = \tilde{G} (\hat{b}^\dagger \hat{\beta}_A + \text{H.c.}) \quad (2)$$

and $\hat{H}_{\text{CR}}(t) = \tilde{G} (\hat{b}^\dagger \hat{\beta}_A^\dagger e^{2i\omega_m t} + \text{H.c.})$. Here $\hat{d}_i = \hat{a}_i - \bar{a}_i$, with \bar{a}_i being the classical cavity amplitude. $G_i = g_i \bar{a}_i$ is the dressed coupling (we take $g_i, \bar{a}_i > 0$ without loss of generality), $\tilde{G} = \sqrt{G_1^2 - G_2^2}$, and $\hat{\beta}_A = \hat{d}_1 \cosh r + \hat{d}_2^\dagger \sinh r$ [$r = \tanh^{-1}(G_2/G_1)$] is a Bogoliubov mode.

We first focus on the resolved-sideband regime $\omega_m \gg \kappa_1, \kappa_2$ and make the rotating-wave approximation (RWA) by neglecting \hat{H}_{CR} . The non-RWA corrections are treated in Sec. IV C. The combined swapping and entangling interactions in \hat{H}_{int} lead to a net entangling interaction between the two

cavity modes; as discussed in [26], this interaction has a fundamentally dissipative nature. It is useful to diagonalize \hat{H}_{int} in terms of three normal modes [14,26]: one ‘‘mechanically dark’’ Bogoliubov mode $\hat{\beta}_B = \hat{d}_1^\dagger \sinh r + \hat{d}_2 \cosh r$ (which is robust to mechanical thermal noise) and two coupled eigenmodes involving both the mechanics and cavities.

The dissipation of each mode is treated via standard input-output theory [27] and is given explicitly by the following Langevin equations:

$$\begin{aligned} \frac{d}{dt} \hat{a} &= -\frac{\gamma}{2} \hat{a} - i(G_1 \hat{d}_1 + G_2 \hat{d}_2^\dagger) - \sqrt{\gamma} \hat{a}^{\text{in}}, \\ \frac{d}{dt} \hat{d}_1 &= -\frac{\kappa_1}{2} \hat{d}_1 - iG_1 \hat{a} - \sqrt{\kappa_1} \hat{d}_1^{\text{in}}, \\ \frac{d}{dt} \hat{d}_2^\dagger &= -\frac{\kappa_2}{2} \hat{d}_2^\dagger + iG_2 \hat{a} - \sqrt{\kappa_2} \hat{d}_2^{\text{in},\dagger}, \end{aligned} \quad (3)$$

where γ is the mechanical damping rate and $\kappa_{1,2}$ are the external damping rates of the two cavities. We will first neglect the effect of internal damping rates $\kappa'_{1,2}$, which are discussed in detail in Sec. IV. In Eq. (3), \hat{d}_j^{in} are the input operators ($\hat{d}_j^{\text{in}} = \hat{a}^{\text{in}}$), whose correlation functions are $\langle \hat{d}_j^{\text{in}}(t) \hat{d}_k^{\text{in},\dagger}(t') \rangle = N_j \delta(t - t') \delta_{i,j}$. Here N_j is the average thermal population of each mode, and in the following discussion, we assume that the cavity thermal populations are always zero (due to the high frequency) while keeping the mechanical thermal population N_m finite.

The frequency-resolved output modes $\hat{d}_i^{\text{out}}[\omega] \equiv \int d\omega' e^{i\omega t} \hat{d}_i^{\text{out}}(t)/\sqrt{2\pi}$ are related to the input by $\hat{d}_i^{\text{out}}[\omega] = \sum_{j=1}^3 S_{ij}[\omega] \hat{d}_j^{\text{in}}[\omega]$ ($j = 3$ denotes the mechanical fields). The scattering matrix $\mathbf{S}[\omega]$ is obtained straightforwardly from the input-output relations $\hat{d}_i^{\text{out}} = \sqrt{\kappa_i} \hat{d}_i + \hat{d}_i^{\text{in}}$ [27] and the system Langevin equations (with RWA) as follows:

$$\mathbf{S}[\omega] = \mathbf{1} + \frac{1}{C_1 \chi_1 \chi_m - C_2 \chi_2 \chi_m + 1} \begin{pmatrix} \chi_1 \left(\frac{C_2}{4} \chi_2 \chi_m - 1 \right) & \frac{\sqrt{C_1 C_2}}{4} \chi_1 \chi_2 \chi_m & \frac{iC_1}{2} \chi_1 \chi_m \\ -\frac{\sqrt{C_1 C_2}}{4} \chi_1 \chi_2 \chi_m & -\chi_2 \left(\frac{C_1}{4} \chi_1 \chi_m + 1 \right) & -\frac{iC_2}{2} \chi_2 \chi_m \\ \frac{iC_1}{2} \chi_1 \chi_m & \frac{iC_2}{2} \chi_2 \chi_m & -\chi_m \end{pmatrix}, \quad (4)$$

with $\chi_i = 2\kappa_i/(\kappa_i - 2i\omega)$ ($i \in \{1, 2, m\}$, $\kappa_m \equiv \gamma$). Notice that at $\omega = 0$ the matrix only depends on the cooperativities.

Given the blue-detuned laser drive, the first question involves the stability of our linearized system. The Routh-Hurwitz conditions [28] yield two requirements [14,26] to guarantee stability. The first is that $\gamma_{\text{tot}} > 0$, where $\gamma_{\text{tot}} = \gamma + 4G_1^2/\kappa_1 - 4G_2^2/\kappa_2$ is the effective damping rate of the mechanical resonator interacting with the two cavities. Focusing on the interesting and relevant regime of strong cooperativities $C_i \equiv 4G_i^2/(\gamma\kappa_i) \gg 1$ and $\kappa_i \gg \gamma$, the two requirements can be combined into

$$G_1^2/G_2^2 > \max(\kappa_2/\kappa_1, \kappa_1/\kappa_2). \quad (5)$$

III. BIPARTITE CAVITY OUTPUT ENTANGLEMENT

We start by discussing the entanglement of light leaving the two cavities. The canonical mode

operators

$$\hat{D}_i^{\text{out}}[\omega, \sigma, \tau_i] = \frac{1}{\sqrt{\sigma}} \int_{\omega-\frac{\sigma}{2}}^{\omega+\frac{\sigma}{2}} d\omega' e^{-i\omega'\tau_i} \hat{d}_i^{\text{out}}[\omega'] \quad (6)$$

describe output temporal modes in a bandwidth σ centered about the frequency ω . τ_i sets the absolute time at which the wave packet of interest is emitted from cavity i ; without loss of generality, we set $\tau_2 = 0$. The covariance matrix of the output operators can be computed via the scattering matrix. Then, the two-mode entanglement can be quantified using the logarithmic negativity $E_N^{\text{out}}[\omega, \sigma, \tau_1]$ [29,30].

For clarity, we restrict ourselves in this section to the zero-bandwidth case $\sigma \rightarrow 0$; the result is then independent of τ_1 ($\hat{D}_i^{\text{out}}[\omega] \equiv \hat{D}_i^{\text{out}}[\omega, 0, \tau_i] e^{i\omega\tau_i}$, $E_N^{\text{out}}[\omega] \equiv E_N^{\text{out}}[\omega, 0, \tau_1]$). We first discuss a simple analytical solution of the bipartite cavity output entanglement and then derive the optimal condition for output entanglement. In the following section, we will relax the assumption of zero bandwidth σ . We will also

discuss other possible imperfections and their influence on output entanglement: mechanical thermal noise, cavity internal losses, and non-RWA corrections.

A. Mapping to a two-mode squeezed thermal state

Using the standard approach (i.e., plugging the system covariance matrix into the definition of logarithmic negativity), the entanglement of the three-mode system can be easily computed numerically. However, we find that mapping the output state to a two-mode squeezed thermal state can yield a simple analytical expression which reveals a number of interesting properties of the output entanglement.

A two-mode squeezed thermal state can be written as

$$\hat{\rho}_{12} = \hat{S}_{12}(R_{12})[\hat{\rho}_1^{\text{th}}(\bar{n}_1) \otimes \hat{\rho}_2^{\text{th}}(\bar{n}_2)]\hat{S}_{12}^\dagger(R_{12}). \quad (7)$$

Here

$$\hat{S}_{12}(R_{12}) = \exp[R_{12}\hat{D}_1^{\text{out}}[0]\hat{D}_2^{\text{out}}[0] - \text{H.c.}] \quad (8)$$

is the two-mode squeeze operator, with R_{12} being the squeezing parameter, and $\hat{\rho}_j^{\text{th}}(\bar{n}_j)$ describes a single-mode thermal state with average population \bar{n}_j . The output state is thus completely characterized by just three parameters: \bar{n}_1 , \bar{n}_2 , and R_{12} , and the entanglement of this state (if $E_N^{\text{out}} \geq 0$) is simply given by

$$E_N^{\text{out}} = -\ln(n_R - \sqrt{n_R^2 - (1 + 2\bar{n}_1)(1 + 2\bar{n}_2)}), \quad (9)$$

with $n_R = (\bar{n}_1 + \bar{n}_2 + 1) \cosh 2R_{12}$. If any of the populations \bar{n}_i is zero (which is the relevant case as discussed below), we find that any finite squeezing $R_{12} > 0$ yields nonzero entanglement.

From the Langevin equation (3), it is easy to verify that $\langle \hat{D}_i^{\text{out}}[\omega] \rangle$ are all zero and only three correlators of the output cavity modes are nonzero: $\langle (\hat{D}_1^{\text{out}}[\omega])^\dagger \hat{D}_1^{\text{out}}[\omega] \rangle$, $\langle (\hat{D}_2^{\text{out}}[\omega])^\dagger \hat{D}_2^{\text{out}}[\omega] \rangle$, and $\langle \hat{D}_1^{\text{out}}[\omega] \hat{D}_2^{\text{out}}[\omega] \rangle$. Thus the covariance matrix of the system is the same as a two-mode squeezed thermal state. Since two Gaussian states with the same covariance matrix represent the same state, this output cavity state can be mapped to a two-mode squeezed thermal state whose nonzero correlation functions are simply

$$\begin{aligned} \langle (\hat{D}_i^{\text{out}}[\omega])^\dagger \hat{D}_i^{\text{out}}[\omega] \rangle &= \bar{n}_i + (\bar{n}_1 + \bar{n}_2 + 1) \sinh^2 |R_{12}[\omega]|, \\ \langle \hat{D}_1^{\text{out}}[\omega] \hat{D}_2^{\text{out}}[\omega] \rangle &= -\frac{e^{i\theta[\omega]}}{2} (\bar{n}_1 + \bar{n}_2 + 1) \\ &\quad \times \sinh 2|R_{12}[\omega]|, \end{aligned} \quad (10)$$

where $\bar{n}_i \equiv \bar{n}_i[\omega]$, $R_{12}[\omega]$ is complex, in general, and $\theta[\omega] \equiv \arg(R_{12}[\omega])$. Using the correlators with $\sigma = 0$ and $\omega = 0$ (i.e., output light near the cavity resonances), we find that R_{12} is real and the output state can be characterized by

$$\bar{n}_{1,2} = \frac{\pm 2N_m}{C_1 - C_2 + 1} + \frac{\sqrt{E^2 - D^2} \mp 4(C_2 + N_m)}{2(C_1 - C_2 + 1)^2} - \frac{1}{2}, \quad (11)$$

where the upper (lower) sign applies to n_1 (n_2), and

$$\tanh 2R_{12} = E/D, \quad (12)$$

where

$$\begin{aligned} D &= (C_1 + C_2)^2 + 2(C_1 + C_2)(1 + 2N_m) + 1 + 4C_1C_2, \\ E &= 4\sqrt{C_1C_2}(C_1 + C_2 + 1 + 2N_m). \end{aligned} \quad (13)$$

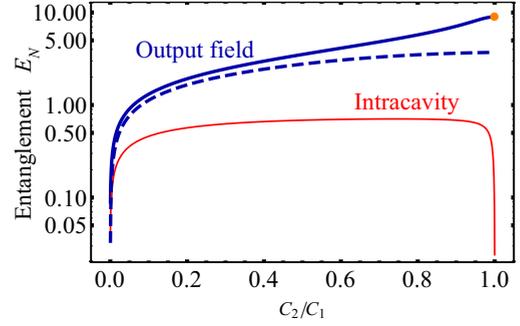


FIG. 2. (Color online) Entanglement of the two cavity output fields on resonance (i.e., $\omega = 0$; thick blue solid/dashed line) and corresponding intracavity entanglement (thin red solid line) as functions of C_2 , with $C_1 = 4000$ and $\omega_m \gg \kappa$ (allowing use of the RWA). The orange dot denotes the value of $\ln 2C_1$ as in Eq. (18) with $\kappa_1 \geq \kappa_2$. Except for the blue dashed line (mechanical bath occupancy $N_m = 100$), results are for zero temperature. The output E_N curves only depend on C_i . For the intracavity curve (thin red solid line), we have also assumed strong coupling, taking $G_1 : \kappa : \gamma = 100 : 10 : 1$.

Notice that such a mapping is unique; that is, no other choice of \bar{n}_1 , \bar{n}_2 , and R_{12} yields the same covariance matrix. From Eqs. (9), (11), and (12), we see that the output entanglement depends only on cavity cooperativities $C_i = 4G_i^2/(\gamma\kappa_i)$ and the mechanical bath temperature (we always assume zero thermal occupancy for the two cavities).

Plugging Eqs. (11)–(13) into Eq. (9), one can obtain the full expression of the output entanglement including thermal effects. By focusing first on zero temperature we obtain

$$\bar{n}_1 = 0, \quad \bar{n}_2 = 4C_2 \frac{\gamma^2}{\gamma_{\text{tot}}^2} = \frac{4C_2}{(1 + C_1 - C_2)^2}, \quad (14)$$

$$\tanh 2R_{12} = \frac{4\sqrt{C_1C_2}(C_2 + C_1 + 1)}{C_1^2 + C_2^2 + 6C_1C_2 + 2(C_1 + C_2) + 1}. \quad (15)$$

We stress that the effective thermal occupancies \bar{n}_j are not simply equal to bath temperatures; in particular, $\bar{n}_2 \neq 0$ even when all input noises are vacuum. The zero-temperature output entanglement is

$$E_N^{\text{out}}[0] = \ln \left(\frac{(1 + C_1 - C_2)^2}{A + B + 2C_2(1 + 2C_1) - 4\sqrt{AB}} \right), \quad (16)$$

with $A = C_2(C_1 + C_2)$, $B = (1 + C_1)^2 + C_1C_2$. Note that an analytic expression for entanglement can also be obtained at finite temperature, but it is too cumbersome to reveal much insight. In the following section, we will discuss in detail the effect of finite temperature in two different regimes. The results at both zero and finite temperature are plotted in Fig. 2.

Equations (9), (14), and (15) give us a simple way to understand entanglement generation. The ideal situation is when the two-mode squeeze parameter $R_{12} \gg 1$ and the thermal occupancy $\bar{n}_i \rightarrow 0$. From Eq. (15), we see that a large R_{12} generically requires large cooperativity. However, Eq. (14) indicates that this limit also yields a large effective temperature for cavity 2 (heuristically, \hat{H}_{int} turns vacuum noise into thermal noise). This heating degrades the purity of the state

[31]; however, as \bar{n}_1 remains zero, it only slightly degrades the entanglement [26].

B. Optimal output entanglement

Equation (16) shows that the zero-temperature entanglement is only a function of C_1, C_2 ; thus weak coupling does not prevent strong entanglement. For fixed C_1 , the expression is optimized when

$$C_2 = C_1 + 1 \equiv C_{2,\text{opt}}. \quad (17)$$

Heuristically, this condition corresponds to having a total mechanical damping $\gamma_{\text{tot}} = 0$. While $E_N^{\text{out}}[0]$ appears to be only a function of C_i , the ratio κ_1/κ_2 also plays an independent role via the stability condition of Eq. (5). If $\kappa_1 \geq \kappa_2$, $C_{2,\text{opt}}$ is also the maximum value of C_2 for which the system is stable. In contrast, if $\kappa_2 \geq \kappa_1$, the system becomes unstable before C_2 reaches $C_{2,\text{opt}}$; hence one cannot achieve the optimal amount of entanglement. We thus see that, in addition to achieving large C_i , it is advantageous to have $\kappa_1 \geq \kappa_2$. Figure 3 illustrates the behavior of $E_N^{\text{out}}[0]$ in these two cases ($C_{2,\text{opt}}$ is indicated as a gray vertical line). Note that a similar dependence on κ_1/κ_2 was observed numerically in [14], but in a regime far from optimal entanglement (i.e., for $C_2 \ll C_{2,\text{opt}}$).

In the large C_1 limit, the maximum achievable entanglement for the two cases reduces to

$$E_N^{\text{out}}[0]_{\text{max}} \simeq \begin{cases} \ln\left(\frac{2C_1}{1+2N_m}\right), & \kappa_1 \geq \kappa_2, \\ -\ln\left[\left(\frac{\kappa_2-\kappa_1}{\kappa_2+\kappa_1}\right)^2 + \frac{4\kappa_2^2\kappa_1 N_m'}{C_1(\kappa_1+\kappa_2)^3}\right], & \kappa_1 < \kappa_2, \end{cases} \quad (18)$$

with $N_m' = N_m(1 + \kappa_2/\kappa_1) + 1$. In both cases, the output entanglement E_N^{out} is maximal at the boundary of system stability, similar to the behavior of a nondegenerate parametric amplifier (NDPA) [32]. However, unlike a NDPA, E_N^{out} does not diverge at this boundary. Further, while E_N^{out} is maximal

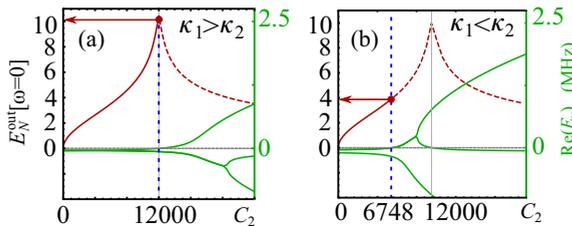


FIG. 3. (Color online) Output entanglement of the two cavity fields at resonance (i.e., $\omega = 0$) as a function of C_2 for $C_1 = 12000$ in two different cases: (a) $\kappa_1 > \kappa_2$ ($\kappa_1 = 1.5\kappa_2 = 2\pi \times 0.3$ MHz) and (b) $\kappa_1 < \kappa_2$ ($\kappa_1 = 0.75\kappa_2 = 2\pi \times 0.3$ MHz). If the instability condition were not considered, the entanglement would reach a maximum finite value at $C_2 = C_1 + 1$ (gray vertical lines). The green lines show the real part of the three eigenvalues (E_v) of the susceptibility matrix; the system becomes unstable when one of the real parts becomes positive, which is indicated by the blue dashed lines. The red dots indicates the maximum entanglement in each case by also considering the stability constraints. We used $\gamma = 2\pi \times 10$ KHz. The dashed portion of the entanglement curve (after it intersects with the blue vertical line) indicates that the system has entered the unstable regime.

at this boundary, the intracavity entanglement is extremely suboptimal at this point. For $\kappa_1 \geq \kappa_2 \gg \gamma$ and $C_2 \simeq C_{2,\text{opt}} \gg 1$, one has extremely large entanglement of the output fields while simultaneously having almost zero entanglement of the intracavity fields (see Fig. 2).

IV. DISCUSSION OF IMPERFECTIONS

So far we have given the analytical solution and the optimal condition for cavity output entanglement in the ideal case, where we have neglected the cavity internal loss, non-rotating-wave terms, and finite bandwidth. However, a real system has various imperfections. We now focus on the case $\kappa_1 = \kappa_2 = \kappa$, $C_j \gg 1$ and carefully examine the influence of various imperfections in two generic regimes.

The first is that of equal couplings $G_1 = G_2 = G$ (i.e., $C_1 = C_2$), which, as discussed, is essentially optimal for maximizing $E_N^{\text{out}}[0]$ (it is also an ideal point to generate quantum-limited amplification [33]). In this regime, the effective coupling \tilde{G} in Eq. (2) vanishes, meaning that the three normal modes of \hat{H}_{int} are degenerate. Consequently, the $\sigma = 0$ entanglement spectrum $E_N^{\text{out}}[\omega]$ has a single peak at $\omega = 0$ [see thick curves in Fig. 4(a)] with a width of $\sim \gamma C^{3/4}$ in the weak-coupling case (red top curve) and $\sim \sqrt{G}(2\kappa^5\gamma)^{1/12}$ in the strong-coupling case (green bottom curve). We stress that achieving large optimal E_N in this regime requires only strong cooperativities and not the more stringent strong-coupling condition $G_j > \kappa_j$ [see Eq. (18)].

Keeping $\kappa_1 = \kappa_2$ and $C_j \gg 1$, another generic regime is where G_2/G_1 is sufficiently smaller than 1 such that the effective coupling \tilde{G} is larger than κ, γ ; this necessarily requires $G_1 > \kappa$. In this regime, the three normal modes of \hat{H}_{int} are spectrally resolved, and $E_N^{\text{out}}[\omega]$ correspondingly has three peaks [14] [see the thin blue curve of Fig. 4(a)]. The entanglement at $\omega = 0$ is necessarily much smaller than the optimal value in Eq. (18). One finds that $C_1 \gg 1$ is not by itself enough to ensure large E_N in this regime; one also needs to be deep in the strong-coupling regime, $G_1 \gg \kappa$. As discussed in [14], this “resolved-modes” regime does, however, offer enhanced protection against mechanical thermal noise, as the central peak is due to the mechanically dark normal mode β_B .

A. Thermal resilience of entanglement

Thermal fluctuation severely limits the coherence of the low-frequency mechanical resonator, and it is important to improve the thermal resilience for protocols where the mechanics acts as a coherent mediator, such as for state transfer [34,35]. The bipartite entanglement mediated by the mechanics also suffers from mechanical thermal noise. While the analytical solution including thermal noise has been derived in the previous section, we discuss here the thermal resilience of the output entanglement in the two representative regimes mentioned above in order to elucidate the function of the mechanically dark mode [14,34–36].

For the first regime $G_1 = G_2 = G$ and $\kappa_1 = \kappa_2 = \kappa$ (i.e., $C_1 = C_2$), the entanglement value at $\omega = 0$ is

$$E_N^{\text{out}}[0] \approx \ln\left(\frac{2C}{1+2N_m}\right) + O(C^{-1}), \quad (19)$$

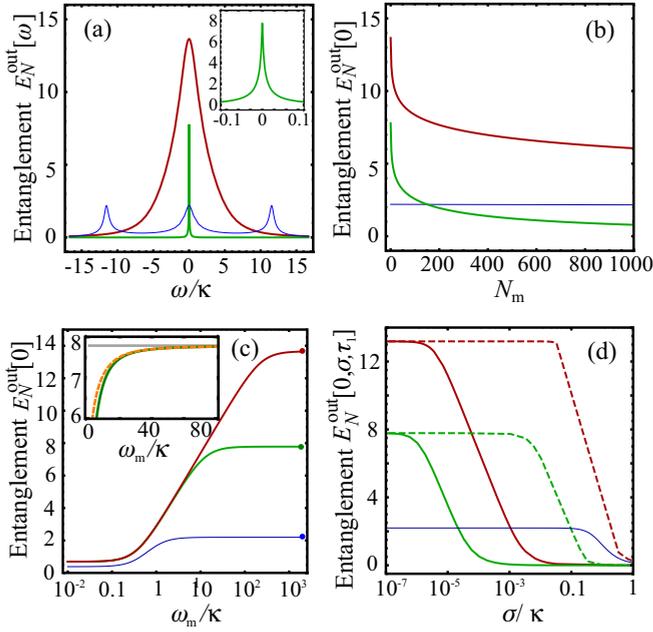


FIG. 4. (Color online) Different aspects of the output entanglement in 3 different cases: strong equal-coupling (red thick upper line, $G_1 = G_2 = 13.3\kappa$), weak equal-coupling (green thick lower line, $G_1 = G_2 = 0.1\kappa$) and resolved normal-modes (blue thin line, $G_1/\kappa = 13.3$ and $G_2/\kappa = 6.7$). For the blue and red curves, $\gamma/\kappa = 1.67 \times 10^{-3}$ while for the green curve $\gamma/\kappa = 3.3 \times 10^{-5}$. (a) Output spectrum in the limit of small mode bandwidth ($\sigma \rightarrow 0$) as a function of mode center frequency ω . The inset shows a zoom-in of the green curve (weak coupling case). (b) Thermal resilience. The output entanglement at $\omega = 0$ is plotted vs N_m for the three cases. (c) The influence of counterrotating terms. For the three cases, the curves show how the output entanglement $\tilde{E}_N^{\text{out}}[\omega = 0]$ including the counterrotating terms approaches the RWA results neglecting those terms (marked by the dots) as ω_m/κ increases. The inset shows a good fit of the analytical expression (29) (dashed lines) with the numerical result (solid line) in the weak-equal-coupling case, and the gray line indicates the RWA result. (d) Effects of nonzero mode bandwidth σ on the output entanglement of modes with center frequency $\omega = 0$. The solid lines are for zero time delay between the two cavity output modes [$\tau_1 = 0$; see Eq. (6)], while the dashed lines are the result including an optimal time delay $\tau_1 = \kappa/(4G^2)$.

We stress that a robust peak in $E_N^{\text{out}}[\omega]$ remains in the weak-coupling case $G < \kappa$ as long as $C \gg 1$.

The entanglement at $\omega = 0$ in the equal-coupling regime shows a prominent decrease with temperature due to the mechanical thermal noise. At low temperature, the equal-coupling regime ($G_1 = G_2$) yields a decent entanglement even for weak coupling ($\kappa > G$), as shown by the green curve in Fig. 4(b).

We turn now to another regime: $\tilde{G} = \sqrt{G_1^2 - G_2^2} > \kappa$, where the three normal modes of the interaction Hamiltonian in Eq. (1) are spectrally resolved. In this regime (as discussed in [14]), $E_N^{\text{out}}[\omega]$ has three resolved peaks, with each peak corresponding to a normal mode. The “dark mode” β_B corresponds to the peak at $\omega = 0$, while the peaks at $\pm\tilde{G}$ are the coupled “hybrid” modes [see thin blue curve in Fig. 4(a)]; all have width $\sim\kappa$. In the simple case $\kappa_1 = \kappa_2$, resolving the

normal modes requires $G_1 > \kappa \cosh r \gg \kappa$, i.e., deep in the strong-coupling regime for a large r (r is defined for the Bogoliubov modes after Eq. (2)). For typical parameters, the maximum entanglement in the resolved-peak regime is far less than the optimal value that would be achieved if C_2 were increased to C_1 [see Fig. 4(b)]. On the other hand, the output entanglement at the central peak can be written as (assuming $N_m e^{2r} \ll \tilde{C}$)

$$E_N^{\text{out}}[0] \approx 4r - 2e^{2r}(2N_m + 1)/\tilde{C}, \quad (20)$$

with the effective cooperativity $\tilde{C} = 4\tilde{G}^2/\gamma\kappa$. This shows that, as the central peak corresponds to the dark mode, the mechanical noise is suppressed by the effective cooperativity and the entanglement is robust to thermal fluctuations [14], as shown in Fig. 4(b). The entanglement at the side peaks (bright modes involving the mechanics) is still sensitive to thermal noise and in the large r limit:

$$E_N^{\text{out}}[\omega = \pm\tilde{G}] \approx 2r - \ln \left[\frac{4\gamma}{\kappa} \left(N_m + \frac{1}{2} \right) \right], \quad (21)$$

which is valid if $\gamma N_m/\kappa \ll 1$.

B. Influence of cavity internal losses

Except the loss through output channels, there is also extra zero-point noise incident on the cavity which can be described by the internal damping rate κ'_i . This can be treated as an additional independent input channel in the Langevin equations for the cavities. In contrast to the generation of intracavity entanglement [26], the output entanglement is sensitive to the internal losses of the cavities [see Eq. (3)].

a. Equal-coupling case. With finite internal loss $\kappa'_1 = \kappa'_2 = \kappa'$ and also assuming $G \gg \gamma, \kappa, \kappa'$, the entanglement reads

$$E_N^{\text{out}}[0] \approx -\ln \left(\frac{\kappa'}{\kappa' + \kappa} + \frac{1}{2C} \right), \quad (22)$$

which recovers the two limits

$$E_N^{\text{out}}[0] \approx \ln 2C \quad (23)$$

at small internal loss ($\kappa/\kappa' \gg C \gg 1$) and

$$E_N^{\text{out}}[0] \approx \ln(1 + \kappa/\kappa') \quad (24)$$

at large internal loss ($\kappa/\kappa' \ll 2C$). In the case of a cavity with a tunable external damping rate, the optimal κ satisfies $\kappa = \kappa'(\sqrt{2C'} - 1)$, with $C' = 4G^2/\kappa'\gamma$. The corresponding entanglement is $E_N^{\text{out}}[0] \approx \frac{1}{2} \ln(C'/2)$. This result is the same as that for the optimal intracavity entanglement, as shown in Eq. (11) of [26] (notice that the definition of C in this paper differs by a factor of 4 compared to that in [26]). Thus, the maximum entanglement is the same for both spectral entanglement and intracavity entanglement.

b. Resolved-peak case. Including internal loss and assuming $\kappa'_i = \kappa'$, $\tilde{G} \gg \kappa, \gamma, \kappa'$, we have

$$E_N^{\text{out}}[0] \approx 4r - \ln \left(\frac{\kappa + e^{4r}\kappa'}{\kappa + \kappa'} + \frac{e^r \sinh r}{\tilde{C}} \right). \quad (25)$$

When $\kappa/\kappa' \ll e^{4r}\tilde{C}/(e^{2r} + \tilde{C})$, this reduces to $E_N^{\text{out}}[0] \approx \ln(1 + \kappa/\kappa')$. The maximum of entanglement in Eq. (25) is

obtained as follows:

$$E_{N,\text{opt}}^{\text{out}}[0] = 4r - \ln \left(1 + \sqrt{\frac{2}{\tilde{C}}} \frac{e^{4r} - 1}{\sqrt{e^{2r} + 1}} + \frac{1 - e^{2r}}{\tilde{C}} \right), \quad (26)$$

with

$$\kappa_{\text{opt}} = \kappa' \sqrt{\tilde{C}(1 + e^{2r})/2 - 1}.$$

However, notice that in order to have resolved peaks, $\tilde{G} \gg \kappa + \kappa'$. This means the optimal condition is normally not satisfied unless $\kappa' \ll \gamma$.

C. Influence of counterrotating wave terms

So far, we have only discussed the dynamics with the RWA, considering the good cavity limit $\kappa \ll \omega_m$. Here we will give the full result including the non-RWA terms and show that the RWA condition can be more stringent in certain regimes.

First, we notice that the counterrotating terms are time independent in the rotating frame with respect to the cavity drives. In this frame, the full Hamiltonian is written as $\hat{H} = \omega_m(\hat{b}^\dagger \hat{b} + \hat{d}_1^\dagger \hat{d}_1 - \hat{d}_2^\dagger \hat{d}_2) + \hat{H}_{\text{int}} + \hat{H}_{\text{CR}}$, with

$$\begin{aligned} \hat{H}_{\text{int}} &= (G_1 \hat{b}^\dagger \hat{d}_1 + G_2 \hat{b} \hat{d}_2) + \text{H.c.}, \\ \hat{H}_{\text{CR}} &= (G_1 \hat{b} \hat{d}_1^\dagger + G_2 \hat{b} \hat{d}_2^\dagger) + \text{H.c.} \end{aligned} \quad (27)$$

Thus, a closed set of equations in the frequency domain can be obtained:

$$\begin{aligned} -i(\omega - \omega_m) \hat{b}[\omega] &= -\frac{\gamma}{2} \hat{b}[\omega] - iG_1(\hat{d}_1[\omega] + \hat{d}_1^\dagger[\omega]) \\ &\quad - iG_2(\hat{d}_2^\dagger[\omega] + \hat{d}_2[\omega]) - \sqrt{\gamma} \hat{b}_{\text{in}}[\omega], \\ -i(\omega - \omega_m) \hat{d}_1[\omega] &= -\frac{\kappa_1}{2} \hat{d}_1[\omega] - iG_1(\hat{b}[\omega] + \hat{b}^\dagger[\omega]) \\ &\quad - \sqrt{\kappa_1} \hat{d}_{\text{in},1}[\omega], \\ -i(\omega - \omega_m) \hat{d}_2^\dagger[\omega] &= -\frac{\kappa_2}{2} \hat{d}_2^\dagger[\omega] + iG_2(\hat{b}[\omega] + \hat{b}^\dagger[\omega]) \\ &\quad - \sqrt{\kappa_2} \hat{d}_{\text{in},2}^\dagger[\omega]. \end{aligned} \quad (28)$$

These equations can be solved analytically. Figure 4(c) shows a comparison of the results for $E_N^{\text{out}}[\omega = 0]$ with and without RWA. The lower curve corresponds to the case where $\tilde{G} > \kappa$ and the normal modes are resolved: counterrotating terms suppress the entanglement but become insignificant once $\omega_m > \kappa$. The two upper curves correspond to the case with equal coupling. In the good cavity limit, the maximum entanglement in the equal-coupling regime is much larger than the resolved-peak regime. Consequently, non-RWA corrections play a larger role, and one can only achieve the RWA result deep into the good cavity limit $\omega_m \gg \kappa$.

For both equal-coupling and resolved-peak cases, the leading non-RWA correction to $E_N^{\text{out}}[0]$ is

$$\bar{E}_N^{\text{out}}[0] - E_N^{\text{out}}[0] \approx -e^{E_N^{\text{out}}[0]} \frac{\kappa^2}{16\omega_m^2}. \quad (29)$$

Here $\bar{E}_N^{\text{out}}[0]$ is the entanglement including the counterrotating terms. This approximate expression is shown by the orange dashed line in the inset of Fig. 4(c). Thus the condition to

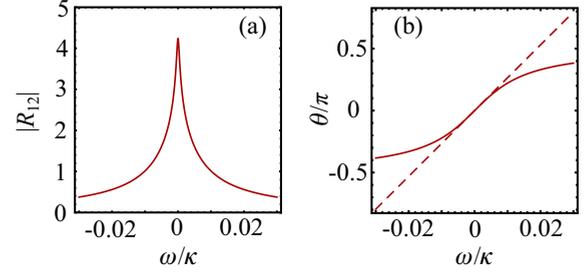


FIG. 5. (Color online) The dependence of the squeezing parameter $R_{12}[\omega] = |R_{12}|e^{i\theta}$ on frequency. The left panel shows the magnitude change of R_{12} , while the right panel shows the phase change of R_{12} . The dashed line in the right panel is the linear dependence given by Eq. (31). The parameters used are $G/\kappa = 0.1$, $\gamma/\kappa = 3.3 \times 10^{-5}$.

justify the use of RWA is

$$\left| \frac{\omega_m}{\kappa} \right| \gg \frac{1}{4} \sqrt{\frac{e^{E_N^{\text{out}}}}{E_N^{\text{out}}}}, \quad (30)$$

which is looser in the case of resolved peaks (due to the smaller E_N^{out}).

D. Time delay to improve the entanglement bandwidth

So far, we have considered the output entanglement with zero bandwidth, i.e., $E_N^{\text{out}}[\omega, \sigma = 0, \tau_1]$. However, in practice, the filter function has a finite bandwidth. Assuming the center frequency is set at $\omega = 0$ (the cavity resonance frequency in the laboratory frame), the entanglement has a nontrivial dependence on the bandwidth σ and the relative time delay τ_1 (taking $\tau_2 = 0$).

The solid lines of Fig. 4(d) show the entanglement of the two output cavity modes for zero time delay $E_N^{\text{out}}[\omega = 0, \sigma, \tau_1 = 0]$ as a function of bandwidth σ . While the equal-coupling case yields large entanglement at $\sigma = 0$, it is much more sensitive to the increase in the bandwidth. $E_N^{\text{out}}[0, \sigma, 0]$ decays on a scale $\sigma \sim C^{-1/4}\gamma$. In contrast, in the resolved normal-mode case, $E_N^{\text{out}}[0, \sigma, 0]$ is less sensitive to increasing the mode bandwidth and is only suppressed significantly when $\sigma \sim \kappa$.

The strong sensitivity to nonzero σ in the case of equal coupling is related to the change in the squeezing phase at different ω . As discussed before, the cavity output state can be characterized by a two-mode squeezed thermal state [see Eq. (7)] with a complex squeezing parameter $R_{12}[\omega]$ whose phase is $\theta[\omega] = \arg(-\hat{D}_1^{\text{out}}[\omega] \hat{D}_2^{\text{out}}[\omega])$ [see Eq. (10)]. At $\omega = 0$ and $\sigma = 0$, $R_{12}[0]$ is real [see Eq. (15)], i.e., $\theta = 0$. For $\omega \neq 0$, a frequency-dependent phase arises [see Fig. 5(b)]. In the large-squeezing limit, i.e., $|R_{12}| \gg 1$, such a phase variation leads to a rapid decrease in entanglement as σ increases. Assuming $\kappa_1 = \kappa_2$ and $G_1 = G_2$, where the magnitude of squeezing is maximized, the peak width of $|R_{12}|[\omega]$ is comparable to that of $E_N^{\text{out}}[\omega]$. The corresponding phase variation is approximately linear in the vicinity of $\omega = 0$ [as shown by the dashed line in Fig. 5(b)],

$$\delta\theta \approx (\kappa/4G^2)\delta\omega. \quad (31)$$

This suggests [as per Eq. (6)] that the optimal entanglement is between a cavity-2 mode emitted at $\tau_2 = 0$ and a cavity-1

mode emitted at $\tau_1 = \kappa/4G^2$. The entanglement with time delay is shown by the red dashed curve in Fig. 4(d). On a heuristic level, one could think that our system first generates entangled phonon-cavity-2 photon pairs via the G_2 interaction in Eq. (2); next, the G_1 interaction swaps the phonon state into the photon state in cavity 1. This physical picture is in agreement with finding that the optimal entanglement involves a positive delay for the cavity-1 output mode, as in Fig. 4(d). Finally, we note that for ω away from zero, the squeezing phase θ has a nonlinear frequency dependence, and hence the optimal filter function for larger σ will not correspond to a simple delay as in Eq. (31).

V. GENUINE TRIPARTITE ENTANGLEMENT OF THE ITINERANT MODES

As mentioned in the Introduction, alternative methods exist to access the mechanical output field. We discuss them in detail below, and motivated by these possibilities, we analyze the multipartite entanglement properties of all three output fields in our system. Note that previous work studied the nonstationary tripartite entanglement of intracavity fields generated by the *closed-system* Hamiltonian \hat{H}_{int} in Eq. (2) [37]; in contrast, our focus here is on the steady-state output entanglement in our *dissipative* three-mode system.

A. Phonon output through an auxiliary cavity

Experimental setups using optomechanical crystals [20,38] can access the mechanical output field via engineered phonon waveguides. For a general optomechanical system where a phonon waveguide is absent, we find it is still possible to access the phonon output by having its damping dominated by the optical damping of an auxiliary cooling cavity (see Fig. 1). This auxiliary cavity will have a large damping rate and will be coupled to the mechanics via a linearized optomechanical coupling (the cavity is strongly driven by a red-detuned laser):

$$\hat{H}_a = G_a(\hat{b}\hat{d}_a^\dagger + \hat{b}^\dagger\hat{d}_a), \quad (32)$$

where \hat{d}_a is the annihilation operator of the auxiliary cavity and G_a is the corresponding coupling. The auxiliary cavity, due to the large damping rate κ_a , can be described by the following steady-state relation:

$$\hat{d}_a = -i\frac{2G_a}{\kappa_a}\hat{b} - \frac{2}{\sqrt{\kappa_a}}\hat{d}_a^{\text{in}}. \quad (33)$$

Plugging this into the equation of motion for the mechanical resonator, one obtains

$$\frac{d}{dt}\hat{b} = -\frac{2G_a^2}{\kappa_a}\hat{b} - i(G_1\hat{d}_1 + G_2\hat{d}_2^\dagger) + \frac{2iG_a}{\sqrt{\kappa_a}}\hat{d}_a^{\text{in}}, \quad (34)$$

where we have neglected other damping channels of the resonator, supposing that G_a^2/κ_a is sufficiently large. Comparing Eq. (34) with the Langevin equation without an auxiliary cavity, $\frac{d}{dt}\hat{b} = -\frac{\gamma}{2}\hat{b} - i(G_1\hat{d}_1 + G_2\hat{d}_2^\dagger) - \sqrt{\gamma}\hat{d}_a^{\text{in}}$, we can identify

$$\hat{b}^{\text{in}} = -i\hat{d}_a^{\text{in}}, \quad \gamma = 4G_a^2/\kappa_a. \quad (35)$$

The input-output relation of the auxiliary cavity is $\hat{d}_a^{\text{out}} = \hat{d}_a^{\text{in}} + \sqrt{\kappa_a}\hat{d}_a$, which, together with Eqs. (33) and (35), gives

$\hat{d}_a^{\text{out}} = -i\sqrt{\gamma}\hat{b} - i\hat{b}^{\text{in}}$; thus

$$\hat{d}_a^{\text{out}} = -i\hat{b}^{\text{out}}. \quad (36)$$

This shows that a strongly damped auxiliary cavity can serve as the output of the mechanical mode.

B. Three-mode output state

We focus on zero frequency and zero bandwidth and consider the ideal case where all dissipative baths are at zero temperature. In this case, the three-mode output state is a pure state $|\Psi_s\rangle$. Since $\bar{n}_1 = 0$ [see Eq. (14)], cavity 1 must be in the ground state if we consider the ‘‘unsqueezed’’ state $|\Psi_s\rangle \equiv \hat{S}_{12}(-R_{12})|\Psi\rangle$. However, $|\Psi_s\rangle$ has residual entanglement between cavity 2 and the mechanical mode. This is clear from the finite value of \bar{n}_2 , which diverges at the instability condition $\gamma_{\text{tot}} = 0$ (the finite population \bar{n}_2 is a consequence of tracing out the mechanical mode). One can compute explicitly the correlations of the state $|\Psi_s\rangle$ and identify it as a squeezed vacuum of cavity 2 and the mechanical mode, with squeezing parameter $R_{2m} = \sinh^{-1}\bar{n}_2$. Hence the output state can be written as a twice-squeezed vacuum

$$|\Psi\rangle = \hat{S}_{12}(R_{12})\hat{S}_{2m}(R_{2m})|000\rangle, \quad (37)$$

where $\hat{S}_{2m}(R_{2m}) \equiv \exp(iR_{2m}\hat{D}_m^{\text{out}}[0]\hat{D}_2^{\text{out}}[0] - \text{H.c.})$ is the two-mode squeeze operator entangling the output of the mechanics at $\omega = 0$ (denoted by $\hat{D}_m^{\text{out}}[0]$, which is defined in a way similar to that of the cavity output) with that of cavity 2. Since the effective temperature represented by \bar{n}_2 diverges at the instability point [see Eq. (14)], the squeezing parameter $R_{2m} = \sinh^{-1}\bar{n}_2$ diverges as well. Equation (37) demonstrates that the effective temperature \bar{n}_2 which degraded the cavity-cavity entanglement in Eq. (14) is a direct consequence of entanglement between cavity 2 and the mechanics. It also demonstrates the asymmetry between the three modes (i.e., there is no direct squeezing between the mechanical and cavity-1 outputs).

Furthermore, Eq. (37) shows that we have genuine tripartite entanglement (GTE): none of the parties can be separated from any other party in a mixture of product states, implying a fully inseparable state [39,40]. To see this, note that the total state is pure, and if one traces over one subsystem, the remaining two are in a mixed state. GTE is also evident from writing the state in the Fock-state basis $|n_1, n_2, n_m\rangle$,

$$|\Psi\rangle = \sum_{pq} \frac{\sqrt{C_{p+q}^p \langle N_m \rangle^{\frac{q}{2}} \langle N_1 \rangle^{\frac{p}{2}}}}{(1 + \langle N_2 \rangle)^{(p+q+1)/2}} |p, p+q, q\rangle, \quad (38)$$

where C_{p+q}^p are binomial coefficients and $\langle N_i \rangle = \langle (\hat{D}_i^{\text{out}}[0])^\dagger \hat{D}_i^{\text{out}}[0] \rangle$ ($i = 1, 2, m$) is the average photon or phonon number of each mode

$$\begin{aligned} \langle \hat{N}_1 \rangle &= \frac{4C_1C_2}{(1 + C_1 - C_2)^2}, \\ \langle \hat{N}_2 \rangle &= \frac{4C_2(C_1 + 1)}{(1 + C_1 - C_2)^2}, \\ \langle \hat{N}_m \rangle &= \frac{4C_2}{(1 + C_1 - C_2)^2}. \end{aligned} \quad (39)$$

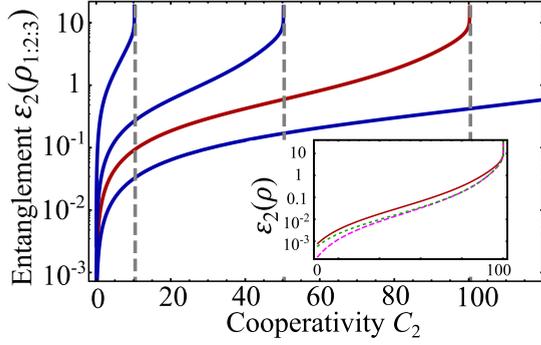


FIG. 6. (Color online) Three-mode entanglement, evaluated by the residual GR2 entanglement with cavity 1 as the focus mode $\mathcal{E}_2(\rho_{1,2,3})$, vs the cooperativity of cavity 2. Here C_1 is fixed to 10, 50, 100, 200 (from top to bottom). The gray dashed lines indicate the onset of system instability. The three-mode entanglement diverges at $\gamma_{\text{tot}} = 0$ or $C_2 = C_1 + 1$. The $C_1 = 100$ (red) curve is replotted in the inset, together with the two residual GR2 entanglements where the focus mode is cavity 2 [$\mathcal{E}_2(\rho_{2,1,3})$] or mechanics [$\mathcal{E}_2(\rho_{3,2,1})$].

$|\Psi\rangle$ only involves Fock states $|n_1, n_2, n_m\rangle$, where $n_2 = n_1 + n_m$; there is thus a perfect correlation between the three systems that is only evident by looking at all three modes. If any two modes are traced out, the remaining third mode is in an impure thermal state. Another interesting observation is that, although the tripartite steady-state equation (37) is generated by interaction between intracavity modes and the input-output relations, the output state described by Eq. (37) could also be achieved by a unitary evolution generated by the following interaction between the output modes:

$$\begin{aligned} \tilde{H} = & R_{12} \sin R_{2m} \hat{D}_m^{\text{out}}[0] \hat{D}_2^{\text{out}}[0] - R_{2m} (\hat{D}_m^{\text{out}}[0])^\dagger \hat{D}_1^{\text{out}}[0] \\ & + i R_{12} \cos R_{2m} \hat{D}_1^{\text{out}}[0] \hat{D}_2^{\text{out}}[0] + \text{H.c.} \end{aligned} \quad (40)$$

This result can be obtained by Wei-Norman decomposition in terms of a closed algebra, $\{\hat{D}_m^{\text{out}}[0]^\dagger \hat{D}_1^{\text{out}}[0] + \text{H.c.}, \hat{D}_m^{\text{out}}[0] \hat{D}_2^{\text{out}}[0] + \text{H.c.}, \hat{D}_1^{\text{out}}[0] \hat{D}_2^{\text{out}}[0] - \text{H.c.}\}$.

C. Three-mode entanglement measure based on Rényi-2 entropy

The tripartite entanglement can be measured by the residue Gaussian Rényi-2 entanglement [21]. We find that it is indeed

$$g_i = \begin{cases} 1, & a_k \geq \sqrt{a_i^2 + a_j^2 - 1}, \\ \frac{\beta}{8a_i^2}, & \alpha_k < a_k < \sqrt{a_i^2 + a_j^2 - 1}, \\ \left(\frac{a_i^2 - a_j^2}{a_k^2 - 1}\right)^2, & a_k \leq \alpha_k, \end{cases} \quad (44)$$

with

$$\begin{aligned} \alpha_k &= \sqrt{\frac{2(a_i^2 + a_j^2) + (a_i^2 - a_j^2)^2 + |a_i^2 - a_j^2| \sqrt{(a_i^2 - a_j^2)^2 + 8(a_i^2 + a_j^2)}}{2(a_i^2 + a_j^2)}}, \\ \beta &= 2a_1^2 + 2a_2^2 + 2a_3^2 + 2a_1^2 a_3^2 + 2a_2^2 a_3^2 + 2a_1^2 a_2^2 - a_1^4 - a_2^4 - a_3^4 - \sqrt{\delta} - 1, \\ \delta &= [(a_1 - a_2 - a_3)^2 - 1][(a_1 + a_2 - a_3)^2 - 1][(a_1 - a_2 + a_3)^2 - 1][(a_1 + a_2 + a_3)^2 - 1]. \end{aligned}$$

nonzero and diverges as one increases C_2 to the instability point $C_1 + 1$ (due to the divergence of \bar{n}_2 and R_{2m}). These calculations also reveal the absence of any direct entanglement between the mechanical and cavity-1 outputs.

The Rényi-2 entropy is given by $S_2(\rho) = -\ln \text{Tr}(\rho^2)$ and allows us to define an entanglement measure $\mathcal{E}_2(\rho_{A:B})$ for bipartite states ρ_{AB} . For pure states one simply has $\mathcal{E}_2(\rho_{A:B}) = S_2(\rho_A)$, with ρ_A being the reduced density matrix of subsystem A . The tripartite entanglement is then characterized through the residual entanglement $\mathcal{E}_2(\rho_{i:j;k})$, given by

$$\mathcal{E}_2(\rho_{i:j;k}) = \mathcal{E}_2(\rho_{i:jk}) - \mathcal{E}_2(\rho_{i:k}) - \mathcal{E}_2(\rho_{i:j}) \geq 0, \quad (41)$$

where $i \neq j \neq k = 1, 2, 3$ represent the three different modes (the third mode denotes the mechanics in our case). In Eq. (41), $\mathcal{E}_2(\rho_{i:jk})$ is the bipartite entanglement partitioning the global system into $A = i$ and $B = jk$, while $\mathcal{E}_2(\rho_{i:j})$ and $\mathcal{E}_2(\rho_{i:k})$ consider the reduced density matrices of subsystems ij and ik , respectively. In general, three different values of $\mathcal{E}_2(\rho_{i:j;k})$ are obtained, depending on the choice of the ‘‘focus mode’’ i . There are special cases when $\mathcal{E}_2(\rho_{i:j;k})$ is invariant under mode permutation [21]; as we explain below, that is not the case for our system.

For pure tripartite Gaussian states, $\mathcal{E}_2(\rho_{i:j;k})$ can be evaluated analytically [21]. The first term in Eq. (41) is

$$\mathcal{E}_2(\rho_{i:jk}) = S_2(\rho_i) = \ln a_i, \quad (42)$$

where a_i is related to the covariance matrix \mathbf{V}_i of subsystem i :

$$a_i = \sqrt{\det \mathbf{V}_i}. \quad (43)$$

Using the covariance matrix for our system, calculated from the Langevin equation, it is possible to obtain explicit formulas for $\mathcal{E}_2(\rho_{1,2,3})$, $\mathcal{E}_2(\rho_{2,1,3})$, and $\mathcal{E}_2(\rho_{3,2,1})$ in terms of the cooperativities $C_{1,2}$. Although we omit them here, it is worth mentioning that these three quantities are all nonzero, which shows that none of the three systems are separable.

The last two terms in Eq. (41) are given by [21]

$$\mathcal{E}_2(\rho_{j:k}) = \frac{1}{2} \ln g_i \quad (i \neq j \neq k),$$

where

Since $\varepsilon_2(\rho_{j:k})$ is the GR2 two-mode entanglement measure in the subspace where mode i is eliminated, it serves as an alternative way to quantify the two-mode entanglement in our system, besides the logarithmic negativity used in Sec. III. We obtain all the two-mode entanglements as follows:

$$\begin{aligned}\varepsilon_2(\rho_{1:2}) &= \ln \frac{(1+C_2)^2 + C_1^2 + 2C_1 + 6C_1C_2}{(1+C_2)^2 + C_1^2 + 2C_1 - 2C_1C_2} \approx \ln \frac{C_2^2 + 6C_1C_2 + C_1^2}{(C_1 - C_2)^2} + O\left(\frac{1}{C_2}\right), \\ \varepsilon_2(\rho_{3:2}) &= \ln \frac{(1+C_1)^2 + C_2^2 + 6C_2 + 2C_1C_2}{(1-C_2)^2 + C_1^2 + 2C_1 + 2C_1C_2} \approx O\left(\frac{1}{C_2}\right), \\ \varepsilon_2(\rho_{1:3}) &= 0,\end{aligned}\tag{45}$$

where the last approximation is in the large- C limit. These results show that the entanglement between cavity 1 and the mechanics is always zero, although the mechanics is entangled with the composite system of the two cavities [$\varepsilon_2(\rho_{3:12}) \neq 0$]. In particular, there is entanglement between the mechanics and cavity 2, although it is much smaller than the entanglement between cavities 1 and 2. These results are all in agreement with those based on the logarithmic negativity.

We now turn to the evaluation of the tripartite entanglement $\varepsilon_2(\rho_{i:j:k})$, which is permutationally invariant only when all $\varepsilon_2(\rho_{i:j:k})$ and $\varepsilon_2(\rho_{i:j})$ are nonzero [21]. The fact that $\varepsilon_2(\rho_{1:3}) = 0$ implies that $\varepsilon_2(\rho_{i:j:k})$ depends on the focus mode; thus we consider all three choices, $i = 1, 2, 3$. Using the results for $\varepsilon_2(\rho_{i:j:k})$, $\varepsilon_2(\rho_{i:j})$ discussed above, Eq. (41) gives

$$\begin{aligned}\varepsilon_2(\rho_{1:2:3}) &= \ln \left(\frac{C_1^2 + (1+C_2)^2 + 2C_1 - 2C_1C_2}{(1+C_1-C_2)^2} \right) - 2 \tanh^{-1} \left(\frac{2C_2}{(1+C_1)^2 + 6C_1C_2 + C_2^2} \right), \\ \varepsilon_2(\rho_{2:1:3}) &= \ln \left(\frac{C_2^2 + (1+C_1)^2 + 6C_2(1+C_1)}{C_2^2 + (1+C_1)^2 + 2C_2(3+C_1)} \right) \\ &\quad + \ln \left(\frac{[C_1^2 + (1+C_2)^2 - 2C_1(C_2-1)][C_1^2 + (1-C_2)^2 + 2C_1(1+C_2)]}{(1+C_1-C_2)^2 [C_1^2 + (1+C_2)^2 + 2C_1(1+3C_2)]} \right), \\ \varepsilon_2(\rho_{3:1:2}) &= \ln \left(\frac{C_2^2 + (1+C_1)^2 + 6C_2 - 2C_1C_2}{(1+C_1-C_2)^2} \right) - 2 \tanh^{-1} \left(\frac{4C_2}{(1+C_1-C_2)^2} \right).\end{aligned}\tag{46}$$

As announced, the three residual GR2 entanglements are unequal. Nevertheless, they are all larger than zero, which confirms the presence of genuine tripartite entanglement. Furthermore, as shown in Fig. 6, all $\varepsilon_2(\rho_{i:j:k})$ diverge at the instability point $\gamma_{\text{tot}} = 0$. This divergence is similar to the case of a parametric amplifier and is related to the divergences of \bar{n}_2 and R_{2m} discussed in subsection VB.

VI. CONCLUSION

We have studied in detail the bipartite and tripartite entanglement of the output fields in a three-mode optomechanical system. For bipartite photonic entanglement, we have found an explicit analytical expression based on identifying the output with a squeezed thermal state. This has allowed us to find an optimal ‘‘impedance matching’’ condition for entanglement generation: tuning the system parameters to achieve this condition yields a dramatic increase of the maximum output entanglement. Strikingly, our optimal condition corresponds to a regime where entanglement between the two optical cavities is nearly zero [26] but at the same time strongly entangled photons are emitted into the output channels.

We also show that large values of the output entanglement can be achieved even in the standard ‘‘weak-coupling’’ regime with large cooperativity (the same regime used for cavity

cooling in numerous experiments): one simply needs to tune parameters to achieve the aforementioned impedance matching condition. Furthermore, we have considered realistic conditions including different types of imperfections: finite temperature, internal losses, sizable counterrotating terms, and finite mode bandwidth. By restricting ourselves to the optimal equal-coupling regime, we find that it is crucial to consider time delays of emitted wave packets; we find the optimal value of this delay and show that it substantially improves the attainable entanglement. Finally, we show how to generate genuine tripartite entanglement of spatially separated, itinerant quanta: we provide a simple analytic characterization of the output state and use a rigorous entanglement monotone to quantify the three-mode entanglement. Our results can also be applied to other parametrically coupled three-mode bosonic systems, in addition to optomechanical systems.

ACKNOWLEDGMENTS

We thank M. Woolley for useful discussions. This work was supported by the DARPA ORCHID program under a grant from the AFOSR. S.C. and Y.D.W. acknowledge support from the Chinese Youth 1000 Talents Program. Y.D.W. also acknowledges the grant from NSFC (No. 11434011).

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