Loss-Enabled Sub-Poissonian Light Generation in a Bimodal Nanocavity

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We propose an implementation of a source of strongly sub-Poissonian light in a system consisting of a quantum dot coupled to both modes of a lossy bimodal optical cavity. When one mode of the cavity is resonantly driven with coherent light, the system will act as an efficient single photon filter, and the transmitted light will have a strongly sub-Poissonian character. In addition to numerical simulations demonstrating this effect, we present a physical explanation of the underlying mechanism. In particular, we show that the effect results from an interference between the coherent light transmitted through the resonant cavity and the super-Poissonian light generated by photon-induced tunneling. Peculiarly, this effect vanishes in the absence of the cavity loss.

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An optical cavity containing a strongly coupled quantum emitter, such as an atom or a quantum dot (QD), constitutes a system in which an optical nonlinearity is present even at a single photon level [1–3]. The eigenenergies of this coupled system form an anharmonic ladder, which gives rise to phenomena like photon blockade and photon-induced tunneling [4–7]. In photon blockade, coupling of a single photon to the system hinders the coupling of the subsequent photons, whereas in photon-induced tunneling, coupling of initial photons favors the coupling of the subsequent photons. In an experiment, the signature of blockade or tunneling is observed by measuring the second-order autocorrelation function $g^{(2)}(0)$; a value of $g^{(2)}(0) < 1$ (> 1) demonstrates the sub-Poissonian (super-Poissonian) photon statistics of the transmitted light and indicates that the system is in a photon blockade (tunneling) regime.

Photon blockade can be used to route photons in a quantum photonic circuit [8], or to mimic interacting bosons for efficient simulation of complex quantum phase transitions [9–11]. While most of the recent experiments focus on photon blockade with a single two-level system and a single cavity [4–7], there have been several theoretical proposals predicting similar effects and sub-Poissonian light generation in systems based on multilevel atoms in a cavity [12] and on a quantum dot interacting with a pair of proximity-coupled nanocavities [13,14] or wave-guides [15].

The cavity quantum electrodynamic (cQED) systems in which photon blockade can be studied depend on three important rate quantities: the coherent coupling strength between the atomic system and the cavity g, the cavity field decay rate κ and the dipole decay rate γ. In all aforementioned proposals, the photon blockade occurs when the coherent interaction strength is larger than the loss rates in the system. In fact, the limit of g/κ, $g/\gamma \rightarrow \infty$ results in vanishing overlap between the energy eigenstates of the anharmonic ladder, which in turn leads to a perfect photon blockade ($g^{(2)}(0) = 0$). In a solid-state optical system based on a photonic-crystal cavity with an embedded single QD as the two-level system, the condition $g \gg \gamma$ is generally easy to satisfy. However, achieving the condition of $g \gg \kappa$, which requires a high quality (Q) factor of the cavity, is generally difficult due to fabrication challenges. As a result, even the best photon blockade with a QD embedded in a solid-state nanocavity reported so far in the literature gives a second-order correlation $g^{(2)}(0) \sim 0.75$ [7]. Though a proposal based on a QD interacting with a photonic molecule (a pair of coupled cavities) predicts efficient blockade even for cavities with easily achievable Q factors [13,14], the suggested scheme requires both individual addressability of each cavity and a large coupling strength between the two cavities. Since nanophotonic cavities are generally coupled via spatial proximity, large coupling poses a major challenge for achieving individual addressability [16].

In this paper, we propose a different approach for generation of strongly antibunched light which employs a bimodal cavity with both of its modes coupled to a QD. We will show that in this approach the cavity loss is actually crucial for achieving the effect, as opposed to photon blockade systems introduced so far in which the cavity loss plays a negative role. Specifically, the effect does not occur in our system in the limit of $g/\kappa \rightarrow 0$, which is intuitively expected, as this is the case of an infinitely large loss (and this is what also happens for the cases of blockade with a single QD strongly coupled to a single cavity and in previous photonic molecule proposals). However, for $g/\kappa \rightarrow \infty$ (zero loss, i.e., an infinite cavity Q-factor), the proposed system fails to generate sub-Poissonian light, in contrast with the single cavity with a strongly coupled QD, where perfect photon blockade occurs in such a limit. Here, we provide an intuitive explanation of how a balance between the coherent QD-cavity interaction and the decay of the cavity field is required to achieve a strong sub-Poissonian output photon stream. Second-order autocorrelation of such a bimodal cavity was analyzed before experimentally [17] and theoretically [18] in the context of semiconductor microdisk cavities, where the right and left hand circularly polarized cavity modes are degenerate. However, the unusual dependence of the sub-Poissonian light on g/κ ratio was not reported before. Additionally, we analyze the nanophotonic platform for possible experimental realization of this effect. We note that the role of cavity loss in generation of entanglement between two cavity modes was previously studied in Ref. [19].

In a conventional strongly coupled QD-cavity system, a QD interacts with a single cavity mode [Fig. 1(a)]. In a bimodal cavity, the QD is coupled to both cavity modes (with photon annihilation operators a and b) although there is no direct coupling between the two modes [Fig. 1(b)]. Assuming the cavity modes are degenerate and the QD is resonant with both of them, the Hamiltonian $\mathcal{H}$ describing such a system (in a frame rotating at the frequency of the laser driving the cavity mode a) is:

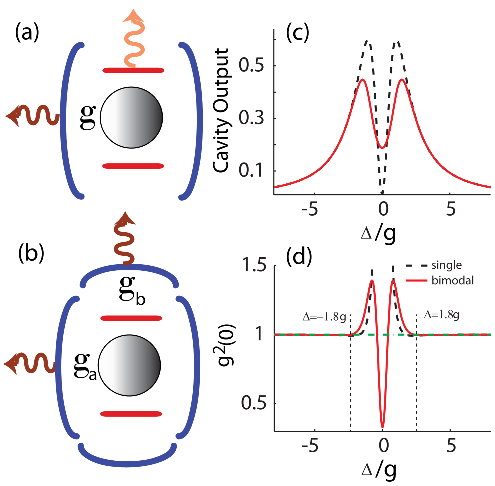

FIG. 1 (color online). (a) Schematic of a QD coupled to a single mode cavity, with a coupling strength of g. (b) Schematic of a bimodal cavity with a coupled QD. The two cavity modes are not directly coupled to each other. However, both of them are coupled to the QD with interaction strengths g_a and g_b. (c) The cavity output $\kappa\langle a^\dagger a\rangle$ as a function of the driving laser detuning Δ from the empty cavity resonance both for a single mode cavity (dashed line) and the bimodal cavity (solid line). The split resonance observed is due to the coupled QD. (d) Second-order autocorrelation $g^{(2)}(0)$ function calculated for the collected output of the driven mode for a single mode (thick dashed line) and bimodal cavity (solid line). The green dashed line marks the Poissonian statistics of a coherent state (always 1). For single mode cavities at $\Delta \sim \pm 1.5g$ and for bimodal cavities at $\Delta \sim \pm 1.8g$, we observe a weakly sub-Poissonian light ($g^2(0)$ slightly less than 1). However, for bimodal cavity a strong sub-Poissonian light is generated when $\Delta = 0$. For bimodal cavities we assumed identical interaction strengths and cavity decay rates for two modes. Parameters used for the simulations: QD-cavity interaction strength $g/2\pi = g_a/2\pi = g_b/2\pi = 10$ GHz, cavity field decay rate $\kappa/2\pi = 20$ GHz, dipole decay rate $\gamma/2\pi = 1$ GHz, and driving laser strength $\mathcal{E}\sqrt{\kappa}/2\pi = 1$ GHz.

$$\mathcal{H} = \Delta(a^\dagger a + \sigma^\dagger\sigma + b^\dagger b) + g_a(a^\dagger\sigma + a\sigma^\dagger) + g_b(b^\dagger\sigma + b\sigma^\dagger) + \mathcal{E}\sqrt{\kappa}(a + a^\dagger). \quad (1)$$

Here, σ is the QD lowering operator, g_a and g_b are the coupling strengths between the QD and the two cavity modes,κ is the cavity field decay rate, $\mathcal{E}$ denotes strength of the driving laser and Δ is the detuning between the driving laser and the cavity modes. The loss in the system is incorporated in the usual way by using the Master equation [16]. The numerical calculations are performed using the integration routines provided in the quantum optics toolbox [20]. Figure 1(c) shows the transmitted light collected from the driven cavity ($\kappa\langle a^\dagger a\rangle$) for both single (dashed line) and double mode cavities (solid line). The cavity output is qualitatively similar for both cases, and the split resonance is caused by coupling of the QD to the cavity and creation of polaritons. For the single mode cavity, the two polaritons are separated by $2g$, while for the bimodal cavity, the separation is $2\sqrt{2}g$ due to the presence of two modes, as will be explained later. Increased cavity transmission at $\Delta = 0$ for the bimodal case is also due to the presence of two modes. However, the second-order autocorrelation functions of the cavity transmission $g^{(2)}(0) = \frac{\langle a^\dagger a^\dagger aa\rangle}{\langle a^\dagger a\rangle^2}$ are strikingly different for two cases [Fig. 1(d)]. For the single mode cavity, one observes photon blockade ($g^{(2)}(0) < 1$), when the driving laser is tuned close to the frequency of the polariton, $\Delta \approx \pm 1.5g$. For the bimodal cavity, sub-Poissonian statistics are observed at three different detunings: $\Delta \approx \pm 1.8g$ and $\Delta = 0$. A slight deviation from the polariton frequencies (for single mode cavity $\Delta \approx \pm g$ and for bimodal cavity $\Delta \approx \pm\sqrt{2}g$) is due to the losses in the system. The weak sub-Poissonian light ($g^2(0) \sim 0.95$) at $\Delta \approx \pm\sqrt{2}g$ is comparable to that observed in the single mode cavity, and it arises from the same mechanism. At $\Delta = 0$, the sub-Poissonian character is much stronger ($g^2(0) \sim 0.4$), and it is this regime in the bimodal cavity that we will focus on. Note that the sub-Poissonian character observed at this frequency of the driving laser cannot be explained by the anharmonic nature of the ladder alone. In fact, in the energy structure of the coupled QD and the bimodal cavity, we always find an available state at this empty cavity frequency [16].

To further illustrate the difference between the photon blockade in a single mode cavity and the effect we observe in a bimodal cavity, we perform numerical simulations for a range of coupling strengths g and cavity field decay rates κ in both systems. Using these simulations, we obtained the values of $g^{(2)}(0)$ for the transmitted light for a single mode cavity (laser tuned to one of the polaritons, i.e., $\Delta = g$) and for a double mode cavity (the laser tuned to the bare cavity frequency, i.e., $\Delta = 0$). Figures 2(a) and 2(b) shows $g^{(2)}(0)$ as a function of g and κ. For a single mode cavity, blockade appears at high g and low κ, as generally expected for any photon blockade system [Fig. 2(a)].

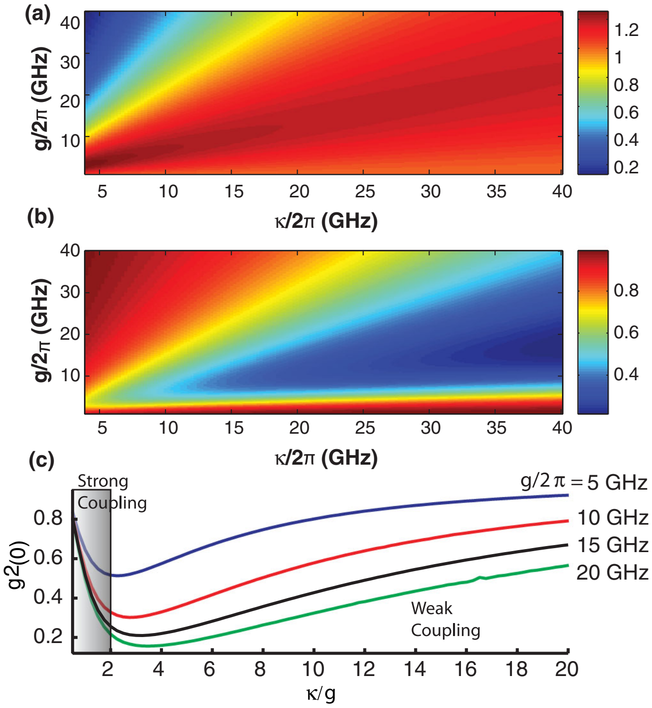

FIG. 2 (color online). (a) Second-order autocorrelation $g^{(2)}(0)$ for the conventional photon blockade in a single mode cavity as a function of the QD-cavity coupling strength g and cavity field decay rate κ. $g^{(2)}(0)$ decreases with increasing value of g/κ, as expected, as a result of reduced overlap of energy eigenstates in the anharmonic ladder. (b) $g^{(2)}(0)$ for the bimodal cavity as a function of g and κ. $g^2(0)$ is calculated for the output of mode a, i.e., for photons leaking from the mode a. We observe that $g^{(2)}(0) \to 1$ (Poissonian output) when $g/\kappa \to 0$ or ∞. However, we can observe very low $g^{(2)}(0)$ even when the QD is not strongly coupled to the two cavity modes ($g < \kappa/2$). (c) $g^2(0)$ as a function of the ratio κ/g for different g showing sub-Poissonian light generation in the bimodal cavity even in the weak coupling regime. For all the simulations $\mathcal{E}/2\pi = 0.1$ GHz such that the QD is not saturated.

However, for a bimodal cavity (when excited at $\Delta = 0$), the effect disappears and the transmitted photon output becomes Poissonian whenever g and κ are disproportionate (i.e., $g/\kappa \to 0$ or $g/\kappa \to \infty$). A strongly sub-Poissonian output can be observed from a bimodal cavity when g and κ are comparable. Figure 2(c) plots the $g^2(0)$ as a function of the ratio κ/g for different g demonstrating sub-Poissonian light in the bimodal cavity even in the weak coupling regime. We stress again that this result cannot be explained just by the anharmonicity of the ladder of energy eigenstates. We note that for the bimodal cavity when pumped at $\Delta \approx \sqrt{2}g$, the light is sub-Poissonian only at high g and low κ, consistent with conventional photon blockade.

To understand the origin of the strongly sub-Poissonian light transmitted through a bimodal cavity, we transform the system's Hamiltonian to a different cavity mode basis: $\alpha = (a + b)/\sqrt{2}$ and $\beta = (a - b)/\sqrt{2}$. The Hamiltonian $\mathcal{H}$ can be written (assuming $g_a = g_b = g$) as $\mathcal{H} = \mathcal{H}_1 + \mathcal{H}_2$ with

$$\mathcal{H}_1 = \Delta(\alpha^\dagger\alpha + \sigma^\dagger\sigma) + \sqrt{2}g(\alpha^\dagger\sigma + \alpha\sigma^\dagger) + \frac{\mathcal{E}\sqrt{\kappa}}{\sqrt{2}}(\alpha + \alpha^\dagger) \quad (2)$$

describing a driven single mode cavity coupled to a QD with a strength of $\sqrt{2}g$ and

$$\mathcal{H}_2 = \Delta\beta^\dagger\beta + \frac{\mathcal{E}\sqrt{\kappa}}{\sqrt{2}}(\beta + \beta^\dagger) \quad (3)$$

describing a driven empty cavity mode. Both cavities are driven at the bare cavity resonances. We monitor $a = (\alpha + \beta)/\sqrt{2}$ which, in the transformed basis, is equivalent to the output from two cavities: one with a coupled QD (α) and the other empty (β), combined on a beam splitter. Figure 3(a) shows the transmitted cavity output for three different cases: cavity α alone, cavity β alone and the combined output. Note the polariton peaks in the combined output at $\pm\sqrt{2}g$ and increased transmission of light at zero detuning due to the empty cavity.

The cavity transmission with a strongly coupled QD driven at the cavity resonance is super-Poissonian due to photon-induced tunneling [6] [α in Fig. 3(b)]. In this regime, the coupling of initial photons into the system is inhibited by the absence of the dressed states at this frequency. However, once the initial photon is coupled, the probability of coupling subsequent photons is increased as higher order manifolds in the ladder of dressed states are reached via multiphoton processes. In our system, as a result of broadening of the dressed states, at the empty cavity resonance one can excite multiple higher order manifolds. Hence, the light transmitted through a cavity in the photon-induced tunneling regime is a superposition of Fock states with small photon numbers and a strong

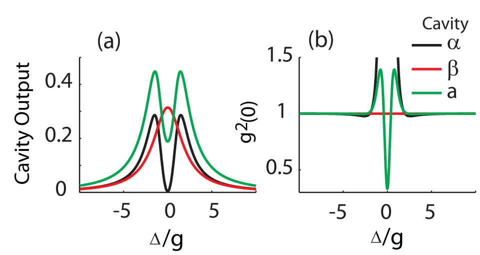

FIG. 3 (color online). (a) Cavity output for an empty cavity β and another cavity α coupled to a QD with a coupling strength of $\sqrt{2}g$. The combined output of these two replicates the output from the bimodal cavity a (Fig. 1). (b) $g^{(2)}(0)$ for these three cases: the empty cavity β gives Poissonian light; the cavity α with coupled QD gives super-Poissonian light due to photo-induced tunneling [6] (the black curve goes to infinity at $\Delta = 0$); the combined output a provides sub-Poissonian light. Parameters for the simulation: $g/2\pi = 10$ GHz, $\kappa/2\pi = 20$ GHz, $\gamma/2\pi = 1$ GHz and $\mathcal{E}\sqrt{\kappa}/2\pi = 1$ GHz.

presence of the vacuum state. As a result, the photon statistics of this light is super-Poissonian [6]. On the other hand, the empty cavity transmission (β in Fig. 3(b)] is a purely Poissonian coherent state. When the outputs of these two cavities are combined on a beam-splitter ($a = (\alpha + \beta)/\sqrt{2}$ in Fig. 3(b)], the output shows sub-Poissonian character. We note that similar interference effect was previously reported in [17]. However, for efficient generation of sub-Poissonian light, one needs comparable transmitted light intensity from both cavities, which calls for a balance between the cavity loss κ and the QD-cavity nonlinear interaction strength g. Using this effective model, the somewhat unusual dependence of $g^{(2)}(0)$ on g and κ can now be explained. When $g/\kappa \to 0$, the coupled system is linear and both of the equivalent cavities transmit just coherent light. On the other hand, although photon-induced tunneling does happen in the limit $g/\kappa \to \infty$, the amount of super-Poissonian light transmitted through the cavity α is so small (as the dressed states separation in the ladder is so large that it is impossible to couple photons at energies between them) that its interference with the coherent light from the empty cavity β will still result in light with Poissonian statistics. To generate enough super-Poissonian light via photon-induced tunneling in cavity (α) which can affect the coherent light from the empty cavity (β), comparable values of dot-cavity interaction strength g and cavity decay rate κ are required.

Finally, we discuss the nanophotonic platform that can be used to implement our proposal. A photonic-crystal cavity with C_6 symmetry can support two degenerate cavity modes with orthogonal polarizations [21]. The two cavity modes are thus not coupled to each other (since their polarizations are orthogonal), and can be easily addressed independently by a laser. At the same time, a QD can be coupled to both cavity modes, if it is placed spatially at the center of the cavity with its dipole moment aligned at a 45° angle to the polarizations of both modes.

Two potential issues can arise from fabrication imperfections in a realistic system: a frequency difference Δ_{ab} between the two cavity modes and a mismatch between the QD coupling strengths g_a and g_b to each mode. These issues can be seen in the preliminary experimental results shown in the Supplement [16]. To examine the robustness of the proposed scheme against these imperfections, we plot their effects on $g^{(2)}(0)$ in Fig. 4. Figure 4(a) shows the numerically calculated $g^{(2)}(0)$ as a function of the detuning between the two cavity modes Δ_{ab}. We observe that the sub-Poissonian character of the transmitted light vanishes when $\Delta_{ab} \geq \kappa$. This negative effect of frequency difference of the two modes can be balanced simply by increasing the cavity decay rate κ, i.e., by lowering the cavity quality factor. This results in an increase of the frequency overlap between the two modes and makes the degeneracy of the two modes more robust. The effects of this improvement outweigh the penalty incurred on the system's performance by reducing the g/κ ratio, and we can see in Fig. 4(a) that a strong sub-Poissonian output can still be produced. Additionally, we analyze the performance of the system as a function of the ratio g_b/g_a, where g_b and g_a are the QD coupling strengths with the cavity modes a and b assuming mode a is coherently driven. It can be shown from the effective model that at a large g_b/g_a ratio, we essentially drive only the empty cavity β and the photon statistics is Poissonian (see Supplemental Material [16]). Similarly, at a small g_b/g_a ratio, we drive only the cavity α with coupled QD and the photon statistics is super-Poissonian due to photo-induced tunneling [16]. When $g_b/g_a \sim 1$, we meet the optimal condition of interference between the coherent state and super-Poissonian state to generate light with sub-Poissonian photon statistics. This can be seen in the numerical simulations of $g^{(2)}(0)$ as a function of g_b/g_a in Fig. 4(b). The system performance is insensitive to the actual value of g_a for a relatively large range, as long as the ratio g_b/g_a is maintained. At the same time, we can see that the lowest value of $g^2(0)$ is achieved for the ratio of coupling strengths $g_b/g_a \sim 0.8$. We note that this ratio depends on the driving strength of the laser, and can be related to the requirement for similar transmission from the cavities α and β.

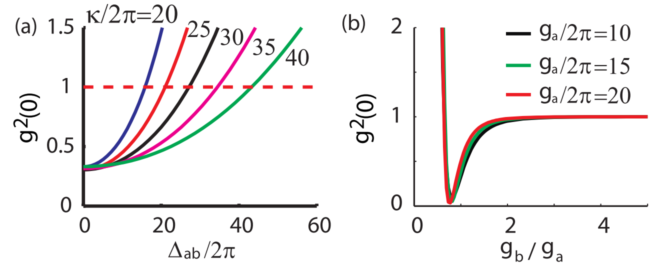

FIG. 4 (color online). (a) Second-order autocorrelation $g^{(2)}(0)$ of the cavity transmission, as a function of the relative detuning Δ_{ab} between two cavity modes for different cavity field decay rates $\kappa = \kappa_a = \kappa_b$. The quality of the sub-Poissonian photon stream in the transmitted output degrades with increasing detuning, which can be compensated by increasing κ, thereby maintaining low $g^{(2)}(0)$. For these simulations we assume $g_a/2\pi = g_b/2\pi = 10$ GHz and $\mathcal{E}/2\pi = 0.1$ GHz. (b) Second-order autocorrelation $g^{(2)}(0)$ of the cavity transmission as a function of the ratio g_b/g_a for different g_a. The transmitted light behaves like a coherent state at high g_b/g_a ratio and like a super-Poissonian state generated via photoinduced tunneling at low g_b/g_a ratio. In between, when $g_b/g_a \sim 1$, we observe strong sub-Poissonian output. Here, $\kappa/2\pi = 20$ GHz for both cavity modes.

In summary, we introduced a scheme for generation of sub-Poissonian light in a cQED system with a bimodal cavity and provided a theoretical and numerical analysis of its performance. For similar system parameters, the bimodal cavity can provide a much better sub-Poissonian character of the transmitted photon stream ($g^{(2)}(0) \sim 0.1$) compared to a single mode cavity [$g^{(2)}(0) \sim 0.9$]. We also introduce an equivalent model which explains the effect as an interference between a coherent state and a super-Poissonian state generated by photon-induced tunneling, and a balance between the nonlinearity and the loss of the system is required to observe it. Moreover, the effect disappears in the absence of the cavity loss ($g/\kappa \to \infty$). This interplay between loss and nonlinearity has great potential to be exploited for the design of realistic coupled cavity arrays for efficient quantum simulation.

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