Generation of two-mode field squeezing through selective dynamics in cavity QED

Pengbo Li
State Key Laboratory for Mesoscopic Physics, Department of Physics, Peking University, Beijing 100871, China
(Dated: February 2, 2008)

We propose a scheme for the generation of a two-mode field squeezed state in cavity QED. It is based on two-channel Raman excitations of a beam of three-level atoms with random arrival times by two classical fields and two high-Q resonator modes. It is shown that by suitably choosing the intensities and detunings of fields the dynamical processes can be selective and two-mode squeezing between the cavity modes can be generated at steady state. This proposal does not need the preparation of the initial states of atoms and cavity modes, and is robust against atomic spontaneous decay.

PACS numbers: 03.65.Ud, 42.50.Dv, 42.50.Pq

Squeezing is one of the most striking features of quantum optics, which can be simply defined as the reduction of quantum fluctuations in a certain quadrature below the vacuum level, at the expense of increasing them in its canonically conjugate variable. Various theoretical schemes and experimental protocols have been proposed or even implemented to produce the squeezed states of electromagnetic field. Recently, with the advent of quantum information and communication, squeezed states of light have played very important roles in numerous quantum information protocols, e.g., the realizations of continuous variable computation and teleportation. Also two-mode squeezed states can lead to efficient distribution of entanglement and implementation of quantum channels by improving the low Squeeze parameters. Two-mode squeezing has already been realized through Kerr nonlinearity in optical fibers and with atomic clouds in optical cavities. In the context of cavity QED, two-mode field squeeze operators in optical cavities with atomic ensembles have been proposed. Also two-mode squeezing of separated atomic ensembles has been presented. Most recently, a scheme for generating two-mode field squeezing has been proposed, which is based on atomic reservoir in four-wave mixing processes in cavity QED. However, to implement this protocol, one has to prepare the two-level Rydberg atoms in a coherent superposition of ground state and excited state before the atoms enter the cavity.

In this paper, we propose a scheme for the generation of a two-mode field squeezed state in cavity QED. It does not need neither the preparation of the initial state of the atoms nor the initial state of the cavity. The whole system has only to stay in the ground states initially. This proposal is based on two-channel Raman excitations of a beam of three-level atoms with random arrival times by two classical fields and two high-Q cavity modes. This process corresponds to a form of atomic reservoir engineering, where the resonator is pumped randomly by a beam of atoms which constitute a spin reservoir. We show that by suitably choosing the intensities and detunings of fields the dynamical processes can be selective, which is utilized to generate two-mode squeezing between the cavity modes at steady state. To implement this scheme it does not require atomic detection nor velocity selection, and is robust against atomic spontaneous decay. With presently available experimental setups in cavity QED this protocol can be realized.

Our proposal relies on the two-channel Raman excitations of a beam of three-level Λ configuration atoms. As sketched in Fig. 1, two classical fields of frequencies of a beam of three-level Λ configuration atoms can lead to efficient distribution of entanglement and implementation of quantum channels by improving the low squeezing parameters. Two-mode squeezing has already been realized through Kerr nonlinearity in optical fibers and with atomic clouds in optical cavities. In the context of cavity QED, two-mode field squeeze operators in optical cavities with atomic ensembles have been proposed. Also two-mode squeezing of separated atomic ensembles has been presented. Most recently, a scheme for generating two-mode field squeezing has been proposed, which is based on atomic reservoir in four-wave mixing processes in cavity QED. However, to implement this protocol, one has to prepare the two-level Rydberg atoms in a coherent superposition of ground state and excited state before the atoms enter the cavity.

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frequency \( \nu_i (i = 1, 2) \). We consider dispersive detunings
\[ |\Delta_1|, |\Delta_2|, |\Delta_1 - \Delta_2| \gg |\Omega_1|, |g_1|, |\Omega_2|, |g_2|. \]
Since level \( \ket{e} \) is coupled dispersively with both levels \( \ket{g} \) and \( \ket{h} \), it can be adiabatically eliminated and atomic spontaneous emission can be neglected. Then we obtain the effective Hamiltonian describing the two-channel Raman excitations of the atoms
\[
H_{\text{eff}} = \left( \frac{|\Omega_1|^2}{\Delta_1} + \frac{|g_2|^2}{\Delta_2} \right) \hat{a}_1 \hat{a}^\dagger_2 \hat{\sigma}_{hh} + \left( \frac{|\Omega_2|^2}{\Delta_2} + \frac{|g_1|^2}{\Delta_1} \right) \hat{a}^\dagger_1 \hat{a}_1 \hat{\sigma}_{gg} \\
+ \left( \frac{\Omega_1 g_1}{\Delta_1} \hat{a}_1^\dagger \hat{a}^\dagger_2 \hat{\sigma}_{gh} + \left( \frac{\Omega_1 g_2}{\Delta_1} \hat{a}_1^\dagger \hat{a}_1 + \frac{\Omega_2 g_2}{\Delta_2} \hat{a}^\dagger_1 \hat{a}^\dagger_2 \right) \hat{\sigma}_{gg} \right)
\]
The first two terms correspond to dynamical energy shifts of levels \( \ket{g} \) and \( \ket{h} \), and the last two terms describe transitions between these levels, accompanied by creation or annihilation of a photon in the respective cavity mode. In the following we assume that \( \Omega_1, \Omega_2, g_1, \) and \( g_2 \) are real for simplicity.

This effective Hamiltonian can be rewritten as
\[
H_{\text{eff}} = H_0 + (\Theta_2 \hat{a}^\dagger_2 - \Theta_1 \hat{a}_1) \hat{\sigma}_{hh} + H.c.,
\]
where
\[
H_0 = \left( \frac{|\Omega_1|^2}{\Delta_1} \right) \hat{a}^\dagger_2 \hat{a}^\dagger_2 - \left( \frac{|\Omega_1|^2}{\Delta_1} \right) \hat{\sigma}_{hh} + \left( \frac{|\Omega_2|^2}{\Delta_2} \right) \hat{a}^\dagger_1 \hat{a}^\dagger_1 \hat{\sigma}_{gg},
\]

\[
\Theta_t = |\frac{\Delta_t}{\Omega_t}|, \quad \Theta_2 = |\frac{\Omega_2}{\Delta_2}| = |\frac{\Omega_2}{\Delta_20}| \]

The use of the two-mode squeezing operator \( S_{12}(\epsilon) = \exp(\epsilon \hat{a}_1 \hat{a}_1^\dagger \hat{a}_2 \hat{a}^\dagger_2) \) we can bring the Hamiltonian (3) to the second order anti-Jaynes-Cummings Hamiltonian \( H = H_0 + H_1 \), with
\[
H_1 = -\Theta_b (\hat{b}^\dagger \hat{b}^\dagger_2 \hat{\sigma}_{hh} + \hat{b}^\dagger \hat{b} \hat{\sigma}_{gg}), \quad \Theta_1 > \Theta_2, \quad (4)
\]
\[
H_1 = \Theta_b (\hat{b}_1^\dagger \hat{b}_2 \hat{\sigma}_{hh} + \hat{b}_2 \hat{\sigma}_{gg}), \quad \Theta_1 < \Theta_2. \quad (5)
\]
Here \( \Theta_b = (\Theta_1 + \Theta_2) \sqrt{(1 - r)/(1 + r)} \) with \( \epsilon = \tanh^{-1} r \), while the value of \( r = \frac{\Theta_1}{\Theta_2} \) if \( \Theta_1 < \Theta_2 \), otherwise \( r = \frac{\Theta_2}{\Theta_1} \) if \( \Theta_1 > \Theta_2 \). The new bosonic operators \( \hat{b}_1, \hat{b}_2 \) can be obtained from \( \hat{a}_1, \hat{a}_2 \) by the two-mode squeezing transformation, \( \hat{b}_j = S_{12}(\epsilon) \hat{a}_j S_{12}(\epsilon)^\dagger \). This Hamiltonian describes an effective two-level atom coupled to the cavity modes. The ratio of \( \Theta_1 \) to \( \Theta_2 \) determines to which of the transformed modes the two-level transition couples.

To get more insight into the coupled system of the effective two-level atom and cavity modes, we define \( |n_1, n_2\rangle_a \) and \( |n_1, n_2\rangle_b \) as the eigenvectors of the number operators \( \hat{a}^\dagger_1 \hat{a}_1 \) and \( \hat{b}^\dagger_1 \hat{b}_1 \), respectively. The corresponding eigenvalues are \( n_j = 0, 1, 2, ..., j = 1, 2 \). The two bases are related by the transformation \( |n_1, n_2\rangle_b = S_{12}^\dagger(\epsilon) |n_1, n_2\rangle_a \). In particular, the vacuum state in the \( b \) basis is a two-mode squeezed state of the two cavity modes, \( \ket{0}_b = S_{12}^\dagger(\epsilon) |0\rangle_a = \sum_n \frac{(\tanh \epsilon)^n}{\cosh \epsilon} |n\rangle_a \). The degree of squeezing is determined by the \( r \) and thus by the ratios \( \frac{|\Omega_1|}{|\Omega_2|} \) and \( \frac{|g_1|}{|g_2|} \). For \( \Theta_1 > \Theta_2 \) (\( \Theta_1 < \Theta_2 \)), the state \( |g, 0, 0\rangle \) (\( |h, 0, 0\rangle \)) is the ground state of the new Hamiltonian, i.e., \( H |g, 0, 0\rangle = 0 \). A general two-mode squeezed state can be realized by utilizing the coherent displacement operator for the two modes, i.e., \( |\alpha_1, \alpha_2, \epsilon\rangle = D_1(\alpha_1)D_2(\alpha_2)S_{12}^\dagger(\epsilon) |0, 0\rangle_a \). Here \( D_i(\alpha_i) = \exp(\alpha_i \hat{a}_i^\dagger - \alpha_i^* \hat{a}_i) \).

After obtaining the selective interaction of the coupled system, we now show how to prepare the cavity modes in the two-mode squeezed states through atomic reservoir engineering. This is achieved by an effective dissipation process in the \( b \) basis and needs two steps to be implemented. Step 1: We set \( \Theta_1 = |\frac{\Omega_1}{\Delta_1}| = |\frac{\Omega_1}{\Delta_10}| > \Theta_2 = |\frac{\Omega_2}{\Delta_2}| = |\frac{\Omega_2}{\Delta_20}| \). Then the atoms enter the cavity in the ground state \( \ket{g} \) and undergo the dynamics of Eq.(4). In this case the average excitations from mode \( \hat{b}_1 \) can be removed. Step 2: Subsequently we set \( \Theta_1 = |\frac{\Omega_1}{\Delta_1}| = |\frac{\Omega_2}{\Delta_2}| < \Theta_2 = |\frac{\Omega_2}{\Delta_2}| = |\frac{\Omega_2}{\Delta_20}| \) and the dynamics of Eq.(5) can be selected. In this situation the atoms enter in another ground state \( \ket{h} \) and absorb in average excitations from mode \( \hat{b}_2 \). In order to select this dynamics one has to change the intensities of the pump fields (Rabi frequencies) and the transition frequencies of the three-level atom (detunings), i.e., \( |\Delta_1| = |\frac{\Omega_1}{\Delta_10}| \Delta_20 \) and
\[
|\Delta_2| = |\frac{\Omega_2}{\Delta_20}||\Delta_10| \]. The relation \( |\Omega_1| - |\Omega_2| > |\Omega_1| - |\Omega_2| \) has to be maintained and the sum of the two detunings in the two steps keep constant, i.e., \( |\Delta_1| + |\Delta_2| = |\Delta_1| + |\Delta_2| \).

This proposal utilizes the atomic reservoir engineering, where the resonator is pumped by a beam of atoms with random arrival times. On the other hand, the atoms should have a low pumping rate in order to ensure that at most one atom is inside the cavity at a time. We assume the weak coupling conditions, but only with respect to the parameters of the effective two-level system, then the interaction of a single atom with the cavity is a small perturbation. Let \( \tau \) be the interaction time, with \( \Theta_1 > \Theta_2 \), and make all atoms be initially in the ground state \( \ket{g} \) in step 1 and in state \( \ket{h} \) in step 2. The differential change on the density matrix \( \hat{\rho}_c \) of the cavity in each step \( j = 1, 2 \) is given by
\[
\frac{\partial \hat{\rho}_c}{\partial t} = -\gamma (\hat{b}^\dagger_2 \hat{b}_2 \hat{\rho}_c - \hat{b}_2 \hat{b}^\dagger_2 \hat{\rho}_c + \hat{\rho}_c \hat{b}^\dagger_2 \hat{b}_2), \quad (6)
\]
where \( \gamma = r_a \Theta^2_b \tau^2 \) and \( r_a \) is the atomic arrival rate. Therefore, in each step \( j \) we have \( \langle \hat{b}^\dagger_2 \hat{b}_2 \rangle_c \) and \( \hat{\rho}_c \) is the density matrix of the cavity. At times \( t \gg 1/\gamma \), we have the vanishing average photon number in mode \( b \). This implies that the steady state of the cavity is the vacuum state in the \( b \) basis. In terms of the original field modes, this procedure means that the atoms pump in phase only the two-mode squeezed state. So we have the following field state at steady state
\[
\hat{\rho}_c^{ss} = |0, 0\rangle \langle 0, 0 | = \hat{S}_{12}^\dagger(\epsilon)|0, 0\rangle_a \langle 0, 0 | \hat{S}_{12}(\epsilon). \quad (7)
\]
We denote the field quadratures for the cavity modes as $\hat{X}_i = \frac{1}{2}(\hat{a}_i + \hat{a}_i^\dagger)$ and $\hat{P}_i = -\frac{i}{2}(\hat{a}_i - \hat{a}_i^\dagger)$, respectively. Then the variances in the sum and difference operators in the state (7) are $V(X_1 \pm X_2) = V(P_1 \mp P_2) = \frac{1}{2}\exp[\pm 2\tanh^{-1}(r)]$. Therefore, two-mode squeezing, i.e., Einstein-Podolsky-Rosen (EPR) correlations are established between the cavity modes at steady state[20, 21]. This state is reached independently of the the initial state of the cavity modes, given that each step is implemented for a sufficiently long time $T$.

It is necessary to analyze the proposal requirements. To realize this scheme, it needs changes in the intensities of the pump fields and the transition frequencies of the atoms. It is fairly easy to tune the intensities of the pump fields in experiments. To change the transition frequencies of the atoms, an external static field can be utilized. This protocol needs neither the preparation of the initial state of the cavity nor the initial state of the cavity. The whole system has only to stay in the ground states initially. It does not need the atomic detection nor control of the atomic velocities and numbers either.

The atomic spontaneous emission is strongly suppressed during the interaction with the cavity modes due to large atom-field detunings. On the other hand, dissipation of the cavity field should be negligible in the experiments. The time $T$ for each step to reach the excited state at a rate $\gamma e^{2\Delta_1/2}$ depends on the initial value $\langle \hat{b}_j^\dagger \hat{b}_j \rangle_0 =: n_0$, i.e., $T = \gamma^{-1}\ln(n_0/e)/n_0$. Here $n_0 = r^2/(1 - r^2)$ when the cavity modes are in the vacuum state initially. For the degree of squeezing $\epsilon \sim 1.83(r \sim 0.95)$, from the above parameters we have a total experimental time $2T \sim 7$ ms, in case of an initially empty resonator. This result is in line with the currently experimental setups. Resonators stable over 100 ms have been reported recently[23]. In Fig. 2 we plot the estimated total time to prepare the squeezed states and the corresponding average photon number per mode at steady state as a function of the parameter $r$. From the figure it can be seen that for the squeezing degree $\epsilon \sim 1.83(r \sim 0.95)$, at steady state one can obtain an average number of 9 photons per cavity mode. This needs about 7 ms to produce the two-mode squeezing, with a fidelity $F \sim 0.99$.

It is noted that the present proposal is valid on conditions that the cavity modes should not decay during the experiment. We discuss this scheme in the weak coupling regime, but one also can get the same results in the strong coupling conditions by randomizing the interaction times. This protocol has two distinct advantages. It does not need the preparation of the initial states of the atoms and the resonators. All the atoms have only to stay in the ground states before entering the empty cavity. This offers an convenience in the experiments. Another advantage is that the atomic decay can hardly influence this scheme. The two-channel Raman excitations offer the other convenience in the experiments.

In conclusion, we have proposed a scheme for the generation of a two-mode field squeezed state in high-Q resonators. This proposal relies on a form of quantum reservoir engineering and the two-channel Raman excitations of a beam of three-level atoms. It does not need neither the preparation of the initial state of the cavity nor the initial state of the cavity. It is shown that by suitably choosing the intensities and detunings of fields the dynamical processes can be selective, which can be utilized to generate two-mode squeezing between the cavity modes at steady state. This protocol is robust against atomic spontaneous decay and can be realized with presently available experimental setups in cavity QED.

This work was supported by the National Natural Sci-
ence Foundation of China under Grants Nos. 10674009, 10334010, 10521002, 10434020 and National Key Basic Research Program No.2006CB921601. Pengbo Li acknowledges the quite useful discussions with Hongyan Li.

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