Preparation of Stationary Fock States in a One-Atom Raman Laser

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We demonstrate the possibility of preparing low-photon-number eigenstates of a single damped cavity mode coupled to a single three-level atom in a Raman lambda configuration. As an example we discuss cesium and show that both the atom-field coupling strength and the cavity loss rate needed for an experimental realization of the proposed scheme lie within 1 order of magnitude of what is achievable in current experimental setups.

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The preparation of eigenstates of the photon-number operator of a single cavity mode, i.e., its stationary states, has been a long-standing issue in quantum optics. On the one hand, such a number state is the prototype of a nonclassical state of the light field, i.e., a state with no classical analog [1], and, on the other hand, many *gedanken experiments* concerning fundamental concepts of quantum measurement theory are based on such states [2]. So far several methods for preparing number states have been proposed [3] in the micromaser as well as in the optical regime. However, most of them are based on the assumption of a lossless cavity, which restricts their applicability to relatively short times, at least in the optical regime. We propose a novel scheme which leads to a *stationary* number state inside the cavity even for a lossy cavity. The method is based on a state selective intracavity feedback mechanism, which permanently monitors the cavity photon number and immediately restores a cavity photon, each time, when a photon has decayed out of the cavity. As we will show below, this rather complicated mechanism can simply be implemented in a single three-level atom in a Raman lambda configuration with intracavity pumping as depicted in Fig. 1. In principle this mechanism is closely related to the dynamic intensity noise reduction scheme for Raman lasers as presented in Ref. [4].

We consider a single three-level atom in a lambda configuration (Fig. 1) interacting resonantly with a quantized mode of an optical cavity on the transition $|2_a\rangle$-$|1_a\rangle$. An external coherent driving field is coupled to the $|0_a\rangle$-$|1_a\rangle$ transition. The cavity mode is damped with the rate κ. Spontaneous decay on the lasing transition $|1_a\rangle$-$|2_a\rangle$ and on the recycling transition $|2_a\rangle$-$|0_a\rangle$ with rates γ_1 and γ_2 is included.

The Hamiltonian describing the interaction with the cavity mode and the coherent driving field reads [4]

$$H_I = i\hbar\frac{1}{2}(\Omega\sigma_{01} - \text{H.c.}) + i\hbar g(a^\dagger\sigma_{21} - \text{H.c.}), \qquad (1)$$

where $\sigma_{ij} = |i_a\rangle\langle j_a|$ are the atomic transition operators, Ω is the Rabi frequency of the pump field, g is the coupling strength of the atom and the cavity, and $a^\dagger$ (a) is the laser mode photon creation (annihilation) operator.

We solve the full atom-field master equation numerically, using a discrete set of bare states $\{|j_a, n_f\rangle, j_a = 0, 1, 2; n_f = 0, 1, ..., n_{\max}\}$ with an appropriate truncation $n_{\max}$ in the photon number [5].

In the following we will demonstrate that under appropriately chosen operating conditions in this system it is possible to generate stationary states of the intracavity field, which are very close to the Fock states. We consider the case of a good cavity ($\kappa \ll \gamma_1, g$) and allow for detuning Δ_p of the pump light Ω from the corresponding transition $|0_a\rangle$-$|1_a\rangle$. In Fig. 2 the steady-state intracavity mean photon number as well as the Mandel Q parameter, defined by $Q = \frac{\langle n^2 - \langle n\rangle^2\rangle}{\langle n\rangle} - 1$, is plotted as a function of the driving field Rabi frequency Ω for $\Delta_p = g$ (solid line) and $\Delta_p = 0$ (dashed line). Note that the decay rates of the atom and the cavity have been set to unrealistic values from an experimental point of view in order to demonstrate the relevant physical effect more clearly. Surprisingly, in the case with $\Delta_p = g$ a first threshold (i.e., transition from zero to one intracavity photon) occurs at a much lower pump field as compared to the case of resonant pumping $\Delta_p = 0$. Within 1 order of magnitude of Ω (note that the pump field Rabi frequency in Fig. 2 is plotted on a logarithmic scale) the intracavity field is then very close to a one-photon Fock state for $\Delta_p = g$

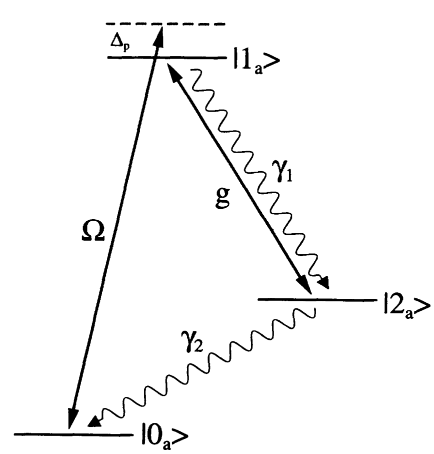

FIG. 1. Schematic representation of the three-level atom.

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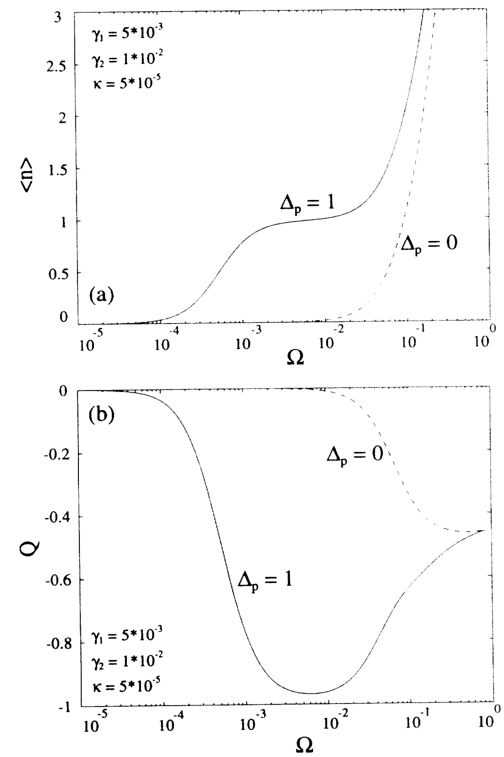

FIG. 2. (a) Steady state intracavity mean photon number and (b) Mandel Q parameter vs Rabi frequency of the pump field Ω. All rates and frequencies are given in units of g.

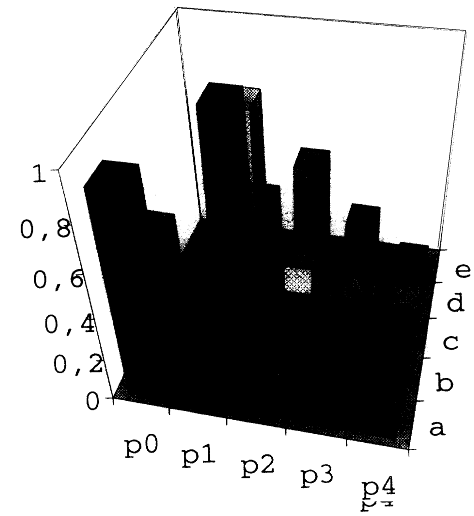

FIG. 3. Photon-number distribution for several values of Ω in units of g: curve a, $\Omega = 10^{-4}$; b, $\Omega = 3\times10^{-4}$; c, $\Omega = 3\times10^{-3}$; d, $\Omega = 3\times10^{-2}$; e, $\Omega = 10^{-1}$. The other parameters are chosen as in Fig. 2.

($Q \simeq -1$ and $\langle n\rangle \simeq 1$), whereas in the same range of Ω the field remains below threshold close to zero photons for $\Delta_p = 0$. At larger pump fields a threshold occurs also in the case $\Delta_p = 0$, whereas the field in the case with nonzero pump detuning loses its extremely strong sub-Poissonian photon statistics. Finally, in the limit of large pump fields in both cases one finds $Q \simeq -0.5$, which is the same value as has been predicted in the case of a multiatom Raman laser [4]. Figure 3 shows the behavior of the photon-number distribution $p_n = \langle n|\mathrm{Tr}_{\mathrm{atom}}\{\rho\}|n\rangle$ for the above parameters for various specific values of Ω in more detail. Increasing the pump strength one gets a transition from a thermal-like photon-number distribution (curve a) via a one-photon eigenstate (curve c) towards a Poisson-like distribution as depicted in curve e.

In a next step in order to understand the basic physical mechanism leading to the generation of Fock states, we demonstrate the dependence of the photon statistics on the pump detuning. Figure 4 shows the behavior of the mean photon number and the Mandel Q parameter for two different cavity damping rates κ as a function of the pump detuning Δ_p in a narrow interval around $\Delta_p = \sqrt{2}g$.

The Rabi frequency of the pump field Ω and the recycling rate γ_2 is chosen such that Q is minimized for $\Delta_p = \sqrt{2}g$, i.e., we get almost a two-photon Fock state. For the smaller value of κ we find a quite sharp resonance centered at $\Delta_p = \sqrt{2}g$. The width of the resonance becomes larger and the minimum value of Q becomes higher for increasing κ.

The aforementioned detuning dependence suggests the following qualitative explanation of the mechanism lead-

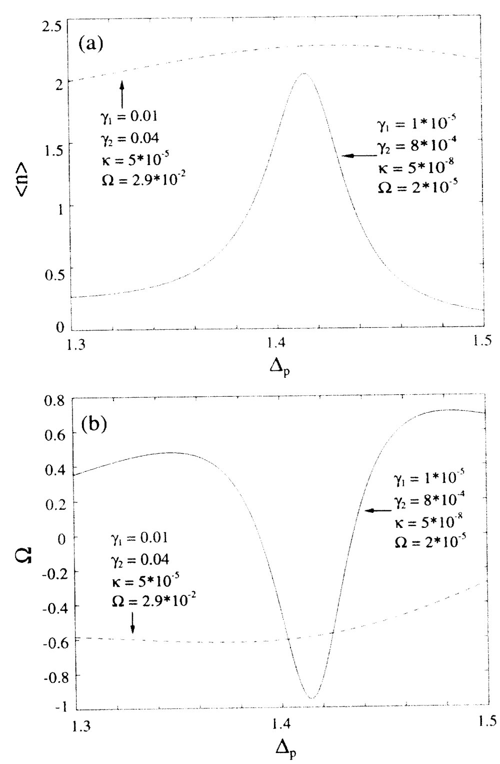

FIG. 4. (a) Mean photon number and (b) Mandel Q parameter vs pump detuning. All rates in units of g.

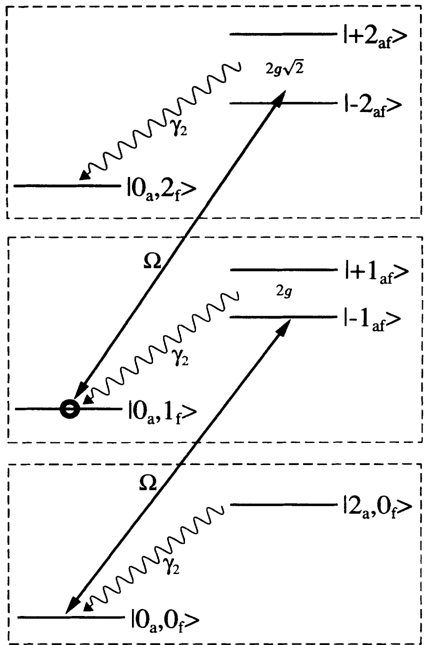

FIG. 5. Lowest dressed levels of the atom-field system.

ing to the above reported effects, which can be given in terms of dressed states of the coupled atom-field system. In Fig. 5 a schematic representation of the lowest energy levels of the combined atom-field system is shown. Under the assumption $\Omega \ll g$ we find the following manifolds of eigenstates, energetically separated by the laser frequency:

$$\{|0_a,0_f\rangle,|2_a,0_f\rangle\},\quad \{|0_a,1_f\rangle,|\pm 1_{af}\rangle\},\quad \{|0_a,2_f\rangle,|\pm 2_{af}\rangle\},\dots \quad (2)$$

$|\pm n_{af}\rangle = \frac{1}{\sqrt{2}}[|1_a,(n-1)_f\rangle \pm i|2_a,n_f\rangle]$ are dressed levels for zero detuning. Note that the ac Stark splitting depends on the intracavity field, i.e., $\Delta_{\mathrm{ac}} = 2g\sqrt{n_{af}}$. For simplicity the transition arrows for the spontaneous decay between the lasing levels and for the cavity decay (these would go straight downwards in the ladder by one step) are not depicted. Let us assume that the pump detuning is chosen such that the pump laser is resonant with the $|0_a,0_f\rangle$-$|+1_{af}\rangle$ transition. Let us further assume that the system is initially in the ground state $|0_a,0_f\rangle$. The population is then coherently transferred to the $|+1_{af}\rangle$ dressed level. The level $|+1_{af}\rangle$ decays partly to the first manifold via γ_1 and κ and to the level $|0_a,1_f\rangle$ via the decay γ_2 on the recycling transition. In this level (which is a one-photon Fock state) the population is "trapped" for two reasons: The decay due to cavity loss back to the ground state happens on the relatively slow cavity decay rate. Additionally, the pump laser is out of resonance with respect to the upward transition to the second manifold $|0_a,1_f\rangle$-$|+2_{af}\rangle$ due to the larger ac Stark splitting of $2\sqrt{2}g$. Hence this transition probability is very small as well. On the other hand, if the system decays via cavity escape of a photon to the ground state, the population is quickly transferred back to the second manifold because the pump laser is in resonance with the transition $|0_a,0_f\rangle$-$|+1_{af}\rangle$. The atom in the cavity thus acts as a *demon*, which permanently monitors the intracavity photon (through its Stark shift) and reacts on any deviation by quickly restoring the desired photon number.

Similar arguments hold for the preparation of Fock states of the intracavity field for higher n. In this case the detuning of the pump laser has to be chosen in such a way that the pump laser is resonant with the $|0_a,(n-1)_f\rangle$-$|\pm n_{af}\rangle$ transition. Note that the effective detuning of the pump laser to the next higher level multiplet $|0_a,(n)_f\rangle$-$|\pm(n+1)_{af}\rangle$ decreases with increasing n. Consequently the requirements for the quality of the cavity, especially concerning a high ratio of g/κ get more rigorous the higher the desired value of n.

As an example for such a system one could think, e.g., of a cesium atom two-photon pumped on the $6S_{1/2}$-$6D_{5/2}$ transition at $\lambda = 883.7$ nm, with the field mode strongly coupled to the $6P_{3/2}$-$6D_{5/2}$ transition at $\lambda = 918$ nm [6]. The lifetime of the $6D_{5/2}$ level and the $6P_{3/2}$ level is 65 and 31 ns, respectively. A coupling strength of the order of $g \simeq 2\pi \times 10$ MHz and a cavity decay rate of approximately $\kappa \simeq 2\pi \times 2.5$ MHz can be achieved in a current experimental setup [6]. Using these parameters we find that the minimum of Q in the case $\Delta_p = g$ is $Q \simeq -0.20$. Reducing the cavity decay κ rate by a factor of 10 and simultaneously increasing the coupling strength g by the same factor, we obtain $Q \simeq -0.80$ for the same detuning. Hence under these operating conditions, which seem able to be reached in the foreseeable future, a state very close to a one-photon number state could be prepared. Of course even much higher values of g/γ_1 and g/κ have already been achieved in micromaser setups [7].

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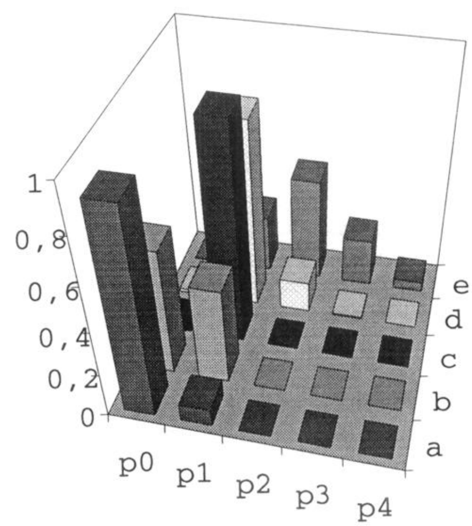

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