# A thresholdless single-atom laser based on multi-photon resonances in a driven Jaynes-Cummings system


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The single atom lasers/masers in which no more than a single atom is in interaction with the quantized field reveal a variety of fundamental phenomena in quantum optics. The schemes of single-atom lasers/masers may be categorized largely into two groups: In the first, the inversion of a two-state atom is timely picked up to provide gain as in the micromaser/microlaser[1, 2], while in the other, a multi-level atom is pumped by various excitations to create inversion in the lasing transition[3, 4]. These, however, may be viewed as miniaturizations of the conventional CW lasers in essence down to the single atom level. In the strong coupling regime, the combined system of the atom–cavity will constitute the "Jaynes-Cummings Molecule" that has infinite number of energy levels known as the Jaynes-Cummings Ladder (JCL)[5, 6]. The system is therefore already a multi-level system, there being no need to use a multi-level atom. In this work, we consider a driven JCM in which a two-state atom interacting with a *non-resonant* single mode of the cavity field is driven by an external field of *arbitrary* frequency. The Hamiltonian of the system is

$$H = \frac{1}{2}\hbar\omega_{\rm A}\sigma_z + \hbar\omega_{\rm C}a^\dagger a + i\hbar g\left(\sigma_+ a - \sigma_- a^\dagger\right) + i\hbar\mathcal{E}\left(\sigma_+ e^{-i\omega_{\rm L}t} - \sigma_- e^{i\omega_{\rm L}t}\right) , \tag{1}$$

where $\omega_{\rm A}$ and $\omega_{\rm L}$ denote the atomic transition and the driving field frequency, respectively; $a(a^\dagger)$, the cavity field annihilation(creation) operator; $\sigma_\pm$, the atomic pseudo-spin operators such that $[\sigma_+, \sigma_-] = \sigma_z$, with $\mathcal{E}$, the driving field amplitude; and $g$, the vacuum Rabi frequency.

We have investigated the variation of the maximum intracavity photon number $\langle a^\dagger a\rangle_M$, scanning the cavity frequency $\omega_{\rm C}$ for a given driving field frequency. An anomalously high excitation of cavity mode was observed at a certain set of detunings as shown in Fig. 1. We found that this high excitation can be understood in terms of multi-photon resonances in the JCL. When $N$ external driving field quanta are absorbed to excite a transition from the lowest state to the lower branch $|N,-\rangle$ or the upper branch $|N,+\rangle$ of the $N$-th manifold in the JCL, the following relation is satisfied:

$$\Delta_{\rm LA} = \left(1 - \frac{1}{2N}\right)\Delta_{\rm CA} \pm \sqrt{\frac{g^2}{N} + \left(\frac{\Delta_{\rm CA}}{2N}\right)^2} , \tag{2}$$

where $\Delta_{\rm LA} \equiv \omega_{\rm L} - \omega_{\rm A}$ and $\Delta_{\rm CA} \equiv \omega_{\rm C} - \omega_{\rm A}$. In other words, when we measure the intracavity photon number as a function of $\Delta_{\rm CA}$, a resonance peak shows up whenever $\Delta_{\rm CA}$ satisfies Eq. (2)

for a given $\Delta_{LA}$. A close examination of Eq. (2) reveals that the lower-branch resonance lines (with "-" sign taken) becomes very closely spaced in $\Delta_{CA}$ for a fixed $|\Delta_{LA}| \gg g$. Therefore, a very high cavity photon number can be reached by the collective excitation of these multiple multi-photon resonances. When damping comes in, individual multi-photon resonance peaks are generally broadened with diminished heights, in the fashion that the higher order peaks are more vulnerable to the damping. However, the peak due to the collective excitation of the lower-branch resonances in Fig. 1(a) can be enhanced by increasing the driving field strength, even for a realistic value for the cavity damping as shown in Fig. 1(b). In this case the intracavity photon number exhibits a laser-like behavior except for the absence of any laser threshold in the input-vs-output curve as shown in Fig. 1(c). Such thresholdless lasing is a unique feature expected for a single-atom laser operating under the strong coupling condition like the present system. Furthermore, we found that introduction of proper atomic damping to the system also makes it possible to achieve a temporally stationary Fock-state in the cavity. In addition, in the strong coupling regime the atom-cavity field coupling establishes the Jaynes-Cummings Ladder system *in advance*, and the external field merely excites the levels as long as $\mathcal{E}/g \leq 10$.

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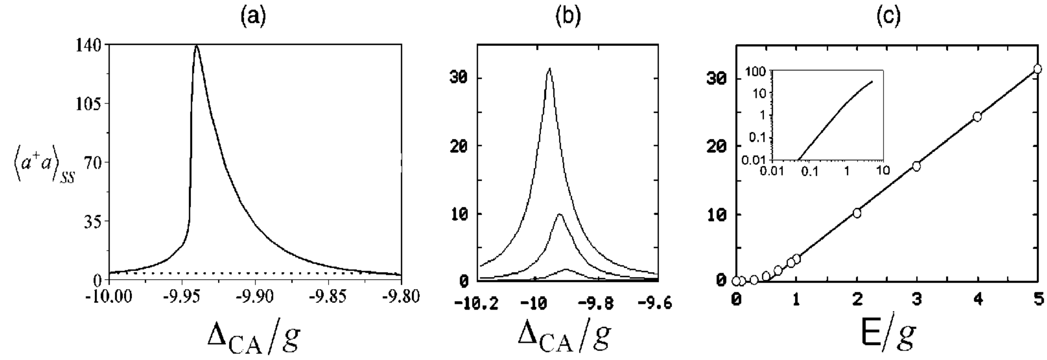


Figure 1: (a) Intracavity photon number as a function of the cavity-atom detuning for a given laser-atom detuning of $10g$. (b) In the presence of the cavity damping of $\kappa/g = 0.05$ for $\mathcal{E}/g = 0.1, 2, 5$. (c) The peak height as a function of the driving field strength.

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