Fast Excitation and Photon Emission of a Single-Atom-Cavity System

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(Dated: December 3, 2008)

We report on the fast excitation of a single atom coupled to an optical cavity using laser pulses that are much shorter than all other relevant processes. The cavity frequency constitutes a control parameter that allows the creation of single photons in a superposition of two tunable frequencies. Each photon emitted from the cavity thus exhibits a pronounced amplitude modulation determined by the oscillatory energy exchange between the atom and the cavity. Our technique constitutes a versatile tool for future quantum networking experiments.

PACS numbers: 42.50.Pq, 32.80.Qk, 37.10.Gh, 42.50.Xa

In this letter, we report on the generation of single optical photons that are much shorter than all other relevant processes. The cavity frequency constitutes a control parameter that allows the creation of single photons in a superposition of two tunable frequencies. Each photon emitted from the cavity thus exhibits a pronounced amplitude modulation determined by the oscillatory energy exchange between the atom and the cavity. Our technique constitutes a versatile tool for future quantum networking experiments.

Single atoms exchanging single optical photons are likely to be the essential components for the processing of information in distributed quantum networks. Both carriers of quantum information exhibit low decoherence rates and high controllability for information stored, for example, in the spin state of an atom and the polarization state of a photon. This fact has made it possible to implement increasingly more complex quantum protocols involving atom-photon entanglement. These implementations are likely to be the essential components for the processing of information in distributed quantum networks. Our technique further opens up new perspectives for shaping single-photon wave packets.

Our new apparatus (similar to that described in [13, 10], see Figure 1) uses an optical cavity operating in the intermediate coupling regime with \( g_{\text{max}} \). Here, \( g_{\text{max}} \) denotes the atom-cavity coupling constant averaged over all Zee-
man sublevels of the \( ^{87}\text{Rb} \) 5S\( _{1/2} \) \( F = 2 \leftrightarrow 5P_{3/2} \) transition for an atom at a field antinode, \( \gamma \) is the atomic polarization decay rate, and \( \kappa \) is the cavity field decay rate. The cavity is frequency-stabilized to an optical fiber and guided to the detection setup. SPCM: single photon counting module, NPBS: non-polarizing beam splitter, EOM: electro-optic modulator, MOT: magneto-optical trap. (b) Measured cavity output photon stream of a single atom with constant laser cooling. The standing wave trap is turned on at \( t = 0 \) with two atoms trapped during the first 300 ms.

FIG. 1: (a) \(^{87}\text{Rb} \) atoms are trapped within the TEM\(_{00} \) mode of the cavity at the intersection of a standing wave dipole trap (\( \lambda = 1064 \) nm) and an intracavity dipole trap (\( \lambda = 785 \) nm, also used for stabilizing the cavity length). Two resonant beams at \( \pm 45^\circ \) to the standing wave trap and perpendicular to the cavity axis provide cooling and fast pulse excitation. The cavity output is coupled to an optical fiber and guided to the detection setup. SPCM: single photon counting module, NPBS: non-polarizing beam splitter, EOM: electro-optic modulator, MOT: magneto-optical trap.
rated by 495 $\mu$m giving a TEM$_{00}$-mode waist of 30 $\mu$m and a finesse of 56000 (mirror transmissions 2 ppm and 101 ppm, total losses 10 ppm). The cavity output mode is coupled into a single-mode optical fiber and directed to a Hanbury Brown-Twiss photon detection setup consisting of a non-polarizing beamsplitter and two single photon counting modules. The detection efficiency for a single photon present inside the cavity is $\approx 0.34$, which includes the directionality of the cavity output ($\approx 0.9$), spectral separation from stabilization light and mode matching into the fiber ($\approx 0.85$), and the efficiency of the detectors ($\approx 0.45$).

Single $^{87}$Rb atoms are loaded into the cavity mode from a magneto-optical trap (MOT) via a running-wave dipole trap beam ($\lambda = 1064$ nm) with a focus between the MOT and the cavity [17]. When the atoms reach the cavity, the transfer beam is replaced by a standing-wave beam ($\lambda = 1064$ nm). This beam is focused at the cavity mode and provides strong spatial confinement along its axis (waist 16 $\mu$m, power 2.5 W, potential depth 3 mK). Additionally, the atoms are confined along the cavity axis by the 785 nm cavity reference laser (trap depth 70 $\mu$K).

Once trapped in the intra-cavity 2D optical lattice, the atoms are exposed to a retro-reflected cooling laser beam incident perpendicular to the cavity axis. The cooling beam is near resonant with the $F = 2 \leftrightarrow F' = 3$ transition (see below) and uses a linear polarization configuration. Light resonant with the $F = 1 \leftrightarrow F' = 2$ transition co-propagates with the cooling beam for optical pumping out of the $F = 1$ ground state. A cavity emission signal of a single atom trapped and cooled inside the cavity is shown in Figure 1(b).

Long trapping times are observed under cavity-enhanced cooling conditions over the range $-70$ MHz $\leq \Delta_{\text{cool}}/2\pi \leq -2$ MHz while keeping $(\Delta_{\text{cav}} - \Delta_{\text{cool}})/2\pi = +5$ MHz, where $\Delta_{\text{cool}}$ and $\Delta_{\text{cav}}$ are the detunings of cooling laser and cavity with respect to the unperturbed $F = 2 \leftrightarrow F' = 3$ atomic resonance. However, most important for this experiment, we are able to achieve trapping times of several seconds even outside the previously studied cavity-cooling regime [15]. This occurs, for example, with a fixed cooling laser frequency at $\Delta_{\text{cool}}/2\pi = -50$ MHz and by varying the cavity frequency from $-45$ MHz $\leq \Delta_{\text{cav}}/2\pi \leq +100$ MHz. This suggests that Sisyphus-like cooling [18] is the dominant mechanism, with resulting atomic temperatures comparable to those measured in [15]. The advantage is now that the cavity frequency is a free parameter while maintaining sufficiently long atom trapping times.

Fast excitation of the atom-cavity system is accomplished by switching off the cooling light and periodically driving the $F = 2 \leftrightarrow F' = 3$ transition with $\approx 3$ ns long laser pulses (FWHM). These pulses are created by amplitude modulation of continuous-wave light using a fiber-coupled electro-optic modulator (EOM, Jenoptik model AM780HF). Due to the finite on-off ratio of the EOM [19], we detune the center frequency of the excitation pulses from the cavity resonance by $-30$ MHz to suppress continuous-wave excitations [20]. Nevertheless, the atom is still excited by the short pulse (measured bandwidth $\approx 200$ MHz). Following the fast excitation, ideally one photon will be produced because the laser pulse is much shorter than the atomic lifetime ($26$ ns) and the on-resonance build-up time for a field inside the cavity ($\tau_{\text{field}} \approx \pi/2g_{\text{max}} = 50$ ns). As the system is driven on a cycling transition, no repumping is required before the next excitation pulse. This scheme allows a pulse repetition rate of up to 5 MHz, limited by the duration of the emitted single photon wave packet ($\leq 200$ ns). For all measurements presented here, the pulse repetition rate is 670 kHz.

Similar to the excitation of an atom in free space [13], the fast laser pulse transfers the atom to the excited state $|e\rangle$. However, the atom-cavity state $|e,n = 0\rangle$, where $n$ is the intracavity photon number, is not an eigenstate of the coupled system. With atom and cavity tuned into resonance, and for the moment neglecting dissipation, the system exhibits oscillations according to

$$|\Psi(t)\rangle = \frac{\Omega}{2} |e,0\rangle + \frac{\Omega}{2} |g,1\rangle ,$$

where $|g\rangle$ is the atomic ground state and $\Omega = 2g$ is the vacuum Rabi frequency [21]. This delays the peak of the photon emission compared to an atom in free space, as displayed in Fig. 2. For longer times, the oscillation is damped out due to atomic and cavity decay resulting in a smooth wave packet envelope.

The single-photon nature of this excitation scheme is verified by a measurement of the intensity correlation function $g^{(2)}(\tau)$ evaluated from photons arriving within 200 ns after the excitation pulse. We observe a high

![FIG. 2: Histogram: normalized arrival time distribution of photons emitted from the trapped atom-cavity system as a function of time after the excitation pulse. Solid filled curve: measured shape of the excitation pulse. Dotted line: exponential decay of the photon emission for an atom in free space. Inset: Schematic of the atom-cavity system, excitation pulse, and an emitted single photon.](image)
suppression (90%) of coincidence events at time \( \tau = 0 \) demonstrating that the protocol does indeed result in single photons. The remaining coincident detections come from multiple trapped atoms (\( \sim 8\% \)) and dark counts of the photon detectors (\( \sim 2\% \)). In contrast to free-space emission [12], the probability of emitting two photons from the atom-cavity system from one excitation pulse is greatly suppressed (\( \sim 10^{-4} \)) as the single-photon field must first build up in the cavity before the photon can be emitted.

Our measured probability of emitting a single photon into the cavity mode following an excitation pulse is \( \sim 8\% \) for \( \Delta_S = \Delta_{\text{cav}} = 80 \text{ MHz} \) and \( \Delta_{\text{pulse}} = 50 \text{ MHz} \). Here \( \Delta_S \) denotes the atomic AC-Stark shift due to the dipole trap, and \( \Delta_{\text{pulse}} \) is the detuning of the center frequency of the excitation pulses (with respect to the unperturbed \( F = 2 \leftrightarrow F' = 3 \) atomic transition). The photon production efficiency is limited by a number of technical difficulties. For instance, as the atom is not prepared in a well defined initial Zeeman sublevel before each pulse, the average excitation probability saturates at \( \sim 50\% \) due to the indeterminate transition strengths. Also, the average photon decay probability into free space (\( \sim 80\% \)) is a limitation since the atom-cavity cooperativity decreases due to motion-induced variation of \( g \). However, with appropriate choice and improvement of excitation and cavity parameters, the photon emission efficiency can in principle approach unity [10, 12].

The shape of the emitted photon can be further controlled by applying a detuning between the Stark-shifted atomic resonance and the cavity resonance \( \Delta_{\text{ac}} = \Delta_S - \Delta_{\text{cav}} \). The coupled system then oscillates between the states \( |e, 0 \rangle \) and \( |g, 1 \rangle \) at a frequency

\[
\Omega' = \sqrt{4g^2 + \Delta_{\text{ac}}^2}. \tag{2}
\]

Note that because \( \gamma \approx \kappa \), shifts of the oscillation frequency due to damping are negligible [21]. We observe these oscillations for a single atom trapped within a standing wave, however, the position-dependent Stark shift reduces the measured contrast. A more constant, and in particular smaller, Stark shift is maintained in a running-wave trap (\( \Delta_S \approx 2\pi \times 17 \text{ MHz} \)). We ensure that less than one atom is present in the cavity at any time by again measuring the \( g^{(2)}(\tau) \) correlation function. As seen in Fig. 3, the emitted photon wave packets exhibit modulations according to the population dynamics of state \( |g, 1 \rangle \). Note that no externally applied driving field is present during the oscillations, and the measured features are not due to many-photon or many-atom effects [22, 24, 25].

We find good agreement between the measured photon wave packet shapes and an analytical model (solid lines in Fig. 3). The model consists of an oscillating term for the occupation of state \( |g, 1 \rangle \) and an exponential damping term due to atomic and cavity decay. Further, we include the experimental shot-to-shot uncertainty of \( \Omega' \) using a Gaussian distribution of fixed width (10 MHz), which accounts for position-dependent Stark shifts and variations of \( g \). We numerically fit this model to the data and extract values of \( \Omega' \) as a function of atom-cavity detuning (Fig. 4). The extracted frequencies match well the predicted hyperbolic function (Eq. (2)) with a reduced chi-squared \( \chi^2 = 1.13 \). These measurements can also be understood as time-domain normal-mode spectroscopy of a coupled single-atom-cavity system in the optical regime. In this interpretation, the observed modulation originates from a quantum beat at the frequency difference between the energy levels of the first pair of atom-cavity dressed states (Fig. 4 inset) [26].

A complementary illustration of the coherent oscillations between the atom and the cavity is investigated by pumping the system along the axis of the cavity (Fig. 5). In this case, a weak 3 ns laser pulse excites the atom-
cavity system such that when an output photon is detected, we know the system was in $|g, 1\rangle$ immediately after excitation. We observe a deviation from a pure exponential decay of the intra-cavity field as the energy is temporarily stored in the atom. Quantitatively, we can retrieve the temporal evolution of the population in state $|e, 0\rangle$ by subtracting this signal from the exponential decay of the empty cavity at rate $2\kappa$. The inset of Fig. 5 compares this difference signal with the measured evolution of $|g, 1\rangle$ from the experiment with transverse excitation. The nearly identical time dependence of the two signals testifies to the coherent exchange of energy between atom and field.

In future experiments, by terminating the atom-cavity oscillations with a suitably timed atomic de-excitation pulse, the fast excitation technique should allow one to design single photons with duration shorter than the system’s decay time $\frac{1}{2\kappa}$. This includes the possibility to generate time-symmetric photons important for quantum networking [17]. Additionally, a single photon in a superposition of two tunable frequencies, as demonstrated here, may be useful as a frequency qubit [18, 21].

Our scheme may also find application in the investigation of higher-lying dressed states in cavity QED systems [21] and for the deterministic generation of multi-photon Fock states $|n\rangle$. Finally, our fast excitation technique can improve existing atom-photon entanglement experiments [8] by reducing unwanted multiple-photon events, and can be extended to multi-photon entanglement protocols [22].

The authors thank K. Murr for useful discussions and B. Bernhard, T. Wilken and R. Holzwarth for providing the frequency comb signal. This work was partially supported by the Deutsche Forschungsgemeinschaft (Research Unit 635) and the European Union (IST program, SCALA). G. L.-K. acknowledges support from the Rosa Luxemburg Foundation. D. L. M. acknowledges support from the Alexander von Humboldt Foundation.

FIG. 5: Measured photon arrival time distribution for excitation of the cavity with no atoms (filled dots) and $\lesssim 1$ atom (histogram). The inset compares the temporal evolution of state $|g, 1\rangle$ for transverse pumping (solid line) with that of $|e, 0\rangle$ for cavity pumping (dashed line), illustrating the complementary dynamics.