A Many-Atom Cavity QED System with Homogeneous Atom-Cavity Coupling

Jongmin Lee, Geert Vrijsen, Igor Teper, Onur Hosten, and Mark A. Kasevich

Physics Department, Stanford University, Stanford, CA 94305, USA
(Dated: November 8, 2013)

We demonstrate a many-atom-cavity system with a high-finesse dual-wavelength standing wave cavity in which all participating rubidium atoms are nearly identically coupled to a 780-nm cavity mode. This homogeneous coupling is enforced by a one-dimensional optical lattice formed by the field of a 1560-nm cavity mode.

OCIS codes: (020.0020) Atomic and molecular physics, (120.3940) Metrology, (140.4780) Optical resonators, (300.6260) Spectroscopy, diode lasers

There has been growing interest in collective interactions of large ensembles of atoms with cavity fields, in addition to experiments [1, 2] pursuing cavity quantum electrodynamics (cQED) with individual atoms. Topics studied include cavity-aided entanglement generation (spin squeezing) for quantum-enhanced metrology [3–5]; opto-mechanics with atoms, where collective motional degrees of freedom are coupled to cavity fields [6, 7]; cavity-enhanced atomic quantum memories for quantum information processing [8]; and ultra-narrow-linewidth lasers using narrow-transition ultra-cold atoms as the gain medium for metrological purposes [9, 10]. Important in many such systems is the inhomogeneity in the coupling strength between the participating atoms and the cavity field, which degrades the coherence of the interactions and complicates the dynamics and the analysis of the basic physics by obscuring the relevant system parameters [11].

Limiting our attention to Fabry-Pérot type cavities, in which the modes are standing waves, homogeneous coupling of atoms to the relevant cavity field (the probe mode) can be achieved by tightly trapping the atoms with a spatial period that is commensurate with the wavelength of the probe. Thus far, experimentally realized trapping configurations have involved incommensurate trap-probe periods, resulting in inhomogeneous atom-probe couplings that often require the definition of effective, averaged coupling constants [7]. Two recent efforts came to our attention that investigate commensurate dual-wavelength cavity designs; one utilizes a traveling-wave cavity to trap and probe atoms in which there is no particular atom registration [12], and the other utilizes a standing wave cavity, for the different purpose of investigating atomic self organization [13].

In this Letter, we present the realization and some characteristics of a many-atom cQED system employing probe and trapping modes that are commensurate. We use a dual-wavelength cavity with high finesse at both 780 nm, used to probe the D₂ transition in ⁸⁷Rb, and 1560 nm, used to trap the atoms in a far-detuned one-dimensional lattice. At the central region of the cavity, depending on the exact wavelength relationship, these commensurate probe and trapping wavelengths allow an in-phase as well as an out-of-phase registration of the atoms (Fig. 1(b)). In the former case the atoms are localized at the maxima of the probe mode profile, attaining a maximal coupling strength, and in the latter they are localized at the minima, showing that properly positioned atoms can be nearly invisible to light circulating inside the cavity. The work presented here builds on some of our previous results [11, 14, 15], but the description is self-contained.

At the heart of our experimental apparatus is a compact cavity assembly schematically shown in Fig. 1(a), constructed from Zerodur glass (low helium permeability and small thermal expansion coefficient (≃ 10⁻⁸/K)). This assembly includes a current-controlled rubidium dispenser (Alvatec) and a two-dimensional magneto-optical trap (MOT), which prepares a collimated beam of atoms that passes through a 1.5 mm aperture into the main chamber to load a three-dimensional (3D) MOT. Extension tubes attached to the main chamber hold the low-loss cavity mirrors. The Zerodur glass contacts, except the mirror end-caps, are held together with a sodium silicate molecular bonding agent, and the glass-metal contacts for the ion pump and the dispenser are sealed with Indalloy. The mirror end-caps, to which the mirror substrates are glued, are attached to the extension tubes with a thin layer of high-temperature epoxy (Epoke 353ND). The epoxy contacts of the chamber can endure a baking tempera-
The spectral lines to drive the cavity are generated from an external-cavity diode laser operating at 1560 nm (New Focus Vortex) stabilized to a TEM00 cavity mode. The 1560 nm master laser is first actively frequency stabilized (∼5 MHz lock bandwidth) to a reference cavity via the Pound-Drever-Hall (PDH) method [14]. A 1560 nm slave diode laser is injection-locked to the light transmitted by the reference cavity to remove amplitude fluctuations, and its output is amplified to ∼250 mW by an erbium-doped fiber amplifier (EDFA) and split into two paths. The first path gets frequency-doubled to 780 nm in a periodically-poled lithium niobate (PPLN) waveguide followed by injection into a 780 nm slave diode laser. The second path is phase-modulated with an electro-optic modulator (EOM) at δm ∼ 40 MHz, and one of the sidebands is locked to the in-vacuum cavity via the PDH method (∼100 kHz lock bandwidth), using an acousto-optic modulator (AOM) situated before the 1560 nm slave diode laser and the piezo-electric transducer of the reference-cavity as the fast and slow feedback elements, respectively. Once locked, the 1560 nm master laser follows a resonance of the reference cavity, which in turn follows a resonance of the in-vacuum cavity as its length drifts. The frequency-doubled 780 nm probe light is then used to produce a heterodyne beatnote measurement between the 780 nm carrier and sidebands of interest.

The relevant spectral lines are shown in Fig. 2(b). The 1560 nm sideband locked to the cavity serves as the trapping lattice light, and a sideband of the 780 nm slave laser (generated by an EOM at ∼6 GHz) serves as the probe light that couples near-resonantly to the trapped atoms, facilitating the measurement of the cavity resonance frequency in presence of intra-cavity atoms; both of these modes are TEM00. The cavity frequency measurement is accomplished via a heterodyne beatnote measurement between the 780 nm carrier and sidebands as the probe sideband is frequency swept over the cavity resonance (similar to PDH method). Not shown in the figures is a microwave horn placed outside of the vacuum chamber that coherently drives the ∼ 6.835 GHz 87Rb hyperfine clock transition of interest (|F = 1, m_f = 0⟩ ↔ |F = 2, m_f = 0⟩).

In a typical experiment, atoms trapped in the 3D MOT are first further cooled to ∼15 μK by switching to a far-detuned MOT (12γ red-detuned) for ∼25 ms followed by a polarization-gradient cooling stage (54γ red-detuned) for ∼7 ms. This cooling takes place in the presence of a weak 1560 nm optical lattice that is required to keep the lasers locked to the cavity. Near the end of polarization-gradient cooling we adiabatically increase the lattice power by up to a factor of 100 and typically load 10^4 − 10^5 atoms distributed over a thousand volumes.
sand lattice sites, with a $1/e$ lifetime of 1.1 s, mainly limited by background gas collisions. The possibility of applying the regular cooling sequence in the full lattice power condition is hindered by the presence of strong red Stark-shift gradients on the $5P$ excited states with an effective frequency detuning $\Delta$, which we typically set around 1 GHz $\gg \gamma$. The resulting refractive index of the $|F = 2\rangle$ atoms shifts the resonance frequency of the probe mode, while the effects of absorption are minor. Note that atoms in $|F = 1\rangle$ states also give rise to probe shifts, but an order of magnitude larger due to the larger detuning, which we will omit for simplicity. The amount of probe mode shift produced by an atom located at position $r_i$ can be expressed in terms of the position-dependent atom-cavity coupling constant $g_i \equiv g(r_i)$, as $\partial \nu_i = g_i^2/\Delta$. The shift produced by all the atoms is then $\partial \nu = \sum_i \partial \nu_i$.

We utilize this cavity shift to show that we can trap the atoms entirely either at the anti-nodes or at the nodes of the probe mode, corresponding to in-phase and out-of-phase registrations, respectively.

Fig. 2(a) shows the inferred atomic registration parameter $\xi = (\sum_i g_i^2)_{\text{trap}}/(\sum_i g_i^2)_{\text{mot}}$ for three different probe mode frequencies separated by one FSR. This parameter compares the coupling strength of an unlocalized ensemble to that of a registered ensemble. Here $(\sum_i g_i^2)_{\text{mot}} = \delta \nu_{\text{mot}} \Delta_{\text{mot}}$, $(\sum_i g_i^2)_{\text{trap}} = \delta \nu \Delta$, where $\delta \nu_{\text{mot}}$ and $\delta \nu$ are the observed cavity shifts before and after the atoms are loaded into the optical lattice, respectively; $\Delta_{\text{mot}}$ and $\Delta$ are the effective detunings for the corresponding cases. For every change in the frequency of the probe in steps of a FSR, the wavelength of the probe changes by half a wavelength resulting in the overlap with the lattice near the cavity center to alternate between in-phase and out-of-phase registrations.

The finite temperature of the atomic cloud leads to imperfect registration, as hotter atoms explore larger volumes in the trapping sites, leading especially to a finite coupling for the out-of-phase registration. Thus, the measured ratio of 6.2 ± 0.2 of the in-phase to out-of-phase atom registration parameters can provide a direct measure of the temperature of the trapped atoms at a given lattice depth. Assuming a thermal distribution for the atoms in the lattice sites, and utilizing the measured differential ac Stark shift of the hyperfine clock states (fig. 2(b)) to infer the lattice depth, we arrive at $\sim 70 \mu$K for the temperature of the atoms in a lattice depth of 870 $\mu$K which gives 598 Hz and 265 kHz for the transverse and axial trap frequencies. Thus, for this configuration, each atomic “pancake” in the 1D lattice have rms widths of 22 $\mu$m in the transverse and 50 nm in the axial directions, to be compared with the probe waist of 111 $\mu$m and the probe lattice period of 390 nm respectively. Due to this finite size, the mean coupling strength $(g^2)$ for the in-phase registration is 74% of the value that would be obtained for perfectly localized atoms, and the coupling strength has a standard deviation of 24% over the ensemble. However, for atom-probe interaction times much larger than the axial trap period of 3.8 $\mu$s, the axial inhomogeneity averages out and the relevant standard deviation, e.g. for obtaining probe induced ac Stark shift inhomogeneities, becomes 14%. For the case of out-of-phase registration, similar calculations
In summary we demonstrated homogeneous coupling of atoms to a standing wave cavity mode and the potential use of the dispersive measurements as a spectroscopic tool. Although in the described version of the apparatus, the cavity read-out noise is at the atomic shot noise for $10^4$ atoms, with further improvements we expect the possibility of generating spin-squeezed states potentially up to 20 dB below shot noise variance. Thanks to the homogeneous atom-cavity coupling, the generated squeezed states could be released into free space to be used as input states to atom interferometric sensors for enhanced sensitivity. In addition, the described apparatus might enable atom counting in mesoscopic ensembles with an actual quantized signal, which so far has been challenging [17].

**Acknowledgments**

This work was funded by DARPA and the MURI on Quantum Metrology sponsored by the Office of Naval Research. We thank the Fejer group for providing the PPLN.

**References**

[1] H. Mabuchi and A. C. Doherty, Science 298, 1372 (2002).
[2] H. J. Kimble, Physica Scripta T76, 127 (1998).
[3] M. Schleier-Smith, I. D. Leroux, and V. Vuletić, Phys. Rev. Lett. 104, 073604 (2010).
[4] I. D. Leroux, M. Schleier-Smith, and V. Vuletić, Phys. Rev. Lett. 104, 073602 (2010).
[5] Z. Chen, J. Bohnet, S. R. Sankar, J. Dai, and J. K. Thompson, Phys. Rev. Lett. 106, 133601 (2011).
[6] F. Brennecke, S. Ritter, T. Donner, and T. Esslinger, Science 322, 235 (2008).
[7] T. Purdy, D. Brooks, T. Botter, N. Brahms, Z. Ma, and D. Stamper-Kurn, Phys. Rev. Lett. 105, 133602 (2010).
[8] H. Tanji, S. Ghosh, J. Simon, B. Bloom, and V. Vuletić, Phys. Rev. Lett. 103, 043601 (2009).
[9] D. Meiser, J. Ye, D. R. Carlson, and M. Holland, Phys. Rev. Lett. 102, 163601 (2009).
[10] J. G. Bohnet, Z. Chen, J. M. Weiner, D. Meiser, M. J. Holland, and J. K. Thompson, Nature 484, 78 (2012).
[11] I. Teper, G. Vrijsen, J. Lee, and M. A. Kasevich, Phys. Rev. A 78, 051803 (2008).
[12] S. Bernon, T. Vanderbruggen, R. Kohlhass, A. Bertoldi, A. Landragin, and P. Bouyer, New J. Phys. 13, 065021 (2011).
[13] K. J. Arnold, M. P. Baden, and M. D. Barrett, Phys. Rev. Lett. 109, 153602 (2012).
[14] A. K. Tuchman, R. Long, G. Vrijsen, J. Boudet, J. Lee, and M. A. Kasevich, Phys. Rev. A 74, 053821 (2006).
[15] R. Long, A. K. Tuchman, and M. A. Kasevich, Opt. Lett. 32, 2502 (2007).
[16] R. W. P. Drever, J. L. Hall, F. V. Kowalski, J. Hough, G. M. Ford, A. J. Munley, and H. Ward, Appl. Phys. B 31, 97 (1983).
[17] H. Zhang, R. McConnell, S. Cuk, Q. Lin, M. Schleier-Smith, I. D. Leroux, and V. Vuletic, Phys. Rev. Lett. 109, 133603 (2012).

Fig. 3. (a) Atom registration parameter as a function of probe detuning from the $F = 2$ to $F' = 3$ transition. Registration ratio: $6.2 \pm 0.2$. (b) Differential ac Stark shift of the clock states as a function of the estimated trap depth: $-0.74 \text{Hz/} \mu \text{K}$, measured by the microwave transition frequency. (c) Rabi oscillations with a period of 10.73 ms and 57 ms coherence time measured via the cavity shift.

show a mean coupling strength of 12% of the maximal.

The dispersive cavity measurements described here can be used as a sensitive spectroscopic tool. For example, fig. 3(c) shows Rabi oscillations due to a particular microwave drive resonantly coupling the clock transition. The measured quantity is the population in the upper clock state after a given duration of microwaves, observed by cavity shifts, showing a coherence time of 57 ms. With similar methods, Ramsey oscillation sequences with echo, implemented inside the lattice $(\pi/2$-pulse, $T/2$-delay, $\pi$-pulse, $T/2$-delay, $\pi/2$-pulse), show $1/e$ coherence times up to $T=205$ ms.