Long storage time of collective coherence in an optically trapped Bose-Einstein condensate

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Our recent work has demonstrated the superradiant writing and reading of collective coherence in a Bose-Einstein condensate [Phys. Rev. Lett. **99**, 220407 (2007)]. This time we report the drastic improvement of the storage time realized by loading the atoms into an optical dipole trap, wherein an unfavorable spin-dependent phase shift and spatial diffusion of atoms can be suppressed. The measured storage time was 0.57(2) ms, which is limited by the temporal variation of atomic momentum due to harmonic oscillations in the trap.

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Recently, coherent conversion of quantum states between atoms and photons has attracted considerable attention in view of its application to quantum information processing [1]. The most popular way to realize this conversion may be using nonlinear light-wave mixing in an ensemble of atoms [2]: Spontaneous Raman scattering creates atomic ground-state collective coherence first, and then its phase-conjugate process converts the coherence back into photons. So far, various applications, including generation of single photons [3–5], correlated photon pairs [6–8], and entangled states [9,10], have been successfully demonstrated with this scheme.

In these applications, the figure of merit is the conversion efficiency and the storage time of the coherence, which strongly depend on the statistical properties of samples. Hence, exploring ideal storage media has been a fundamental subject in this research area. In most of the previous experiments, the sample used was laser-cooled atoms gathered in a magneto-optical trap [3–5,7–10], exhibiting a conversion efficiency of ~50% and a storage time of several microseconds. These are basically limited by the low optical density and Doppler-limited decoherence of atoms, respectively.

More recently, we have successfully demonstrated the conversion between atomic coherence and photons using atomic Bose-Einstein condensates and bidirectional superradiant Raman scattering (SRS) [11]. By the grace of the large optical density and small momentum width of condensates, a high conversion efficiency of over 70% and a long storage time of about 0.13 ms were achieved. However, this experiment was carried out with free-falling condensates after release from a magnetic trap. The resultant mean-field expansion of condensates led to rapid dephasing [12,13] and limited the storage time, which would otherwise be much longer [14].

Here in the present work, we improved the storage time by loading condensates into a far-off-resonant optical dipole trap. Because of the absence of a spin-dependent phase shift and mean-field expansion, optical traps provide us ideal circumstances for a coherent conversion experiment compared with magnetic traps and free-falling atoms (see below). The storage time was measured to be 0.57 ms, which was more than 4 times longer than the result of our free-space experiment. We also demonstrated that the prolonged storage time is limited by the temporal variation of atomic momentum due to harmonic oscillations in the trap.

Figure 1 shows the setup and the energy-level configuration of the experiment. The write-read process of the atomic coherence is almost the same as that in our previous work [11]. An optically trapped condensate of ^{87}Rb atoms in the state $|1\rangle \equiv |5S_{1/2};F=2,m_F=2\rangle$ was illuminated by counterpropagating "write" and "read" beams from the radial direction (the optical trap will be detailed later). These beams were both π polarized with respect to the quantization axis z and tuned nearly to the transition $|1\rangle \equiv |5S_{1/2};F=2,m_F=2\rangle \rightarrow |3\rangle \equiv |5P_{1/2};F=2,m_F=2\rangle$ and $|2\rangle \equiv |5S_{1/2};F=1,m_F=1\rangle \rightarrow |4\rangle \equiv |5P_{1/2};F=1,m_F=1\rangle$, respectively. The detuning from the resonance was set to be $\Delta_W = 2\pi \times -1.0$ GHz for the write and $\Delta_R = 2\pi \times -1.8$ GHz for the read beam. The light intensities were adjusted in such a way that the single-atom

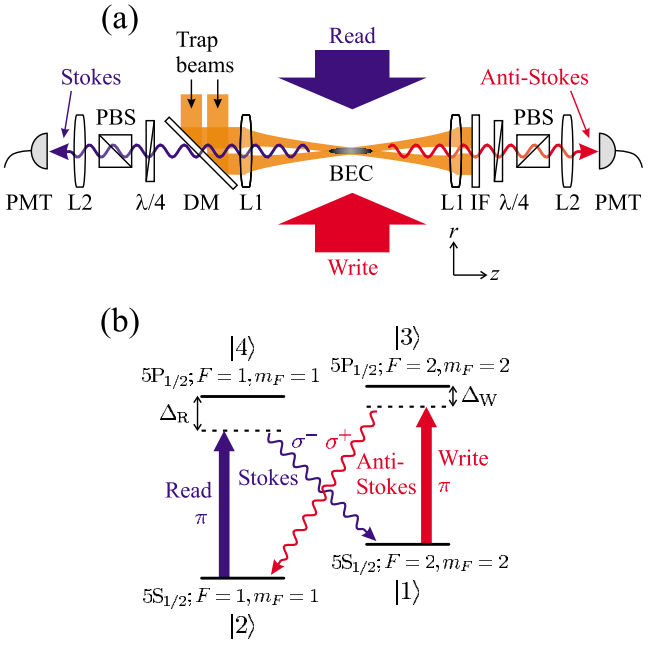

FIG. 1. (Color online) (a) Geometry and (b) energy-level diagram of the experiment. *L*1, *L*2, achromatic lens; DM, dichroic mirror; IF, interference filter; λ/4, quarter-wave plate; PBS, polarization beam splitter; and PMT, photomultiplier tube.

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Raman scattering rates for the write and read processes are almost equal.

The write beam induces anti-Stokes SRS [15], by which the atoms in the initial state $|1\rangle$ are pumped into the state $|2\rangle$, accompanied by the emission of σ^+-polarized photons along the long axis of the condensate (this radiation mode is referred to as the end-fire mode). When the wave vector of the write beam and the end-fire mode are denoted as $\boldsymbol{k}_W$ and $\boldsymbol{k}_E$, respectively, the atoms pumped into the state $|2\rangle$ receive the recoil momentum $\hbar\boldsymbol{q}=\hbar(\boldsymbol{k}_W-\boldsymbol{k}_E)$ from photons and form a macroscopic coherence "grating" with the original condensate.

The read beam induces Stokes SRS [16], whereby the recoiling atoms are coherently pumped back to the state $|1\rangle$ with the emission of σ^--polarized photons along the opposite direction to the anti-Stokes photons. In the present scheme, the Stokes process can be interpreted as the diffraction of the read beam by the preformed coherence grating. The underlying physics is thus similar to the four-wave mixing of light in nonlinear crystals [17].

The scattered anti-Stokes and Stokes photons were detected with two photomultiplier tubes (PMTs). Although SRS occurs along both the $\pm z$ directions, resulting in two pairs of correlated anti-Stokes and Stokes photons, we monitored only one pair by selecting the polarization of the photons with quarter-wave plates and polarization beam splitters in front of the PMTs.

In the present energy-level configuration, the states $|1\rangle$ and $|2\rangle$ have a different Lande's g factor. Therefore, the presence of an inhomogeneous magnetic field gives rise to rapid dephasing [16,18], which will drastically reduce the storage time. Therefore, in our previous work [11], the experiment was carried out just after the magnetic trap was turned off. Although the storage time was indeed one order of magnitude improved compared with that in the magnetic trap, the subsequent limitation was set by the mean-field expansion of condensates in free space [12,13]. The most straightforward solution for this problem is to load the atoms into the optical potential produced by linearly polarized laser beams. When the detuning of the trap beams is much larger than the frequency difference between the D_1 and D_2 lines, the light shift becomes independent of the internal state of atoms. Eventually, the spin-dependent phase shift, the mean-field expansion, and the free fall of atoms can be prevented simultaneously.

In the present experiment, the optical trap was produced by shallowly crossed two laser beams, as shown in Fig. 1(a). These beams were generated by two independent laser diodes operated at a wavelength of 964 and 974 nm and linearly polarized along orthogonal directions with each other. In this case, the optical potential is approximately proportional to the sum of their intensities and no lattice structure is formed in the intersection region. The beam waist of each beam was fixed to 44 μm and the trap depth and frequencies were adjusted through the intensities. The crossing angle was chosen to be 0.13 rad, allowing us to prepare the trapped condensate with the Fresnel number $\mathcal{F}=\pi d^2/(4\lambda l)$ of about 0.9, where λ is the wavelength of the scattered light, and d and l are the diameter and the length of the cloud, respectively. Thus, the condition for the diffraction-limited superradiance $\mathcal{F}<1$ holds [11,19] and the collective coherence can be treated as a pure single mode.

Note that we adopted this crossed-beam configuration in order to satisfy the following two practical requirements: First, l should be much smaller than the diameter of the write and read beams ≈ 1 mm for the homogeneous pumping over the sample. Second, the diffraction angle of the end-fire mode, $\approx\lambda/d$, should be smaller than 0.14 rad limited by the numerical aperture of the apparatus. Unfortunately, these were impossible to realize with a conventional single-beam trap, which has only one controllable parameter d/l.

The procedure of storage-time measurement is as follows. After the condensate production, the trap-beam intensities were increased to certain values and the driving current of the magnetic trap was decreased to zero in accordance with a hyperbolic tangent function for about 250 ms. Then, the condensate containing $N\approx 8\times 10^5$ atoms was adiabatically transferred to the optical trap with an efficiency of almost 100%. Next, the write beam was applied to the atoms for 30 μs to induce anti-Stokes SRS, by which about 4% of the atoms were transferred into the state $|2\rangle$. A coherence grating is then formed between the recoiling atoms and the condensate and begins to evolve in the trap after turning off the write beam. After a variable interval time, the read beam was applied to the atoms to induce Stokes SRS, which converts the coherence grating into Stokes photons.

Figure 2(a) shows an example of the timing sequence and the observed wave forms of the superradiant Raman pulses. The anti-Stokes and Stokes pulses show a tendency of exponential growth and exponential decay, respectively. The ratio of these pulse areas, which represents the conversion efficiency, is plotted versus interval time between the write and read beams in Fig. 2(b). Open circles are the result of the experiment performed in free space, exhibiting a $1/e$-storage time of 0.13 ms [11]. Solid circles are the result obtained in the optical trap when the trap frequency along the radial (axial) direction ω_ρ (ω_z) was $2\pi\times 143$ Hz ($2\pi\times 11$ Hz). In comparison with the result of the free-space experiment, the decay line shape could also be well fitted with a Gaussian, but the storage time was considerably improved to 0.57 ms.

The measured storage time is basically limited by the time evolution of the grating vector due to harmonic oscillations in the trap. In the present setup configuration, anti-Stokes SRS gives atoms the recoil momentum along the directions at an angle of 45° with the z axis. The atoms then begin to oscillate in the trap with different frequencies for the radial and axial directions. As a result, the grating vector temporary changes as $\boldsymbol{q}(t)=[k_\rho(t),k_z(t)]=[k_\rho(0)\cos\omega_\rho t, k_z(0)\cos\omega_z t]$, as illustrated in Fig. 3(a). In contrast, the phase-matching condition of the Stokes process is satisfied only inside the sphere with the radius of $2\pi/d$ centered at $\boldsymbol{q}(0)$, where the radial diameter of condensate d is given in the Thomas-Fermi limit by

$$d=\frac{2}{\omega_\rho}\sqrt{\frac{2\mu}{m}}, \tag{1}$$

with m being the atomic mass and μ the chemical potential of condensate written in the form

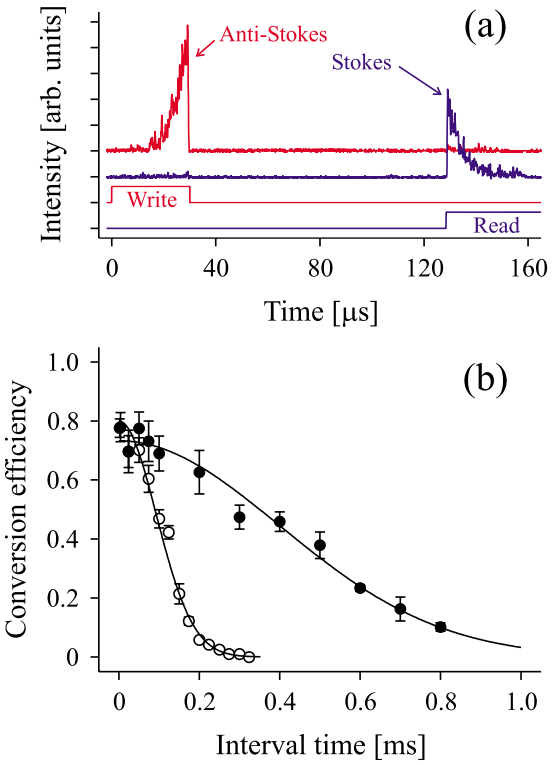

FIG. 2. (Color online) (a) Example of an experimental timing and observed wave forms of the superradiant Raman pulses. (b) Conversion efficiency versus interval time between the write and read beams. Open and solid circles represent the results taken in free space and in the optical trap, respectively. The solid lines are Gaussian fit to the data.

$$\mu = \frac{\hbar\bar{\omega}}{2}\left(15Na\sqrt{\frac{m\bar{\omega}}{\hbar}}\right)^{2/5}. \tag{2}$$

Here, $\bar{\omega}=(\omega_\rho^2\omega_z)^{1/3}$ is the geometrical mean trap frequency and a is the s-wave scattering length (5.8 nm for Rb atoms). Note that the radius of the sphere $2\pi/d$ corresponds to the diffraction angle of the end-fire mode, $\approx\lambda/d$, which determines the tolerance of the phase-matching angle for the write and read beams [5].

Taking the uncertainty of $\boldsymbol{q}$ into account, we find the duration of the phase-matching condition:

$$\Delta t \approx \frac{2}{\omega_\rho}\sqrt{\frac{\lambda}{d}}. \tag{3}$$

The overall dependence of Δt on ω_ρ is therefore $\omega_\rho^{-3/5}$.

In order to verify this argument, we measured the storage time for several trap frequencies. The result is shown in Fig. 3(b). The solid line is the theoretical curve calculated from Eq. (3), together with Eqs. (1) and (2), with no fitting parameter. Agreement between the theory and the experiment is satisfactory.

The above experiment revealed that the storage time is not determined by the dephasing (or the transverse relaxation), but limited by the sloshing motion of atoms in the trap, suggesting that the collective coherence would survive even after Δt. However, the anisotropy of the trap potential

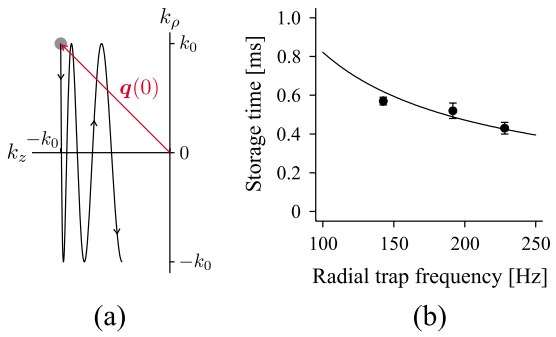

FIG. 3. (Color online) (a) Trajectory of the grating vector $\boldsymbol{q}(t)$ in an anisotropic harmonic potential. The initial grating vector $\boldsymbol{q}(0)$ is assumed to be $(k_\rho,k_z)=(k_0,-k_0)$ with $k_0=2\pi/\lambda$. The shaded region represents the tolerance of the phase-matching condition. (b) Dependence of the storage time on the radial trap frequency $\omega_\rho/(2\pi)$. The solid line is the phase-matching time given by Eq. (3).

prevents $\boldsymbol{q}(t)$ to return back to the initial location any longer, eventually limiting the storage time to Δt. Indeed, no significant Stokes pulse could be observed after one oscillation period along the radial direction ($t=2\pi/\omega_\rho$).

Another possible source that degrades the storage time may be the mismatching of the density distribution of the recoiling atoms. In the present experimental condition, the atoms transferred into the state $|2\rangle$ corresponded to only 4% of the condensate. Therefore, their steady-state density distribution is substantially different from that of the initial condensate. This mismatching may induce collective excitations (shape oscillations) for the recoiling atoms and hence additional phase evolution depending on the excitation mode [12,20,21].

The most promising way to solve these problems may be to load the atoms into an optical lattice with an isotropic trap frequency ω_0 for all directions. In this case, atomic motion can be approximated to be one dimensional and the initial state is expected to be revived at every oscillation period [22]. In addition, when the energy spacing between vibrational states is much larger than the mean-field energy at each lattice site, the external states of the condensate and the recoiling atoms reduce to the motional coherent states $|0\rangle_c=|0\rangle_h$ and $|iqr_0\rangle_c=e^{iq\hat{r}}|0\rangle_h\propto\Sigma_{n=0}^{\infty}(iqr_0)^n|n\rangle_h/\sqrt{n!}$, respectively [23]. Here, $q=|\boldsymbol{q}(0)|=2\sqrt{2}\pi/\lambda$, $r_0=\sqrt{\hbar/(2m\omega_0)}$, $\hat{r}$ is the position operator, and $|n\rangle_h$ is the nth harmonic-oscillator eigenstate. The state $|iqr_0\rangle_c$ shows merely the center-of-mass oscillation in the trap potential keeping its initial momentum width unchanged. This strongly suppresses the collective excitations and may realize a much longer storage time exceeding 100 ms (this will be limited by the atom number fluctuations [24,25]). We finally note that another solution to realize a longer storage time would be using ultracold fermions, in which the interatomic interaction is entirely absent [26].

In conclusion, we have improved the storage time of collective coherence in a Bose-Einstein condensate by loading the atoms into an optical dipole trap. The measured storage

time was 0.57 ms, which is more than 4 times longer than that obtained in the free-space experiment. The limitation of the storage time is set by the anisotropic harmonic oscillation of atoms in the trap potential. The long storage time achieved is particularly beneficial for applied experiments in a quantum regime where the number of scattered photons is reduced to less than unity [1,3–5,7–10].

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[1] L.-M. Duan, M. D. Lukin, J. I. Cirac, and P. Zoller, Nature (London) **414**, 413 (2001).
[2] M. D. Lukin, P. Hemmer, and M. O. Scully, Adv. At., Mol., Opt. Phys. **42**, 347 (2000).
[3] C. W. Chou, S. V. Polyakov, A. Kuzmich, and H. J. Kimble, Phys. Rev. Lett. **92**, 213601 (2004).
[4] T. Chanelière, D. N. Matsukevich, S. D. Jenkins, S.-Y. Lan, T. A. B. Kennedy, and A. Kuzmich, Nature (London) **438**, 833 (2005).
[5] A. T. Black, J. K. Thompson, and V. Vuletić, Phys. Rev. Lett. **95**, 133601 (2005).
[6] C. H. van der Wal, M. D. Eisaman, A. André, R. L. Walsworth, D. F. Phillips, A. S. Zibrov, and M. D. Lukin, Science **301**, 196 (2003).
[7] A. Kuzmich, W. P. Bowen, A. D. Boozer, A. Boca, C. W. Chou, L. M. Duan, and H. J. Kimble, Nature (London) **423**, 731 (2003).
[8] V. Balić, D. A. Braje, P. Kolchin, G. Y. Yin, and S. E. Harris, Phys. Rev. Lett. **94**, 183601 (2005).
[9] D. N. Matsukevich and A. Kuzmich, Science **306**, 663 (2004).
[10] C. W. Chou, H. de Riedmatten, D. Felinto, and S. V. Polyakov, S. J. van Enk, and H. J. Kimble, Nature (London) **438**, 828 (2005).
[11] Y. Yoshikawa, K. Nakayama, Y. Torii, and T. Kuga, Phys. Rev. Lett. **99**, 220407 (2007).
[12] Y. Castin and R. Dum, Phys. Rev. Lett. **77**, 5315 (1996).
[13] E. W. Hagley, L. Deng, M. Kozuma, M. Trippenbach, Y. B. Band, M. Edwards, M. Doery, P. S. Julienne, K. Helmerson, S. L. Rolston, and W. D. Phillips, Phys. Rev. Lett. **83**, 3112 (1999).
[14] J. Stenger, S. Inouye, A. P. Chikkatur, D. M. Stamper-Kurn, D. E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **82**, 4569 (1999).
[15] Y. Yoshikawa, T. Sugiura, Y. Torii, and T. Kuga, Phys. Rev. A **69**, 041603(R) (2004).
[16] D. Schneble, G. K. Campbell, E. W. Streed, M. Boyd, D. E. Pritchard, and W. Ketterle, Phys. Rev. A **69**, 041601(R) (2004).
[17] See, for example, A. Yariv, *Quantum Electronics* (Wiley, New York, 1989).
[18] Y. Yoshikawa, Y. Torii, and T. Kuga, Phys. Rev. Lett. **94**, 083602 (2005).
[19] M. Gross and S. Haroche, Phys. Rep. **93**, 301 (1982).
[20] S. Stringari, Phys. Rev. Lett. **77**, 2360 (1996).
[21] D. S. Jin, J. R. Ensher, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Phys. Rev. Lett. **77**, 420 (1996); M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. M. Kurn, D. S. Durfee, C. G. Townsend, and W. Ketterle, *ibid.* **77**, 988 (1996).
[22] M. Horikoshi and K. Nakagawa, Phys. Rev. Lett. **99**, 180401 (2007).
[23] M. Morinaga, I. Bouchoule, J.-C. Karam, and C. Salomon, Phys. Rev. Lett. **83**, 4037 (1999).
[24] J. Javanainen and M. Wilkens, Phys. Rev. Lett. **78**, 4675 (1997).
[25] G.-B. Jo, Y. Shin, S. Will, T. A. Pasquini, M. Saba, W. Ketterle, D. E. Pritchard, M. Vengalattore, and M. Prentiss, Phys. Rev. Lett. **98**, 030407 (2007).
[26] G. Roati, E. de Mirandes, F. Ferlaino, H. Ott, G. Modugno, and M. Inguscio, Phys. Rev. Lett. **92**, 230402 (2004).