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Transporting Long-Lived Quantum Spin Coherence in a Photonic Crystal Fiber

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Confining particles in hollow-core photonic crystal fibers has opened up new prospects to scale up the distance and time over which particles can be made to interact with light. However, maintaining long-lived quantum spin coherence and/or transporting it over macroscopic distances in a waveguide remain challenging. Here, we demonstrate coherent guiding of ground-state superpositions of ^{85}Rb atoms over a centimeter range and hundreds of milliseconds inside a hollow-core photonic crystal fiber. The decoherence is mainly due to dephasing from the residual differential light shift from the optical trap and the inhomogeneity of an ambient magnetic field. Our experiment establishes an important step towards a versatile platform that can lead to applications in quantum information networks and a matter wave circuit for quantum sensing.

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Long-lived quantum spin coherence is one of the key requirements in precision measurements and quantum networks [1–3]. In atomic interferometric sensors, such as atomic fountain clocks and atom interferometers, atoms are set free in a region of space well shielded from decoherence sources [1]. In quantum memories, the information is encoded in the coherence of spin states, which are normally confined locally in a well-engineered trap to be immune from decoherence [3]. In either case, the atoms and coherence are localized within zero or one spatial dimension. To extend the use of quantum coherence into fully three-dimensional coordinates, conveying atoms in a quantum superposition state over a configurable path has been a long-standing goal.

Unlike photons, the quantum coherence of spin states is more susceptible to decoherence from the guiding environment. For neutral atoms, the restoring force used for confining atoms is generally through the coupling to the gradient of optical or magnetic fields [4]. Coherent guiding of the Bose-Einstein condensate using a magnetic trap has been demonstrated on the scale of a few hundred micrometers [5], but the ability to guide and maintain coherence over longer distances is challenging. Although optical conveyor belts in free space have transported a superposition state of atoms over a 1 mm range, the Rayleigh range over which a laser beam stays focused limits the guiding distances [6]. Moreover, the methods above cannot be easily reconfigured to the desired trajectories.

Optical fiber technologies have provided a new platform to extend the scalability and flexibility for guiding atoms. For optical nanofibers, atoms are trapped a few hundred nanometers away from the surface by the evanescent waves of the guided mode [7]. The coherence time of stationary atoms has been demonstrated to a few milliseconds [8].

Trapping and guiding of atoms in hollow-core photonic crystal fibers [9–11] have been demonstrated over centimeter distances [12–19]; however, the ability to maintain the coherence of quantum superposition states over a large distance is still unclear. A moving atom interferometer has been demonstrated inside a hollow-core photonic crystal fiber, but the coherence time was limited by the dephasing caused by the trapping potential to tens of microseconds [16]. Here, we study the quantum coherence of ^{85}Rb atoms trapped by the fundamental mode of a hollow-core photonic crystal fiber and extend the coherence time to hundreds of milliseconds by mitigating decoherence from the inhomogeneous broadening of the differential light shift (DLS). We further demonstrate the transportation of quantum spin coherence over a range of centimeters.

The details of the experimental setup are shown in Fig. 1. A 4-cm-long hollow-core photonic crystal fiber from GLOphotonics (PMC-CTiSa-Er-7C) is mounted vertically inside an ultrahigh vacuum chamber. The fiber inner core diameter is $63\text{ }\mu\text{m}$, and the $1/e^2$ mode field radius W is $22\text{ }\mu\text{m}$. The cladding area of the fiber has a hypocycloid-core kagome lattice structure to inhibit coupling between the fundamental mode and higher order modes [20]. It also supports a significant spatial separation between the fundamental mode and the inner wall to minimize the interaction between the surface and atoms [20]. The dominant atom-surface interaction in our experiment is the temperature dependent van der Waals potential $U_L = k_B T_E \alpha_0 / (4r^3)$, where k_B is the Boltzmann constant, T_E is the equilibrium temperature of the surface, α_0 is the static polarizability of the atom, and r is the distance of the atoms from the inner fiber wall [21]. This interaction causes atoms at different positions having different resonant frequencies which results in inhomogeneous dephasing

FIG. 1. Experimental configuration. (a) Experimental setup. NPBS: nonpolarizing beam splitter. PBS: polarizing beam splitter. DM: dichroic mirror. QWP: quarter-wave plate. PM fiber: polarisation maintaining fiber. APD: avalanche photodiode. HCF: hollow-core fiber. All the optical components are outside the vacuum chamber. The polarization of the two optical dipole beams is adjusted by the quarter wave plates for differential light shift cancellation. The coupling efficiency of the dipole beams is 65%. (b) Time scales for atoms' position in the setup. The left scale shows the position of the atoms relative to the fiber in the moving lattice at 2.2 cm/s starting from MOTs position at $t_p = 0$ ms. The right scale shows the position of the atoms in the moving lattice at 2.2 cm/s (long ticks) followed by free-falling under gravity while still confined radially by the top dipole beam (short ticks) starting at $t_p = 250$ ms. For coherence measurements of free-falling atoms, we reset the timing when atoms begin the free fall. (c) Relevant atomic energy levels. (d) Time sequences. Each experimental cycle includes 400 ms for cooling atoms. B_x , B_y , and B_z are external magnetic fields for shifting the atomic ensemble and defining quantization axis for atom-light interactions. The π pulse is present for spin-echo sequences and absent for Ramsey sequences.

when measuring an ensemble of atoms. For $T_E = 300$ K and $r = 26.5$ μm , the ground state energy shift of ^{85}Rb is at the level of a few mHz which is negligible in our experiment.

A three-dimensional magneto-optical trap (MOT) is aligned about 5 mm above the fiber tip to capture and cool room temperature ^{85}Rb atoms from background vapor. After sub-Doppler cooling, there are about 10^9 atoms at a temperature $T_{\text{atom}} = 10$ μK . Atoms are released from the MOT at $t_p = 0$ and loaded into a moving optical lattice formed by a pair of counterpropagating fields in the fiber. The velocity v is determined by $v = \delta f \lambda / 2 = 2.2$ cm/s, where $\delta f = 50$ kHz is the frequency detuning of the two lattice fields, and $\lambda = 875$ nm is the lattice wavelength. Push beams with 2 ms duration resonant on both the $F = 3$ to $F' = 4$ and $F = 2$ to $F' = 3$ transition are sent horizontally to push atoms away from the vicinity of the fiber tip to ensure only atoms inside the fiber participate in the coherence time measurements. The root mean square radius r_0 of the atomic cloud in the fiber is $[W^2 k_B T_{\text{atom}} / (2U)]^{1/2} \sim 5$ μm , where $T_{\text{atom}} \sim 90$ μK is the measured atom radial temperature in the lattice, and $U = 537$ μK is the optical trapping potential.

When atoms are inside the fiber, the detuning between the lattice beams is ramped down to zero to form a stationary lattice. The atoms are then optically pumped to $F = 2$, $m = 0$ via one 1 ms long intrafiber π -polarized optical pump pulse resonant on the $D1$ line $F = 2$ to $F' = 2$

transition and one linearly polarized depump pulse resonant on the $D2$ line $F = 3$ to $F' = 3$ transition. We study the coherence of the hyperfine clock states $F = 2$, $m = 0$ and $F = 3$, $m = 0$ of stationary ^{85}Rb atoms using microwave Ramsey $\pi/2$ - T - $\pi/2$ and spin-echo $\pi/2$ - $T/2$ - π - $T/2$ - $\pi/2$ sequences, where $T(T/2)$ is the pulse separation time. These sequences have been widely used to identify reversible decoherence mechanisms and, more importantly, to characterize irreversible decoherence mechanisms of atomic coherence [22]. For the hyperfine ground states of alkali-metal atoms, different polarizabilities of the states in the optical potential cause different energy shifts which lead to the inhomogeneous DLS of the transition due to the nonuniform transverse profile of the trapping potential.

At the end of a microwave Ramsey or spin-echo sequence, we perform state-selective detection of atoms in $F = 3$. This is achieved by measuring the transmission T_r of a 3 nW, 50 μs probe pulse, resonant (far below the saturation power of 30 nW) on the $F = 3$ to $F' = 4$ transition, through the fiber. The measured transmission is converted to optical depth $\text{OD} = -\ln(T_r)$, a quantity directly proportional to atom number in $F = 3$ [16]. Throughout this Letter, we typically measure a maximum $\text{OD} \sim 1$, which corresponds to about 15 000 atoms. By scanning the phase ϕ of the last $\pi/2$ microwave pulse, we map out the Ramsey fringe as a sinusoidal oscillation in the OD vs microwave phase ϕ . The inset in Fig. 2(a) shows an

FIG. 2. Coherence time measurement of stationary atoms trapped inside the fiber. (a) Contrast vs pulse separation time T . The coherence times T_c for open triangles, squares, and circles are 3.0(1), 37.2(7), and 60.1(1) ms respectively. The trapping potential of the stationary lattice is 537 μ K. Atoms are transported into the fiber using a moving lattice at 2.2 cm/s for 200 ms and then kept stationary while coherence measurements proceed. Inset: Exemplary Ramsey fringe for pulse separation time $T = 3$ ms. The error bars indicate the standard error of 4 experimental runs. The continuous line is a sinusoidal fit to the data from which we extract the contrast C . (b) Spin-echo measurement with DLS cancellation of two different trapping potentials 279 μ K (squares) and 179 μ K (circles). The solid lines are fits using the exponential function $A \times \exp(-T/T_c)$, and the $1/e$ decay times T_c are 101(2) and 252(8) ms, respectively. Atoms are transported into the fiber using a moving lattice at 2.2 cm/s for 250 ms and then kept stationary while coherence measurements proceed. (c) Spin-echo measurements at different positions of the fiber with DLS cancellation. The $1/e$ lifetimes for 250, 550, and 750 ms are 106(2), 108(2), and 106(2) ms, respectively which correspond to 0.5, 7.0, and 11.4 mm from the upper tip of the fiber, respectively. The trapping potential of the lattice is 279 μ K.

exemplary Ramsey fringe for pulse separation time $T = 3$ ms. The contrast C of the Ramsey fringe is obtained from fitting the function $\text{OD}_{\text{avg}} \times [C \times \sin(\phi + \phi_0) + 1]$ to the data with C , ϕ_0 , OD_{avg} as fit parameters. The contrast $C(T)$ is then measured as a function of pulse separation time T , see Fig. 2(a), and fitted with the function [22] $[1 + (T/T_c)^2]^{-3/2}$ where T_c is the coherence time. Inhomogeneous broadening of the transition from the lattice has limited our Ramsey coherence time T_c to 3.0(1) ms as shown in Fig. 2(a).

In principle, the spin-echo sequence can remove this dephasing by reversing the sign of the phase accumulated during the period between the second and third pulse as long as the optical potential experienced by the atoms is time independent [22]. With the spin-echo sequence, the coherence time T_c has improved to 37.2(7) ms as shown in Fig. 2(a) (circles). The spin-echo contrast decay data are fitted with $A \times \exp(-T/T_c)$, where T_c and A are the fitting parameters. Time-dependent fluctuations of the potential due to thermal motion of the atoms in the potential, laser power stability, or acoustic noise affecting fiber coupling could still cause the residual dephasing. To minimize the DLS, we follow the scheme using a combination of the polarization of the lattice laser beams and an external magnetic field to engineer the polarizability of the $F = 2$ and $F = 3$ states [23–29]. The cancellation works by using elliptically polarized dipole beams to generate a fictitious magnetic field which causes a Zeeman-like energy shift, called the vector light shift, of the hyperfine clock states. Figure 2(a) shows the contrast decay of spin-echo interference fringes as a function of the time T with and without DLS cancellation. With spin-echo and with DLS

cancellation, the coherence time T_c has further improved to 60.1(1) ms as shown in Fig. 2(a) (squares).

As indicated by previous studies, perfect cancellation of the DLS between the hyperfine ground states of alkali-metal atoms in a single trapping beam wavelength does not exist due to hyperpolarizability or nonlinear ac Stark shifts [27,28]. The coherence time of our stationary atoms in the waveguide is limited by this residual light shift from the trapping laser. In Fig. 2(b), we compare the spin-echo signal at two different trapping potentials 279 μ K and 179 μ K and observe the improvement of the coherence time from 101(2) ms to 252(8) ms. The spin relaxation rates [22] calculated at the peak trapping potentials are 0.01 and 0.03 s^{-1} , respectively, which are negligible for decoherence. We also measure the spin-echo coherence time of the superposition state at different locations along the fiber. The detuning of the lattice beams is ramped from 50 kHz to 0 kHz at $t_p = 250$ ms, 550 ms, and 750 ms, which corresponds to about 0.5, 11.0, 11.4 mm from the upper tip of the fiber, respectively. As shown in Fig. 2(c), the coherence time of stationary atoms is consistent in three different locations. This demonstrates that the irreversible decoherence is consistent along the fiber.

To demonstrate the transportation of the coherent superposition state in the hollow-core fiber, we apply the initial $\pi/2$ microwave pulse in a Ramsey or spin-echo sequence at $t_p = 250$ ms to put atoms in a superposition state and then let the relative phase of the two states evolve while atoms are in motion. Figure 3(a) shows the contrast of the spin-echo sequence when atoms are in the 537 μ K deep, 2.2 cm/s moving optical lattice. The transportation distance is limited by the residual DLS similar to Fig. 2(a).

FIG. 3. Contrast decay measurement of moving atoms in the fiber. (a) Contrast of spin-echo measurements of atoms in a moving lattice at 2.2 cm/s vs transportation distance with (squares) and without (circles) DLS cancellation. The trapping potential of the moving lattice is 537 μ K. The first $\pi/2$ pulse is applied at $t_p = 250$ ms. (b) Comparison of contrast measurements of free-falling atoms in an optical dipole trap with different conditions. Atoms are set free to fall under gravity by switching off the bottom dipole beam at $t_p = 250$ ms while remaining confined radially by the 134 μ K trapping potential from the top dipole beam. The data shows the contrast of the Ramsey fringes with (open squares) and without (open triangles) DLS cancellation and the spin-echo sequence with (circles) and without (diamonds) DLS cancellation.

We also switch off the bottom dipole beam at $t_p = 250$ ms to cause atoms to free fall under gravity, guided only by the 134 μ K deep top dipole beam. In Fig. 3(b), we compare the results of different measurement conditions when atoms are under free fall. Without the DLS cancellation, the spin-echo coherence time greatly exceeds the Ramsey coherence time. With the cancellation, however, these two sequences show a similar decoherence trend. We could still observe the contrast after 55 ms of the Ramsey pulse separation time which corresponds to the transportation of 1.5 cm. Figure 4(a) shows the lifetime of atoms inside the stationary lattice at different positions of the fiber. Atoms are transported by a moving lattice at 2.2 cm/s into the fiber and held at $t_p = 500, 700, 900$, and 1100 ms for lifetime measurement, which correspond to 6.0, 10.0, 14.8, and 19.2 mm from the upper tip of the fiber, respectively. The lattice depth is 537 μ K. We measure the decay of the atom number as a function of time and fit with an exponential decay function. The $1/e$ lifetimes of the atoms are 1.87(4), 2.59(7), 2.33(5), and 1.74(7) s, respectively. The minimum lifetime of 1.7 s indicates the background pressure inside the fiber is better than 1×10^{-8} torr [13] and sets the upper bound of our coherence time measurements. Figure 4(b) shows the fluorescence images of atoms at different times during transportation by a moving lattice at 4.4 cm/s.

The long coherence time of stationary atoms in our experiment can be used to build a fiber-based atomic clock [30]. The decoherence is due to the residual DLS from the 11 mG inhomogeneous magnetic field gradient around the fiber holder over our sample size of 5 mm [29] which translates into few Hz of residual DLS at 537 μ K trapping

FIG. 4. Atoms in the fiber. (a) Lifetime measurements of atoms trapped in a stationary lattice. (b) Fluorescence images of atoms at different times during transportation by a moving lattice at 4.4 cm/s. The atoms are probed with resonant light on the $F = 3$ to $F' = 4$ cycling transition, and scattered photons are imaged from the side of the fiber onto a CCD camera. The fiber location is indicated by the blue rectangle. The 5 mm scale bar is calibrated using calculated lattice velocity and the centroid position of the atoms vs time. Atoms that are not following the moving lattice potential fall faster than atoms in the moving lattice, which can be seen in the image of transportation time 35 ms.

potential. This can be improved by removing the magnetic field gradient or exciting ring-shaped higher-order modes of the fiber with blue detuned dipole laser frequency [31]. A factor of 10 improvements can be expected when we lower the trapping potential by a factor of 10 while keeping the same ratio of atoms' temperature to potential depth.

The source of decoherence on moving atoms is most likely due to the inhomogeneity of the local magnetic field along the atoms' trajectories. The 11 mG magnetic field gradient corresponds to tens of Hz inhomogeneous broadening on the clock states through second-order Zeeman shift which is cancelled for stationary atoms through the spin-echo sequence. The inhomogeneity of the magnetic field is also reflected in the fluctuation of the data in Fig. 3. This can be easily improved by an order of magnitude by removing the magnetic substance on our fiber holder. This will translate into more than 1-meter transportation of the quantum state in the free-falling case. We observe no dependence of the coherence time on the external magnetic field current noise as well as the gradient when we double the magnetic field. The coherence time is also independent of the trapping potential depth used in the free-falling sequence.

The distance of the hollow-core fiber enhanced quantum state transportation demonstrated in this work is already an order of magnitude longer than the free space scheme [6]. In the future, we plan to study the coherence of external states of atoms (matter waves) inside the fiber. If long matter wave coherence times approaching the internal state coherence times demonstrated here can be achieved, then the prospects for a large enclosed area matter wave interferometer is promising. Considering a fiber with a 5 cm bending radius at 3 dB bending loss [32], a matter wave circuit with 30 cm perimeter for quantum sensing purposes can be envisioned [33].

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