Guiding laser-cooled atoms in hollow-core fibers

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Laser-cooled atoms from a low-velocity atomic source are guided in a hollow-core optical fiber using the evanescent-wave dipole force from blue-detuned laser light launched into the glass region of the fiber. The transverse velocity of the guided atoms corresponds to a temperature of 50 μK. We achieve a maximum flux through a 23.5-cm-long fiber of 590 000 atoms/second with a laser power of 55 mWatts at a detuning of 6 GHz. With larger detunings of 40 GHz, spontaneous emission from the atoms inside the fiber can be suppressed and the atom's internal-state population is preserved. We identify two major loss mechanisms for the guiding process and discuss possible solutions.

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A laser tuned above (blue-detuned) or below (red-detuned) an atomic resonance attracts or repels atoms from regions of high laser intensity respectively. In the first demonstration of atom fiber optics [1], room-temperature rubidium atoms from a vapor cell were guided through hollow-core fibers by injecting red-detuned laser light into the hollow region. The light, guided in the fiber by grazing incidence, prevents the atoms from hitting the wall by attracting them to the region of high laser intensity in the center of the hollow core. In subsequent experiments, atoms have been guided by an evanescent-light field from blue-detuned laser light injected into the annular glass region [2,3,7]. If the repulsive light potential is large enough to overcome the atomic transverse kinetic energy and the attractive van der Waals potential, the atoms reflect conservatively from the potential barrier and follow the path of the fiber [4]. In this paper we demonstrate and characterize guiding laser cooled ^{87}Rb atoms through hollow-core fibers using recently developed laser cooling techniques. Related work is reported by Wokurka [5] and Dall [6].

Our experimental apparatus consists of two chambers, a source and a detection chamber, connected by a glass or steel tube that holds the fiber and conduction limits the gas flow between the two chambers (Fig. 1). The detection chamber is pumped by a 40 l/sec ion pump and typically reaches a pressure of 10^{-9} Torr. The source chamber is pumped by a 25 l/sec ion pump and is maintained at a pressure of approximately 10^{-8} Torr of rubidium vapor by heating a rubidium ampoule that is attached to the chamber.

We prepare a laser-cooled atom beam in the source chamber with a vapor-cell magneto-optical trap (MOT) [8]. A diode laser in a master-oscillator power-amplifier configuration (MOPA) [9] provides 350 mW of single frequency light tuned near the $5S_{1/2}(F=2)\rightarrow 5P_{3/2}(F'=3)$ transition in rubidium for trapping and cooling in the MOT. The light is divided into three beams, each directed into the chamber along orthogonal axis, and retro-reflected to supply cooling along all directions. A 30-mW external-cavity diode laser [10] supplies light tuned to the $5S_{1/2}(F=1)\rightarrow 5P_{3/2}(F'=2)$ transition to repump atoms that fall into the $F=1$ ground state back into the cycling transition. A 500-μm hole is drilled in the center of the mirror that provides one of the retroreflected beams, and this mirror is placed inside the vacuum chamber. Thus, one of the six confining laser beams has a dark region in the center of its cross section. The radiation-pressure imbalance for atoms in the MOT that fall in the shadow of the hole accelerates those atoms toward the mirror. The resulting atomic beam is referred to as a low-velocity intense source (LVIS) [11]. Typically, we measure an atomic flux of approximately $\sim 1\times 10^{9}$ atoms/sec and a beam brightness of $\sim 1\times 10^{13}$ atoms/sr sec. Previous studies of LVIS have established that the transverse-velocity distribution may be estimated from the hole geometry [11], for the present configuration, the transverse velocity is in the range $v_t=8.0\pm 1.5$ cm/sec. A time-of-flight measurement found the longitudinal velocity to be $v_l=10.0\pm 2.0$ m/sec.

An LVIS offers three advantages over room-temperature atoms. First, the atoms have a much smaller longitudinal velocity, which allows for a longer interaction time for experiments with atoms inside the fiber. Second, lower transverse velocities correspond to longer de Broglie wavelengths and permit a lower confining dipole potential. The dipole potential (at large detunings) is proportional to the guiding laser light intensity and inversely proportional to the detuning, so a smaller transverse energy allows for a larger detuning while maintaining a sufficient guiding potential. Since the scattering rate is proportional to the intensity and is inversely proportional to the square of the detuning, larger detunings allow a smaller spontaneous-emission probability. Finally, the overall atom flux entering the fiber can be larger than the flux achieved from a room-temperature vapor, resulting in better signal-to-noise ratio compared to room-temperature atom guiding, which enables the use of longer fibers (30.5 cm here). The fibers used in the experiments described here are capillary tubes with a 100-μm inner and 160-μm outer diameter [12].

One end of the fiber is placed inside the hole in the mirror, and the other end is supported inside a 3-cm-long, 19-

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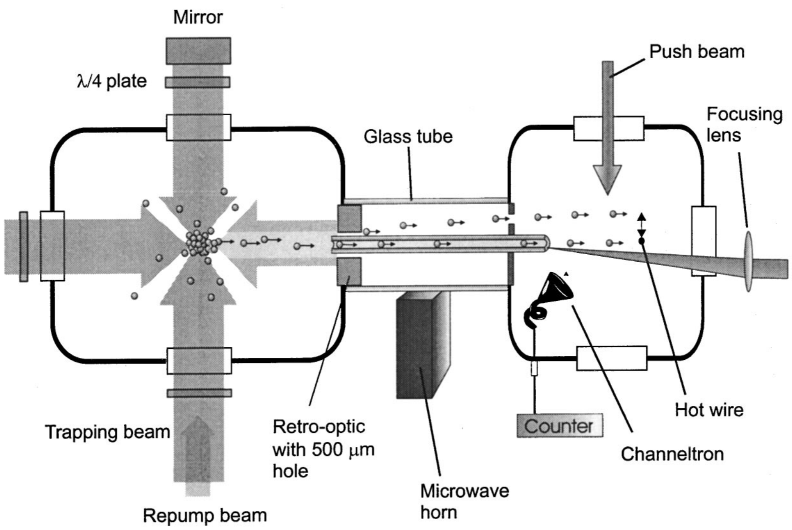

FIG. 1. Schematic of experimental setup. A beam of laser- cooled atoms generated in the left source chamber travels toward the fiber between the source and detection chamber. Some atoms bypass the fiber and enter the detection chamber displaced from the guided atoms. In the detection chamber guided and unguided LVIS atoms can be counted separately and the atoms internal state can be probed with the push-beam present.

gauge steel cylinder, which is fixed in the center of a solid copper gasket held between the flange of the detection chamber and the flange of the connection tube. Atoms that overlap with the fiber opening are guided toward the detection chamber (Fig. 1). We detect the guided atoms after they exit the fiber by ionizing them with a hot wire and counting those ions with a channeltron. A 5.5-W Spectra Physics Millennia laser pumps a Coherent 899 Ti:Sapphire laser to produce up to 400 mW of single frequency guiding light. The guiding laser light enters through a view port in the detection chamber, propagates between the hot wire and channeltron assembly, and focuses on the output end of the fiber (Fig. 1). Our guiding light is coupled into the fiber at an 8° angle with respect to the fiber axis and is blue-detuned from the $5S_{1/2} \rightarrow 5P_{3/2}$ transition. To focus the guiding light onto the 30-μm wide glass facet of the fiber, we use a 125-mm focal-length lens from outside the vacuum chamber. Starting with a beam waist of $\simeq 10$ mm we achieve a focal spot of about 15–25 μm at the fiber facet. The light propagation through the fiber is multimode, and due to the long focal length of our coupling lens in combination with a very shallow coupling angle, the guiding light mainly excites lower order speckle modes inside the fiber. In these experiments we do not employ the speckle-smoothing technique used previously [13]. The absolute guiding frequency is measured within ± 50 MHz with a Burleigh WA-1500 Wavemeter.

We have guided atoms through several fibers of lengths varying from 17 to 30.5 cm. In our 30.5-cm-long fiber we typically measure a flux of 70 000 atoms/sec hitting the hot wire. The 70-μm diameter hot wire placed ~ 2.5 cm from the output facet of the fiber intercepts a small fraction of the diverging atomic beam. Since the hot-wire distance from the fiber is large compared to the diameter of the fiber hole, the spatial distribution of the atomic flux at the hot wire represents the transverse-velocity distribution of guided atoms emerging from the fiber. The hot wire, mounted on a vacuum feed-through, translates perpendicular to the fiber axis. We measure the atom flux in counts per second as the hot wire is moved across the beam of atoms. The integral of the profile gives the total flux. Observed count rates range between 400 000 and 500 000 atoms/sec depending on the coupling efficiency of the guiding light into the fiber. 590 000 atoms/sec is the highest flux observed, which was measured through a 23.5-cm long fiber. The measured beam profile is translated into a transverse-velocity distribution and compared to the normalized original LVIS distribution (Fig. 2). Assuming the longitudinal velocity of guided atoms did not change significantly, we find a transverse velocity for the guided atoms of 9.4 ± 1.7 cm/sec. The uncertainty in the transverse-velocity measurements is largely due to a $\sim 10\%$ uncertainty in the distance from the MOT center to the mirror hole and the distance from the end of the fiber to the hot wire. The statistical uncertainty is significantly smaller. Within this systematic error the LVIS and guided-atom transverse-velocity distributions agree. The measured veloc-

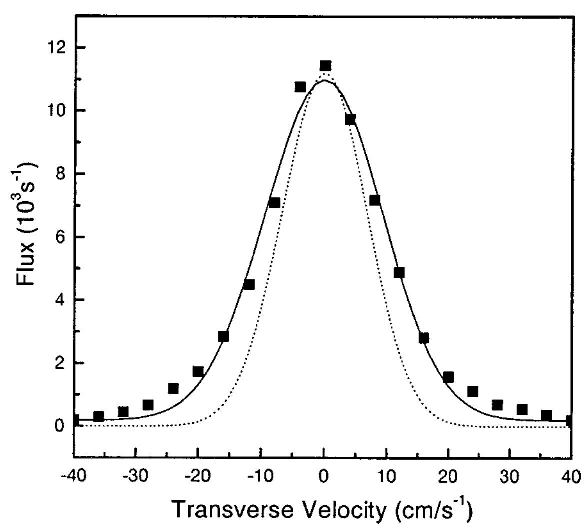

FIG. 2. Typical transverse-velocity distribution of LVIS and guided atoms. The measured transverse-velocity profile of the guided atoms through a 100-μm fiber is fitted to a Gaussian (solid line) and compared to the normalized initial LVIS-velocity distribution (dotted line). For this curve the guiding light is 4.5 GHz blue-detuned. We measure a transverse velocity of $v_t = 9.4 \pm 1.7$ cm/sec for the guided atoms and $v_t' = 8.0 \pm 1.5$ cm/sec for LVIS atoms. The small change in transverse velocity indicates little heating due to spontaneous emission during guiding.

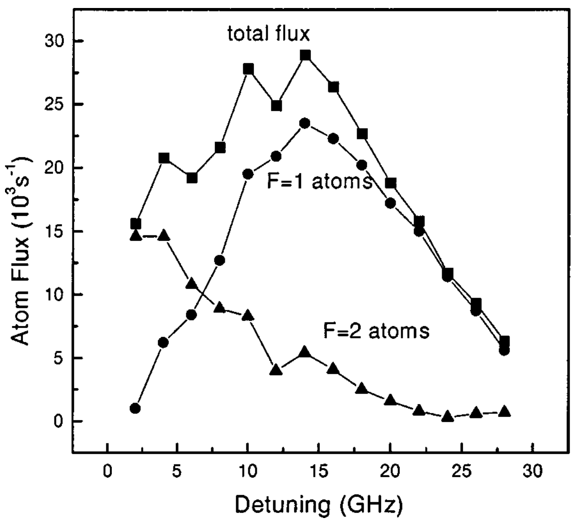

FIG. 3. Detuning dependence of the guided atoms internal state. At small detunings the atoms are optically pumped into the $F=2$ ground state as they reflect off the evanescent-light field (triangles). At large detunings the total flux (squares) consists to 90% of atoms in the $F=1$ ground state (circles) which indicates suppression of spontaneous emission during the guiding process.

ity implies that the dipole potential inside the fiber is sufficiently high to guide the transverse velocities of our source, and that there is little heating of the atoms inside the fiber due to atomic absorption and spontaneous emission of photons from the evanescent light field.

To further analyze spontaneous emission inside the fiber, we introduce another laser beam tuned to the $5S_{1/2}(F=2) \rightarrow 5P_{3/2}(F'=3)$ cycling transition of ^{87}Rb to interrogate the internal state of atoms. This ''push beam'' intersects the atomic beam transverse to its propagation direction between the fiber output and hot wire. All atoms in the $F=2$ ground state exiting the fiber are in resonance with this laser light and are pushed away from the hot wire. Previous experiments have shown that 90% of the atoms from LVIS are originally in the $F=1$ state before they enter the fiber. This can be understood because when atoms leave the MOT region they are no longer illuminated by repump light and are optically pumped into the $F=1$ ground state. With the hot wire positioned in the guided-atom beam-center we measure the total number of atoms with the push beam blocked and the number of atoms in the $F=1$ state with the push beam unblocked. Figure 3 shows atom flux as a function of guiding-light detuning with respect to the $5S_{1/2}(F=1) \rightarrow 5P_{3/2}(F'=2)$ transition. At small detunings over 90% of the atoms are pushed from the beam. This implies that the push beam is at least 90% efficient, and that at least 90% of atoms are in the $F=2$ state after being guided. This indicates atoms undergo spontaneous emission as they are optically pumped into the state whose transition is further detuned from the laser frequency. The overall flux is lower at the smaller detunings, implying that atoms are being heated by the absorption and emission of photons until their transverse kinetic energy is too large to be guided. The flux increases as the detuning is increased, since the scattering rate decreases while the potential is still strong enough to capture the entire transverse-velocity distribution. A dramatic demonstration of the decrease in the scattering rate is the complete reversal of the internal population from 2 to 20 GHz (Fig. 3). At 20 GHz detuning the relative number of atoms arriving at the detector in the $F=2$ state is consistent with the internal-state distribution at the fiber input, thus the spontaneous emission is small.

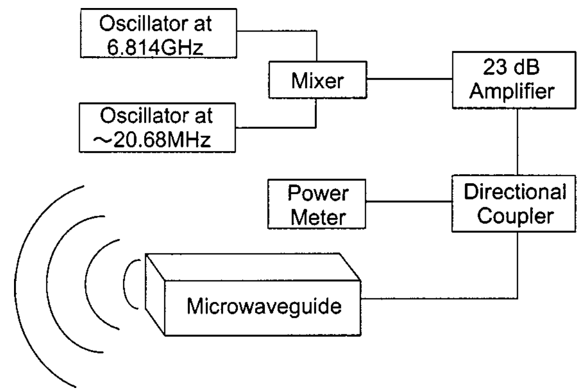

FIG. 4. Microwave setup. A gigahertz and megahertz oscillator are mixed to give the microwave transition frequency. For fine tuning the megahertz oscillator can be adjusted to within 1 Hz. The field is amplified and fed into a microwave guide which then radiates into free space.

For future applications of atom interferometry in hollow-core fibers, the guiding process must preserve the coherence of the internal atomic state. We examine the degree of population preservation by probing the $|F=1,m_f=0\rangle \leftrightarrow |F=2,m_f=0\rangle$ ^{87}Rb ''clock'' transition during the guiding process. A microwave field is generated by mixing an oscillator at $\simeq 6.8$ GHz with another high-resolution tunable source at $\simeq 20$ MHz, which allows us to tune the sidebands with a precision of 1 Hz (Fig. 4). Both signal generators are stabilized to 1 part in 10^{11} by a GPS signal. After amplification through a 23-dB solid-state amplifier the signal is split into two signals. One signal is used to monitor the microwave power and the other signal is fed into a waveguide. The waveguide terminates in free space next to the glass connection tube between the two vacuum chambers midway along the fiber (Fig. 1). Microwaves exiting the waveguide propagate transverse to the fiber inside the connection tube. Stray magnetic fields around the microwave region are shielded and a quantizing magnetic field of 1 Gs is applied along the axis of the fiber to lift the degeneracy between the magnetic sublevels of the ground state.

In our current apparatus we can examine independently the atoms guided through the fiber or a selection of atoms from the LVIS beam that propagates outside the fiber (Fig. 1). The latter atoms exit through the 500-μm hole in the retroreflecting mirror, but pass the fiber opening. Since the co-propagating MOT light passing through the mirror hole induces an ac-Stark shift in the transition, spectroscopy is done with the MOT beams turned off. We load the MOT for 160 msec and then turn off all trapping beams with a mechanical shutter. The first atoms arriving at the detector (those within 27 msec of blocking the MOT light) traveled through the microwave region while still illuminated by laser

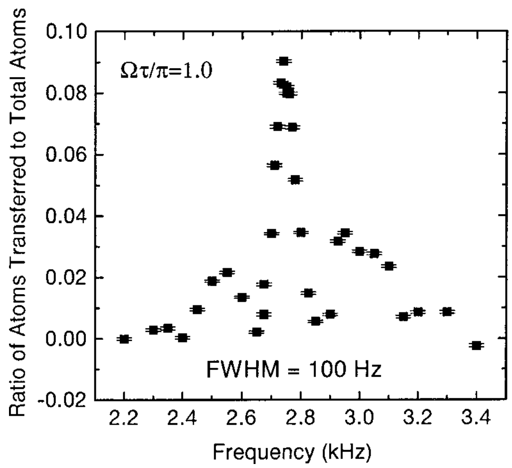

FIG. 5. Ratio of atoms transferred by the microwave field outside the fiber. The 100 Hz FWHM of the central peak is consistent with the estimated interaction time of 10 msec. For the absolute microwave frequency add 6.83468 GHz to the frequency in the graph.

light. These atoms are omitted from the measurements. Atoms that arrive in the following 9 msec time window are used for our data. Atoms are counted in 1 msec time intervals and 9 such consecutive intervals are averaged to produce a single count rate. The ratio of the $F=1$ atoms with and without the microwave field is computed and averaged over 220 runs (Fig. 5).

We conduct the same experiment as above on atoms guided inside the fiber to measure the preservation of internal atomic states. To suppress spontaneous emission we detune the guiding light by ~ 40 GHz to the blue from atomic resonance. Figure 6 shows the percentage of atoms arriving in the $|F=1,m_f=0\rangle$ state versus the microwave frequency at different microwave field strengths. The error bars represent the standard deviation of the mean and do not include any drifts or underlying structure unresolved in our measurement. That we observed a resonance line shape indicates we can detune the guiding light far enough to preserve the atom's internal-state population inside the fiber while the dipole force remains strong enough to guide atoms. This experiment was not possible in our earlier configuration with room-temperature atoms, since the number of atoms guided at large detunings was low.

While the microwave resonance curves show that the atoms preserve their state population during the guiding process, Fig. 6 also shows evidence for inhomogeneous broadening inside the fiber. Microwave resonance curves of atoms traveling outside the fiber show a linewidth as low as ~ 100 Hz (Fig. 5). This linewidth is consistent with the transit-time limited linewidth expected from an estimated interaction time with the microwave field of ~ 10 msec [14]. The smallest linewidth observed inside the fiber was more than an order of magnitude larger. This broadening is attributed to inhomogeneous stray light fields inside the fiber. Since our fibers do not have a low index of refraction cladding around the light-guiding glass region, some guiding light scatters where dust particles touch the fiber. Calculations show that less than 500 nW of scattered guiding light inside the fiber is sufficient to induce an ac-Stark shift of 5

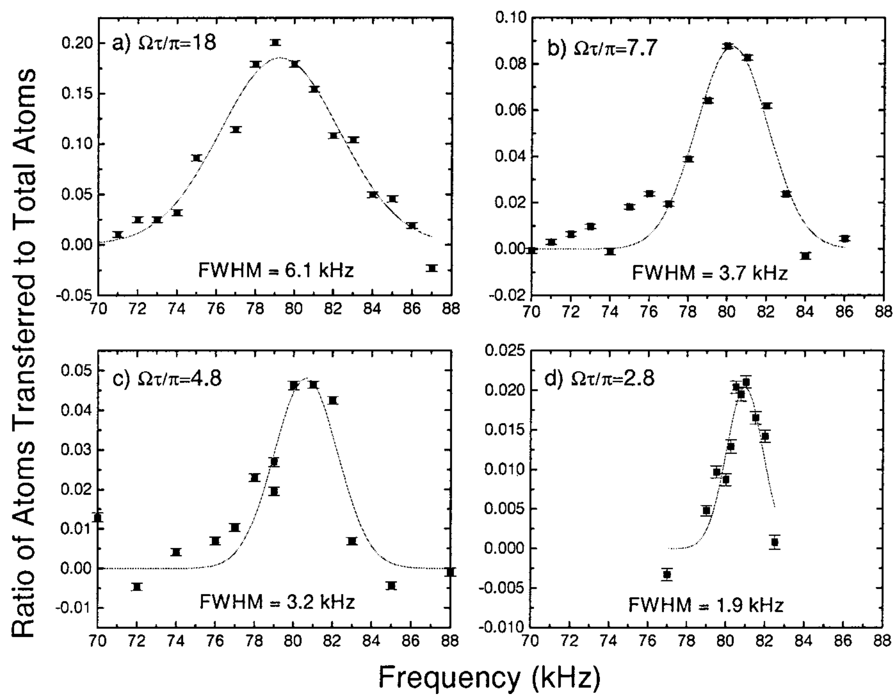

FIG. 6. Ratio of guided atoms transferred by the microwave field. The observation of a resonance line shape indicates the internal-state population of guided atoms is preserved at a guiding light detuning of 40 GHz. As the microwave-field strength is decreased the line shape narrows down (a)→(d). The inhomogeneous line broadening is attributed to an inhomogeneous ac-Stark shift inside the fiber from scattered light. For absolute microwave frequencies add 6.8346 GHz to the frequencies in the graphs. Curves are Gaussian fits used to estimate the linewidth of each curve.

kHz, which accounts for our observed line broadening. Further evidence for the inhomogeneous broadening is the narrowing of the line shape as we reduce the microwave field strength. Without inhomogeneous broadening the line shapes are expected to remain unchanged as the microwave power changes. If scattered light is indeed the cause, this problem will be ameliorated by using fibers with an annular core surrounded by a cladding.

We can exclude possible broadening due to photon absorption during the guiding process. The scattering rate R at a guiding light detuning of 40 GHz and a turning-point intensity of $I=1.3\ \mathrm{W/cm^2}$ is $R=35$ photons/sec. The atom spends most of its time during the guiding process in the dark region of the fiber and only sees a strong light field during its turn around time of $\sim 2\times 10^{-6}$ sec. This results in a probability of 5×10^{-4}/bounce that the atom absorbs a photon. With an average of 30 bounces inside the fiber it is unlikely that the observed inhomogeneous broadening is due to spontaneous emission. The calculated attenuation length for light guided by grazing incidence and launched at a coupling angle of $8°$ is 1.5 mm, so it is unlikely that light mistakenly coupled into the hollow region is responsible for the observed broadening.

A comparison between the direct LVIS flux and guided atoms allows us to estimate guiding losses. For a 23.5-cm-long fiber the output of LVIS provides 2×10^7 atoms/sec into the opening facet of the fiber, but only 6×10^5 atoms/sec are detected, corresponding to a guiding efficiency of 3%. We identify two loss mechanisms: loss due to the speckle pattern of our multimode fiber and loss due to collisions with room-temperature background atoms inside the fiber.

Since the light propagation through the annular glass region of the fiber is multimode, light coupled into different modes can interfere at the inside surface of the fiber. This complicated interference, or speckle pattern, creates dark regions where atoms see no evanescent-light field, and atoms approaching the glass wall in those regions stick due to van der Waals forces. Once touching the fiber wall atoms thermalize to the fiber temperature (300 K) and leave the wall with a kinetic energy too large to be guided by the dipole potential. The lost atoms slowly diffuse by random walk toward the fiber opening, where they become part of the background.

Washing out the speckle pattern increases the guided-atom flux. Donley [13] demonstrated with guiding room-temperature atoms an increase in flux moving the speckle pattern inside the fiber by changing the input angle with an AOM. It is postulated that if the speckle are moved fast relative to the atomic transit time over the characteristic speckle size, the atoms see an effectively smooth potential. Washing out the speckle improved the flux in those experiments by a factor of 2. Our current experimental setup does not allow us to wash out the speckle pattern with an AOM, but we expect to use this technique in future guiding experiments. Further evidence for loss due to speckle is the sensitivity of flux with respect to the coupling of the guiding light. Maximizing the optical coupling efficiency of the guiding light does not automatically lead to the best guiding results.

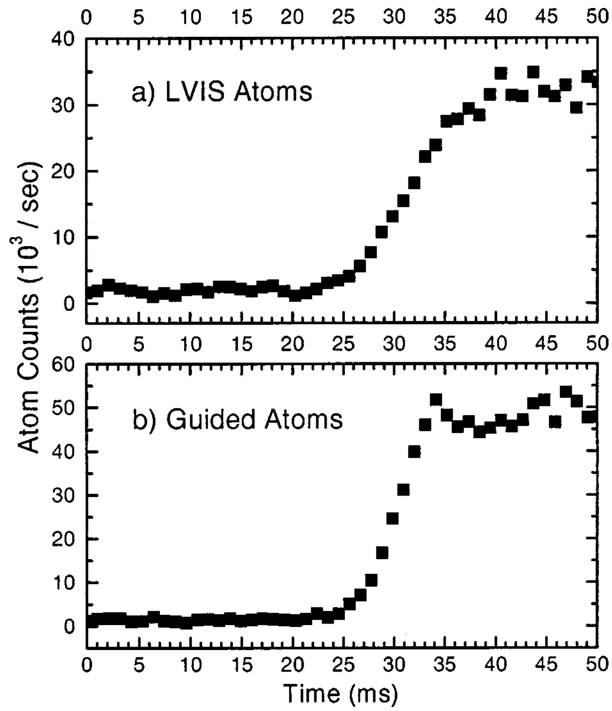

FIG. 7. Time-of-flight measurement. Graph (a) shows LVIS atoms bypassing the fiber and (b) atoms guided through the fiber. The flux of guided atoms saturates after 39 msec compared to 34 msec for guided atoms. This indicates that the lower velocity class of guided atoms is cut. Slower atoms have an increased probability to collide. The slope change is a result of the narrowed velocity distribution of guided atoms.

Instead we have to probe different coupling conditions to maximize atomic flux. We believe the speckle pattern is the major factor in this sensitivity.

A second loss mechanism is collisions with background atoms. We observe an increase in the maximum atom flux through the fiber over a period of days each time we pump down to vacuum. This increase can be attributed to slow conduction limited approach to the equilibrium pressure inside the fiber.

A further indicator for losses due to high background pressure and speckle inside the fiber is a change of the longitudinal-velocity distribution for guided atoms. Figure 7 shows a time-of-flight measurement comparing the longitudinal-velocity distribution of guided atoms to the velocity distribution of LVIS atoms. For this measurement we chopped the atom flux by blocking the hole in the retroreflecting mirror with a laser beam. This beam is tuned to the cycling transition and pointed transverse to the atoms' propagation direction. As the atoms intercept the beam they are pushed away from the mirror hole and recycled back into the MOT. To measure the atom's longitudinal-velocity distribution we unblock the atomic flux and count the number of atoms arriving at the detector for 55 msec within one millisecond time windows. The flux for the guided atoms reaches its maximum after 34 ± 1 msec compared to the LVIS atoms at 39 ± 1 msec. This time-of-flight measurement indicates that the longitudinal-velocity distribution has changed for the guided atoms. The slowest guided atoms are cut off from the distribution. We believe the slow atoms are either lost due to collisions with background atoms, or due to an increased probability of encountering a dark spot in the evanescent-light field. Slow atoms with the same average transverse velocity spend more time inside the fiber and have a larger chance to collide with background atoms as well as to hit the fiber wall.

We have guided 500 000 laser cooled atoms per second in fibers as long as 30.5 cm and as many as 590 000 atoms/sec in 23.5-cm fibers. Further, we have shown that with sufficiently large guiding-light detuning we can guide atoms along such fibers while preserving the population distribution. This is an important step toward realizing an atom interferometer inside hollow-core optical fibers. We also have identified some of the dominant loss mechanisms for guiding atoms and suggested possible solutions to increase the total flux in the future.

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