Laser-Guided Atoms in Hollow-Core Optical Fibers

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We have used optical forces to guide atoms through hollow-core optical fibers. Laser light is launched into the hollow region of a glass capillary fiber and guided by grazing-incidence reflection from the walls. When the laser is detuned 1–30 GHz red of the Rb *D*2 resonance lines, dipole forces attract atoms to the high-intensity region along the axis and guide them through the fiber. We show that atoms may be guided around bends in the fiber and that in initial experiments the atoms experience up to 18 reflections from the potential walls with minimal loss.

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An atom placed in an optical beam is attracted to or repelled from regions of high intensity, depending on the polarizability of the atom at the optical frequency. This ponderomotive force is the basis of several atom-trapping techniques [1] and is also the basis of Cook and Hill's original proposal [2] for an atom mirror using evanescent optical fields. Out of the light-invoked atom mirror notion grew the concept of atom waveguides. The idea, first proposed by Ol'Shanii, Ovchinnikov, and Letokhov [3], and extended by Savage and co-workers [4,5], is to guide atoms down a hollow-core optical fiber using light also guided by the fiber.

Fiber-guided atoms may facilitate many atomic physics experiments. For example, atoms could be extracted from a low-quality supply chamber and transported to an ultrahigh vacuum analysis chamber. With atom fiber guides, one has substantial control over atom trajectories. The losses from transverse momentum diffusion in evanescent mirror cavities [6] can be eliminated by the transverse confines of a fiber guide. Furthermore, by using optical access through the fiber walls, atoms can be manipulated and probed without the constraints of a cumbersome vacuum enclosure. At sufficiently low temperatures, the atomic de Broglie wavelength becomes comparable to the transverse dimensions of the hollow core. In this regime, atoms propagate in modes much like the optical modes of conventional fibers. This presents the exciting prospect of fiber-atomic interferometry in analogy with fiber-optic interferometry.

In this work we report on an experimental demonstration of atom guiding through short, hollow-core optical fibers using laser light. We implement the configuration suggested by Ol'Shanii, Ovchinnikov, and Letokhov which involves a red detuned laser beam launched into the hollow region of a hollow-core fiber. Atoms in the guide propagate in a manner similar to light in a multimode fiber: axial motion is unconstrained and transverse motion consists of a series of lossless reflections from the potential established by the optical fields. Atoms exit the fiber with a numerical aperture that increases with increasing guiding light intensity. We show that atoms can be steered through bends of the flexible fiber. We have also transported atoms through a portion of fiber exposed to atmosphere, demonstrating that the glass walls are sufficient to maintain vacuum in the guide.

The theory of atom guiding in hollow fibers is straightforward. Laser light is coupled into modes [7] which propagate along the fiber axis by grazing incidence reflection from the glass walls. In cylindrical coordinates, the intensity profile for the lowest order EH_{11} mode is approximately $I(\rho) = I_0 J_0^2(\chi\rho)$ in the limit $ka \gg 1$ where $k = 2\pi/\lambda$ and a is the radius of the fiber hollow. I_0 is the peak field intensity and χ is found by solving the approximate characteristic equation:

$$J_0(\chi a) = \frac{i\chi}{2k}\frac{n^2+1}{\sqrt{n^2-1}}J_1(\chi a). \qquad (1)$$

χa, given by $2.405 + 0.022i$ for a 40-μm hollow-core diameter fiber at $\lambda = 780$ nm, is related to the axial propagation coefficient, β, by $\chi^2 = k^2 - \beta^2$. n is the index of refraction of the glass. The imaginary part of β is the attenuation coefficient of the mode amplitude and is given explicitly in the $ka \gg 1$ limit by

$$\mathrm{Im}(\beta) = \left(\frac{\chi a}{2\pi}\right)^2 \frac{\lambda^2}{2a^3}\frac{n^2+1}{\sqrt{n^2-1}}. \qquad (2)$$

Explicitly, the attenuation length, $[\mathrm{Im}(\beta)]^{-1}$, for a 40-$\mu$m-diameter fiber is 6.2 cm.

For the intensity profile given in Eq. (1), we can define a mode diameter as the diameter at which the intensity falls to e^{-1} of the peak value. This diameter, 22 μm for the EH_{11} mode, is substantially smaller than the physical diameter of the core, which implies that the guided atoms may be localized in a transverse area much smaller than the physical area of the core. This fact also allows us to ignore atom-wall loss terms such as van der Waals interactions and quantum tunneling, which would be important for small atom-wall distances [5]. In curved fibers, the real part of β is unchanged to first order, but the imaginary part has an additional term, which is important when the radius of curvature R becomes comparable to the attenuation length of the straight fiber. The intensity

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profile to first order in $1/R$ takes on an asymmetric, elliptical shape, with the center shifted toward larger R.

The dipole potential depth felt by the atoms at a radial distance ρ for a given electric field $E(\rho)$ is [8]

$$U(\rho) = \frac{\hbar\Delta}{2}\ln\left(1 + \frac{2\Omega(\rho)^2}{\Delta^2 + \gamma^2}\right), \qquad (3)$$

where $2\Omega(\rho) = dE(\rho)/\hbar$ is the atomic Rabi frequency, d is the dipole moment of the atom, $\Delta = \omega - \omega_0 - kv_z$ is the laser detuning from resonance, and 2γ is the spontaneous decay rate of the upper atomic state. Atoms with sufficiently small transverse velocities are confined in this two-dimensional potential. Equating the atoms' classical kinetic energy to the potential barrier height, we obtain the maximum transverse velocity confined, $v_m = [2U(0)/m]^{1/2}$, where m is the mass of the atom.

Typical experimental parameters, 45 mW of laser light propagating in a 40-μm-diameter core and a detuning of -6 GHz, yield a potential depth of 71 mK and a transverse capture velocity of 3.7 m/s. In our experiment, atoms are loaded randomly from a thermal vapor surrounding the fiber opening. To obtain a simple estimate of the guided atom flux, we assume that all atoms that impinge on the opening of the fiber with sufficiently small transverse energy are guided. Integrating the Maxwell velocity distribution up to v_m in the transverse direction and over all axial velocities, we obtain

$$F_0 \approx \frac{1}{2}\sqrt{\frac{m}{2\pi k_B T}}\, n_0 A_h v_m^2 = 10^5\ \mathrm{s}^{-1}, \qquad (4)$$

where we take the atom density, $n_0 = 10^{16}\ \mathrm{m}^{-3}$, near room temperature, and A_h is an effective area that we take to be the area of the EH_{11} mode.

In a straight fiber, no constraint exists on the axial velocities of the guided atoms. In bent fibers, on the other hand, atoms may be guided only if the transverse guiding force can provide adequate centripetal force. The tightest bend radius depends on how deeply the atom is bound in the transverse potential and is approximately $R_{\min} = mr_0 v_z^2/U(0)$, where v_z is the atomic velocity along the fiber, and r_0 is the mode radius. Atoms with velocities faster than v_z will stick to the fiber wall for bend radii $R \le R_{\min}$. For typical experimental parameters the value of $R_{\min}$ for the median v_z is 18 cm.

Transverse heating of the atoms by spontaneous scattering of photons is one limit to the distance atoms may be guided through fibers. To estimate this upper limit, we assume that the atomic transition is saturated so that atoms scatter photons at a maximum rate, γ. The transverse energy accumulated after $N = \gamma\tau$ scattering events is $E_t \approx (\hbar k)^2 N/2m$. Setting this equal to the potential, $U(0)$, we obtain a guidance time for Rb of $\tau = 0.12$ s and an average guidance distance of $v_{z,\mathrm{ave}}\tau = 40$ m. For the parameters used in the present experiment, transverse heating is negligible even at small detunings. However, for cold transverse temperatures this heating mechanism will be important. Since the spontaneous scatter rate falls from the saturated value as Δ^{-2} while the potential scales as Δ^{-1}, the guidance distance can be extended by detuning the laser farther from resonance.

The experimental apparatus, shown in Fig. 1, consists of two separate vacuum chambers connected by a 3.1-cm-long capillary fiber with an outer diameter of 144 μm and hollow-core diameter of 40 μm. Light from a titanium sapphire standing wave laser is coupled primarily into the EH_{11} mode with an aspheric lens. We typically observe a 50% coupling efficiency and an attenuation loss of 7% per cm of fiber length for the EH_{11} mode. A single intracavity etalon narrows the laser bandwidth to 2 GHz and allows tuning over ± 50 GHz. The pressure in the detection chamber is 10^{-8} Torr. The input chamber contains Rb metal and is heated to produce a Rb partial pressure of 10^{-6} Torr. The guided atoms leaving the fiber are surface ionized on a heated Pt or Re wire in the second chamber. The resulting ions are detected with a channeltron electron multiplier and recorded with a pulse counter.

Measurements of the detuning dependence of the guided atom flux are presented in Fig. 2 for two laser intensities. The zero point of the detuning, δ, is taken to be the average transition frequency of the $5s_{1/2}(F)$-$5p_{3/2}(F')$ multiplet of ^{85}Rb and ^{87}Rb. Qualitatively, the detuning dependence of atom flux is as expected: atoms are guided by red detuned light, but not by blue detuned light. Particularly striking is the sharp turn-on of the guided atom signal. The signal rises to half maximum at $\delta \approx -2$ GHz and full maximum at $\delta \approx -3$ GHz. For detunings larger than a few GHz, the guided atom signal falls off approximately as δ^{-1}, as expected from an expansion of Eq. (3). With increasing intensity the signal increases and the position of maximum flux shifts to larger negative detunings.

To obtain a precise fit to the data, optical pumping effects, the finite laser bandwidth, and the ground-state hyperfine splittings would have to be considered. In particular, optical pumping redistributes the population of the ground-state hyperfine levels and results in a sharper threshold than predicted from a simple two-state model

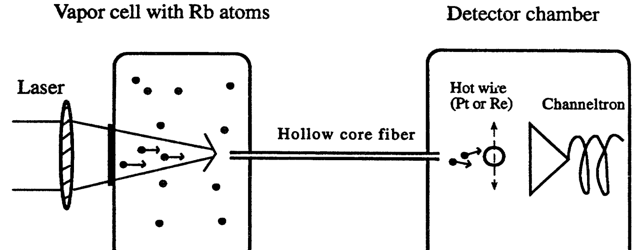

FIG. 1. Experimental apparatus. Laser light is coupled into the grazing incidence modes of a hollow-core fiber. Atoms with small transverse velocities are extracted from a vapor cell in the first chamber and guided through the hollow fiber to a detection chamber.

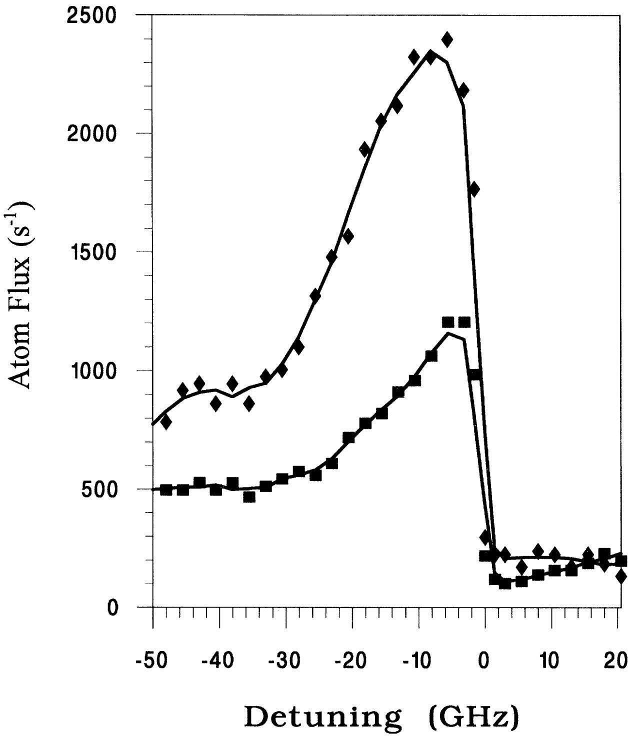

FIG. 2. Guided atom signal versus laser detuning from resonance. For the upper curve, $I_0 = 3.6 \times 10^3$ W/cm^2 in the guiding modes, and for the lower curve, $I_0 = 1.3 \times 10^3$ W/cm^2. The data show a sharp increase in the guided atom signal when the laser is tuned slightly to the red of the $D2$ resonance line of Rb. The solid line is included to show the trend of the data.

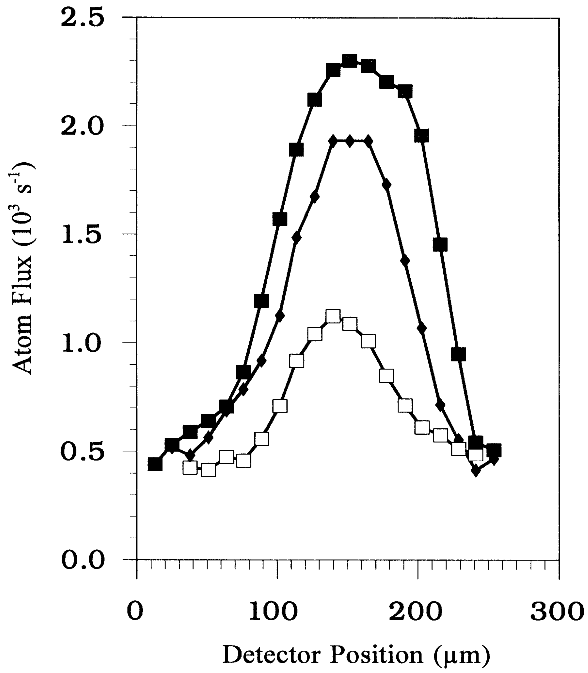

FIG. 3. Spatial distribution of flux measured by translating the surface ionizer at 4 mm from the exit of the fiber. The measurements show broadening of the distribution with increasing laser intensity. The half width of the upper curve at 5.9×10^3 W/cm^2 corresponds to an average of 18 specular reflections from the potential walls. Background counts come from three sources: ballistic atoms passing straight through the fiber, thermal atoms diffusing slowly through the fiber, and hot wire noise. By bending the fibers slightly and reducing the noise on the hot wire, we have achieved background counts of 10 s^{-1}.

for the guided atom flux near $\delta = 0$. Additional optical pumping effects will be apparent in the signal's intensity dependence, shown in Fig. 4.

Overall, the guided atom count rate of $\sim 10^4$ s^{-1} is in reasonable agreement with the expected flux of $\sim 10^5$ s^{-1}. The discrepancy, also observed with fiber lengths up to 6 cm, is attributed primarily to uncertainties in the detector calibration. Smaller uncertainties arise from the messy optical intensity profile that exists in the first 400 μm or so of the fiber, before higher-order modes have radiated away. Some of these modes produce finite laser intensity at the fiber walls and effectively reduce the potential gradient created by the fundamental EH_{11} mode. In addition, the derivation of Eq. (3) does not include a number of effects such as optical pumping, and the guiding or funneling of atoms into the fiber.

In Fig. 3 we present measurements of the spatial distribution of the exiting atoms with increasing laser powers. Broadening is clearly evident as the power is increased. The half-widths, when corrected for the detector wire width and fiber diameter, scale as $I^{1/2}$, as expected for low intensities. For the 45 mW curve in Fig. 3, the exit cone angle of 15 mrad corresponds to an atomic numerical aperature of 0.015. This corresponds to the atoms being reflected on the average 18 times from the potential walls without losses.

We present measurements in Fig. 4 of the power dependence of the flux guided through straight and curved fibers. For $R = \infty$, or straight fiber case, we see that at the largest intensities the guided flux begins to saturate as expected from the form of Eq. (3). The thick curve is a plot of Eq. (4) using a detuning of $\Delta = -6$ GHz measured from the $5s_{1/2}(F = 2)$-$5p_{3/2}(F')$ transitions of ^{85}Rb. At intensities smaller than 2×10^6 W/m^2, the data obey a power dependence determined by a $\Delta = -3.0$ GHz detuning from the $5s_{1/2}(F = 3)$-$5p_{3/2}(F')$ transition, as shown by the thin line in Fig. 4. The switchover at higher power agrees qualitatively with optical pumping of atoms in the upper ground-state hyperfine levels to the lower levels. At small intensities the optical pumping rate is small and negligible population is transferred into the far detuned state. However, at higher intensities, most of the atoms are pumped into this state, and the

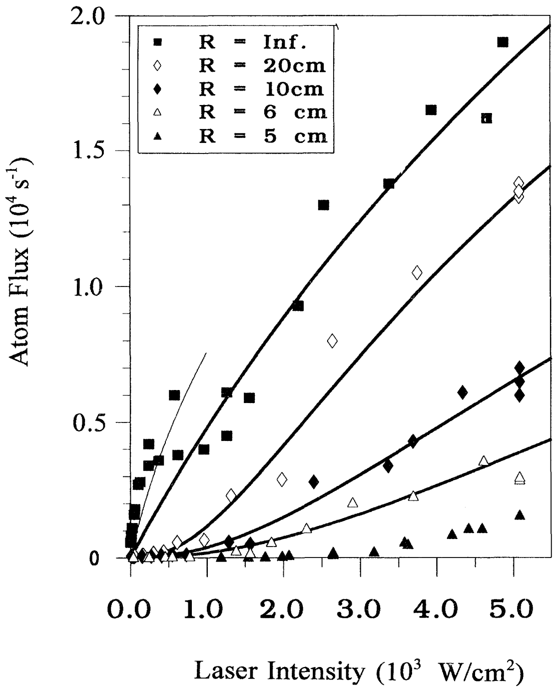

FIG. 4. Intensity dependence of the guided atom flux in 40-μm diameter; curved fibers for radii of curvature are indicated in the legend. The thick line for $R = \infty$ is a plot of Eq. (4), normalized to the data, with $\Delta = -6$ GHz and assuming that the atoms are optically pumped into the lowest ground-state hyperfine level. The thin line assumes that at low intensity the atoms are distributed equally between the ground-state levels. The solid lines for $R < \infty$ are included to show the trend of the data.

atoms experience the weaker potential determined by the $\Delta = -6$ GHz detuning.

Obviously, a primary interest in using fibers to guide atoms is the ability to guide the atoms around curves [4]. The data of Fig. 4 show the dependence of the guided atom flux on intensity and minimum bend radius, R. The fiber is bent by translating the output tip of the fiber while holding the input tip fixed. At small intensities the flux turns on as a power law, reflecting the fact that only the slow velocity tail of the Maxwell distribution is guided around the bend. At high intensities the potential saturates and the flux intensity dependence consequently also saturates.

At bend radii comparable to or smaller than the mode attenuation length, $R = 6$ cm, the flux turns on only at the highest intensities. At these radii the optical intensity profile becomes asymmetric [7] and the mode intensity is enhanced at the wall of the fiber. As a result, the optical guiding potential is weaker and atom losses are higher than expected from our simple picture. It is apparent from these data that the tightest bend through which atom guiding can be achieved is limited by a critical radius for effective optical guiding and not by a critical radius that depends on atomic properties.

In conclusion, we mention a few additional applications of guided atoms in fibers. As an atom transport system, a curved fiber could act as a velocity filter, allowing only atoms with small longitudinal as well as small transverse velocities to be extracted from a thermal cell and piped to a UHV system. This would allow, for example, large numbers of atoms to be trapped in a magneto-optic trap by reducing collisional loss from thermal background atoms.

We have already guided atoms in fibers with holes as small as 10 μm. Guiding in smaller fibers is feasible but more challenging because of the fast attenuation of the guiding light in simple capillary fibers. In future work we hope to launch optically single-mode light into an annular core that surrounds the hollow and guide the atoms through the fiber with a blue detuned evanescent field [5,6,9]. This should lead to longer guiding distances in the smaller fibers and less spontaneous scattering.

With smaller fiber diameters and colder transverse temperatures, the atoms' de Broglie wavelength becomes comparable to the size of the hole, and the transverse atomic motion will be quantized. In such a situation, atomic modes interfere to produce atomic speckle patterns. Atoms with recently achieved temperatures of 200 nK [10] launched into a 2-μm-diameter hollow would propagate in a *single* transverse atomic mode. This shall be another step to realizing an atom fiber interferometer of the Mach-Zehnder type or a Sagnac loop for rotational inertia sensing.

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