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Evanescent-wave guiding of atoms in hollow optical fibers

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We use evanescent laser light to guide atoms through hollow-core optical fibers. The light, detuned to the blue side of rubidium's D_2 resonance lines, is launched into the glass region of a hollow capillary fiber and guided through the fiber by total internal reflection from the glass walls. Atoms interacting with the evanescent component of the field are repelled from the wall and guided through the fiber hollow. A second laser tuned to the red side of resonance is used to initially inject the atoms into the evanescent guide. An optical intensity threshold for guiding is observed as the evanescent-field-induced dipole forces exceed the van der Waals forces.

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I. INTRODUCTION

An atom placed in a near-resonant laser field is either attracted to or repelled from regions of high intensity depending on the sign of the laser's detuning from atomic resonance. We have demonstrated that the optical forces induced by laser light guided in a fiber may be used to reflect atoms from the inner wall of a hollow-core optical fiber in a recent work [1,2]. In that demonstration, light was coupled to the lowest-order grazing incidence mode [3] and the laser frequency was tuned to the red side, so that atoms were attracted to the high-intensity region at the center of the fiber. Atoms guided in this way undergo a series of lossless oscillations in the transverse plane and unconstrained motion along the axis.

Atoms can also be guided by the evanescent light field of the glass surface surrounding a hollow fiber. With a detuning on the blue side of resonance, atoms are expelled from the high-intensity-field region near the fiber wall. The intensity in the evanescent field is significant at a distance of ≈$\lambda/2\pi$ into the hollow region. Consequently, the atoms are nearly specularly reflected from the potential walls. Atom propagation through the fiber in this case is similar to the propagation of light in a multimode, step-index fiber.

Evanescent guiding has several advantages over guiding by grazing incidence modes: heating of the atoms due to spontaneous scattering of photons is small in the evanescent case because the atoms spend most of the time in a dark region away from the high laser intensity at the wall. In the grazing incidence configuration, atoms are guided in the high-intensity region, and consequently the spontaneous scattering rate is relatively high. Furthermore, in evanescent-wave guiding, the optical potential is generated by light traveling in lossless guided modes. Small-diameter atomic guides of very long length may be practical. By contrast, grazing incidence optical modes decay exponentially with distance [3], effectively limiting the guiding distance to a few attenuation lengths. For smaller fibers the attenuation length, which scales as the radius cubed, is an increasingly severe limitation. Evanescent guiding evidently has a greater practical potential for atom guiding applications.

In this paper we report an experimental demonstration of atom guiding in hollow fibers using evanescent fields. We find that severe optical mode-matching constraints, resulting from light scattered into the hollow part of the fiber, can be ameliorated with the help of a second *escort* laser beam detuned to the red side of atomic resonance. We also observe a threshold intensity level for evanescent guiding that is indicative of van der Waals forces: the repulsive barrier formed by the evanescent wave must be sufficient to overcome attractive van der Waals forces. A measure of these attractive forces is relevant to the design of other atom waveguide configurations [4–6].

II. THEORY

Comprehensive theories of atom guiding using optical forces may be found elsewhere [1,2,4]. Here we present only the fundamental concepts. An atom interacting with a near-resonant inhomogeneous laser field experiences a conservative ponderomotive energy shift given by [7]

$$U(\rho)=\frac{\hbar\Delta}{2k_B}\ln\left(1+\frac{2[\Omega(\rho)]^2}{\Delta^2+\gamma^2}\right), \tag{1}$$

where $\Delta=\omega_L-\omega_0-kv_z$ is the laser detuning from resonance and $k=2\pi/\lambda$. $\Omega(\rho)=dE(\rho)/\hbar$ is the atomic Rabi frequency in the presence of an oscillating electric field, d is the atomic transition dipole moment, and γ is the spontaneous decay rate. We have written the potential as an equivalent temperature, as indicated by Boltzmann's constant k_B. For large detunings from resonance and weak fields, Eq. (1) reduces to the familiar form $U(\rho)=\hbar\Omega^2(\rho)/\Delta k_B$. With a positive detuning from resonance the positive potential shift acts to repel atoms from high-intensity regions. Conversely, atoms are attracted to high-intensity regions of light having a negative detuning from resonance.

Laser light in the evanescent configuration is coupled into modes of the annular glass region of the fiber. Approximate expressions for the guiding potential are most easily obtained using ray optics to describe the propagation of light in the

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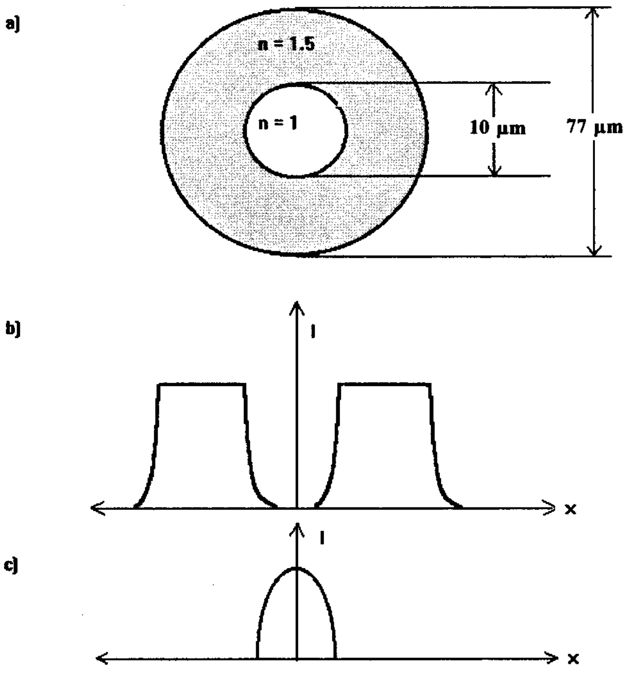

FIG. 1. (a) Cross section of hollow capillary fiber used to guide atoms. (b) Flat topped optical intensity profile assumed when light is injected into the glass region of the fiber. The extent of the evanescent field extending into the vacuum is exaggerated for clarity. (c) Transverse intensity profile of the escort laser. The actual profile is $I(\rho)=I_0J_0^2(\chi\rho)$ where χ is a constant.

hollow fiber [8]. As a further simplification we ignore the curvature of the fiber walls and approximate the waveguides as a dielectric slab. For light striking the glass-vacuum interface at an angle θ and polarization perpendicular to the plane of incidence, the evanescent component of the field extending a distance x into the vacuum is given by

$$E(x)=E_0\alpha\ \exp(-\kappa x), \tag{2}$$

where E_0 is the electric-field amplitude incident on the interface, and the factors α and κ are given in terms of the index of refraction n, incidence angle θ, and laser wavelength λ by $\alpha=2\sqrt{n^2/(n^2-1)}\cos\theta$, and $\kappa=(2\pi/\lambda)(n^2\sin^2\theta-1)^{1/2}$. We assume that the intensity profile is uniform in the glass region, as shown in Fig. 1. In particular, we are ignoring interference among modes, which gives rise to an optical speckle pattern. The intensity on the inner wall of the fiber is then approximately the total power in the guide divided by the cross-sectional area of the glass region, $I(0)=P/A$. The field intensity is related to the electric-field strength by $E=\sqrt{2I/n\epsilon_0c}$, giving an evanescent intensity profile of $I(x)=I(0)\alpha^2\exp(-2\kappa x)$. We assume an incident angle corresponding to the numerical aperture of the coupling lens, 0.1, giving ≈ 0.26. With a typical laser power of 500 mW and a fiber cross-section area of $1.8\times10^{-8}\ \mathrm{m}^2$, the evanescent intensity at the wall is $I(0)\alpha^2=1.9\times10^6\ \mathrm{W/m}^2$ corresponding to a potential height at the walls of $U(0)=22\ \mathrm{mK}$.

In the absence of an optical potential, the atoms are attracted to the glass wall by long-range, van der Waals forces. To estimate the effect of the van der Waals potential we again treat the waveguide as an infinite dielectric slab. In this case, the van der Waals potential is given by [9]

$$U_{\mathrm{vdW}}=-\frac{1}{4\pi\epsilon_0}\left(\frac{\epsilon-1}{\epsilon+1}\right)\frac{\langle g|d^2|g\rangle}{8k_Bx^3}, \tag{3}$$

where ϵ is the dielectric constant, $\langle g|d^2|g\rangle$ is the matrix element of the square of the dipole operator, and x is the distance from the wall. The effective potential, consisting of the van der Waals and evanescent potentials, is everywhere attractive for small intensities. The intensity above which an atom will experience a positive potential we call the threshold intensity. Slightly above threshold the potential is positive throughout the hollow region except very close to the wall where the attractive van der Waals potential dominates. Just above threshold the potential exceeds zero at a distance $x=3/2k$ from the fiber wall and occurs when $U_{\mathrm{ev}}(0)\approx10^{-4}$ K. The corresponding intensity threshold is $I_{\mathrm{th}}\sim10^5\ \mathrm{W/m}^2$ for a 1-GHz detuning from resonance.

The uniform intensity and slab waveguide assumption overestimates the actual potential height. First, the slab waveguide approximation ignores the fact that some laser power is coupled to sagittal, or skew, rays which may have inner radial turning points larger than the core radius and will not contribute to the evanescent potential. Thus, the effective intensity of the guide is reduced by the fraction of light coupled to these rays.

Second, the preceding treatment ignores interference between optical modes that give rise to optical speckle and, consequently, to modulation of the intensity of the evanescent field. Atoms encountering a "dark" region in the evanescent field are not shielded from the attractive van der Waals forces and may be lost from the atomic beam. We calculate that room-temperature atoms spend insufficient time in the dark to be pulled into the wall before the potential changes sign. On the other hand, slower atoms may be lost in these regions.

Evanescent guiding requires that the blue detuned field be confined to the glass waveguide. Typically, some of the laser light scatters from the fiber and couples to grazing incidence modes existing in the hollow region. Some small fraction of light in the hollow region can easily dominate the evanescent portion and drive the atoms into the walls. We found it difficult in practice to match the injected laser beam sufficiently well. A rough estimate of the mode-matching constraints is obtained by assuming that efficient guiding is possible only when the laser intensity at the wall, $I=I_0\alpha^2$, exceeds the intensity coupled into the EH_{11} grazing incidence mode by, say, a factor of 10. This suggests that the scattered light must be suppressed to better than 0.05% in a fiber with a 144-μm outside diameter and a 20 μm inside diameter.

To circumvent the mode-matching problem a second laser is used to escort atoms through the spatial transient region and into the region where the evanescent potential is dominant. This escort laser is coupled into the lowest-order EH_{11}, grazing incidence mode which has an intensity profile given by $I=I_0J_0^2(\chi\rho)$ with $\chi a\approx2.40$ [1,3] and a the fiber hole radius. I_0 is the peak intensity on the axis and ρ is the radial distance from the fiber center. With a red detuning from resonance atoms are attracted to the high-intensity region along the axis and initially guided into the fiber.

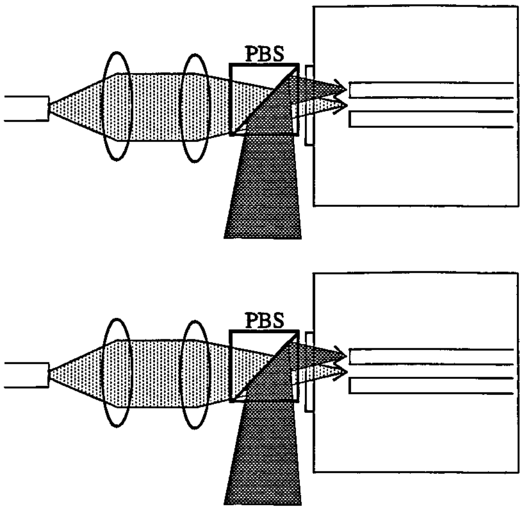

FIG. 2. Optical coupling scheme. The escort and evanescent laser beams are combined on a polarizing beam splitter (PBS) and separately focused onto the fiber hollow and glass regions.

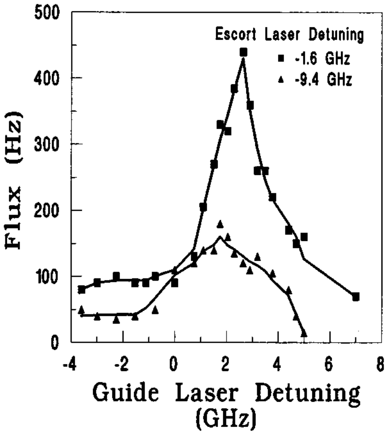

FIG. 3. Evanescent-wave guiding of atoms injected into the guide with a red detuned escort laser. For an escort laser detuning of -1.6 GHz, upper curve, and an evanescent-wave laser power of 500 mW, the guided-atom signal is enhanced by a factor of 4 at a detuning of $+3$ GHz. For larger escort laser detunings (-9.4 GHz for the lower curve) the number of injected atoms is smaller but the fractional signal enhancement compared to the absence of the evanescent laser is nearly the same.

The grazing incidence modes are leaky, having an intensity attenuation length [3], $L_e \cong 2.4a^3/\lambda^2 = 3.8$ mm, where $a = 10$ μm. The potentials formed by scattering of the blue detuned laser and by the red detuned escort laser both decay within a few centimeters of the fiber input. As the escort potential decays, atoms with the highest transverse energy are lost from the atomic beam. However, when the evanescent potential is present, the atoms that would normally be lost from the grazing mode light may be retained in the evanescent potential and guided through the remaining distance. In this way atoms are escorted by the red detuned laser into the region where only an evanescent potential exists.

III. RESULTS

The experimental setup for guiding atoms is similar to that of Ref. [1] and consists of two vacuum chambers that are connected by a short length of hollow core fiber. The chamber on the input side of the hollow fiber contains a thermal cell of Rb. Laser light is coupled through a window in this chamber and into the fiber. Atoms with sufficiently small transverse velocities are loaded at random from the vapor into the fiber guide. The guided atoms emerge in the second chamber and are detected with a hot wire and channeltron.

Figure 2 shows the optical scheme used for launching the laser light and atoms: a high-power (500 mW) laser beam blue detuned from resonance is focused into the annular region of the fiber end; it is coupled primarily to the guided modes but also to the leaky and radiative modes. A second and weaker laser beam, tuned to the red of atomic resonance is focused into the follow region where it couples to the EH_{11} grazing incidence mode. The optical power in the grazing incidence mode is concentrated within a small region in the fiber core, allowing a potential depth comparable to that of the evanescent field case to be created with nearly two orders of magnitude less power. Thus, a relatively weak, $\sim$10-mW diode laser is sufficient to escort the atoms. A few centimeters from the fiber input, the EH_{11} mode amplitude is sufficiently attenuated so that the evanescent potential begins to dominate.

In Fig. 3 we show the enhancement of the atom flux guided through a 6-cm-long fiber with a 20-μm core diameter using this injection scheme. With the red detuned escort laser alone 200 atoms/s are guided through the fiber. Using a mode attenuation length of 4 mm, the intensity and potential decay by a factor of 500 through the fiber, implying that approximately 10^5 atoms/s were initially launched but then lost. Launching 500 mW of evanescent laser power into the glass region recovers some of the lost flux when the laser is tuned to the blue side of resonance but not to the red side, as expected. The flux enhancement is at least a factor of 3 at an optimum detuning of $+3$ GHz. Increasing the escort laser detuning to -9.4 GHz reduces the number of atoms injected into the evanescent guide and thus decreases the overall guided atom signal. The fractional enhancement, determined as the ratio of guided atom flux with and without the presence of the evanescent guide laser, stays roughly the same as the launch laser is detuned out to -20 GHz. Tuning the escort laser to the blue side of resonance inhibits the injection of atoms into the evanescent guide and completely suppresses the guided atom flux.

The intensity dependence of evanescent guiding is qualitatively different than for grazing incidence modes. In grazing incidence configuration atoms are confined near the center of the fiber by a harmonic potential and only weakly interact with the van der Waals potential near the walls. As previously observed [1] this leads to a linear intensity dependence of the flux for low intensities. For evanescent guiding the atoms interact strongly with the attractive van der Waals potential, which results in an intensity threshold for guiding. Measurements of the flux enhancement with increasing laser power presented in Fig. 4 show the expected threshold phenomena. For intensity levels below 6 MW/m^2 no enhancement in the flux is observed. Above 6 MW/m^2 the flux increases roughly linearly with laser intensity. Precise

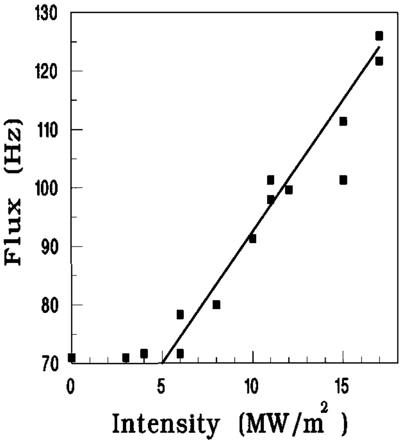

FIG. 4. Intensity dependence of the evanescent-wave-guided atom signal. A threshold for guiding atoms, attributed to attractive van der Waals forces, is observed at 6×10^6 W/m^2. Above threshold the flux increases linearly with intensity.

measurements of the intensity threshold are complicated by the uncertainties in the number of modes excited and the effect of mode interference on the evanescent potential. The threshold intensity without correction for any of these effects is approximately 6×10^6 W/m^2 and is roughly a factor of 10 larger than predicted. We note that more precise measurements may be facilitated with the use of single-mode hollow core fibers [4].

IV. CONCLUSION

In conclusion, we have observed a factor of 3 enhancement in guided atom flux through a hollow core optical fiber by using an evanescent field to repel atoms from the inner wall. An intensity threshold is observed for evanescent guiding that is attributed to the intensity required to overcome van der Waals attraction of the atoms to the fiber wall. The two-color guiding combination of guide and escort laser beams ameliorates the problem of mode matching. We anticipate using this method to inject atoms into a 1.4-μm-diam guide where they will then be guided up to 1 m in the dark region with evanescent fields.

Finally we mention a few applications of evanescent-wave atom guides. Fiber-guided atoms are of particular interest for atom-fiber interferometry [4]. In narrow fibers (1 μm) and at cold temperatures (<1 μK) the transverse atomic motion will be quantized. Interference between these atomic modes will give rise to atomic speckle patterns, the simplest of interferometers. At colder temperatures (<100 nK) the atoms will propagate in the lowest mode, and with an atom-fiber beam splitter an interferometer of the Mach-Zender type may be constructed. The evanescent guiding scheme is particularly useful in that heating and associated loss of coherence of the atoms due to spontaneous emission is minimized.

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