Optical interface created by laser-cooled atoms trapped in the evanescent field surrounding an optical nanofiber

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Trapping and optically interfacing laser-cooled neutral atoms is an essential requirement for their use in advanced quantum technologies. Here we simultaneously realize both of these tasks with cesium atoms interacting with a multi-color evanescent field surrounding an optical nanofiber. The atoms are localized in a one-dimensional optical lattice about 200 nm above the nanofiber surface and can be efficiently interrogated with a resonant light field sent through the nanofiber. Our technique opens the route towards the direct integration of laser-cooled atomic ensembles within fiber networks, an important prerequisite for large scale quantum communication schemes. Moreover, it is ideally suited to the realization of hybrid quantum systems that combine atoms with, e.g., solid state quantum devices.

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Laser-trapped atoms are well isolated from their environment and can be coherently manipulated as well as efficiently interrogated using resonant light [1]. This makes them prime candidates for the implementation of quantum memories and quantum repeaters, necessary, e.g., for the operation of long distance quantum communication networks [2–5]. At the same time, solid state quantum devices, such as quantum dots or superconducting circuits, are readily miniaturized and integrated using well established technologies [6]. For these reasons, the possibility of combining atomic and solid state devices in so-called hybrid quantum systems, which combine the advantageous properties of both approaches, has recently attracted considerable interest [7–9]. Two prerequisites have to be fulfilled in order to realize such a hybrid quantum system. On the one hand, the atoms would have to be efficiently interfaced with resonant probe light for manipulation and interrogation. On the other hand, the atoms would have to be trapped in order to be placed in close vicinity of the charged or magnetized solid state devices in order to be coupled via electric or magnetic interaction. Here, we demonstrate that both tasks, trapping and optically interfacing neutral atoms, can be simultaneously accomplished by means of tapered optical fibers with a nanofiber waist.

The coupling of laser cooled atoms with light by means of optical fibers has been an active field of research over the past years. For this purpose, two types of optical fibers have been employed: In hollow core fibers, the atoms are funneled into a capillary in the centre of the fiber where they couple to the guided fiber mode [10, 11]. This implies that at least one end of the hollow core fiber has to terminate inside the vacuum chamber and that the device can thus not be directly connected to a fiber network. The situation is different when using optical nanofibers with a diameter smaller than the wavelength of the guided light. In this case, the atoms remain at the outside of a fiber and couple to the evanes-
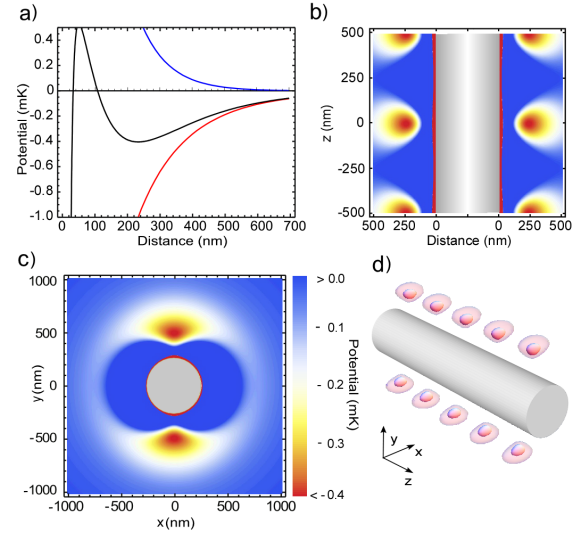

FIG. 1: (a, black line) Potential as a function of distance from the surface of a 500-nm diameter nanofiber for a ground state cesium atom induced by a two-color evanescent field plus the van der Waals potential. The red and blue lines show the individual light induced potentials for a red- and blue-detuned field at 1064 nm and 780 nm respectively. We assumed a power of $P_{\text{red}} = 2 \times 2.2$ mW (standing wave) and $P_{\text{blue}} = 25$ mW and orthogonal linear polarization of the red and blue fields. (b) Contour plots of the same potential as in (a). The red-detuned standing wave ensures axial confinement. (c) Azimuthal plot of the same potential as in (a) and (b). The planes of the plots in (a)–(c) are chosen to include the trapping minima. (d) Contour plot of the resulting array of trapping sites on both sides of the fiber showing equipotential surfaces 40 μK and 125 μK above the trapping minimum.

cent field surrounding the fiber [12, 13]. Such nanofibers can be realized as the waist of tapered optical fibers (TOFs) which allows one to optimally match the mode of a standard single mode optical fiber with the fundamental nanofiber mode, thus ensuring high transmission of

the device [14, 15] as well as direct integrability into fiber networks. Moreover, a nanofiber can be passed through an operating magneto-optical trap (MOT), thereby facilitating the coupling of atoms and light [12, 16]. The ultimate goal in both lines of research is to combine the coupling scheme with three dimensional trapping of the atoms in order to maximize both the number of coupled atoms, resulting in the highest possible optical depth, as well as the interaction time. In this context, it has been proposed to realize a two-color optical dipole trap which makes use of a red- and blue-detuned evanescent light field around the optical nanofiber [17, 18].

Figure 1 shows the potential calculated for a ground state cesium atom subjected to such a two-color evanescent light field around a 500-nm diameter nanofiber. At that diameter the nanofiber only guides the fundamental HE_{11} mode for both wavelengths. The red-detuned light field, as well as the van der Waals force attract the atoms towards the nanofiber while the blue-detuned light field repels the atoms from the fiber. Due to the different radial decay lengths of the red- and blue-detuned evanescent fields one can thus create a radial potential minimum at a few hundred nanometers from the nanofiber surface by properly choosing the respective powers, see Fig. 1 (a). Confinement along the fiber axis is achieved by launching an additional, counter-propagating red-detuned laser beam through the fiber, thereby realizing a red-detuned standing wave, see Fig. 1 (b). Azimuthal confinement of the atoms stems from the azimuthal dependence of the evanescent field intensity for the quasi-linearly polarized HE_{11} mode, see Fig. 1 (c). In order to maximize the azimuthal confinement we use orthogonal linear polarizations for the red- and blue-detuned fields. Figure 1 (b) is shown in the plane of polarization of the red-detuned field. Figure 1 (d) shows the two resulting 1d arrays of trapping minima on both sides of the fiber, visualized by the equipotential surfaces 40 μK and 125 μK above the trapping minimum. The calculated trapping frequencies for the parameters used in Fig. 1 are 200 kHz, 315 kHz, and 140 kHz in the radial, axial, and azimuthal direction, respectively. Large detunings of the trapping light fields are chosen in order to ensure a low scattering rate, compatible with a theoretical coherence time of 50 ms and trap lifetime of up to 100 s. Further decoherence mechanisms due to surface interactions are expected to be negligible at the distances of $\approx$ 100 nm considered here because of the low conductivity of glass [19].

Figure 2 (a) shows a schematic of our setup. We use a laser at 1064 nm which is red-detuned with respect to the D1 (894 nm) and D2 (852 nm) transitions of cesium. Using a beam splitter, two beams are generated and coupled into both ends of the TOF in order to realize the standing wave. A laser at 780 nm is used for forming the blue-detuned potential and is superposed with one of the red-detuned laser beams using a dichroic mirror (DM). The probe laser is resonant with the D2 transition. It
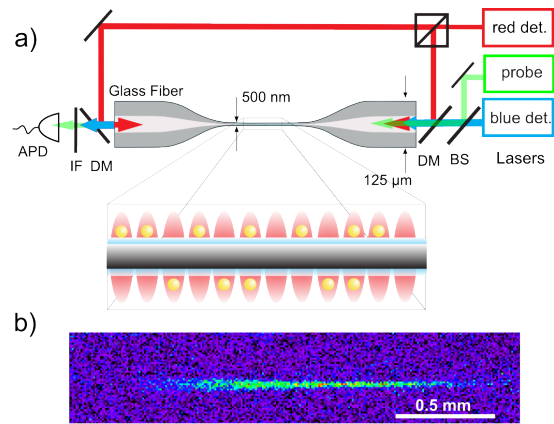

FIG. 2: (a) Experimental setup of the fiber-based atom trap. The blue-detuned running wave in combination with the red-detuned standing wave create the trapping potential. A resonant laser is used for probing the atoms via the evanescent field. (b) Fluorescence image of the trapped atomic ensemble.

is superposed with the blue-detuned laser beam using a beam splitter (BS) and its power transmitted through the TOF ($\approx$ 1 pW) is measured using an avalanche photodiode (APD) in combination with an interference filter (IF). Typical powers of the trapping lasers are 2–4 mW for each of the red-detuned beams and 10–30 mW for the blue-detuned beam. The state of polarization of the dipole laser beams at the nanofiber waist can be monitored and aligned by observing the angular distribution of the Rayleigh scattered light, emitted by the nanofiber perpendicular to its axis using CCD cameras. The probe laser has a short term linewidth of about 1 MHz.

The TOF has been fabricated by stretching a standard single mode fiber while heating it with a travelling hydrogen/oxygen flame in a computer controlled fiber pulling rig [20]. The nanofiber waist has a homogeneous diameter of 500 nm over its length of 5 mm. In the 4 cm long tapered sections the weakly guided LP_{01} mode of the unstretched fiber is adiabatically transformed into the strongly guided HE_{11} mode of the nanofiber waist and back [14, 15]. This results in a highly efficient coupling of light into and out of the nanofiber yielding an overall transmission through the TOF of 97 %. The lasers are coupled into the ends of the TOF using conventional fiber couplers and the TOF enters and exits an ultrahigh vacuum chamber via a vacuum feed-through. Inside the chamber (pressure $\approx$ 8 $\times$ 10^{-10} mbar), a six-beam magneto-optical trap (MOT) produces a cold cesium atom cloud with a $1/e^2$-diameter of 1.2 mm which is spatially overlapped with the nanofiber.

Loading of the trap is accomplished as follows: The red- and blue-detuned trapping light fields are present in the nanofiber at all times. During the first 2 s, the atoms are captured and cooled in the MOT. In the following 100 ms the atoms are transferred and cooled into the

trapping minima along the nanofiber. For this purpose, the power of the MOT cooling laser, repump laser and the magnetic field gradient are ramped down to zero and the detuning of the cooling laser is increased to about -80 MHz. We note that due to the small trapping volumes the loading is expected to operate in the so-called collisional blockade regime resulting in an occupancy of at most one atom per trapping site [21]. The resulting maximum average occupancy of 0.5 in conjunction with the distance of ≈ 500 nm between the standing wave antinodes thus limits the maximum number of trapped atoms to 2000 per millimeter.

In order to image the trapped atoms, we have positioned a home-built microscope objective with a numerical aperture of 0.29 inside the vacuum chamber [22]. This allows us to collect the fluorescence light, induced by the resonant excitation of the trapped atoms, and thus create an image on the chip of an EMCCD camera. Figure 2 (b) shows the fluorescence of a trapped ensemble of Cs atoms recorded 20 ms after loading the trap. Fluorescence is observed over a length of ≈ 1.2 mm corresponding roughly to the diameter of the cold atom cloud in the MOT. For this image the probe laser was detuned by -10 MHz with respect to the AC-Stark shifted D2 ($F = 4$ to $F' = 5$) transition of Cs and its power was set to 500 pW, corresponding to the saturation intensity at resonance at the position of the atoms. The probe light was pulsed with a pulse length of 2 ms, corresponding to the exposure time of the EMCCD camera. The fluorescence image shown in Fig. 2 (b) is the sum of 320 single background corrected exposures from consecutive experimental runs.

We investigate the spectral properties of the trapped atomic ensemble by measuring the absorption of the probe light as a function of its detuning. As a reference, the green line in Fig. 3 (a) shows the transmission of the probe light versus the detuning with respect to the D2 ($F = 4$ to $F' = 5$) transition of Cs without the fiber trap after abruptly switching off the MOT lasers and magnetic field. In this case, the measured absorption due to the cold atom cloud around the nanofiber reaches 20 % and the linewidth is only slightly larger than the natural linewidth of Cs due to the atom-surface interactions [12]. The black squares in Fig. 3 (a) show the probe transmission directly after loading the fiber trap. We observe a strong absorption resulting from a dramatic increase of the number of atoms in the evanescent field due to trapping of atoms inside the two-color trap.

The fitted line profile (solid red line) yields a maximum optical depth of $OD = 13$ (2) for a detuning of 13 MHz and a FWHM of $\Gamma = 20$ MHz. The shift and broadening can be attributed to the state dependent light-shift of the transition frequency induced by the trapping laser fields. Compared to this inhomogeneous broadening due to the transitions to all excited substates the broadening due to the thermal motion of the atoms inside the trapping potential is negligible. For the measurement in
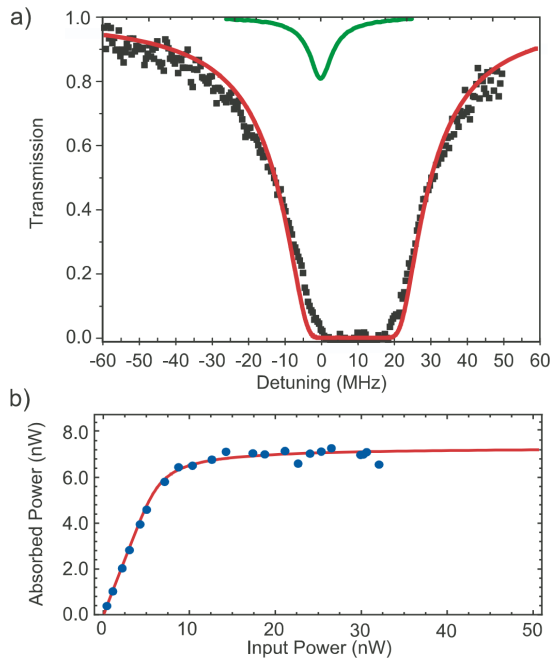

FIG. 3: (a) Transmission spectrum of the probe beam through the nanofiber after loading the trap (black squares). For reference the spectrum of the MOT-cloud (green line) is plotted. The red line is a theoretical fit, see text. (b) Saturation measurement (blue circles) yielding the number of trapped atoms. The red line is a theoretical fit, see text.

Fig. 3 (a) the probe light power was about 1 pW. This low power ensures that the scattering rate of the atoms (30 kHz) is smaller than their oscillation frequency in the trap (≈ 140 kHz), resulting in strongly suppressed recoil heating due to off-resonant raman scattering [23]. This maximizes the number of scattered photons before atom loss, thereby optimizing the signal.

The APD signal is recorded with a digital storage oscilloscope and averaged over 64 traces. The transmission is then calculated according to

$$T = \frac{(P_{\mathrm{at}} - P_{\mathrm{bg}})}{(P_0 - P_{\mathrm{bg}})}, \qquad (1)$$

where P_{at}, P_0, and P_{bg} are the APD signals with and without atoms and the background signal, respectively. The transmission spectrum in Fig. 3 (a) is well described by

$$T(\Delta) = \exp\left\{-OD \sum_i \frac{C_i}{1 + 4(\Delta_i/\Gamma_0)^2}\right\}, \qquad (2)$$

(solid red line), where the exponent accounts for the Lorentzian line profiles corresponding to the transitions between the differently light-shifted new eigenstates, $\Delta = \omega - \omega_{\mathrm{D2}}$ is the detuning of the probe laser frequency with respect to the atomic resonance frequency in free space

ω_{D2}, and $\Delta_i = \Delta - \Delta_i^{\text{LS}}$, where Δ_i^{LS} is the state dependent light shift induced by the linearly polarized trapping lasers. $\Gamma_0 = 5.2$ MHz is the natural line width of the Cs D2 transition. The coefficients C_i account for the degeneracy and relative strength of the transitions and are chosen such that the sum in the exponent is normalized to one. Optical pumping induced by the probe light as well as collective radiative effects are not included in this model and might account for the slight discrepancy between the theoretical prediction and the experimental data.

In order to determine the number of trapped atoms, we carry out a saturation measurement: We tune the probe laser to the Stark shifted resonance of the trapped atoms and measure the absorbed power as a function of the incident power, see Fig. 3 (b). At high saturation, the atomic ensemble absorbs about $P_{\text{Abs}} \approx 7.5$ nW of probe light power. By comparing this value with the power radiated by a single fully saturated Cs atom of $P_{\text{Cs}} = 3.8$ pW we infer that $N = P_{\text{Abs}}/P_{\text{Cs}} = 2000$ atoms are present in the fiber-based trap. The solid red line is a theoretical fit based on a saturation model taking into account the spatially varying intensity along the atomic ensemble due to absorption. We find that the number of stored atoms decreases exponentially with a time constant of about 50 ms, smaller than what would be expected from losses due to background gas collisions. This effect is currently still under investigation, one possible loss mechanism being heating of the atoms due to intensity fluctuations of the trapping lasers.

From the optical depth and the number of atoms we infer an average absorbance per atom of $\varepsilon = OD/N \approx 0.65$ %. We note that in the absence of inhomogeneous broadening the absorbance of the atomic ensemble would be increased by a factor of ≈ 2.5. Under these circumstances and for low saturation, the absorbance per atom would then reach $\varepsilon_0 = \eta\varepsilon \approx 1.8$ %. This value is consistent with our expectation that a single atom at a radial distance of about 230 nm from the fiber surface would absorb a fraction of $\sigma/A_{\text{eff}} = 1.5$ %, where σ and A_{eff} are the absorption cross section of the unperturbed D2 ($F = 4$ to $F' = 5$) transition of cesium and the effective mode area of the nanofiber guided mode [24, 25] respectively.

Summarizing, we have trapped and interfaced neutral cesium atoms in a one-dimensional optical lattice created by a two-color evanescent field surrounding an optical nanofiber. Due to the atoms' very close proximity (230 nm) to the nanofiber surface, the atoms efficiently interface with resonant light sent through the nanofiber. We have observed an absorbance of about 0.7 % per atom and an overall optical depth of 13 for approximately 2000 trapped atoms. Our system is well suited to the realization of hybrid quantum systems, coupling, e.g., solid state quantum devices with optically interfaced laser-trapped atoms. Such a coupling scheme would in particular profit from the possibility of positioning the atoms in close vicinity of the solid state surface without exposing the latter to the evanescent trapping light field. Moreover, our work paves the way towards non-linear optics and quantum communication applications with fiber-coupled atomic ensembles. Finally, it should be possible to realize a fiber-mediated coupling between the trapped atoms. In conjunction with the trapping in 1d periodic chains, this would then allow the study of collective states of light and matter, e.g., tailoring or even fully suppressing the spontaneous emission of the ensemble into free space [26].

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