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Temperature measurement of cold atoms using transient absorption of a resonant probe through an optical nanofibre

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Abstract

Optical nanofibres are ultrathin optical fibres with a waist diameter typically less than the wavelength of light being guided through them. Cold atoms can couple to the evanescent field of the nanofibre-guided modes and such systems are emerging as promising technologies for the development of atom-photon hybrid quantum devices. Atoms within the evanescent field region of an optical nanofibre can be probed by sending near or on-resonant light through the fibre; however, the probe light can detrimentally affect the properties of the atoms. In this paper, we report on the modification of the local temperature of laser-cooled ^{87}Rb atoms in a magneto-optical trap centred around an optical nanofibre when near-resonant probe light propagates through it. A transient absorption technique has been used to measure the temperature of the affected atoms and temperature variations from 160 μk to 850 μk, for a probe power ranging from 0 to 50 nW, have been observed. This effect could have implications in relation to using optical nanofibres for probing and manipulating cold or ultracold atoms.

Keywords: optical nanofibres, hybrid quantum systems, temperature, laser-cooled rubidium

(Some figures may appear in colour only in the online journal)

1. Introduction

Optical nanofibres (ONFs) are ultrathin optical waveguides with sub-wavelength diameters [1] and have been used extensively in recent years for probing and manipulating cold atoms and other quantum systems [2, 3]. Due to the very high evanescent field intensities and the very strong light confinement in the transverse direction, ONFs can be used to study nonlinear optics phenomena, such as Autler−Townes splitting, electromagnetically induced transparency, slow light generation and quantum state storage, in atomic systems [4–8]. Atoms around the waist of an ONF can be probed by two means: (i) collecting the emitted atomic fluorescence that couples into the nanofibre [9–11] or (ii) by measuring the transmission or the polarisation variation of an on-resonant probe beam sent through it [12–14]. Previously, ONFs have been used to measure the temperature of a cloud of cold atoms via spring constant measurements [15], a release-

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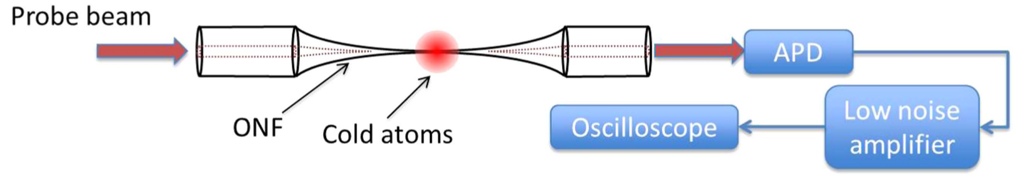

Figure 1. Schematic of the experimental setup used for measuring the temperature of atoms near the surface of an optical nanofibre. APD: avalanche photodiode; ONF: optical nanofibre.

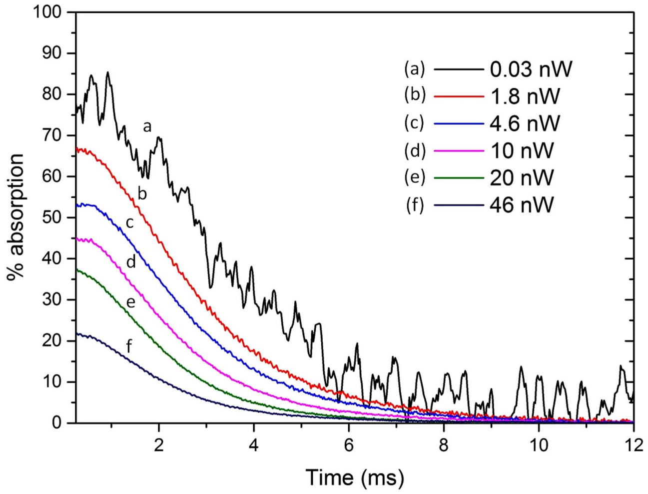

Figure 2. Measured transient absorption for different input probe powers through the ONF as the atom cloud is allowed to expand. Fluctuations in the background light level become dominant for measurements at the very low probe power of 0.03 nW.

recapture technique [16] and photon correlations [17]. Here, we present an alternative technique for temperature measurement based on the absorption of a probe beam. In contrast to the fluorescence-based measurements, this enables us to study the effect of the probe itself on the local temperature of the cloud and provides a method by which we can directly modify it. The ONF integrated into a magneto-optical trap (MOT) is used to measure the temperature of the atoms at the very central region of the atom cloud. Thence, we study the effect of a resonant probe beam on the local temperature of the atoms, i.e. those atoms closest to the nanofibre surface, and show a good fit with theory. Atoms coupled to ONFs could be used for preparing fibre-coupled quantum nodes in quantum computing [18] and the studies presented herein provide significant advances in the understanding of the ONF-atom system.

2. Fabrication of an optical nanofibre

There are various ways for fabricating ONFs including using a CO_2 laser [19], acid flow etching [20], flame-brushed heat-and-pull technique [21], direct drawing from bulk material [22], self-modulated taper-drawing [23], an electric ceramic microheater [24] and electrospinning [25]. We prepared our ONFs using the 'heat-and-pull' technique [21]. Unjacketed, standard optical fibre, with a cladding diameter of 125 μm and a core diameter between 4 and 10 μm, is heated to a temperature between 1200 °C–1500 °C which is above the annealing temperature of silica. Hence, its viscosity is lowered sufficiently to allow deformation, while remaining below the softening temperature so that the glass does not sag under its own weight. Meanwhile, the fibre is pulled simultaneously at both ends using computer-controlled motors. This leads to a tapering of the original fibre and provides an ONF with a submicron waist diameter. ONFs for use with cold atoms must be prepared in a way that will ensure very high light transmission through the waist region (i.e. very low losses), therefore necessitating that the tapering process be adiabatic [26]. In other words, there should be no coupling from the fibre-guided mode under consideration (e.g. the fundamental, LP_{01} mode) to other fibre-guided (or cladding) modes. In the experiments reported here, the diameter of the ONF is ~350 nm with a transmission of ~84% for 780 nm light when installed in the ultrahigh vacuum chamber needed for the MOT. At this diameter, only the fundamental mode can propagate through the ONF for 780 nm light.

3. Temperature measurements using transient absorption

The ONF is installed in the MOT chamber and details of the method are described elsewhere [15]. A schematic of the experimental setup is shown in figure 1. A standard MOT arrangement is used for cooling the ^{87}Rb atoms [14] and the atom cloud is aligned with the ONF by monitoring coupled fluorescence through one of the fibre pigtails. A 780 nm probe beam locked to the $5S_{1/2}\ F = 2 \rightarrow 5P_{3/2}\ F' = 3$ transition is sent through the ONF and interacts with the cold atoms around the waist. The transmission of the probe beam is collected on an avalanche photodiode and subsequently amplified using a low-noise amplifier before being displayed on an oscilloscope. The average temperature of atoms in a MOT can be measured using a transient absorption technique [27]. After trapping the atoms, the MOT beams are switched off and the atom cloud freely expands. As a consequence, absorption of the probe beam passing through the ONF reduces (i.e. its transmission through the fibre increases) since the number of atoms interacting with the evanescent field decreases as a function of the reduction of the atom cloud density during the expansion phase. The time evolution of the absorption signal can be used to characterise the average temperature of the atoms interacting with the evanescent field. Transient absorption measurements were made for various input probe powers, ranging from

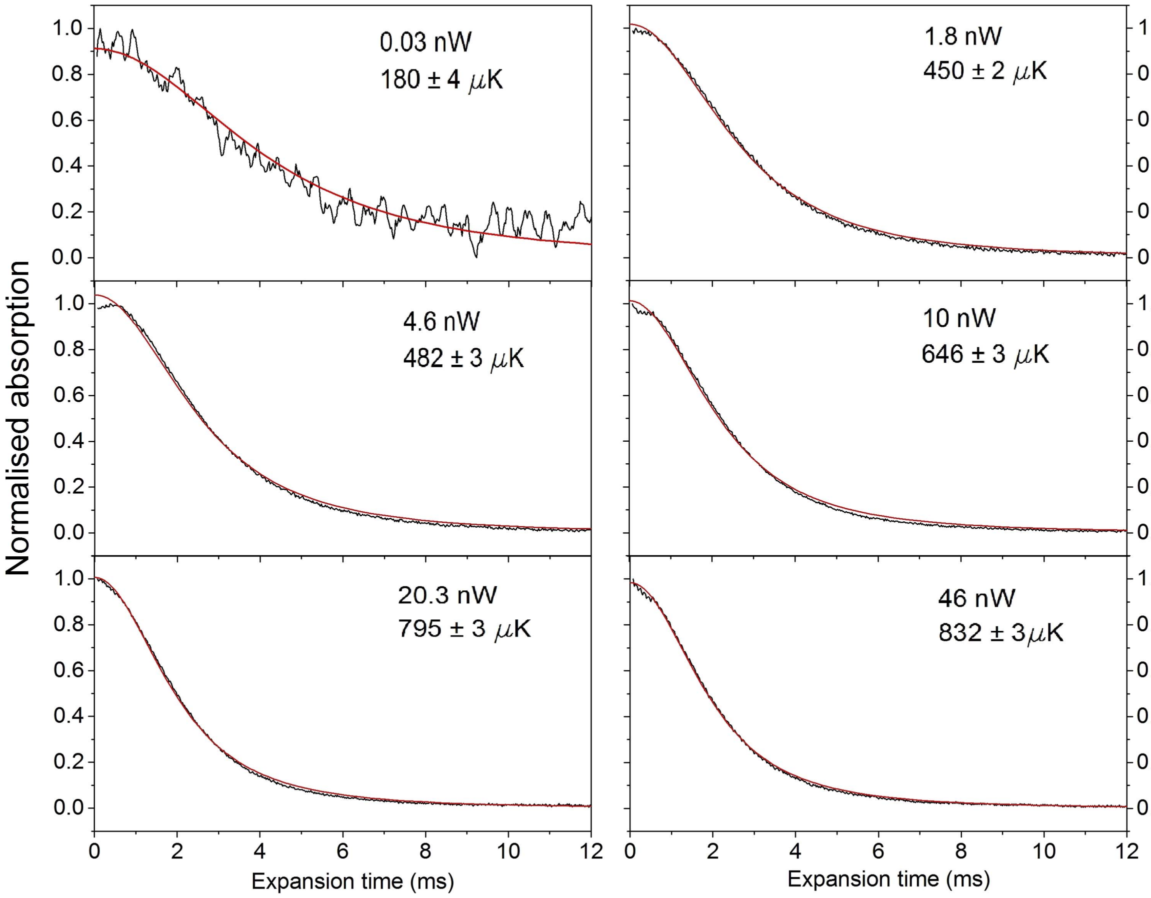

Figure 3. Transient absorption with theoretical fits for various probe powers. The corresponding temperature values found from the fits are shown with the standard error obtained from the fitting parameters.

0.03 nW to 46 nW. From figure 2, we see that the maximum percentage absorption obtained for an unexpanded cloud reduces with power.

To determine the temperature of the atoms from the transient absorption signals, let us first assume that the cloud of atoms has a Gaussian density distribution at some initial time, $t < 0$, and expands ballistically once the trapping beams are switched off at $t = 0$. Thence, the density distribution, $\rho(r, t)$, evolves as [27]

$$\rho(r, t) = A(t)e^{-r^2/(w_0^2+\bar{v}^2t^2)}, \tag{1}$$

where r is the radial coordinate, w_0 is the initial Gaussian waist of the cloud, $\bar{v}$ is the average thermal velocity of the atoms and $A(t)$ is the peak density at a time, t, given by

$$A(t) = N/[\pi(w_0^2 + \bar{v}^2t^2)]^{3/2}, \tag{2}$$

where N is the total number of atoms in the trap.

The density of the atom cloud, in the region close to the fibre surface, is perturbed by the presence of the ONF [28]. This is due to finite radius of the ONF which produces shadowing around it. Atoms are less likely to enter this shadow region. Also, atoms colliding with the fibre are either adsorbed or expelled with a high kinetic energy. The amount of shadowing at a radial distance, r, from the fibre surface is determined by a quantity α/π, where α is given by $\arcsin(a/r)$ for an ONF of radius a. This effect is incorporated by approximating the atomic cloud density as [28]

$$\rho_{\mathrm{ONF}}(r, t) = \frac{Ne^{-r^2/(w_0^2+\bar{v}^2t^2)}}{\pi^{3/2}(w_0^2 + \bar{v}^2t^2)^{3/2}}\left[1 - \frac{\arcsin(a/r)}{\pi}\right]. \tag{3}$$

According to Beers law, the differential change in the intensity of a probe passing through an absorbing medium is given by

$$\mathrm{d}I = -\sigma_a\rho I(r)\mathrm{d}r, \tag{4}$$

where σ_a is the absorption cross-section, ρ is the density and $I(r)$ is the field intensity at a radial distance, r. Looking at the transient behaviour of the absorption during free expansion at various powers (figure 2), we can estimate the temperature change of the cloud locally near the ONF due to the presence of the probe beam. The extension of the evanescent field from the fibre surface is very small (typically < 100 nm) compared to the diameter of the cloud ($\sim$1 mm) and, therefore, the probe beam is only expected to influence atoms in the evanescent field region. Fitting the transient absorption curves with equation (4) provides a value for $\bar{v}$ for which the corresponding temperature can be determined from $T = M\bar{v}^2/3k_B$.

Figure 3 shows the normalised transient absorption spectra from figure 2 and the theoretical fittings, from which we can determine the average local temperature of the atoms in the interaction region (see figure 4). The effect of probe power on

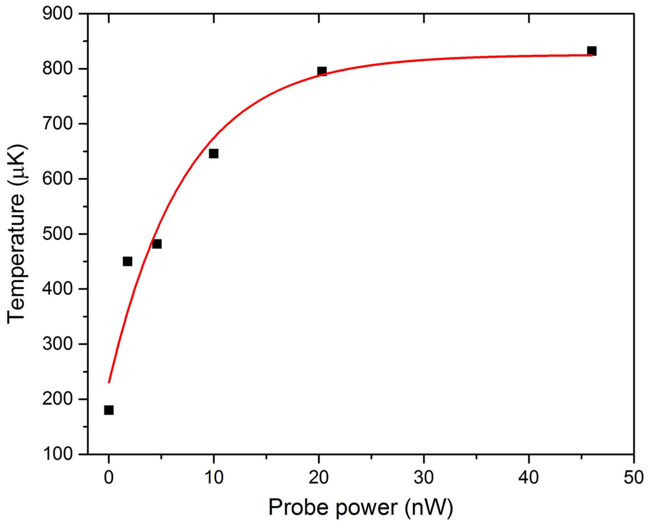

Figure 4. Temperature measured by the transient absorption technique with a probe propagating through the ONF. The solid line shows an exponential fit. The error bars associated with the temperature values (as estimated from the fitting parameters in figure 3) are not visible on the scale of the data points.

temperature is evident. The average temperature of the cloud is measured to be 160 μk when no probe beam propagates through the ONF and is measured by taking fluorescence images of the cloud with a CCD camera during ballistic expansions for various expansion times. The minimum probe power of 30 pW provides a temperature close to this average temperature, i.e. 180 μK as opposed to 160 μK with no probe present. This is expected, since the low power probe should have a minimal heating effect on the atoms. As the probe beam power is increased, the probe beam intensity in the evanescent field region increases; hence, the random recoils of the atoms due to the probe light gets increased leading to a local heating effect. The temperature increases as a function of the probe power and reaches a maximum value (figure 4) for the saturation of absorption of the atoms.

4. Conclusion

We have measured the temperature of cold atoms using a transient absorption method whereby an on-resonant probe beam is passed through an optical nanofibre. The effect of the probe beam on the local temperature of the atoms shows the significant influence of probe intensity. This result is crucial since probe light is regularly passed through ONFs to confirm the presence of atoms in nanofibre-based traps [29, 30] and the detection technique clearly has an impact on the atom cloud parameters. We have observed an increase in the local temperature with probe power until saturation was reached. It should be noted that saturation effects due to the probe beam may affect the temperature measurements. In future work, it would be desirable to use a separate, very weak measurement beam to measure the temperature influence of the stronger probe beam. Furthermore, it is well-known that the temperature of a cold atom cloud is not uniform [31]; using our method, it should be possible to spatially map the temperature of the cloud by moving the nanofibre in a radial direction from the centre. This work could have implications on the dynamics of cold atoms in an ONF-cold atom system [5]. A recent proposal on quantum nondemolition measurements and spin squeezing using the dispersive response of nanofibre-trapped atoms [32] relies on measuring the intensity and polarisation of the guided probe light and our work emphasises the importance of using ultralow probe powers, well below any saturation limits.

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