Imaging and Localizing Individual Atoms Interfaced with a Nanofiber Waveguide

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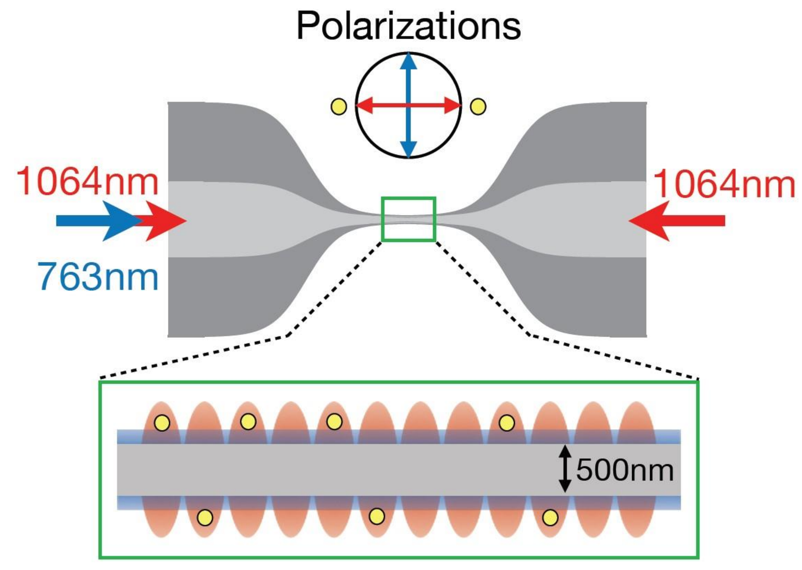
Abstract: Single particle-resolved fluorescence imaging is an enabling technology in cold-atom physics. However, so far, this technique has not been available for nanophotonic atom-light interfaces. Here, we image single atoms that are trapped and optically interfaced using an optical nanofiber. Near-resonant light is scattered off the atoms and imaged while counteracting heating mechanisms via degenerate Raman cooling. We detect trapped atoms within 150 ms and record image sequences of given atoms. Building on our technique, we perform two experiments which are conditioned on the number and position of the nanofiber-trapped atoms. We measure the transmission of nanofiber-guided resonant light and verify its exponential scaling in the few-atom limit, in accordance with Beer-Lambert's law. Moreover, depending on the interatomic distance, we observe interference of the fields that two simultaneously trapped atoms emit into the nanofiber. The demonstrated technique enables postselection and possible feedback schemes and thereby opens the road toward a new generation of experiments in quantum nanophotonics.

Experimental Setting and Challenges

We load atoms from a MOT into a nanofiber-based two-color optical dipole trap. The atoms are localized in a 1D array, about 270 nm from the nanofiber.

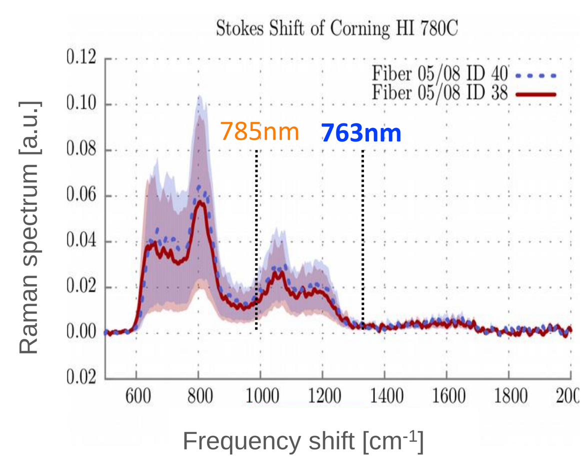


Single-atom sensitivity requires
- Long exposure times
- Low background counts
- High signal count rates

Challenges:
- Trap lifetime is too short without cooling (due to phonon induced heating)
- Heating by probe laser
- Raman scattering in nanofiber
- Rayleigh scattering of molasses laser

Trap parameters

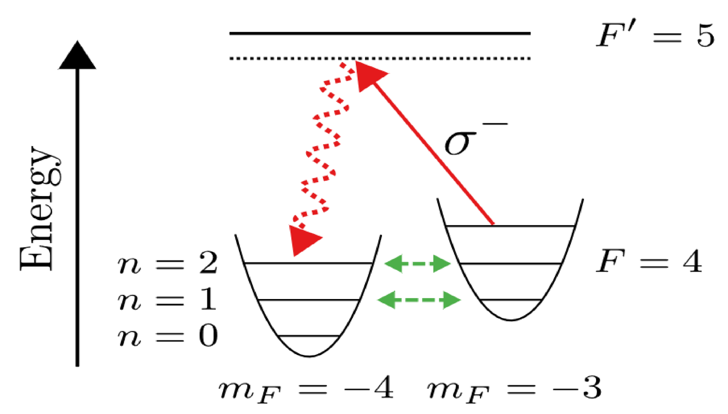
Red power	2.0 mW (total)
Blue power	17.8 mW
Trap depth	175 uK
Lifetime	50 ms



Solution:
1. Blue Trap laser: 785 nm → 763 nm (7x reduction of Raman scattering rate)
2. Repumper on D1 transition
3. Degenerate Raman Cooling

Degenerate Raman Cooling

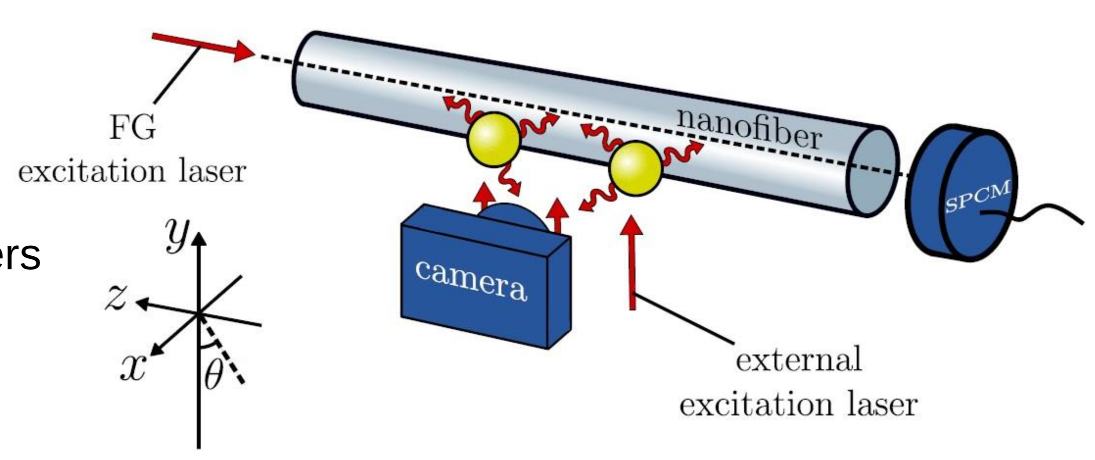
Advantages:
- Single laser to cool the 3D motion of the atoms
- Possible with fiber-guided and external light fields
- Lifetime: 50 ms → 1 s, limited by background gas pressure

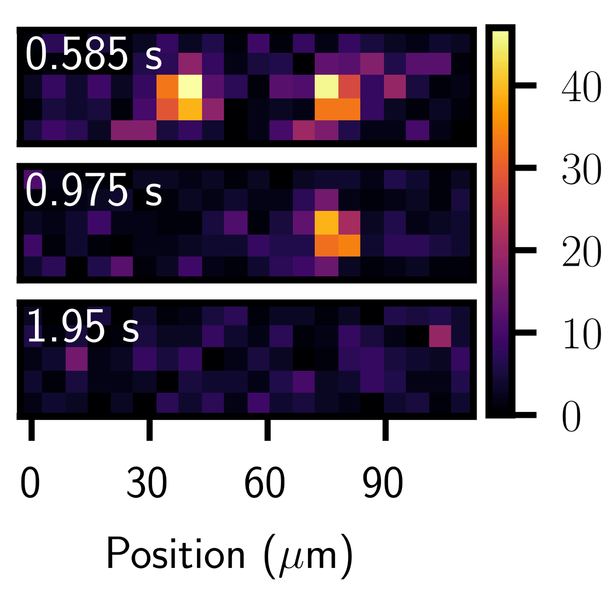


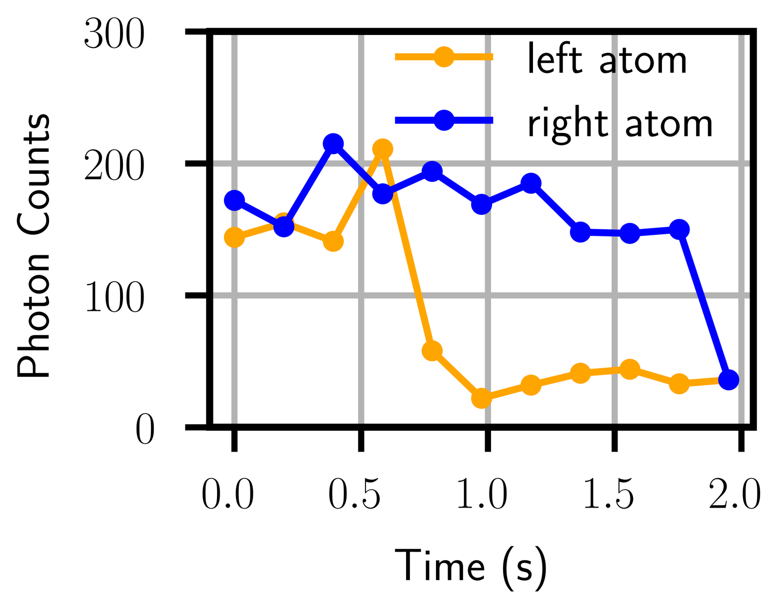
- m_F levels are tuned into resonance via external magnetic field
- Fictitious magnetic field gradient → spin-phonon coupling rate of ≈ 35 kHz
- Optically pump atoms to lower vibrational states
- Lamb-Dicke parameter of about 0.1-0.2
- Scattered photons are used for imaging

Imaging of Single Atoms

Imaging Setup:
In-vacuum objective
NA = 0.27
PSF = 10 µm
Andor EMCCD camera + filters
$f_{tubelens}$ = 100 mm
Field of view ≈ 300 µm
Magnification ≈ 3

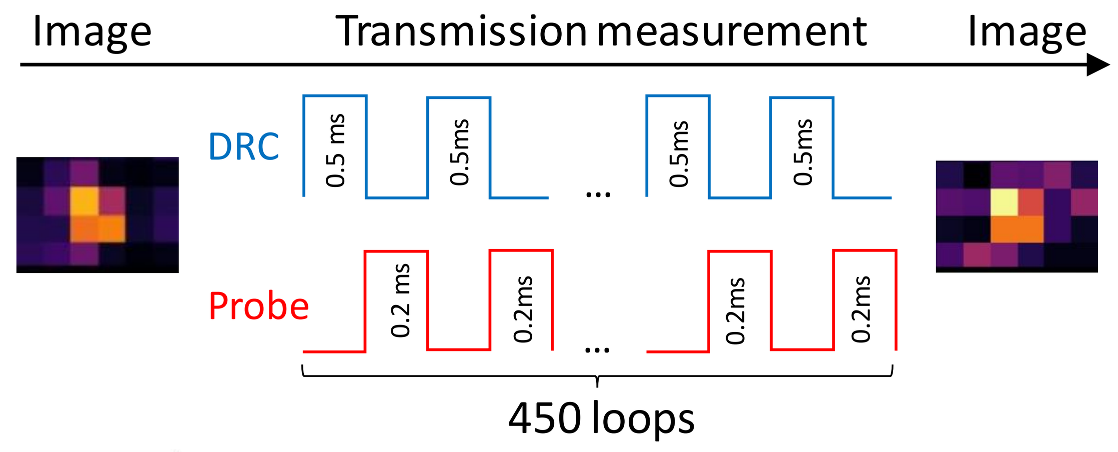


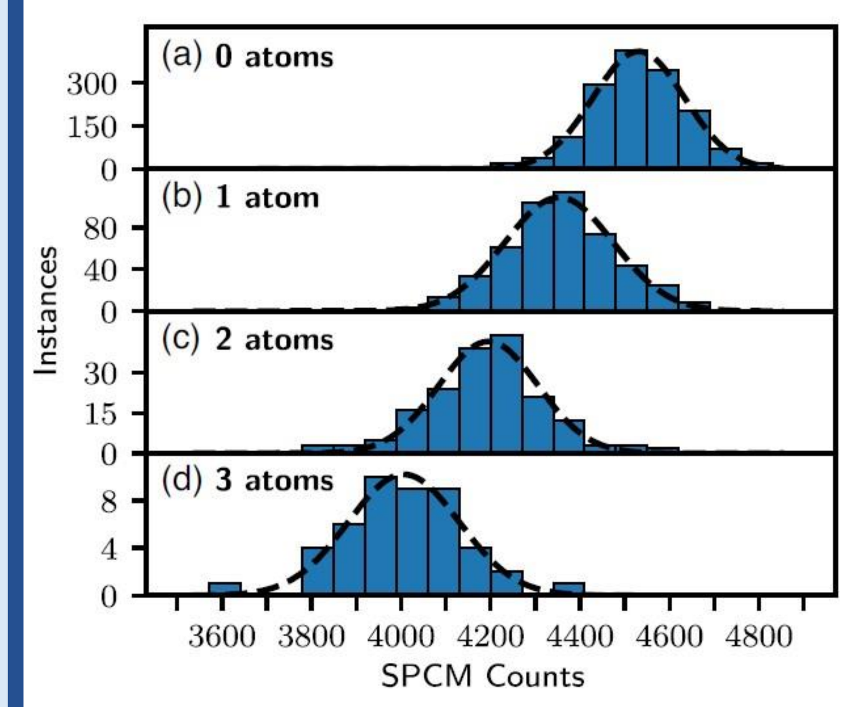




Resonant Transmission

Interleaved scheme:
- Detection-cooling loop
- Post selected on images
- Filters + VBG + cavity: 47 % filter loss

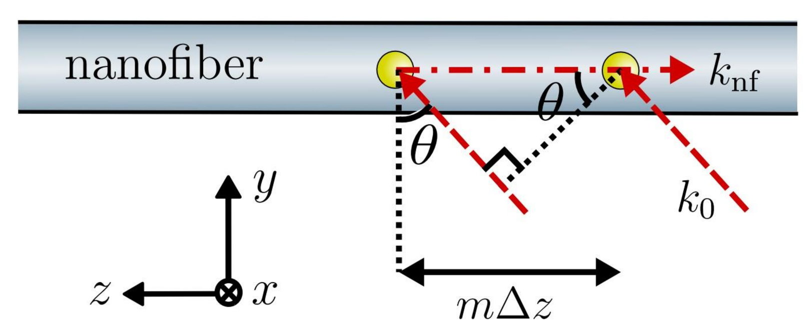


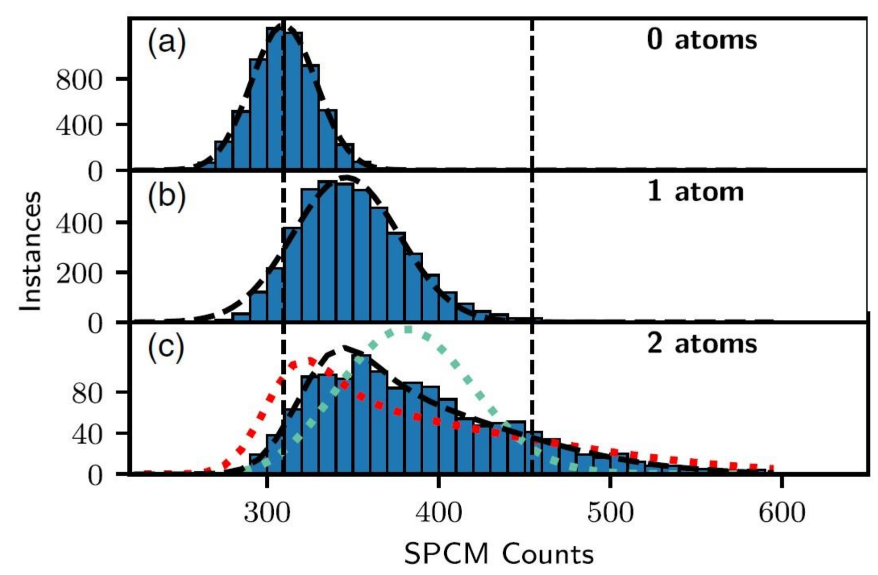


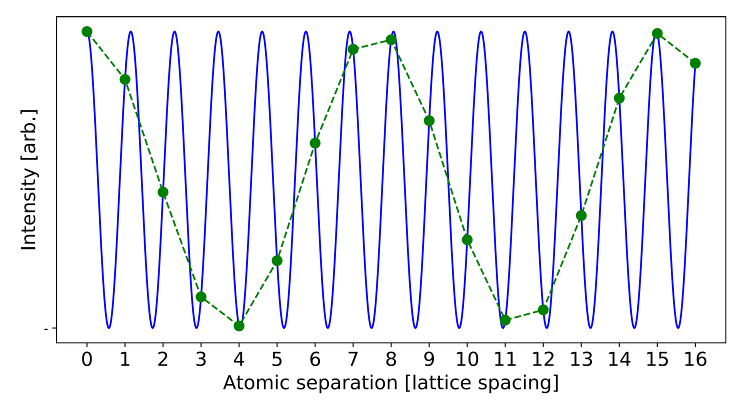
- We measure the transmission for 0,1,2 and 3 atoms with a resonant, fiber-guided light field
- With each additional atom, the extinction increases by 0.039(1), 0.039(1), 0.043(3) respectively.
- These values are constant within their error, and thus in agreement with Beer-Lambert's law

Emission into the Fiber

- Atoms are excited from the side, under an angle θ
- SPCM detects light scattered into the fiber mode with single-atom sensitivity
- For two atoms → scattered fields interfere, depending on the atomic separation
- Differential mode fluctuations (≈ 29%) lead to a reduced interference contrast

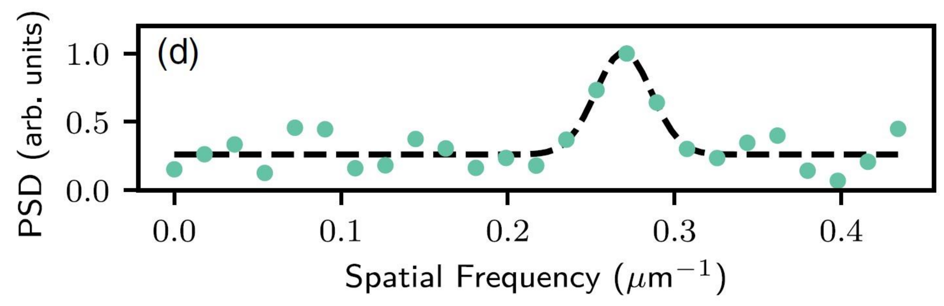






Atoms are positioned on a lattice → undersampling of the interference fringes

- We measure SPCM counts as a function of atomic separation
- Fourier trafo: Spatial frequency corresponds to θ = 20°, close to the estimated value of 16°



Summary & Outlook

- In-situ imaging and precision localization of single atoms coupled to a nanophotonic system
- Beer-Lambert's law in the few atom limit
- Interference of the light fields scattered into the nanofiber mode by two atoms

Our technique could enable new experiments, including:
- Collective effects, mediated by the waveguide, e.g. sub- and superradiance with exactly known number of emitters
- Reacting on real-time images, addressing of single atoms

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