Trapping and Interfacing Cold Neutral Atoms Using Optical Nanofibers

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Arno Rauschenbeutel
Vienna Center for Quantum Science and Technology,
Atominstitut, TU Wien, Austria
Introduction: Nano Quantum Optics

Goal:
Control of light–matter interaction using integrated nano-devices.

Motivation:
• Applications in research and technology (sensing, filters, switching, non-linear optics, cavity QED, etc.)
• Combine optical technologies and quantum physics for quantum communication & information processing.

Task:
Find suitable nano-devices to interface light & matter.
Introduction: Glass Fibers: “Backbone” of the Modern Communication Society
Introduction: Tapered Fibers

- Problem: Light field in standard optical fibers cannot be accessed from outside.

- Trick: Narrow down optical fiber until light field gets to the surface.
Overview

• Optical nanofibers
  – Properties and fabrication

• Nanofiber-based atom trap
  – Trapping potential
  – Experimental realization
  – Experiments with fiber-trapped atoms

• Summary / Outlook
Optical Nanofibers

- Significant part of the optical power propagates outside of optical nanofiber in form of evanescent wave:
Tapered Optical Fibers

• Tapered optical fibers allow one to couple light in and out of nanofiber waist:

125 µm

500 nm

taper transition

taper transition

• Adiabatic mode transformation ⇒ up to 99% transmission!
Fabrication of Tapered Fibers

- Tapering standard optical fibers by flame pulling:
Tapered Fibers of Predetermined Shape

A. Stiebeiner et al., Opt. Express, 18, 22677 (2010)
Single Atom Absorption

Single atom should have significant effect on transmission!
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Evanescent field around fiber exerts dipole force on atoms.

Blue light is more tightly bound to nanofiber than red light.

Axial Trapping Potential

Two counterpropagating red beams create standing wave
⇒ axial confinement:

![Diagram showing axial confinement](image-url)
Azimuthal Trapping Potential

- Quasi linearly polarized HE\(_{11}\) mode.
- Parameters: \(a = 250\) nm, \(n_1 = 1.46\) (silica), \(n_2 = 1\) (vacuum / air), and \(\lambda = 852\) nm.
Azimuthal Trapping Potential

Linear polarization breaks cylindrical symmetry
⇒ azimuthal confinement:
1d Optical Lattice

Resulting potential:
Array of trapping sites on both sides of the fiber!
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Experimental Setup

- **Trapping lasers:**
  - Nd:YAG 1064 nm, 2 x 2.2 mW, standing wave
  - Diode laser 780 nm, 25 mW, running wave
- **Fiber diameter:** 500 nm ⇒ trap depth ~ 0.4 mK
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- **Fiber diameter:** 500 nm
  \[ \Rightarrow \text{trap depth} \approx 0.4 \text{ mK} \]

Fluorescence of ~2000 atoms trapped 200 nm above fiber!

At most 1 atom per potential well (collisional blockade)!
A Conveyor Belt for Atoms

Mutually detuning the two laser beams sets the standing wave in motion → controlled transport of atoms!

atomic velocity: \( v = \Delta \nu \cdot \frac{\lambda}{2} \)

\( \Delta \nu \): mutual detuning, \( \lambda \): laser wavelength
A Conveyor Belt for Atoms

Spectroscopy of Trapped Atoms

- Inhomogeneous line width $\leftrightarrow$ state dependent light shifts.
- Optically dense (OD 32) ensemble of fiber coupled atoms!
- 1.6% absorption per atom!

E. Vetsch et al., PRL 104, 203603 (2010)
• Storage time ~ 50 ms
• Loss mechanism still under investigation.
• Possibly: Heating due to mechanical vibrations of the fiber.

E. Vetsch et al., PRL 104, 203603 (2010)
Atom Number Measurement

- Absorbed power saturates at ~ 8 nW
- Maximum scattered power per atom ~ 4 pW
- Number of trapped atoms ~ 2000

E. Vetsch et al., PRL 104, 203603 (2010)
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Dispersive Interaction

Strength of atom-light coupling depends on polarization

⇒ dispersive interaction leads to birefringence

\[ \phi_{||} = 2.8 \times \phi_{\perp} = 1.6 \times \Delta \phi \]
Dispersive Interaction

Probe light polarized at 45° with respect to atomic axis:

\[
\begin{align*}
S_0 &= P \cdot \cos(\Delta \phi) \\
S_1 &= \quad 0 \\
S_2 &= P \cdot \sin(\Delta \phi) \\
S_3 &= \quad 0
\end{align*}
\]

Resulting Stokes vector:
$S_3 = P_{\sigma^+} - P_{\sigma^-}$

S. Dawkins et al., PRL 107, 243601 (2011)
**Measurement of Phase Shift**

- Probed transition: $F=4 \leftrightarrow F'=5$
- OD $\sim 28$ for $N_{\text{atom}} = 1000$
- OD / $N_{\text{atom}} \sim 2.8 \%$
- Phaseshift per atom: $2.0^\circ \cdot \text{MHz}$

S. Dawkins *et al.*, PRL **107**, 243601 (2011)
Non-Destructive Atom Detection

- Probe detuning: +165 MHz with respect to $F=4 \leftrightarrow F'=5$
- Probe power: 5 pW

S. Dawkins et al., PRL 107, 243601 (2011)
Major experimental advantages:

- No thermal motion and collisions (atoms are trapped in optical lattice with at most one atom per lattice site).
- Quantum fields are intrinsically mode matched and coupled into single mode optical fiber.
A state-insensitive, compensated nanofiber trap

C Lacroûte\textsuperscript{1,4}, K S Choi\textsuperscript{1,2,4}, A Goban\textsuperscript{1,4}, D J Alton\textsuperscript{1}, D Ding\textsuperscript{1}, N P Stern\textsuperscript{1,5} and H J Kimble\textsuperscript{1,3}

3.2. Effect of the light shifts in a ‘non-magic’ trap

\[ \sigma_\phi \simeq 2^\circ \]. This leads to fast decoherence of the hyperfine states, even with state cooling. Specifically, we estimate a spin-wave coherence time of \( \tau_m = 1/\delta n_\phi \lesssim 5 \mu s \) from the \( \delta n_\phi = 200 \text{ kHz} \) splitting between the sublevels of the \( ^4 \text{S}_1 \) atomic ground state.

\textit{New Journal of Physics} 14 (2012) 023056 (h/t)
HE\textsubscript{11} Mode: Field Components

- Quasi linearly polarized HE\textsubscript{11} mode.
- Parameters: $a = 250$ nm, $n_1 = 1.46$ (silica), $n_2 = 1$ (vacuum / air), and $\lambda = 852$ nm.
Fictitious B-Field

State-Dependent Azimuthal Potential

$6S_{1/2} \ F=3 \ and \ 4$

ground state
wave function
spread

Azimuthal position $\varphi$

Trap potential (mK)
Ramsey & Spin-Echo Signal (Preliminary)

- Hyperfine ground state transition: \( m_F = 0 \rightarrow m_{F'} = 0 \)
- Reversible dephasing time: \( T_2^* \approx 290 \, \mu s \)
- Irreversible dephasing time: \( T_2' \approx 2 \, ms \)
Summary

• Nanofiber-based atom trap:
  – Trapping of cold atoms in the evanescent field around nanofibers.
  – Realization of optically dense 1d arrays of individual fiber-coupled atoms (collisional blockade).
  – Dispersive (non-destructive) atom number measurement demonstrated.
  – Coherence properties encouraging for realization of coherent operations.
Fiber Coupled Atoms!
Write two fiber Bragg gratings (FBGs) into unprocessed part of tapered optical fiber.

Write two fiber Bragg gratings (FBGs) into unprocessed part of tapered optical fiber.

- Exp. finesse: $F = 86$ ($T_{TOF} = 98.3\%$)
- Single atom coop.: $C = \frac{g^2}{2\kappa\gamma} = 30$
- Cs, $F = 4, m_F = 0 \rightarrow F' = 5, m_{F'} = 0$
  \[ \Rightarrow (g, \kappa, \gamma)/2\pi = (33, 8.6, 2.6) \text{ MHz} \]
  \[ \Rightarrow \text{Coherent strong coupling!} \]

Combination with atom trapping scheme possible:

\[ \Rightarrow OD_{\text{eff}} \approx 1000 \text{ @ 2000 atoms}! \]

Outlook: Double Helix Potential

$\sigma^+ - \sigma^-$-polarized red-detuned standing wave combined with $\sigma^+$-polarized blue-detuned running wave
Outlook: Double Helix Potential

Students: Bernhard Albrecht, Christian Junge, Rudolf Mitsch, David Papencordt, Jan Petersen, Daniel Reitz, Michael Scheucher, Danny O‘Shea, Ariane Stiebeiner, Christian Wuttke

Group Technician: Thomas Hoinkes

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… for your attention.