Atom/Photon Manipulation Using Optical Nanofibers

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CONTENTS

MON: Atom/Photon Manipulation Using Optical Nanofibers: Cold Atoms
TUE: Atom/Photon Manipulation Using Optical Nanofibers: Quantum Dots
WED: Cavity QED With an Optical Nanofiber
THU: How Do Cold Atoms Feel a Hot Optical Nanofiber?
Atom/Photon Manipulation Using Optical Nanofibers:

Cold Atoms

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How Various Freedoms of Atoms/Photons Are Manipulated Using Coherent Optical Technologies

**Manipulation of Atoms**
- Laser Cooling, Trapping
- Atom Optics
- Quantum Gases: Bosonic (BEC), Fermionic

**Manipulation of Optical Responses**
- Electromagnetically Induced Transparency
- Slow Light, Frozen Light

**Manipulation of Vacuum**
- Cavity QED
- Photonic Crystals

**Novel Applications**
- Quantum Information Technology, Metrology
- Generating Single Photons
- Entangled Single-Photon Pairs
EIT Nonlinear Optics

H-atom

2s-level as two-photon allowed metastable state

Efficient Generation of Vacuum Ultraviolet Radiation


Extension of EIT to “Condensed Phase”

Solid Hydrogen

Arbitrary and Efficient Parametric Sideband Generation

Slow Light in a Transparent medium

EIT in a Fiber Propagation Mode

- Fiber mode can be *tailored* via Electromagnetically Induced Transparency (EIT)

- Medium: Solid Hydrogen
  
  *Extremely Narrow Spectrum*
  
  *Very Small Inhomogeneity*

Evanescent field interacts with EIT Atoms/Molecules.

Sub-Wavelength Diameter Optical Fiber

*Nature, 426, 816 (2003); Tong, Mazur group*
Optical Fiber Micro-Coil Resonator

\[ Q_{\text{exp}} = 95000 \]

Supercontinuum Generation in Submicron Fibre Waveguides

Russell Group, University of Bath

Tight Focusing & Long Interaction Length

![Graph showing output power vs. wavelength.]
Propagation through a Tapered Optical Fiber

- Fiber mode can be tailored via Electromagnetically Induced Transparency (EIT)

- Medium: Solid Hydrogen
  
  *Extremely Narrow Spectrum*
  
  *Very Small Inhomogeneity*

Evanescent field interacts with EIT Atoms/Molecules.

Manipulating Optical Response Using Ultra-Thin Optical Fibers

“Other than Solid Hydrogen - - - -

Liquid, Gas?”

Liquid : Spectroscopic Applications
Detection of Molecules

Gas Phase Atoms: Limiting Factor → Transit Time Broadening

Interaction Length Across a Thin Fiber < ~1 µm

Atom Velocity @ 300 K ~ 200 m/s   Transit Time ~ 5 ns
@ 100 µK ~ 10 cm/s               ~ 10 µs
Atoms on an Optical Nanofiber

“Modified spontaneous emission around the nanofiber”
“Optically dense system with a few atoms”
“Superradiant system”
“Atom-surface interaction”

Work Atom: Cold Cs-Atoms
Fiber: Conventional Single-Mode Fiber
**Single Mode Optical Fiber**

Step Index Structure

\[
E(r) = \begin{cases} 
J_1(hr) & r < a \\
\frac{J_1(ha)}{K_1(qa)} K_1(qr) & r \geq a
\end{cases}
\]

**HE\textsubscript{11} Mode:**

“No Cut-Off”

**Single Mode Condition**

\[
V = \frac{2\pi a}{\lambda} \sqrt{n_1^2 - n_2^2}
\]

Typical Core Size: 5-10 µm Dia.
How optical nanofibers can modify the spontaneous emission.

\[
\gamma_{ij} \propto |\mu_{ij}|^2 \rho(\nu_{ij}) \quad \rho(\nu_{ij}): \text{Mode Density of Electromagnetic Field}
\]

The peaks in occur around \( k_0 a = 1.45 \), which correspond to \( a = 200 \text{ nm} \) for the cesium D2 line.

(20%-28%) of Total Spontaneous Emission Can be channeled into the Guided Modes

Fam Le Kien, S. Dutta Gupta, V. I. Balykin, and K. Hakuta, Physical Review A, 72, 032509 (05)
How atoms on optical nanofiber can create optically dense system.

A few tens of atoms on a nanofiber may work as an Optically Dense System.

Single Cs-atom near an optical nanofiber

Fam Le Kien, S. Dutta Gupta, V. I. Balykin, and K. Hakuta,

A few tens of atoms on a nanofiber may work as an Optically Dense System.
How optical nanofibers can work for Superradiance.

\[ |u\rangle = |ee\rangle, \quad |b\rangle = |gg\rangle, \quad |+\rangle = \frac{1}{\sqrt{2}} (|eg\rangle + |ge\rangle), \quad |-\rangle = \frac{1}{\sqrt{2}} (|eg\rangle - |ge\rangle) \]

\[ |+\rangle : \text{Superradiant State} \]
\[ |-\rangle : \text{Subradiant State} \]

How to prepare optical nanofibers.

Length of Nanofiber: ~2 mm
Advanced Optical Nanofiber Production System

Adiabatic Tapering: Core-Mode Cut-off Region
Multiple Tapering Using $\text{H}_2/\text{O}_2$ Micro-Burner

Optical Transmission:  > 97%
Diameter of Nanofiber:  > 200 nm
Length of Nanofiber:  2 - 5 mm
Magneto Optical Trap of Cs Atoms

For experimental realization, Laser Cooling Technology and Thin Fiber Technology must be combined.
Fluorescence Measurement
with MOT beam
- Atoms Around Nanofiber -

Diameter of Nanofiber: 400 nm
Length of Nanofiber: 2 mm
MOT Atom Density: $2 \times 10^{10}$ cm$^{-3}$
Number of Atoms Around Nanofiber < 10
Laser Scattering and MOT Fluorescence Through Nanofiber

“How ideal is our Nanofiber?”

Irradiating Photon Flux: ~ $1.36 \times 10^{12}$ photons/s

Observed Scattering Counts ~ $8 \times 10^5$ photons/s

Scattering Probability $\eta_{\text{nanofiber}}$ ~ $10^{-7}$

Expected fluorescence counts

Single Fluorescence Cycle: ~ 192 ns

Photons from Single Atom : $5.2 \times 10^6$ photons/s

Coupling Efficiency into the Guided Mode: ~ 6 %

Transmission of Nanofiber : ~ 40%

Atoms Around a Nanofiber: ~ 5 Atoms

Detector Efficiency: 45 %

Possible Fluorescence Photon Counts observable at one end of Nanofiber : $4.6 \times 10^5$ Counts/s

Observed Fluorescence Counts ~ $3 \times 10^5$ Counts/s

Suppression Of Scattered Light And High Coupling Efficiency Of Fluorescence.

MOT Profile Measurement:
Scanning MOT Position Across a Nanofiber along Z-Direction

Scattering Probability: $\eta_{\text{nanofiber}} \sim 10^{-8}$
Peak-Fluorescence-Count $\sim 1.5 \times 10^4$ Counts/s

K. P. Nayak et al., quant-ph / 0610136;
Spectroscopy of Cold Atoms
Using Optical Nanofibers

Standing Wave

Probe laser beam
Intensity = 3.3 mW/cm²
Diameter = 2 mm

Chamber

SPCM
Phonon counting system

MOT
Attenuator

Cooling

Repump

Probe

Photon Counting

Time Sequence

Energy Levels:
- F' = 5
- F' = 4
- F' = 3
- F' = 2

Transition Frequencies:
- F = 3: 9.2 GHz
- F = 4: 151 MHz
- F = 5: 201 MHz
- F = 4: 251 MHz

Time Sequence:
- Cooling: OFF, ON
- Repump: OFF, ON
- Probe: ON, OFF
- Photon Counting: ON, OFF
LIF Spectrum of Cod Atoms Around the Nanofiber

Peak Position:
- Atomic Resonance
- FWHM: 15 MHz
- Broader than Natural Width

Number of Atoms < 10

Only atoms very close to the nanofiber surface are detected.
Photon Correlation Measurement

Hanbury-Brown & Twiss Setup

Probe laser beam

Line Focus ~ 100μm
Intensity ~ 60mW/cm²

MOT Chamber

SMF

3dB Coupler

Correlator

APD1

APD2
Photon Anti-bunching in Resonance Fluorescence Reveals Single Atom Behavior

\[ \text{Coincidences} \propto N g^{(2)}(\tau) + N(N - 1) \]

- \( N \sim 1 \text{ Atom} \)
- \( N \sim 2 \text{ Atoms} \)
- \( N < 1 \text{ Atom} \)

Scattering Background

Time Bin = 1 ns
Integration Time = 3 minutes
Experiment Time = 1 hour

\( (I_D = 4 \text{ A}) \)
\( (I_D = 3.8 \text{ A}) \)
Photon Correlation Measurement

- Probe laser beam
  - Line Focus ~ 100µm
  - Intensity ~ 60mW/cm²
- MOT Chamber
- SMF
- 3dB Coupler
- Correlator
- APD1
- APD2

"Are both the same?"

Graph showing:
- Two Atoms
- One Atom

Anti Bunching
Traveling Wave Excitation Scheme

One-End Correlation Vs Opposite-End Correlation

Bunching Anti-Bunching

Coincidences / min

Delay Time ($\tau$)  Delay Time ($\tau$)
Theory for Random Distribution of Atom Position

\[
G_N^{(2)}(a; b) = \sum_j \left\langle A_j^\dagger(a) A_j^\dagger(b) A_j(b) A_j(a) \right\rangle + \sum_{j \neq j'} \left[ \left\langle A_j^\dagger(a) A_j(a) \right\rangle \left\langle A_{j'}^\dagger(b) A_{j'}(b) \right\rangle \right]
\]

\[
+ \left\langle A_j^\dagger(a) A_j(b) \right\rangle \left\langle A_{j'}(b) A_{j'}(a) \right\rangle + \left\langle A_j^\dagger(a) A_j^\dagger(b) \right\rangle \left\langle A_{j'}(b) A_{j'}(a) \right\rangle
\]

\[
G_N^{(2)}(\tau) \propto N g^{(2)}(\tau) + N(N-1) \left\{ \mu_0 + \mu \left| g^{(1)}(\tau) \right|^2 \delta_{f_a,f_b} + \mu' \left| g^{(1')}(\tau) \right|^2 \delta_{f_a,-f_b} \right\}
\]

\[
G_n^{(2)}(\tau) \propto n g^{(2)}(\tau) + n^2 \left\{ \mu_0 + \mu \left| g^{(1)}(\tau) \right|^2 \delta_{f_a,f_b} + \mu' \left| g^{(1')}(\tau) \right|^2 \delta_{f_a,-f_b} \right\}
\]

In present experiment we must also consider the atom number fluctuations

Photon Correlations: Observable Through an Optical Nanofiber

\[ G^{(2)}(\tau) \propto n g^{(2)}(\tau) + n^2 \left\{ \mu_0 + \mu \left| g^{(1)}(\tau) \right|^2 \delta_{f_a, f_b} + \mu' \left| g^{(1')}(\tau) \right|^2 \delta_{f_a, -f_b} \right\} \]

Theoretical Predictions:
\[ \mu_0 \sim 0.33 - 0.37 \quad \mu = \mu' \sim 0.17 - 0.35 \]

Single-Atom Correlation Functions

\[ g^{(2)}(\tau) \propto \langle A_j^\dagger(a) A_j^\dagger(b) A_j(b) A_j(a) \rangle \]

\[ g^{(1)}(\tau) \propto \langle A_j^\dagger(a) A_j(b) \rangle \quad g^{(1')}(\tau) \propto \langle A_j^\dagger(a) A_j^\dagger(b) \rangle \]
Traveling Wave Excitation Scheme

One-End Correlation

\[ G_n^{(2)}(\tau) \propto n g_n^{(2)}(\tau) + n^2 \left\{ \mu_0 + \mu' \left| g_n^{(1')}(\tau) \right|^2 \right\} \]

\[ \mu_0 = 0.36 \quad \mu' = 0.22 \]

\[ \mu_0 = 0.36 \quad \mu = 0.22 \quad \mu' = 0 \]
Both Side Correlation

“Traveling Wave Excitation”
Effect of Excitation Geometry

Spatial Dependence of the Phase of the Excitation Beam may affect the Photon Correlations

\[ g^{(1')}(\tau) \propto \left\langle A_j^\dagger(a) A_j^\dagger(b) \right\rangle \]
\[ g^{(1')}(\tau) \propto \left[ E^{(-)}(r_j) \right]^2 \propto (e^{-ikr_j})^2 \]
\[ \rightarrow \exp(-2i\mathbf{k} \cdot \mathbf{r}_j) \rightarrow 0 \]

Traveling Wave Excitation \[ g^{(1')}(\tau) \]-term Disappears.

\[ g^{(2)}(\tau) \propto \left\langle A_j^\dagger(a) A_j^\dagger(b) A_j(b) A_j(a) \right\rangle \]
\[ g^{(1)}(\tau) \propto \left\langle A_j^\dagger(a) A_j(b) \right\rangle \]
Effect of Excitation Geometry:
Standing Wave Excitation

$$g^{(1')} (\tau) \propto \left\langle A_j^\dagger (a) A_j^\dagger (b) \right\rangle$$

$$g^{(1)} (\tau) \propto \left[ E^-(r_j) \right]^2 \propto (e^{-i k \cdot r_j} + e^{i k \cdot r_j})^2$$

$$\rightarrow \exp(-2i k \cdot r_j) + \exp(2i k \cdot r_j) + 2 \rightarrow 2$$

Standing Wave Excitation $$g^{(1')} (\tau)$$-term Appears.
Opposite-End Correlation: Experiments
Traveling Wave Vs Standing Wave Excitation

![Diagram showing the setup for opposite-end correlation experiments with traveling and standing wave excitations. The diagram includes a setup with beams labeled D3, SMF, and MOT, indicating the presence of a probe laser beam and a chamber. The graphs show the coincidence counts over delay time for both traveling and standing waves, with the traveling wave showing a single peak for a delay time of approximately 5.2 A, and the standing wave showing two peaks.](image-url)
Opposite-End Correlation

Traveling Wave Vs Standing Wave Excitation

\[ G_n^{(2)}(\tau) \propto n g^{(2)}(\tau) + n^2 \left\{ \mu_0 + \mu' \left| g^{(1')}(\tau) \right|^2 \right\} \]
Photon Correlations: Traveling Wave Exc.

One-End Correlation

- $I_0 \sim 5.0$ A, $n \sim 9.2$
- $I_0 \sim 4.6$ A, $n \sim 4.4$
- $I_0 \sim 3.8$ A, $n \sim 0.4$

Opposite-End Correlation

- $I_0 \sim 5.0$ A, $n \sim 11.3$
- $I_0 \sim 4.6$ A, $n \sim 4.8$
- $I_0 \sim 3.8$ A, $n \sim 0.5$

$\mu_0 = 0.36$
$\mu = 0.22$
$\mu' = 0$

K. P. Nayak, Fam Le Kien, M. Morinaga, K. Hakuta
Phys. Rev. A 79, 021801 (09)
Photoabsorption spectroscopy of a few atoms around an optical nanofiber

Number of atoms ~ 10

Probe input power= 10fW
How long do atoms dwell around the nanofiber?

Exponential Decay Time  \(1.8 \mu s\)
Atom Dwelling Time
Transit Distance 200 nm @ 100 \(\mu\)K

“Atoms might be free around the nanofiber.”
Atoms on an Optical Nanofiber

A system of “atoms on an optical nanofiber” is becoming a promising workbench for Quantum Optics.

Further Improvements

1. Atom Number Control: Trap Atoms Around an Optical Nanofiber
2. Extend to Quantum Dots
3. Measure the Channeling Efficiency
4. Enhance the Channeling Efficiency
Atom Number Control: Optical Dipole Trap Using Guided Mode

Optical potential: \( U_{\text{opt}}(r) = \frac{\hbar \Omega^2(r)}{4\delta} \)

\[
\begin{align*}
\Omega(r) &= \frac{\mu E(r)}{\hbar} \\
\delta &= \omega - \omega_0
\end{align*}
\]

Red-Detuned Light

Blue-Detuned Light

Two-Color Trap (Push-Pull Type)
Two-Color Trap (Push-Pull Type)

Atom Trapping using Thin Optical Fiber via Dipole Force due to Evanescent Field

\[ V_{\text{int}} = \frac{\hbar\Omega^2}{4\delta} \]
\[ F_{\text{dip}} = -\frac{\partial V_{\text{int}}}{\partial r} = \frac{\hbar\Omega}{2\delta} \frac{\partial\Omega}{\partial r} \]

Atom Trapping: **Auto Balance Method**

*Balance between Dipole Force and Centrifugal Force*

Atom Near a Thin Fiber

Hamiltonian

\[
H = -\frac{\hbar^2}{2M} \nabla^2 + U(r) = -\frac{\hbar^2}{2M} \left( \frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} + \frac{1}{r^2} \frac{\partial^2}{\partial \varphi^2} + \frac{\partial^2}{\partial z^2} \right) + U(r)
\]

in Cylindrical Coordinates

\[
\Psi(r) = \frac{1}{2\pi} R(r) e^{im\varphi} e^{ikz}, \quad R(r) = \frac{u(r)}{\sqrt{r}}
\]

Schroedinger Equation

\[
\left( -\frac{\hbar^2}{2M} \frac{\partial^2}{\partial r^2} + U_{\text{eff}}(r) \right) u(r) = \tilde{E} u(r)
\]

\[
U_{\text{eff}}(r) = \frac{\hbar^2}{2M} \left( \frac{m^2}{r^2} - \frac{1}{4} \right) - GK_0^2(qr)
\]

Effective Potential : Due to Centrifugal Force + Dipole Force
Trapping Potential with Van der Waals Interaction: A Numerical Example

Work Atom: Cs Atom
Trapping Field: $\lambda = 1.3 \, \mu m$
Fiber Radius: $2a = 400 \, \text{nm}$

Pre-cool Atoms in MOT to $100\,\mu K$
Then load them into the “Fiber Trap”

$\mathbf{m} = 230$

Necessary Intensity $\rightarrow$ 1 MW/cm²  $\leftarrow$ 27 mW Input!

Trapping Atoms Along Nanofiber

Trapping via Guided Fields:

One Bad News: High Laser Intensity in the Fiber $\rightarrow$ Generation of Raman, Fluorescence Light etc. Enemy of Single Photons

Trapping via "Non-Guided" Fields:

Plane Wave Irradiation along X-Axis: Wavelength 937 nm, Intensity 40 kW/cm²
A system of “cold atoms on an optical nanofiber” is becoming a promising workbench for Quantum Optics.