Optical Nanofibers, a platform for quantum optics

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Tapered optical fibers

Waveguide (photonic circuit) for light

Optical interface for atoms
(strong coupling light/atoms)
Light rays in a fiber with total internal reflection

\[ n_{\text{core}} > n_{\text{cladding}} \]

\[ n_{\text{cladding}} > n_{\text{air}} \]
Evanescent waves:

\[ \mathbf{k}_T = k_T \sin(\theta_T) \mathbf{x} + k_T \cos(\theta_T) \mathbf{z} \]

\[ \sin(\theta_T) = \frac{n_1}{n_2} \sin(\theta_I) > 1 \]

\[ \cos(\theta_T) = \sqrt{1 - \sin^2(\theta_T)} = i \sqrt{\sin^2(\theta_T) - 1} \]

\[ \mathbf{E}_T = \mathbf{E}_0 e^{i(\mathbf{k}_T \cdot \mathbf{r} - \omega t)} \]

\[ \mathbf{E}_T = \mathbf{E}_0 e^{-\kappa z} e^{i(kx - \omega t)} \]

\[ \kappa = \frac{1}{\lambda/2\pi} \sqrt{(n_1 \sin(\theta_I))^2 - n_2^2}, \quad k = \frac{n_1}{\lambda/2\pi} \sin(\theta_I) \]
Two-Layer fiber surrounded by air

\[ \beta = k^*n_{\text{eff}} \], propagation constant of a fiber mode
Lowest order fiber modes
Intensities
Polarization of the lowest order modes

$TE_{01}$

$TM_{01}$

$HE_{11}$

$HE_{21}$
Higher order fiber modes

\[ V = \frac{2\pi R}{\lambda} \sqrt{n_1^2 - n_2^2} \]
Evanescent field in the nanofiber. The wave decays in a length of $\lambda/2\pi$. The nanofiber guides the mode and there is no radiation nor diffraction. Very different from a focused beam.
Very large radial gradients of $E$

- \( \text{Div } E = 0 \) implies large longitudinal components.

\[
\frac{\partial E_r}{\partial r} + \frac{\partial E_z}{\partial z} = 0
\]

- The evanescent field can have a longitudinal component of the polarization! No transverse fields!
Polarization at the fiber waist

\[ \nabla \cdot \vec{E} = 0 \]

\[ \nabla_T \cdot \vec{E} + \frac{2\pi}{\lambda} i E_Z = 0 \]

Rotates like a bicycle
Nanofiber mode structure

\[ |E|^2 = \mathcal{E}^2 \left[ K_0^2(qr) + \omega K_1^2(qr) + f K_2^2(qr) \right] \]

Circulary polarized
Fabrication and optical properties of nanofibers
Conservation of Volume

\[ \frac{dr}{dx} = - \frac{r}{2L} \]

\[ r(t) = r_0 \exp \left( -\frac{v_f t}{2L_0} \right) \]
Nanofiber Fabrication: Heat and Pull

125 micron diameter

10 micron diameter waist

2 mrad taper
Nanofiber Fabrication

(a) Optical microscope

Radius (μm)

(b) Relative Difference \( \times 10^{-2} \)

Fiber axis (cm)
Modes beating
Transmission \( t \) = \( \frac{PD2(t)}{PD1(t)} \)/Normalization

Setup
Normalized transmission through the fiber while pulling

2 mrad linear taper
500 nm waist

Transmission beats

Transmission = 99.95 ± 0.02 %
Loss = 2.6 x 10^{-5} dB/mm
Oscillations during pull
Optical properties of nanofibers
Production of higher order modes
Can be due to many factors:

- Index / density fluctuations
- Impurity ions / atoms
- Roughness at core-cladding interface
- Bubbles at core-cladding interface
Rayleigh Scattering

(a) Light escapes core

waist

Light returns to core

50 μm

85 mm
• Low Loss fibers for fundamental and higher order modes.

• There is a lot of interesting nanomechanics (torsional and string modes of the nanofiber) that I have not mentioned!
Fundamental mode of an optical nanofiber linearly polarized.

- Decreasing mode area increases atom-light interaction
- Radius ~ 250 nm
- Decay length: ~100 nm
- Intensity of 1 mW in the evanescent field $5 \times 10^8 \text{mW/cm}^2$ about $10^8$ the saturation intensity of the D$_2$ line of Rb.
Atoms interacting with light (decay) near an ONF.
\[ \gamma_{Tot} = \gamma_{rad} + \gamma_{1D} \]

\[ \gamma_{Tot} \neq \gamma_0 \]

\[ \gamma_{0} \]

Not to scale
Cooperativity

\[ C_1 = \frac{\beta}{(1 - \beta)} = \frac{\gamma_{1D}}{\gamma_{rad}} \]

\( C_1 \) is the ratio of what goes into the selected mode to what goes into all the rest.
ONF Optical Density

\[ OD_1(\vec{r}) = \frac{\sigma_0}{A(\vec{r})} \]

50nm away from the surface, 1 atom can block 10% of the light!!

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Cooperativity and Optical Density

\[ C_1 = OD_1 \left( \frac{1}{n_{\text{eff}} \gamma_{\text{rad}}} \right) \left( \frac{\gamma_0}{\gamma_{\text{rad}}} \right) \]

Enhancement
Many atoms interacting with light (decay) near an ONF. Super- and sub-radiance.
Super- and Sub-radiance
(a classical explanation)

\[ P = \frac{\varepsilon}{\Delta t} = IA \Rightarrow \Delta t = \frac{\varepsilon}{IA} \]

For N dipoles \( \varepsilon \Rightarrow N\varepsilon \)
Super- and Sub-radiance
(a classical explanation)

Normal radiance

\[ I = |E_0|^2 = I_0 \]

\[ \Delta t = \tau_0 \]
Super- and Sub-radiance
(a classical explanation)

Normal radiance

Super-radiance

\[ I = |E_0|^2 = I_0 \]
\[ \Delta t = \tau_0 \]

\[ I = 4I_0 \]
\[ \Delta t = \frac{1}{2} \tau_0 \]
Super- and Sub-radiance
(a classical explanation)

Normal radiance

Super-radiance

Sub-radiance

$I = |E_0|^2 = I_0$

$\Delta t = \tau_0$

$I = 4I_0$

$\Delta t = \frac{1}{2}\tau_0$

$I = 0$

$\Delta t = \infty$
Super- and Sub-radiance
(a classical explanation)

Normal radiance

Super-radiance

Sub-radiance

\[ \Delta t = \tau_0 \]

\[ \Delta t = \frac{1}{2} \tau_0 \]

\[ \Delta t = \infty \]
Super- and Sub-radiance
(a classical explanation)

Super-radiance

Super- and sub-radiance are interference effects!

Sub-radiance

Super- and sub-radiance are interference effects!
Observation of infinite-range interactions
Infinite Range Interactions
Infinite Range Interactions
Infinite Range Interactions
Infinite Range Interactions

$U_{1D} \propto \exp(ikr)$

$\Omega_{12} \propto \sin kz$

$\gamma_{12} \propto \cos kz$

The limit is now how many atoms can we put within the coherence length associated with the spontaneous emission.
Long distance modification of the atomic radiation
Experimental idea
The idea behind the experiment
The idea behind the experiment

We look for modifications of the radiative lifetime of an ensemble of atoms around the ONF.
The idea behind the experiment

The sub- and super-radiant behavior depend on the phase relation of the atomic dipoles along the common mode.
Measuring the Radiative Lifetime
Measuring the Radiative Lifetime
Two distinct lifetimes

\[ \tau \approx 0.9\tau_0 \]

\[ \tau \approx 7.7\tau_0 \]
Two distinct lifetimes

\[ \tau \approx 0.9 \tau_0 \]

\[ \tau \approx 7.7 \tau_0 \]
The slope (0.02) is smaller than $\gamma_{1D} (0.10)$ because it is an average over different realizations, not all of them superradiant.
Understanding the Signal
Understanding the Signal

(a)

(b) $\gamma_{12}^{(\text{rad})}/\gamma_0$

(c) $\gamma_{12}^{(1\text{D})}/\gamma_{1\text{D}}$

Legend:

- $\Delta \phi$
- $\lambda$
- $r$

- $V$
- $H$
Fitting the Simulation

(a) 

Log$_{10}$ normalized count rate

(b) 

Normalized residuals

$\log_{10}$ normalized count rate

$t/\tau_0$
Fitting the Simulation

Average number of atoms

\( \gamma / \gamma_0 \) vs. Optical density
Can we see a collective atomic effect of atoms around the nanofiber?
Long distance modification of the atomic radiation
Splitting the MOT in two

\[ \approx 400 \lambda \]
Evidence of infinite-range interactions

Average number of atoms

Both MOTs
Right MOT
Left MOT
Final remarks

• Low Loss fibers for fundamental and higher order modes.
• Coupling atoms to evanescent mode.
• Birefringence of system tells of trapped atoms dynamics.
• Collective effects in the lifetime sub-radiance and super-radiance.
Thank you!