Probing cold-atom-optical-nanofiber interface with frequency-jump atomic spectroscopy

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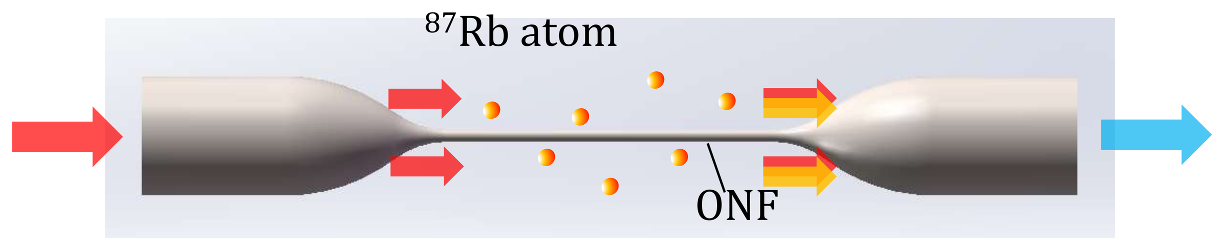
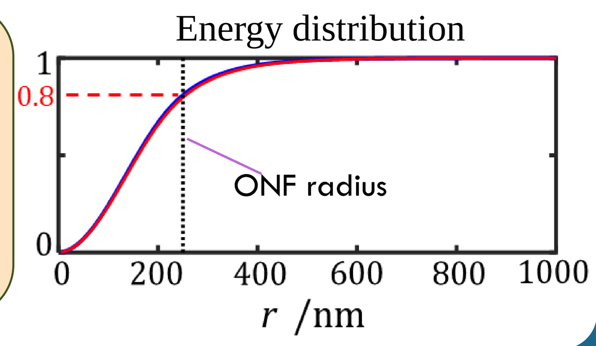
Introduction

- **Motivation:** Optical nanofiber (ONF) supports strong, evanescent coupling between guided photons with near-field atoms over macroscopic distances[1]. At the ONF interface, response of individual atoms to light is modified. Precise characterization of the optical response of the ONF-coupled atoms is not only important for understanding the interactions, but also crucial for achieving precise quantum control with the nanophotonic quantum optical platform.
- **This work:** We demonstrate a frequency-jump approach for simultaneous retrieving the absorption (OD) and phase shift (ϕ) spectrum of atoms at the ONF-interface. Firstly, the probe pulse establishes a steady state process with atoms, then the frequency of probe pulse is shifted out of atomic resonance to serve as a reference field. By demodulating the beat signal, the time-dependent amplitude and phase of the atomic forward emission is reconstructed.
- **Advantage of this work: (a)** Common-mode of probe pulse and atomic forward scattering field is achieved by Evanescently filed on Nanofiber interface, providing the accuracy of our single-mode coherent spectroscopy. **(b)** Comparing to traditional absorption or fluorescence method, the transient spectroscopy does not require laser frequency scan and is therefore substantially more data-efficient.**(c)** The simultaneous OD and ϕ retrieval supports self-calibration of atom numbers participating the interaction. The coherent technique is therefore helpful for suppressing atom-number drifts in the nanoscopic atomic spectroscopy.



probe pulse: E_p atomic forward scattering field: E_s Transmitted field: E_t

- 20% of probe pulse energy is distributed as Evanescently filed over hundreds nanometers on Nanofiber interface.
- Transmission efficiency of nanofiber is theoretically greater than 99%.
- The nanofiber interface maintains a long distance, uniform strong focused light, which achieves a strong coupling with near-field atoms.



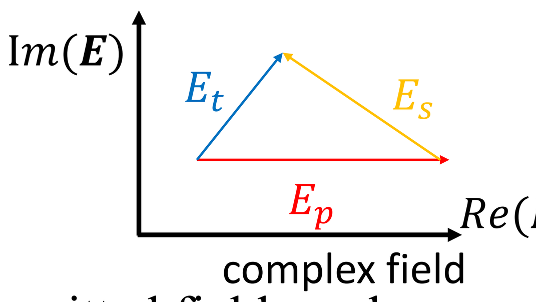
Forward scattering field

When a laser beam sent through a medium filled with resonant pointlike scatterer, the power lose in the coherent transmission, $\propto 1-e^{-b}$. In general, since the positions of the scatterer are random, the reemitted field is incoherent. But in the forward direction, there exist cooperative effects of the atomic ensemble.

☐ Steady state

When **steady state** is built between the atoms and probe pulse, the transmitted field, according to Beer-Lambert law, $E_t = E_p \exp[-\frac{OD(\Delta)}{2} + i\phi(\Delta)]$, and can be regarded as the **destructive interference** result of the probe pulse and the forward scattered field, $E_t = E_p + E_s$.

$OD(\Delta)$ and $\phi(\Delta)$ respectively represent real and imaginary part of complex phase shift

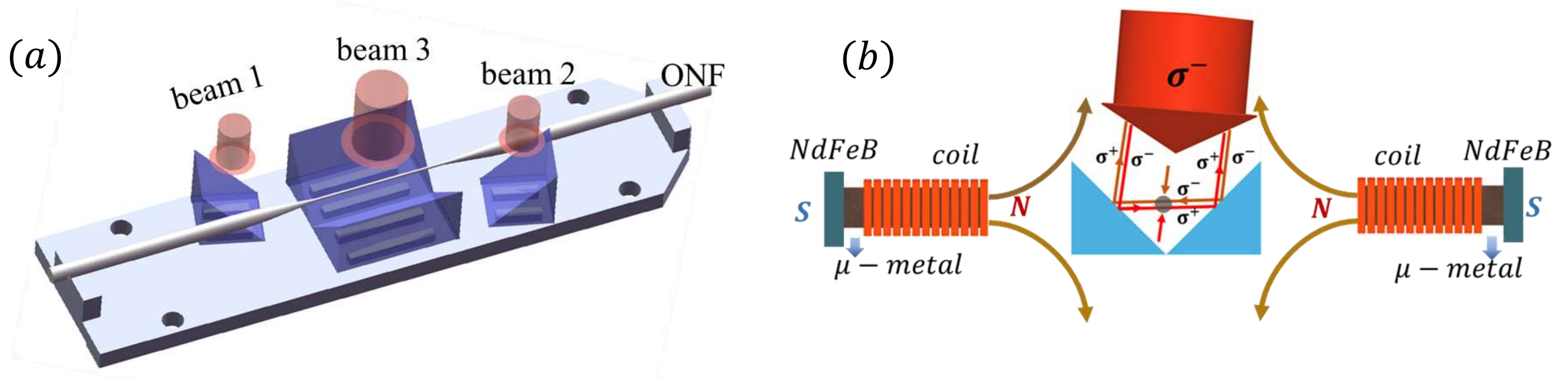


☐ Transient state

If the probe pulse is **turned off** at this moment, then transmitted field can be entirely described as the decay of the forward scattered field, $E_t = E_s$. The phase of forward scattering field at transient state is related to steady state, and the frequency perform as atomic resonance frequency

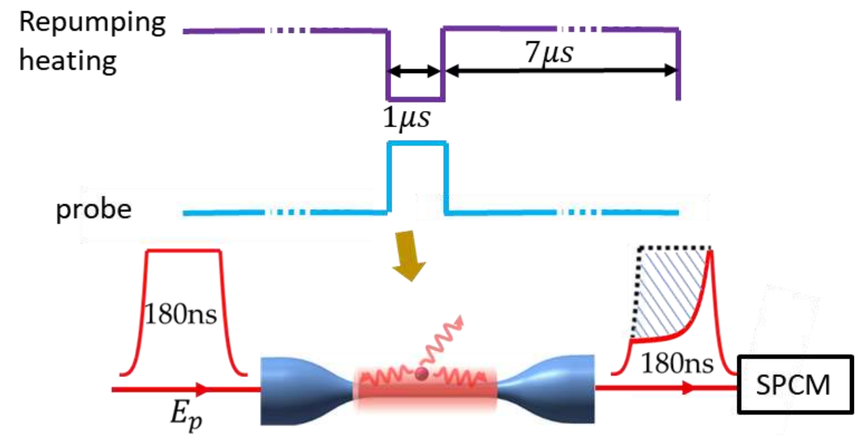
Experimental Setup

- **Cold atom + ONF interface based on 2D+MOT loading**



- Zero-field lines along the direction of the nanofiber allow non-interrupting measurements.
- 2D MOT geometry naturally support ONF interface with suppressed on-axis field.
- Compact setup with low power consumption.

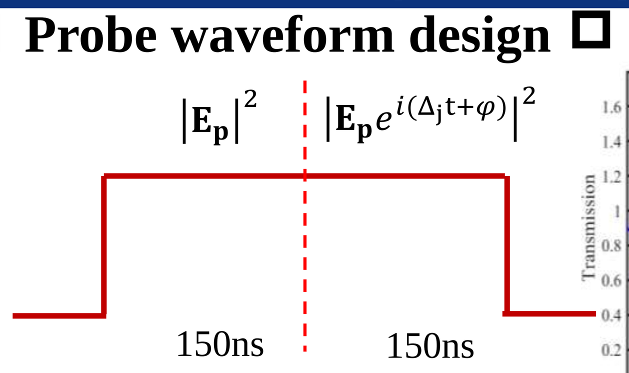
- **Time sequence**

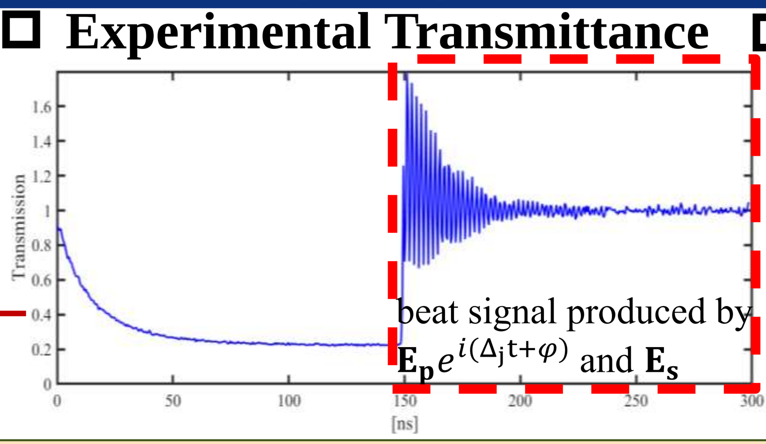


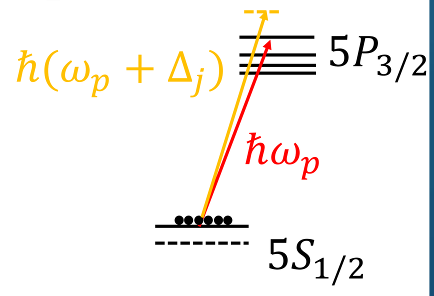
- Time sequence constituted by two part, $7\mu s$ for cold atom preparation, $1\mu s$ for probe waveform design. Date rate reach up to 125k/sec, provide excellent signal-to-noise ratio.
- Using single-phone counter module to detect output pulse.

"Single-shot" E_s-retrieval with Frequency-Jump Spectroscopy

☐ Probe waveform design ☐ Experimental Transmittance ☐ Experimental parameter

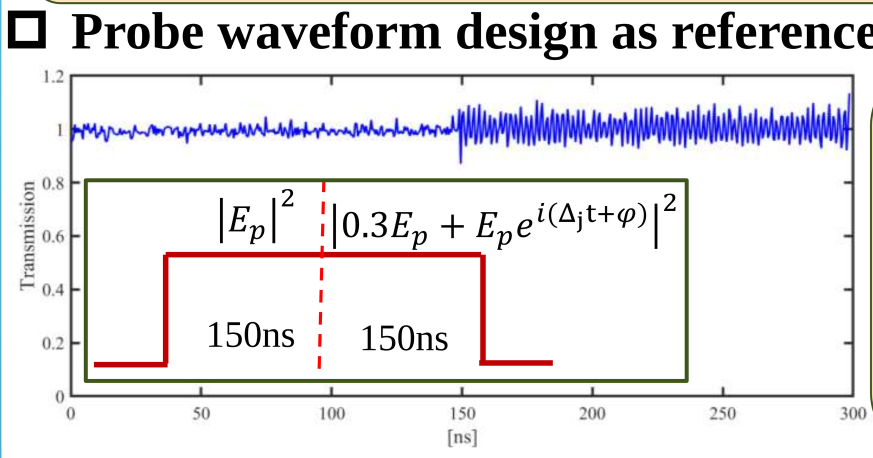






The first 150ns probe pulse $\mathbf{E_p}$ is to build steady state with atoms, then the next 150ns probe pulse perform a frequency-jump $\mathbf{E_p}e^{i(\Delta_j t+\varphi)}$, to serve as a reference field for detecting atomic forward scattering field $\mathbf{E_s}$. $\Delta_j = +2\pi \times 500Mhz$

☐ Probe waveform design as reference(without atomic signal)

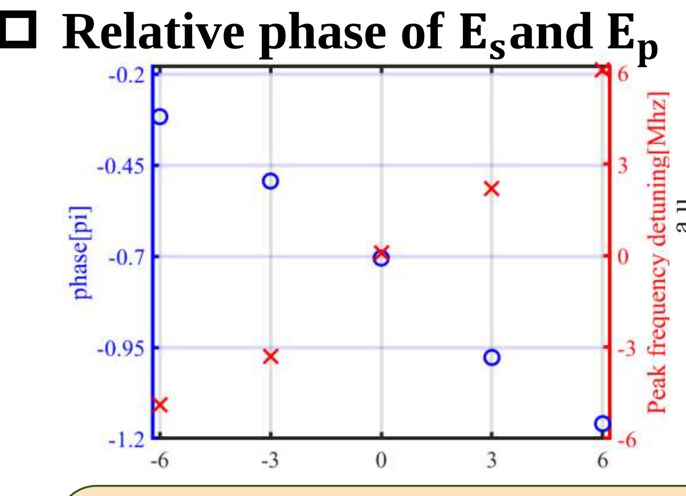


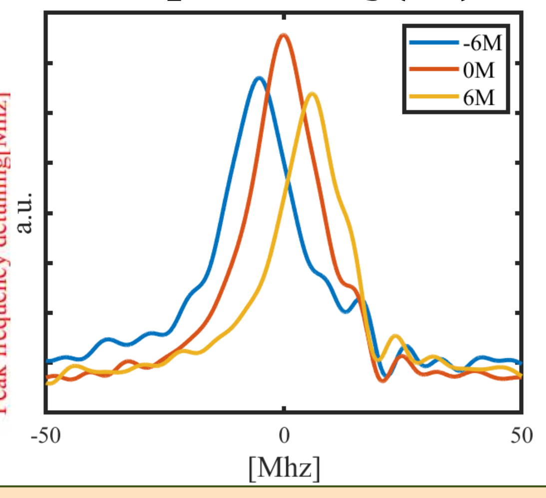
- This Probe waveform without atomic signal is designed to measure the relative phase between E_p and $E_p e^{i(\Delta_j t+\varphi)}$, φ is caused by dispersive elements in the optical path.
- Reference Probe waveform help to demodulate the beat signal with the calibrated frequency and phase.

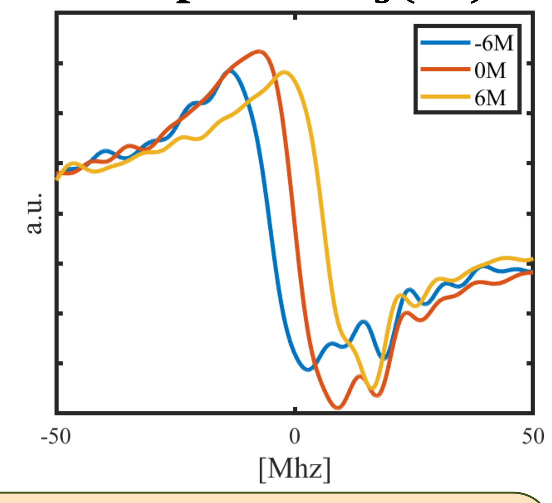
Typical Result

☐ Central frequency of $\mathbf{E_s}(\omega)$ ☐ Re part of $\mathbf{E_s}(\omega)$ ☐ Im part of $\mathbf{E_s}(\omega)$

☐ Relative phase of $\mathbf{E_s}$ and $\mathbf{E_p}$

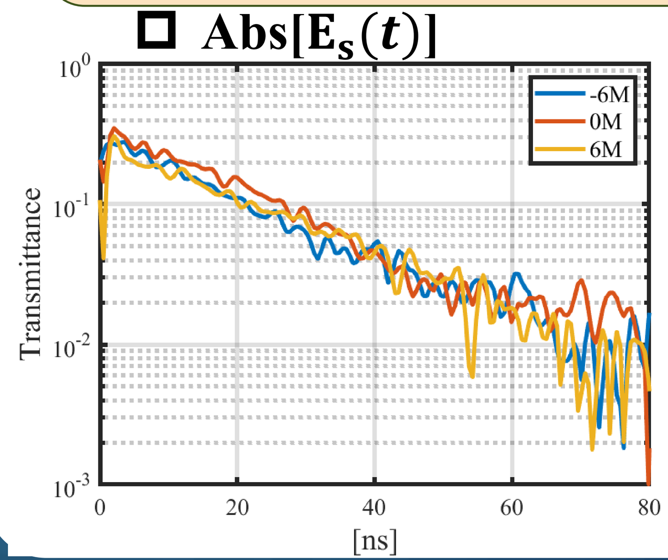


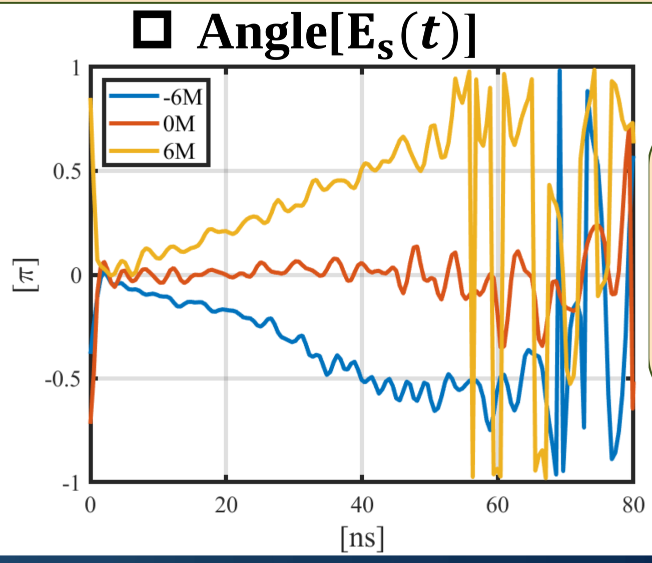




- Through Fourier analysis of the positive and negative frequency parts of the beats with and without atoms, we can determine the central frequency of $\boldsymbol{E_s}$, as well as the relative phase between $\boldsymbol{E_s}$ and $\boldsymbol{E_p}$. We present five data points above.
- Demodulate the beat signal, we can obtain the spectrum of $\mathbf{E_s}(\omega)$.

☐ Abs[$\mathbf{E_s}(t)$] ☐ Angle[$\mathbf{E_s}(t)$]





Through the spectrum of $\mathbf{E_s}(\boldsymbol{\omega})$, we reconstruct the temporal evolution of $\mathbf{E_s}(\boldsymbol{t})$ through inverse Fourier transform.

Reference

[1] P. Solano et al, Optical Nanofibers: A New Platform for Quantum Optics, Adv. At. Mol. Opt. Phys. **66** (2017) 439.

[2] Y. Ma et al, Composite picosecond control of atomic state through a nanofiber interface, Phys. Rev. Applied **20** (2023) 024041

[3] Cooperative Emission of a Pulse Train in an Optically Thick Scattering Medium, Phys. Rev. Lett. **115** (2015) 223601

Summary&Next Plan

- **Summary:** We develop a frequency-jump spectroscopy method to measure the complex-valued time-dependent profile of atomic forward emission at a cold-atom-optical-nanofiber interface. Frequency-dependent response is obtained within "single-shot" without requiring laser frequency scan .
- **Next Plan**: We can retrieve atomic complex phase shift $\varphi = \phi + i\mathrm{OD}/2$ by applying linear dispersion theory [3]. The results may help to unveil microscopic effects beyond Beer-Lambert law and linear excitation physics.

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