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Report Title

Final report: Nanoscale Plasmonic Structures for Trapping and Manipulation of Isolated Atoms

ABSTRACT

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Final Report

Nanoscale Plasmonic Structures for Trapping and Manipulation of Isolated Atoms

Abstract

An optical trap for a single atom has been demonstrated in the vicinity of a nanowire mounted on an optical fiber. Raman sideband cooling of a single atom to the two-dimensional ground state in the radial direction and to about 10 vibrational levels in the axial direction has been demonstrated. The loading of the nanotrap at the thip of the silver nanowire has not been achieved.

Introduction

The objective of this project is to trap atoms in a nanoscale optical potential formed several tens of nanometers from the tip of a silver nanowire. An atom trapped at these distances should experience very strong coupling to the plasmonic modes of the nanowire. This strong interaction will allow efficient excitation and fluorescence collection from the atom, which is important for applications in quantum information processing.

This year, we have finished building and begun using an apparatus to load atoms into the nanowire trap using a moveable optical tweezer beam containing a single atom. In addition to loading single atoms into nanoscale potentials, this apparatus also has use as an atomic microscope: single atoms confined to less than 100 nm in the optical tweezer can probe many properties of their local environment in a non-perturbative way.

Apparatus for trapping atoms near nanostructures

Our approach to trapping an atom in the nanowire tip trap (NTT) consists of multiple steps. First, a single atom is loaded from a MOT into small-volume “optical tweezer” trap (OTT) at a distance of several tens of microns from the nanowire tip. Then, using a fast scanning mirror, we move the focus of the OTT to the position of the nanowire tip. Once there, the OTT laser power is ramped down while the NTT laser power is ramped up, with the goal of adiabatically transferring the atom from the OTT to the NTT. This is outlined schematically in figure 1a.

Our apparatus differs from other cold atom experiments in its combination of different techniques. Using an airlock allows to mount and exchange a nanowire close to the laser cooled atoms while maintaining UHV conditions. Combined with a high numerical aperture lens to create a scanning OTT, our setup allows us to position and study single atoms close to solid state structures.

Nanowires coupled to optical fibers

During the previous year, we have also made improvements to the fabrication procedure used for attaching nanowires to optical fibers (Figure 1x). Specifically, improvements in the adiabaticity of the fiber tapers now allows us to have greater than 5% coupling efficiency from the nanowire to the optical fiber. This figure is a very conservative estimate based on our limited ability to measure this parameter, and is likely much larger.

Using a single atom in the OTT as a microscope

In preparation for loading the NTT, we conducted a series of experiments where the OTT is scanned to the tip of the nanowire. The goal of these measurements is to extract information about the behavior of the atom near the nanowire tip, which includes contributions both from atom-nanowire interactions (ie, van der Waals forces) and deformations of the OTT potential resulting from OTT light scattering from the nanowire. Both effects are too complex to treat accurately with simple analytic models, but are addressable using numerical techniques recently developed by our collaborators at ITAMP and MIT (Johannes Feist and Steven Johnson's group).

This measurement is performed by bringing a single atom in the OTT to a position near the tip of the nanowire, holding for a short time, and returning to a point far from the tip where the presence of the atom can be detected using fluorescence. The probability that the atom survives this journey is computed from several hundred trials, which takes several minutes.

Figure 2a is a typical dataset, showing the recapture probability as a function of the distance between the OTT holding point and the nanowire tip. The principal qualitative feature shows that when the turning point is far from the nanowire, the atom is unaffected and when the holding point is close, the atom is lost. The length scale delineating close and far is measured to be around 250 nm, which is comparable to the spatial extent of the atom in the dipole trap due to thermal motion. However, we have not yet settled the question of what exactly happens to the atom at the tip: is it pulled into the nanowire surface by van der Waals forces, or does it become untrapped by changes in the OTT potential resulting from light scattering?

To gain more information about the processes at the tip, we can adapt the experimental sequence in several ways. Figure 2a shows two curves taken with different polarization of the OTT with respect to the nanowire axis. The difference in recapture probability suggests that the deformation of the optical potential plays a significant role in determining the behavior of the atom near the nanowire. We are currently trying to understand this effect using numerical simulations of the optical fields.

Other parameters we can change include the trap depth, ramp speed, and hold time at the turning point. We can also imagine doing spectroscopy on the atom near the tip to determine properties of its local environment, such as the AC Stark shift (probes local field intensity and polarization), or the characteristic frequency of the confining potential. Additionally, it is possible to measure effects arising from a nearby surface, such as van der Waals potentials and changes in the local density of states of the electromagnetic field that should modify the atomic spontaneous emission rate.

Combining all of these techniques, a single atom in an OTT can be used as a very sensitive microscope, capable of measuring a wide range of properties with a high degree of spatial resolution.

Loading the nanowire tip trap

At this point, we have demonstrated that the pieces are in place to try loading the nanowire trap. Thus far, we have attempted the following sequence: transfer an atom from the OTT to the NTT, turn the OTT off briefly, then turn it back on and recapture the atom from the NTT. Any atoms in the OTT at this point must have been trapped at the NTT while the OTT was off.

Using this measurement, we have not successfully loaded an atom into the NTT. However, we have observed an interesting effect: if we have the blue-detuned NTT light on as the atom is brought to the nanowire tip, the loss probability can be suppressed (figure 2b). This effect is only present if the NTT light is polarized along the axis of the nanowire, perhaps indicating that field enhancement at the nanowire surface is generating a repulsive potential that shields the atom from van der Waals forces. However, further study and comparison with numerical simulations will be required to confirm this interpretation.

We attribute the failure to load the NTT to the relatively large position uncertainty of the atom compared to the NTT volume. We believe that the steps outlined in the next section will make it easier to load an atom into the NTT.

Next steps

There are two contributions to the position uncertainty: instability in the pointing of the OTT beam (~ 100 nm), and thermal motion of the atom (~ 200 nm in plane of focus and ~ 1 micron along OTT propagation direction). The beam instability is primarily due to the scanning galvanometer mirrors, which are being replaced with piezo scanning mirrors that are better by at least a factor of 10.

The thermal motion of the atom is being improved by further cooling the atom in the OTT using Raman sideband cooling. In principle, it should be possible to cool the atom to its three-dimensional ground state, in which case its spatial extent would be around 30 nanometers. We have already demonstrated cooling by a factor of ~ 5 ,

and are working to improve this result. It is worth pointing out that cooling an atom to the ground state of the OTT would be a result of broad interest, as thermal motion is presently a limitation for several quantum information experiments involving single atoms in similar traps.

Outlook

We have completed the construction of our apparatus, demonstrated its basic functionality and its potential for use both as a microscope and a vehicle for loading atoms into optical nanotraps. We expect that with the improvements outlined above, we will soon be able to achieve our goals of loading the NTT and making detailed measurements of the behavior of an atom near a nanowire on sub-100nm length-scales.

The scanning OTT is naturally a very versatile instrument, and we believe that it will find applications beyond our immediate goals. In particular, we envision using it to trap atoms near other nanostructures such as photonic crystal cavities, which seems like a promising approach for quantum information processing. Additionally, we could use it to facilitate trapping arrays of atoms near arrays of metallic nanoparticles, which is promising for simulating condensed matter systems with strong and long-range interactions mediated by surface plasmons.

Figures:

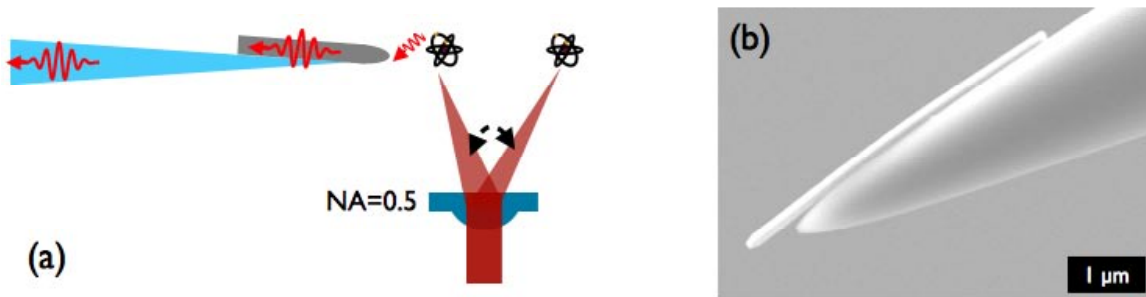


Figure 1 – (a) Schematic of scanning OTT near the nanowire. (b) SEM image of a silver nanowire ($d \sim 100$ nm) on the tip of a tapered optical fiber.

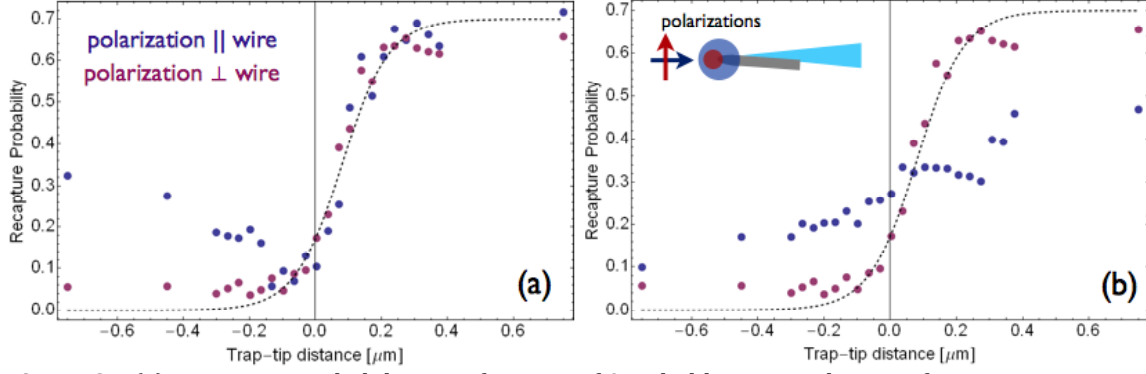


Figure 2 – (a) Recapture probability as a function of OTT holding point distance from nanowire tip (along the wire axis). Negative distances indicate that the OTT was scanned over the nanowire. Blue points were taken with the OTT polarized along the wire axis; red points, perpendicular. (b) Recapture probability vs. hold point when the blue-detuned NTT beam is also turned on as the OTT approaches the wire. The relative sizes and polarizations of the two beams are shown in the inset. The extra losses at positive distances are attributed to heating from the blue-detuned beam.