Nanowaveguides integrated with a mirror as a scalable platform for collective atom-light interaction

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We have demonstrated a silicon nitride nanowaveguide that has high fiber-to-waveguide coupling efficiencies for both near-infrared wavelengths of 760 nm and 1064 nm. A carefully designed inverse taper improves the coupling efficiency from around 1% to more than 60%, and is estimated by a propagation loss measurement with multiple waveguides of different lengths. Such dual-color waveguides may be used to confine laser-cooled atoms in the evanescent field, creating a potentially scalable nanophotonic platform for atomic sensor and quantum information applications.

The atom-light interaction can be harnessed for a number of quantum-based applications, such as quantum information processing and atomic sensing. Enhancing the atom-light interaction by using a small mode area has been demonstrated in several platforms such as a hollow-core fiber, a hollow-core waveguide, a tapered fiber, and a nanowaveguide. In contrast to work with thermal alkali vapors, laser-cooled ultracold atoms trapped in the evanescent field of a waveguide can exhibit much stronger coupling between the atoms and photons due to the proximity of the atoms to the waveguide and the small mode area. In addition, the cold, trapped atoms will have a longer residence time in the field and thus a longer coherence time. All-optical switching with optically trapped atoms has previously been implemented in a hollow fiber and nanofiber-based optical lattices for $^{133}$Cs atoms were also demonstrated. Although nanofiber atom traps create strong atom-light interactions, they are not easily scalable to realize complex photonic circuits.

Here we present a scalable nanowaveguide platform, which can operate as the atom-light interface between an evanescent field probe and cold neutral atoms. An open-window at the middle of the waveguide is used to interface atoms through the evanescent field. Atoms loaded from an atom-chip mirror MOT (magneto-optical trap) will be optically-trapped with a two-color evanescent field atom trap provided by the waveguide fields. We present measurements characterizing the optical properties of such waveguides, focusing on designs that can simultaneously support the two optical frequencies necessary for atom trapping.

Fig. 1 (a) shows the schematic image of a nanowaveguide atom chip design, and Fig. 1 (b) shows the image of the real waveguide sample. Instead of using a nanofiber or a nanophotonic crystal waveguide, we consider an integrated design of a nanowaveguide and an atom chip mirror MOT which has the advantage of good heat dissipation and good scalability compared to a nanofiber.

and a nanophotonic crystal waveguide. The transporting and loading procedure from a mirror MOT to a nanowaveguide atom trap needs to be carefully considered because the two-color evanescent field atom trap minimum will be around 200 nm above the waveguide surface.

Using the simulation software, FimmProp (see Fig. 2), we designed a nanowaveguide (800 nm x 300 nm, $n_{SiN_4} = 2.05$ and $n_{SiO_2} = 1.46$) that guides 760 nm blue-detuned trapping light, 1064 nm red-detuned trapping light, and 780 nm probe light for $^{87}$Rb atoms. The inverse-tapered structure which expands the waveguide mode is widely used as a mode converter, which can offer good mode matching and coupling efficiency between a nanowaveguide and an optical fiber. Some works have shown properties and applications at telecom wavelengths but its advantages and applications have seldom been reported at shorter wavelengths such as 1064 nm and 760 nm which are used in atomic physics and
in nonlinear optics. According to the simulation, the horizontal and vertical mode field sizes ($1/e^2$ in power) of the waveguide without inverse tapers are (808 nm, 478 nm) at 1064 nm and (704 nm, 386 nm) at 760 nm. For a vacuum compatible platform, we used a fiber-to-waveguide coupling geometry based on gluing the fiber to the waveguide chip with UV-epoxy (Epotek OGG 166-31). We used Fibercore SM750 (core diameter = 3.82 pm, cladding diameter = 125 pm, NA = 0.14) fiber, with mode-field diameters of 6.3 pm at 1064 nm ($n_{core} = 1.45635, n_{clad} = 1.44963$) and 4.46 pm at 760 nm ($n_{core} = 1.46077, n_{clad} = 1.45405$). This would lead to a coupling efficiency between the waveguide mode and the fiber mode of only 1%, which is too low to provide sufficient intensity to trap atoms with reasonable laser powers. We thus designed an inverse taper to improve the mode matching and increased the coupling efficiency to more than 60%. Simulations show that the maximal coupling efficiencies for both 760 nm and 1064 nm near-infrared wavelengths will be achieved with a taper-end width of ~70 nm and a 500 µm taper length that satisfies the adiabaticity condition; Fig. 2(b) shows the simulation. A longer taper, such as 1 mm in length, can increase the coupling efficiency by a few percent, but a longer linear taper induces more propagation loss in practice. Therefore, we chose to work with a 500 µm taper. In addition, we leave an additional rectangular at the end of the linear taper because of the uncertainty of the cleaving technique to have a good waveguide facet (Fig. 1(c) shows the SEM image of the inverse taper-end).

The general fabrication process of our nanowaveguide is described in Fig. 3. A one-centimeter long Si3N4 waveguide with an inverse taper at both ends is fabricated on a 5 µm-thick thermal SiO2 layer (Fig. 2(a)). The Si3N4 was deposited by LPCVD and electron beam lithography (EBL) was used to pattern the nanowaveguide and inverse-tapered structure. EBL is designed to write nano-scale structures; due to its limited writing-field size of several hundred micrometers, our one-centimeter long waveguide will cross 100 writing fields (each is 100 µm by 100 µm) so some stitching error randomly occurs at writing field boundaries. In order to get a continuous, long waveguide, a Fixed Beam Moving Stage (FBMS) and writing-field overlapping technique were used to eliminate stitching errors. Also since we have a 5-µm-thick SiO2 insulating substrate, another conducting polymer was deposited on top of the ebeam resist (PMMA) to reduce charging effects. After the e-beam lithography, ICP fluorine etching was used to etch the Si3N4. We used PECVD to deposit another 4 µm-thick SiO2 above the Si3N4 core. Then with a photolithography pattern and gold deposition, an opening window is made by buffered oxide etch (BOE) in the middle of the sample right on the waveguide. This SiO2 layer helps to form a complete cladding for waveguide at both ends to improve coupling. The window opening in the center of the waveguide will allow the trapping of atoms in future experiments. Finally, the sample is polished from the backside down to around 100 µm-thick and cleaved to create a flat and vertical coupling facet. Since the atom trap needs to be done under high vacuum environment in a glass chamber, the optical alignment between the fiber and the waveguide should be permanently fixed. Consequently, we glued the fiber onto the waveguide facet with UV epoxy. Although there may be some misalignment between the fiber and the waveguide while curing the epoxy, the larger beam size due to the inverse taper offers better tolerance to this misalignment compared to a pure waveguide or a tapered fiber.

To evaluate the coupling efficiency, we also measured the propagation loss of the waveguide. The cut-back technique has been widely used for waveguide propagation loss measurements for years. However, the accuracy of this measurement is highly dependent on the cleaving quality. Small differences in the cleaving may lead to big changes in the propagation loss which then make the propagation loss measurement unreliable. Here we use another method to measure the propagation loss without cleaving the chip more than twice. Figure 4 shows the pattern used for this measurement. Each waveguide contains 2 half-circle bends which are exactly the same. They have a 400 µm diameter, which is used to minimize the bending loss. Each waveguide is 4 mm different in length with the neighboring waveguide. After cleaving just once, we can assume that the coupling loss for each waveguide is the same so it can offer better accuracy than the traditional cut-back technique. We estimated the propagation loss to be -6.34 dB/cm (1064 nm) and -7.69 dB/cm (760 nm). The measured coupling efficiency per facet is derived to be -6.34 dB/cm (1064 nm) and -7.69 dB/cm (760 nm).
79.4% (760 nm) with the taper-end width set to 70 nm.

We realized a silicon nitride nanowaveguide with high coupling efficiencies at both near-infrared wavelengths of 760 nm and 1064 nm. The inverse taper increases the fiber-to-waveguide coupling efficiency to a value larger than 60%. The propagation loss measurement was done with multiple waveguides of different lengths. This platform is designed for a two-color (760 nm and 1064 nm) evanescent-field atom (87Rb) trap in UHV with a 780 nm probe, and is compatible with a gold mirror magnetooptical trap that will laser cool and confine atoms near the waveguide. (Using a gold mirror deposited on the SiO2 layer above the Si substrate (without a waveguide), we have successfully obtained a UHV mirror MOT.) A centimeter-long nanowaveguide with a two-color evanescent field atom trap is expected to confine many atoms loaded from a mirror MOT, creating a high optical depth atomic sample with a strong atom-light interaction. When this nanowaveguide atom trap operates as an optically guided atom interferometer, we can use this platform for inertial atomic sensors and atomic magnetometry. In general, the evanescent field nanowaveguide platform can be used for bio-molecule sensing, gas detection, and chemical solution sensing, which may be enhanced with dual color operation. Moreover, this scalable nanophotonic platform has a potential for a collective-atom-based quantum network, with the ability of fabricating scalable photonic circuits and UHV operation due to its good heat dissipation through the substrate.

FIG. 3. Fabrication Process

FIG. 4. (a) Propagation loss measurement patterns with multiple waveguides in different lengths (b) The image of a waveguide pattern with a bending. (c) The propagation loss vs. the waveguide length. The estimated propagation losses from two samples A and B are -6.05 dB/cm and -6.63 dB/cm (1064 nm); -7.50 dB/cm and -7.88 dB/cm (760 nm). Based on those slopes, we regard the propagation loss as -6.34 dB/cm (1064 nm) and -7.69 dB/cm (760 nm). The offsets from an input power and a bending loss are calibrated as zero.

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