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Coupling single atoms to a nanophotonic whispering-gallery-mode resonator via optical guiding

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We demonstrate an efficient optical guiding technique for coupling cold atoms in the near field of a planar nanophotonic circuit, and realize large atom-photon coupling to a whispering-gallery mode in a microring resonator with a single-atom cooperativity $C \gtrsim 8$. The guiding potential is created by diffracted light on a nanophotonic waveguide that smoothly connects to a dipole trap in the far field for atom guiding with subwavelength precision. We observe atom-induced transparency for light coupled to a microring, characterize the atom-photon coupling rate, extract guided atom flux, and demonstrate on-chip photon routing by single atoms. Our demonstration promises new applications with cold atoms on a nanophotonic circuit for chiral quantum optics and quantum technologies.

Ultracold atoms strongly coupled to photonic fields are model systems for realizing quantum nonlinear optics [1], quantum networks [2, 3], and quantum simulations of many-body physics [4–6]. Interfacing cold atoms with nanoscale photonic waveguides [7–15] and resonators [16–27] in quasi-linear (1D) and planar (2D) geometries further promises stronger atom-light interactions and novel quantum functionalities via dispersion engineering, controlled photon propagation, topology, and chiral quantum transport, thus leading to new paradigms for quantum optics beyond conventional settings in cavity and waveguide quantum electrodynamics (QED) [28, 29].

To date, the key challenge for atom-nanophotonic integration remains to be efficient transporting and trapping of cold atoms on nanoscale dielectrics. Success so far has been limited to suspended 1D structures, which are surrounded by vacuum and allow for laser-cooled atoms to be loaded directly into optical traps in the near field (distance $z \lesssim$ optical wavelength above surface). Examples include optical nanofibers [8, 9], where an array of atoms can be localized in a lattice of two-color evanescent field traps formed by guided light. Through external-illumination, a tight optical trap can also form on top of a suspended waveguide [15, 16, 23]. For deterministic atom trapping, optical tweezers or an optical conveyor belt have been utilized to initiate atom loading in free space, followed by transport to a proximal photonic crystal [16, 30]. These guiding and trapping techniques enable demonstrations of cooperative atom-photon coupling [10–12, 15], and collective Lamb shifts with trapped atoms [31]. Waveguide-interfaced atomic quantum memories [13], photonic phase gate [18], and atom-photon/atom-atom entanglement [27] have also been realized.

Extending optical trapping to 2D photonic structures, however, faces immediate challenges. Due to restricted trap opening to freespace and reduced laser cooling efficiency in the near field above a dielectric plane, potentially caused by unbalanced radiation pressure from surface reflection and scattering or from increased heating rates due to mechanical vibrations [32], unobstructed atom loading into a near field trap has shown limited success probability [33, 34]. This has prevented further explorations of atom-light coupling on more complex and interesting planar structures such as 2D photonic crystals [35] and whispering-gallery mode (WGM) microring resonators with propagation-direction-dependent, chiral atom-light interactions [36–38]. Without tackling the challenges of cooling and trapping, thermal atomic vapors have already been coupled to integrated ring resonators [39, 40] and waveguides [41–44], but with much limited single-atom interaction time and cooperativity.

In this letter, we overcome such restrictions using a technique for precision guiding of cold atoms from far field ($z \gtrsim 250 \mu m$) to a nanoscale optical trap in the near field with subwavelength precision. This scheme is projected to work with generic dielectric nanostructures – a far-off resonant optical beam forms a tapered guiding potential towards a bottom-illuminated structure (Fig. 1), where diffracted light in the near field can precisely direct trapped atoms towards the surface like a geometrically defined ‘optical funnel’. We show that the end of an optical funnel ($z \lesssim 100 \text{ nm}$) can be plugged using a repulsive evanescent field potential that could also counteract atom-surface Casimir-Polder attraction to form a stable trap [Fig. 1(d)]. We implement an optical funnel for guiding cold atoms and coupling them, for the first time, to a nanophotonic microring resonator in a fiber-integrated circuit [45–47]. We achieve synchronous atom guiding towards a designated spot on a microring, and report observation of atom-photon coupling in a WGM of the microring resonator with single-atom cooperativity $C \gtrsim 8$ during the atom-transit. We extract a peak atom flux $\approx 240 \text{ ms}^{-1}$, under a peak atom-photon coupling rate $g_{\text{max}}/(2\pi) \approx 136 \text{ MHz}$ for a spin-polarized atom. Our scheme is complementary to an optical conveyor belt [30, 33], and can be extended to guiding and

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trapping atom arrays in generic planar nanostructures.

We begin the experiment by collecting \( \sim 10^5 \) laser-cooled cesium atoms (temperature \( \sim 20 \mu \text{K} \) following polarization gradient-cooling, PGC) at \( z \approx 250 \mu \text{m} \) above a transparent silica membrane that hosts a racetrack-shaped \( \text{Si}_3\text{N}_4 \) microring resonator [45, 48]. The atoms are loaded into an optical funnel that points towards the microring waveguide of width \( \approx 950 \text{nm} \) and height \( \approx 326 \text{nm} \), respectively. The funnel potential is formed in a red-detuned, bottom-illuminating beam (wavelength \( \lambda_b \approx 935.3 \text{nm} \)), with a beam waist of \( 7 \mu \text{m} \) and a polarization locally parallel to the waveguide. Over the top, the zeroth-order diffraction exhibits strong intensity gradient, diffracting from a 200 nm \( 1/e^2 \)-transverse width into a circular far-field dipole beam profile; see Fig. 1(b) and [45]. This guiding potential in the near field is robust against beam misalignment by more than the width of the microring waveguide \( ( \gtrsim 1 \mu \text{m} \) ), which we confirmed in simulation and experimentally. Higher order diffractions do not form funnels because they display intensity maxima that are several micrometers away from the waveguide. Localized atoms in the optical funnel can be fluorescence imaged at distances \( z \lesssim 10 \mu \text{m} \) [33, 34], as shown in Fig. 1(c).

We plug the optical funnel using a repulsive evanescent field formed by a ‘blue’ WGM (wavelength \( \lambda_b \approx 849.55 \text{nm} \)). A plugged funnel potential exhibits a stable trap minimum in the near field. We adjust the power of the bottom beam, \( P_t \approx 15 \text{mW} \), and that of the blue-detuned beam, \( P_b \approx 33 \mu \text{W} \), to form a closed trap with trap minimum at \( z \approx 280 \text{nm} \) and a trap depth of \( k_B \times 250 \mu \text{K} \), where \( k_B \) is the Boltzmann constant; see Fig. 1(d).

We detect guided atoms in the near field by probing atom-WGM photon interactions. The ‘probe’ WGM resonance is thermally stabilized to the \( F = 4 \leftrightarrow F' = 5 \) transition in D2 line. Probe photons are sent through one end of a bus waveguide to couple to the clockwise circulating (CW) WGM (coupling rate \( \kappa_c \approx \pi \times 0.77 \text{GHz} \)). The intrinsic photon loss rate is \( \kappa_i \approx \pi \times 0.95 \text{GHz} \), and the total photon loss rate is \( \kappa = \kappa_c + \kappa_i \approx \pi \times 1.72 \text{GHz} \) [45]. Resonant probe photons are drawn into the microring and dissipate, reducing the bus waveguide transmission to \( T_0 = |(\kappa_c - \kappa_i)/\kappa|^2 \approx 0.01 \). Interaction with an atom will lead to an increased transparency \( T > T_0 \) [45, 49]. We note that a WGM photon is nearly circularly-polarized in the near field. Interaction with the probe WGM (in CW circulation) can thus drive \( \sigma^+ \) transitions with spin axis defined transversely to the waveguide; an atom can also emit a photon in the counter-clockwise circulating (CCW) WGM via the \( \sigma^- \) transitions, inducing reflection in the bus waveguide; see discussions in [45]. In our microring, CW and CCW WGM resonances are degenerate.

Our probe sequence is illustrated in Fig. 2 inset. We prepare atoms in the \( F = 4 \) ground state and then shut off the PGC light, allowing them to be guided towards the microring surface. After a wait time \( \Delta t \), two weak probe pulses are sent through the bus waveguide, each with a duration of \( 1 \text{ ms} \), to measure the transmission \( T \) (\( T_0 \)) in the presence (absence) of atoms; the bottom beam is switched off for \( 3 \text{ ms} \) between the two pulses to release guided atoms. Each experiment is repeated 100 times for averaging.

In Fig. 2, we observe increased transmission and a clear maximum up to \( T \approx 0.26 \) at \( \Delta t \approx 5 \text{ ms} \), indicating a peak atom flux arriving at the near field. Interestingly, transmission resurges at \( 16 \text{ ms} \lesssim \Delta t \lesssim 21 \text{ ms} \). This is due to longitudinal reflection of most guided atoms in a rapidly narrowing optical funnel [50, 51], regardless of
the presence of the repulsive potential barrier. These reflected atoms are later drawn back towards the surface for recoupling. We have performed atomic trajectory simulations [52] to confirm the observed oscillatory behavior and guiding effect [45].

We note that transparency is more pronounced with coupling to guided atoms in a plugged optical funnel, due to the fact that a repulsive barrier can increase the atom-WGM photon interaction time. To see this, in Fig. 3(a) we overlay sample atomic trajectories and position-dependent atom-photon coupling strength $\tilde{g}$, calculated using the CW WGM field distribution [53] and averaged over $g$ of all magnetic sub-levels [45]. Note that $\tilde{g}$ is constant along the waveguide (y-axis). Most trajectories exhibit a longitudinal classical turning point in the near field $z = 110 \pm 20$ nm and within $|x| \lesssim 0.3 \mu$m. Corresponding time-dependent coupling strengths $\bar{g}(t)$ are plotted in Fig. 3(b). Averaging over all trajectories, we find peak cooperativity and a larger Purcell broadening $\bar{C}$ for polarized atoms in a plugged funnel. Insets in (c-d) illustrate the levels involved in recoupling. 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The spectrum indeed shows a broader linewidth due to the cycling transits of spin-polarized atoms in the waveguide. During the optical pumping process, it is achieved that nearly continuous single-atom transits during the entire 1 ms probe window.

To confirm single atom-photon coupling, we extract possible non-classical photon correlations during each detection of atom-transit. We first identify atom-transit events in the time-stamped signals by imposing a threshold of 2 counts within a 1.6 µs running window. We then analyze the normalized intensity correlation $g^{(2)}(\tau)$, similar to Eq. (2), but using signals in a 2 µs window centered around each post-selected transit events. For details, see the Supplemental Material [45]. In Fig. 4(b-
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be studied using multiple optical funnels formed on a mi-

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coupled to the microring mode (CW-WGM) cooperativity $C^+ \approx 8$, which we determined from a theory fit [45]. We also confirm that photon anti-bunching can be observed over an extended time period whenever there are guided atoms coupled to the microring [Fig. 4(d)]; $g^2(0)$ remains nearly at a constant level, including the time around $\Delta t \approx 5$ ms when we observe the peak atom flux. This suggests the transmitted photons observed in Figs. 2-3 are indeed routed by single atoms, one at a time, instead of multiple atoms simultaneously coupled to the same resonator mode, in which we expect more complex behavior in photon correlations. Nonetheless, correlated photon transport gated by multiple atoms is an interesting topic in its own right [56, 57]. This can be studied using multiple optical funnels formed on a microring resonator.

In conclusion, we have demonstrated an optical trapping technique that guides single atoms on a planar nanophotonic resonator with subwavelength precision. Using our technique, single atom trapping probability may be improved by pulsing on a lattice beam [15, 16, 23, 26, 33] to localize atoms in the near field following an instantaneous feedback from probing a WGM resonator [26]. To further cool and localize single atoms in a near field trap, evanescent-wave cooling [58, 59], Raman sideband cooling [60, 61], or cavity cooling [62, 63] may be implemented. The achieved single-atom, single-mode (CW-WGM) cooperativity $C^+ \geq 8$ is currently limited by the quality factor $Q \approx 2 \times 10^5$ of the coupled microring circuit. We expect significant improvement in the cooperativity parameter by more than 5-fold with a better $Q > 10^8$ [34, 48] following improvements in waveguide surface roughness and material quality. Our work would enable new applications, for example, in chiral quantum optics [21, 22, 36, 64-67] based on cold atoms coupled to an on-chip WGM resonator. Our system also holds a promise for realizing photon-mediated atom-atom interactions and quantum many-body physics [5, 6, 68–71] with multiple trapped atoms.

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