

Tailored-waveguide based photonic chip for manipulating an array of single neutral atoms

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Abstract: We propose a tailored-waveguide based photonic chip with the functions of trapping, coherently manipulating, detecting and individually addressing an array of single neutral atoms. Such photonic chip consists of an array of independent functional units spaced by a few micrometers, each of which is comprised of one silica-on-silicon optical waveguide and one phase Fresnel microlens etched in the middle of the output interface of the optical waveguide. We fabricated a number of photonic chips with 7 functional units and measured optical characteristics of these chips. We further propose feasible schemes to realize the functions of such photonic chip. The photonic chip is stable, scalable and can be combined with other integrated devices, such as atom chips, and can be used in the future hybrid quantum system and photonic quantum devices.

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OCIS codes: (020.7010)Laser trapping; (270.5585)Quantum information and processing; (250.5300)Photonic integrated circuits; (130.2755)Glass waveguides; (050.1965)Diffraction lenses.

References and links

1. N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, "Sub-poissonian loading of single atoms in a microscopic dipole trap," *Nature* **411**, 1024 (2001).
2. D. Jaksch, J. I. Cirac, P. Zoller, S. L. Rolston, R. Côté, and M. D. Lukin, "Fast quantum gates for neutral atoms," *Phys. Rev. Lett.* **85**, 2208 (2000).
3. M. D. Lukin, M. Fleischhauer, R. Cote, L. M. Duan, D. Jaksch, J. I. Cirac, and P. Zoller, "Dipole blockade and quantum information processing in mesoscopic atomic ensembles," *Phys. Rev. Lett.* **87**, 037901 (2001).
4. T. Grönzweig, A. Hilliard, M. McGovern, and M. F. Anderson, "Near-deterministic preparation of a single atom in an optical microtrap," *Nat. Phys.* **6**, 951 (2010).
5. D. D. Yavuz, P. B. Kulatunga, E. Urban, T. A. Johnson, N. Proite, T. Henage, T. G. Walker, and M. Saffman, "Fast ground state manipulation of neutral atoms in microscopic optical traps," *Phys. Rev. Lett.* **96**, 063001 (2006).
6. M. P. A. Jones, J. Beugnon, A. Gaëtan, J. Zhang, G. Messin, A. Browaeys, and P. Grangier, "Fast quantum state control of a single trapped neutral atom," *Phys. Rev. A* **75**, 040301 (2007).
7. S. Kuhr, W. Alt, D. Schrader, I. Dotsenko, Y. Miroshnychenko, A. Rauschenbeutel and D. Meschede, "Analysis of dephasing mechanisms in a standing-wave dipole trap," *Phys. Rev. A* **72**, 023406 (2005).
8. E. Urban, T. A. Johnson, T. Henage, L. Isenhower, D. D. Yavuz, T. G. Walker, and M. Saffman, "Observation of Rydberg blockade between two atoms," *Nat. Phys.* **5**, 110 (2009).

9. A. Gaëtan, Y. Miroshnychenko, T. Wilk, A. Chotia, M. Viteau, D. Comparat, P. Pillet, A. Browaeys, and P. Grangier, "Observation of collective excitation of two individual atoms in the Rydberg blockade regime," *Nat. Phys.* **5**, 115 (2009).
10. L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson, T. G. Walker, and M. Saffman, "Demonstration of a neutral atom controlled-NOT quantum gate," *Phys. Rev. Lett.* **104**, 010503 (2010).
11. T. Wilk, A. Gaëtan, C. Evellin, J. Wolters, Y. Miroshnychenko, P. Grangier, and A. Browaeys, "Entanglement of two individual neutral atoms using Rydberg blockade," *Phys. Rev. Lett.* **104**, 010502 (2010).
12. T. Xia, M. Lichtman, K. Maller, A.W. Carr, M. J. Piotrowicz, L. Isenhower, and M. Saffman, "Randomized benchmarking of single-qubit gates in a 2D array of neutral-atom qubits," *Phys. Rev. Lett.* **114**, 100503 (2015).
13. C. Knoerschild, X. L. Zhang, L. Isenhower, A. T. Gill, F. P. Lu, M. Saffman, and J. Kim, "Independent individual addressing of multiple neutral atom qubits with a micromirror-based beam steering system," *Appl. Phys. Lett.* **97**, 134101 (2010).
14. H. Labuhn, S. Ravets, D. Barredo, L. Béguin, F. Nogrette, T. Lahaye, and A. Browaeys, "Single-atom addressing in microtraps for quantum-state engineering using Rydberg atoms," *Phys. Rev. A* **90**, 023415 (2014).
15. X. He, P. Xu, J. Wang, and M. Zhan, "Rotating single atoms in a ring lattice generated by a spatial light modulator," *Opt. Express* **17**, 21007 (2009).
16. F. Nogrette, H. Labuhn, S. Ravets, D. Barredo, L. Béguin, A. Vernier, T. Lahaye, and A. Browaeys, "Single-atom trapping in holographic 2D arrays of microtraps with arbitrary geometries," *Phys. Rev. X* **4**, 021034 (2014).
17. J. Reichel and V. Vuletić, *Atom Chips* (Wiley-VCH, 2011).
18. J. Fortgh and C. Zimmermann, "Magnetic microtraps for ultracold atoms," *Rev. Mod. Phys.* **79**, 235 (2007).
19. A. Politi, M. J. Cryan, J. G. Rarity, S. Yu and J. L. O'Brien, "Silica-on-silicon waveguide quantum circuits," *Science* **320**, 646 (2008).
20. M. Kohnen, M. Succo, P. G. Petrov, R. A. Nyman, M. Trupke, and E. A. Hinds, "An array of integrated atom - photon junctions," *Nat. Photonics* **5**, 35 (2011).
21. G. Lepert, M. Trupke, M. J. Hartmann, M. B. Plenio, and E. A. Hinds, "Arrays of waveguide-coupled optical cavities that interact strongly with atoms," *New J. Phys.* **13**, 113002 (2011).
22. A. Lengwenus, J. Kruse, M. Schlosser, S. Tichelmann, and G. Birkel, "Coherent transport of atomic quantum states in a scalable shift register," *Phys. Rev. Lett.* **105**, 170502 (2010).
23. R. Dumke, M. Volk, T. Muther, F. B. J. Buchkremer, G. Birkel, and W. Ertmer, "Micro-optical realization of arrays of selectively addressable dipole traps: a scalable configuration for quantum computation with atomic qubits," *Phys. Rev. Lett.* **89**, 097903 (2002).
24. R. Schoelkopf and S. Girvin, "Wiring up quantum systems," *Nature* **451**, 664 (2008).
25. N. Schlosser, G. Reymond, and P. Grangier, "Collisional blockade in microscopic optical dipole traps," *Phys. Rev. Lett.* **89**, 023005 (2002).
26. R. Scarmozzino, A. Gopinath, R. Pregla, and S. Helfert, "Numerical techniques for modeling guided-wave photonic devices," *J. Sel. Top. Quantum Electron.* **6**, 150 (2000).
27. R. Scarmozzino and R.M. Osgood, Jr., "Comparison of finite-difference and Fourier-transform solutions of the parabolic wave equation with emphasis on integrated-optics applications," *J. Opt. Soc. Amer. A* **8**, 724 (1991).
28. G. D. Marshall, A. Politi, J. C. F. Matthews, P. Dekker, M. Ams, M. J. Withford, and J. L. O'Brien, "Laser written waveguide photonic quantum circuits," *Opt. Express* **17**, 12546 (2009).
29. C. Tuchendler, A. M. Lance, A. Browaeys, Y. R. P. Sortais, and P. Grangier, "Energy distribution and cooling of a single atom in an optical tweezers," *Phys. Rev. A* **78**, 033425 (2008).
30. T. A. Savard, K. M. O'Hara, and J. E. Thomas, "Laser-noise-induced heating in far-off resonance optical traps," *Phys. Rev. A* **56**, 1095(R) (1997).
31. Yu-ju Lin, I. Teper, Cheng Chin and V. Vuletić, "Impact of the Casimir-Polder potential and Johnson noise on Bose-Einstein condensate stability near surfaces," *Phys. Rev. Lett.* **92**, 050401 (2004).
32. D. M. Harber, J. M. Obrecht, J. M. McGuirk, and E. A. Cornell, "Measurement of the Casimir-Polder force through center-of-mass oscillations of a Bose-Einstein condensate," *Phys. Rev. A* **72**, 033610 (2005).
33. D. M. Harber, J. M. McGuirk, J. M. Obrecht, and E. A. Cornell, "Thermally induced losses in ultra-cold atoms magnetically trapped near room-temperature," *J. Low Temp. Phys.* **133**, 229 (2003).
34. A. Tauschinsky, R. M. T. Thijssen, S. Whitlock, H. B. van Linden van den Heuvell, and R. J. C. Spreeuw, "Spatially resolved excitation of Rydberg atoms and surface effects on an atom chip," *Phys. Rev. A* **81**, 063411 (2010).
35. E. A. Hinds, K. S. Lai, and M. Schnell, "Atoms in micron-sized metallic and dielectric waveguides," *Phil. Trans. R. Soc. Lond. A* **355**, 2353 (1997).
36. H. Kübler, J. P. Shaffer, T. Baluktsian, R. Löw, and T. Pfau, "Coherent excitation of Rydberg atoms in micrometer-sized atomic vapour cells," *Nat. Photonics* **4**, 112 (2010).
37. J. A. Sedlacek, E. Kim, S. T. Rittenhouse, P. F. Weck, H. R. Sadeghpour, and J. P. Shaffer, "Electric field cancellation on quartz by Rb asorbate-induced negative electron affinity," *Phys. Rev. Lett.* **116**, 133201 (2016).
38. R. P. Abel, C. Carr, U. Krohn, and C. S. Adams, "Electrometry near a dielectric surface using Rydberg electromagnetically induced transparency," *Phys. Rev. A* **84**, 023408 (2011).
39. B. P. Anderson and M. A. Kasevich, "Loading a vapor-cell magneto-optic trap using light-induced atom desorp-

- tion," *Phys. Rev. A* **63**, 023404 (2001).
40. D. Schrader, I. Dotsenko, M. Khudaverdyan, Y. Miroshnychenko, A. Rauschenbeutel, and D. Meschede, "Neutral Atom Quantum Register," *Phys. Rev. Lett.* **93**, 150501 (2004).
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1. Introduction

Single neutral atom trapped in an optical dipole trap [1] has excellent coherence properties and long lifetime. And qubit which is encoded in two hyperfine ground states of the single atom can be initialized by optical pumping and measured with nearly 100 % efficiency by using state-dependent optical fluorescence detection. Controlled quantum gates and entanglements can be realized through appropriate interactions between atoms by using the Rydberg blockade mechanism [2, 3]. All these characteristics make trapped single neutral atom a promising candidate for storing and processing quantum information.

In the last few years, a few impressive achievements have been obtained in this research field, such as near-deterministic preparation of a single atom [4], single-qubit operations [5–7], Rydberg blockade between two trapped atoms [8, 9], neutral atom controlled-NOT quantum gate [10] and entanglement [11], single-atom addressing in an array of neutral-atom qubits [12–14], and so on. In these researches, optical dipole microtrap is formed by a tightly focused Gaussian beam with high numerical-aperture lens. Scaling of optical dipole microtrap is realized by using spatial light modulators [12, 15, 16]. Meanwhile, above trapped-single-atom schemes, realized in bulk optics, suffer from severe drawbacks, such as bad stability, poor precision and large physical size. Consequently, these schemes by using bulk-optical components are limited in the future practical applications.

To beat these limitations, people developed a new research field, so called atom chip [17, 18], which combines the well developed techniques for manipulation of atomic quantum states with the advanced microfabrication technology. The fast development of atom chip advances the applications of cold atom physics in atom interferometer, atom clock and quantum information processing. Recently, silica-on-silicon waveguide quantum circuits were used to implement the first integrated linear optical control-NOT gate [19]. An optical waveguide integrated on atom chip was used to engineer quantum state of flying atoms [20], where the atoms could not be trapped. Arrays of waveguide-coupled optical cavities were proposed in [21]. Besides, coherent transport of two-dimensional array of small atom ensembles in a shift register architecture was realized [22] by using a two-dimensional array of spherical, diffractive microlenses with a pitch of 125 μm [23]. Inspired by these works, we propose a photonic chip which consists of an array of independent functional units spaced by a few micrometers, each of which is comprised of one silica-on-silicon optical waveguide and one phase Fresnel microlens etched in the middle of the output interface of the optical waveguide. Such photonic chip can be used to trap, coherently manipulate and detect an array of single neutral atoms. And this chip has additional functions: individually addressing and controlling the interactions between neighboring single atoms by using the Rydberg blockade mechanism. Moreover, the monolithic nature of such photonic chip means that it is miniaturized, stable, scalable in one-dimension and two-dimension, and can be combined with other integrated devices, such as atom chip, making it more applicable in future hybrid quantum system [24] and photonic quantum devices.

In this paper we describe the design and fabrication of such photonic chip, and measurements of the propagation characteristics of lights through this chip. We further describe realistic schemes for trapping, coherently manipulating, detecting and individually addressing an array of single neutral atoms with such photonic chip.

2. Design, optimizations of relevant parameters and fabrication of the photonic chip

To realize the functions of trapping, coherently manipulating, detecting and individually addressing an array of single neutral atoms, the photonic chip must be designed to satisfy several key requirements: (i) single mode operation: light for trapping single atom and fluorescence from the trapped single atom should propagate in the optical waveguides in single-mode; (ii) mode matching: the transverse mode sizes of dipole trap light beam, fluorescence light in the waveguides should be comparable to the core size of conventional single-mode optical fiber; (iii) the crosstalk between neighbouring waveguides should be as low as possible; (iv) dipole trap light should be tightly focused by the microlens to a spot with a waist size of typically smaller than $4\ \mu\text{m}$, in collisional blockade regime [25], resulting in only one atom trapped in one dipole trap; (v) trapped single atoms should be close to each other, to realize the controlled interactions between neighboring atoms by using the Rydberg blockade mechanism.

In the following discussion, rubidium-87 atom with the resonance wavelength of 780 nm, is chosen as the trapped atom. The wavelength of dipole trap light is chosen to be about 830 nm. The most promising material to meet these requirements is silica (SiO_2), with a low level of doping, grown on a silicon substrate. An appropriate refractive index contrast is chosen to give single-mode operation at both 780 nm and 830 nm in optical waveguides with a $4\text{-}\mu\text{m}$ -square core, which is comparable to the core size of conventional single-mode optical fiber. An array of parallel optical waveguides are spaced at the output interface of the chip by several micrometers. These waveguides flare out at the input interface of the chip so that optical fibers can be connected. A phase Fresnel microlens with an appropriate focal length is etched at the output interface of each optical waveguide. The center of phase Fresnel microlens coincides with the center of the optical waveguide. The schematic of the photonic chip is shown in Fig. 1.

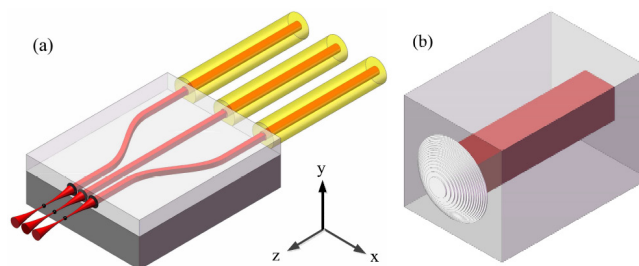


Fig. 1. Schematic of the photonic chip. An array of parallel optical waveguides (a)(for clarity, only three are shown) with a $4\text{-}\mu\text{m}$ -square core are spaced at the center of the chip by $10\ \mu\text{m}$. A phase Fresnel microlens with 16 steps and focal length of $13\ \mu\text{m}$ is etched in the middle of the output interface of each waveguide, as shown in (b). The center of microlens coincides with the center of optical waveguide. The dipole trap light is transported into the chip through optical fiber connected at the input interface of the chip, and focused by the microlens to form optical dipole microtrap with a waist size of about $1.5\ \mu\text{m}$, which can trap only one atom. Due to the array arrangement of waveguides and microlenses, the chip can be used to trap single-atom array.

In order to choose optimal parameters of the photonic chip, we performed several simulations of the propagation characteristics of the lights through the waveguides and microlenses using Rsoft's beam propagation method (BPM) package [19, 26, 27].

Several simulations of single waveguide with different refractive index contrasts were performed to determine the appropriate parameters which satisfy the key requirements of single mode operation and mode matching. The optimal refractive index contrast is chosen to be about 0.7% when the waveguide core is set to $4\text{-}\mu\text{m}$ -square. The intensity profiles of the dipole trap

light at 830 nm and fluorescence light at 780 nm in the waveguide with the chosen parameters are shown in Fig. 2.

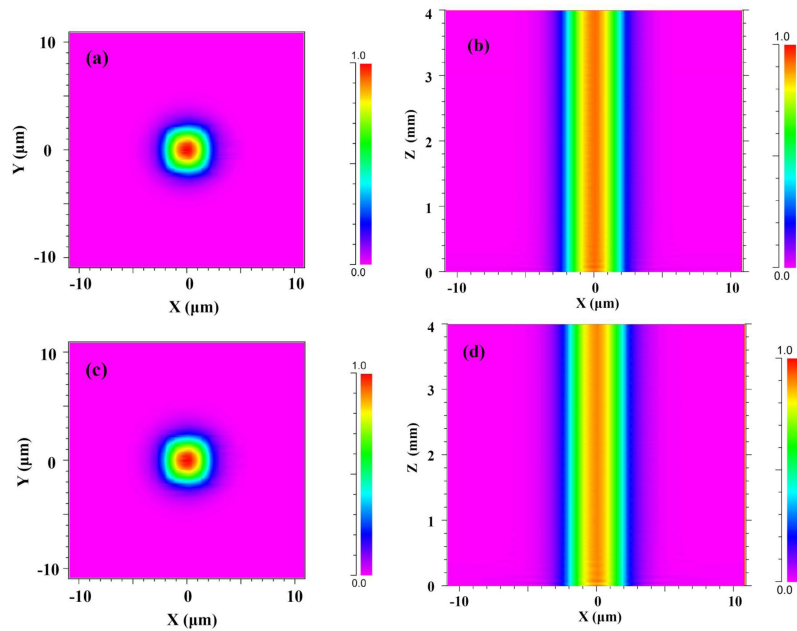


Fig. 2. Simulations of the propagation characteristics of the lights at 780 nm and 830 nm in single waveguide with optimal refractive index contrast of 0.7 % and a 4- μm -square core. (a) and (c) show the transverse intensity profiles of the fundamental modes of lights at 780 nm and 830 nm, respectively. (b) and (d) show the intensity profiles of the lights at 780 nm and 830 nm in the direction of propagation, respectively. These results imply that the lights at 780 nm and 830 nm propagate in the waveguide with chosen parameters in single mode.

Fixing the refractive index contrast and core size of single waveguide, we simulate the propagation characteristics of the light at 780 nm in 3 parallel waveguides with different separations, as shown in Fig. 3. To realize the controlled interactions between neighboring atoms by using Rydberg blockade mechanism, the separation between neighboring waveguides should be expected to be as small as possible. On the other hand, the crosstalk will be a severe problem if the waveguides are too close to each other, as shown in Fig. 3(a), from which obvious crosstalks exist when the separation is 8 μm . After detailed simulations, the separation between neighboring waveguides is chosen to be 10 μm as a compromise, where the crosstalk between neighboring waveguides is negligible, as shown in Fig. 3(b), and Rydberg blockade also works well [8]. The same simulations of the light at 830 nm were also performed, and the results show that the separation of 10 μm is a good choice.

We further simulated the intensity field profiles of the lights at 780 nm and 830 nm through the photonic chip to determine the focal length of phase Fresnel microlens. The microlens is set to 16 steps to minimize the transmission loss. We find that if the focal length is chosen to be less than 10 μm , the lights are tightly focused, but the waist of the focused lights is too close to the microlens; If the focal length is increased to more than 20 μm , the light beams are weakly focused, resulting in that single atom could not be trapped. The optimal focal length of the microlens is chosen to be 13 μm , where the light at 830 nm is tightly focused to a spot with waist radius of 1.5 μm at the distance of about 11 μm from the microlens, and the light at 780

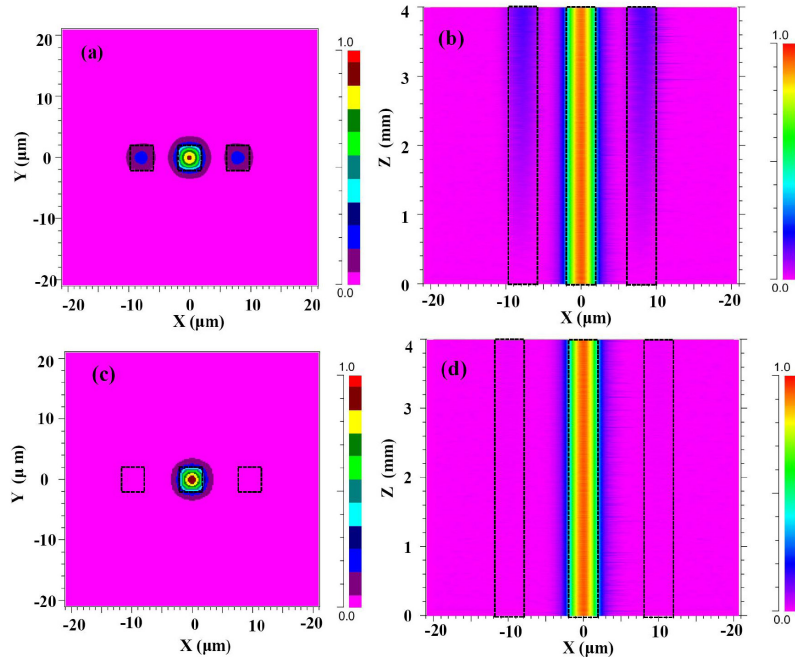


Fig. 3. Simulations of the propagation characteristics of light at 780 nm in 3 parallel waveguides with different separations. The dashed black squares and rectangles represent the waveguide core. The intensity profiles in transverse (a) and in the propagation (b) directions in 3 parallel waveguides with the separation of 8 μm are shown, in which there is obvious crosstalk between neighbouring waveguides. (c) and (d) show the intensity profiles in transverse and propagation directions in 3 parallel waveguides with the separation of 10 μm , respectively. With this separation, the crosstalk is negligible and Rydberg blockade also works well.

nm is focused to a spot with waist radius of about 1.4 μm at the distance of about 10 μm from the microlens. The corresponding intensity field profiles of the lights at 830 nm and 780 nm through the chip are shown in Figs. 4(a) and 4(b), respectively.

Choosing appropriate parameters, such as refractive index contrast, size of the optical waveguide core and focal length of the microlens, the photonic chip works for other neutral atoms as well. The photonic chip can easily scale up in one-dimension by arranging the parallel optical waveguide one by one linearly. Scaling in two-dimension can be realized by arranging the waveguides in two-dimension fabricated by using direct UV laser waveguide writing technique [28].

When an atom is placed into the focused laser, a dipole potential $U_{dip} = \frac{3\pi c^2}{2\omega_0^3} \frac{\Gamma}{\Delta} I(r)$ arises from the induced dipole moment of the atom in the light field, where $\Delta = \omega - \omega_0$ is the detuning, Γ is atomic natural linewidth, ω_0 is atomic resonant transition frequency, ω and $I(r)$ are the frequency and intensity of the laser, respectively. In our case, the dipole laser wavelength is 830 nm, $\Delta < 0$. The resulting dipole potential is negative, thus atom will be attracted to the position with maximum intensity. The trap depth U_t is given by $U_t = U_{r1} - U_{r2}$, where $U_{r1} = \frac{3\pi c^2}{2\omega_0^3} \frac{\Gamma}{\Delta} \frac{P}{\sigma_1}$ is the dipole potential in the focus, $U_{r2} = \frac{3\pi c^2}{2\omega_0^3} \frac{\Gamma}{\Delta} \frac{P}{\sigma_2}$ is the dipole potential at the output interface of the chip, σ_1 and σ_2 are the area of transverse mode of light at the focus and microlens surface, respectively. Obviously, the trap depth U_t is proportional to the input laser power P .

As a rule [29], the trap depth U_t should be large compared to the mean atomic energy, i.e. $U_t > \eta k_B T$, where T is the atom temperature, $\eta = 5 - 10$. As an example, for an atom with a temperature $T = 50 \mu\text{K}$, the trap depth should be at least $U_t \sim 500 \mu\text{K}$, which corresponds to an input power about 12 mW. The axial and radial dipole potentials are calculated with the input power 12 mW, shown in Figs. 4(c) and 4(d).

The extremely small focal spot $w_0 \sim 1.5 \mu\text{m}$ at 830 nm means that the dipole trap formed by the focused light has extremely small trap volume, which is proportional to w_0^4 . Due to the collision blockade effect, only one atom can be trapped in this trap.

The lifetime of single atom in a dipole trap is determined mainly by the collisional induced loss with the background gas atoms, heating induced losses arising from the Stark shift, and the intensity fluctuation of the dipole light [30]. Under the condition that the background pressure is a few 10^{-7} Pa, and both the position and intensity of the dipole light are well stabilized, the lifetime of single atom can be several second. In our case where the single atom is more than $10 \mu\text{m}$ away from the dielectric surface and the trap depth is enough high, the Casimir-Polder surface effect does not effect the trapped atom significantly [31–33].

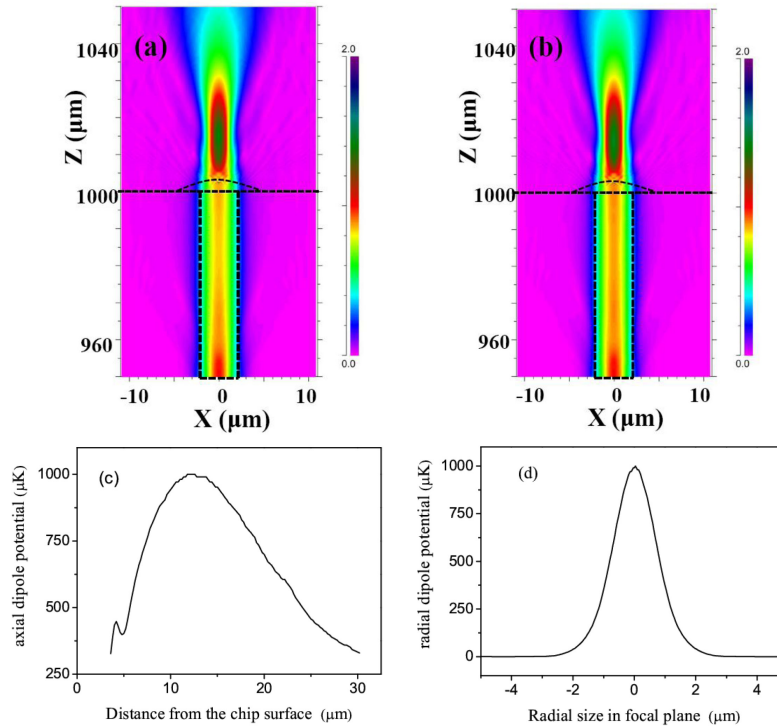


Fig. 4. Simulations of the intensity profiles of the lights at 830 nm (a) and 780 nm (b) focused by the microlens with 16 steps and the focal length of $13 \mu\text{m}$. The waveguide core (dashed black square) and microlens (dashed black arc) are superimposed on the intensity profiles. The light at 830 nm is strongly focused by the microlens to a spot with a waist size of about $1.5 \mu\text{m}$ at the distance of about $11 \mu\text{m}$. The propagation characteristics of the focused light at 780 nm is nearly same as that at 830 nm. (c) and (d) are the axial and radial dipole potential, respectively, when the power of the dipole microtrap is about 12 mW.

Following the above design, we fabricated a number of photonic chips with 7 functional units. The chips were made in two steps: fabrication of optical waveguides and etching of phase Fres-

nel microlenses. The optical waveguides were manufactured on a 0.5-mm-thick silicon wafer. A 15- μm -thick layer of silica as the lower cladding of the waveguides, was grown by thermal oxidation. A second layer of silica, doped with germanium to achieve a 0.7 % refractive index contrast, was created by flame hydrolysis deposition. The waveguide cores were created with standard optical lithography techniques. A further 20- μm -thick silica layer of upper cladding was doped with boron and phosphorus to match the refractive index of the lower cladding. After the output interface of the optical waveguides was polished, 7 phase Fresnel microlenses were fabricated by focused Ion beam etching technique as following: the center of phase Fresnel microlens was carefully aligned to coincide with the center of each optical waveguide. Turning on the focused ion beam with calculated phase pattern, a series of 16 concentric rings with different height were etched into the output interface of the waveguide to generate a π phase shift. The diameter of fabricated microlens is 9.47 μm , the height of each step is 113 nm.

3. Measurements of propagation characteristics of lights through the photonic chip

We measured the propagation characteristics of the light at 830 nm and 780 nm through the photonic chips to confirm whether the fabricated photonic chips satisfied the design requirements.

Firstly, we measured the focal spot sizes of light at 830 nm focused by microlens. The light emitting from the chip was Gaussian transformed by a doublet lens with a focal length of 30 mm, where the magnification is 39, and the waist spot of the transformed light was imaged on an EMCCD camera, as showed in Fig. 5. The image indicates that the light propagates well in the waveguide in single mode, and the crosstalk between neighbouring waveguides is negligible. The magnified waist spot size was Gaussian fitted to about 59 μm . Accordingly, the waist sizes focused by microlens are 1.5 μm , which agrees with the simulation value. Figure 5(b) shows array of optical microtaps where two independent light beams at 830 nm are transported into two neighbouring waveguides respectively.

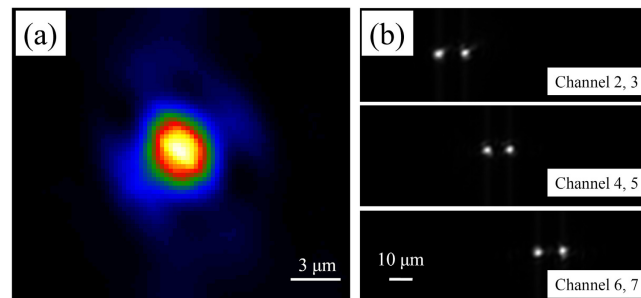


Fig. 5. Images of lights from the waveguides. (a) Magnified image of the waist spot of the light at 830 nm focused by microlens, where the magnification is 39. (b) Array of optical microtaps where two independent light beams at 830 nm are transported into two neighbouring channels respectively.

We further compared the propagation features of the light at 780 nm emitting from two neighbouring channels with the separation of 10 μm . Channel 1 is a waveguide, channel 2 is comprised of a waveguide and a microlens with the focal length of 13 μm . In the experiment EMCCD camera was moved along the optical axis and the corresponding light spots were measured, where the magnification is 8.5. From the results shown in Fig. 6, we can conclude that the light emitting from channel 2 diverges more severely, which implies that this light has a smaller waist size, in other words, this light is focused by microlens. The lights are approximated to

Gaussian beams. In the far field region where the measurements were performed, the angle of divergence θ remains unchanged, $\theta = \lambda/(\pi w) = y/[1000(x - a)]$, where w is the spot size, a is the position of the waist. The measured data are linearly fitted where the linear fitting function is $y = 1000(x - a)\lambda/(\pi w)$. The fitted value w is divided by the magnification 8.5. Then we can conclude that the waist size of the laser beam focused by the microlens is $w_0 = 1.5 \mu\text{m}$, which is in collisional blockade region. The size of the light emitting from channel 1 is about $2.3 \mu\text{m}$.

Both of the measurements confirmed that the chip could be used to trap an array of single atoms.

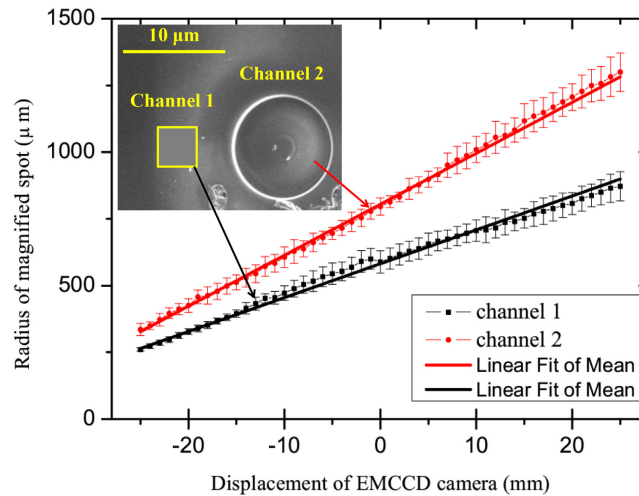


Fig. 6. Measurements of the propagation characteristics of the light at 780 nm emitting from channel 1 and 2 where the magnification is 8.5. Inset: the SEM image of channel 1 and 2. The measured data are nearly linear. The waist size of the light focused by the microlens is fitted to be about $1.5 \mu\text{m}$, which is in collisional blockade region. The size of the light emitting from channel 1 is about $2.3 \mu\text{m}$.

4. Schemes for trapping, manipulating, detecting and addressing an array of single neutral atoms with the photonic chip

With the chip in hand, in the future, array of single atoms could be formed and manipulated in the following way:

4.1. Trapping of array of single atoms

Several independent dipole trap light beams with appropriate power are transported by single-mode optical fibers into the photonic chip, and tightly focused by the microlenses on the output interface of the chip, forming an array of parallel dipole microtraps with waist sizes of about $1.5 \mu\text{m}$. Dilute cold atom cloud is transported into the region where array of dipole microtraps locate, by means of releasing from a magneto-optical trap above the photonic chip, or moving a cold atom cloud by atom chip combined with the photonic chip. The density of cold atom cloud which is proportional to the loading rate of dipole microtrap, should be low enough to ensure only one atom, on average, in each microtrap volume. To induce light-assisted collisions and image the sample, the atoms are illuminated by a weak quasi-resonant probe beam and a repumping laser beam. Because of collisional blockade mechanism, only a single atom can be loaded in each dipole microtrap with enough high trap depth and very small trap volume.

4.2. Fluorescence detection of single atom

The fluorescence from the trapped single atom is collected by the microlens, and transported to a single-photon counting avalanche photodiode (APD) by the corresponding waveguide and optical fiber. Small transverse mode size of the optical waveguide limits the solid angle of the microlens, resulting in about 1% of collection efficiency of fluorescence signal. Moreover, fluorescence collected by other microlens could not propagate in the corresponding waveguide due to large incident angle.

4.3. Single-qubit operation

We define the logical states as $|0\rangle \equiv |F = 1, m_F = 0\rangle$ and $|1\rangle \equiv |F = 2, m_F = 0\rangle$. The trapped single atom is optically pumped into the state $|1\rangle$. Single-qubit manipulations between the states $|0\rangle$ and $|1\rangle$ are performed by two-photon simulated Raman transitions. Raman lasers are red-detuned by about 60 GHz from the D1 transition and separated by 6.8 GHz. Raman lasers are superimposed on the dipole trap light prior to transporting into the photonic chip by the same optical fiber. The propagation characteristics of the coherent manipulation lights in the photonic chip are nearly the same as that of the dipole trap light. The coherent manipulation light, focused by microlens nearly at the waist of the dipole trap, will only interact with the corresponding trapped single atom, and will not illuminate the neighbouring atoms. By this way single qubit operation between two hyperfine ground states can be realized.

4.4. Two-photon processes for Rydberg excitation

In our case, the separation between neighboring atoms is $10\ \mu\text{m}$. Thus single atom must be excited to high-lying Rydberg levels with principle quantum number $n > 80$ to get a strong two-atom blockade effect [8]. Two-photon Rydberg excitation scheme in our chip illustrated in Fig. 7, is similar to the schemes in [8] and [9]. The relevant levels are shown in Fig. 7(a). We choose the intermediate state $|5P_{3/2}, F = 2\rangle$ and the Rydberg state $|80D_{5/2}, m_j = 5/2\rangle$. The 80d Rydberg levels provide $B/2\pi > 3\ \text{MHz}$ of blockade shift for the separation $10\ \mu\text{m}$, which is sufficient for a strong two-atom blockade effect [8]. First two atoms are prepared in the ground state $|5S_{1/2}, F = 2\rangle$. Then the atoms are excited to the Rydberg state by a two-photon transition with a π -polarized laser at 780 nm and a σ^+ -polarized laser at 480 nm, as represented in Fig. 7 (a). The 780 nm beam is tuned about 1 GHz to the red of the $|5S_{1/2}, F = 2\rangle \rightarrow |5P_{3/2}, F = 2\rangle$ transition. Each 780 nm beam transports through the chip and illuminates the single atom, as shown in Fig. 7(b). One 480 nm beam with waist of about $5\ \mu\text{m}$ illuminates the single atoms along x next to the chip. During the excitation, the dipole traps should be turned off.

The Rabi frequency of the two-photon transition from the ground state to the Rydberg state is $\Omega = C_\Delta \Omega_{780} \Omega_{480} / 2\Delta$, where Ω_{780} is Rabi frequency of the 780 nm laser, Ω_{480} is Rabi frequency of the 480 nm laser, Δ is the laser detuning from the intermediate state, $C_\Delta = (\Delta - \Delta_{23}/2)/(\Delta - \Delta_{23})$ with $\Delta_{23}/2\pi = -267\ \text{MHz}$ being the hyperfine splitting of the $|5P_{3/2}, F = 2, 3\rangle$ levels. For typically experimental parameters of $\Delta/2\pi = -1\ \text{GHz}$, laser beam powers of $P_{780} = 0.5\ \mu\text{W}$, $P_{480} = 20\ \text{mW}$ and waists $w_{780} = 1.5\ \mu\text{m}$, $w_{480} = 8\ \mu\text{m}$, the Rabi frequency of the two-photon transition $\Omega/2\pi = 5.3\ \text{MHz}$.

Rydberg atom with a large polarizability will strongly interact with nearby walls [34–37] and electric fields [38]. The strong interaction will shift the Rydberg energy levels and reduce the lifetime of the Rydberg state. Spreeuw's group [34] studied the surface effects due to adatoms accumulated on the surface during experiments, they suggested to prevent the effects by using a magnetic field gradient to push the atoms away from the surface, or to use different coating material on the surface, or to increase the desorption rate of adatoms. Pfau's group [36] studied the coherent excitation of Rydberg atoms with $n = 30 - 50$ in a thermal vapor microcell. They found that microcells with a size on the order of the blockade radius (about $2\ \mu\text{m}$) are robust.

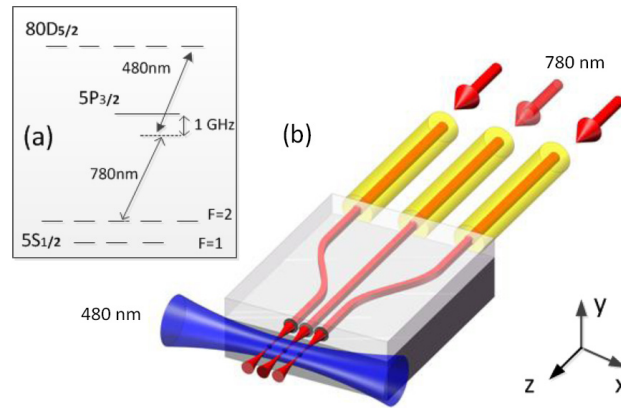


Fig. 7. Two-photon Rydberg excitation scheme to be used in the chip. (a) The relevant levels and laser excitation frequencies. (b) The arrangement of the excitation lasers for two-photon processes.

A very recent work [37] reported a way to cancel the electric field on quartz surface by Rb adsorbate-induced negative electron affinity. Actually our device works in very dilute atomic cloud and high vacuum condition. Few Rb atoms absorbed on surface can be expelled by using light induce atom desorption method [39].

4.5. Individually addressing

For each trapped atom, there is one and only one independent “channel” comprised of optical fiber, waveguide and microlens to transport dipole trap light, fluorescence light and coherent manipulation light. In contrast to previous experiments which used either a microelectromechanical beam steering system [13], magnetic field gradient [40], auxiliary Stark shifting optical beams in conjunction with microwave fields [12] or Rydberg excitation laser [14], individual addressing in our photonic chip is realized by switching independently the coherent manipulation light by electro-optical modulators in the light path. The switch time can be as short as a few ns, determined by the electro-optical modulators.

5. Conclusion

In conclusion, we designed and fabricated a tailored-waveguide based photonic chip, and measured the optical characteristics of this chip. The results confirmed that the chip can be used to trap, coherently manipulate, detect and individually address array of single neutral atoms. This photonic chip will find important applications in hybrid quantum system and photonic quantum devices in the future.

Acknowledgments

We acknowledge fruitful discussions with Yi Wang, Wei He, Peng Xu and Xiaodong He. We thank Yan Li, Yongmei Zhao, An Ji (Engineering research center for semiconductor integrated technology, Institute of semiconductors, CAS), and Yewu Guo (Micro-nano manufacturing technology Tianjin Co., Ltd.) for fabrication of the photonic chip. This work was supported by the National Basic Research Program of China under Grant No. 2012CB922101 and the National Natural Science Foundation of China under Grant No. 11004223.