

An ion trap apparatus with high optical access in multiple directions

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ABSTRACT

Optical controls provided by lasers are the most important and essential techniques in trapped ion and cold atom systems. It is crucial to increase the optical accessibility of the setup to enhance these optical capabilities. Here, we present the design and construction of a new segmented-blade ion trap integrated with a compact glass vacuum cell, in place of the conventional bulky metal vacuum chamber. The distance between the ion and four outside surfaces of the glass cell is 15 mm, which enables us to install four high-numerical-aperture (NA) lenses (with two $NA \leq 0.32$ lenses and two $NA \leq 0.66$ lenses) in two orthogonal transverse directions, while leaving enough space for laser beams in the oblique and longitudinal directions. The high optical accessibility in multiple directions allows the application of small laser spots for addressable Raman operations, programmable optical tweezer arrays, and efficient fluorescence collection simultaneously. We have successfully loaded and cooled a string of $^{174}\text{Yb}^+$ and $^{171}\text{Yb}^+$ ions in the trap, which verifies the trapping stability. This compact high-optical-access trap setup not only can be used as an extendable module for quantum information processing but also facilitates experimental studies on quantum chemistry in a cold hybrid ion-atom system.

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I. INTRODUCTION AND MOTIVATION

In the past few decades, thanks to the development of various optical tools in modern atomic, molecular, and optical (AMO) research, human capability has been greatly elevated to precisely control light, matter, and their interactions at the quantum level. In cold atom systems, magneto-optical trap (MOT),^{1,2} optical lattice,^{3–5} and optical tweezers are widely used to explore various quantum phenomena,^{6–12} as the quantum nature of the systems can be visibly manifested at ultra-low temperatures. In trapped ion systems, optical controls including laser cooling,^{13–17} atomic level manipulation,^{15,18} motional state manipulation,^{14,19} and quantum logic operations^{20,21} are essential tools in the quantum information processing (QIP).¹⁸ The current trapped ion and cold atom apparatus is able to implement a basic part of the optical tool kit. However, with the development of the AMO and QIP experiments, it becomes more and more necessary to combine multiple optical tools in one system. For example, a trapped ion equipped with optical tools from the cold atom system can be used as a cold hybrid ion-atom system, which has recently emerged as a promising platform for

fundamental research in quantum physics at the ultra-low temperatures,^{22–24} such as cold ion-neutral collisions,^{23,25–28} optically trapping ions in dipole traps and optical lattice,^{5,29–32} and sympathetic cooling of molecules and ions.^{33,34}

One of the most powerful and urgently needed tools compatible with trapped ions is the programmable optical tweezer, which has been widely utilized in cold neutral atoms^{6–10,12} and molecules^{11,35} for decades. Optical tweezers are tightly focused off-resonant dipole traps with beam waist down to about a few micrometers. Programmable optical tweezer arrays can be applied, for example, by a high numerical aperture (NA) objective and an acousto-optic deflector (AOD) to address individual atoms or ions. Employing optical tweezers in an ion trap has several major significances. First, it allows us to optically trap ions in the absence of radio-frequency (RF) field,^{4,5,32} which helps us to get rid of the heating due to RF micromotion.^{31,36} Second, it allows us to trap single neutral atoms optically and spatially overlap them with electrically trapped single ions, which will eventually pave the way toward coherent chemistry with full quantum control at ultra-low temperature. Third, the

programmable optical tweezer arrays can be used as the “optical segmentation,”³⁷ which allows us to engineer localized phonon modes of individual ions pinned by optical tweezers in a long ion chain.^{37,38} The frequencies of the motional ground modes of the ions in optical tweezers are lifted from the background. Multi-qubit entangling gates can be performed on these pinned ions in the optical tweezers, which is a promising route to address the challenge of scale and parallel quantum computations with long one-dimensional ion strings^{37,39} or two-dimensional ion crystals.⁴⁰ However, an optical tweezer in the ion trap requires an additional high NA objective to the already complex optical configurations of the trapped ion system. For most ion traps, it is difficult or not feasible to have enough optical access for high focused laser beams for addressable Raman operations (Raman beams),⁶⁰ programmable optical tweezer arrays, and efficient fluorescence collection simultaneously. A metal vacuum chamber with optical viewports is usually used as the vessel of ion traps because of its compatibility with the ultra-high vacuum (UHV) and its on-demand customization.^{41–45} Nevertheless, the bulky metal vacuum chamber can only provide high NA on one or two sides of the system, meanwhile greatly limiting the NA on other sides, even for the customized compact vacuum chamber⁴⁶ or the chamber with re-entrant windows.⁴⁷ Another method is to integrate high NA mirror systems in the vacuum,^{48–52} which is difficult to be applied in multiple directions. Therefore, a new ion trap with high optical access in multiple directions is needed to address these challenges.

The development of cold neutral atom technologies has proven that a glass vacuum cell can support complex AMO experiments.^{53,54} It is a well-established technique to prepare cold atom ensembles in an MOT or an optical lattice and prepare cold atom arrays by optical tweezers in a glass vacuum cell.^{2,9} Therefore, integrating an ion trap with a compact glass vacuum cell is a promising route to build an advanced hybrid ion-atom system with high optical access in multiple directions. We note that several ion traps have been placed inside glass vacuum envelopes already and have proved the feasibility of using the glass cell in ion traps.^{55–57} For example, in Ref. 57, the micro-structured trap in a glass cap has a NA of 0.4 for imaging. In Ref. 56, the X-junction ion trap inside a glass envelope has a NA of about 0.45 on one side and a smaller NA on other sides. Nevertheless, due to the restrictions from the ion trap structure or the surrounding metal envelope, these traps only have a high NA on a single side, instead of multiple directions.

In this article, we present the design and construction of a segmented-blade ion trap fit inside a compact cubic glass vacuum cell. With a distance of 15 mm from trap center to four outside surfaces of the glass cell, it enables us to use simultaneously two NA = 0.32 lenses and two NA = 0.66 lenses in two orthogonal transverse directions around the cell. At the same time, there is enough remaining angle range for laser beams in the oblique and longitudinal directions. This ion trap provides adequate optical access, allowing high focused Raman beams, programmable optical tweezer arrays, and efficient fluorescence collection to be applied simultaneously. We have successfully loaded and cooled a string of $^{174}\text{Yb}^+$ and $^{171}\text{Yb}^+$ ions in the trap, verifying the trapping stability. This compact high-optical-access trap setup not only can be used as a suitable platform for implementing scalable and parallel tweezer gates for quantum computing with long ion strings^{37,39,40} but also

facilitates experimental studies on quantum chemistry in a cold hybrid ion-atom system.

The designs and constructions of the blade trap, as well as the technical challenges, are described in detail in the following part.

II. DESIGN AND FABRICATION

A. System design

We first introduce the design of the trap architecture. The trap size needs to be minimized to fit in the glass cell. A compact segmented blade trap is used because of many advantages.^{58–61} It is easy to be constructed and is capable of trapping a string of ions. With multiple control electrodes, the micro-motion of the ions can also be well compensated.⁶² A blade trap also provides good optical access in multiple directions. The angles between adjacent blades can be optimized according to the customer's demand. For our purpose, we set the angles to allow a NA of 0.66 on two sides of the cell and a NA of 0.32 on the other two sides respectively. Here, we set the trap axis to be along the z-axis in the horizontal xz plane. The 0.66 NA of the trap can be arranged either in the vertical direction (y-axis) or the horizontal direction (x-axis), depending on different purposes. This can be done by simply rotating the setup by 90°, with little changes of the mounting method. The cubic glass cell used in this work has fully transparent and flat surfaces. It has an inner size of $22 \times 22 \times 92 \text{ mm}^3$ and a wall thickness of 4 mm. The distance between its center and four outside surfaces is only 15 mm, which is well within the working distance of the high NA objectives.⁶³ The supportive structures need to be optimized to provide the necessary ultra-high vacuum environment, electrical connections, and atom sources.

An overall design is shown in Fig. 1. The bottoms of four segmented blades are attached to the ceramic holder via a silicon mounting wafer. The blade trap is then placed at the center of a cubic glass vacuum cell. Several stainless capillary tubes are glued on the ceramic holder with a piece of ytterbium ablation target clamped on the tube end. Ablation laser pulses are first applied to one of the Yb targets to generate Yb atoms.^{64,65} The sputtered neutral atoms are photo-ionized in the trap center by a two-photon process.⁶⁶ Flexible printed circuit (FPC) boards attached to the ceramic holder are

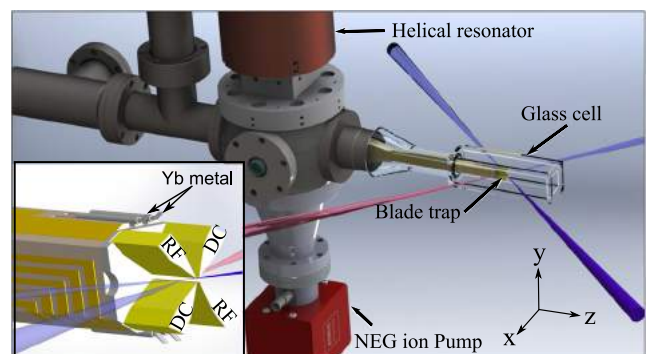


FIG. 1. Overview of the trap. A segmented blade trap is placed at the center of a cubic glass cell. The ceramic holder and the glass cell are fixed on a stainless steel vacuum chamber. The helical resonator, vacuum pumps, vacuum valves, and feedthroughs for both DC and RF electrodes are also attached. The inset shows the detail of the trap. Several ytterbium metal pieces with natural isotopic abundance are used as laser ablation targets.

used as the filter board. The gold-plated blades are wire bonded to the FPC board. A non-evaporable getter (NEG) ion pump is used to maintain the ultra-high vacuum. A helical resonator is mounted on top of the chamber to supply high RF voltages.

Possible experiments provided by our high-optical-access trap are illustrated schematically in Fig. 2. As shown in Fig. 2(a), two $NA = 0.66$ sides can be used for both optical tweezers and efficient fluorescence collection above and below the trap, while two $NA = 0.32$ sides can be used for counter-propagating Raman beams on left and right sides of the trap. Laser beams can also illuminate the trap obliquely. This optical configuration perfectly satisfies the strict requirements of the scalable and parallel optical tweezers gates proposed in Refs. 37–39, where the motional spectrum of ions in a long chain can be altered by optical tweezers to implement multi-qubit entangling operations. Another example is that our new trap also provides adequate optical access for many advanced cold atom experiments. As shown in Fig. 2(b), cold atoms can be loaded in a dipole trap from a MOT near the ion trap and then moved to the ion trap center. On two horizontal sides of the trap, lasers for addressable Raman operations and optical tweezers can be used to control the coherent interactions between single cold atoms and single trapped ions. In this work, the $NA = 0.66$ side of our trap is arranged in the horizontal direction (x -axis).

B. Fabrication process

In the following, we will illustrate the fabrication process of our trap.

1. The blades and electrodes

The core part of the trap consists of four gold-plated blades, as shown in Fig. 3. The blade is a pentagonal prism with a 30° knife

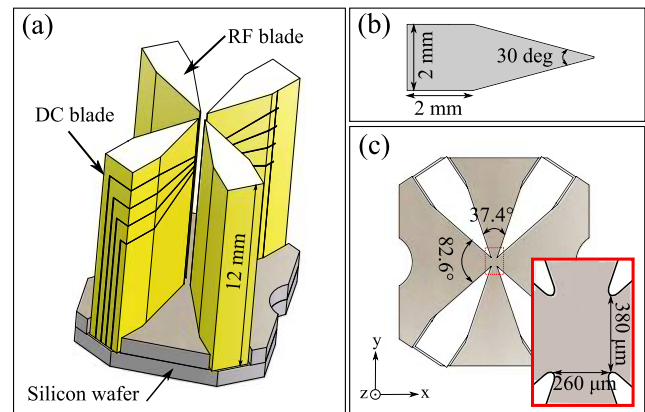


FIG. 3. Design of the segmented blade trap. (a) Blade sets and mounting scheme. Four blades are SiO_2 pentagonal prisms with an $8\text{-}\mu\text{m}$ -thick golden layer coated on their side surfaces. The DC blades and RF blades are the same, except that DC blades are segmented into five electrodes by laser cutting. The blades are mounted on a double-layer silicon mounting wafer, which consists of a top layer with four grooves and a bottom layer with a smooth surface. The trap center is 9 mm away from the blade bottom and 3 mm from the blade top. (b) Cross section of the blade. (c) Silicon mounting wafer. Four positioning grooves define the positions and angles of blades.

angle. The substrate of the blades is fused silica, which is easy to be machined to the optical surface of nano-metric roughness. However, it is difficult to polish the sharp blade edge without creating any defect mechanically. These defects of size ranging from a few micrometers to dozens of micrometers will cause irregularities or high-order components of the trap potential, which will affect the

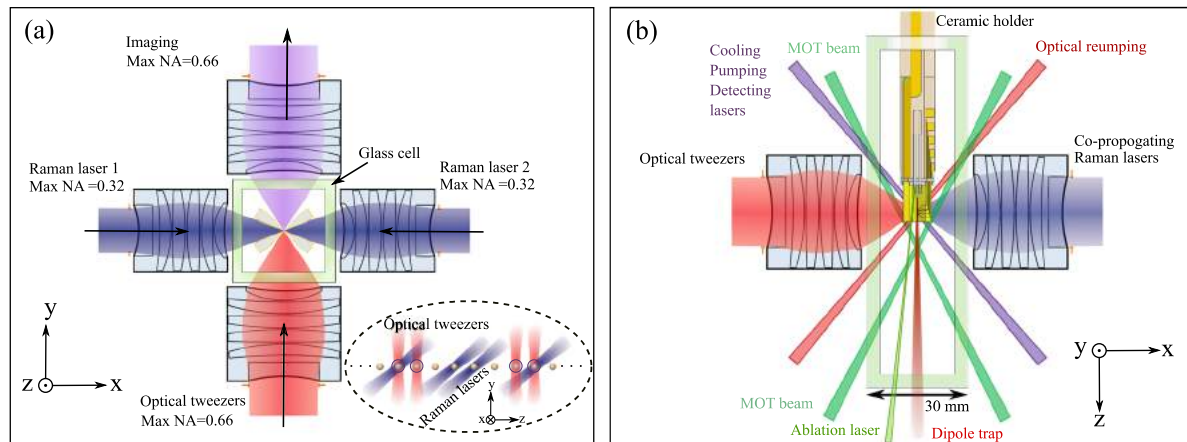


FIG. 2. Optical configurations enabled by the high-optical-access ion trap. (a) The multi-directional high optical accessibility of the trap allows the application of tightly focused counter-propagating Raman beams ($2 \times NA0.32$), programmable optical tweezer arrays ($1 \times NA0.66$), and efficient fluorescence collection ($1 \times NA0.66$) simultaneously. This configuration satisfies the requirement of the scalable and parallel optical tweezers gates proposed in Refs. 37–39. In the inset (dashed circle), the ions pinned by optical tweezers (red) are marked in the black circles. The motional frequencies of the pinned ions can be lifted. Lasers for Raman operations (blue) are used to perform multi-qubit entangling gates. (b) This trap is also suitable for research on the hybrid system. Multiple laser beams can incident obliquely around the cell, such as the cooling, detecting, pumping lasers. A 3D MOT of cold atoms can be generated near the blades (the MOT laser in y direction is not shown). A dipole trap in the direction of $(x, y, z) = (0, -1, -1)$ can be used to trap the cold neutral atoms and transport them to the trap center by changing its focus. When the cold atom is in the ion trap center, single atoms can be loaded in the optical tweezers. The co-propagating Raman beams can be used to control the interaction of the cold atoms and trapped ions. Two lenses with a NA of 0.32 (not shown) can be used on the other two sides of the glass cell for both imaging and global Raman beams. The trap holder and the laser ablation scheme are also shown. It is worth noting that the directions of the 0.66 NA in (a) and (b) are different.

performance of the trap.^{67–69} These defects will also cause undesirable scattering of the UV light from the trap electrodes, which affects the fluorescence detection. Therefore, we applied a CO₂ laser machining to polishing the blade edges. The SiO₂ glass can be well processed to form a smooth surface by the thermal reflow effect of the CO₂ laser, which has been successfully used in the fabrication of the whispering gallery mode cavities with ultra-high quality factors.⁷⁰ Figure 4(a) depicts the schematic sketch of the laser machining setup. Figures 4(b)–4(g) show the treatment of the blade edge using a CO₂ laser, after which the blade edge becomes a uniformly smooth convex surface.

Before gold plating, all blades should be cleaned thoroughly to remove contamination. First, a group of blades mounted on a Teflon holder is immersed in acetone, isopropanol, deionized water, 20% hydrofluoric acid, and deionized water step by step to remove the fused silica particles. Then, they are immersed in a Piranha solution at 90 °C for 60 min to remove the organic contamination. Afterward, they are cleaned in an ultrasonic bath with deionized water, acetone, isopropanol, and deionized water. Finally, we dry the blade surface using nitrogen gas. After cleaning, these blades are shifted to individual holders for gold coating. A 20-nm-thick titanium adhesion layer and a 100-nm-thick gold seed layer are sputtered on five side surfaces using magnetron sputtering. The top and bottom surfaces are used for transferring and fixation of the blade during the fabrication.

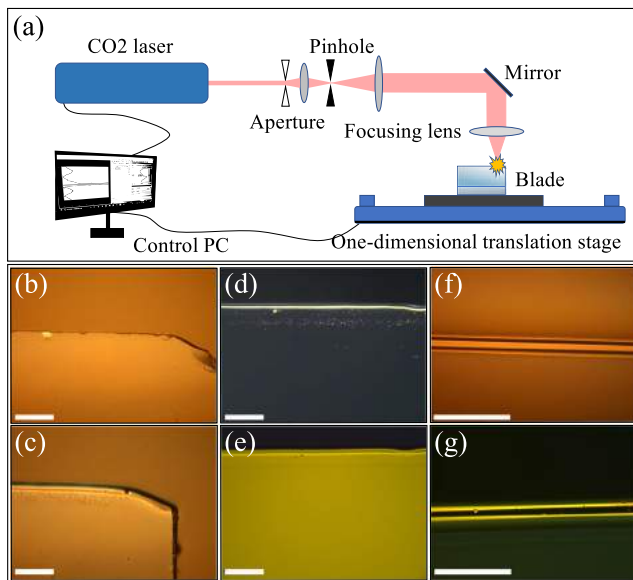


FIG. 4. Polishing the SiO₂ blade edge by CO₂ laser machining. (a) Optical scheme for laser machining. The blade is mounted on a one-dimensional electrical translation stage. A CO₂ laser beam is focused on the blade edge with a beam waist of 100 μm. [(b) and (c)] Blades before and after laser machining, respectively. The original blade has a defective knife edge, which is fused to a smooth one after the thermal reflow process. (d) Blade observed under a microscope in a dark field mode. Small SiO₂ particles of the size of 1–5 μm generated by laser machining can be observed near the blade edge. A 20% hydrofluoric acid solution can effectively remove these particles. A smaller CO₂ laser power could also be helpful to get rid of these particles. (e) Side surface of a blade after electroplating. [(f) and (g)] Front view of the blade edge before and after electroplating. The edge has a smooth surface with few defects. All scale bars in sub-figures are 100 μm.

Therefore, there is no gold on them. Then, we use electroplating to increase the thickness of the gold layer to 8 μm. The photographs of the blade surface and edge before and after gold plating are shown in Figs. 4(d)–4(g).

Once the blades are gold plated, the gold surface of the DC blade is segmented into five electrodes by laser cutting. The laser cutting system uses a 355 nm laser with a positioning precision of ±1 μm and a minimum cutting width of 15 μm. The cutting depth is deep enough to prevent any potential short circuits. The cutting process is performed on five side surfaces. It is important to ensure that the cut patterns on adjacent surfaces are well connected with the misalignment less than the cut width. Figure 5 shows a photograph of a DC blade after laser cutting. The trap center is 9 mm from the blade bottom and 3 mm from the blade top. On the blade edge, three inner segments are 250 μm wide and are separated by 25-μm-wide gaps. Two outermost segments act as the static voltage end-cap electrodes. Those segments cross the blade surfaces and become

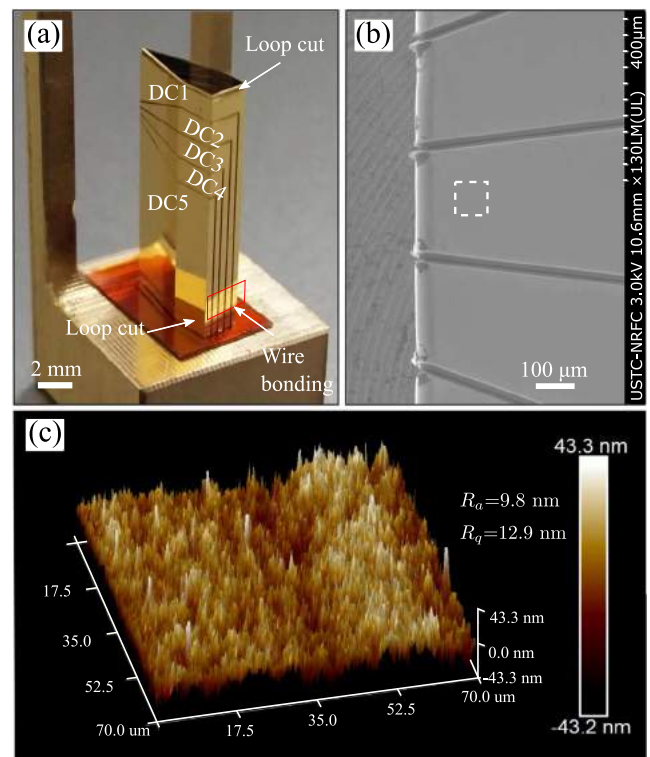


FIG. 5. (a) Photograph of a DC blade after laser cutting. All side surfaces are laser structured into five electrodes. Electrodes DC2, DC3, and DC4 are 250 μm wide on the blade edge. The gap between the electrodes is 25 μm wide. The center point of DC3 on the blade edge is 9 mm from the blade bottom and 3 mm from the blade top. A pair of closed-loop cuts is placed near the top and bottom to avoid potential short caused by the redundant gold. The tracks on the blade back in the red frame will be wire bonded to the filter board. (b) A close-up view of the DC electrodes. The laser cutting process leaves some silica dross on the blade edge. (c) Surface roughness of the blade electrode measured by an atomic force microscope (AFM). In an area of 70 × 70 μm², the arithmetic mean deviation of the contour (R_a) is 9.8 nm, while the root mean square of the surface roughness (R_q) is 12.6 nm. The corresponding measured area is marked in (b).

parallel on the back surface of the blade, where connections between the electrodes and the filter board are placed via wire bonding.

2. The mounting wafer

A double-layer silicon mounting wafer is used as the alignment holder to fix the positions of the blades, as shown in Fig. 3(c). The wafer is a 500- μm -thick mono-crystalline silicon wafer, which has a volume resistivity of $\sim 10^4 \Omega \text{ cm}$. The wafer is double-side polished and has a 300 nm oxidation film. A wafer is cut through with an array of the mounting patterns. Each mounting pattern has four slots of the same shape as the bottom of the blades. This wafer is stacked on another mono-crystalline silicon wafer with a good surface. Then, they are bonded tightly using the hydroxide catalysis bond, which is reliably used in the fabrication of the detectors of the gravitational wave.⁷¹ For silicon, the hydroxide catalysis bond will not break at a temperature as high as 300 °C, which is well above the baking temperature of 220 °C. Due to the difference in the thermal expansivity, however, the bonds between different materials will break at such a high baking temperature. Once the two wafers are bonded, they are laser cut to some small octagonal wafers, as shown in Fig. 3(c). Four positioning grooves on the mounting wafer define the positions of four blades, with a rectangle zone of $260 \times 380 \mu\text{m}^2$ surrounded by blade edges and two pairs of optical access angles of 82.6° and 37.4° between four blades.

3. The glass vacuum cell

Our UHV compatible glass cell is made of six 4-mm-thick optical-surface-quality glass plates (Pyrex, Corning) by the optical bonding process (Akatsuki Tech). Outside surfaces of the glass cell have anti-reflective coatings optimized for the wavelength range of 355–500 nm. The measured transmittance of a single plate is 95% at 369 nm and 93% at 532 nm. The glass vacuum cell is a $30 \times 30 \times 100 \text{ mm}^3$ cubic cell with an internal size of $22 \times 22 \times 92 \text{ mm}^3$. The cubic cell is followed by a glass connecting tube and a glass-to-metal seal to a metal 4.5 in. ConFlat (CF) flange on the end, as shown in Fig. 1. The connecting tube has a 45-mm-long bottleneck with a diameter of 17 mm. The glass cell is bakeable to a temperature as high as 250 °C.

4. The ceramic holder and filter board

A 25-cm-long ceramic (99% Al_2O_3) holder is used to place the blade trap at the center of the glass cell. As shown in Fig. 6(a), the long neck of the holder has four squared grooves to increase the gas conductance at the bottleneck of the connecting glass tube. Threaded holes on the base part of the holder are used to mount the holder tightly on the stainless steel chamber using metal grabbers. The details of the bottom are shown in Fig. 6(b). Filter boards and RF wires are glued on the holder surfaces and clamped by a pair of ceramic clamping plates, as shown in Fig. 6(c). The clamping plates are screwed onto the holder body. Strand wires are put inside the holes in the clamping plates and then clamped on the filter board using screws. Figure 6(d) shows the head of the holder. The blade set is fixed on the top. The holder head has the same shape as the octagonal silicon mounting wafer such that the back surfaces of the blades are in parallel with the holder surfaces, which is beneficial to the wire bonding process. On the holder's head, there are two 0.8-mm-wide and 10-mm-long grooves on opposite surfaces. Several metal tubes of a diameter of 0.8 mm are used to clamp a piece of

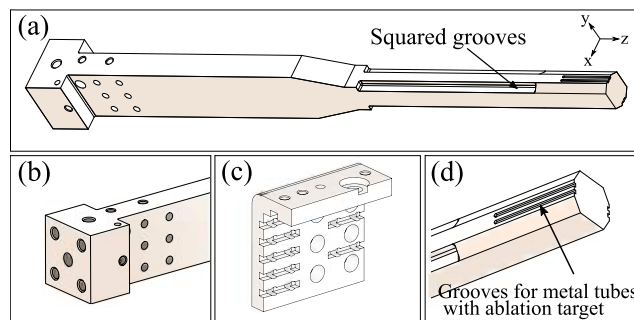


FIG. 6. (a) Ceramic holder. Four 75-mm-long squared grooves with a cross section of $3.5 \times 2.0 \text{ mm}^2$ are placed on the neck of the ceramic holder in order to increase the gas conductance. (b) Threaded holes on the base part for mounting the holder on a stainless steel chamber. (c) Ceramic clamping plates. Wires connecting the filter board and the feedthrough are clamped in the holes between the ceramic clamping plate and the ceramic holder. (d) Head of the holder. A pair of grooves for mounting the hollow metal tubes is shown. The ytterbium ablation target is clamped on one end of the hollow tube. There are four grooves in total.

ytterbium ablation target. This design gets rid of using conventional electrically heating ovens.

We use a flexible printed circuit (FPC) as the filter board, which bridges the electronic connections from the blades to the vacuum feedthroughs, as shown in Fig. 7. FPC is used due to its convenience, flexible configuration, and low cost. The FPC is made of a 35- μm -thick ground copper layer, a 25- μm -thick polyimide film, and a 35- μm -thick routing copper layer. All copper layers have a 100-nm-thick gold coating in order to prevent the oxidation of the tracks. No adhesive is used in the fabrication of the FPC. More than 95% of the polyimide surface is covered by metal, which helps us to reduce the total out-gassing rate. The RF track is made of a 3-mm-wide and 200- μm -thick silver belt, which is coated with a 100 nm gold layer in order to improve the wire bonding performance. The RF tracks and the FPC filter boards are glued on different sides of the ceramic holder. The ceramic substrate has a volume resistivity of $\sim 10^{14} \Omega \text{ cm}$ and a loss tangent of $\sim 10^{-4}$, which has a negligible effect on the RF dissipation. However, as the silver RF tracks are near 20 cm long and 3 mm wide, the stray capacitance between one RF track and the DC filter boards is estimated to be 16 pF. This result is confirmed by an LCR meter and a vector network analyzer. The total capacitance between RF and ground is 27 pF, where 2 pF is from the blades and 9 pF is from the wires and the feedthrough. The RF track and wires can be replaced by a single strand wire with a diameter of 1 mm, which can help us to decrease the total capacitance by at least 10 pF.

C. Assembling

In the following, we will illustrate the assembling procedure of the trap.

Before assembling, all vacuum components have been cleaned thoroughly in an ultrasonic bath with acetone. The stainless steel vacuum chamber, the ionization vacuum gauge, the vacuum feedthrough, grabbers, and all metal tubes are assembled and connected to a turbopump for pre-baking. They have been baked at a temperature of 250 °C for a week. In the assembling, we use an UHV

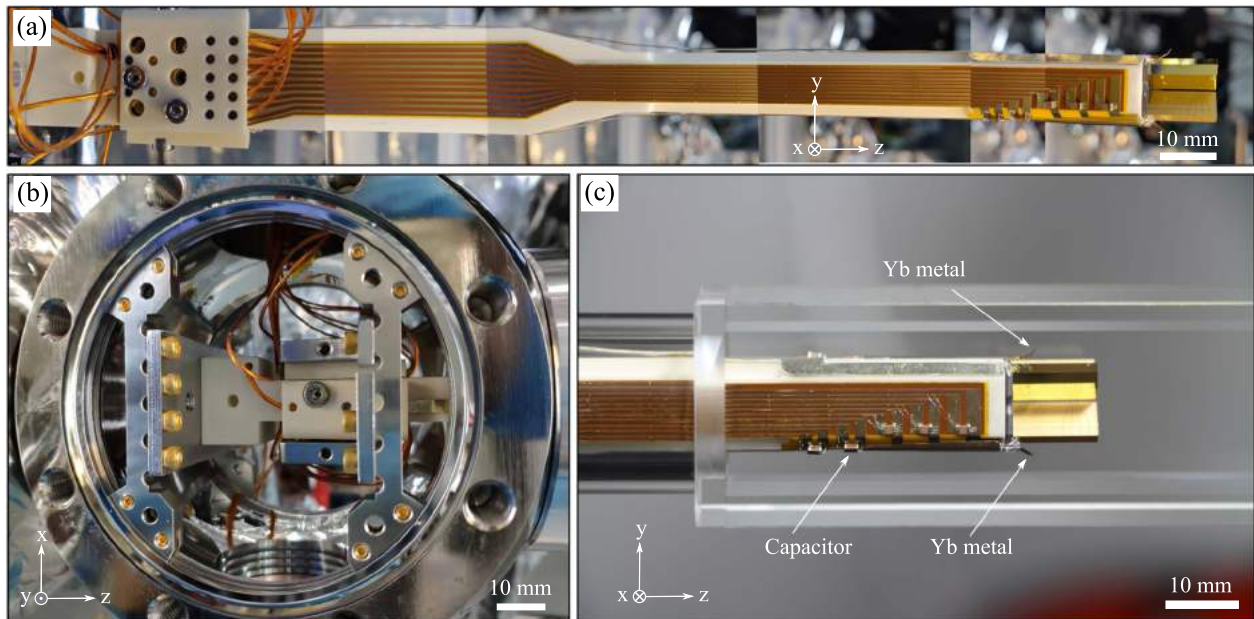


FIG. 7. (a) Ceramic holder with blades and wires attached. This is the combination of several photos. The blade set on the silicon mounting wafer is attached to the top of the holder. A pair of flexible printed circuit (FPC) boards with bypassing ceramic capacitors is used as the filter board, which is glued on the holder. The FPC board consists of a ground copper layer, polyimide layer, and a routing copper layer. The DC electrodes are connected to the filter board via wire-bond connections. A pair of ceramic clamping plates is used to clamp strand wires, which connect the filter board and the feedthrough. (b) Ceramic holder in the vacuum chamber. In order to minimize the vibration of the trap as the ceramic holder is 25 cm long, the bottom, left and right sides of the holder are tightly mounted on the 4.5 in. spherical square vacuum chamber using grabbers. (c) Blade trap at the center of a glass cell. The 0.66 NA of this trap is arranged in the horizontal direction (x-axis). Yb metal slices are clamped on the end of four stainless capillary tubes with the faces of the snippets toward the trap center. The capillary tubes are glued on the grooves of the ceramic holder.

compatible glue (05106C-AB from SPI) for adhesion between different materials. The trap shown in Fig. 7 is prepared in the following procedures:

1. The silicon mounting wafer is placed in front of a pair of vertical and horizontal microscopes. A small amount of UHV glue is put in the grooves. When the blade is put on the grooves one by one, they are aligned roughly. The alignment can be optimized under microscopes precisely in 10 min before the glue hardens. Afterward, they are put in a vacuum tube with a pressure of 1×10^{-4} Torr and then baked at 220°C for 2 h. The vacuum helps us to accelerate the release of tiny bubbles in the glue. The relative displacement of the blades after baking is negligible.
2. Ten 870 pF filter capacitors are glued on a pair of FPC filter boards using the UHV glue, with the termination of the capacitors overlapped with DC and ground tracks. The FPC boards are then baked on a heating stage in the atmosphere at 200°C for 1 h. The RF tracks and the FPC filter boards are glued on the ceramic holder and baked in a vacuum afterward.
3. The ytterbium material (natural isotope abundance) is cut into small snippets, which are clamped on the ends of the stainless tubes with a diameter of 0.8 mm. Four tubes are glued on the grooves of the ceramic holder. The silicon mounting wafer with the blade set is glued on the top. The surface of the ytterbium snippet is facing the trap center. During the baking in

vacuum, the holder is always kept vertical. Otherwise, the silicon wafer will slip away. In our trap, the whole silicon wafer displaces about 0.8 mm from the center.

4. The capacitors are wire bonded on the FPC boards using $25\ \mu\text{m}$ aluminum wires. At least three aluminum wires are placed on each termination of the capacitor. All blades are wire bonded to the filter boards, with at least 5 wires on each DC electrode and 15 wires on each RF electrode.
5. The ceramic clamping plates are screwed on the ceramic holder. Strand wires from the Polyether ether ketone (PEEK) sockets are clamped in the holes between the clamping plates and the ceramic holder, as shown in Fig. 7(a).
6. The vacuum chamber after pre-baking is disassembled. The ceramic holder is placed through a 2.75 in. CF flange and is mounted tightly on the chamber, as shown in Fig. 7(b). Then, the glass vacuum cell is carefully aligned and mounted onto the 2.75 in. CF flange of the vacuum chamber using a guide rail. Now, the blade trap is at the center of the glass cell, as shown in Fig. 7(c).
7. The PEEK connector is connected to the feedthrough, and the vacuum chamber is connected to pumps.

D. Vacuum

One concern of our trap is the pumping speed limited by the 45-mm-long bottleneck of the connecting glass tube. The internal diameter is 17 mm, which is further blocked by the ceramic holder.

Although the neck of the ceramic holder is optimized to increase the gas conductance, the maximal effective pumping speed at the connecting tube is only about 5 l/s. The polyimide film on the FPC, which is one of the main out-gassing resources, is covered by metal layers on both sides. The UHV compatible glue used in many places is baked inside the vacuum. These methods help us to decrease the final overall out-gassing rate. Furthermore, inside the vacuum, we use vented stainless steel screws with drilled holes that prevent gas pockets from forming beneath the screws. Otherwise, the small gas conductance from the pockets will lead to pumping time as long as several months.

We complete the vacuum chamber with a metal valve and a 200 l/s non-evaporable getter (NEG) pump with a diode ion pump featuring 6 l/s (Ar) connected (NEX Torr D200-5). The system is connected to a 100 l/s turbopump and a mechanical pump. The system is then baked at 220 °C for 20 days. After cooling down to room temperature, the ultimate vacuum is 1.0×10^{-10} Torr at the gauge and the current of the ion getter pump is 2 nA. When turning off the gauge, the current of the ion getter pump decreases rapidly from 2 to 0 nA. From this, we infer that the final pressure in the chamber is below 5.0×10^{-11} Torr that is in the UHV range. The gauge is kept off henceforth.

E. Shielding

The distance between the trap and the inside (outside) surfaces of the glass cell is 11 mm (15 mm), which is comparable to other traps with high NA.^{49,72,73} Nevertheless, the stray electric field noise still needs serious consideration. The glass cell is a dielectric substance. The charges caused by the photoelectric effect from borosilicate glass may accumulate on the glass cell and will be neutralized very slowly⁷⁴ because of its poor surface and volume conductivity.^{75,76} This stray field will affect the trapping stability.⁷⁷ The DC electric field induced by the 453 nm laser was studied using Rydberg atoms in Ref. 78, where an electric field around 500 V/m can be detected in the cell by illuminating a 453 nm laser of several mW/mm² on the walls. Fortunately, the blades surrounding the trap center perform as a shield of the stray electrical field. We estimate the shielding performance in COMSOL Multiphysics. A charge density of $100 \text{ e}/\mu\text{m}^2$ is applied to a $30 \times 60 \text{ mm}^2$ glass plate 15 mm away from the trap.⁷⁹ The electric field at the trap is calculated. The maximal component E_x at the trap center is $2.83 \times 10^4 \text{ V/m}$ in the absence of the blades. Nevertheless, E_x decreases to about 10 V/m if the blades are grounded, which corresponds to a reduction by more than three orders of magnitude. The remaining stray field can be well compensated by applying suitable voltages on the DC electrodes. To shield possible electric fields from charges accumulated on four objectives, we make a metal mesh on the outside surface of the glass cell using aluminum wires with a diameter of $25 \mu\text{m}$.⁸⁰ The mesh is fixed on the cell tightly using copper foil tape. The 9-cm-long glass connecting tube after the glass cell is also covered by the copper foil tape. The mesh and the copper cover are then grounded to the stainless steel chamber. The remaining stray field at the trap center will be studied in future works. To further shield the stray field, it is better to have a grounded copper mesh inside the glass cell. An ITO coating on the inner surface might be helpful if the transmission of the ITO coating can be optimized for all lasers.

Another noise that may degrade the performance and stability of the trap is the mechanical vibration. This is an important concern for our trap because the blade set is attached to the top of a long ceramic holder. In the presence of mechanical vibrations, the counter-propagating Raman beams pointing to the ions will experience an unwanted relative phase shift,^{61,81} which will lead to instability of the interaction between the highly focused laser beams and the trapped ions. Therefore, the bottom and two sides of the ceramic holder are tightly mounted on three metal mounting plates, which are then connected with four metal grabbers on the stainless steel chamber, as shown in Fig. 7(b). This forms a stable and tight support for the holder. As a comparison, the ion trap in Ref. 56 is mounted on a hollow RF resonator with a length of more than 40 cm and an inner diameter of 3 cm. No obvious mechanical vibrations have been reported. As shown in Fig. 8, the whole setup is mounted on a massive granite table of size $60 \times 70 \times 10 \text{ cm}^3$, which is supported by four 20-cm-long posts with a diameter of 3.8 cm on the optical table. Granite is selected because of its stiffness and non-magnetism. The granite table is stacked with a 19-mm-thick breadboard for optics alignment and two layers of 2-mm-thick μ -metal for future magnetic field shielding. The thick and heavy stone table can damp the mechanical vibration noise from the optical table. An accelerometer (CT1050LC, Chengtec) with a sensitivity of 500 mV/g is used to measure the vibration on the optical table and the granite table, as shown in Fig. 9. A resonating speaker is used as a noise source at the optical table center. When the speaker is off, the native vibrations in the laboratory can be measured. The voltage output of the accelerometer is proportional to the acceleration, which gives the power spectral densities (PSDs) of the acceleration. The PSD is then converted to the displacement (amplitude) spectral densities (ASDs).⁸² Figure 9 shows that the vibration on the granite table is close to the optical table at the frequency below 200 Hz, while the granite table slightly outperforms the optical table above 200 Hz. Then, the speaker is turned on. The frequency of the speaker

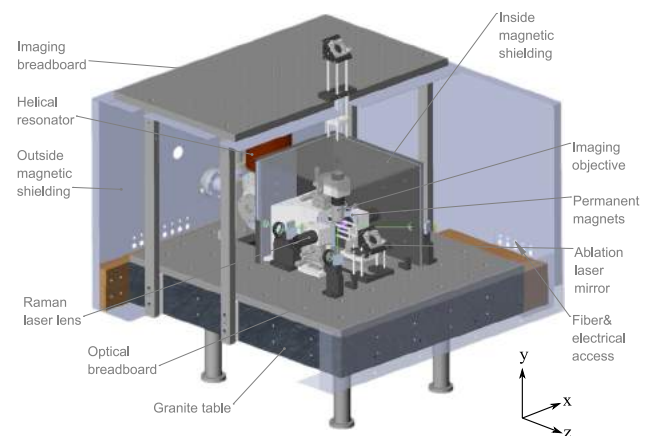


FIG. 8. Schematic of the granite table and magnetic shielding enclosures. The trap is placed on a granite table. There are two holes on the granite table, one for the NEG getter ion pump and the other one for the vertical objective and laser beams. Two magnetic field shielding enclosures cover the table and the trap, respectively. Electrical cables and optical fibers are supplied via the holes on the shielding. The optical breadboard is the working surface. The vertical imaging objective guides the light to the upper imaging breadboard. The CCD and PMT are not shown.

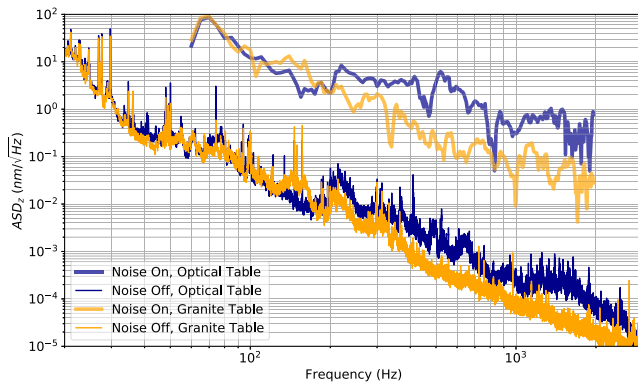


FIG. 9. Displacement (amplitude) spectral densities (ASD). The lower two traces show ASD of the optical table (blue) and the granite table (orange) with the noise source turned off. The upper two traces show the peak ASD of the optical table (blue) and the granite table (orange) with the noise source turned on.

is scanned with a step of 5 Hz from 50 to 2000 Hz, the working range of the accelerometer. For each frequency, the ASD is calculated, and the peak ASD is recorded, which is always at the source frequency. The peak ASD for every frequency is shown in Fig. 9. It shows that for frequency above 200 Hz, the granite table outperforms the optical table obviously as the excited peak ASD is nearly one order of magnitude lower than the peak ASD of the optical table. We note that the vibration above 200 Hz is on a similar timescale of a typical quantum experiment.⁶¹ Therefore, using the 10-cm-thick granite table is beneficial.

The magnetic shielding made of enclosed μ -metal is also proven beneficial to keep the qubit alive for a longer time.⁸³ Therefore, the whole setup will be covered in a magnetic shielding made of 2-mm-thick μ -metal in the future. The glass cell, as well as four objectives, will be covered in a smaller shielding box. A test performed on another trap in the laboratory shows that utilizing a permanent magnetic field, a 2-mm-thick μ -metal shielding box with a side length of 1 m, and the line trigger technique improves the coherence time from 0.9 to 20 ms for the Zeeman qubit $^2S_{1/2}|F=0, m_F=0\rangle$ and $^2S_{1/2}|F=1, m_F=1\rangle$ of a single $^{171}\text{Yb}^+$ ion, comparable with the result reported in Ref. 84. Such an improvement is also expected in our blade trap.

III. ION TRAPPING EXPERIMENT

A. Optical setup and ionization

In our trap, the qubit is encoded in the 12.6-GHz hyperfine clock transition $|0\rangle \equiv ^2S_{1/2}|F=0, m_F=0\rangle$ and $|1\rangle \equiv ^2S_{1/2}|F=1, m_F=0\rangle$ of $^{171}\text{Yb}^+$. The $^{174}\text{Yb}^+$ ions are used for testing the trap due to its simple electronic transition. The optical setup of both isotopes can be found in Ref. 66. Figure 10 shows the optical configuration in our trap. The ionizing lasers (399 and 369 nm), Doppler cooling lasers (369 nm), and optical repumping lasers (935 and 638 nm) are incident to the trap at 45° for loading ions. The cooling laser, pumping laser, and detecting laser at 369.5 nm combined in one laser beam are also incident to the trap at 45° . As shown in Fig. 10, the fluorescence scattered by the ions is

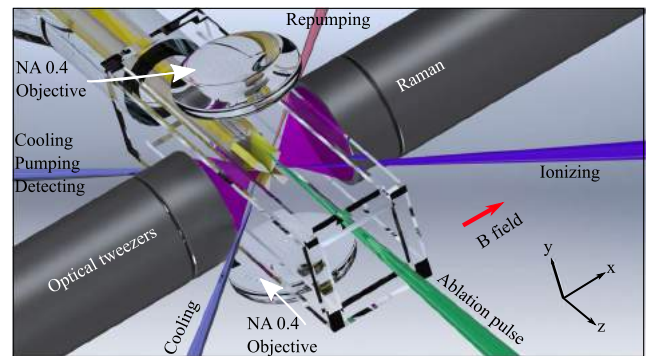


FIG. 10. Configuration of laser beams. The 532 nm ablation laser pulses are focused on a small piece of Yb metal through the front viewport of the glass cell. The Yb metal is clamped on the top of a metal tube and is located 8 mm away from the trap. The ablated neutral atoms propagating to the trap zone are then isotope selectively ionized by the ionizing laser beam, which is a combination of a 399 nm laser and a 369 nm laser. The 369 nm cooling, optical pumping, and detecting lasers are combined in one beam and incident on the cell surface at an angle of 45° . On the left and right sides of the glass cell, two lenses with a NA of 0.66 are used for the co-propagating Raman beams and optical tweezers. The black lens tubes help us to decrease the air disturbance. Above and below the trap, two lenses with a NA of 0.32 can be placed for fluorescence collection and the global Raman beams.

collected by a 0.32 NA objective lens above the glass cell and focused on a digital camera for imaging.

A 532 nm Q-switched Nd:YAG pulsed laser is used for laser ablation.^{64,65} As compared to the electrically heating oven method, the main advantages of the laser ablation method are the needless of wire connections, negligible effect on the vacuum, and quick generation of atom vapor. As shown in Fig. 10, the laser is focused onto the ytterbium metal surface through the front window of the glass cell. The beam waist on the target is $300\ \mu\text{m}$. A single laser pulse has a pulse duration time of 2 ns and a maximum pulse energy of 0.3 mJ, which operates at a repetition rate of 10 kHz. In our experiment, the shutter of the laser is triggered every 0.5 s by a signal generator and about 50 single laser pulses are released. The neutral atoms in the targeted area of the material are ablated. Some of the neutral atoms propagating to the trap zone are excited by a resonant 399 nm laser and ionized by a 369 nm laser beam by a two-photon photo-ionization process. This 369 nm laser detuned ~ 200 MHz from resonance also acts as a pre-cooling laser for the hot ions. When the ions with suitable speed are captured by the trap, they can be rapidly cooled by a weaker Doppler cooling laser with a detuning of -10 MHz from the $^2S_{1/2} \leftrightarrow ^2P_{1/2}$ transition. With the same method, $^{174}\text{Yb}^+$ ions can be loaded efficiently. Although the ytterbium material of natural isotope abundance is used in the setup, $^{171}\text{Yb}^+$ ions can also be efficiently loaded using the corresponding laser wavelengths.

B. Ion trapping

We use a bifilar helical resonator to apply the high RF voltage and biased static voltages on RF electrodes. The driving frequency is $2\pi \times 14.41$ MHz, and the measured Q factor of the helical resonator with the trap loaded is 30. The input RF power to the helical resonator is in the range of 25–33 dBm. RF power more than

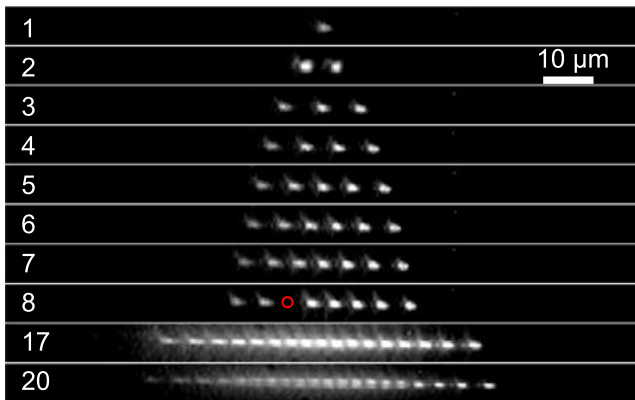


FIG. 11. CCD camera images of one-dimensional $^{174}\text{Yb}^+$ ions crystals labeled with the ion numbers. For loading, 30 dBm (1 W) of RF power is applied to the helical resonator. The static voltages are 1.5 V for DC1 and DC5, 0.2 V for DC2 and DC4, and 0.2 V for DC3 and RF bias. Each static voltage is filtered by a resistor-capacitor low pass filter with a corner frequency of 50 kHz. In the eight-ion crystal, there is a dark ion circled in red.

33 dBm will cause a slight drift in the resonant frequency because of the thermal dissipation. The trap can reach thermal equilibrium in several minutes. A suitable set of DC voltages is applied to each electrode. Once loaded, a string of $^{174}\text{Yb}^+$ ions can be trapped stably for few hours. As shown in Fig. 11, ions can be loaded one by one while maintaining the one-dimensional ion crystal structure.

A tickle oscillating voltage of 200 mV is applied on DC3 to find the motional frequencies of a single ion. When the frequency of the tickle voltage is in resonance with the motional frequency of the ion, the ion is heated and becomes delocalized in that direction. Inner electrodes DC2 and DC4 on both DC blades are applied with 1 V (other electrodes are grounded), 33 dBm (2 W) of power is applied to the helical resonator, the axial frequency of the ion is measured to be $2\pi \times 0.270$ MHz, and the radial frequencies are $2\pi \times 1.617$ and $2\pi \times 1.655$ MHz, respectively. In order to calibrate the voltage gain of the helical resonator, we simulate the trap potential numerically and compare the simulation with the experiments. The input voltage U_0 applied on the helical resonator and the calculated RF voltage U_{RF} are linearly fitted to give the voltage gain $G = \frac{U_{RF}}{U_0}$ of 13.1. For an input RF power of 25–33 dBm, the RF voltage amplitude on the trap is inferred to be 74–185 V.

C. Cold atom

Our trap can also be used for the cold hybrid ion-atom system. Although we have not yet been able to perform an experiment on cold atoms, it is worth giving some prospects for it. Figure 2(b) shows a possible optical configuration of how to load cold atoms in the trap center. Since we only have the ytterbium material as the ablation target, it is only possible to load Yb atoms in the current setup. If needed, other ablation targets of different species should be mounted on the ceramic holder during the installation. An atom source like a dispenser can also be placed in the glass cell before assembling the trap.⁸⁵

The 532 nm pulsed laser can be used to generate the atom vapor.⁶⁵ It is possible to directly load the atoms in a standard red-detuned six-beam MOT at 399 nm.⁸⁶ This method is simpler than using a typical Zeeman slower or a 2-D MOT at 399 nm as the pre-cooled source.^{85,87} Each MOT beam is about 5 mm in diameter. The 3D MOT is expected to capture about 10^5 – 10^6 Yb atoms in a few seconds with the help of a magnetic-field gradient of about 70 G/cm.²⁵ The loading efficiency can be adjusted by changing the ablation laser power or the MOT laser power. A 3D MOT at 556 nm can be used to achieve colder atoms at the price of more complicated laser beams. The MOT will locate several mm away from the blades. A far-off-resonance optical dipole trap at 532 or 1064 nm crosses the MOT and the ion trap center at $\sim 45^\circ$ to the y- and z-axis in the y-z plane. The dipole trap then transports the atoms to the ion trap center by changing the beam focus. Once the cold atom ensemble is overlapped with the trap center, optical tweezers can be used to load single atoms.

IV. SUMMARY

In this work, we have proposed the design and demonstrated the fabrication of a compact blade trap experimental apparatus with high optical accessibility for advanced cold atom experiments. The trap structure is optimized so that it can be installed in a compact glass vacuum cell, which enables two $\text{NA} \leq 0.32$ lenses on two sides and $\text{NA} \leq 0.66$ lenses on the other two sides simultaneously. Laser ablation is applied to generate neutral Yb atoms, and single atoms are ionized by a two-photon process. The performance of this apparatus is verified by trapping $^{174}\text{Yb}^+$ and $^{171}\text{Yb}^+$ ions for several hours. With sufficient optical accessibility to support efficient photon collection and individual ions addressing using four high NA lenses, this apparatus is a suitable candidate for quantum information processing research, including quantum simulation, quantum computation, and quantum networks. This setup also has the potential to combine the advantages of trapped ions, neutral atoms, and optical tweezers in one apparatus, which will pave the way for precise control of quantum chemistry in a cold hybrid ion-atom system.

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DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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