

Compact strontium atomic beam source based on a two-dimensional grating magneto-optical trap

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We present a two-dimensional grating magneto-optical trap (2D gMOT) for strontium, which produces a slow atomic beam in a compact form factor. The strontium 2D gMOT, using permanent magnets with an atomic dispenser, cools and traps atoms along two dimensions in the diffraction plane of a grating chip using the $^1S_0 \rightarrow ^1P_1$ (blue) transition. The system is configured in such a way that the atoms emitted from the dispenser source do not degrade the diffraction efficiency of the grating for long-term stable use. The performance of the 2D gMOT is analyzed with plug and probe beams, where the atomic source achieves a flux of 2.1×10^8 atoms/s and mean velocity of 6.4 m/s for an input laser power of 75 mW. The velocity measurement allows for the precise characterization of atom-photon scattering properties, showing that the compact 2D gMOT is suitable for portable quantum devices such as atomic clocks, quantum sensors, and precision spectroscopy.

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I. INTRODUCTION

Alkaline-earth atoms are prominent candidates for next-generation quantum technologies, including precision atom interferometry, quantum information processing, and optical clocks [1–7]. Applications using laser-cooled strontium have generated significant interest due to their favorable properties for quantum-enhanced precision metrology, atom-atom entanglement, and deployment of atomic standards [8–11]. Consequently, there is growing demand for portable and compact atomic sources suitable for field applications [12–16].

Traditional atomic beam sources for cold strontium commonly use high-temperature ovens coupled with Zeeman slowers to produce collimated, low-velocity atomic beams [17–19]. Although in-vacuum ovens have been developed to reduce vacuum-chamber sizes [16,

20,21], these configurations typically still require bulky Zeeman slowers, limiting their practical compactness. A more promising approach for miniaturizing atomic beam sources involves using two-dimensional magneto-optical traps (2D MOTs). These systems can produce slow atomic beams without needing Zeeman slowers; however, conventional 2D MOT designs demand extensive optical access and complex beam arrangements [22–29].

To address these challenges, recent efforts have focused on developing grating-based MOTs, which simplify optical setups by generating multiple cooling beams through diffraction from microfabricated grating structures [30–36]. This significantly reduces the complexity and size of laser-cooling systems, making them suitable for compact instrumentation [37].

In this work, we introduce and characterize a two-dimensional grating MOT (2D gMOT) for strontium atoms. The design incorporates an atomic dispenser placed immediately beneath a narrow gap between custom-designed and fabricated grating chips. This configuration ensures efficient and stable atomic loading while preventing strontium from depositing on the grating patterns, enabling long-term use. The 2D gMOT in this study is capable of selectively cooling multiple strontium

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isotopes, including ^{88}Sr , ^{87}Sr , and ^{86}Sr . The atomic flux and velocity distribution of the resulting slow atomic beam is directly measured using a plug-and-probe detection method, providing precise characterization without relying on indirect loading-rate measurements of an adjacent three-dimensional MOT. The demonstrated performance confirms that the compact 2D gMOT can provide an efficient source of cold strontium atoms for portable quantum technology applications.

II. EXPERIMENTAL SETUP

A. Vacuum system and laser apparatus

Figure 1(a) illustrates the design of the vacuum system along with key components for the 2D gMOT. The ultrahigh-vacuum system is composed of an octagonal chamber (Kimball Physics; MCF450-SphOct-Ec2A8) equipped with a DN63CF (4.5-inch or approximately 114-mm outer diameter; OD) primary viewport for the incident cooling laser beam, and perpendicularly surrounding DN16CF (1.33-inch or approximately 33.8-mm OD) viewports for the repumping laser beams and optical access for imaging. The electrical feedthrough for the atomic dispenser and vacuum pumps are attached via the bottom DN63CF port of the octagonal chamber. An ion pump (Vacon 10 l/s pump) keeps the vacuum pressure at the high 10^{-9} -Torr level when the dispenser is on and at approximately 1×10^{-9} Torr when the dispenser is off.

Two rectangular grating chips with dimensions of $20 \text{ mm} \times 30 \text{ mm}$ are installed side by side in the vacuum chamber with a 2-mm separation gap that is secured with a custom holder made of Macor, as shown in Fig. 1(a). The grating grooves are oriented parallel to the y axis, i.e., along the gap. When a single laser beam is incident on this geometry, diffracted beams from the grating chips can be directed toward the gap between the two gratings, enabling a beam for 2D laser cooling. The atomic dispenser (AlfaVakuo; AS-Sr-3F) is installed beneath the grating chip such that the outlet for the atomic vapor is positioned approximately 5 mm directly below the 2-mm gap, near the midpoint along the length of the gap, for efficient 2D gMOT loading.

Note that the grating chips act as a partial block for the atomic jet from the dispenser, which is tilted by approximately 6° with respect to the z axis in the xz plane, as depicted in Fig. 1(a). The tilted geometry of the dispenser source directs the atomic jet at an angle to the symmetry axis of the two gratings. This intentional asymmetry prevents thermal atoms from the dispenser from colliding with the laser-cooled atoms, which contributes significantly to achieving optimal 2D gMOT performance.

The 2D (blue) gMOT for strontium is realized using three lasers: a cooling laser at 461 nm, in addition to two repumping lasers at 679 and 707 nm. The cooling beam drives the $^1S_0$ to $^1P_1$ transition from a Toptica DL PRO HP

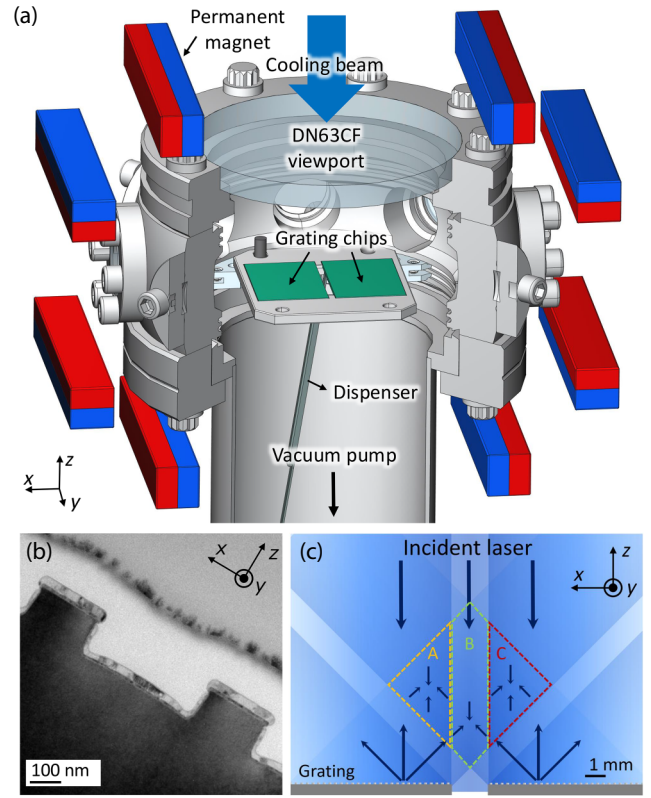


FIG. 1. (a) Cutaway illustration of the 2D gMOT vacuum chamber, with grating chips shown in green. The cooling beam (not illustrated) is incident from the top DN63CF viewport. (b) Cross-sectional TEM image of the grating chip. (c) Schematic of diffracted cooling beams formed by the grating chips with trappable regions A, B, and C.

461 laser. The cooling beam is delivered to the gratings after double-passing an acousto-optic modulator (AOM) for laser frequency and amplitude control, along with two (quarter- and half-wave) plates for polarization control of the input beam. The $1/e^2$ beam waist of the incident cooling beam is set to 11.4 mm at the grating chips using a zoom lens (Thorlabs; BE02-05-A), which was optimized for the maximum 2D gMOT atomic flux when the cooling laser beam power is 75 mW, indicating a $I_{\text{max}}/I_{\text{sat}}$ of approximately 0.91. Atoms being driven to the $^1P_1$ state for laser cooling can decay via the $^1D_2$ state to the metastable $^3P_2$ state. Therefore, a repumping scheme using 707- and 679-nm lasers to return the atoms to the ground state by pumping them into the $^3P_1$ state is required for efficient cooling [38].

The 707-nm (Toptica DL PRO 707) and 679-nm (home-made external cavity diode laser) repumping lasers provide 149 and 46 mW/cm^2 of laser intensity to the atoms, respectively. The frequencies of both repumper lasers are stabilized using the optical frequency measurements from a wavelength meter (HighFinesse; WS-8) [39], while the frequency of the cooling laser can be stabilized with either

the wavelength meter or the saturated absorption signal from a hollow cathode lamp (Hamamatsu Photonics; L2783-38NE) [40]. The two repumping beams are combined and copropagate along the elongated 2D gMOT (y axis) with beam sizes of 1.6 and 0.91 mm, respectively, through a DN16CF side viewport.

B. Gradient magnetic field and grating chips

To construct the two-dimensional grating magneto-optical trap, eight pairs of permanent magnets are arranged encircling the 2D gMOT center position to produce a quadrupole magnetic field gradient in the xz plane [22, 41]. Two permanent N45 neodymium bar magnets (CMS Magnetics) with dimensions of 76.2 mm $\times$ 12.7 mm $\times$ 6.35 mm are stacked, depicted as blue and red pairs in Fig. 1(a), and placed in holders made from nonmagnetic materials such as polyether ether ketone (PEEK) and brass. The magnet holders are designed to allow adjustment of the relative positions of the magnet pairs. Additionally, the magnet holders are mounted on a two-axis translation stage, enabling the center of the magnetic quadrupole field to be precisely controlled in the xz plane. In our experiment, the positions of the magnets were decided by taking into consideration the field gradient and geometrical limitations due to the vacuum chamber. The magnets with dipoles aligned along the x direction are spaced 107 mm apart in the x direction and 119 mm apart in the z direction. Similarly, the magnets with dipoles aligned along the z direction are spaced 157 mm apart in the x direction and 69 mm in the z direction. The magnetic field gradient for the intended configuration of the magnets was measured using a Hall probe in the absence of the vacuum chamber. The measured magnitude of the magnetic field gradient was 65.9 G/cm along the x axis and 76.5 G/cm along the z axis, which matches well with the expected values of 67.8 G/cm and 76.5 G/cm based on numerical simulations.

The grating chips are fabricated on 200-mm-diameter silicon wafers using deep-ultraviolet lithography and plasma-etching techniques. A $4\times$ reticle was used to define the grating structures, with feature sizes four times larger than the target dimensions (229-nm line width, 423-nm spacing). Using standard projection lithography with scanner systems such as deep or extreme ultraviolet tools, the mask pattern is reduced by a factor of 4 and precisely projected onto the wafer. The wafer is first cleaned and coated with a bottom antireflective coating (BARC) and photoresist to thicknesses of 300 and 1400 Å, respectively, using an automated track system (TEL; ACT8). The lithography process is performed using an ArF scanner (ASML; XT1250D) operating at a 193-nm wavelength to precisely define the grating patterns. After development of the photoresist, the exposed BARC layer is sequentially etched using inductively coupled plasma reactive-ion etching (ICP-RIE). The silicon surface was etched to a

depth of 120 nm using a fluorine-based RIE process with Cl_2/HBr chemistry (LAM Research; TCP-9600DFM) to define the grating structures. The residual photoresist on the silicon wafer is then removed by oxygen plasma ashing using a photoresist stripper system (PSK; DAS2000), followed by a sulfuric-peroxide mixture (SPM) cleaning process to sequentially eliminate remaining organic and inorganic residues. The optimized geometry of the grating is precisely controlled by the thickness of the Al thin film conformally deposited by physical vapor deposition on the etched surface of the Si wafer. A 10-nm-thick titanium adhesion layer and a 20-nm-thick aluminum thin film are deposited using a multitarget sputtering system (SORONA; SS0818). The fabricated grating structures exhibit less than 2% deviation from the target line width of 249 nm, which corresponds to the final Al thin-film pattern after deposition. The line width was measured using a critical dimension scanning electron microscope (CD-SEM). This deviation refers only to the lateral critical dimension and does not include line-edge roughness, pattern straightness, or etch depth. The across-wafer critical dimension (CD) uniformity on the 200-mm-diameter silicon wafer is measured to be 0.61%. The fabricated grating chip is singulated from the 200-mm-diameter wafer to an overall dimension of 20 mm $\times$ 30 mm by cutting the wafer using the saw blade of a dicing machine (DISCO; DAD3350).

The grating chips are made by depositing aluminum on silicon substrates with ridge grating structures. The target dimensions of the ridges were determined using finite-element-method (FEM) calculations for 461-nm wavelength taking into account the intensity and polarization of the diffracted beams (COMSOL MULTIPHYSICS). Specifically, the designed height (120 nm), width (249 nm), and spatial period (652 nm) of the ridge patterns are targeted for a first-order diffraction angle of 45° , a differential phase shift of 19.25° between the s - and p -polarization field components, and a diffraction efficiency of 38%. Figure 1(b) shows a transmission electron microscope (TEM) image of the grating cross section. The height, width, and spatial period of the grating ridges are measured to be 119.2, 247.7, and 652.0 nm, respectively, deviating well below 1% from the target dimensions. Experimental measurements with the cooling laser confirm that the diffraction angle is precisely the targeted 45.0° . To evaluate the phase shift, a circularly polarized beam was normally incident on the grating, and the polarization of the diffracted beam was measured with a polarimeter (Thorlabs; PAN5710VIS). The phase shift between the s - and p -polarization field components is measured to be 23.9° while the diffraction efficiency is 28.5%. Unlike the diffraction angle, the field-component measurements diverge considerably from the targeted values; nevertheless, they are capable of producing well-performing 2D gMOTs.

Figure 1(c) depicts the grating-chip-assisted cooling beam configuration in the xz plane, where the elongated

axis of the 2D gMOT is along the y direction. The cooling beam is incident along the $-z$ direction and centered roughly on the gap between the gratings. The position of the incident beam and the center of the magnetic field are precisely tweaked when optimizing the 2D MOT for maximum atomic flux. Three regions, where a 2D MOT can be formed, are illustrated as distinct areas enclosed with dashed lines in Fig. 1(c). In regions A and C, four beams are combined to form a 2D MOT, namely, the incident beam, the reflected beam, and two diffracted beams. The reflected beam is not present in region B due to the 2-mm gap; nonetheless, radiative forces can still be balanced to form a 2D MOT. Depending on the presence of the reflected beam, the radiative pressure along the z direction will differ, yielding a difference in the optimized 2D gMOT position along the z axis for regions A and C compared to region B. It is impossible to trap atoms outside these three regions due to the geometric imbalance of the radiation pressure on the laser-cooled atoms.

C. Laser cooling atoms with the 2D gMOT

The laser-cooled strontium atoms in the 2D gMOT originate from the dispenser installed beneath the grating gap. The thermal atoms from the dispenser are emitted through the gap predominantly along the z direction. The atomic jet is slightly tilted toward the $-x$ direction and diverges out of the gap within well-defined angles in the xz plane. Due to the tilted geometry of the atomic jet, the thermal atoms enter the laser-cooling regions B and C, but they completely avoid region A.

Figure 2(a) shows a camera image (Excelitas Technologies; PCO pixelfly) of atoms exiting the grating gap that are fluorescing due to photon scattering by the 461-nm laser beam. The laser frequency is blue-detuned with respect to atoms at rest by 500 MHz, and the dispenser current is 5.0 A. Note that in the image, the fluorescence corresponds to the atomic jet interacting with the reflected and diffracted laser beams, while the incoming beam propagating along the $-z$ direction is off resonant. The divergence of the atomic jet can be clearly observed with angles from 1.55° to 10.22° clockwise relative to the z axis.

To further characterize the atomic jet, we performed laser spectroscopy for the selected region, as indicated by the red dashed box in Fig. 2(a). Figure 2(b) shows the atomic fluorescence signal as a function of the incident laser frequency for different dispenser currents. The scattered points represent the measured data, while the solid lines are fits based on the Maxwell-Boltzmann distribution for an atomic beam. In this case, the fluorescence spectra are shown for red-detuned laser frequencies, i.e., when the atoms are interacting with the incident laser beam propagating in the opposite direction to the atomic jet. The inset shows the estimated atom temperature, obtained

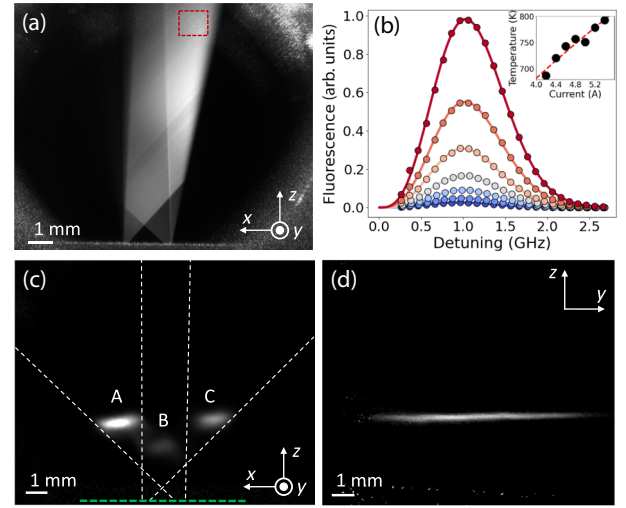


FIG. 2. (a) Image of the fluorescing atomic jet from the dispenser due to the blue-detuned 461-nm laser beam. (b) Fluorescence spectra via scanning of the laser frequency of the atoms ejected from the dispenser for various dispenser currents ranging from 4.2 to 5.4 A. The estimated temperatures obtained by fitting to Maxwell-Boltzmann distributions are shown in the inset. (c) Composite front image (xz plane) of three 2D gMOTs for ^{88}Sr in regions A, B, and C. The green dashed line indicates the position of the grating chip. (d) Side image (yz plane) of the 2D gMOT for strontium.

from the Maxwell-Boltzmann distribution curve fit, as a function of the applied dispenser current. Specifically, the estimated temperatures are approximately 415 to 521 $^\circ\text{C}$ for dispenser currents of 4.2 to 5.4 A. The dashed red line in the inset represents an exponential fit to the atomic flux as a function of dispenser current, with an exponent of approximately 0.504. This measurement is consistent with expectations based on thermal equilibrium between Joule heating and radiative heat loss (Stefan-Boltzmann law) under steady-state conditions, which should lead to a flux dependence of approximately $\propto I^{0.5}$.

As described in Fig. 1(c), 2D MOTs can be formed in regions A, B, and C. A combined image of three 2D gMOTs for ^{88}Sr in the xz plane is shown in Fig. 2(c). This processed image was created by combining three separate images showing the formation of 2D gMOTs in each region. The boundaries of the three trappable regions are indicated by the white dashed lines. To generate a 2D gMOT in a particular region, for optimal cooling, the position of the set of permanent magnets is adjusted relative to the grating with a two-axis translation stage. Note that the positions of the quadrupole magnetic field centers do not necessarily coincide with the MOT positions; instead, they are placed to optimally balance the radiation pressure and maintain trap stability in each region. When the 2D gMOT is placed in region B, the atoms tend to be trapped in a lower position along the z direction compared to regions A

and C due to the difference in radiation pressure caused by the gap between the gratings. Collisions between atoms in the 2D gMOT and the atomic jet exiting the dispenser are also a contributing factor to the capture efficiency. Region A is free from these collisions and atoms are most efficiently trapped. Conversely, the atomic jet overlaps with most of region B, where these collisions are expected to be significant, hindering the loading of the 2D gMOT. The atomic jet partially affects region C, which results in the 2D gMOT appearing to be slightly shifted to the $-x$ direction. Comparing the fluorescence signal of the 2D gMOT in the three trapping regions, regions B and C are approximately 16% and 44% of that in region A, respectively.

A camera image along the x -axis viewport is shown in Fig. 2(d). This side view shows that the 2D gMOT in region A is elongated along the y axis, i.e., the axis of the low-velocity atoms escaping the 2D gMOT. The axial length of the 2D gMOT is measured to be 9.6 mm $1/e^2$ diameter, which is estimated via Gaussian fitting of the atomic fluorescence distribution. In this study, the axial length of the 2D gMOT is set by the input laser beam diameter, and it is not limited by the size of the grating chip. The study of the 2D gMOT in subsequent sections is based on that in region A.

III. RESULTS AND DISCUSSION

A. Atomic-flux and velocity measurements

The 2D gMOT has no cooling-laser-beam component along the y (axial) direction for confinement. Therefore, laser-cooled atoms can exit from both sides of the 2D gMOT along the axial direction, producing a slow atomic beam source. Note that many setups include a push beam to break the symmetry along the y axis and increase the atomic flux along one of the exiting directions [22,23,25,28]. Such techniques are not applied to the current study due to the specific method chosen for measuring the number of atoms and velocity distribution of the slow atomic beam shown in Fig. 3(a). The 2D gMOT, depicted as a blue elongated atomic sample, generates a slow atomic beam that travels along the y axis. The propagation direction of the slow atomic beam of interest is represented by a solid yellow arrow.

The characteristics of 2D MOTs are often investigated by capturing the atomic flux with a 3D MOT and measuring its loading rate [22,24,34]. In this study, the performance of the slow atomic beam is estimated with an intersecting on-resonance ($^1S_0 \rightarrow ^1P_1$) probe beam and measuring the fluorescence signal from the passing atoms. Additionally, an on-resonance plug beam, which is placed between the 2D gMOT and the probe beam, can be used to block the slow atomic beam and extinguish the fluorescence signal at the probe. The time delay of the atomic-flux response at the probe with respect to the plug beam switching on and off can indicate the velocity distribution of the

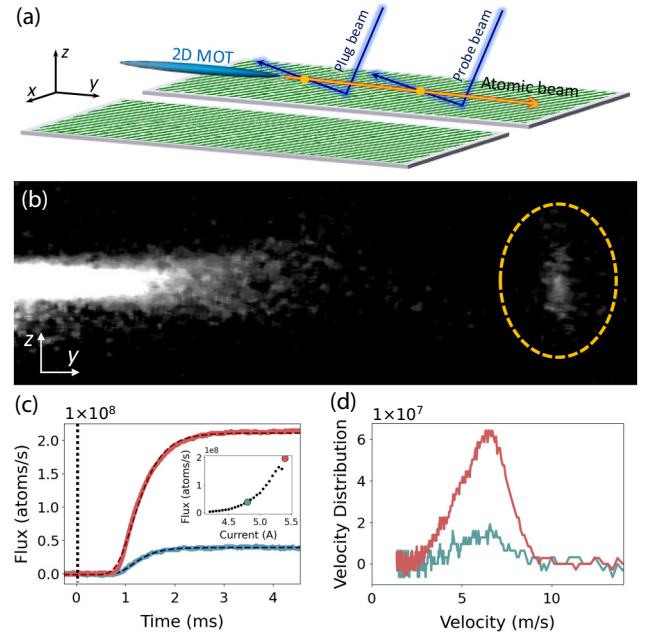


FIG. 3. (a) Schematic of the slow-atomic-flux measurement setup with a plug and probe laser beam diffracting from the grating chip. (b) Camera image of atoms in the 2D gMOT and slow atoms passing through the probe beam marked by the yellow dashed circle. (c) Time-dependent atomic flux measured at the probe region when the plug beam is turned off at $t = 0$. The red (green) curve corresponds to a dispenser current of 5.4 A (4.8 A). The inset shows the steady-state flux as a function of the dispenser current. (d) Velocity distribution of the slow atomic beam source obtained from the time-dependent flux measurements.

slow atomic beam. This time delay is dependent on the velocity of the slow atoms and the distance they travel from the plug beam to the probe beam, which is 6.7 mm in our experiment. Using this technique, the flux and velocity distribution of the 2D gMOT are simultaneously measured. Notably, the plug and probe beams intersect with the trajectory path of the slow atomic beam via first-order diffraction with the grating chip. This configuration allows for better management of the plug and probe beams; i.e., it prevents uncontrolled scattering due to reflections from the walls of the vacuum chamber and metallic structures under the grating gap.

Figure 3(b) shows an image of the 2D gMOT in the yz plane. A portion of the 2D gMOT and fluorescing atoms from the slow atomic beam as they interact with a probe beam, indicated with a yellow dashed circle, can be seen. An image relay system with a numerical aperture (NA) of 0.127, including a spatial filter at the intermediate focal point, was installed to enhance the signal-to-noise ratio by minimizing the detection of background scattered light. A photomultiplier tube (PMT, Hamamatsu; H14066-01) is placed after the spatial filter for time-dependent measurements. The divergence of the atomic beam can be

estimated from fluorescence images to be 10.3° when the atomic flux is 2.1×10^8 atoms/s. The 2D gMOT density can also be roughly estimated using the fluorescence images to be of the order of 4×10^9 atoms/cm³. At this density, atomic collisions are expected to be minimal, allowing the axial and transverse velocity distributions to remain mostly independent. For higher densities, however, cross-thermalization is expected to affect the axial velocity and divergence of the atomic beam [23].

Figure 3(c) shows measurement examples of the time-dependent atomic flux measured by the probe beam when the plug beam is removed, with a trapping beam power of 75 mW and a detuning of 1.45Γ . The green and red curves correspond to dispenser currents of 4.8 and 5.4 A, respectively, and the atomic flux is derived from the fluorescence signal at the probe detected by the PMT. The vertical dotted line at $t = 0$ indicates when the plug beam is turned off with an AOM. Once the plug beam is extinguished, the slow atoms from the 2D gMOT can reach the probe region, leading to a delayed detection of the atoms with the PMT. The atomic flux is defined as the number of atoms passing through the probe-beam region per unit time. The Gaussian-profiled probe beam has a $1/e^2$ radius of 0.29 mm at the intersection with the slow atomic beam. The PMT was operated with a gain of 8×10^5 , and the detected current was used to estimate the total number of photons scattered by the probe beam interacting with the passing atoms. The scattering rate from the on-resonance probe beam was calculated assuming an intensity of $I/I_{\text{sat}} \simeq 5.8$. The number of photons emitted by a single atom while traversing the probe beam is given by the scattering rate multiplied by the transit time. Hence, the total atomic flux can be determined by dividing the estimated total photon scattering rate by the calculated photon-emission rate per atom. The dashed lines represent curve fits using the generalized logistic function. The steady-state atomic flux was extracted from the upper asymptote of the fitted function, while the velocity was determined based on the 6.7-mm travel distance from the plug to the probe beam divided by the transit time. The most probable velocity can be estimated by identifying the time at which the derivative of the flux is maximum.

The inset in Fig. 3(c) shows the measured steady-state atomic flux for various dispenser currents. The two data points for dispenser currents of 4.8 and 5.4 A are indicated with color-matched circles, with values of 3.8×10^7 and 2.1×10^8 atoms/s, respectively. The atomic flux exhibits an exponential dependence on the dispenser current. While a current higher than 5.4 A would provide a substantially greater atomic flux, it was limited in this study to minimize vacuum contamination and prolong the dispenser lifetime.

Figure 3(d) shows the velocity distribution numerically derived from the measurement data of Fig. 3(c). The y axis is scaled such that the area under each curve is equal to the total atomic flux measured for the corresponding

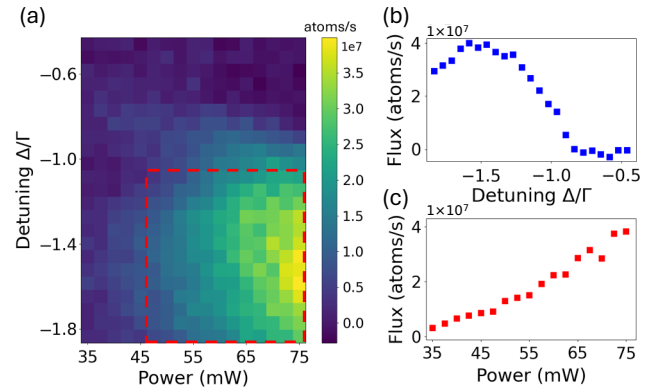


FIG. 4. Atomic flux as a function of laser detuning and optical power at a dispenser current of 4.8 A. (a) Measured two-dimensional scan, where the red dashed box indicates the scan region in Fig. 5. (b) Average atomic flux as a function of laser detuning for optical powers from 70 to 75 mW. (c) Average atomic flux as a function of optical power for laser detunings from -1.5Γ to -1.6Γ .

dispenser current. The velocity distribution is maximum at approximately 6.4 m/s regardless of the dispenser current. Unlike Maxwell-Boltzmann distributions such as that in Fig. 2(b), the distributions in Fig. 3(d) have an upper velocity limit, beyond which the probability rapidly drops. This difference suggests that the atom velocity along the axial direction of the 2D gMOT is constrained by the transverse capture velocity. Therefore, we can expect the velocity distribution of the slow atomic beam to be primarily determined by the 2D gMOT laser-cooling and trapping parameters.

The main characteristics of the 2D gMOT atomic beam—namely, the steady-state flux and most probable velocity—are measured as a function of the frequency detuning and optical power of the 461-nm cooling laser. Figure 4(a) shows a two-dimensional scan of the steady-state atomic flux obtained from the time-dependent plug-and-probe measurements. The upper asymptote of the generalized logistic fit function for the probe fluorescence signals, averaged over 256 measurements, was used. As in conventional 2D MOTs, the atomic flux increases as the optical power increases with the (red) detuning of the cooling laser beam.

Figure 4(b) shows how the atomic flux responds to the laser frequency detuning for optical power ranging from 70 to 75 mW. A maximum atomic flux of 4.0×10^7 atoms/s is observed at a detuning of approximately -1.5Γ . Figure 4(c) presents the average atomic flux as a function of optical power, for the detuning range from -1.5Γ to -1.6Γ . The atomic flux continues to increase past the maximum optical power available in our experimental setup. Note that the optical intensity of the incident cooling beam, with a power of 75 mW, is approximately 1.18 times the saturation intensity. Since only a fraction of the incident power

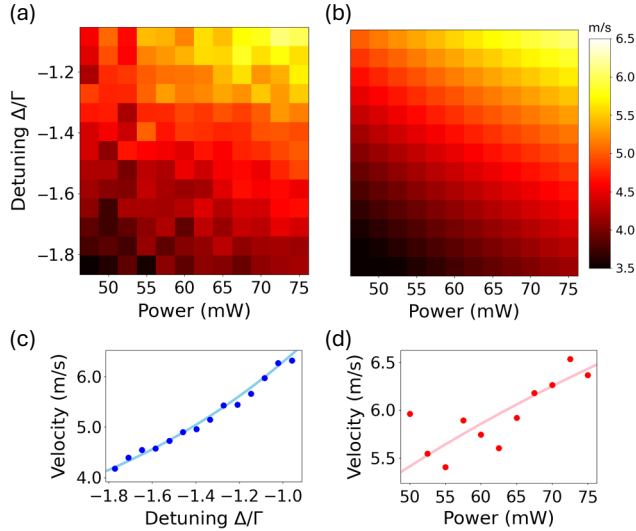


FIG. 5. Velocity of the atomic beam as a function of laser detuning and optical power. (a) Measured two-dimensional scan corresponding to the region indicated by the red dashed box in Fig. 4(a). (b) Two-dimensional model fit of the measured atomic beam velocity. (c) Average velocity as a function of laser detuning for powers from 70 to 75 mW. (d) Average velocity as a function of optical power for laser detunings from -1.5Γ to -1.6Γ .

is diffracted by the grating structure, the optical intensity of the beam components for confinement along the horizontal (x) direction is well below saturation. Therefore, we expect the atomic flux to increase further when applying higher optical powers than those used in this study.

Figure 5(a) shows the experimentally measured atom velocities of the slow atomic beam source, i.e., the mode of the velocity distribution in measurements such as Fig. 3(d), as a function of cooling-laser power and detuning. The scan range corresponds to that of the red dashed region in Fig. 4(a), referring to where the atomic fluorescence signal is large enough to provide credible velocity measurements. The 2D fit of this dataset is shown in Fig. 5(b) employing a simple capture-velocity model, where the characteristic trappable velocity is proportional to the square root of the photon scattering rate, i.e., $v_c \propto \sqrt{\Gamma_{\text{scatt}}}$, where the photon scattering rate is given by $\Gamma_{\text{scatt}} = \Gamma/2(s/1 + s + (2\delta/\Gamma)^2)$. Here, Γ is the natural linewidth, s is the effective saturation parameter, and δ is the detuning [42–44].

Applying this model to fit the measured data in Fig. 5(a) allows us to estimate the atomic resonance frequency and laser intensity for a given I_{sat} . We compared this fit estimate value to an independent resonance-frequency measurement obtained via direct laser spectroscopy of strontium atoms emerging from a separate atomic beam oven in an adjacent chamber. The two independent methods for measuring the resonance frequency of the $^1S_0 \rightarrow ^1P_1$

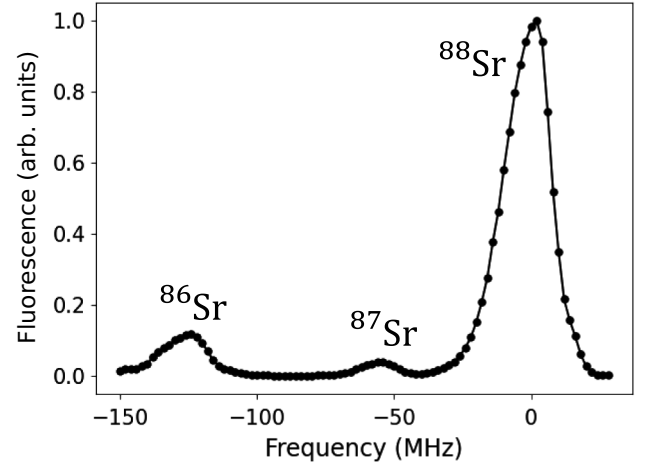


FIG. 6. Fluorescence spectrum of strontium isotopes from the 2D gMOT. Experimental data (black circles) are interpolated with a solid black line to guide the eye.

transition agreed relatively well. The 2D fit of the atomic velocity, i.e., Fig. 5(b), gave a resonance frequency value that was 3.4 MHz higher than that obtained from direct spectroscopy with the atomic beam oven. Figures 5(c) and 5(d) show one-dimensional subset projections of the two-dimensional atomic beam velocity data shown above. The scatter points represent averaged values of the atomic beam velocity over the same ranges as those used in Figs. 4(b) and 4(c). The solid lines are the corresponding fitted data, i.e., Fig. 5(b), portraying how well the model fits to the measured data. As expected, the velocity of the slow atomic beam from the 2D gMOT increases as the laser frequency approaches resonance, and as the optical power is increased.

B. 2D gMOT of different isotopes

In our experimental setup, we observed the capture of not only ^{88}Sr atoms but also other nearby isotopes, namely, ^{87}Sr and ^{86}Sr . Figure 6 is the measured 2D gMOT fluorescence spectrum for a cooling-laser power of 70 mW, showing laser-cooled strontium isotopes ^{86}Sr , ^{87}Sr , and ^{88}Sr . The ^{86}Sr and ^{87}Sr 2D gMOTs appear when the cooling-laser frequency is offset by -124.5 and -54.5 MHz, respectively, relative to that of the ^{88}Sr isotope. These frequencies are consistent with the reported isotope resonance values [45–52]. The 2D gMOT capture performances for each isotope were relatively determined by the area under the corresponding isotope spectrum in Fig. 6. The measured proportions of the laser-cooled isotopes were 10.1%, 2.60%, and 87.3% for ^{86}Sr , ^{87}Sr , and ^{88}Sr , respectively, while their corresponding natural abundances are 9.86%, 7.00%, and 82.6% [52].

The low proportion of the 2D gMOT for the ^{87}Sr isotope, when taking into account its natural abundance, can be attributed to its complex energy structure. Laser cooling

and trapping ^{87}Sr , with a nuclear spin of $9/2$, is known to be less efficient compared to that of ^{86}Sr and ^{88}Sr . Moreover, recent studies of grating MOTs have shown that the fermionic isotope ^{87}Sr forms at a different axial equilibrium position than bosonic isotopes [53]. We also observe that the trapping position of ^{87}Sr is displaced closer to the grating by 0.31 mm relative to those of ^{86}Sr and ^{88}Sr . This displacement can also contribute to the discrepancy between the measured spectra of the laser-cooled isotopes (Fig. 6) and the natural abundances since the apparatus was optimized for ^{88}Sr . Note that the natural abundance of the ^{84}Sr isotope is only 0.56%, and it was thus excluded from the analysis.

IV. CONCLUSION

We have demonstrated a two-dimensional grating magneto-optical trap for strontium atoms with a single input laser beam for the $^1S_0 \rightarrow ^1P_1$ cooling transition incident on a homemade grating structure. The compact 2D gMOT setup effectively trapped the strontium isotopes ^{86}Sr , ^{87}Sr , and ^{88}Sr . A 2-mm spatial gap along the grating grooves enabled the installation of an atomic dispenser directly beneath the grating chips, facilitating efficient cooling and trapping of high-velocity atoms from the dispenser. The atomic flux and velocity of the laser-cooled atomic source were measured using plug and probe laser beams, which allowed for the precise characterization of the slowly transiting atoms. Due to the absence of a push beam, the resulting atomic velocities were relatively low compared to conventional 2D MOT systems.

Our measurements confirmed that the atomic velocity is proportional to the square root of the photon scattering rate. Specifically, we achieved an atomic beam flux of 2.1×10^8 atoms/s and a mean velocity of 6.4 m/s at a dispenser current of 5.4 A and an incident optical power of 75 mW. Although they are preliminary and have significant room for further improvement, these results can be competitive with recent developments in slow strontium beam sources [16,21,22], as they show promise in achieving high final loading rates into 3D MOTs while minimizing size, weight, and power (SWaP). For example, the commercially available strontium atomic beam source from AOSense has a substantially higher atomic flux of 10^{11} atoms/s, and its correspondingly higher mean velocity of approximately 40 m/s [21] can significantly limit the final capture rate into a 3D MOT. Assuming a Maxwell-Boltzmann velocity distribution [54], we calculate that our 2D gMOT can outperform the AOSense source for 3D capture velocities below 8.3 m/s. The 2D gMOT can also offer a clear advantage in power consumption and size. The AOSense source requires 10 W for oven operation, while our system operates at 3.4 W for the low dispenser currents used in this study. The longitudinal length of the 2D gMOT along the atomic beam direction is currently

constrained by the 12-cm length of the vacuum chamber, which can be reduced below 8 cm through the use of custom vacuum parts and magnet design optimization. These aspects are particularly significant when considering future experiments, where we plan to load atoms into a three-segment grating-chip-based 3D gMOT for maximal compactness. While 3D gMOTs can offer a smaller physical package, they are inherently limited by a relatively low capture velocity. Based on our calculations, the estimated capture velocity for our 3D gMOT is approximately 7.4 m/s, which confirms the adequacy of our 2D gMOT's performance.

Grating-chip-based systems for laser cooling and trapping offer potential for further miniaturization and provide a path toward photonic integrated-circuit engineering for more complex designs targeting specific applications. Compact slow-velocity atom sources with low flux can also be particularly advantageous for systems with low atom-number requirements, such as ion traps [55–57] and portable atomic clocks [12–15], as they minimize the contamination of the vacuum chamber. Future design optimizations to this work will include refining the gap size to achieve an optimal balance between maximizing the throughput of the atomic jet from the dispenser and the trapping region determined by the diffracted cooling-beam profiles.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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