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(54) **Title:** SYSTEMS AND METHODS FOR A HIGH FLUX JET LOADED COLD ATOMIC BEAM SOURCE FOR STRONTIUM

(57) **Abstract:** The present subject matter relates to techniques of a source for the preparation and capture of ultracold strontium (Sr) atoms via a dispenser-based two-dimensional magneto-optical trap (2D MOT). The disclosed system can include a vacuum system, a dispenser assembly, a laser system, and a magnetic field generator. The system is distinguished with a high atom flux of the Sr atoms with a loading rate up to 10^9 atoms per second.

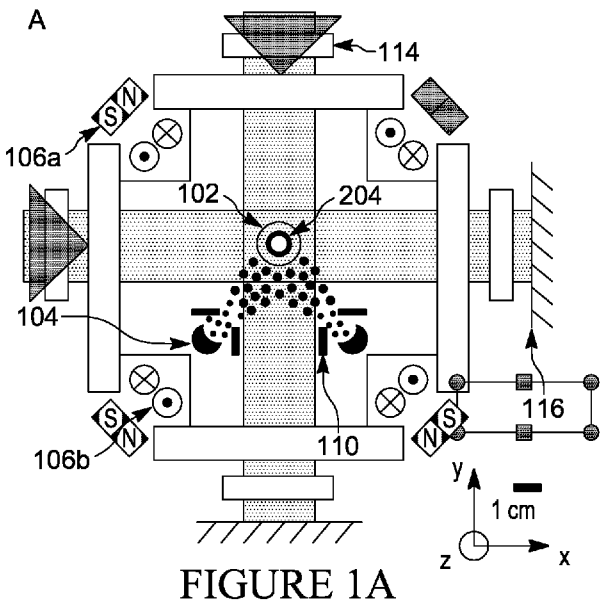


FIGURE 1A

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SYSTEMS AND METHODS FOR A HIGH FLUX JET LOADED COLD ATOMIC BEAM SOURCE FOR STRONTIUM

CROSS-REFERENCE TO RELATED APPLICATION

This PCT application claims priority to U.S. Provisional Patent Application No. 63/346,689, which was filed on May 27, 2022, the entire contents of which are incorporated by reference herein.

GRANT INFORMATION

This invention was made with government support under grant numbers 1936359 and 2040702 awarded by the National Science Foundation. The government has certain rights in the invention.

BACKGROUND

The disclosed subject matters are related to a source for the preparation of ultracold atoms, more specifically to the system and methods for a high flux jet loaded cold atomic beam source for strontium.

Atoms having two valence electrons, including ytterbium and strontium, have become increasingly used in ultracold quantum science endeavors, and other industries.

The atomic structure of such atoms can allow for a wide range of internal transitions, due, at least in part, to the presence of singlet and triplet electronic states. Each of the broad, narrow and ultranarrow linewidths of such transitions can be utilized in certain laboratory and industrial applications, such as laser cooling or quantum operations. Such

atoms can also offer features of magic wavelengths, tune-out wavelengths, and optically trappable Rydberg states.

Strontium can be used for quantum science in technology, such as the creation of atomic clocks. However, use of strontium on a broad scale can be inhibited in view of a need for robust and compact hardware for the preparation of ultracold strontium. Due to its high melting and boiling points, strontium can tend to stick to the inner walls and viewports of vacuum chambers, which prevents sources based on vapor cells from being utilized. Rather, certain strontium sources rely upon an effusive over combined with a Zeman slower, having a cold atom flux of up to 10^9 atoms per second but are typically large (approximately 1 meter) and use power intensive (and delicate) electromagnets.

As an alternative, certain magneto optical traps ("MOTs") can also be used as a source. Some two-dimensional MOTs create an atomic beam via transverse laser cooling in two dimensions. While certain two-dimensional MOTs can provide high atom flux (in a relatively small footprint), such sources can have some drawbacks, e.g., being bulky, not easy to manufacture, or having a large footprint.

As such, there is a need for a technique for providing atom sources having a high atom flux within a compact setup and a small, efficient footprint.

SUMMARY

The disclosed subject matter provides a dispenser-based two-dimensional magneto optical trap (2D MOT) system for strontium (Sr). An example system includes a vacuum system, including at least one ultra-high vacuum component and a central component, a dispenser assembly adapted to release Sr atoms into the vacuum system, a laser for cooling the Sr atoms in two dimensions to form a 2D MOT to trap ultracold Sr atoms, and a magnetic field generator configured to locate fine positions of the 2D MOT.

In certain embodiments, the magnetic field generator made of permanent magnets is attached to a 3D printed mount, providing a magnetic field gradient without consuming power.

In certain embodiments, the system includes a 3D MOT, serving as flux measurement unit for ultracold Sr atoms. In certain embodiments, the total travel distance between the 2D MOT and the 3D MOT is 40-50 cm.

In certain embodiments, the ultra-high vacuum component includes a science chamber, or/and a central component includes a six-way cross.

In certain embodiments, the 2D MOT is configured to create an atomic beam for Sr atoms via a push beam.

In certain embodiments, the dispenser assembly includes at least one U-shaped dispenser.

In certain embodiments, the system further comprises a shield around the dispenser to block the atoms from coating on viewports of the dispenser assembly.

In certain embodiments, the vacuum system further comprises a differential pumping tube to which the 2D MOT is aligned.

In certain embodiments, the distance of the output opening of the dispenser assembly and the 2D MOT trap region is 0.5-5.0 cm.

In certain embodiments, the differential pumping tube connects the 2D MOT and 3D MOT.

In certain embodiments, one or more coil pairs are wound around the ports of a six-way cross using standard magnet wire in the magnetic field generator.

The disclosed subject matter also provides methods for trapping strontium (Sr) based on two-dimensional magneto optical trap (2D MOT). An example method includes releasing Sr atoms into a vacuum system via a dispenser, cooling Sr atoms by laser cooling in two dimensions to create a 2D MOT, trapping the Sr atoms in a magnetic field using permanent magnets, and collecting the trapped and ultracold atoms.

In certain embodiments, the method also includes measuring atom flux of the collected ultracold Sr atoms via a 3D MOT.

In certain embodiments, the method includes measuring atom flux by loading a push beam to push the ultracold Sr atoms into a glass cell in the 3D MOT.

In certain embodiments, the method includes measuring atom flux via a fluorescence image detection.

In certain embodiments, the dispenser assembly releases Sr atoms by at least heating a filling of loaded bulk Sr therein.

In certain embodiments, the dispenser releases Sr atoms without a mechanical shutter.

In certain embodiments, the temperature of the dispensers ranges from 100-700℃.

In certain embodiments, the magnetic field gradient of the permanent magnets is from 50-150 G/cm.

The disclosed subject matter also provides for utilization of ultracold Sr atoms trapped via the disclosed techniques in a quantum operation. That quantum operation can be one or more of an optical clock, quantum simulator, and quantum computer, using the trapped ultracold Sr atoms for the quantum operation.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A-1D provide diagrams of implementation of the 2D MOT system. Figure 1A provides an axial view, and Figure 1B provides side view. Figure 1C provides an image of the dispenser assembly of the 2D MOT system and the mounting structure thereon. The cylinder in the middle is the end of a mounting tube that holds the dispenser assembly. Figure 1D provides a schematic setup diagram for the 2D MOT system.

Figures 2A-2B provide a schematic diagram of laser cooling of Sr. Figure 2A provides a diagram of atomic levels and relevant optical transitions for cooling and repumping in the setup. Figure 2B provides a schematic diagram of the system for 461 nm laser light via a master laser.

Figures 3A-3B provide a calibration of 2D and 3D MOT parameters in some embodiments of the present disclosed subject matter. Figure 3A provides a diagram of Doppler spectroscopy on the atom jet, with an Inset indicating the temperature of the dispensers as a function of dispenser current. Figure 3B provides a fluorescence image of the 3D MOT after loading, corresponding to about 107 Sr atoms. Figure 3C provides a diagram of loading curve of the 3D MOT.

Figures 4A-4C provide performance measurement results for the 2D MOT system. Figure 4A provides a diagram of optimization of the achievable loading rate as a function of laser detuning and laser power at the dispenser temperature of 440 °C. Figure 4B provides a diagram of loading rate as a function of dispenser temperature.

Figure 4C provides a diagram of loading rate as a function of push beam power. Data sets in Figure B-C are recorded at a detuning of $-1.5\ \Gamma$ and laser power of 150(2) mW.

It is to be understood that both the foregoing general description and the following detailed description are exemplary and are intended to provide further explanation of the disclosed subject matter.

DETAILED DESCRIPTION

The present disclosure provides techniques for systems, methods, and utilization for a high-flux jet loaded cold atomic beam source for strontium.

Reference will now be made in detail to the various exemplary embodiments of the disclosed subject matter, which are illustrated in the accompanying drawings. The structure and corresponding method of operation of the disclosed subject matter will be described in conjunction with the detailed description of the system. The accompanying drawings, where like reference numerals refer to identical or functionally similar elements throughout the separate views, serve to further illustrate various embodiments and to explain various principles and advantages all in accordance with the disclosed subject matter.

For clarity, but not by way of limitation, the detailed description of the presently disclosed subject matter is divided into the following subsections:

I. Definitions;
II. Setup with MOT Design for Jet-Loaded Atomic Beam Source for Sr;
III. System and Method for Jet-Loaded Cold Atomic Beam Source; and
IV. Utilization.

I. Definitions

The terms "comprise(s)," "include(s)," "having," "has," "can," "contain(s)," and variants thereof, as used herein, are intended to be open-ended transitional phrases, terms, or words that do not preclude additional acts or structures. The singular forms "a," "an," and "the" include plural references unless the context clearly dictates otherwise. The present disclosure also contemplates other embodiments "comprising," "consisting of," and "consisting essentially of," the embodiments or elements presented herein, whether explicitly set forth or not.

As used herein, the term "about" or "approximately" means within an acceptable error range for the particular value as determined by one of ordinary skill in the art, which will depend in part on how the value is measured or determined, i.e., the limitations of the measurement system. For example, "about" can mean within 3 or more than 3 standard deviations, per the practice in the art. Alternatively, "about" can mean a range of up to 20%, up to 10%, up to 5%, and up to 1% of a given value. Alternatively, e.g., with respect to biological systems or processes, the term can mean within an order of magnitude, within 5-fold, and within 2-fold, of a value.

As used herein, the term "atoms with two valence electrons" refers to atoms with a level structure that features singlet and triplet electronic states, including not limiting to ytterbium (Yb), strontium (Sr), cesium (Cs), rubidium (Rb), erbium (Er), dysprosium (Dy), any other alkaline-earth, and lanthanide elements. With the specific electronic structure, they have become increasingly used in ultracold quantum science endeavors, and other industries, in recent years.

As used herein, the term "MOT" or "magneto-optical trap" refers to a conception, including a system or method, capable to capture or trap atoms, in conjunction with laser cooling. The MOT system or apparatus can be generally

integrated with a magnetic field and laser system, the combination of which allows the atoms to be captured and maintained because the atoms are moving slowly enough at low temperature to be trapped using magnetic fields.

As used herein, the term "atom flux" refers to the rate at which atoms move through a given area, including a hole or opening, per unit time, generally used in the field of quantum physics. The measurement of atom flux can be implemented using a spectrometry. Atom flux can be quantified using the unit: the amount of atoms that flow through a unit area in a unit time, for example but not limited into, atoms per second.

As used herein, the term "differential pumping tube" refers to a tube with a varying diameter that is used to connect two regions of a vacuum system with different vacuum levels, to provide a stable transition between high-low vacuum regions.

As used herein, the term "science chamber", refers to a vacuum chamber.

As used herein, the term "Zeeman slower" refers to a device used in atomic physics to cool and slow down an atomic beam by using the Zeeman effect and laser cooling.

As used herein, the term "optical clock" refers to a type of atomic clock that uses natural vibrations of atoms as a frequency reference to keep track of time. Optical clocks can use the much higher frequencies of visible or ultraviolet light, and have a wide range of potential applications and practical uses in areas such as navigation, geodesy, and telecommunications.

As used herein, the term "atomic beam" refers to a stream of atoms that can be produced by heating a solid or gas containing the atomic species of interest, and

then expanding the resulting vapor through a small nozzle or hole. The atoms in the beam are typically in a high-energy state and reactive.

As used herein, the term "ultracold strontium (Sr) atom" refers to an atom, e.g., Sr, of the element strontium that has been cooled to a substantially low temperature, for example near absolute zero. At these temperatures, the kinetic energy of the atoms is low enough to cause the atoms to move slowly and allow atoms to be trapped and manipulated. Ultracold Sr atoms can be created using laser cooling and trapping techniques.

As used herein, the term "magic wavelength" refers to a specific wavelength of light that has the unique property of exerting the same force on an atom in different energy states. For Sr atoms, with magic wavelength of around 500-550nm, atom arrays with submicron spacing are feasible, enabling more accurate optical clock operation, quantum computation and quantum simulation in applications.

As used herein, the term "tweezer experiment" is a type of experiment within the field of physics, in which individual particles, typically including atoms or molecules, are trapped and manipulated using tightly focused laser beams. In such a tweezer experiment, the laser beams can act like a pair of tweezers, grabbing and moving small particles with high precision.

Ranges provided herein are understood to be shorthand for all of the values within the range. For example, a range of 1 to 50 is understood to include any number, combination of numbers, or sub-range from the group consisting of 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, or 50 as well as all intervening decimal values between the aforementioned integers such as, for

example, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, and 1.9. Ranges disclosed herein, for example, "between about X and about Y" are, unless specified otherwise, inclusive of range limits about X and about Y as well as X and Y. With respect to sub-ranges, "nested sub-ranges" that extend from either endpoint of the range are specifically contemplated. For example, a nested sub-range of an exemplary range of 1 to 50 can include 1 to 10, 1 to 20, 1 to 30, and 1 to 40 in one direction, or 50 to 40, 50 to 30, 50 to 20, and 50 to 10 in the other direction.

II. Setup with MOT Design for Jet-Loaded Atomic Beam Source for Sr

[0001] The present discourse provides a design and setup for the systems and methods of a jet-loaded atomic beam source for Sr. The setup can achieve a compact, maintenance-free, less power-consuming, mechanical shutter-free system and a convenient and user-friendly method, with an output of a cold Sr atom flux of up to 10^8 atoms per second. The setup can overcome some drawbacks for Zeeman slower or commercial apparatus, for example, being bulky, large footprint, not particularly easy to manufacture, and non-affordable.

In certain embodiments, an exemplary 2D MOT system for a high flux jet-loaded cold atomic beam source for Sr is provided, comprising a vacuum system, a dispenser assembly, a laser system, and a magnetic field generator. In some examples, but no way of limitation, a setup for the 2D MOT system can be shown as Figures 1A-1D, illustrating certain components and/or connection thereof.

In certain embodiments, as shown in Figure 1D indicating the all-inclusive schematic view for the 2D MOT system 200, the setup features a majority of off-the-shelf components, making it reproducible and compact. For 2D MOT

implementation, at least an ion pump 208, dispenser 104, magnet 106, and laser system 108 are integrated in the system,

A valve 210 in between 2D MOT 102 and glass cell 206 allows independent vacuum servicing on either side, allowing to replace the dispensers if they ever get depleted. Additionally, some ion pumps 208 are located in the vacuum system for providing vacuum environment. Optionally, a 3D MOT 202 is located in a glass cell 206 for Sr atom flux measurement, connecting with the 2D MOT 102 via a differential pumping tube, further merging with an ion pump to reinforce the vacuum. The 2D MOT 102 and 3D MOT 202, separated by a differential pumping tube 204, are located less than half a meter away.

The vacuum system is constructed from commercially available ultra-high vacuum (UHV) components. A 2D-MOT chamber is configured to being a six-way cross made of non-magnetic stainless steel (316SS). The vacuum environment is maintained by the ion pump 208 with a pumping speed of 20 l/s. The 2D MOT chamber is connected to the science chamber of the main apparatus through an exit port. The exit port is comprised of a tube that is 90 mm long with an inner diameter of 2 mm and serves as a differential pumping tube, allowing for a pressure differential of about 104 between the 2D MOT 102 and the science chamber. A bore is set with vertically offset 3 mm above the center of the six-way cross to account for the gravitational drop of the atomic beam on the way to the science chamber. Transverse cooling light released by the laser system 108 enters from four uncoated Kodial glass viewports on the sides. The axial flange opposite to the exit port is designed to accept mounting structures for the dispensers 104 and electric connections 112, and has a through-hole for a push beam 210.

Such a design allows for a relatively short distance between the 2D MOT 102 and the science chamber. The 2D MOT 102 is formed about 1 cm away from the opening of the differential pumping tube and exits the differential pumping tube after about 10 cm of travel. The total travel distance between the 2D MOT 102 and a 3D MOT 202 (the further measurement unit in the integrated system for jet load atomic beam source) is less than half a meter. This is substantially shorter than the 75 cm in an earlier realization of a Sr 2D MOT. Closer proximity increases the usable atomic flux as the atomic beam fans out less due to transverse motion on the way to the science chamber. This issue could be more pronounced than in alkali 2D MOTs, as the transverse temperature of Sr remains relatively high (about 1 mK). In the setup, the solid angle of the atomic beam that can be captured is 126 mrad, which can be further increased.

During operation of the 2D MOT 102, the pressure in the 2D MOT chamber remains as low as 1×10^{-9} torr due to the low vapor pressure of Sr.

In the setup of the dispenser assembly, Sr atoms are introduced into the system by generating a hot atomic jet that emerges from a resistively heated dispenser 104, containing bulk atomic Sr. The dispenser assembly can be custom designed. In certain embodiments, the dispenser 104 is arranged to bring the output opening thereof as close as possible to the 2D MOT trapping region, shown as Figures 1A-1B. This allows for direct capture of cold Sr atoms from the dispenser jet, minimizing the amount of atoms that fly-by uncaptured and stick to the chamber walls.

In certain embodiments, the dispenser assembly is configured via two U-shaped dispensers produced by a commercial vendor (AlfaVakuo), shown as Fig. 1C. They are comprised of a steel tube, filled with bulk Sr with natural abundance. The opening is a 5 mm long slit that before activation is sealed with indium. In certain

embodiments, a framework with the two dispensers with 2 mm diameter has a filling of 40 mg of Sr. In certain embodiments, larger capacity dispenser(s) with a filling of more than 200 mg of Sr can be accommodated with a similar design. The distance between the output opening of the dispenser assembly and the 2D MOT trapping region is about 1.5 cm. For electrical connection, the flat legs of the dispensers are connected to BeCu in-line barrel connectors that are isolated from the vacuum flange with ceramic spacers (FTACERB068, Kurt J. Lesker).

In order to block the hot atom jet from coating the viewports of the system 200, a shaped shield 110, e.g., an L-shaped shield, is placed around the dispensers 104 made from stainless steel (SAE 304) sheet metal, shown in Figure 1C. The shield 110 comprises a cut-out that restricts the solid angle of the fanned-out hot atom flux, but the cut-out is narrow enough to protect the viewports from Sr coating and large enough to fully expose the trapping region.

In certain embodiments, a laser system 108 can be included in the integrated setup. The laser system can provide laser cooling to create the 2D MOT. The relevant transitions for laser cooling and repumping of ^{88}Sr are shown in Figure 2A. In certain embodiments, for the operation of the 2D MOT, laser light at 461 nm is used, and for the operation of a 3D MOT, repumping lights at 679 nm and 707 nm are used. As shown in Figure 2B, a master laser 2010 is stabilized to a Sr spectroscopy cell and provides light for two injection-locked lasers, Injection 1 2020 and Injection 2 2030 as shown in Figure 2B. These lasers provide the optical power at 461 nm for the 2D and 3D MOT, respectively. The output of injection laser 1 is split into two beam paths for the 2D MOT and the push beam 210.

In certain embodiments, the 461 nm laser system consists of two diode lasers that are injection-locked to a master laser 2010, shown as Figure 2B. which is stabilized to a Sr spectroscopy cell, provides light for two injection-locked lasers, 2020 and 2030. These lasers provide the optical power at 461 nm for the 2D and 3D MOT, respectively. The output of injection laser 1 is split into two beam paths for the 2D MOT and the push beam. The master laser is a commercial external cavity diode laser (ECDL) (Toptica DL Pro) stabilized to a hollow cathode lamp via polarization spectroscopy in a spectroscopy device 2040. It injects two 500 mW diodes (Nichia NDB4916E). Each diode is housed in a temperature-stabilized mount (Thor-labs LDM56F) with a collimation lens (Thorlabs C330TMD-A, f = 3.1 mm, NA = 0.7). Injection happens via an optical isolator (Newport ISO-04-461-MP). With a few mW of seed power, the lasers stay stably locked. The repumping transitions at 679 nm and 707 nm are addressed with laser light from ECDLs that are stabilized to a high-precision wavemeter (HighFinesse WS-7).

The 2D MOT 102 is operated with a total power of 150 mW of 461 nm light, equally distributed onto the two retro-reflected arms (see Fig. 1A). The light is delivered to the setup using a polarization maintaining fiber (OZ Optics QPMJ-3A3A-400). The beams are shaped to a $1/e^2$ -radius of 6 mm using an out-coupler lens (f = 8 mm) and a magnifying telescope (f = 25 mm and f = 200 mm). The push beam is typically operated at a power of 50 -100μW and has a $1/e^2$-radius of 0.8 mm.

Furthermore, under the setup, the quadrupole magnetic field for the 2D MOT is generated via certain permanent magnets 106a, providing the necessary field gradients without consuming power. They are screwed onto a slender aluminum mount that is attached to a robust 3D-printed mount that allows for position adjustments of the magnets 106. Four rectangular permanent magnets 106a (N45 3"x1/2"x1/4", CMS Magnetics) are used.

Mechanical tuning of the magnet location allows adjustments of the field gradient between 20 and 200 G/cm at the trapping region of 2D MOT. The gradients are measured prior to installation of the magnet assembly and match the simulated field distribution. It has been observed that an optimal performance is achieved at a magnetic field gradient of 64 G/cm, but the 3D MOT loading rate remains relatively insensitive over a broad range, i.e., 50-150 G/cm. To allow for fine positioning of the 2D MOT location with respect to the differential pumping tube 204, some additional Helmholtz coil pairs are wound around the ports of the six-way cross using standard magnet wire. Further, certain bias electromagnets 106b are used to apply in the field to control the moving direction of atoms.

III. System and Method for Jet-Loaded Cold Atomic Beam Source

The present disclosure provides systems and methods for jet loaded cold atomic beam source for alkaline-earth and lanthanide atoms, including but not limiting to, Sr, Cs, Yb, Rb, Er, and Dy.

In certain embodiments, a dispenser-based two-dimensional (2D) magneto optical traps (MOT) system for strontium (Sr) is provided. The system can comprise the following components, but not by way of limitation: a vacuum system including a science chamber and a 2D MOT chamber, a dispenser assembly capable of releasing Sr atoms into the vacuum system, a laser system, releasing cooling laser for cooling Sr atoms in two dimensions, forming a 2D MOT to trap ultracold Sr atoms, and a magnetic field generator, configured to locate fine positions of the 2D MOT location.

In certain embodiments, a vacuum system can include at least one ultra-high vacuum component (UHV) and a central component of which includes a six-way cross composed of non-magnetic stainless steel. For example, but not by way of limitation, UHV component can include a science chamber, and the central component can include a 2D

MOT chamber. In certain embodiments, the 2D-MOT chamber is connected to the science chamber through an exit port. In certain embodiments, the vacuum is maintained with an ion pump, having, for example but not limitation, a pumping speed of 20 liters per second.

In certain embodiments, the vacuum system further comprises a differential pumping tube to which the 2D MOT is aligned, to maintain a high vacuum in the 2D MOT trap region to create an atomic beam for Sr atoms. In certain embodiments, the differential pumping tube can allow a pressure differential of about $1*10^4$-$5*10^4$ between the 2D MOT and the science chamber. In certain embodiments, the fine-alignment between 2D MOT and differential pumping tube is adjusted by electromagnets attached to the six-way cross. In certain embodiments, the differential pumping tube can connect the 2D MOT and 3D MOT.

In certain embodiments, the laser system can release transverse cooling light in a two-dimensional direction to form a 2D MOT (in the 2D MOT chamber). The distance between the 2D MOT and the science chamber can be a relatively short. For example, but not by way of limitation, the 2D MOT is formed about 0.1-5.0 cm away from the opening of the differential pumping tube and exits the differential pumping tube after about 5-10 cm of travel.

In certain embodiments, the system further comprises a 3D MOT, serving as flux measurement unit for ultracold Sr atoms. In certain embodiments, the total travel distance between the 2D MOT and a 3D MOT can be 40-50 cm. In certain embodiments, the solid angle of the atomic beam that can be captured is 110-150 mrad. In certain embodiments, the pressure in the 2D MOT chamber can be $1*10^{-8}$ - $1*10^{-9}$ torr.

In certain embodiments, Sr atoms can be introduced into the system by generating an atomic jet via a dispenser. The dispenser assembly can include a U-shaped

dispenser and a steel tube filled with strontium with natural abundance and a slit-shaped opening.

In certain embodiments, the distance of the output opening of the dispenser assembly and the 2D MOT trap region is from 0.5-5.0cm, including from 1.0-4.0cm, from 1.5-3.0cm, from 2.0-2.5cm, 1.0cm, 1.5cm, 2.0cm, 3.0cm and 4.0cm.

In certain embodiments, the dispenser assembly can have a load capacity of Sr from 20-1000mg, including from 40-900mg, from 100-800mg, from 300-700mg, from 400-600mg, from 450-500mg, 40mg, 200mg, 400mg, 500mg, and 600mg. The load amount can be accommodated on demands.

In certain embodiments, the laser system can release a laser light at various wavelengths, including, but not limited to from 450-750nm, including from 460-710nm, from 500-650nm, 550-600nm, 461nm, 679nm, and 707nm.

In certain embodiments, the system further can comprise a shield. The dispenser assembly is aligned to a through hole for regulating the atomic beam from the dispenser assembly, and also not limiting the atom flux of Sr. Using a push beam initiated by the laser system a measurement can be realized. For example, using the push beam, the relative absorption versus detuning as the change of resistive current through the dispenser is measured. As the atoms get hotter, the absorption profile gets broader. Fitting those curves based on measurement, a conversion of supplied current into the temperature of the atoms out of the dispensers is realized.

In certain embodiments, the system can further include a 3D MOT, serving as flux measurement unit for ultracold Sr atoms. For example, the push beam is used to push the ultracold Sr atoms into a glass cell in the 3D MOT for measuring the trapped atoms flux.

Further, taking a time series of fluorescence images and converting this series to atomic number, the amount of atoms trapped per second and trapped in total are obtained.

In certain embodiments, the magnetic field generator can generate one or more magnetic fields via one or more permanent magnets. For example, but no way of limitation, the magnetic field gradient can be from 50-150 G/cm, including from 60-130G/cm, from 80-120 G/cm, and from 90-100 G/cm.

Further, the present disclosure provides a method for trapping strontium (Sr) based on two-dimensional magneto optical trap (2D MOT). In certain embodiments, the method can include releasing Sr atoms into a vacuum system via a dispenser assembly; cooling Sr atoms by laser cooling in two dimensions, thereby creating a 2D MOT; trapping the Sr atoms in a magnetic field using permanent magnets; and collecting the trapped and ultracold atoms.

In certain embodiments, the method can further comprise measuring atom flux of the collected ultracold Sr atoms by a 2D MOT via the loading rate of a 3D MOT. For example, but not by way of limitation, using a push beam to push the ultracold Sr atoms into a glass cell in the 3D MOT and measuring the accountable fluorescence indicators can perform a measurement of atom flux.

In certain embodiments, the loading rate for Sr atoms is 10^8 atoms per second.

In certain embodiments, the dispenser temperature is from 100-700°C.

In certain embodiments, the push beam power is from 50-250 μW.

IV. Utilization.

Further, the present disclosure provides utilization of systems and method for a jet-loaded cold atomic beam source for Sr, in the fields of quantum applications, including not limiting to optical clock, quantum simulator, and quantum computer, etc.

EXAMPLES:

Example 1: Calibration of System Parameters

According to the above setup for the 2D MOT system, in the example the experimental setup and process for the system and method are based on the setup, unless otherwise specified. For example, the 2D MOT is formed about 1 cm away from the opening of the differential pumping tube and exits the differential pumping tube after about 10 cm of travel. The total travel distance between the 2D MOT and a 3D MOT is less than half a meter. This is shorter than the 75 cm in an earlier apparatus of a Sr 2D MOT. Closer proximity increases the usable atomic flux as the atomic beam fans out less due to transverse motion on the way to the science chamber. In the setup, the solid angle of the atomic beam that can be captured is 126 mrad, which can be further increased depending on the demands. During operation of the 2D MOT, the pressure in the 2D MOT chamber remains as low as $1*10^{-9}$ torr due to the low vapor pressure of Sr.

Regarding the dispenser assembly, the opening is configured to be a 5 mm long slit that before activation is sealed with indium. Two U-shaped dispensers with 2 mm diameter have a filling of 40 mg of Sr for heating to release. Larger capacity dispensers with a filling of more than 200 mg of Sr can be accommodated. The distance between the output opening of the dispenser assembly and the 2D MOT trapping region is about 1.5 cm. An L-shaped shield is placed around the dispensers, having a cut-out that restricts the solid angle of the fanned-out hot atom flux, but is narrow enough to protect the viewports from Sr coating and large enough to fully expose the trapping region.

Regarding the laser system, the 2D MOT is operated with a total power of 150 mW of 461 nm light. The beams are shaped to a $1/e^2$ -radius of 6 mm using an out-coupler lens (f = 8 mm) and a magnifying telescope (f = 25 mm and f = 200 mm). The push beam is typically operated at a power of 50 -100μW and has a $1/e^2$-radius of 0.8 mm.

Beside the above setup, in the instant example the temperature of the hot atom jet out of the Sr dispensers is characterized as a function of dispenser current in the current experiment. Here, Doppler spectroscopy is applied on the atom jet using the on-axis push beam, and the relevant transitions for laser cooling and re-pumping are set as follows: for the operation of the 2D MOT only laser light at 461 nm is used; for the operation of the 3D MOT, we also use repumping light at 679 nm and 707 nm. It has been assumed that in the direction of the push beam, the velocity distribution of the Sr atoms is well-approximated by a one-dimensional Maxwell-Boltzmann distribution. By fitting the measured Doppler profiles, an approximate value for the dispenser temperature at different currents has been obtained, as shown in Figure 3A. From the observation based on Figure 3A, it shows an angular distribution of the atomic jet and an asymmetry of the Doppler profiles from absorption on the 461 nm transitions of the isotopes ^{86}Sr and ^{87}Sr that are slightly red-detuned compared to the dominant isotope ^{88}Sr.

In the following, the performance of the 2D MOT by measuring the loading rate of the 3D MOT is characterized The loading rate of the 3D MOT is a measure of the trappable flux and smaller than the total atom flux out of the 2D MOT. As such, it is a conservative lower bound for the cold atom flux from the source. The 3D MOT is comprised of three retro-reflected beam pairs and a magnetic quadrupole coil with its symmetry axis aligned vertically. The horizontal (vertical) beams use a power of 4 mW (2.5 mW) and have

a $1/e^2$-radius of 3.5 mm (2.5 mm). The detuning of the cooling beams is −1.5 Γ. The magnetic quadrupole field has a gradient of 45 G/cm along the vertical axis.

The atom number in the 3D MOT is evaluated via fluorescence imaging during loading using an EMCCD camera (Andor iXon Ultra 888), as shown in Figure 3B. The atom number calibration of fluorescence imaging has been confirmed via absorption imaging. The loading rate L is extracted by fitting the observed MOT loading curves (shown in Figure 3C) to the solution of the differential equation $N(t) = -\alpha N(t) + L$, where $N(t)$ is the atom number at time t and α is the single-body loss rate.

Example 2: Performance of the 2D MOT

In the instant example, the performance of the 2D MOT as a function of the relevant experimental parameters was investigated. First, a scan of the detuning and optical power of the cooling light was performed, as shown in Figure 4A. As a result, peak performance for a detuning of −1.5 Γ and an optical power of 120 − 150 mW were determined. The near peak performance is observed over a fairly broad parameter range of detuning and optical power.

As shown in Figure 4B, the atomic flux can be smoothly tuned over several orders magnitude via the dispenser temperature. For the highest dispenser temperature at 635 °C, a loading rate of up to 10^8 s^{-1} was observed. In daily operation, a temperature of 440 °C is able to provide a loading rate and 3D MOT size that is sufficient for Sr tweezer experiment. Finally, an investigation of the loading rate as a function of push beam power was made, with a result as shown in Figure 4C. A pronounced peak is shown at around 60 μW, which corresponds to an intensity of $I = 0.14 I_{sat}$. For lower powers, the atomic beam is not effectively pushed through the differential pumping tube and fans out too much before reach-

ing the 3D MOT region. For higher powers, the atomic beam is accelerated to velocities beyond the capture velocity of the 3D MOT at about 30 m/s.

The atomic flux out of the 2D MOT can be effectively stopped by simultaneously switching off the cooling and push beams. An additional mechanical shutter is not needed.

In the performance example experiment of the 2D MOT system, data sets in loading rates measurement are recorded at a detuning of $-1.5\ \Gamma$ and laser power of 150(2) mW.

Compared to dispenser-based 2D MOT Sr sources reported in the art, the present disclosed subject matter can achieve an enhancement of cold Sr atom flux by three orders of magnitude, via the close proximity of the dispensers to the 2D MOT cooling region, consequently facilitating efficient capture from the dispenser jet and minimizing the amount of atoms that fly by uncaptured. Compared to Sr sources based on certain ovens, the present disclosed subject matter achieves a substantially equivalent atom flux, but significantly reduces the size and complexity by replacing the oven with a dispenser assembly and eliminating the Zeeman slower. Due to the small heat capacity of the dispenser assembly, the atomic flux out of the dispenser can also be switched on and off on the second scale by controlling the current, compared to tens of minutes for an oven. The total electrical power consumption of the setup is 13 W (including dispensers and shim coils, without lasers), which is ideal for the use in setups with stringent SWaP requirements. The presented atomic beam source can also be useful for applications in which blackbody radiation needs to be suppressed, e.g., for precision measurements on the Sr clock transition and when using Rydberg states, as the hot dispensers do not have a direct line-of-sight with the science chamber. Not limiting to ^{88}Sr, the disclosed subject matter can be applied to cooling and

trapping of all other naturally occurring isotopes of Sr with the observed flux scaled by the respective percentages of the natural abundance. As shown in Figures 4A-4C, the loading rate has been reached at 10^8 s^{-1} with at around 630 °C. Notably, the actual atomic flux will be larger than the measured loading rate in the example(s) because the measured loading rate is a lower bound of the atoms being delivered to the glass cell.

Further, the example has demonstrated that the 3D MOT loading can be further enhanced by modifying parameters, for example, but no ways of limitations, by shortening the distance between the 2D MOT and the 3D MOT or/and removing the glass metal transition.

This change allows to reach a loading rate of 10^8 s^{-1} at dispenser temperatures below 500 °C. Alternatively, the loading rate of Sr atoms can be up to10^9 s^{-1} under specific modification of the systems or methods.

The present disclosure is not to be limited in scope by the specific embodiments described herein. Indeed, various modifications of the disclosure in addition to those described herein will become apparent to those skilled in the art from the foregoing description and the accompanying figures. Such modifications are intended to fall within the scope of the appended claims.

Publications are cited throughout this application, the disclosures of which are incorporated herein by reference in their entireties.

WHAT WE CLAIM IS:

1. A dispenser-based two-dimensional magneto optical trap (2D MOT) system for strontium (Sr), comprises:

a vacuum system, including at least one ultra-high vacuum component and a central component,

a dispenser assembly adapted to release Sr atoms into the vacuum system;

a laser system, for cooling the Sr atoms in two dimensions, forming a 2D MOT to trap ultracold Sr atoms; and

a magnetic field generator, configured to locate fine positions of the 2D MOT.

2. The system of claim 1, further comprising a 3D MOT, serving as flux measurement unit for ultracold Sr atoms.

3. The system of claim 2, wherein the total travel distance between the 2D MOT and the 3D MOT is 40-50 cm.

4. The system of claim 1, wherein the ultra-high vacuum component includes a science chamber, or/and a central component includes a six-way cross.

5. The system of claim 1, wherein the 2D MOT is configured to create an atomic beam for Sr atoms via a push beam.

6. The system of claim 1, wherein the dispenser assembly includes at least one U-shaped dispenser.

7. The system of claim 1, further comprising a shield around the dispenser to block the atoms from coating on viewports of the dispenser assembly.

8. The system of claim 1, wherein the vacuum system further comprises a differential pumping tube to which the 2D MOT is aligned.

9. The system of claim 1, wherein the distance of the output opening of the dispenser assembly and the 2D MOT trap region is 0.5-5.0 cm.

10. The system of claim 8, wherein the differential pumping tube connects the 2D MOT and 3D MOT.

11. The system of claim 1, wherein one or more coil pairs are wound around the ports of a six-way cross using standard magnet wire in the magnetic field generator.

12. The system of claim 1, wherein the magnetic field generator is attached to a 3D mount, providing a magnetic field gradient without consuming power.

13. A method for trapping strontium (Sr) based on two-dimensional magneto optical trap (2D MOT), comprises the following:

releasing Sr atoms into a vacuum system via a dispenser;

cooling Sr atoms by laser cooling in two dimensions, thereby creating a 2D MOT;

trapping the Sr atoms in a magnetic field using permanent magnets;

collecting the trapped and ultracold atoms.

14. The method of claim 13, further comprise measuring atom flux of the collected ultracold Sr atoms via a 3D MOT.

15. The method of claim 14, wherein measuring atom flux by loading a push beam to push the ultracold Sr atoms into a glass cell in the 3D MOT.

16. The method of claim 15, wherein measuring atom flux via a fluorescence image detection.

17. The method of claim 13, wherein the dispenser assembly releases Sr atoms by at least heating a filling of loaded bulk Sr therein.

18. The method of claim 13, wherein the dispenser releases Sr atoms without a mechanical shutter.

19. The system of claim 13, wherein the temperature of the dispenser temperature is from 100-700°C.

20. A utilization of ultracold Sr atoms trapped via a system of claim 1 in a quantum operation selected from a group consisting of an optical clock, quantum simulator, and quantum computer, comprising using the trapped ultracold Sr atoms for the quantum operation.

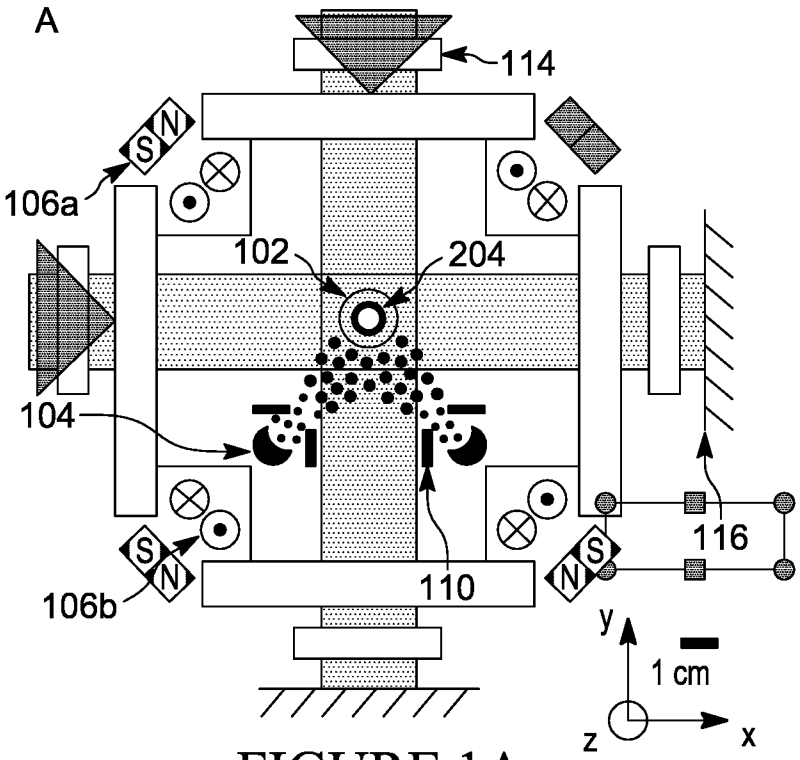


FIGURE 1A

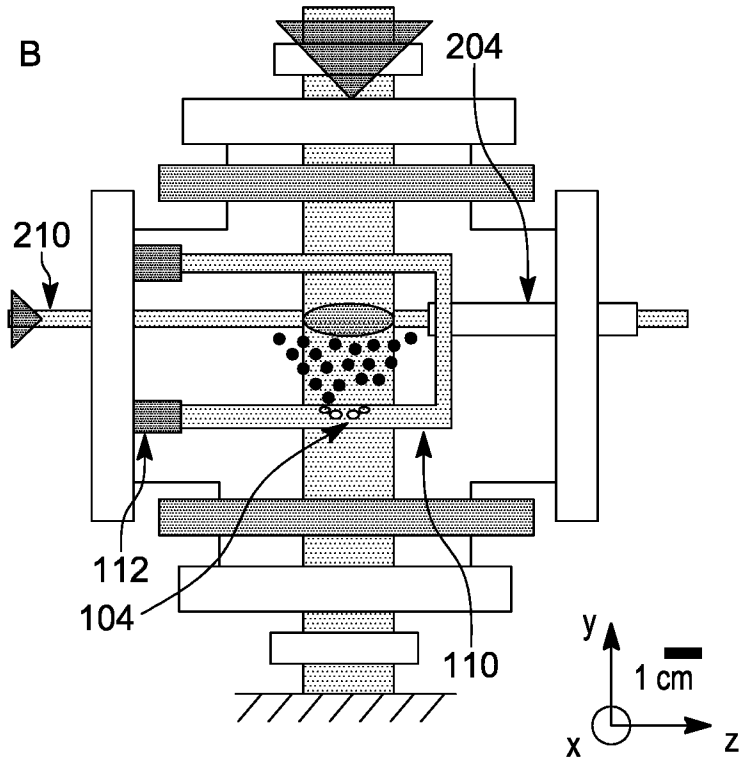


FIGURE 1B

C

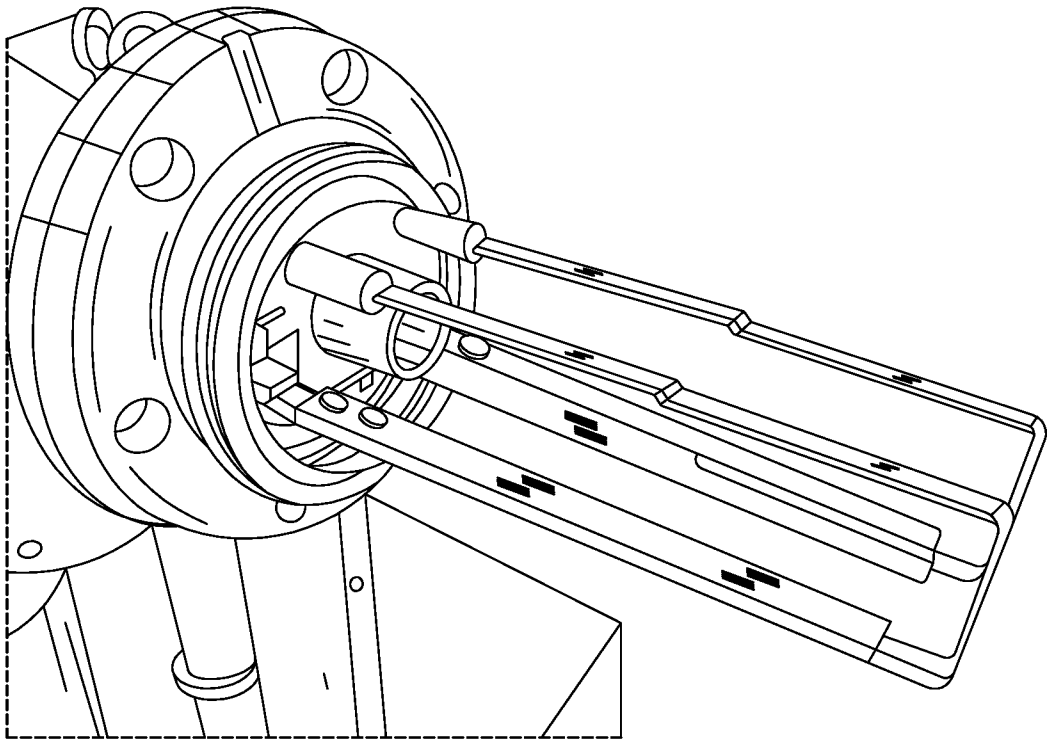


FIGURE 1C

D

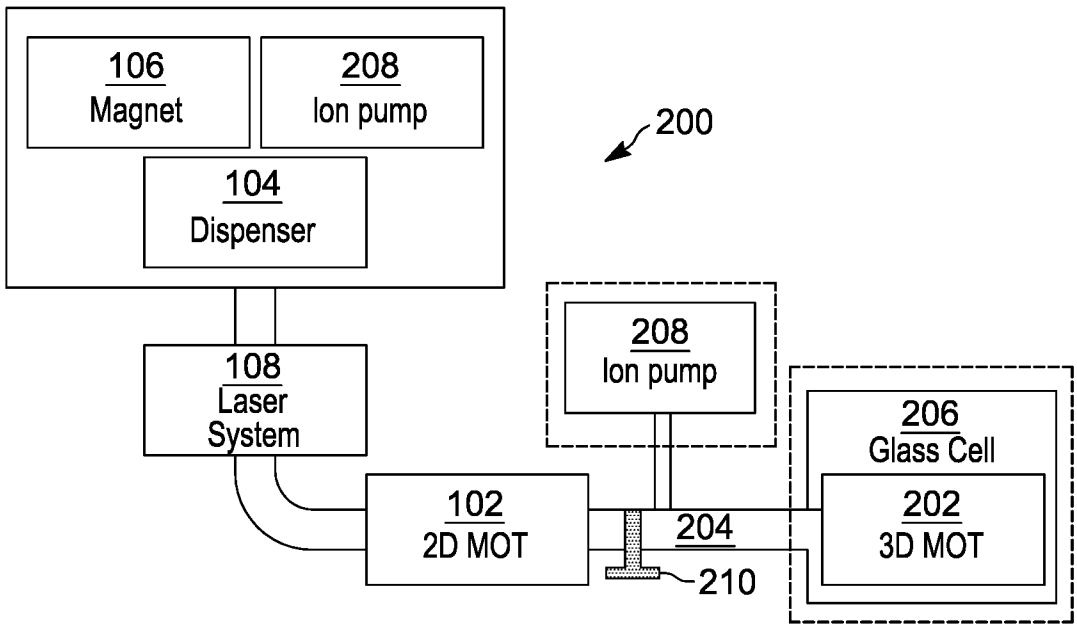


FIGURE 1D

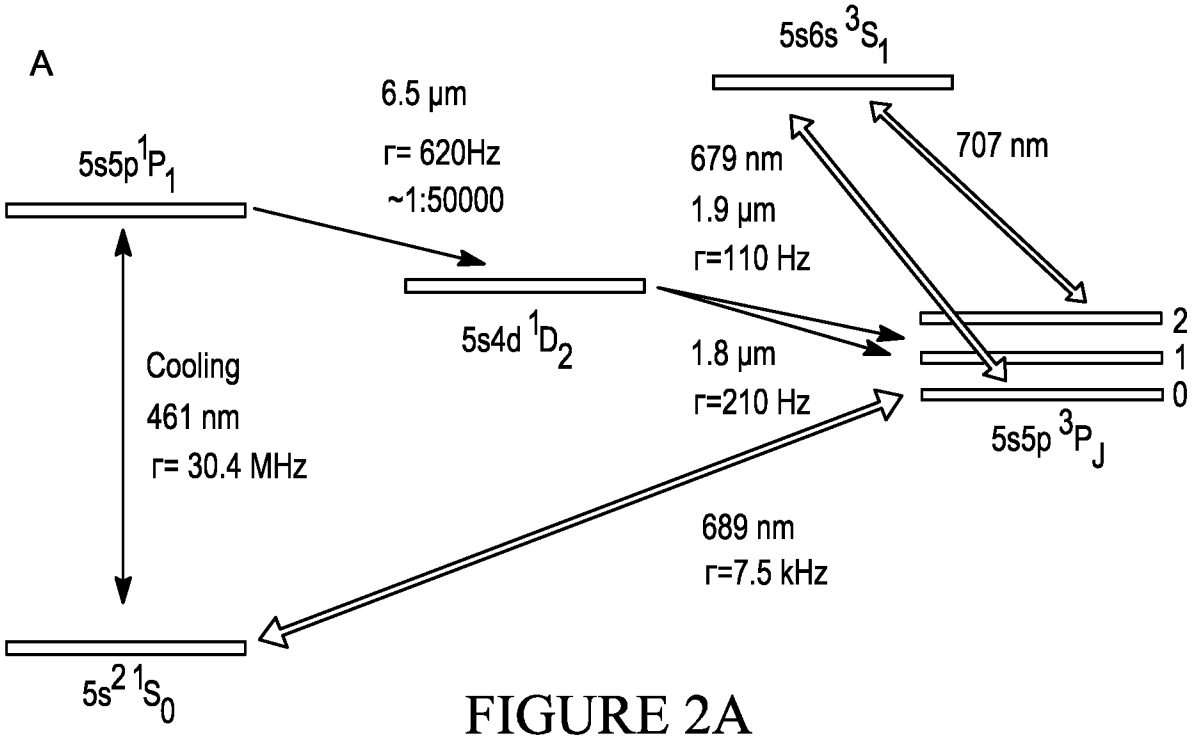


FIGURE 2A

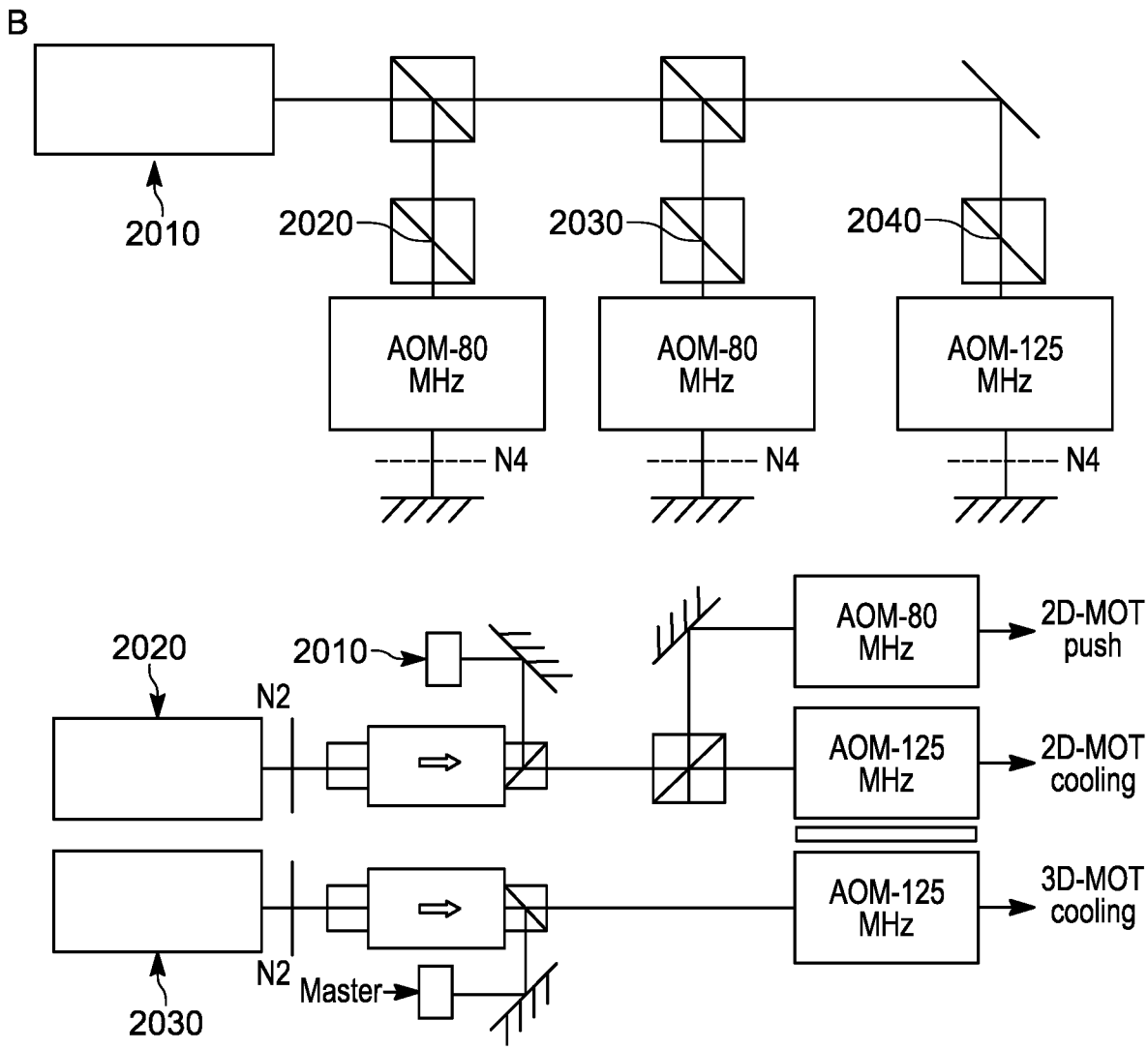


FIGURE 2B

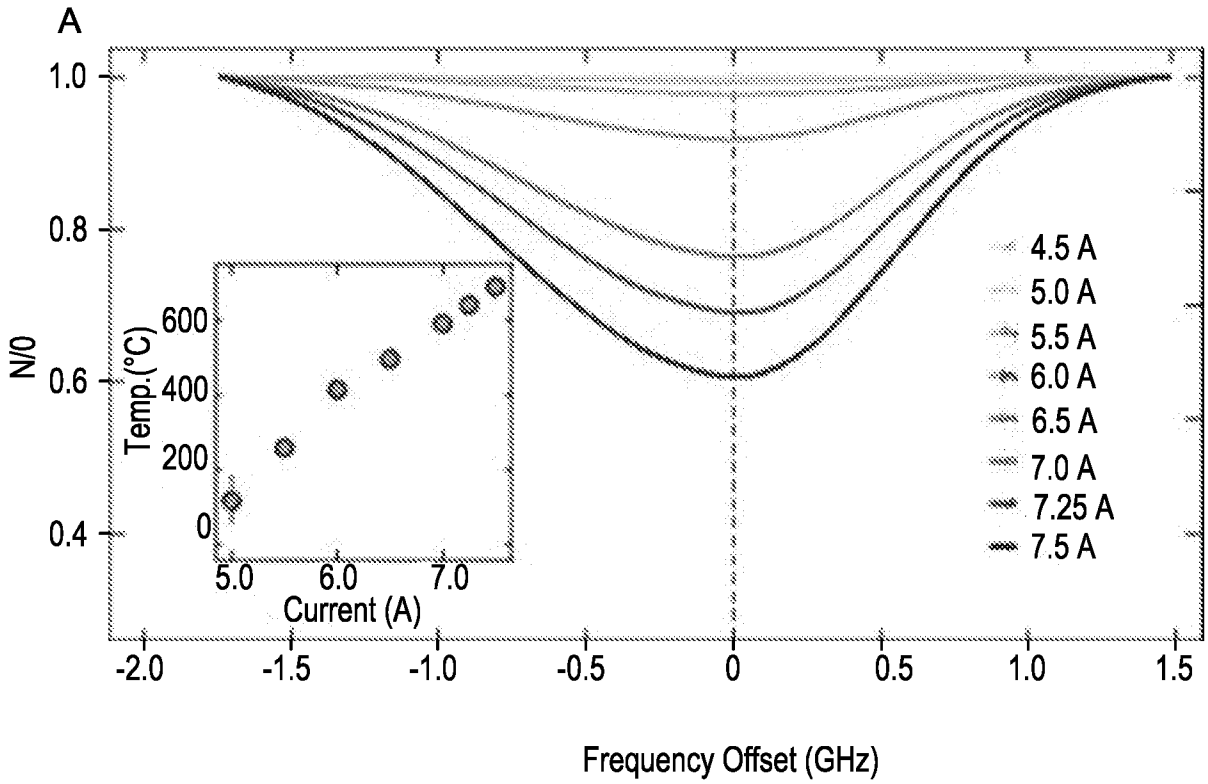


FIGURE 3A

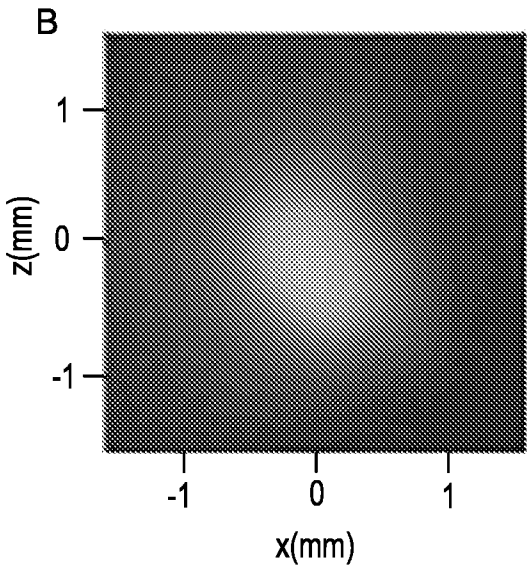


FIGURE 3B

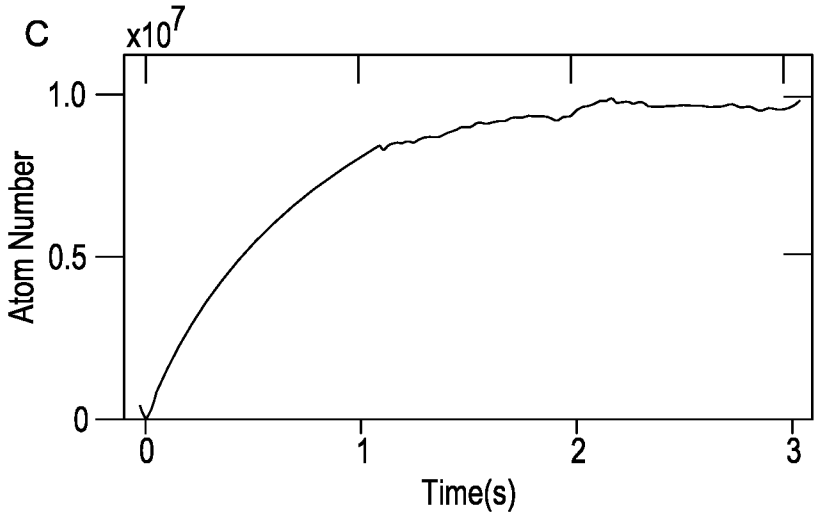


FIGURE 3C

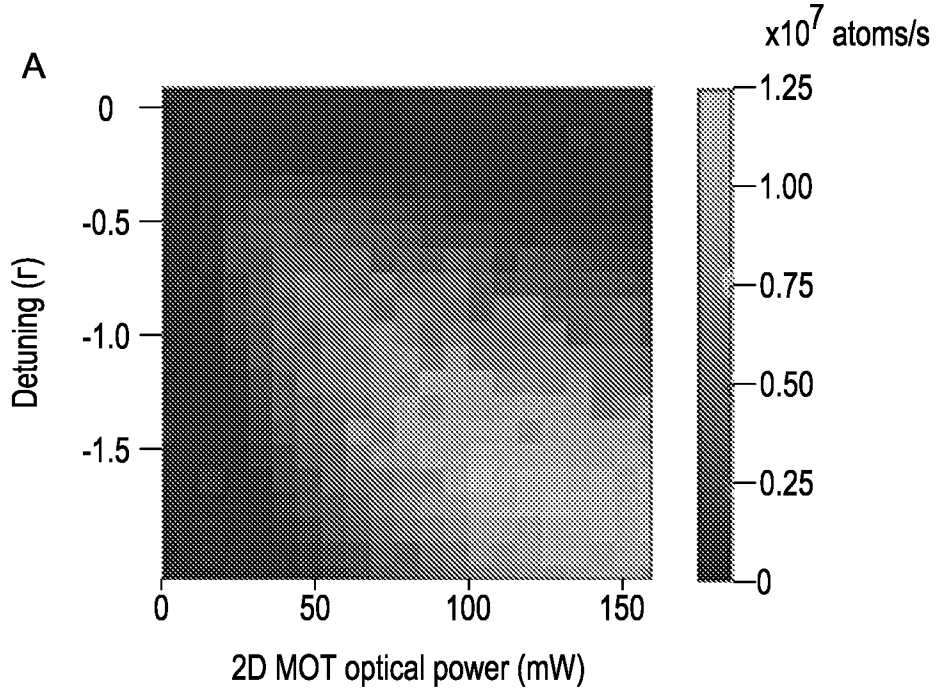


FIGURE 4A

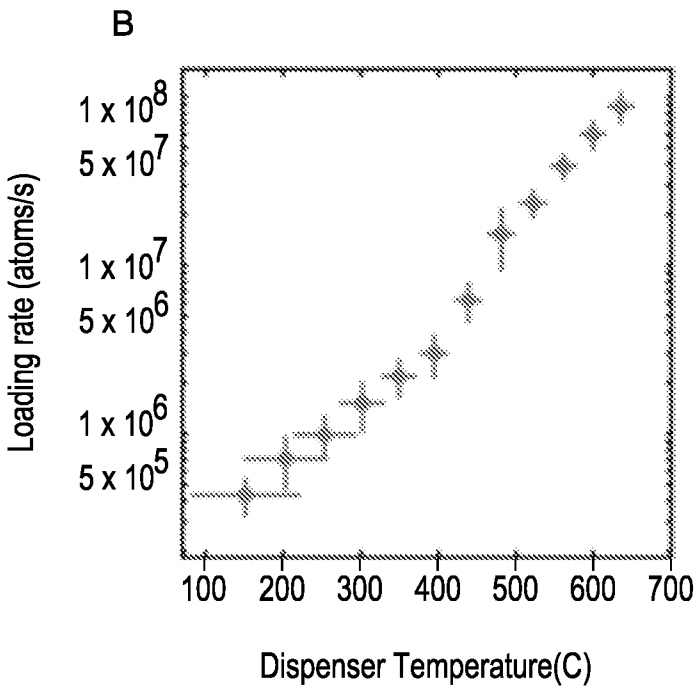


FIGURE 4B

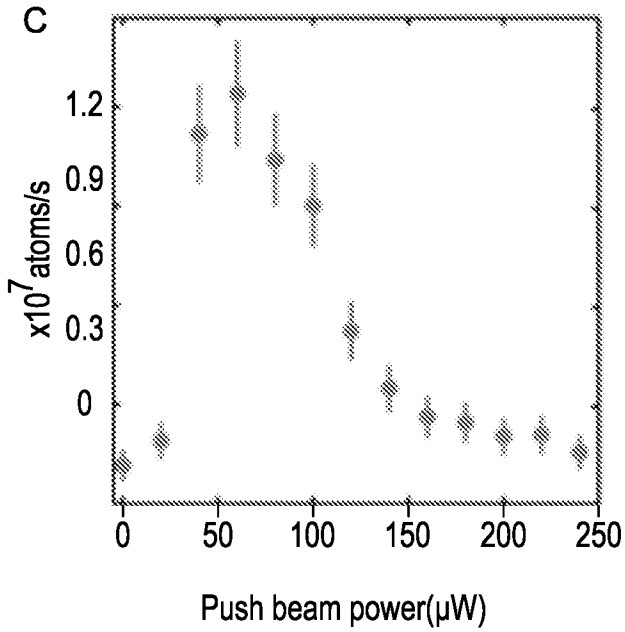

C
1.2
0.9
0.6
0.3
0
x10^7 atoms/s
0
50
100
150
200
250
Push beam power(μW)

FIGURE 4C

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US 23/22900

A. CLASSIFICATION OF SUBJECT MATTER

IPC - INV. G21K 1/08, G21K 1/093, G21K 1/00, H05H 3/02, H01F 7/06 (2023.01)
ADD. G21K 1/06 (2023.01)

CPC - INV. G21K 1/08, G21K 1/093, G21K 1/00, G21K 1/006, H05H 3/02, H01F 7/06
ADD. G21K 1/06

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
See Search History document

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
See Search History document

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
See Search History document

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	LAM et al. "Compact 2D Magneto-Optical Trap for Ultracold Atom Setups" Atomic Physics, 02 July 2021 (02.07.2021); entire document, especially abstract, Fig. 1a-1c, Fig. 2, Fig. 1 caption, Fig. 2 caption, pg. 1-3. [online] <https://arxiv.org/abs/2012.06688>	1-20
Y	US 2020/0120785 A1 (GOVERNMENT OF THE UNITED STATES OF AMERICA, AS REPRESENTED BY THE SECRETARY OF COMMERCE) 16 April 2020 (16.04.2020) entire document; especially para [0025]	1-20
Y	US 2009/0013826 A1 (MCBRIDE et al.) 15 January 2009 (15.01.2009) entire document; especially Fig. 4A, para [0003], para [0006], para [0047]	6
Y	US 2013/0048846 A1 (DU et al.) 28 February 2013 (28.02.2013) entire document; especially para [0003], para [0025]	11, 15
Y	US 2006/0257296 A1 (LIPP) 16 November 2006 (16.11.2006) entire document; especially para [0084]	19

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"D" document cited by the applicant in the international application
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 July 2023	AUG 02 2023
Name and mailing address of the ISA/US Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Authorized officer Kari Rodriquez Telephone No. PCT Helpdesk: 571-272-4300