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Patent

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Coke Moya Smead

ACTING DIRECTOR OF THE UNITED STATES PATENT AND TRADEMARK OFFICE

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Patent Term Notice

If the application for this patent was filed on or after June 8, 1995, the term of this patent begins on the date on which this patent issues and ends twenty years from the filing date of the application or, if the application contains a specific reference to an earlier filed application or applications under 35 U.S.C. 120, 121, 365(c), or 386(c), twenty years from the filing date of the earliest such application (“the twenty-year term”), subject to the payment of maintenance fees as provided by 35 U.S.C. 41(b), and any extension as provided by 35 U.S.C. 154(b) or 156 or any disclaimer under 35 U.S.C. 253.

If this application was filed prior to June 8, 1995, the term of this patent begins on the date on which this patent issues and ends on the later of seventeen years from the date of the grant of this patent or the twenty-year term set forth above for patents resulting from applications filed on or after June 8, 1995, subject to the payment of maintenance fees as provided by 35 U.S.C. 41(b) and any extension as provided by 35 U.S.C. 156 or any disclaimer under 35 U.S.C. 253.



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Lin et al.

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(54) **QUANTUM CHARGE-COUPLED DEVICE**

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(73) Assignee: **National Taiwan University**, Taipei (TW)

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(21) Appl. No.: **17/993,887**

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Related U.S. Application Data

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(60) Provisional application No. 63/283,548, filed on Nov. 29, 2021.

(57)

ABSTRACT

(30) **Foreign Application Priority Data**

Sep. 6, 2022 (TW) 111133656

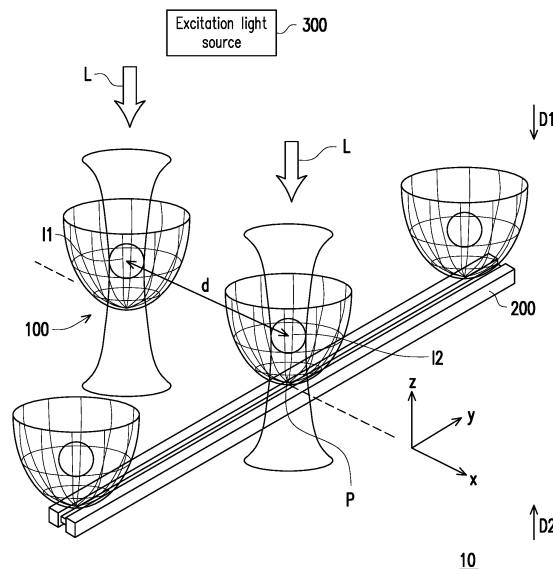
A quantum charge-coupled device including a first ion, a second ion, a fixed ion trap, an adjustable ion trap, and an excitation light source is provided. The fixed ion trap is configured to stationarily trap the first ion. The adjustable ion trap works as an ion rail disposed beside the fixed ion trap, wherein the ion rail is configured to make the second ion move at a constant velocity along the ion rail. The excitation light source is configured to irradiate an incident light beam. The incident light beam includes a series of light pulses and covers the first ion and the second ion when a distance between them becomes less than or equal to a proximity range, such that a quantum entangled state is directly built between the first ion and the second ion in uniform motion.

(51) **Int. Cl.**
G06N 10/40 (2022.01)

(52) **U.S. Cl.**
CPC **G06N 10/40** (2022.01)

(58) **Field of Classification Search**
CPC G06E 1/00; G06N 10/00; B82Y 10/00
See application file for complete search history.

11 Claims, 5 Drawing Sheets



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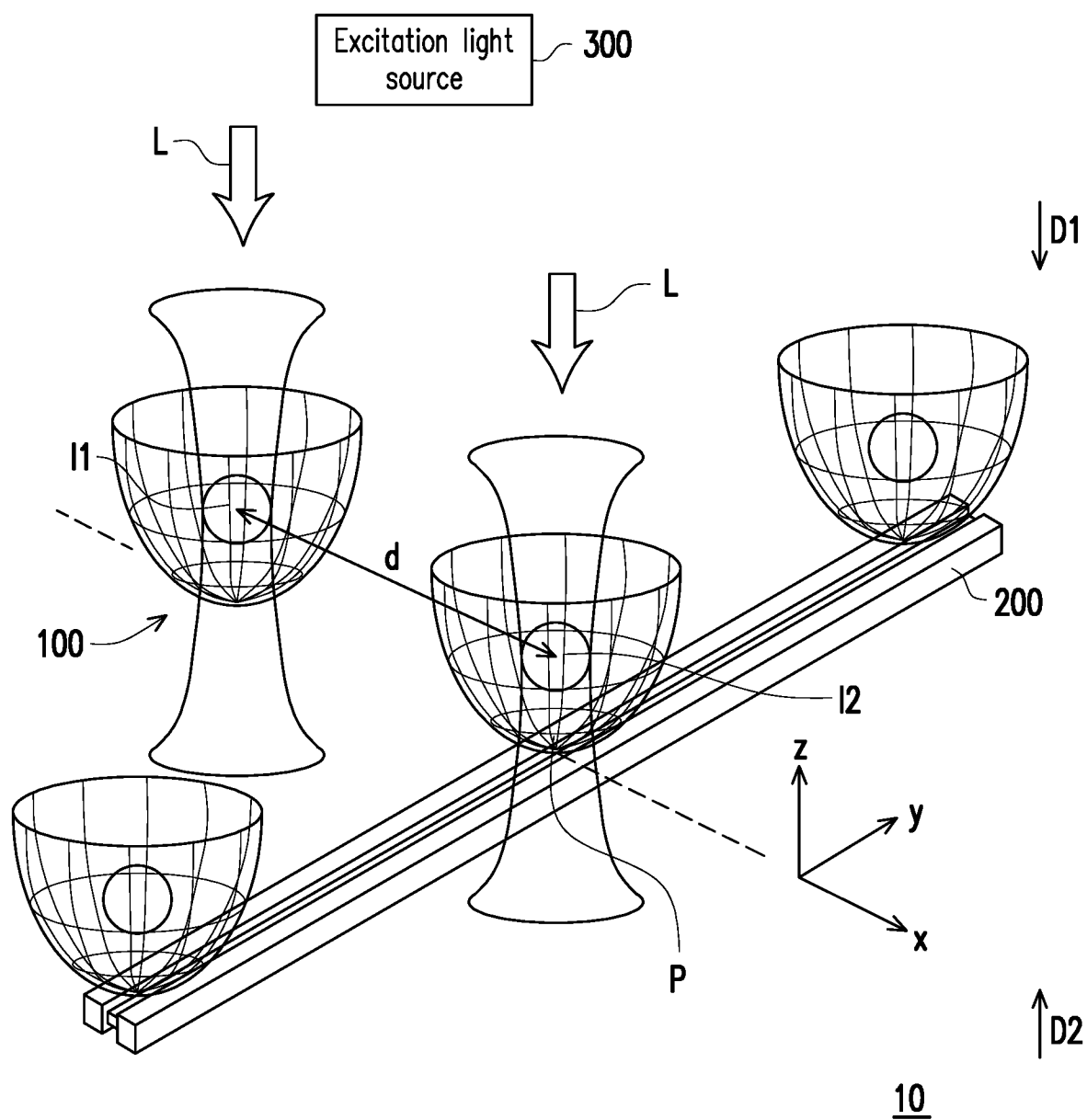
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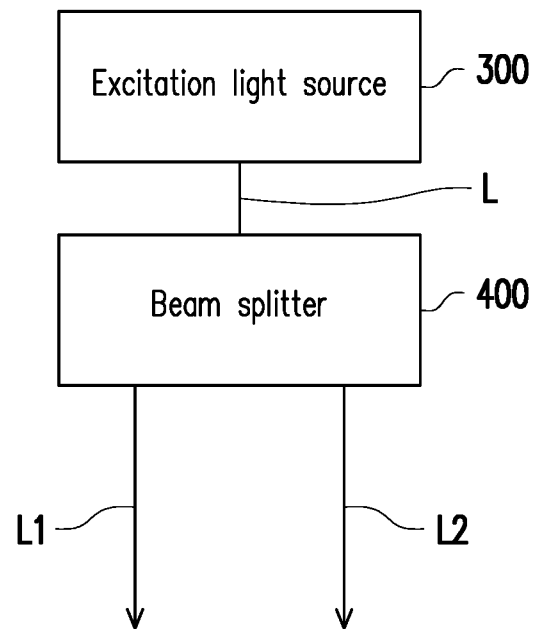


FIG. 2

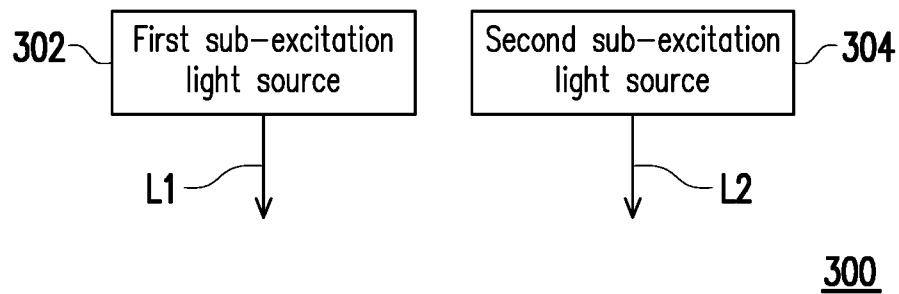


FIG. 3

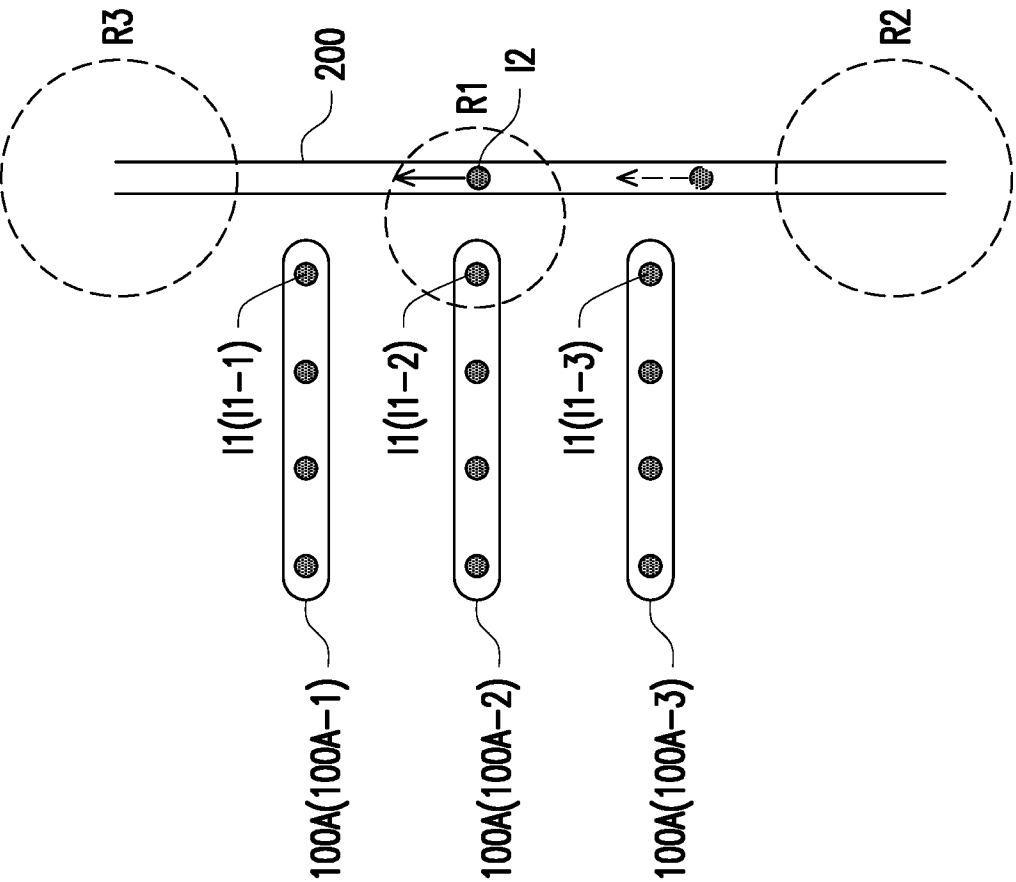


FIG. 4

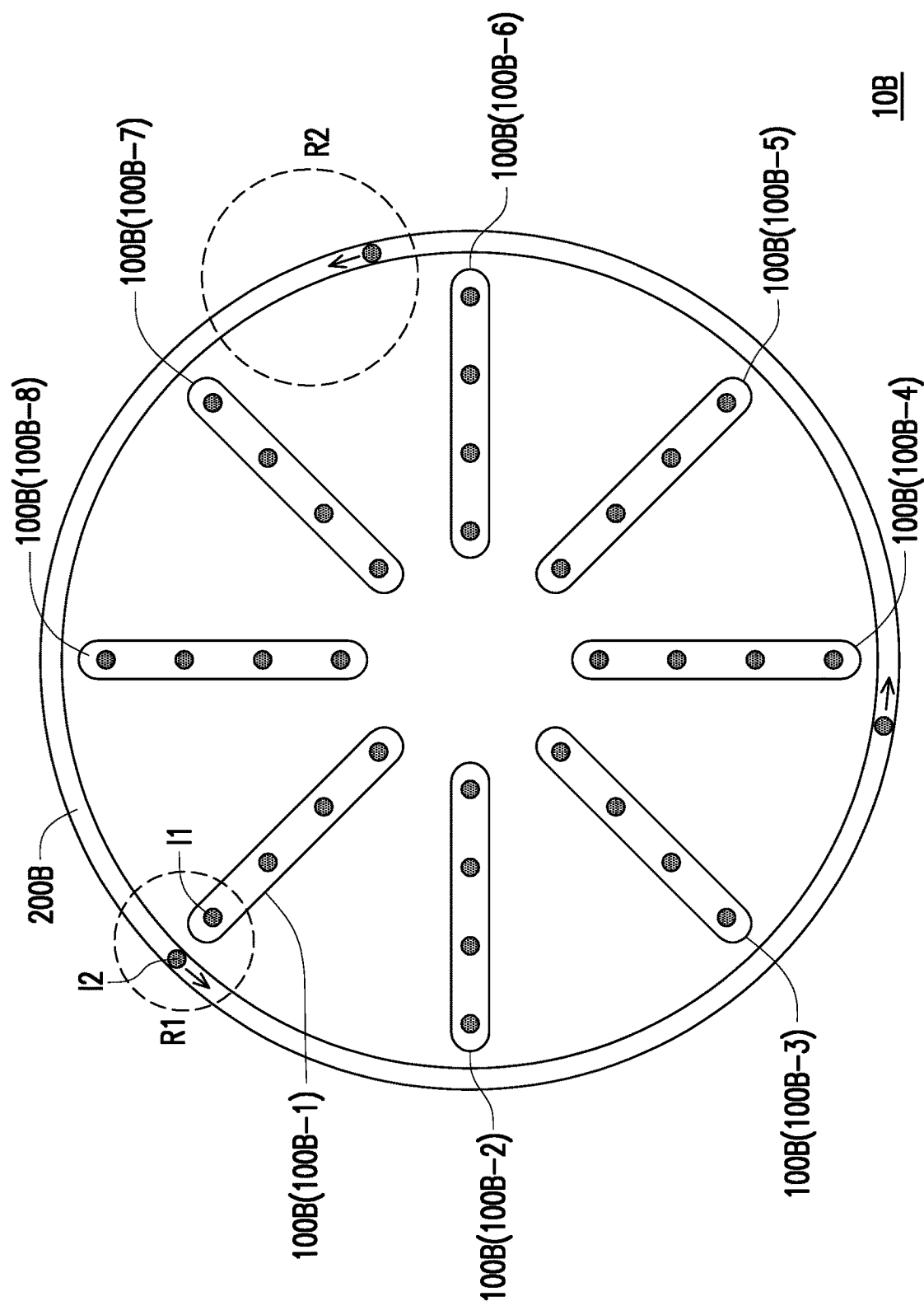


FIG. 5

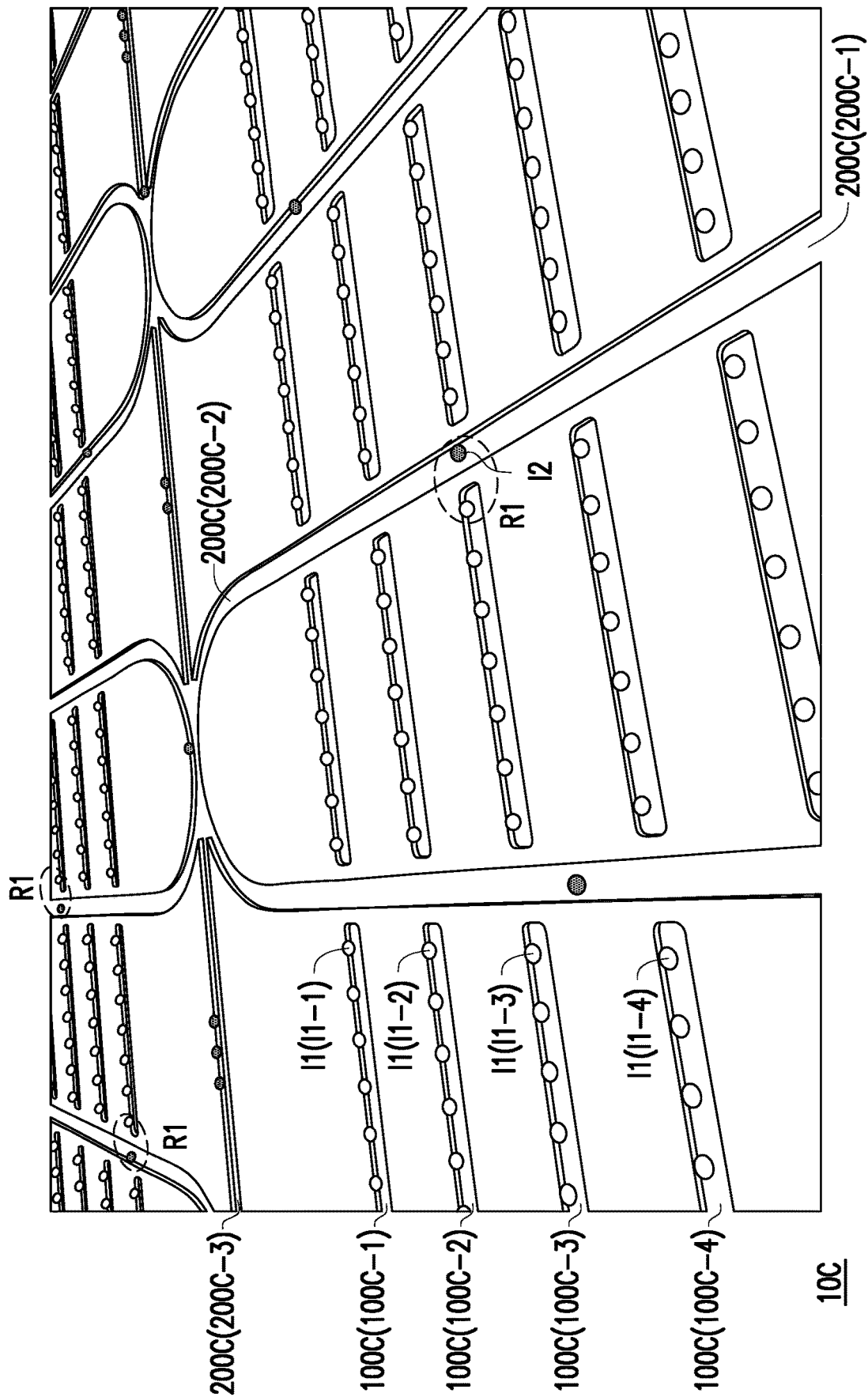


FIG. 6

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QUANTUM CHARGE-COUPLED DEVICE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the priority benefit of U.S. provisional application Ser. No. 63/283,548, filed on Nov. 29, 2021, and Taiwan application serial no. 111133656, filed on Sep. 6, 2022. The entirety of each of the above-mentioned patent applications is hereby incorporated by reference herein and made a part of this specification.

BACKGROUND

Technical Field

The disclosure relates to a quantum charge-coupled device for quantum information processing with trapped ions, and more particularly, to a scalable ion trap device consisting of stationarily trapped ion arrays and travelling ions, and to a non-stop quantum entangling gate scheme between them.

Description of Related Art

Recent development of quantum technology has driven a new wave of technological and industrial revolution and has become a strategic mission of countries around the world. Up to present, great countries and economies including the United States, European Union, China, India, and many others have invested a huge number of resources in the race of quantum technology research such as quantum communications, quantum metrology and sensing, quantum simulation, and quantum computing. Among all the implementation hardware platforms, the ion trap system has shown its promise for its long-lived quantum state coherence and unbeatable quantum gate fidelity, and therefore become one of the most leading platforms in the development of a general-purpose quantum computer.

To scale up an ion trap platform is still very challenging. Ion shuttling on a quantum charge-coupled device provides a solution and has become the current mainstream technology used by major companies such as IonQ, Quantinuum, and Universal Quantum. The key concept of the quantum charge-coupled device is the flexibility to transport ions so that they can interact with any other ion qubits in various regions to accomplish parallel quantum computing tasks with arbitrary inter-qubit connectivity. Since the realization of a two-qubit quantum logic gate still requires both ions to be in a relatively stationary potential energy well, to make this scheme of ion shuttling work must involve ion array separation, ion acceleration, turning, deceleration, re-emerging, and re-cooling. It can be expected that huge time and energy costs are wasted in re-configuring and re-cooling the ions, which lacks efficiency and creates a bottleneck in computing capability and practical scalability.

SUMMARY

The disclosure provides an alternative quantum charge-coupled device, which may effectively reduce the heat generation caused by the acceleration and deceleration required for transporting ions in the process of implementing a quantum entangling logic gate.

An embodiment of the disclosure provides a quantum charge-coupled device, which includes a first ion, a second ion, a fixed ion trap, an adjustable ion trap, and an excitation

2

light source. The fixed ion trap is configured to stationarily trap the first ion. The adjustable ion trap works as an ion rail disposed beside the fixed ion trap, and is configured to make the second ion move at a constant velocity along the ion rail.

5 The excitation light source is configured to irradiate an incident light beam, which includes a series of light pulses and covers the first ion and the second ion when a distance between them becomes less than or equal to a proximity range, such that a quantum entangled state is directly built
10 between the first ion and the second ion in uniform motion.

Based on the above, in the quantum charge-coupled device according to an embodiment of the disclosure, since the second ion is arranged to move at a constant velocity
15 along the ion rail formed by the adjustable ion trap, this design eliminates the need of a large number of steps for controlling and cooling the ions, thereby saving a significant amount of operating power and time, and reducing the system complexity. Furthermore, this architecture can be
20 easily extended to a large-scale quantum computing platform.

BRIEF DESCRIPTION OF THE DRAWINGS

25 FIG. 1 is a schematic diagram of a quantum charge-coupled device according to a first embodiment of the disclosure.

FIG. 2 is a schematic diagram of another excitation light source in FIG. 1.

30 FIG. 3 is a schematic diagram of yet another excitation light source in FIG. 1.

FIG. 4 is a schematic diagram of a quantum charge-coupled device according to a second embodiment of the disclosure.

35 FIG. 5 is a schematic diagram of a quantum charge-coupled device according to a third embodiment of the disclosure.

FIG. 6 is a schematic diagram of a quantum charge-coupled device according to a fourth embodiment of the disclosure.
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DESCRIPTION OF THE EMBODIMENTS

FIG. 1 is a schematic diagram of a quantum charge-coupled device according to a first embodiment of the disclosure. Referring to FIG. 1, an embodiment of the disclosure provides a quantum charge-coupled device **10**, which includes a first ion **11**, a second ion **12**, a fixed ion trap **100**, an adjustable ion trap **200**, and an excitation light
50 source **300**.

In the embodiment, the fixed ion trap **100** is configured to stationarily trap the first ion **11**. The fixed ion trap **100** is of about a few megahertz (MHz), e.g., 5 MHz, in trapping frequency, and can be carried out by, for example, a Paul trap, a micro-fabricated Paul trap (Microtrap), a Micro-Penning trap, or other single atom/ion trapping mechanisms.

In the embodiment, the adjustable ion trap **200** is a linear Paul trap with segmental side electrode control forming a one-dimensional rail for ion transport. Specifically, the adjustable ion trap **200** works as an ion rail disposed beside the fixed ion trap **100**, and is configured to provide a local confining trap of about a few megahertz (MHz), e.g., 5 MHz, in trapping frequency by applying voltages of the side electrodes. The position of the second ion **12** on the adjustable ion trap **200** is seen at the lowest potential energy position of the side electrode voltage configuration, and is made in a uniform motion by tuning the configuration.
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In the embodiment, the excitation light source **300** is configured to irradiate an incident light beam **L**, wherein the incident light beam **L** includes a series of light pulses and covers the first ion **I1** and the second ion **I2** when a distance between them becomes less than or equal to a proximity range such that a quantum entangled state is directly built between the first ion **I1** and the second ion **I2** in uniform motion. The series of light pulses may include Raman light pulses formed by at least two or three laser beams of different tones, but the disclosure is not limited thereto. When the phase-space trajectory of the coupled motional normal modes between the first ion **I1** and the second ion **I2** forms a closed curve, a logic gate for quantum entanglement can be realized between the first ion **I1** and the second ion **I2**. The remaining details of the quantum entangled state formed between the first ion **I1** and the second ion **I2** are not described here.

In the embodiment, the aforementioned proximity range is, for example, a range that is approximately larger than a distance **d** between the first ion **I1** and a position **P** shown in FIG. 1, or a proximity range **R1** shown in FIG. 4. In an embodiment, the proximity range is in the range of around 10 micrometers (μm) to tens of micrometers, e.g., within the range of 20 micrometers.

In the embodiment, the incident light beam **L** is irradiated toward the position **P** of the adjustable ion trap **200** when the second ion **I2** is passing by the first ion **I1**. The incident light beam **L** is irradiated to the first ion **I1** and the position **P** from a first direction **D1** or from a second direction **D2**. The first direction **D1** may be a direction (e.g., a z-axial direction in FIG. 1) perpendicular to the direction of the connection line between the first ion **I1** and the position **P** (e.g., an x-axial direction in FIG. 1) and the moving direction of the second ion **I2** (e.g., a y-axial direction in FIG. 1), and the first direction **D1** is opposite to the second direction **D2**. Incidentally, for the convenience of illustrating that the incident light beam **L** covers both the first ion **I1** and the second ion **I2**, FIG. 1 shows two separate light beams **L**, but the incident light beam **L** may be one light beam.

FIG. 2 is another schematic diagram of an excitation light source in FIG. 1. Please refer to FIGS. 1 and 2 simultaneously. In another embodiment, the quantum charge-coupled device **10** further includes a beam splitter **400**. The beam splitter **400** is disposed between the excitation light source **300** and the fixed ion trap **100** or disposed between the excitation light source **300** and the adjustable ion trap **200**. The beam splitter **400** divides the incident light beam **L** into a first incident light beam **L1** and a second incident light beam **L2**, wherein the first incident light beam **L1** includes a series of light pulses and the second incident light beam **L2** includes a series of light pulses. The first incident light beam **L1** is irradiated toward the first ion **I1**, and the second incident light beam **L2** is irradiated toward the position **P** of the adjustable ion trap **200** that is closest to the first ion **I1**.

FIG. 3 is a schematic diagram of yet another excitation light source in FIG. 1. Referring to FIG. 3, in yet another embodiment, the excitation light source **300** of the quantum charge-coupled device **10** may include a first sub-excitation light source **302** and a second sub-excitation light source **304**. The first sub-excitation light source **302** is configured to emit the first incident light beam **L1** toward the first ion **I1**. The second sub-excitation light source **304** is configured to emit the second incident light beam **L2** toward the position **P** of the adjustable ion trap **200** that is closest to the first ion **I1**. The first incident light beam **L1** and the incident light beam **L2** need to be phase-locked.

In addition, in still yet another embodiment, the excitation light source **300** may be a resonant short-pulsed laser. When the resonant short-pulsed laser is chosen to be used as the excitation light source **300**, the operation of the entangled logic gates may be sped up using the standard pulsed force gate protocols, which are not described here.

In the embodiment, the quantum charge-coupled device **10** further includes a controller (not shown). The controller is electrically connected with the adjustable ion trap **200** and the excitation light source **300**. Moreover, the excitation light source **300** is controlled by the controller to irradiate the incident light beam **L** when the distance between the first ion **I1** and the second ion **I2** becomes less than or equal to the proximity range.

The aforementioned controller includes, for example, a central processing unit (CPU), a microprocessor, a digital signal processor (DSP), a programmable controller, a programmable logic device (PLD), or other similar devices, or a combination of the said devices, which are not particularly limited by the disclosure. Further, in an embodiment, each of the functions performed by the controller may be implemented as a plurality of program codes. These program codes will be stored in a memory, so that these program codes may be executed by the controller. Alternatively, in an embodiment, each of the functions performed by the controller may be implemented as one or more circuits. The disclosure is not intended to limit whether each of the functions performed by the controller is implemented by ways of software or hardware.

Based on the above, in the quantum charge-coupled device **10** of an embodiment of the disclosure, the second ion **I2** is arranged to move at a constant velocity along the ion rail formed by the adjustable ion trap **200**. When the distance between the first ion **I1** and the second ion **I2** is less than or equal to the proximity range, the incident light beam **L** is irradiated on the first ion **I1** and the second ion **I2** such that a quantum entangled state is directly built between the first ion **I1** and the second ion **I2** in uniform motion. That is, during the process of the second ion **I2** approaching the first ion **I1**, the adjustable ion trap **200** keeps the second ion **I2** moving at a constant velocity, and does not need to move the second ion **I2** specifically with acceleration or deceleration. Therefore, this design eliminates a large number of steps for controlling and cooling the second ion **I2**, thereby saving a significant amount of operating power and reducing the system complexity. Furthermore, this architecture can be easily extended to a large-scale quantum computing platform.

FIG. 4 is a schematic diagram of a quantum charge-coupled device according to a second embodiment of the disclosure. FIG. 4 shows that a region **R2** where the second ion **I2** can be cooled and initialized, the proximity range **R1** where the first ion **I1** and the second one **I2** are irradiated and interact, and a region **R3** where the second ion **I2** can be reset and recycled.

Referring to FIG. 4, a quantum charge-coupled device **10A** of FIG. 4 is substantially similar to the quantum charge-coupled device **10** of FIG. 1, and the main differences are as follows. In the embodiment, the first ion **I1** may be generalized to multiple ions **I1-1**, **I1-2**, and **I1-3**, and a fixed ion trap **100A** includes multiple sub-fixed ion traps **100A-1**, **100A-2**, and **100A-3**. The sub-fixed ion traps **100A-1**, **100A-2**, and **100A-3** stationarily trap the sub-ions **I1-1**, **I1-2**, and **I1-3**, respectively. When the distance between each of the sub-ions **I1-1**, **I1-2**, and **I1-3** and the second ion **I2** is less than or equal to the proximity range **R1**, the incident light beam **L** is irradiated on each of the sub-ions

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I1-1, I1-2, and I1-3 and the second ion I2, enabling quantum logic operations to be realized between each of the sub-ions I1-1, I1-2, and I1-3 and the second ion I2.

In the embodiment, the sub-fixed ion traps 100A-1, 100A-2, and 100A-3 are linear ion traps or ion trap arrays, and the adjustable ion trap 200 is a linear rail. The advantages of the quantum charge-coupled device 10A are similar to the advantages of the quantum charge-coupled device 10 in FIG. 1, so details are not described herein again.

FIG. 5 is a schematic diagram of a quantum charge-coupled device according to a third embodiment of the disclosure. Referring to FIG. 5, a quantum charge-coupled device 10B of FIG. 5 is substantially similar to the quantum charge-coupled device 10A of FIG. 4, and the main differences are as follows. In the embodiment, sub-fixed ion traps 100B-1, 100B-2, 100B-3, 100B-4, 100B-5, 100B-6, 100B-7, and 100B-8 of a fixed ion trap 100B are linear ion traps or ion trap arrays, and an adjustable ion trap 200B is a large circular rail. This design does not need to reverse the moving direction of the second ion I2. Moreover, the curvature of the large circular rail is small such that there is not too significant non-inertial motion, which may be locally regarded as a constant velocity. The advantages of the quantum charge-coupled device 10B are similar to the advantages of the quantum charge-coupled device 10A in FIG. 4, so details are not described herein again.

FIG. 6 is a schematic diagram of a quantum charge-coupled device according to a fourth embodiment of the disclosure. Referring to FIG. 6, a quantum charge-coupled device 10C of FIG. 6 is substantially similar to the quantum charge-coupled device 10B of FIG. 5, and the main differences are as follows. In the embodiment, sub-fixed ion traps 100C-1, 100C-2, 100C-3, and 100C-4 of a fixed ion trap 100C are fixed linear ion traps or ion trap arrays, and an adjustable ion trap 200C includes multiple sub-adjustable ion traps 200C-1, 200C-2, and 200C-3. The sub-fixed ion traps 100C-1, 100C-2, 100C-3, and 100C-4 are configured to stationarily trap the sub-ions I1-1, I1-2, I1-3, and I1-4, respectively. The sub-adjustable ion traps 200C-1, 200C-2, and 200C-3 include linear rails (e.g., the sub-adjustable ion traps 200C-1 and 200C-3) and curved rails (e.g., the sub-adjustable ion trap 200C-2). When the second ion I2 moves along the adjustable ion trap 200C, the moving rail of the second ion I2 may be controlled through the adjustable ion trap 200C, for example, switching from moving on the sub-adjustable ion trap 200C-1 to moving on the sub-adjustable ion trap 200C-2 and then switching to moving on the sub-adjustable ion trap 200C-3. The second ion I2 may also complete state reset, re-cooling, and appropriate acceleration to a fixed speed during the switching process. The advantages of the quantum charge-coupled device 10C are similar to the advantages of the quantum charge-coupled device 10B in FIG. 5, so details are not described herein again.

In summary, in the quantum charge-coupled device of an embodiment of the disclosure, the second ion is arranged to move at a constant velocity along the ion rail formed by the adjustable ion trap. During the process of the second ion approaching the first ion, the adjustable ion trap keeps the second ion moving at a constant velocity, and does not need to move the second ion specifically with acceleration or deceleration. Therefore, this design eliminates a large number of steps for controlling and cooling the second ion, thereby saving a significant amount of operating power and reducing the system complexity. Furthermore, this architecture can be easily extended to a large-scale quantum computing platform.

6

What is claimed is:

1. A quantum charge-coupled device, comprising:
 - a first ion;
 - a second ion;
 - a fixed ion trap, configured to stationarily trap the first ion;
 - an adjustable ion trap, working as an ion rail disposed beside the fixed ion trap and configured to make the second ion move at a constant velocity along the ion rail; and
 - an excitation light source, configured to irradiate an incident light beam, wherein the incident light beam comprises a series of light pulses and covers the first ion and the second ion when a distance between them becomes less than or equal to a proximity range, such that a quantum entangled state is directly built between the first ion and the second ion in uniform motion.
2. The quantum charge-coupled device according to claim 1, wherein the adjustable ion trap is a linear rail.
3. The quantum charge-coupled device according to claim 1, wherein the proximity range falls within a range of 10 micrometers to 20 micrometers.
4. The quantum charge-coupled device according to claim 1, wherein the incident light beam is irradiated toward a position of the adjustable ion trap when the second ion is passing by the first ion.
5. The quantum charge-coupled device according to claim 1, further comprising:
 - an beam splitter, disposed between the excitation light source and the fixed ion trap or disposed between the excitation light source and the adjustable ion trap, wherein the beam splitter divides the incident light beam into a first incident light beam and a second incident light beam, the first incident light beam is irradiated toward the first ion, and the second incident light beam is irradiated toward a position of the adjustable ion trap that is closest to the first ion.
6. The quantum charge-coupled device according to claim 1, wherein the excitation light source comprises:
 - a first sub-excitation light source, configured to emit a first incident light beam toward the first ion; and
 - a second sub-excitation light source, configured to emit a second incident light beam toward a position of the adjustable ion trap that is closest to the first ion,
 wherein the first incident light beam and the second incident light beam are phase-locked.
7. The quantum charge-coupled device according to claim 6, wherein the excitation light source is a resonant short-pulsed laser.
8. The quantum charge-coupled device according to claim 1, wherein the first ion comprises a plurality of sub-ions, the fixed ion trap comprises a plurality of sub-fixed ion traps, and the sub-fixed ion traps stationarily trap the sub-ions, respectively,
 - wherein when a distance between each of the sub-ions and the second ion is less than or equal to the proximity range, the incident light beam is irradiated on each of the sub-ions and the second ion, enabling quantum logic operations to be realized between each of the sub-ions and the second ion.
9. The quantum charge-coupled device according to claim 8, wherein the sub-fixed ion traps are linear ion traps or ion trap arrays, and the adjustable ion trap is a linear rail.
10. The quantum charge-coupled device according to claim 8, wherein the sub-fixed ion traps are linear ion traps or ion trap arrays, and the adjustable ion trap is a circular rail.

7

11. The quantum charge-coupled device according to claim **8**, wherein the sub-fixed ion traps are fixed linear ion traps or ion trap arrays, the adjustable ion trap comprises a plurality of sub-adjustable ion traps, and the sub-adjustable ion traps comprise linear rails and curved rails.

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